PERFORMANCE OF VEGETATED ROADSIDES IN REMOVING STORMWATER POLLUTANTS

A Thesis

by

PAVITRA RAMMOHAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Civil Engineering

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Approved by:

Co-Chairs of Committee,	Francisco Olivera
	Ming-Han Li
Committee Member,	Anthony Cahill
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ABSTRACT

Performance of Vegetated Roadsides in Removing Stormwater Pollutants.

(May 2006)

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Stormwater runoff from highways can contain pollutants such as suspended solids, nitrogen and phosphorus, organic material, and heavy metals. Growing awareness leading to regulatory requirements reflects the need to protect the environment from highway runoff effects. The management practice discussed in this study is the use of vegetated roadsides. The primary objective of this research is to document the potential treatment values from vegetated roadsides typical of common rural highway cross sections in two Texas cities: Austin and College Station. Three sites in each city were examined in this study over a 14-month monitoring period.

No significant difference between the edges of pavement pollutant concentrations were observed at any of the research sites in the two study areas. This allowed for direct comparisons of the vegetated roadsides and their associated site characteristics such as annual daily traffic (ADT), dry period, and rainfall intensity.

The scatter plots of College Station data show that concentrations of total suspended solids (TSS), total Pb, and chemical oxygen demand (COD) in runoff are dependent on the antecedent dry period and decrease with longer dry periods. The results show that pollutant concentrations are not highly dependent on ADT. However, the results show that the number of vehicles during the storm (VDS) was evaluated and accepted as a satisfactory independent variable for estimating the loads of total Pb and TSS. The results of correlation analysis show that the concentrations of total Pb and chemical oxygen demand are significantly correlated with TSS levels. The findings indicate that nitrate concentrations in runoff is most dependent on the average daily traffic using the highway during the preceding dry period as well as the duration of that dry period.

Sites 2 and 3 in College Station are steeper but outperformed Site 1 which has much flatter slopes. This could be accounted for by the poor vegetative cover (brown patches) at Site 1. In the Austin sites, the permeable friction course appeared to have a significant impact on the quality of runoff leaving the road surface.

On the whole, the results of this study indicate that vegetated roadsides could be used as a management practice for controlling and treating stormwater runoff from Texas highways.

To my parents

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CHAPTER I

INTRODUCTION

Regulatory agencies have recently focused attention on nonpoint sources of pollution causing environmental problems. Vegetated roadsides are sections of grassy areas adjacent to the pavement to receive stormwater runoff from the highways. Stormwater runoff from highways can contain pollutants, such as total suspended solids (TSS), heavy metals (including total and dissolved copper (Cu), lead (Pb), and zinc (Zn)), nitrogen and phosphorus, chemical oxygen demand (COD) and organic material.

Today, sources of urban runoff, including highways, are regarded as the formidable obstacles that may hamper achieving water resource goals (USEPA, 1993).Growing concern regarding the harmful effects of these constituents on receiving waters has lead to regulatory measures since the 1970s. Regulatory requirements reflect the need to protect the environment from the deleterious effects of urban and highway runoff. The United States Environmental Protection Agency's (USEPA'S) National Pollutant Discharge Elimination System (NPDES) regulations pertaining to stormwater runoff are evidence of this effort. Stromwater quality in Texas is under the jurisdiction of the USEPA and the Texas Commission on Environmental Quality (TCEQ).

This thesis follows the style of *Journal of Environmental Engineering*

The USEPA's Clean Water Act of 1972 was amended in 1987 to include stormwater discharges. According to this act, the states are required 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. Water bodies that are deemed not supportive of the beneficial uses are designated as contaminated and are placed on what is known as the 303(d) list. The state reviews the 303(d) list and updates it every four years.

A total maximum daily load (TMDL) for the constituents contributing to the contamination must be developed for each of the listed stream segments. TMDL is an estimate of the maximum pollution load a water body can receive from point and nonpoint sources and still maintain the specified standards (USEPA, 1991). The TMDL process involved the identification of possible measures to reduce the excess load from controllable contributing sources and to bring water bodies into compliance. The Texas Commission of Environmental Quality (TCEQ), in cooperation with the Texas State Soil and Water Conservation Board (TSSWCB), implemented TMDL projects in Texas.

A well developed management and allocations of wasteload will allow the beneficial uses to be realized. All parties responsible for discharges to the water body are required to take adequate measures to reduce their pollutant discharges in order to achieve their individual wasteload allocations. Controlling the nonpoint sources is a much greater challenge than reducing pollutant discharges for non-point sources. These reduction measures are known as best management practices (BMPs) for nonpoint source discharges such as stormwater runoff from highways.

Hence, both environmental response and regulatory reasons indicate the need for a stormwater management plan for highways. The Texas Department of Transportation (TxDOT) builds and maintains highways in Texas, and is responsible for controlling and mitigating the negative effects of highway stormwater runoff on receiving water bodies.

Increased urbanization leads to development projects including construction of new roadways and highways to accommodate the growing population, thereby causing increased pollution of the water segments. Increases in road surface area will decrease the permeable ground cover over which infiltration of rainwater and runoff can occur. This will lead to rapid discharges to receiving water bodies. These trends in development add further significance to evaluate the contributions of constituents in runoff from roadways and to control their effects.

The BMP investigated in this study includes the non-structural BMP called the vegetated roadsides. Vegetated filter strips (VFS) are “vegetated sections of land designed to accept runoff as overland sheet flow from upstream development” (Schueler, 1992, p.79). They could adopt any natural vegetated form, from grassy meadow to small forest. The dense vegetative cover has been proved to facilitate pollutant removal (Schueler, 1992).The mechanisms of pollutant removal in vegetated roadsides are filtration by grass blades, sedimentation, adsorption, infiltration into the soil, and biological and chemical activity in the grass/soil media. Though vegetated swales have not been accepted as primary controls for the treatment of stormwater runoff, grassed swales are typically used as an alternative to curb and gutter drainage systems. In most cases, swales were used in combination with other BMPs to meet stormwater management requirements (Schueler, 1987).However; there is a body of research that supports the use of vegetated filters as a primary pollution control method. A more detailed understanding of the preferred characteristics and benefits of vegetated roadsides can be developed by regulatory agencies through future research in this area. There remains a number of important site-specific questions regarding the pollutant removal that can be anticipated. Rainfall patterns, soils and typical road cross-sections also play a significant role in ensuring the full benefit of vegetated shoulders and channels (Barrett et al., 2004). This documentation can also be used as part of the design of systems that results in meeting specific requirements in stormwater quality.

Roadside vegetated shoulders are now commonly used as low-cost practices in various countries such as North America, Australia, France, and Germany, in order to convey impermeable runoff from the highway surface. Therefore it is important to evaluate and document the extent to which these vegetated roadsides may reduce pollutant loads in runoff and mitigate the effects of discharge untreated highway runoff directly into receiving water bodies.

1.1 Objectives and scope of the study

The objectives of this study are the following:

1. To measure the efficiency of vegetated roadsides in removing constituents in highway runoff at College Station and Austin sites.
2. To determine the effects of rainfall intensity, dry period, and ADT on pollutant concentrations.

3. To document the potential treatment values from vegetated roadsides.

The scope of this study covers highway stromwater runoff and testing of roadside vegetation for highway runoff pollutant removal. The highway contaminants analyzed in this study include TSS, nutrients, heavy metals, COD, and fecal coliform.

1.2 Organization of the thesis

A brief introduction to all the following chapters is done in this section. Chapter I presents the objectives and scope of the study.

Chapter II includes the acknowledgement of the past research work performed on the study of water quality benefits from vegetated roadsides in treating stormwater runoff. The report includes numerous studies that have focused on identifying the sources of highway runoff, characterizing highway runoff, determining factors affecting highway runoff quality, and gaining a better understanding of pollutant transport processes. A deeper understanding of the benefits offered by vegetated roadsides has been reported.

Chapter III involves the summary of activities carried out as part of this study. This chapter discusses the primary criteria used for site selection, site setup, installation of the sampling equipments, description of the sampler and zero meter flow strip, sampling procedures followed, a brief introduction to the vegetation survey conducted at the two study areas. The chapter also involves the tools used to perform statistical analysis on the dataset.

Chapter IV includes the results and analysis performed on the dataset of College Station and Austin. The chapter discusses the statistical analyses (including summary statistics, ANOVA tests, post hoc analysis, correlation and regression analysis) of both of the study areas. The overall performance of vegetated roadsides at both of the sites is discussed. In Austin sites, the comparison between the pollutant concentrations from the permeable friction course and traditional asphalt surface is performed. Following that, the comparisons drawn between the key findings from each of the research areas are reported.

Chapter V includes the summary and concluding remarks based on the findings from the two study areas. The chapter highlights the key findings of this study and provides recommendations based on the findings.

Appendix section includes the boxplots of each constituent at each of the College Station and Austin sites, the findings of the survey conducted to understand the current state of practice among other state department of transportation (DOTs), vegetation survey results at both of the study areas, traffic count data and results of soil content analyses at College Station sites, and the results of the field experiment.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Highway runoff, nonpoint source pollution, has become one of the environmental concerns in recent years. It is widely recognized that highway runoff contains a range of toxic pollutants that can have adverse impacts on receiving waters, both ground and surface. Past studies on stormwater runoff from multilane highways with more than 100,000 vehicles per day have indicated that, though highways may represent only 5-8% of the urban catchment, highway runoff can contribute as much as 50% of TSS, 16-25% of total hydrocarbons (HCs), and between 35-75% of the total metal pollutant input budgets to a receiving water body (Ellis and Revitt, 1991; Luker and Montague, 1994). Increased development and urbanization causes an increase in total channels and in turn an increase in the overall drainage density. Coupled with the lower infiltration rates and extensive effective impervious cover in urbanized areas, this leads to increased amounts of runoff and shorter concentration times for the drainage basin, producing larger peak discharges (Marsh, 2005). Some roadway runoff is collected and treated by BMPs or other urban drainage systems; however, much of the runoff from highways drains untreated before entering the receiving water body. Numerous studies over the last 25 years have focused on identifying the sources of highway runoff, characterizing highway runoff, determining factors affecting highway runoff quality, and gaining a better understanding of pollutant transport processes (Habibi, 1973; Asplund et al., 1980; Kerri et al., 1976, as cited in Wang et al., 1981; Yousef et al., 1985; Barrett et al., 1995; Irish et al., 1998; Barrett et al., 2004).

2.2 Sources of pollutants

Major sources of pollutants on highways identified in past studies include vehicles (exhaust emissions, fuel losses, lubrication system losses, and tire wear), dustfall, and precipitation. There are many factors affecting the type and amounts of these pollutants and they include: traffic volume and type, local land use, and weather patterns (Barrett et al., 1995). Roadway maintenance practices such as sanding and deicing, or the use of herbicides on highway right-of-ways have been found to act as source of pollutants (Barrett et al., 1995).

Other possible, but infrequent, sources of pollutants include spills of recreational vehicle waste, agricultural or chemical products, or oil and gas losses from accidents. According to Asplund et al. (1980), these losses are related to traffic volume and could lead to a large pollutant load locally.

2.2.1 Vehicles

Motor vehicles have been identified as both a direct and indirect source of constituents on highways. They deposit quantities of grease, oil, and other petroleum products (Yousef et al., 1985). Pollutants emitted by automobiles are deposited on the highway system or transported by advective (EPA defines it as “transportation of contaminants by the flow of a current of water or air”) and diffusive (EPA defines it as “the movement of suspended or dissolved particles from a more concentrated to a less concentrated area").As a direct source, vehicles contribute constituents from normal operation and frictional parts wear. Indirect or accumulated pollutants are solids that are acquired by the vehicle for later deposition, often during storms (Asplund et al., 1980, also cited by Barrett et al., 1995). Other transport mechanisms include stormwater washoff or splashing of contaminated stormwater from roadway surface by vehicles (Yousef et al., 1985). Once the contaminants are washed off the highway surface, they are carried with the runoff water to receiving water bodies or they may infiltrate into the soil. Yousef et al. (1985) point out that the extent of infiltration will depend on the existing soil, moisture conditions, rainfall intensity and duration of rainfall, soil type, vegetation cover, and the topography of adjacent lands.

Heavy metals in highway runoff originate from various aspects of vehicle operations. The metals they contribute include gasoline and exhaust emissions (Pb, Ni), lubricating oils (Pb, Ni, and Zn), grease (Zn, Pb), tire wear (Cd, Zn), concrete paving wear (various metals depending on aggregate source), asphalt paving wear (Ni, V), bearing wear (Cu, Pb), brake lining wear (Cu, Cr, and Ni) and wear of moving engine parts (Fe,Mn,Cr,Co) (Kerri et al.,1976, as cited in Wang et al., 1981).

Habibi (1973) states that the particulate matter discharged from the exhaust of cars is a complex mixture of Pb salts, iron as rust, base metals, soot, carbonaceous material, and tars. Past studies indicate that most of the emitted Pb is in the particulate inorganic form (Laxen and Harrison, 1977, as cited in Wang et al., 1981).The composition and total particulate emission rate are determined by many factors including the mode of vehicle operation, the age and mileage of the car, and the type of fuel. It was found that Pb occurs in two distinct particle size ranges: < 1 µm and 5 - 50 µm (Habibi, 1973).

Past studies indicate that vehicle exhaust is mainly responsible for all of the carbon monoxide, nitrogen oxides, and Pb compounds emitted (Barrett et al., 1995). They found that it accounts for about 65% of the hydrocarbons, with the remainder derived from crankcase blowby and evaporation from the carburetor. Furthermore, they state that wear of automotive components and corrosion of bodywork contribute to heavy metals discharge in the runoff. Pollutant generation by wear and abrasion is inferred from mass loss estimates. Leakage of brake fluid, antifreeze compounds, transmission fluid, engine oil, and grease results in a direct input to the highway surface (Ball et al., 1991).

2.2.2 Atmospheric deposition

Atmospheric sources contribute a significant amount of the pollutant load in highway runoff. The deposition may occur in precipitation during rainfall storms or as dustfall during dry periods (Barrett et al., 1995).

2.2.3 Roadway maintenance practices

Kramme et al. (1985) reports that a number of day to day highway maintenance practices may adversely affect water quality. The proximity of the maintenance activity to a water body has been found to increase the likelihood of adverse effects. The nature of the materials and methods used in the activity may also affect the impact. According to Kramme et al. (1985a, also cited in Barrett et al., 1995), the factors that increases the chance of adverse impact include the following:

1. Exposing or moving soil or sediment, excessive mowing, including activities that result in accidental or incidental removal of vegetative cover
2. The use or disposal of toxic components, especially if such components are leachable
3. The use or disposal of materials containing nutrients (application of fertilizers, pesticides, and insecticides)
4. The use or disposal of materials that could change the turbidity, pH, or suspended or dissolved solids content of the receiving body of water

2.3 Characteristics of highway runoff

The nature and type of pollutants in highway runoff can be influenced by traffic conditions, precipitation and atmospheric conditions, and road conditions (Barrett et al., 1995). Important precipitation and atmospheric characteristics that may affect the quality of runoff include antecedent dry periods, storm intensity, and volume of storm-derived runoff (Barrett et al., 1995).

Irish et al. (1998) demonstrate that each of the stormwater constituents were dependent upon a unique subset of the identified variables, indicating that processes responsible for the generation, accumulation, and washoff of stormwater pollutants are constituent specific . According to Irish et al.(1998), the constituents in highway runoff could be classified as (1) those such as TSS, that are influenced by conditions during the dry period and may be mitigated by dry period activities, such as street sweeping; (2) those constituents that are most influenced by conditions during the rainfall event and may only be mitigated in a cost effective manner through the use of runoff controls; and (3) those constituents that are influenced equally by both periods and that may be mitigated using a combination of street sweeping and structural runoff controls.

The identification of constituent specific explanatory variables suggests the mitigation that would be more appropriate for specific constituents in non-point source pollution control. Irish et al. (1998) identified the variables that could influence the loading of a constituent in storm runoff from a highway, during the three different periods: (1) the current storm; (2) the antecedent dry period; and (3) the preceding storm. The variables selected to characterize the current storm included measures of rainfall duration, intensity, volume of runoff, and the number of vehicles passing the sampling site. The antecedent dry period was characterized by the time since the last rainfall event and the number of vehicles since the previous storm. The variables associated with the preceding storm included duration, intensity, and volume of runoff (Irish et al., 1998).

According to Irish et al. (1998), TSS loadings and volatile suspended solids (VSS) are influenced by antecedent dry period conditions and runoff intensity during the preceding storm. However, Irish et al. (1998) addresses that 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. Other investigators report only slight correlations between stormwater runoff quality and the ADT count. Though Vehicles during a storm (VDS) are cited as a more significant indicator of expected pollutant loads than ADT, Barrett et al. (1995) point out, that VDS count may only be reflecting the importance of runoff volume on the runoff quality. According to Barrett et al. (1995), the effects of antecedent dry periods are already contributing to the pollutant loads. No strong correlations have been reported for short dry periods and lower pollutant loads. Barrett et al. (1995) argue that rainfall intensity has a direct impact on pollutant concentrations because particulate matter (suspended solids) are more easily mobilized during high intensity storms and low intense storms lacks the energy to mobilize the pollutants. According to them, runoff volume is currently thought to have little effect on pollutant concentrations (but is important in determining total loads to a receiving body).

The first flush phenomenon refers to the washing off of the pollutants from the highway caused by the initial stages of a rain. Therefore, many stormwater treatment systems are designed to remove and treat that first flush. Barrett et al. (1998) report that grassy medians could be effective in reducing stormwater loads from highways. According to Young et al. (1996), the first flush effect is referred to as the half-inch rule, in which 90% of stormwater constituents are believed to be washed off in the first half inch of runoff. They also found that the first flush effect is well pronounced for areas with highly impervious covers. Barrett et al. (1998), report that most of the washoff occurs during the initial stages of runoff before the peak runoff and is strongly correlated with rainfall intensity. Past studies reported that peak concentrations of heavy metals were observed shortly after the initiation of runoff, usually within the first thirty minutes (Yousef et al., 1985). They also reported a tendency for solids to settle out in the stormsewers during the latter stages of the storm flow. A first flush effect was observed by Hewitt and Rashed (1990), for the dissolved metals. Past studies show that 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 and are most likely found in the dissolved rather than the particulate phases. P is the limiting nutrient in aquatic productivity due to its usually low concentrations in the environment and its biological demand (as cited in Yousef et al., 1985). The principle step of lake restoration projects has been to control and limit the input loading as well as the internal cycling of P. Inorganic phosphates are the most significant and occur largely as orthophosphate (PO_4^{-3}), or as condensed phosphates, such as metaphosphate (PO_3^{-}), trisphosphate ($P_3O_{10}^{-5}$), and pyrophosphate ($P_2O_7^{-4}$). Dissolved phosphates makes up 5 to 50% of the P.

The nutrients such as nitrogen and P can have sources and sinks dependent upon the form of the nutrient. For example, NH_4^+ has a relatively high soil partition coefficient while NO_3^- does not partition onto the soil but can have a high plant uptake rate (Yonge, 2000). Nutrients, unlike most heavy metals, can be significantly impacted by micro and macrobiological activity. As a result, nitrogen and P compounds will tend to cycle in a system, especially in temperate zones that experience annual growth, death, and decay cycles. Plants can act as a sink of nutrients during growth and dead vegetation will act as a source during the bacterial decay process. The net flux of nutrients in the vadose zone will be a function of plant type, soil type, time of year, moisture content, and bacterial activity (Yonge, 2000). Past studies indicate 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 (Folkeson, 1994).

Though some reports concluded that the concentrations of nitrate and nitrite do not have a strong correlation with TSS levels (Barrett et al., 1995), other studies indicated that nitrate and total P concentrations in runoff are most dependent on ADT during the preceding dry period as well as the duration of that dry period (Irish et al., 1998).

Barrett et al. (1995), reported correlations between solids and polycyclic aromatic hydrocarbons (PAHs), total organic carbon (TOC), COD, and extractable organics. Metals usually adsorb onto the surface of the particulate matter and are washed off from the highway. Past studies showed that Pb loadings are significantly correlated with solids while Zn, Fe, Cd, Cu, and Cr loadings are found to be slightly correlated with solids (Barrett et al., 1995). Irish et al. (1998) reported 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. Barrett et al. (1995), reported that the effects of sanding and deicing during the winter months could increase loadings of suspended and dissolved solids to receiving waters.

2.4 Factors affecting highway runoff water quality

There are many mechanisms for the removal of pollutants from highways. These include stormwater runoff, wind, vehicle turbulence, and the vehicles themselves. Asplund (1980) report that the removal mechanism is determined by the highway conditions, especially whether the highway is wet or dry. Figure 2.1 shows the removal mechanisms for each case and the possible factors influencing the removal process. According to Asplund (1980), the mechanical scrubbing action of the tires along with natural or vehicle created winds, could scour the road and transport the pollutants away from the vehicle lanes and the highway. The researcher report that most of the pollutants deposited on the driving lanes are rapidly blown on to the median strips or completely off the highway. The mechanism adopted during the wet weather periods is accomplished through scrubbing of the pavement either by the rainfall intensity or by mechanical energy from vehicles during the storm with subsequent removal via the stormwater runoff (Asplund, 1980).

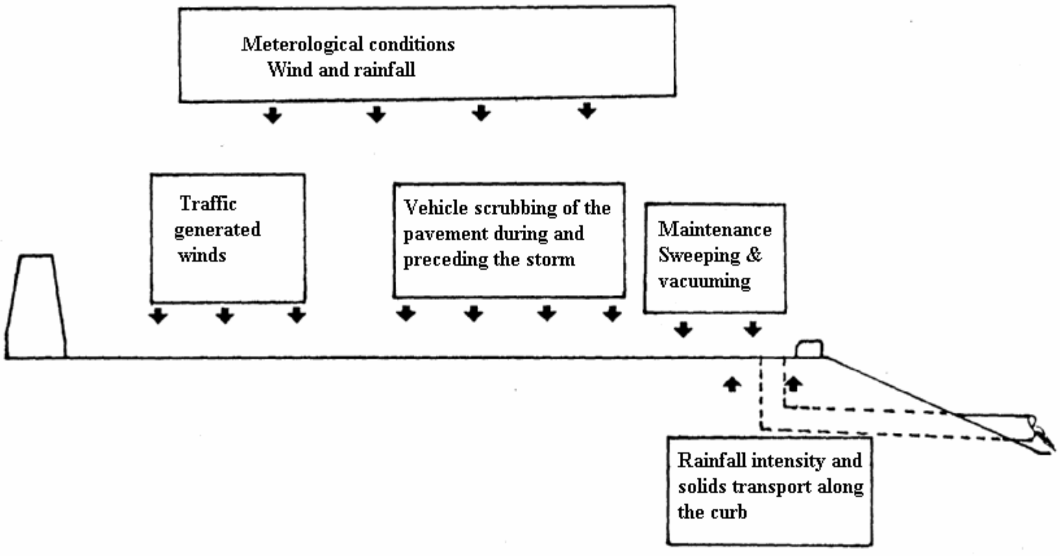


Figure 2.1. Pollutant removal mechanisms (Asplund, 1980)

Past studies reported that only 8% of the Pb emitted by vehicles was removed in runoff, while 6% was deposited in soils adjacent to the roadway and about 86% was dispersed by the atmosphere away from the vicinity of the road (Hewitt and Rashad, 1990). They also found that between 70% and 99% of PAHs were removed from the road by the atmosphere. During periods of wet weather, the primary removal mechanism is found to be stormwater runoff (Asplund, 1980). Though the traditional method for determining pollutant inputs to the roadside is collection and analyses of runoff, past studies have found wind transport to be a more important mechanism for pollutants entering vegetated treatment systems than runoff (Lind and Karo, 1995; Burch et al., 1985; as cited in Zanders, 2005)

The remainder of this section will concentrate on how the traffic volume, precipitation characteristics, highway surface type, and the nature of the pollutants could influence the highway runoff water quality. Complex interactions between these variables could obscure simple correlations between individual variables and water quality.

2.4.1 Traffic volume

Motor vehicles are one of the major sources of metals and other contaminants to highway runoff; therefore, the amount of traffic on a given stretch of highway should have an influence on the accumulation of pollutants on the highway surface. However, past studies report that vehicle turbulence can also remove solids and other pollutants from highway lanes and shoulders (Asplund et al., 1980), obscuring the relationship between individual variables traffic volume, pollutant loads, and concentrations in runoff. Furthermore, there are two measures of traffic volume which must be considered: ADT and VDS. The observations made in several reports indicate that there is only a slight dependence of the quality of stormwater runoff on ADT. Past studies found that runoff concentrations are two to four times higher at urban high-traffic sites (ADT > 30,000) compared to nonurban low-traffic sites (ADT < 30,000) sites (Driscoll et al., 1990). However, regression analyses of the data from the urban sites indicated no strong or definitive relationship between ADT and pollutant level. The data indicated no correlation of TSS, total solids, BOD, oil and grease, P, nitrate, TKN, or heavy metals with traffic density. However, for some organic pollutants, including VSS, COD, and TOC, results showed the most consistent degree of correlation with traffic density and ADT explained about 40 percent of the site differences. Conversely, some of the reports have found that VDS could be a better significant factor in the determination of pollutant loads than either ADT or the antecedent dry period (Kerri et al., 1985).

Based on past studies, several additional traffic factors which might influence runoff quality include the following (Kobriger and Gupta, 1984):

1. Vehicular mix (percentage trucks/cars)
2. Congestion factors (braking), ramps, weaving
3. Level of service - numbers of lanes, variations in traffic flow
4. Vehicle Speed

2.4.2 Precipitation characteristics

Several studies have attempted to determine the importance of the factors of a storm event which could be relevant to the resultant water quality of runoff from a highway surface. The three factors are the number of dry days preceding the event, the intensity of the storm, and the volume of the storm-derived runoff.

(a) Antecedent dry period

Past studies report that the accumulation of Fe, Pb, Zn, and airborne particulates was a linear function of antecedent dry period (Moe et al., 1982). Some reports did not find a correlation between antecedent dry period and peak load concentration, but the negative correlation with discharge in the previous 24 hrs reflected the role of runoff in cleansing the road surface. From these reports, it can be inferred that rainfall effectively removes pollutants from the road surface and that a short antecedent dry period will result in lower pollutant loads (Harrison and Wilson, 1985). However, Barrett et al. (1995) argue that changes in the rate of deposition of pollutants on the road surface and removal processes such as air turbulence (natural or the result of vehicles), volatilization, and oxidation could reduce the correlation between pollutant load and longer antecedent dry period.

(b) Rainfall intensity

Past studies indicated that the intensity of the storm can have a marked impact on the type and quantity of pollutants in runoff. This is due in large part to the fact that many pollutants are associated with particles, which are more easily mobilized in high intensity storm events (Hoffman et al., 1985).Pollutant concentrations were found to occur during high flow rates when transport of contaminants was most efficient. Peaks in pollutant concentrations during lower flow conditions occurred due to reduced dilution during these periods (Barrett et al., 1995).

(c) Runoff volume

The third precipitation characteristic, the runoff volume, has a little effect on pollutant concentrations but is important in determining the total load to the receiving water. Past studies determined the correlation between runoff volume and eight pollutant concentrations using 184 paired data sets from 23 sites (Driscoll et al., 1990). The statistical results indicated only 10% of the data sets were significantly correlated at the 95% confidence level, and only 15% were significantly correlated at the 90% confidence level. Additionally, even for the few sets with significant correlation, the correlations were weak, i.e., on average they explain about 20% of the concentration variability.

Based on the past findings, the concentrations of runoff pollutants were greater during shorter, low volume storms in which there was no runoff from unpaved areas (Dorman et al., 1988). Larger storms dilute the highway runoff and thereby lower the pollutant concentrations with runoff from unpaved areas. Even though concentrations are lower, loadings of pollutants are generally greater from longer storms, as they facilitate the transportation of constituents throughout the duration of the event. Many solids and other pollutants that accumulate on the pavement and in the gutter between storms are quickly washed off, but other sources such as vehicles and atmospheric fallout were found to release pollutant constituents (Kerri et al., 1985).

2.4.3 Highway surface type

The type of highway paving materials was found to affect the amount of pollutants in highway runoff. Past studies determined that oil and grease loadings were highest from an asphalt-paved surface, but concluded that land use was the most important factor in determining runoff quality (Gupta et al., 1981). Driscoll et al. (1990) reported that highway surface type was an unimportant factor that could affect the amount of pollutants.

Growing interest in the use of porous pavements is due to their potential to be effective runoff control methods. Porous asphalt is an alternative to traditional asphalt which is obtained by eliminating the fine aggregate from the asphalt mix. A layer of porous asphalt about two inches thick is placed on top of an existing road base. Past studies report that the asphalt in an overlay layer generally has 15-20% void space. They report that when rainfall hits the friction course, it drains through the permeable friction course (PFC) until it hits the impervious road bed at which point it will drain away from the road just as with traditional road surfaces (Kearfott, 2005). The volume of surface runoff and the amount of spray created during rain events were found to be greatly reduced as a result of the semi-permeable nature of this surface. This suppression of spray has been found to improve visibility and increase the safety level for motorists (Kearfott et al., 2005). They also reported that PFC provided a reduction in the noise level produced by vehicles on the road.

Barrett et al (1995) report higher pollutant loadings and concentrations for COD, TOC, Pb, and Zn in runoff from asphalt surfaces than from concrete surfaces. They also reported that TSS and oil/grease concentrations and loadings were higher from concrete surfaces in some cases. Thus past research on porous pavements show that they could 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).

2.4.4 Pollutant characteristics

The pollutant form (dissolved or particulate) influence the concentration and behavior of pollutants in runoff to a large extent. Past studies show that metals are predominantly washed from highways after adsorption upon particulate materials such as bituminous road surface wear products, rubber from tires, and particles coated with oils. Additionally, the degree of association with solids varies between different metals (Barrett et al., 1995). Gupta et al. (1981) found that dissolved metal fractions in runoff were small for Pb, Zn, and Fe. Pb values were found to be low and often below detectable limits of 0.05 mg/L. Metal loadings were tested for statistical correlation with solids loadings. The results of the past studies show that Pb was significantly correlated with solids at a 99% confidence limit for six out of six sites, while Zn, Fe, and Cd were correlated at five of the six sites, Cu and Cr at four sites, and Hg at only one (Gupta et al., 1981).

Hewitt and Rashed (1992) report that Pb is the metal most associated with particulates. The particulate fractions for Pb, Cu, and Cd in their research study were respectively 90%, 75%, and 57%.

2.4.5 Surrounding land use and seasonal considerations

Past studies have found significant differences in highway runoff quality between urban areas and rural areas (Driscoll et al., 1990). Reports show that traffic densities are significantly different between these two categories of land use; no clear correlation with

ADT within each grouping was observed. This leads to the conclusion that atmospheric quality differences between urban and rural areas could be an important influence. Driscoll et al. (1990) report that unusual factors, such as high Zn concentration in runoff at a site adjacent to a smelter, and high solids loading resulting from the eruption of mountains, could influence the quality of runoff.

2.5 Vegetative controls for highway runoff

Vegetative controls are common management practices adopted for abatement and control of highway runoff pollution. Vegetative swale trenches located along highways, such as the median of major interstate freeways. Past studies have determined that pollutants could be retained in a swale by adsorption, precipitation, and/or biological uptake (Yousef et al., 1985). Swales are usually less expensive to construct than curbs and gutters but require more land. The primary maintenance activities include mowing and periodic sediment cleanout (Schueler et al., 1992). Swales can be used alone or in combination with other measures such as detention basins, wetlands, or infiltration systems. The primary removal mechanism in vegetative controls is sedimentation and the secondary mechanisms include infiltration and adsorption (Dorman et al., 1996).Vegetative controls have been identified as the least expensive technique for managing highway runoff (Barrett et al., 1995). Swales provide sufficient runoff control to replace curbs and gutters in single-family residential subdivisions and on highway medians; however, they fail to control large storms (Schueler et al., 1992). Conventional swale designs have achieved mixed performance in removing particulate pollutants such as suspended solids and trace metals and are generally unable to remove significant amounts of soluble nutrients (Schueler et al., 1992). The grassy swales not only cost less but also increase the perviousness of highway drainage, thereby reducing the runoff volume, whereas, curb and gutter systems tend to concentrate and quickly transport the pollutants from the highway (as cited in Kaighn and Yu, 1996).

The two types of vegetative controls discussed in the following lines are grassy swales and vegetated buffer/filter strips. Grassy swales are earthen conveyance systems in which pollutants are removed from urban stormwater by filtration through grass and infiltration through soil (Schueler et al., 1992). They act to remove pollutants by the filtering action of grass, by settling, and in some instances, by infiltration into the subsoil. Swales were the first type of continuous flow, contaminant removal mechanism studied that had the potential to treat relatively large volumes of runoff from major highway sections.

Swales encourage settling of suspended solids and do not require curb and gutter systems. Past studies indicate TSS removals of 65-70% for some grassy swales (Barrett et al., 1998). Vegetated filter strips are vegetated sections of land designed to accept runoff as overland sheet flow from upstream development and they conventionally have slopes less than 5% (Schueler et al., 1992). They cannot treat high velocity flows; therefore, they are recommended for use in agriculture. Filter strips differ from grassed swales in that swales are concave vegetated conveyance systems, whereas filter strips have relatively level surfaces (Schueler et al., 1992). Results from a study in California show 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). Concentration reductions were consistently found to occur for TSS and total metals and frequently for dissolved metals (Barrett et al., 2004). Barrett et al (2004) found that nutrient concentrations were unchanged by the buffer strips. The reports showed that the water quality performance declined rapidly as vegetative cover dropped below 80% and a minimum of 65% vegetation cover was required to achieve reduction in constituent concentration. Field studies indicate that strips tend to have short life spans because of lack of maintenance, improper location and poor vegetative cover (Schueler et al., 1992).

According to Yousef et al. (1987), dissolved metal concentrations existing in ionic species, were found to be better removed than P and nitrogen. They found that swales built on dry soils with good drainage and high infiltration rates showed better removal efficiencies for highway contaminants. They also recommended that designs of swales with reduced slopes, offering maximum on-site retention, could increase the swale efficiency in removing pollutants. They also found that sandy soil offering good infiltration rates could be ideal for swale systems in areas with sufficient depth above groundwater elevation.

Swale length, shape, slope, flow rate, type of vegetation, and infiltration rates are some of the variables that could influence the removal efficiency (Kaighn and Yu, 1996). Dorman et al. (1996) report that TSS removal varied among three swale sites, each with the same length. The swale that created the shallowest depth of flow offered the longest detention times and thereby removed the most TSS. Removal of metals was also found to be directly related to TSS removal. Dorman et al (1996), found that 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. They also found that nutrient removal varied widely among the sites and was not related to TSS removal.

Past reports indicate 84% and 70% removal of TSS by buffer strips. They found that stiff grass hedges could remove 90% of coarse sediment (larger than 125 µm) and 20% of the finer sediment (smaller than 32 µm) (Meyer et al., 1995; as cited in Kaighn and Yu, 1996).The removal rates in buffer strips were found to be 63.9% for TSS, 59.3% for COD, -21.2% for total P (indicating an increase over the strip), and 87.6% for Zn (Kaighn and Yu, 1996). Results from other studies confirmed that pollutants that are associated with larger particles are easily captured by the vegetated buffer strips. According to Walsh et al. (1997), simulated highway runoff was applied to a constructed grasslined channel and was sampled at 10, 20, 30, and 40 meters along the length of the channel. They observed high removal efficiencies for suspended solids and metals and majority of pollutant removal was found to occur within the first 20 meters.

Yonge et al. (2000) point that reduction in TSS concentration has been achieved although negative concentration reductions were observed on an infrequent basis. High removal efficiencies of TSS (greater than 85%) at the two experimental sites could be compared with those observed in structural controls such as sedimentation/filtration systems. Kaighn and Yu (1996) in their study have recognized that the quality of highway runoff entering the two test swales were better than that observed at the edge of pavement site. Dorman et al. (1996) analyzed the performance of three vegetated channels for treating highway runoff and reported high TSS removal efficiencies of 98%. These results indicate that filter strips may be more effective at treating runoff from relatively small drainage areas such as highways. Walsh et al. (1997) indicate that vegetated strips between seven and nine meters in length can be effective, but increased water depths and velocities are believed to have a negative effect on pollutant removal efficiencies.

Ellis (1999) suggested that water quality improvements could be aided by the introduction of a level spreader at the inlet and the use of check dams on long swale lengths or with longitudinal gradients above 3%. The researcher suggests that simple, shallow, and broad V-shaped grass troughs (5-8m wide with side slopes of up to 9-12%) could be more appropriate than conventional trapezoidal swale geometry. This form facilitates pollutant removal occurring across the entire side slopes of the trough rather than relying on the more restricted surface area offered by the base of the swale channel. Additionally, the suggested swale geometry would favor the processes of denitrification, as pollutant uptake by plants requires shallow percolation and relatively long retention times.

Two-year water quality monitoring project undertaken in California assessed the efficiency of highway roadsides in removing contaminants from stormwater. Caltrans selected eight sites for performing this study. Each consisting of concrete V-shaped ditches placed parallel to the road at various distances from the edge of pavement. Those sites were characterized by varying slopes and vegetative covers. The relationship between length of filter strip and resulting pollutant concentrations was found to be nonlinear. Upon comparison with initial studies conducted as part of the Caltrans BMP retrofit study, results indicate that existing vegetated areas along the highways perform similarly to systems engineered specifically for water quality improvements (Caltrans, 2003a; Barrett et al., 2004).

Past studies indicated that concentrations of organic carbon, dissolved solids, and hardness were observed to increase and the constituents exhibited a decrease in concentration. Steady state levels were generally achieved within 5m of the edge of pavement (Barrett et al., 2004). Vegetation type and height, highway width, and hydraulic residence time were found to have little or no impact on the pollutant concentrations (Barrett et al., 2004), while vegetation density and slope did have an impact. Experimental results show that in case of sites with greater than 80% vegetation coverage, the critical buffer widths (producing irreducible minimum concentrations for constituents, whose concentrations decreased) were found to be 4.2m for slopes less than 10%, 4.6 m for slopes between 10% and 35%, and 9.2m for slopes between 35% and 50%. Based on the evaluation of data in past studies, for sites with less than 80% coverage, the critical buffer widths for slopes greater than 10% was found to be 10m. However, the study could not show the minimum concentration produced to be a function of buffer width, highway width, vegetation coverage, hydraulic residence time, vegetation type, or slope.

2.6 Concluding remarks

In summary, the literature review of vegetated buffer strips adjacent to highways have provided mixed results. Some of them indicate that well maintained grassy swales could serve as a primary treatment method, while some indicate that swales should be used as a transport channel to a more appropriate treatment process (structural control).There are numerous factors that could explain the differences in reductions of pollutants. Site characteristics such as vegetation type and density, ADT, slope, and soil type, could play an important role in the effectiveness of a vegetated area at removing pollutants from stormwater runoff. Variations in site performance also occur on a storm by storm basis; therefore, average performance trends should be based on long study period.

Highway shoulder borrow ditches have different soil conditions and the analysis of soil is required. As the sheet flow runs through the vegetated slopes, there are chances of the runoff picking the heavy metals such as Zn, Pb, and nutrients like P accumulated in the soil, leading to high levels in the collected sample and thereby not reflecting the pollutant load coming from the highway runoff. There are research studies considering the influence of rainfall intensity and traffic on pollutant concentration, but they should be extended to provide understanding of the correlation with the soil content. State regulatory and transportation agencies are therefore interested in gaining a better understanding of the effectiveness of highway roadsides for stormwater pollution control in Texas. Hence, the benefits of vegetated roadsides must be documented so that the roadsides can be used as part of the design for meeting stormwater quality requirements.

CHAPTER III

MATERIALS AND METHODS

3.1 Site descriptions

3.1.1 General description of the sites

Three sites in two Texas cities: College Station and Austin were selected to represent a different region of the state. Kearfott (2005) has given the detail site description of the Austin sites. Vegetated roadsides at each of the three sites selected differ in characteristics such as slope and vegetation type composition. All three sites are located consecutively on the south bound lane on the west shoulder of SH 6 between the University Drive and the Harvey Road. The sites are adjacent to the SH 6 and are directly exposed to the heavy traffic on the highway. The slope of the grassy shoulder at Site 1 is 6-8% (flattest), Site 2 is 18-20% (steepest) and that of Site 3 is 14 - 15%. All the sites have ample room to accommodate all the sampling equipment. The 2003 Bryan District office estimate of the ADT for this stretch of highway was 76,000 vehicles per day.

The key characteristics of the Austin sites include the following:

1. The criteria for selecting the sites included slope, soil type, ADT, and vegetation characteristics
2. The slope of the grassy shoulder at Site 1 is 12% (flattest), Site 2 is 18% (steepest) and that of Site 3 is 18 %(Sites 2 and 3 are adjacent to each other)
3. Site 1 and Sites 2 & 3 were exposed to high ADT of 43,000 and 35,000 respectively

4. The average vegetative cover for Site 1 was calculated to be 82.55%, with a range of 57.64% near the road edge to 93.77% near the bottom of the sloped vegetated shoulder. The average vegetation density of Sites 2 and 3 is calculated to be 96.97% and 100% respectively
5. Site 1 was chosen to study the performance of vegetated roadsides receiving highway runoff from two different surface types: PFC and traditional asphalt surface
6. GKY First Flush samplers were installed to collect the runoff at the gravity-fed collection end of each pipe
7. The sites were mowed in May, July, September, and late December 2004
8. Fire ant mounds were found to be a frequent, recurring problem at all of the research sites
9. The statistical analysis of the data was performed, using software such as SPSS and Minitab, to determine significant differences in concentrations measured at each of the research sites.

The primary criteria that were used for site selection at College Station are the following:

1. Average daily traffic. When choosing the sites in College Station, ADT greater than 50,000 vehicles per day was one of the factors taken into account. ADT is an important consideration in site selection because it has been shown that the character and quality of the runoff from the roadway remains reasonably constant through out a runoff event where ADT is relatively high.
2. Roadside slope. The slopes concentrated on in College Station area range between 6(H):1(V) and 4(H):1(V). The selected slope reflects the most common roadside characteristics of rural cross section highways. Roadside slopes of 6:1 are preferred where possible and slopes of 4:1 are considered to be the maximum slope for a recoverable roadside. Steeper slopes are found in special roadside conditions but are usually limited to embankments and the downhill sides of cut slopes.
3. Roadside vegetation width. When deciding on the appropriate road width for conducting the research, roadside width ranging from 8 to 11m (26 to 36ft) from the paved shoulder to the high water mark of the borrow ditch was chosen. Roadside widths varying from 8 to 11m (26 to 36 ft) will allow samples to be taken at representative distances from the shoulder to account for the variance in roadside width.

4. Vegetation type and condition. Vegetation type has been found to influence the rate of erosion and sediment transport on slopes. This factor is related to the growth habit of the species mix. Typical roadside vegetation comprising of turf, short grass were observed at the chosen sites. The observed species are herbaceous in nature (not woody). Maintenance activities included mowing at regular intervals conducted by the Texas Transportation Institute (TTI) crew maintaining the growth of the vegetation at each site.
5. National Resources Conservation Service (NRCS) Hydrologic soil group. Soil is yet another factor other than the mix of vegetation species influencing the character of the roadside vegetation. The soil chemistry and the relative permeability of the soils may have some impact on the amount of infiltration that occurs and an overall storm water pollutant load reduction of the soil/vegetation matrix.

A map indicating the locations of the three College Station sites is presented in Figure 3.1. Aerial and site photographs of all the three research sites are presented in Figures 3.2, 3.3, and 3.4.

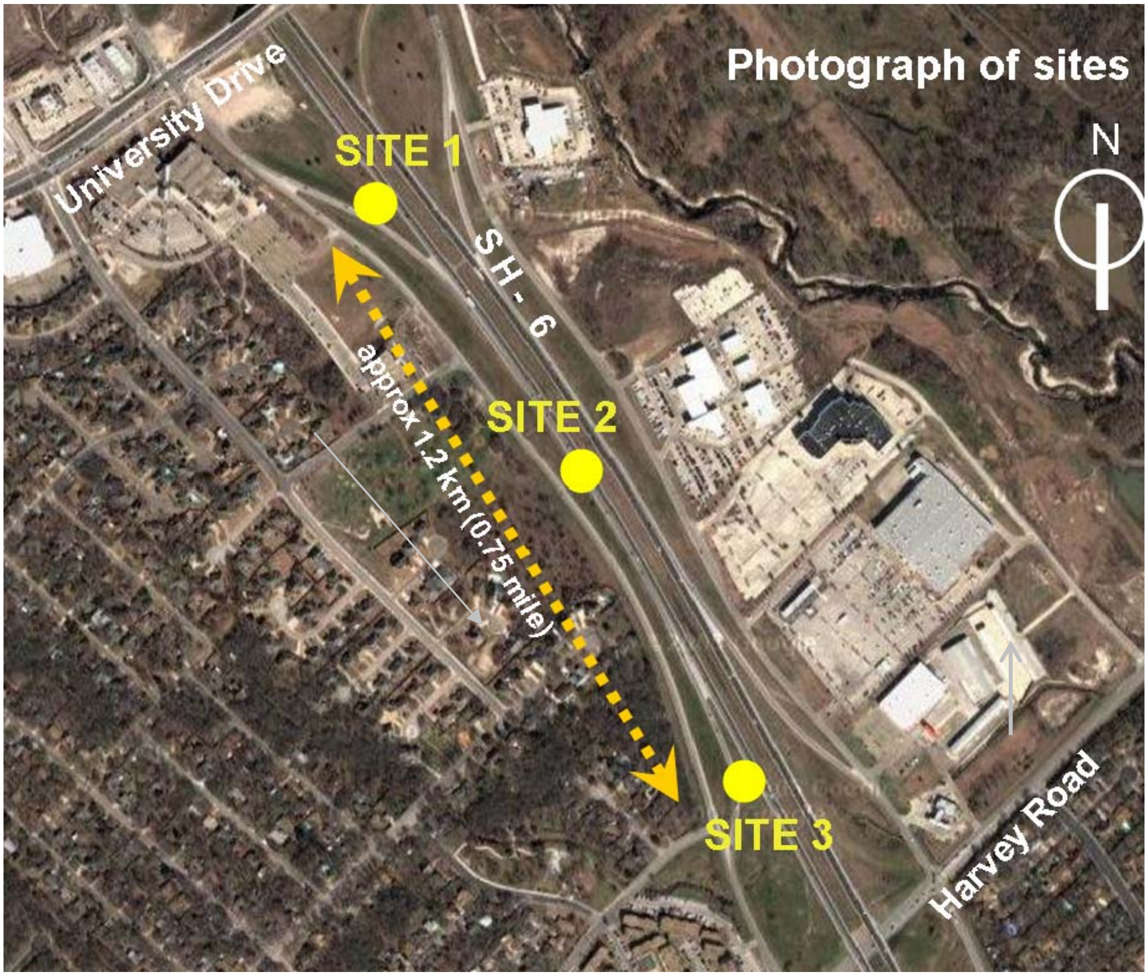
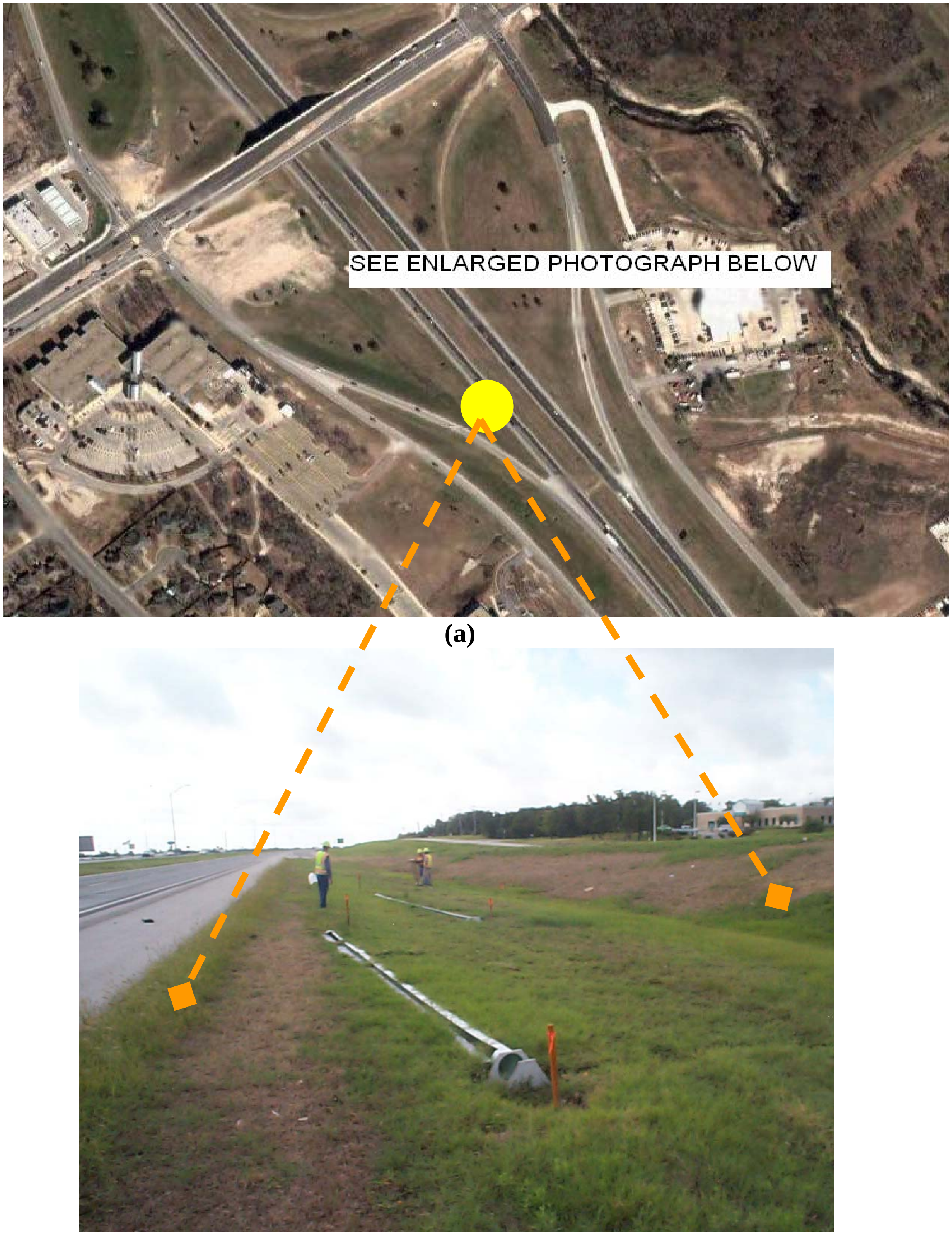
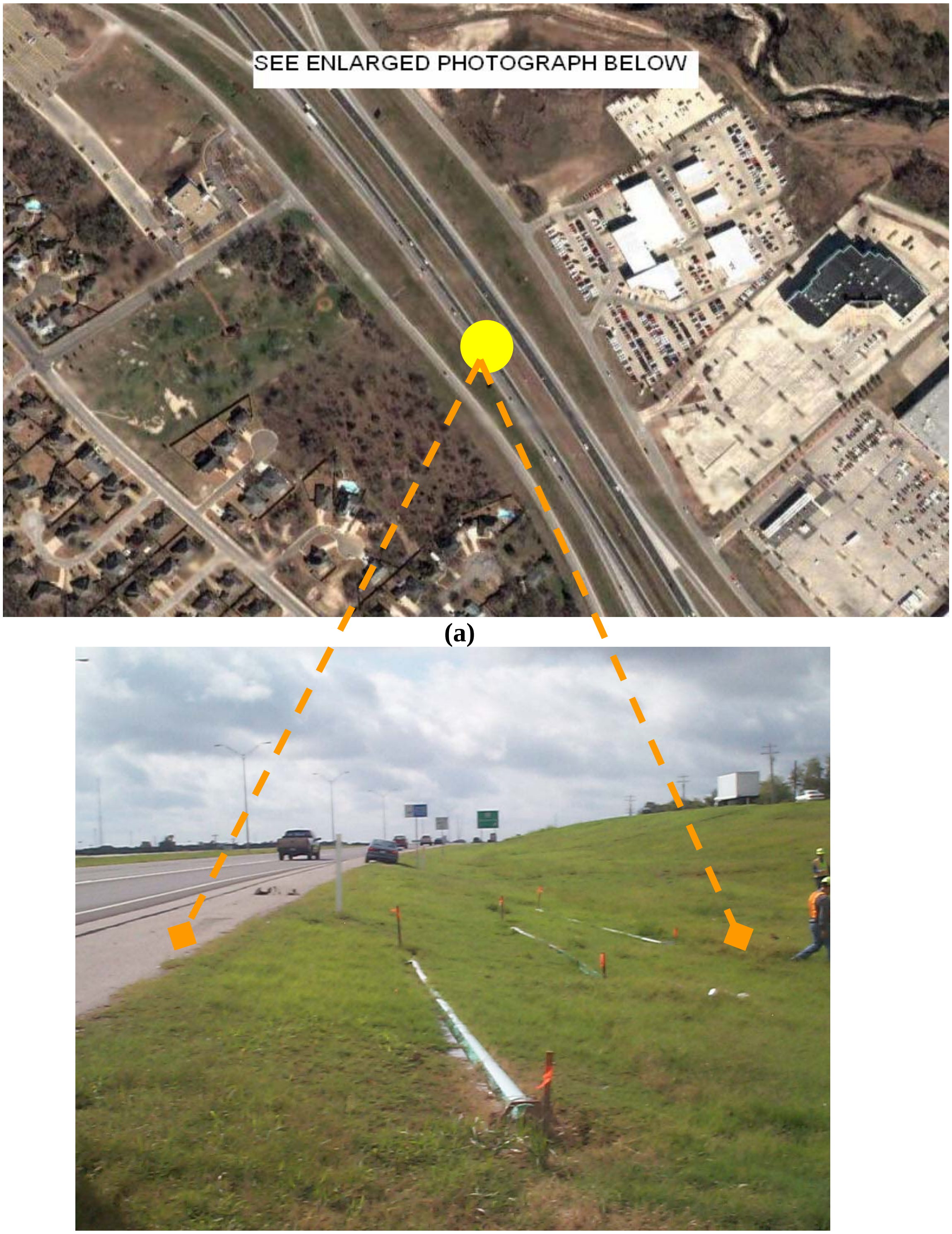


Figure 3.1. Aerial photograph of all the College Station sites (not to scale) (Aerial photograph: USGS, 2005)



(b) View toward the south

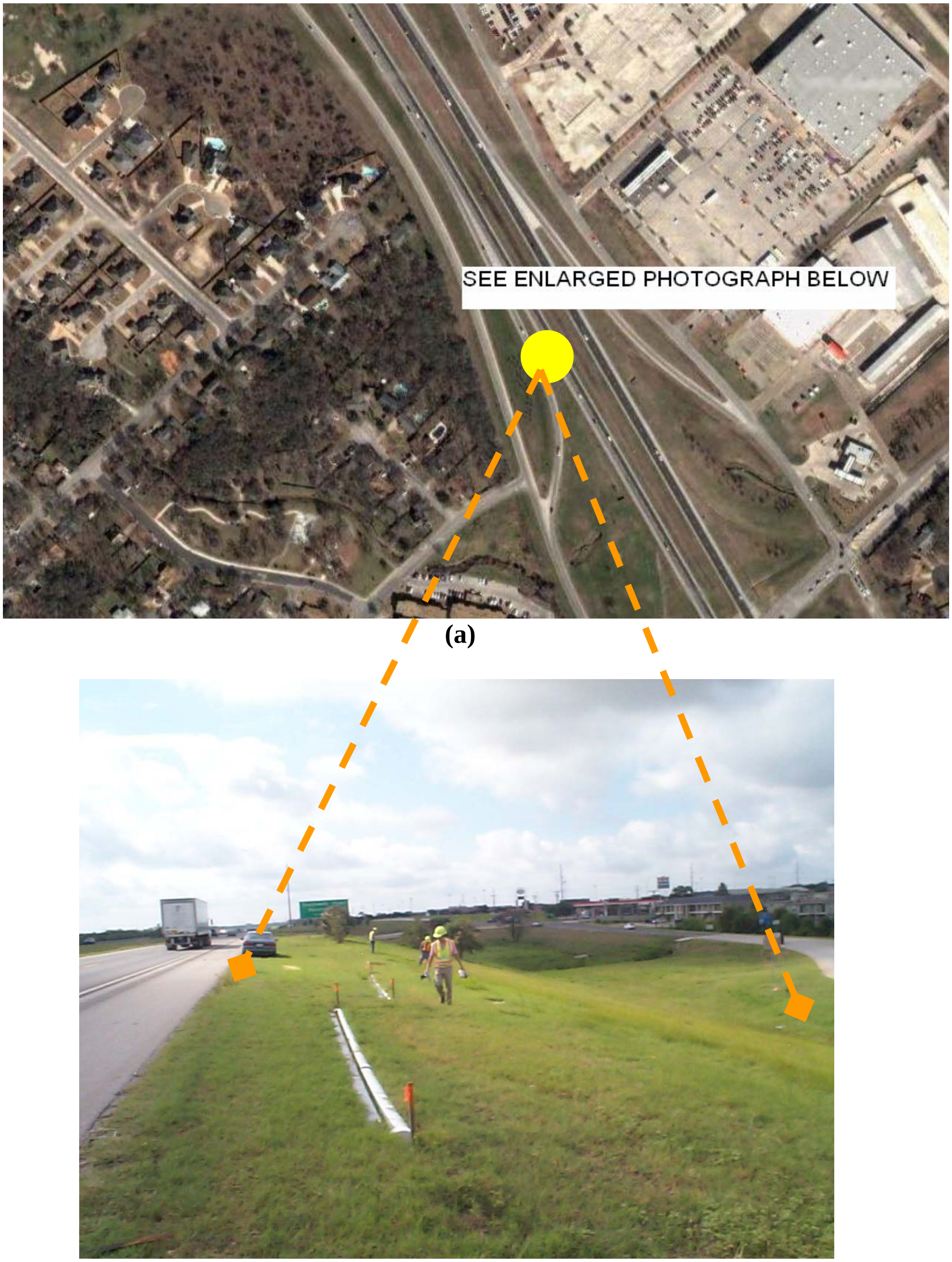
Figure 3.2. Photograph of Site 1 at College Station (a) Aerial (b) Experimental site (Aerial photograph: Google Maps, 2005)



(a)

(b) View toward the south

Figure 3.3. Photograph of Site 2 at College Station (a) Aerial (b) Experimental site (Aerial photograph: Google Maps, 2005)



(a)

(b) View toward the south

Figure 3.4. Photograph of Site 3 at College Station (a) Aerial (b) Experimental site (Aerial photograph: Google Maps, 2005)

3.2 Site setup

3.2.1 Preparation

Each site was assessed prior to installation of the collection and sampling systems. The equipment consisted of four GKY First flush samplers and associated collection troughs at each site. Placement of pipes and samplers was determined according to the schematic diagram presented in Figure 3.5 and were marked with spray paint and landscaping flags.

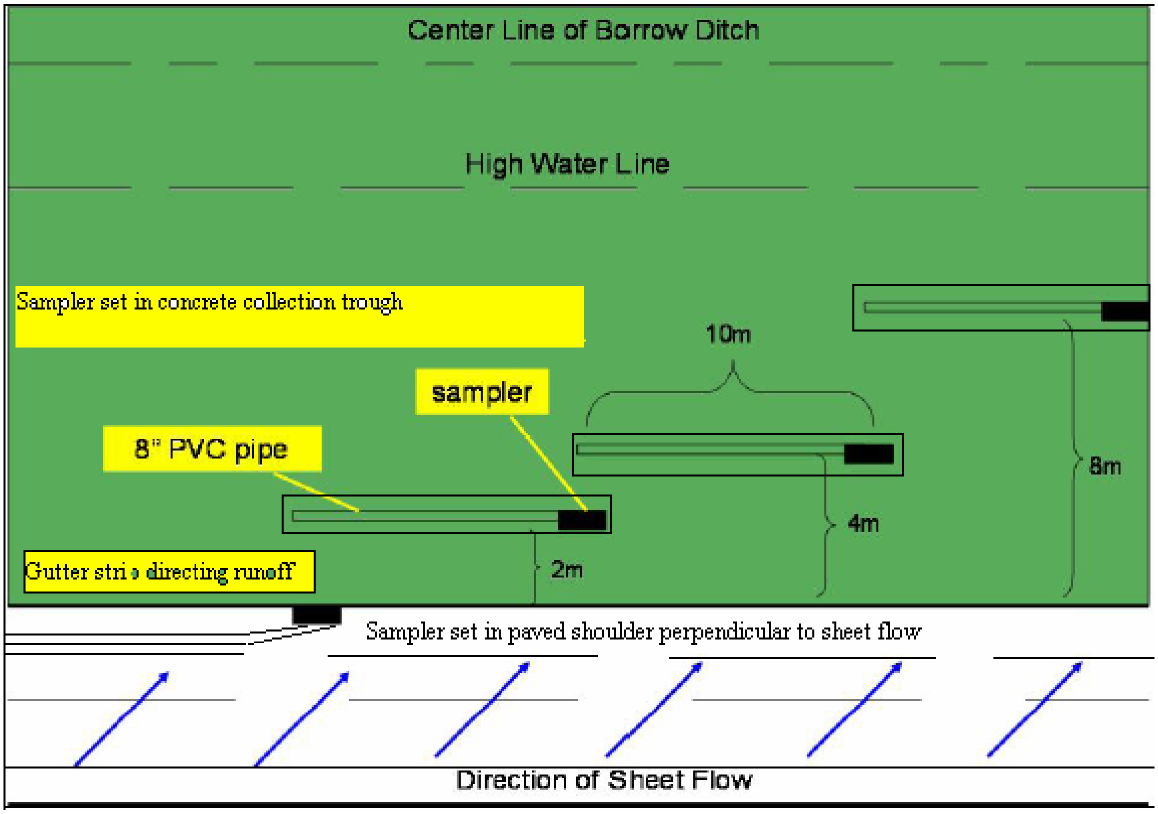


Figure 3.5. Schematic diagram of site layout (not to scale)

3.2.2 Installation

A series of runoff collection and sampling systems were installed at each site in January 2004. Each plot consisted of four samplers at the edge of the paved shoulder to collect water directly from the pavement. The collection systems consisted of 10m (30ft) length of standard 0.2 m (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 lead the runoff into the pipe. Shallow trenches were dug along the highways at two, four, and eight meter distances from the edge of pavement at each site to accommodate the collection pipes. Photograph of the collection pipe is shown in Figure 3.6.

Figure 3.6. Design of a collection pipe

Zero meter flow strips (gutter strips) were laid in March 2004 at all the College Station sites to direct the runoff to the sampler at the edge of the pavement in the case of a rainfall. The flow strips were D-shaped gaskets, 25mm (1 inch) high, with the flat surface placed on the pavement. A diagram of the D-shaped gasket is shown in Figure 3.7.

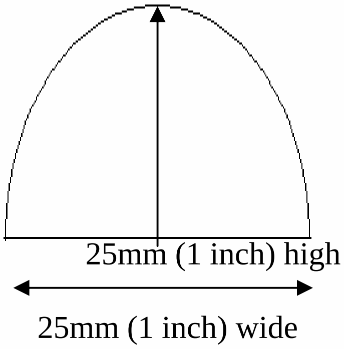


Figure 3.7. D-shaped gasket (Zero meter flow strip)

Longitudinal slope of the pavement surface is between 0.5 % and 1 %. It offers the appropriate velocity head to the flow strips in order to channel the runoff to the samplers. Samples collected prior to December 2004 had the flow strips installed at the edge of the pavement. The flow strip was removed in December 2004 and the collections following that date did not have the zero meter flow strip. Collection pipes were situated in a manner such that the metal flashing was flush with ground level. The pipes were placed slightly askew rather than exactly parallel to the edge of pavement to ensure that runoff would easily flow to one end of the collection pipe. The longitudinal slope for each collection pipe is approximately 1.5%. A photograph of a collection pipe is shown in Figure 3.8.

Figure 3.8. An installed collection pipe with the sampler at College Station

The samplers were installed to collect the runoff at the gravity-fed collection end of each pipe. The samplers used in this study are passive storm water samplers that can hold up to 5 liters (L) of water. The lid of each sampler is constructed with five sampling ports, each of which can be plugged, facilitating better control of the rate at which collected runoff enters the sampler.

Plastic flaps on the underside of each port serve 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 enabling easy transportation of the samples in the vehicle.

The sampler used is the “GKY First Flush Sampler”. These samplers were specifically designed for this type of application and delivered reasonable performance in storm water collection. The advantage of the samplers is that they are inexpensive and easy to install. The disadvantage of the samplers is that they should remain closed with all the inlets plugged during dry periods. This requires site visits during a rainfall event in order to open the inlets and to clean any excess debris out of the collection troughs. It was found that the samplers collected litter and the inlets became blocked by leaves, grass and other residue when they were left open for long periods. Since the samplers are not automated, the experimental plots were placed on a highway that is easily accessible to the research laboratories. Figure 3.9 shows a diagram of the GKY sampler and its components.

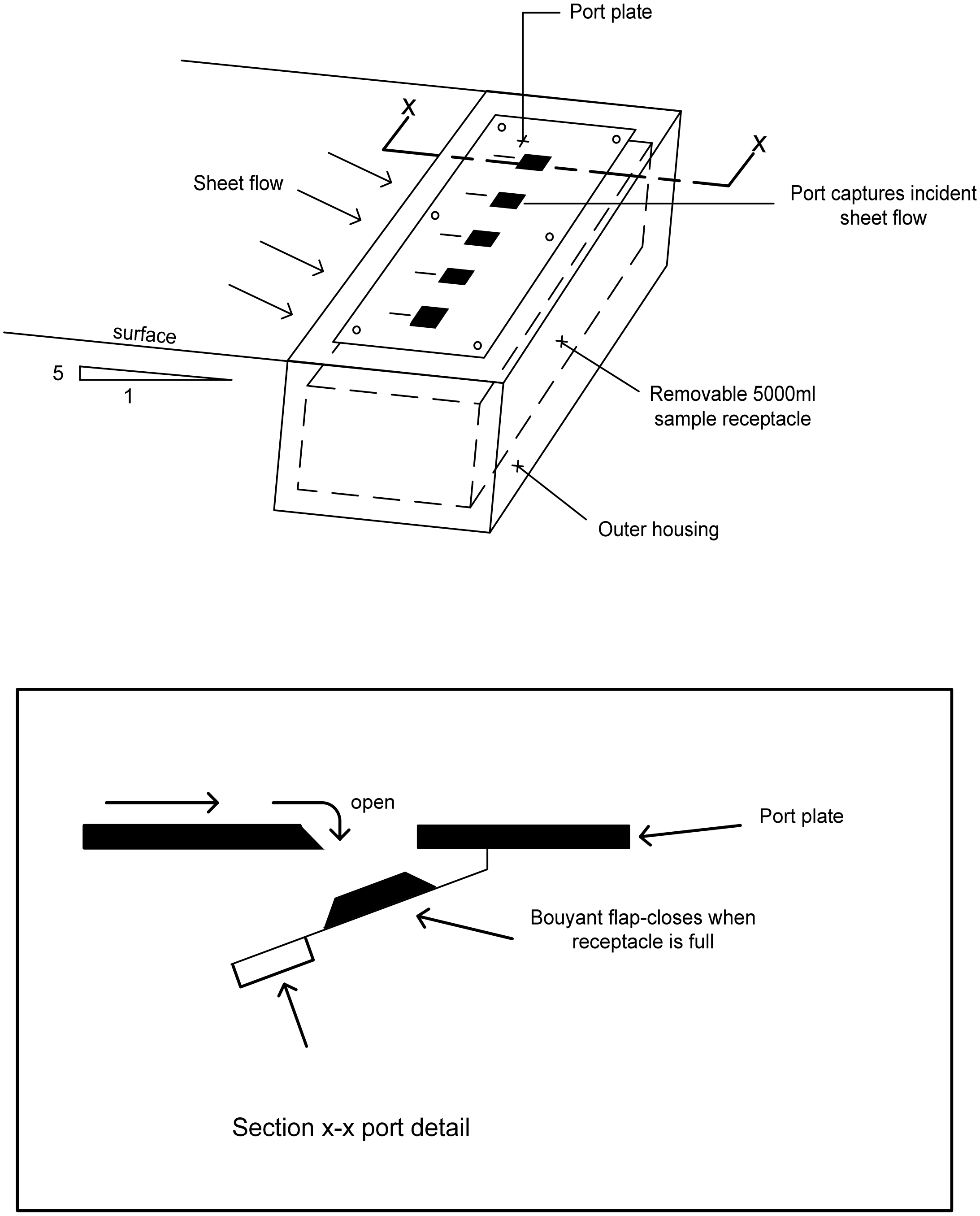


Figure 3.9. GKY First Flush Sampler (GKY 2005)

Samplers were also 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 the installed sampler at the edge of pavement is shown in Figure 3.10.

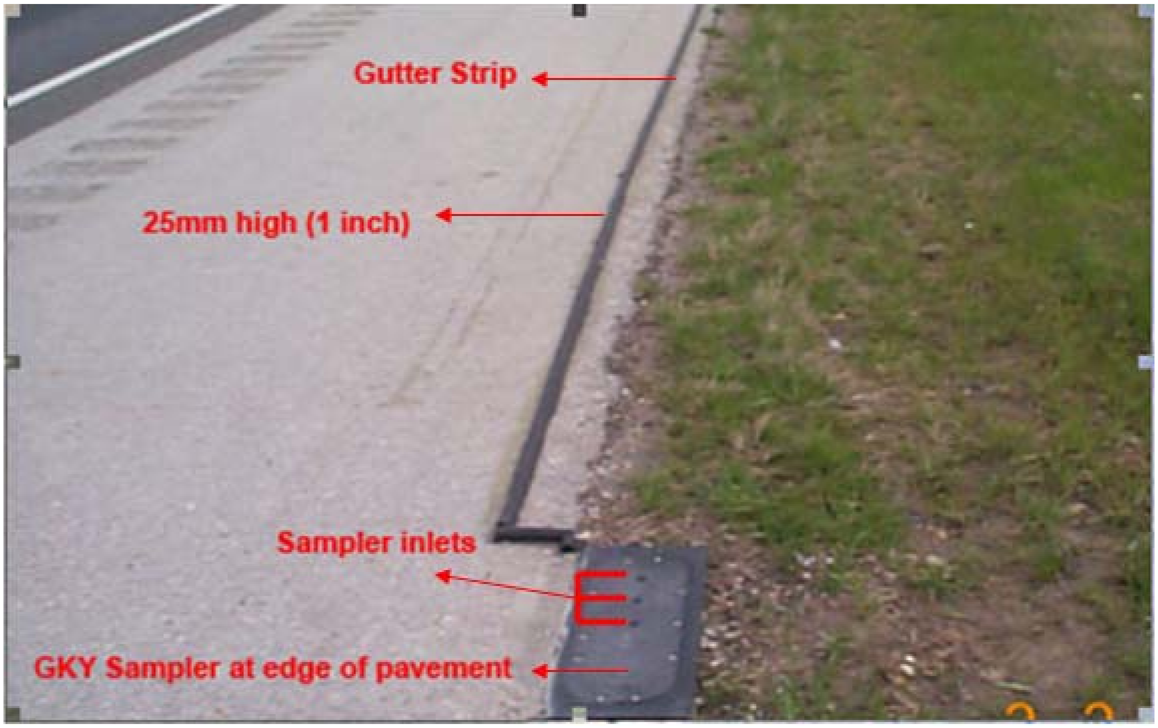


Figure 3.10. Installed sampler at the edge of pavement at College Station

3.2.3. Pre-sampling and maintenance

The sites were disturbed during the installation of the collection pipes and samplers. Sampling activities did not begin immediately after installation was complete. A few large storms were allowed to pass unsampled allowing the site condition to stabilize. Periodic mowing of the sites was conducted by TTI mowing crew. Mowing occurred three times a year at each site. Sites were mowed in mid April, July, and November 2004, and also in June 2005. TTI mowing crew adopted the same Standard mowing practices as that of TxDOT. The practices for highway shoulders include cutting only and not collection of grass clippings. At least one storm was allowed to elapse before sampling activities were resumed. This delay in sampling ensured that runoff conditions from each storm sampled were not a function of loose grass and dirt in the path of the runoff.

Other required maintenance activities were performed at each site between rain events. Such activities included litter and debris collection, treatment of fire ant mounds, and replacement of the lids of the GKY samplers. Fire ants were noticed to be a problem in April 2004 and were believed to be affecting the test results.

This issue is discussed in detail in section 4.13.

3.3 Sampling procedures

Preparatory activities were performed at each site prior to each predicted storm event. Each collection pipe was cleaned out to remove any dirt, leaves, grass, or litter 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 grass clippings. The rain gauge station has been set up by Transportation Operations Group, TTI, The Texas A&M University System, on the South bound lane on the west shoulder of the right-of-way and was used to collect data. Figure 3.11 shows the photograph of the rain gauge station.

Figure 3.11 Location of the rain gauge station at the College Station site

Upon collection of rain sample, the plastic white containers were removed and capped. Occasionally sites were visited during rain events to visually inspect the systems in action and to ensure that runoff was being directed 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. During each site visit, records of sampling, any specific activity carried out in the site, and general site conditions were made in a log book.

3.4 Vegetation survey

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

3.5. Analytical procedures

Collected 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 storm water analyses. According to the norms of the standard laboratory methods, the holding time for fecal coliform bacteria is 24 hours. Samples were delivered to the laboratory as soon after rain events as possible, so that they are analyzed within 24 hours of collection. If samples were collected outside of the lab’s normal business hours, samples were stored in a 4°C (39.2°F) cold room until they could be transported to the laboratory. The following constituents (listed in Table 3.1) commonly contained in the highway runoff were proposed for analysis and reporting.

Table 3.1. List of stormwater constituents

Constituent
Total Suspended Solids(TSS)
Metals:
Lead (Pb)
Zinc (Zn)
Copper (Cu)
Nutrients
Nitrate/Nitrite (NO3-N+NO2-)
Total Nitrogen
Kjeldahl Nitrogen
Phosphorus
Dissolved Phosphorus
Other
Chemical Oxygen Demand (COD)
Fecal Coliform

For each site, the differences between the influent, shoulder mounted sampler (at the edge of the pavement), and the three slope mounted samplers (two, four and eight meters) were reported for each of the above mentioned target constituents. The data analysis involved determining the percent removal of the constituents from the influent stream. The objective of the analysis is to earn a better understanding of maximum potential treatment values that can be delivered by the vegetated shoulders and channels. The analytical parameters and methods are presented in Table 3.2.

Table 3.2. 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	µg/L	SW8270C	varies

3.6 Statistical analysis

The analytical results from each storm event sampled were inspected to ensure all the appropriate QA/QC procedures were followed by the laboratory and that the reports from LCRA were complete. The data were compiled into a database for each of the sites and inspected qualitatively to observe preliminary trends. Several statistical diagnostic tests were performed on the data to determine the overall distribution and to inspect and evaluate any low or high outliers.

Analysis of variances (ANOVA) was used to compare the mean concentrations measured at various distances at each of the selected sites to determine whether the null hypothesis is satisfied (means are equal) or not. It analyzes the means and variances of set of values and determines whether or not they are significantly different from one another. The test returns a value called “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 the data sets. Conversely, a P-value approaching 0 indicates that the two data sets of values are as statistically difference from each other as possible. Multiple comparisons (Post hoc analyses) were performed in order to detect significant inequalities among pollutant concentrations measured at various distances at each of the selected sites.

In this study, P-values less than or equal to 0.05 have been accepted as indicating a statistically significant difference between data sets. If there was no statistically significant difference in the means, then it is concluded that the vegetated roadsides had no impact on runoff concentrations. SPSS, a commercially available software package was used for these tests. The analyses were repeated using another software package called Minitab and the results were found to be consistent. A box and whiskers plot (also called a boxplot) is a graphical tool that has been used in this study to visually compare data sets. Within the "box", the line through the middle denotes the median of the data range. 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 represent data points in the range. Points that extend beyond the length of the whiskers are indicated with an asterisk (meaning that it is an unusual point in the dataset).

Dixon-Thompson test for log-normal assumption was used to detect outliers (Dixon, 1953). In this test, the data points are ranked from smallest to largest, with the smallest value denoted as X_1 and the largest value denoted as X_n. The subscript indicates the rank of the value from smallest to largest. The test statistic R and critical Value R_C depend on the sample size (n). The equations 1, 2, and 3 given below could be used to compute both R and R_C .

For a sample size (n) ranging from 8 to 10,

the low outlier test statistic is given by:

$$R = \frac{X_2 - X_1}{X_{n-1} - X_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

the high outlier test statistic is given by:

$$R = \frac{X_n - X_{n-1}}{X_n - X_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The polynomial for computing the critical value, R_C is given by:

$R_C = 1.23 – 0.125n + 0.005n^2$ ………………… (3)

The null hypothesis is rejected and the data points are termed as outliers when R is greater than R_C . The Dixon-Thompson test statistic R was determined for each constituent, each site, and each distance. The reason for not lumping all the distances is because a data point that may be an outlier for one distance may not be an outlier for the other distance.

CHAPTER IV

RESULTS AND ANALYSIS

4.1. Introduction

As mentioned earlier**,** the primary objective of this study is to document the removal efficiency of constituents in (urban) stormwater runoff by vegetated roadsides typical of common rural highway cross sections in Texas. The highway contaminants analyzed in this study include TSS, nutrients, heavy metals, and fecal coliform. Two Texas cities: College Station and Austin were selected for the comparison of the effects of precipitation characteristics, ADT, and different vegetation types on pollutant removal. Three sites were selected in each city. The chapter will present the statistical analyses, including summary statistics, ANOVA tests, post hoc, and correlation analyses of both of the study areas.

4.2 Precipitation characteristics and sample collection records

In the 15 -month study period, a total of 10 storms were successfully sampled at College Station, and 13 storms at Austin sites, from February 2004 to May 2005. Dates on which runoff samples were collected and the corresponding rainfall volumes at the two study areas are presented in Table 4.1. It should be noted that sample collection dates are usually one day later than the actual rainfall event dates.

Table 4.1. Rainfall volume and sample collection dates

College Station	Rainfall volume mm (inch) *
Collection Date	**All Sites**
3/5/04	13.46 (0.53)
3/25/04	11.43 (0.45)
5/2/04	27.69 (1.09)
8/2/04	11.43 (0.45)
8/23/04	9.4(0.37)
10/3/04	54.1 (2.13)
11/18/04	39.37 (1.55)
1/13/05	22.1 (0.87)
1/28/05	26.9(1.06)
5/9/05	37.85 (1.49)

***** Rainfall data obtained from rain gage station set up by TTI, The Texas A&M University System

Austin	Rainfall volume mm (inch)*	
Collection Date	**Site 1**	**Sites 2 &3**
2/24/2004	16.3(0.64)	34.3(1.35)
3/1/2004	12.7(0.5)	12.7(0.5)
3/26/2004	NA[**]	7.62(0.3)
4/12/2004	44.5(1.75)	25.4(1)
5/14/2004	42(1.65)	36.8(1.45)
6/3/2004	20.3(0.8)	10.2(0.4)
6/9/2004	63.5(2.5)	69.9(2.75)
10/25/2004	NA[**]	63.5(2.5)
11/1/2004	NA[**]	44.5(1.75)
11/15/2004	22.9(0.9)	25.4(1)
11/22/2004	26.7(1.05)	139.7(5.5)
1/28/2005	33.02(1.3)	38.1(1.5)
3/3/2005	25.4(1)	20.3(0.8)

***** Rainfall data obtained from a nearby off-site weather station

** NA Not Available

4.3 Vegetation composition

4.3.1 Vegetation matrix on the selected sites at College Station

Vegetation survey was based on visual assessment and quantification was conducted in August 2004.The results of the vegetation survey conducted are presented in Table 4.2. This study conducted by the TTI crew at the Austin sites shows much less species diversity. Austin sites were found to exhibit more uniformity of species between the sites than College Station sites. One example of the roadside vegetation condition is shown in Figure 4.1.

Figure 4.1. Quadrat-based visual measures (1.22m (4 feet) X 1.22m (4 feet)) to define roadside vegetation condition

Table 4.2. Observed vegetation with associated percentage cover

College Station	**Site 1**		**Sites 2 and 3**
Dominant Species	Bahiagrass (*Paspalum nutatum)* Bermudagrass (*Cynodon dactylon*) King Ranch Bluestem (*Bothriochloa ischoemum)*	90%	Bermudagrass **}**100
	Johnsongrass(*Sorghum halepense*) Sowy Chloris (*Chloris virgata*	10%	
Observed other species on all sites	Barnyardgrass (*Echinochloa crus- galli*) Crabgrass *(Digitaria sanguinalis)* Croton sp. Dallisgrass (*Paspalum dilatatum*) Dichondra (*Dichondra brachypoda***)** Euphorbia sp. Frogfruit (*Phyla Nodiflora*) Gailardia (*Gaillardia aristata*) Mesquite (*Prosopis spp.)* Milkweed (*Asclepias tuberose)* Morning Glory (*Convolvulus duatinus*) Noseburn (*Tragia ramose)* Nut sedge (*Cyperus rotundus)* Sensitive Briar (*Mimosa hystricina)* Side oats grama (*Bouteloua curtipendula*) Silver Bluestem *(Bothriochloa laguroides)* Sowthistle (*Sonchus arvensis)* Vervain (*Verbena hastate***)** Windmillgrass (*Chloris verticillata* nutt***)***		
Austin	**Sites 1,2, and 3**		
Dominant Species	King Ranch Bluestem (*Bothriochloa ischoemum)* Bermudagrass (*Cynodon dactylon*)		
Observed other species on all sites	other minor species		

4.4 Analytical methods

ANOVA was used to compare the mean concentrations measured at various distances at each of the selected sites to determine whether the null hypothesis is satisfied (means are equal) or not. Multiple comparisons (Post hoc analyses) were performed in order to detect significant inequalities among pollutant concentrations measured at various distances at each of the selected sites.

The purpose of this analysis is to determine whether statistically significant differences existed between constituent concentrations at various distances from the edge of the pavement across the vegetated roadsides. In past research, ANOVA has been used to determine whether concentrations measured at each buffer width differed significantly (Barrett et al., 2004). Also, Strecker et al. (2001) report that the use of standard statistical descriptions, box and whisker plots, and probability plots of data could be employed to demonstrate differences in event mean concentrations (EMCs) as well as effectiveness of the BMP. They state that a graphical look at the distribution through boxplots could provide insight into the applicability of the method. In this study, the statistical methods including ANOVA tests and post hoc analysis using Tukey method were employed to perform pairwise comparison of all treatment means between various distances at each of the selected sites. Regression analyses were conducted to understand the correlation between the individual constituents and the influence of precipitation characteristics and traffic on pollutant concentrations. Statistics including mean, range, and standard deviation were used for describing the data set. Box and whisker plots were employed for displaying the data for this study and understanding the performance of vegetated roadsides in stormwater pollutant removal.

The constituent data were natural-log transformed prior to applying ANOVA and post hoc analyses to satisfy the condition of normal distribution of the dataset. ANOVA was applied to the edge of the pavement and all vegetated roadside widths at each site. Thus the ANOVA compares the means and variances of set of values and determines whether or not they are significantly different from one another. Additionally, post hoc analyses using Tukey method were employed to perform pairwise comparison to compare each treatment mean with each of the other treatment means. The objective of this application is to detect significant inequalities.

4.5 Sampling results and inspection of data

All of the data collected at College Station sites are presented in Tables 4.3, 4.4 and 4.5. All of the data collected at Austin sites are presented in Tables 4.6, 4.7 and 4.8. Concentrations which were not detected at a parameter’s reporting limit are indicated in the tables as “ND” and for the purpose of analyses; the value has been taken to be 0. The data from each sampled storm event were qualitatively inspected upon receipt from the laboratory. It should be noted that collection and sampling of stormwater in a field setting is influenced by many uncontrollable factors such as fire ant mounds located upslope of the sampling system, and mal-functioning of the sampling system. There were instances during this study when samples could not be collected from all samplers at every research site. The samplers occasionally malfunctioned, primarily due to tipping of the sampler within its holder or the port plate was thrown away by the wind. 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. In the event of insignificant amount of rainfall such as in July, August, September, and December 2004, the samplers were not sufficiently filled to be sent for analyses. Occasions when samples were not collected at particular sites are noted in the Tables.

As part of the inspection of the dataset at College Station sites, the data points from the Site 2, eight meter sampler on 05/01/2004 rain event, were excluded from the analysis. These points are invalid because they are resultant of invalid sampling done just before the reinstallation of the system at eight meter. The sampler at eight meter in this site was reconditioned in August 2004 since the sampler was submerged in water during the earlier rainfall event. The collection pipe was reconditioned from eight meters to six meters and the drainage ditch was dug deeper in order to avoid pooling of water and direct the runoff towards the swale. These points were not excluded because they are outliers, but they resulted from invalid sampling. The constituent data excluding the 12 invalid data points were natural-log transformed prior to applying ANOVA and post hoc analysis. Upon transformation, probability plots were constructed for the datasets to confirm that the resulting data was normally distributed. Common practice suggests that a minimum of 10 data points are required to conduct normality test. In these analyses, the normality test was performed on the standardized residuals of 30 data points. The normality test was performed for each constituent, and each distance (zero meter of all sites, two meter of all sites, and four meter of all sites). This comparison is valid because the test was done on the standardized residuals of the transformed data.

Furthermore, the level of uncertainty on field work is usually greater than lab work. Removing outliers is a common treatment before the data is analyzed. For this purpose, the Dixon-Thompson test is applied to detect outliers. A detailed description of the test is provided in chapter III (section 3.6). In order to preserve the integrity of an already small data set, very few data points were excluded from the final analyses. The seven points that were excluded are:

1. Total Cu, Site 1, 4m sampler, 05/08/2005 rain event
2. Total P, Site 1, 2m sampler, 05/08/2005 rain event
3. Nitrates, Site 1, 4m sampler, 01/27/2005 rain event
4. COD, Site 2, 8m sampler, 05/08/2005 rain event
5. TSS, Site 2, 2m sampler, 03/04/2004 rain event
6. COD, Site 3, 8m sampler, 03/04/2004 rain event
7. Dissolved Zn, Site 3, 8m sampler, 08/01/2004 rain event

There are a total of 1475 data points excluding 12 invalid points and seven data points designated as outliers.

The inspection of Austin dataset is also performed. In the event of insignificant amount of rainfall, the eight meter samplers of all sites were found to result in an empty, or near empty, sampling container. Occasions when samples were not collected at particular sites are noted in the tables. The holding time for fecal coliform bacteria is 24 hours and it has been reported that fecal coliform levels were only analyzed for a fraction of the storms collected. In an attempt to exclude data points that resulted out of invalid sampling, the data from the first storm sampled (2/24/2004 collection date) was eliminated from the final analyses.

Kearfott (2005) report that the first set of samples produced uncharacteristic results due to lingering negative effects of equipment installation and installation-related disturbances to the vegetation and soil. There are a total of 1475 Austin data points excluding the data from the first sampling event.

Table 4.3. EMCs for all storm events monitored at College Station Site 1

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved P (mg/L)				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
3/5/4	143	154	225	326	2.95	2.77	2.61	2.88	.41	0.27	0.32	0.35	0.37	0.25	0.2	0.3	0.29	.09	0.1	.08	15.2	13	9.5	9.9	4.5	4.1	4	4
3/25/4	53	81	153	134	2.87	2.19	2.15	1.96	ND	ND	0.48	0.5	0.18	0.22	0.2	0.2	0.09	.06	0.1	.06	16.5	9.9	7.9	8.4	12	5.2	6	5
5/2/4	158	192	56	104	3.37	2.11	0.9	1.65	.4	0.17	0.17	0.11	0.27	0.23	0.1	0.1	0.14	.09	.02	.03	15.9	6.5	5.2	4.5	6.3	4.8	3	3
8/2/4	218	46	10	56	0.91	1.9	1.66	2.23	.4	0.45	1	ND	0.19	0.48	0.3	0.7	0.16	.35	0.3	.54	22.4	8.8	4.8	8.3	6.2	5.3	6	1
8/23/4	22	9	9	4	0.55	1.73	1.29	1.54	.33	0.64	0.36	0.34	0.06	0.26	.14	0.2	0.03	0.2	0.1	.13	5.67	7.3	4.3	4.1	5.3	2.4	3	4
10/3/4	8	22	34	76	0.64	2.18	7.53	8.49	.26	ND	ND	ND	0.1	1.24	1.2	1.4	0.07	1	0.9	.8	6.62	5.8	7.6	13	4.5	5	9	10
11/18/4	15	43	8	11	5.34	0.65	0.9	1.1	.25	0.24	0.04	0.03	0.09	0.68	0.3	.14	ND	.44	0.2	ND	7.99	16	2.9	3	4.9	6.4	2	2
1/13/5 ^	421	100	229	162	2.93	0.87	1.66	5.31	.74	0.14	0.12	7.2	0.58	0.13	0.1	0.2	0.27	.06	ND	ND	29.5	11	9.3	4	3.3	2.1	3	2
1/28/5 ^	115	50	44	48	0.64	2.35	0.43	0.86	.35	0.63	53.7	0.1	0.22	0.32	0.2	.23	0.08	.24	0.1	ND	13.2	12	6.7	3.4	10	8.1	4	2
5/9/5 ^	11	94	83	46	1.11	7.55	5.34	2.81	.55	0.77	0.19	1.47	0.12	6.31	2	.54	0.06	6.1	1.8	.33	10.3	13	119	11	5.4	11	11	8

	Total Lead (µg/L)				Dissolved Lead (µg/L)				Total Zn (µg/L)				Dissolved Zn (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
3/5/4	8.8	11.6	15.1	13.7	4.12	1.03	ND	ND	160	245	358	456	53.3	122	238	258	82	97	82	82	2360	17E2	3E2	160
3/25/4	4.1	5.04	7.32	5.27	ND	ND	ND	ND	111	156	412	287	66.6	87.6	317	229	117	74	72	78	74E2	11E2	1E2	15E2
5/2/4	7.8	2.56	2.47	2.2	ND	ND	ND	ND	137	118	78.6	218	54.6	114	159	194	93	50	40	42	11E2	9E2	650	7E2
8/2/4	14	2.82	ND	2.48	ND	ND	ND	ND	224	255	365	1520	76.6	204	479	953	122	110	80	135	3000	76E3	21E3	2E5
8/23/4	1.2	ND	ND	ND	ND	ND	ND	ND	43	374	309	452	25.5	324	290	394	28	46	39	51	17E3	6E4	3E3	31E3
10/3/4	1.1	1.51	1.72	4.52	ND	ND	1.08	1.13	46	88.1	215	353	38.8	225	305	276	33	65	215	279	280	968E3	132E4	144E3
11/18/4	2.2	8.63	ND	ND	ND	ND	ND	ND	34	232	80.2	48.3	17.9	122	73	45	26	73	21	26	9E3	113E2	42E3	511E2
1/13/5 ^	23	9.84	12.3	2.6	ND	ND	2.84	ND	241	238	471	99.1	24.5	108	409	120	138	49	48	86	28E2	580	910	2140
1/28/5 ^	8.4	4.16	4.55	2.01	4.04	ND	1.78	ND	133	538	445	81	97.9	340	212	67	61	71	32	29	<100	1E3	<100	55E2
5/9/5 ^	1.6	1.12	11.7	ND	ND	ND	ND	ND	42	133	855	420	27.2	81.6	198	369	33	128	100	78	6E2	17E3	57E2	44E3

▨	Outlier, excluded from the analyses
ND	not detected at reporting limit
^	Samples collected without Zero meter flow strip at the edge of the pavement
#	Samples not collected due to fire ants

Table 4.4. EMCs for all storm events monitored at College Station Site 2

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus(mg/L)				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
3/5/4	219	▒ 618	486	184	2.4	3	3.1	2.2	.37	.37	0.3	.14	.2	.45	0.7	0.2	.1	0.2	.27	.06	27	20.2	22.4	11	6.4	4.5	4.4	4.7
3/25/4	69	120	130	55	2.9	2.6	1.5	2.3	.76	.63	0.2	.44	.4	.47	0.2	0.35	.1	0.2	0.12	0.1	27	19.2	6.4	8.6	11	5.1	4.5	3.7
5/2/4	500	46	82	▤ 475	2.8	1.5	1.9	▤ 4.7	.16	.24	0.1	▤ 0.2	.4	.41	0.2	▤ 0.52	.2	0.2	0.11	▤ .16	31	9.7	3.72	▤ 7.97	4.3	3.4	3.9	▤ 3.7
8/2/4	180	116	38	#	1.5	5.3	4.1	#	.26	1.8	.04	#	.2	1.5	2.1	#	.1	1.4	1.96	#	20	19.6	9.24	#	7.7	15	10	#
8/23/4	19	11	8	4	.64	1.3	1.4	2.9	.26	.44	0.3	.34	.1	.37	0.5	0.53	.1	0.3	.4	.45	8.3	6.1	7.07	7.9	4.8	3.5	5.2	4.2
10/3/4	20	42	52	40	1.6	2.1	.96	1.9	0.1	ND	0.2	.17	.2	1.1	0.9	1.14	.2	0.8	0.69	.95	10	12.1	10.8	5.2	3.8	5.8	5.6	6
11/18/4	103	48	16	46	1.5	1.9	2	1.9	.05	.05	.02	.04	.2	0.2	0.6	0.44	ND	.03	0.47	0.3	15	7.88	5.17	6.7	6.6	5.2	4.1	4.4
1/13/5 ^	504	61	148	293	4	4.9	4.7	4.8	7.8	5.3	0.8	2	.4	.43	0.5	0.46	.2	.08	0.14	0.1	17	13.1	15.2	4.7	2.6	3.3	3.1	2.3
1/28/5 ^	81	107	59	67	0.7	1.2	.86	.57	.15	ND	ND	ND	.1	.25	0.1	0.08	ND	0.2	0.09	.06	7.3	6.05	3.97	2.8	3.2	3.6	4	3.1
5/9/5 ^	29	24	33	59	1.3	5.9	5	14	.74	2.1	2	0.7	.3	0.6	0.6	1.63	.2	.33	0.47	1.2	9.4	28.7	6.91	26	7.4	5.5	4.4	4.8

	Total Lead (µg/L)				Dissolved Lead (µg/L)				Total Zn (µg/L)				Dissolved Zn (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
3/5/4	15	20	22	10	ND	ND	ND	ND	192	372	360	205	31	78	59	209	87	105	139	60	1280	31E2	13E2	260
3/25/4	18	12	2.9	11	ND	ND	ND	ND	218	443	82	324	75	427	95	195	132	129	48	75	53E2	44E3	7E2	12E2
5/2/4	23	5	2.3	▤ 13	ND	ND	ND	▤ ND	259	220	164	▤ 159	33	88	65	▤ 79	119	72	51	▤ 85	1E3	2E3	650	▤ 3500
8/2/4	10	4	ND	#	ND	ND	ND	#	155	367	557	#	81	288	799	#	92	126	122	#	2480	312E3	2E5	#
8/23/4	2	ND	ND	ND	ND	ND	ND	ND	43	154	98	317	33	124	90	276	33	33	53	29	8E2	28E3	8E3	3E3
10/3/4	4	2	5	ND	ND	ND	ND	ND	43	165	486	189	24	174	306	242	38	93	143	73	23E2	55E4	642E3	118E3
11/18/4	6	3	ND	2.2	ND	ND	ND	ND	66	71.4	31	59	33	50	24	52	36	26	26	32	28E3	158E2	59E2	13E3
1/13/5 ^	9	13	19	4	ND	ND	ND	ND	131	316	379	113	90	44	55	134	121	91	91	87	1330	4E2	25E2	19E2
1/28/5 ^	3	4	1.5	1.5	ND	ND	ND	ND	50	109	47	54	20	61	44	53	19	25	29	18	4E2	4E2	7E2	3E2
5/9/5 ^	1	1	ND	1.5	ND	ND	ND	ND	26	150	54	1110	23	111	57	212	37	97	57	▒ 420	25E2	<100	100	16E2

▒ Outlier, excluded from final analyses ▤ Invalid data points, excluded from final analyses

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

Table 4.5. EMCs for all storm events monitored at College Station Site 3

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)				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
3/5/4	148	482	406	216	2.6	4.68	3.48	3.52	.84	.45	0.41	0.4	.35	.37	.41	0.3	.27	.14	.11	0.1	18	17	14	13.5	7.1	5.39	4.65	5.13
3/25/4	276	214	48	270	3.4	2.37	1.82	1.7	2	.73	0.32	.26	.2	.26	.22	.18	.1	.08	.06	0.05	17	9.6	8.4	4.76	6.2	6.93	4.37	4.56
5/2/4	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
8/2/4	144	72	138	38	1.1	3.72	2.75	3.96	.47	1.2	0.18	ND	.15	.73	.91	2.2	.13	.62	.81	1.83	32	18	8.5	9.48	14	13.7	9.24	7.92
8/23/4	7	4	7	4	.91	1.35	1.26	1.26	.05	.26	0.22	.18	.08	.19	.23	.48	.03	.16	.19	0.43	6.8	9.6	4.6	3.11	4.4	8.38	3.68	2.25
10/3/4	76	28	52	46	.67	1.73	3.59	1.77	ND	ND	ND	ND	.39	.32	1.1	.51	.22	.21	.62	0.42	18	8.2	11	4.57	3.4	5.56	6.17	4.29
11/18/4	46	56	66	24	1.2	1.87	1.44	0.91	0.4	.17	0.06	.09	.18	.31	.23	.14	.04	.14	.03	ND	12	8.7	6	3.2	6.4	5.2	3.73	2.09
1/13/5 ^	341	418	928	315	2.9	8.8	5.56	3.48	1.9	11	0.23	7.5	.32	1	.68	.26	.16	.26	.04	ND	14	18.2	16	4.58	4.3	4.74	2.3	1.85
1/28/5 ^	47	170	284	114	1.5	0.87	1.11	3.9	2.2	.05	0.03	.97	.11	.08	.1	.26	.06	.04	.03	0.17	14	12	13	6.28	6.1	4.14	2.81	3.61
5/9/5 ^	35	12	67	16	1.8	1.99	2	2.22	.26	2.5	1.43	1.3	.17	.21	.23	.33	.13	.13	.1	0.18	7.7	6.1	4.6	6.1	`5.8	4.24	3.82	4.22

	Total Lead (µg/L)				Dissolved Lead (µg/L)				Total Zn (µg/L)				Dissolved Zn (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
3/5/4	6.3	18	14	9.9	ND	ND	ND	ND	176	646	325	486	110	216	157	313	106	96	122	.85	20	13E2	15E2	28E2
3/25/4	4.6	9.3	4.6	2.4	ND	ND	ND	ND	120	633	179	245	40	226	52	210	122	83	84	53	7E3	5E2	22E2	17E2
5/2/4	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
8/2/4	12	3.7	3.1	1.9	ND	ND	ND	1	223	708	572	1080	77.3	600	647	1020	144	151	149	175	3E3	223E3	49E3	252E3
8/23/4	1.2	ND	ND	ND	ND	ND	ND	ND	36.3	432	396	496	30	402	329	438	56	39	32	32	18E3	11E3	8E3	>400
10/3/4	6.9	ND	4.5	1.7	ND	ND	1	ND	151	235	932	320	39.7	95.4	746	261	123	75	214	78	32E3	183E3	305E3	124E3
11/18/4	4.7	4.3	3.3	1.6	ND	ND	ND	ND	60.8	125	54.6	63.6	27.7	71.4	39	51	40	41	24	24	222E2	258E2	15E3	62E2
1/13/5 ^	7.7	21	28	8.1	ND	ND	ND	4	95.8	443	309	239	31.4	165	47	302	105	133	108	57	11E2	72E2	39E2	56E2
1/28/5 ^	6.7	7.7	11	4.8	1.3	ND	ND	ND	123	169	204	362	22.1	138	75	228	75	31	37	62	2E2	3E2	7E2	35E3
5/9/5 ^	1.3	ND	1.2	ND	ND	ND	ND	ND	25.3	95.8	65.1	384	24.6	82.5	63	289	55	52	50	75	38E2	167E2	2E2	21E2

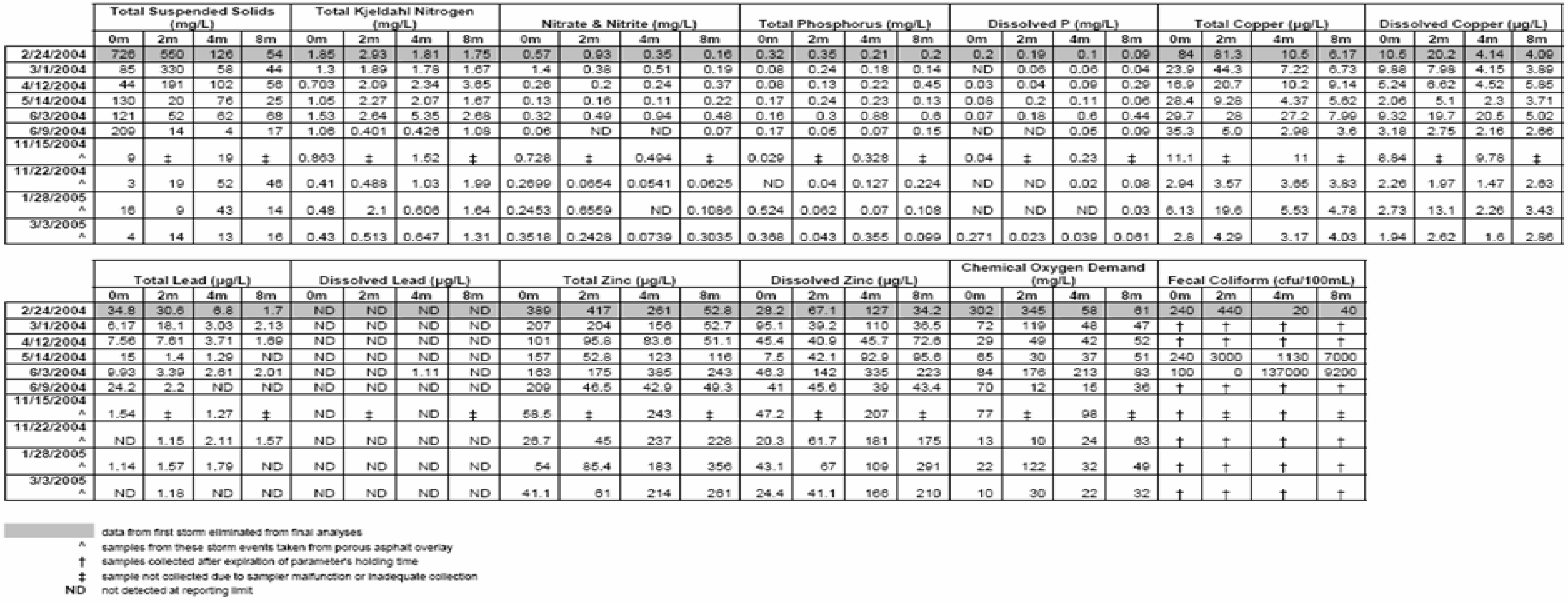
▨ Outlier, excluded from final analyses

\# Sample not collected due to Fire ants

ND not detected at reporting limit

^ Samples collected without Zero meter flow strip at the edge of the pavement

Table 4.6. EMCs for all storm events monitored at Austin Site 1

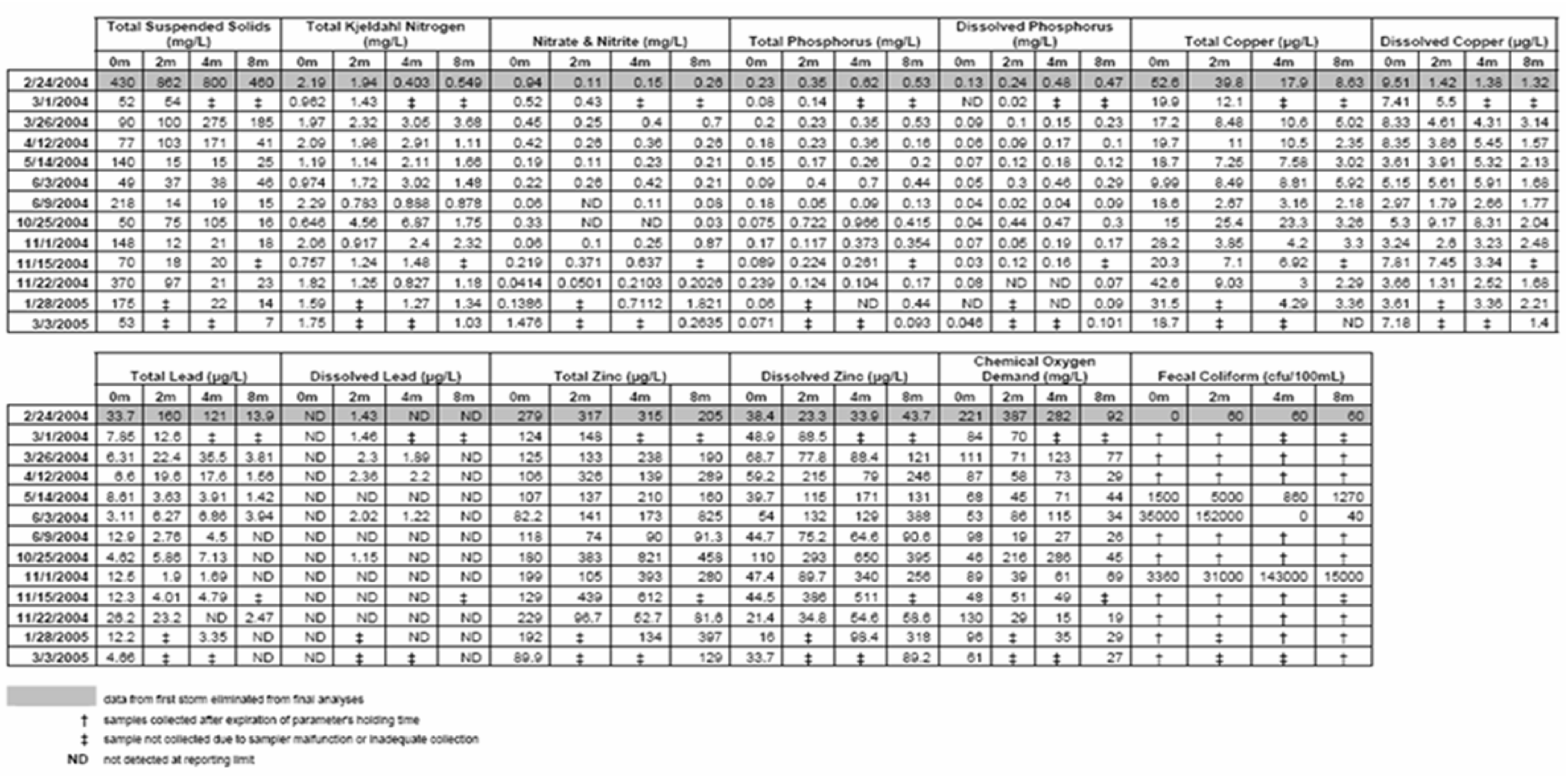


	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved P (mg/L)				Total Copper (µg/L)				Dissolved Copper (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	726	550	126	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	5.95
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	9.26	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	26	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	1.09	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	3.66	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	93	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	‡	59.5	‡	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	281	24.4	41.1	168	210	10	30	22	32	†	†	†	†

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

Table 4.7. EMCs for all storm events monitored at Austin Site 2



	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)			
	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
3/1/2004	52	64	‡	‡	0.962	1.43	‡	‡	0.52	0.43	‡	‡	0.08	0.14	‡	‡
3/26/2004	90	100	275	185	1.97	2.32	3.06	3.68	0.46	0.25	0.4	0.7	0.2	0.23	0.36	0.53
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
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
6/3/2004	49	37	38	46	0.974	1.72	3.02	1.49	0.22	0.26	0.42	0.21	0.09	0.4	0.7	0.44
6/9/2004	218	14	19	15	2.29	0.783	0.888	0.878	0.06	ND	0.11	0.08	0.18	0.06	0.09	0.13
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
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
11/15/2004	70	18	20	‡	0.757	1.24	1.48	‡	0.219	0.371	0.637	‡	0.089	0.224	0.261	‡
11/22/2004	370	97	21	23	1.82	1.26	0.827	1.18	0.0414	0.0501	0.2103	0.2026	0.239	0.124	0.104	0.17
1/28/2005	176	‡	22	14	1.59	‡	1.27	1.34	0.1386	‡	0.7112	1.821	0.06	‡	ND	0.44
3/3/2005	53	‡	‡	7	1.75	‡	‡	1.03	1.476	‡	‡	0.2635	0.071	‡	‡	0.093

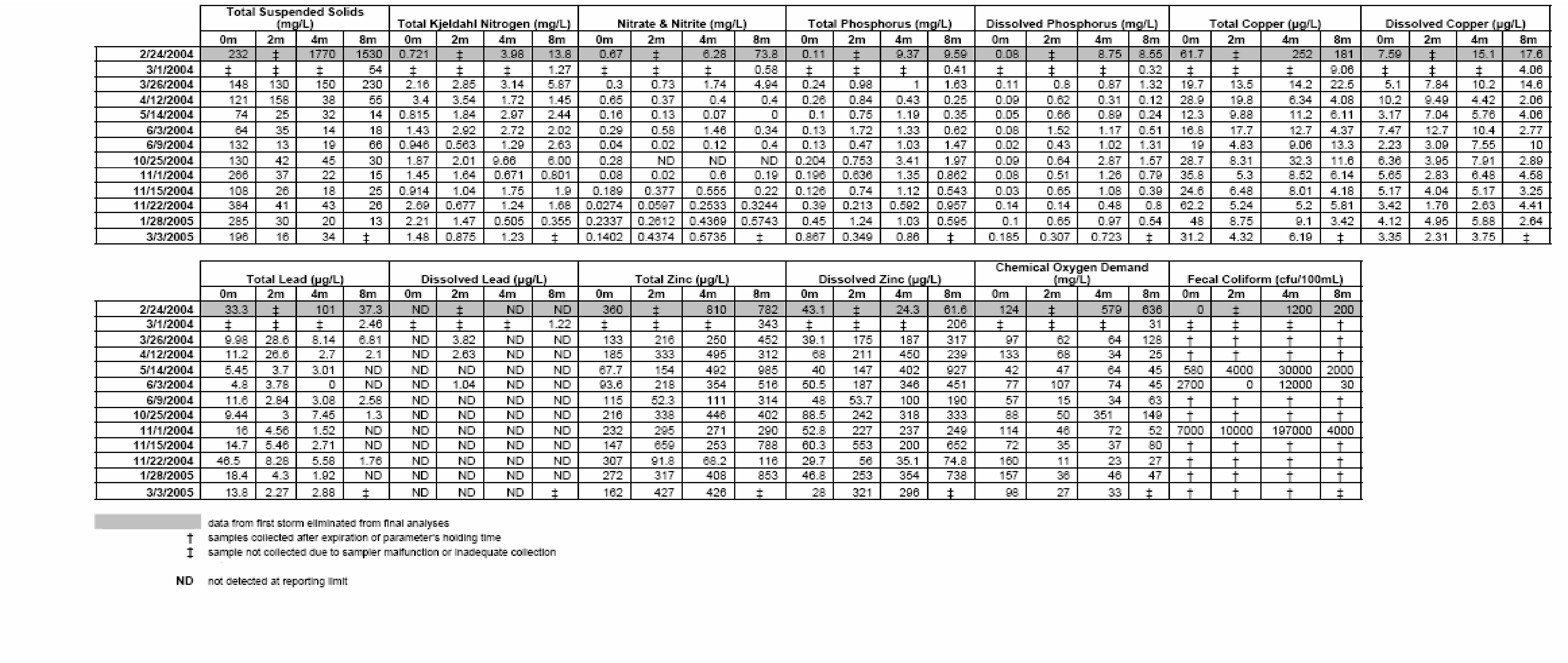
	Dissolved Phosphorus (mg/L)				Total Copper (µg/L)				Dissolved Copper (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	0.13	0.24	0.46	0.47	62.6	39.8	17.9	8.63	9.51	1.42	1.36	1.32
3/1/2004	ND	0.02	‡	‡	19.9	12.1	‡	‡	7.41	5.5	‡	‡
3/26/2004	0.09	0.1	0.15	0.23	17.2	8.48	10.6	6.02	8.33	4.61	4.31	3.14
4/12/2004	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	0.07	0.12	0.18	0.12	18.7	7.26	7.58	3.02	3.61	3.91	5.32	2.13
6/3/2004	0.05	0.3	0.46	0.29	9.99	8.49	8.81	6.92	6.15	5.61	5.91	1.68
6/9/2004	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	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	0.07	0.06	0.19	0.17	28.2	3.85	4.2	3.3	3.24	2.6	3.23	2.48
11/15/2004	0.03	0.12	0.16	‡	20.3	7.1	6.92	‡	7.81	7.45	3.34	‡
11/22/2004	0.08	ND	ND	0.07	42.6	9.03	3	2.29	3.66	1.31	2.52	1.68
1/28/2005	ND	‡	ND	0.09	31.5	‡	4.29	3.36	3.61	‡	3.36	2.21
3/3/2005	0.046	‡	‡	0.101	18.7	‡	‡	ND	7.18	‡	‡	1.4

	Total Lead (µg/L)				Dissolved Lead (µg/L)				Total Zinc (µg/L)			
	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	316	205
3/1/2004	7.85	12.6	‡	‡	ND	1.46	‡	‡	124	148	‡	‡
3/26/2004	6.31	22.4	35.5	3.81	ND	2.3	1.89	ND	125	133	238	190
4/12/2004	6.6	19.6	17.6	1.56	ND	2.36	2.2	ND	106	326	139	289
5/14/2004	8.61	3.63	3.91	1.42	ND	ND	ND	ND	107	137	210	160
6/3/2004	3.11	6.27	6.86	3.94	ND	2.02	1.22	ND	82.2	141	173	825
6/9/2004	12.9	2.76	4.5	ND	ND	ND	ND	ND	118	74	90	91.3
10/25/2004	4.62	5.86	7.13	ND	ND	1.15	ND	ND	180	383	821	458
11/1/2004	12.5	1.9	1.69	ND	ND	ND	ND	ND	199	105	393	280
11/15/2004	12.3	4.01	4.79	‡	ND	ND	ND	‡	129	439	612	‡
11/22/2004	26.2	23.2	ND	2.47	ND	ND	ND	ND	229	96.7	62.7	81.6
1/28/2005	12.2	‡	3.35	ND	ND	‡	ND	ND	192	‡	134	397
3/3/2005	4.66	‡	‡	ND	ND	‡	‡	ND	89.9	‡	‡	129

	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
2/24/2004	38.4	23.3	33.9	43.7	221	387	282	92	0	60	60	60
3/1/2004	48.9	88.5	‡	‡	84	70	‡	‡	†	†	‡	‡
3/26/2004	68.7	77.8	88.4	121	111	71	123	77	†	†	†	†
4/12/2004	59.2	216	79	246	87	58	73	29	†	†	†	†
5/14/2004	39.7	116	171	131	68	46	71	44	1500	5000	860	1270
6/3/2004	54	132	129	388	63	86	115	34	35000	152000	0	40
6/9/2004	44.7	75.2	64.6	90.6	98	19	27	26	†	†	†	†
10/25/2004	110	293	650	395	46	216	286	45	†	†	†	†
11/1/2004	47.4	89.7	340	256	89	39	61	69	3360	31000	143000	15000
11/15/2004	44.5	386	511	‡	48	51	49	‡	†	†	†	‡
11/22/2004	21.4	34.8	64.6	68.6	130	29	15	19	†	†	†	†
1/28/2005	16	‡	98.4	318	96	‡	35	29	†	‡	†	†
3/3/2005	33.7	‡	‡	89.2	61	‡	‡	27	†	‡	‡	†

▨ 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 4.8. EMCs for all storm events monitored at Austin Site 3



	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)				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	‡	†	†	†	‡

▨ 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

4.6 Summary statistics at College Station sites

Tables 4.9, 4.10, and 4.11 contain the summary statistics (arithmetic mean, range, and standard deviation) of the monitoring data collected at each site for each constituent. As mentioned earlier, the constituent data points were natural-log transformed prior to applying ANOVA and post hoc analyses. Using post hoc analyses, each treatment mean is compared with each of the other treatment means. The cells with an arrow head indicate whether the observed concentrations at specified distances from the edge of pavement exhibit statistically significant increases (shown by a up arrow) or decreases (shown by a down arrow) in concentration at the 95% confidence interval.

Constituents with no arrows in the cells indicate that no statistically significant changes in concentration occurred for that constituent across the width of the vegetated roadsides. Cells with an arrow in the cell only in the right-most column 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 arrows in the cells indicate that a significant increase or decrease occurred at each of the distances shown by an arrow at the cell location. In addition, boxplots were created to examine trends that occurred at each site. Selected boxplots are presented to illustrate some of the trends observed at the research sites. The entire set of plots for each site can be found in Appendix A.

4.6.1 Site 1

The summary statistics and the post hoc analyses results (showing P values) for rainfall events monitored at Site 1 are presented in Table 4.9. Total and dissolved Cu exhibited statistically significant decrease in concentrations between the zero and eight meter sampling points. Figures 4.2 and 4.3 show boxplots of the changes in total and dissolved Cu concentration at this site. The plots show the general trend of decreasing concentrations with increasing distance from the edge of the pavement for these constituents. The only constituents that exhibit a statistically significant increase in concentration at this site were total and dissolved Zn. The concentrations of Zn at Site 1 are higher due to reasons explained in section 4.13.

Table 4.9. Summary statistics for College Station Site 1

Constituent	**Sample Location**			
	Edge of Pavement	**2m**	**4m**	**8m**
	Mean Range Std Deviation P-value	**Mean Range Std Deviation P-value**	**Mean Range Std Deviation P-value**	**Mean Range Std Deviation P-value**
TSS (mg/L)	116 8 – 421 130	79 9 – 192 58 1	85 8 – 229 87 0.978	97 4 – 326 95 1
TKN (mg/L)	2.13 0.549 – 5.34 1.61	2.43 0.65 – 7.55 1.91 0.917	2.45 0.433 – 7.53 2.25 0.991	2.88 0.861 – 8.49 2.34 0.714
NO3/NO2-N (mg/L)	0.41 0.25 – 0.75 0.15	0.42 0.14 – 0.77 0.24 0.996	0.33 0.037 – 1 0.3 0.73	1.26 0.029 – 7.2 2.44 0.996
Total P (mg/L)	0.22 0.064 – 0.584 0.16	0.42 0.125 – 1.24 0.35 0.344	0.47 0.05 – 2.03 0.64 0.756	0.4 0.12 – 1.36 0.39 0.515
Dissolved P (mg/L)	0.13 0.03 – 0.29 0.09	0.87 0.06 – 6.05 1.85 0.409	0.38 0.02 – 1.75 0.58 0.918	0.28 0.03 – 0.8 0.29 0.913
Total Cu (µg/L)	14.33 5.67 – 29.5 7.42	10.23 5.79 – 15.9 3.22 0.584	6.47 2.94 – 9.49 2.28 0.007 ⇩	6.95 3.01 – 13.4 3.64 0.006 ⇩
Total Pb (µg/L)	7.17 1.08 – 22.9 6.92	5.25 1.12 – 11.6 3.84 0.991	7.88 1.72 – 15.1 5.24 0.899	4.68 2.01 – 13.7 4.17 0.97
Total Zn (µg/L)	117 33.6 – 241 76.3	237.7 88.1 – 538 134.8 0.12	358.9 78.6 – 855 223.2 0.014 ⇧	393.4 48.3 – 1520 424.8 0.034 ⇧
Dissolved Cu (µg/L)	6.18 3.26 – 11.6 2.61	5.4 2.11 – 10.7 2.55 0.869	5.1 2.27 – 11 2.76 0.71	4.21 1.38 – 9.81 2.75 0.148
Dissolved Pb (µg/L)	0.00 0.0 – 4.12 0.00	0.00 0.0 – 1.03 0.00 NA*	0.00 0.0 – 2.84 0.00 NA*	0.00 0.0 – 1.13 0.00 NA*
Dissolved Zn (µg/L)	48.3 17.9 – 97.9 26.3	172.8 81.6 – 340 96 <0.0001 ⇧	268 73.3 – 479 119 <0.0001 ⇧	290.4 44.5 – 953 260.3 <0.0001 ⇧
COD (mg/L)	73.3 26 – 138 42.97	76.3 46 – 128 27.41 0.929	72.9 21 – 215 56.05 0.999	88.6 26 – 279 74.34 0.966

NA* Not Available

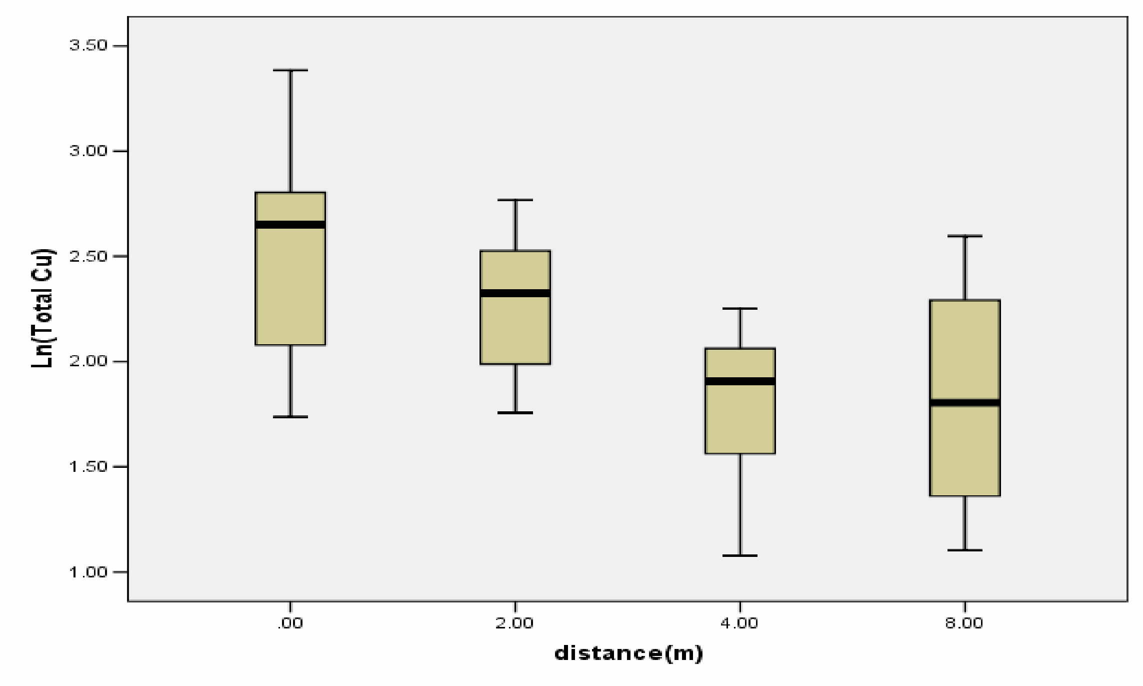


Figure 4.2. Boxplot of total Cu EMCs at College Station Site 1

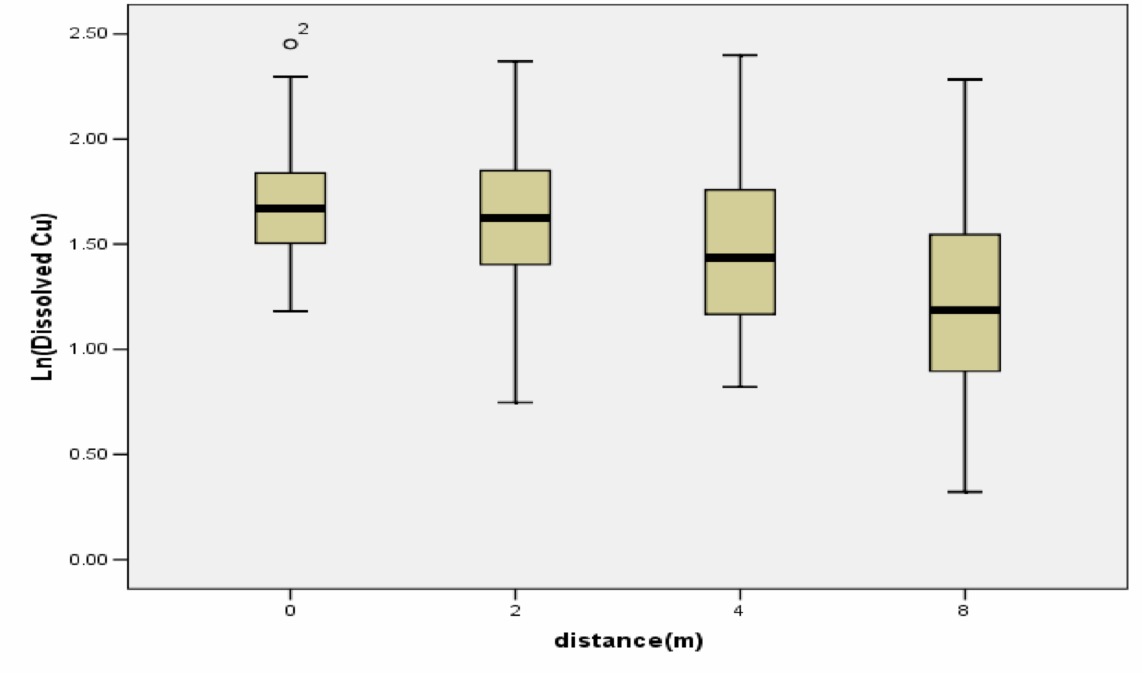


Figure 4.3. Boxplot of dissolved Cu EMCs at College Station Site 1

4.6.2 Site 2

The summary statistics and the post hoc analyses results (showing P values) for rainfall events monitored at Site 2 are presented in Table 4.10. A brief discussion on the summary statistics is described in this section. The changes observed in this site were increases in some constituent concentrations such as total and dissolved P, total and dissolved Zn over the vegetated sampling area. The concentrations of Zn at Site 2 are found to be increasing with increasing distances from the edge of pavement. The reason for higher concentrations is explained in section 4.13. Total Cu exhibited decreases in concentrations with increasing distances from the edge of pavement.

Figures 4.4 and 4.5 show boxplots of the changes in total P and TSS concentrations at this site. Figure 4.4 shows the trend of increasing concentrations with increasing distances from the edge of pavement for total P. Figure 4.5 shows the trend of decreasing concentrations with increasing distances from the edge of pavement for TSS.

Table 4.10 Summary statistics for College Station Site 2

Constituent	**Sample Location**			
	Edge of Pavement	**2m**	**4m**	**8m**
	Mean **Range** **Std deviation** **P-value**	**Mean** **Range** **Std deviation** **P-value**	**Mean** **Range** **Std deviation** **P-value**	**Mean** **Range** **Std deviation** **P-value**
TSS (mg/L)	172.4 19 – 504 185.8	63.89 11 – 120 40.58 0.616	105.2 8 – 486 141.5 0.74	93.5 4 – 293 95.99 0.735
TKN (mg/L)	1.94 0.64 – 3.99 1.06	2.94 1.16 – 5.85 1.76 0.554	2.55 0.86 – 5.01 1.57 0.858	3.77 0.57 – 13.7 4.18 0.554
NO3/NO2-N (mg/L)	1.06 0.054 – 7.78 2.37	1.37 0.05 – 5.32 1.76 0.756	0.44 0.02 – 1.97 0.62 0.843	0.48 0 – 2.03 0.66 0.999
Total P (mg/L)	0.24 0.051 – 0.434 0.14	0.58 0.198 – 1.5 0.41 0.067	0.64 0.114 – 2.14 0.58 0.079	0.6 0.08 – 1.63 0.52 0.167
Dissolved P (mg/L)	0.14 0.05 – 0.18 0.04	0.36 0.03 – 1.36 0.41 0.685	0.47 0.09 – 1.96 0.56 0.303	0.4 0.06 – 1.18 0.44 0.718
Total Cu (µg/L)	17.23 7.28 – 31.1 8.78	14.26 6.05 – 28.7 7.44 0.878	9.09 3.72 – 22.4 5.811 0.061	9.12 2.84 – 26 7.27 0.057
Total Pb (µg/L)	9.05 1.34 – 23.1 7.5	7.0 1.15 – 19.7 6.38 0.93	8.66 1.51 – 21.5 9.02 0.985	3.7 0 – 10.5 4.23 0.688
Total Zn (µg/L)	118.3 26 – 259 84.3	236.7 71.4 – 443 128 0.179	225.8 31.4 – 557 199.8 0.632	296.35 54.2 – 1110 344.73 0.303
Dissolved Cu (µg/L)	5.81 2.6 – 11.4 2.64	5.49 3.25 – 15.1 3.51 0.968	4.95 3.04 – 10.4 2.04 0.894	4.13 2.3 – 5.95 1.11 0.431
Dissolved Pb (µg/L)	0.00 None 0.00	0.00 None 0.00 NA*	0.00 None 0.00 NA*	0.00 None 0.00 NA*
Dissolved Zn (µg/L)	44.3 20.2 – 89.4 26.6	144.5 44.1 – 427 ⇧ 123.1 0.02	159.3 24.3 – 799 238.4 0.094	171.6 51.6 – 276 ⇧ 83.89 0.004
COD (mg/L)	71.4 19 – 132 43.25	79.7 25 – 129 39.35 0.953	75.9 26 – 143 44.48 0.988	57.38 18 – 87 27.26 0.885

NA* Not Available

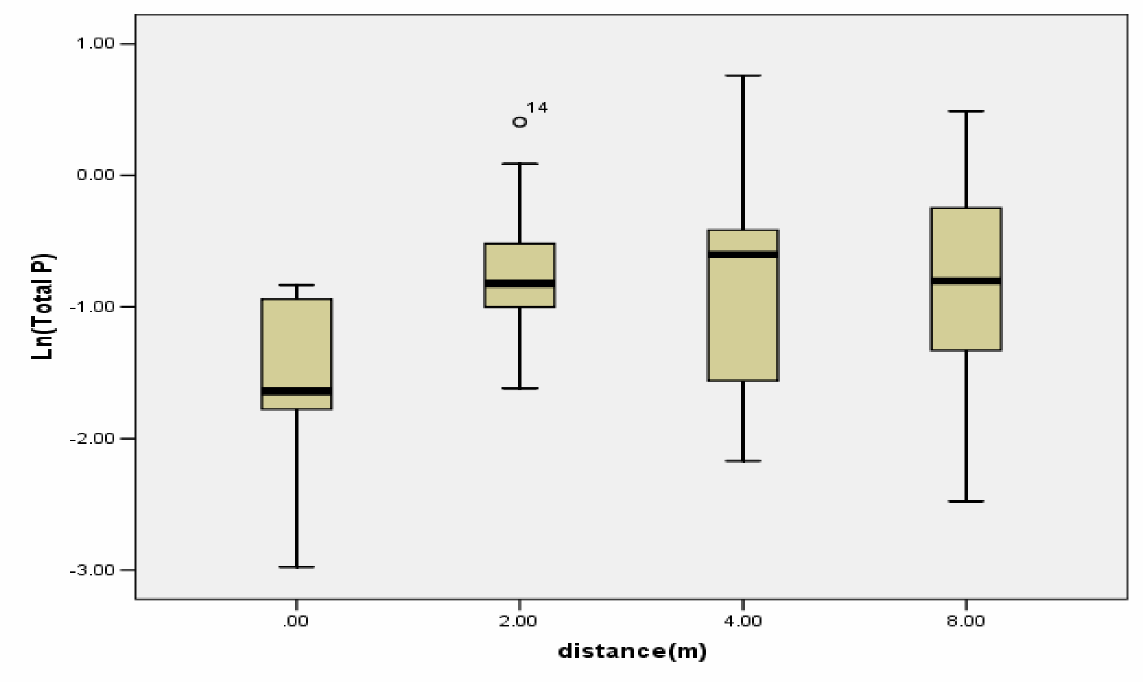


Figure 4.4. Boxplot of total P EMCs at College Station Site 2

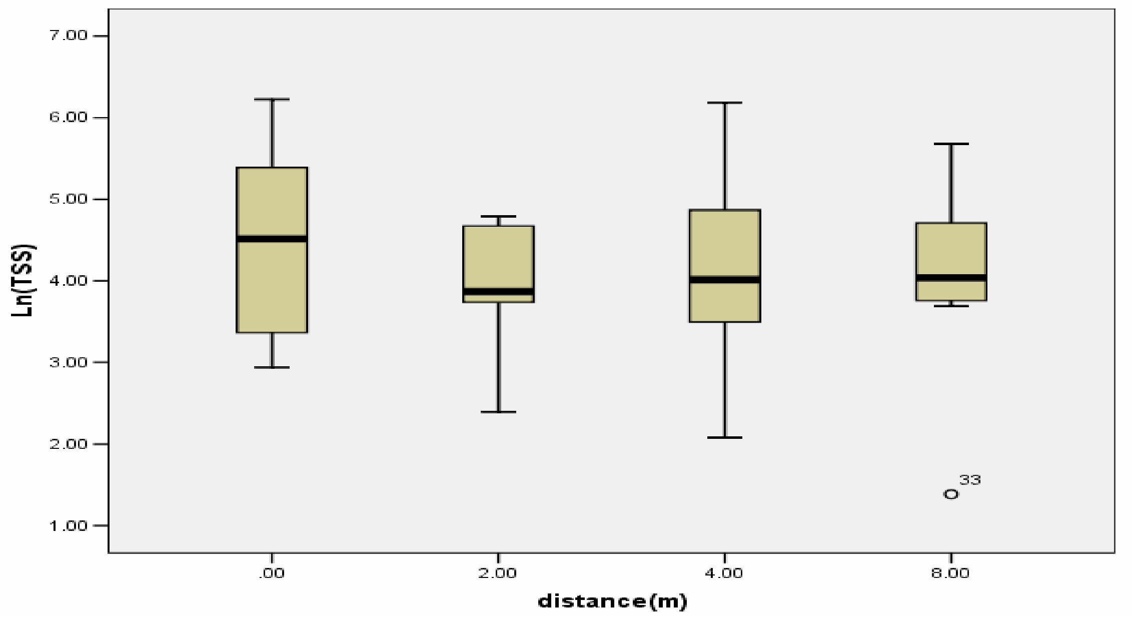


Figure 4.5. Boxplot of TSS EMCs at College Station Site 2

Comparison is drawn between the concentrations of various constituents at Site 2 before and after reconditioning. The results of the analysis are presented in Table 4.11.

Table 4.11 Comparison of EMCs at Site 2, before and after reconditioning

Constituents	P-Values(transformed data)
Total Suspended Solids	0.197
Total Kjeldahl Nitrogen	0.931
Nitrate/ Nitrite-Nitrogen	0.758
Total P	0.531
Dissolved P	0.166
Total Cu	0.532
Total Pb	0.002
Total Zn	0.723
Dissolved Cu	0.962
Dissolved Pb	NA
Dissolved Zn	0.821
COD	0.42

*NA Not Available

The only constituent found to have P-values less than 0.05 is the total Pb. This value indicates statistical significant difference in concentrations before and after the reconditioning at eight meter.

The believed reason for lower concentrations of total Pb is that the influence of vehicles during the storm (VDS) (expressed in no. of vehicles) upon the concentrations of total Pb. The increasing trend of total Pb with increasing VDS has been found by regression analysis, which has been discussed in detail in section 4.11.

Table 4.20 contains the VDS during the rainfall events. Upon comparing the mean VDS (19,990) during the storm events (the first four events) prior to reconditioning and the mean VDS (19400) during the storm events (the last six events) after reconditioning, it is apparent that the roadsides were exposed to heavier traffic prior to reconditioning at Site 2. It is believed that higher the traffic using the highway during the storm, higher would be the concentrations of total Pb. This explains the reason for the higher mean concentrations of total Pb (11.17µg/L) prior to reconditioning when compared to the lower mean concentrations of total Pb (1.52 µg/L) after reconditioning. Also, the corrective measure of reconditioning the sampler which was originally submerged in water could provide a more representative value of the total Pb concentrations.

4.6.3 Site 3

The summary statistics and the post hoc analyses results for rainfall events monitored at Site 3 are presented in Table 4.12. . The summary statistics include the mean, range, and standard deviation for all constituents. The results of the post hoc analyses include P-values based on pairwise comparison using Tukey method.

Total Cu exhibited statistically significant decreases in concentrations with increasing distances from the edge of pavement. A brief discussion on the summary statistics is described in this section. Figures 4.6 and 4.7 show boxplots of the changes in TSS and total Cu concentrations at this site.

The plots show the trend of decreasing concentrations with increasing distance from the edge of the pavement for these constituents. Figure 4.6 shows the trend of decreasing concentrations with increasing distances from the edge of pavement for TSS. Figure 4.7 shows the trend of decreasing concentrations with increasing distances from the edge of pavement for total Cu.

Table 4.12. Summary statistics for College Station Site 3

Constituent	Sample Location			
	Edge of Pavement	2m	4m	8m
	Mean Range Std deviation P-value	Mean Range Std deviation P-value	Mean Range Std deviation P-value	Mean Range Std deviation P-value
TSS (mg/L)	124.4 7 – 341 115.7	161.8 4 – 482 178.7 0.999	221.8 7 – 928 295.2 0.972	115.9 4 – 315 120.1 0.972
TKN (mg/L)	1.79 0.674 – 3.41 0.96	3.04 0.87 – 8.8 2.46 0.413	2.56 1.11 – 5.56 1.45 0.573	2.53 0.91 – 3.96 1.19 0.565
NO3/NO2-N (mg/L)	1.01 0.05 – 2.19 0.87	2.04 0.045 – 10.97 3.67 1	0.36 0.031 – 1.424 0.45 0.446	1.52 0.093 – 7.49 2.67 1
Total P (mg/L)	0.22 0.08 – 0.385 0.08	0.39 0.081 – 1.01 0.3 0.535	0.46 0.104 – 1.11 0.36 0.311	0.51 0.143 – 2.15 0.63 0.283
Dissolved P (mg/L)	0.13 0.03 – 0.27 0.09	0.2 0.08 – 0.62 0.17 0.82	0.22 0.03 – 0.81 0.29 0.999	0.45 0.05 – 1.83 0.62 0.311
Total Cu (µg/L)	15.57 6.81 – 32.2 7.47	11.87 8.23 – 18.2 4.55 0.675	9.51 4.55 – 16.4 4.17 0.121	6.18 3.11 – 13.5 3.35 0.001 ⇩
Total Pb (µg/L)	5.66 1.22 – 11.5 3.2	10.77 3.73 – 21.4 7.37 0.466	8.77 1.21 – 28.1 8.98 0.946	4.35 1.61 – 9.92 3.41 0.879
Total Zn (µg/L)	112.4 25.3 – 223 65.4	387.4 95.8 – 708 239.8 0.015 ⇧	337.4 54.6 – 932 276.1 0.071	408.4 63.6 – 1080 285 0.01 ⇧
Dissolved Cu (µg/L)	6.41 3.41 – 14 3.08	6.48 4.14 – 13.7 3.02 1	4.53 2.3 – 9.24 2.08 0.31	3.99 1.85 – 7.92 1.89 0.079
Dissolved Pb (µg/L)	0.00 0.0 – 1.29 0.00	0.00 None 0.00 NA*	0.00 0.0 – 1.25 0.00 NA*	0.00 0.0 – 3.75 0.00 NA*
Dissolved Zn (µg/L)	44.8 22.1 – 110 29.5	221.8 71.4 – 600 174.6 0.002 ⇧	239.5 39 – 746 275.6 0.015 ⇧	261.45 50.6 – 438 109.84 <0.0001 ⇧
COD (mg/L)	91.78 40 – 144 36.38	77.89 31 – 151 42.55 0.866	91.11 24 – 214 63.6 0.936	69.5 24 – 175 46.59 0.612

NA* Not Available

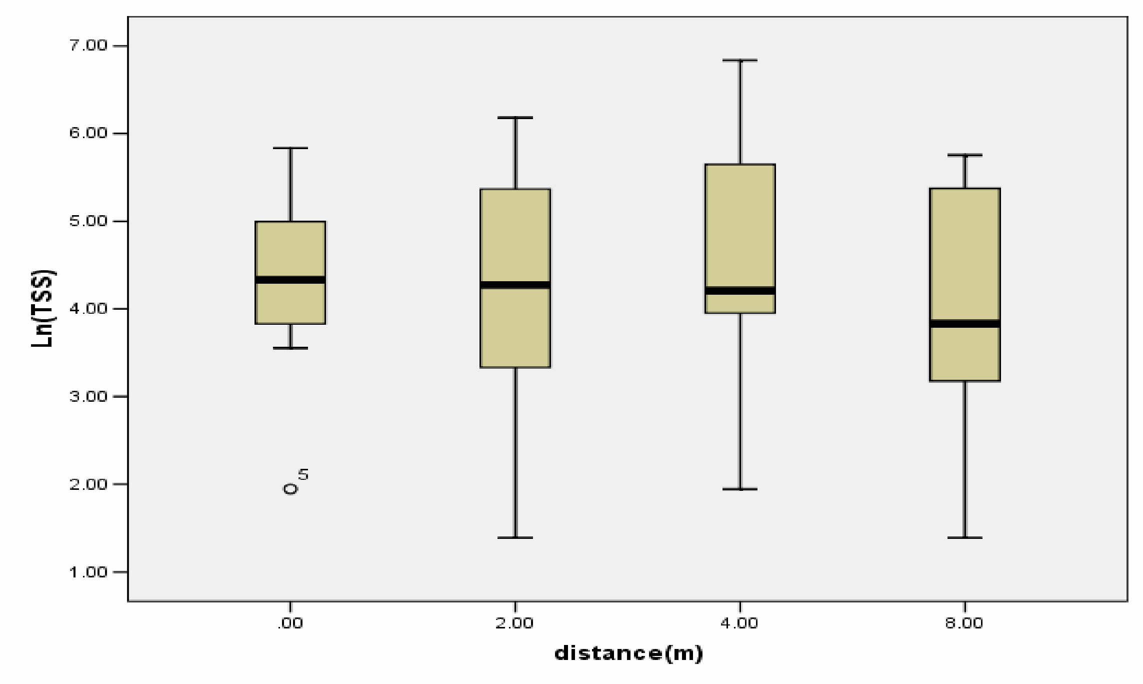


Figure 4.6. Boxplot of TSS EMCs at College Station Site 3

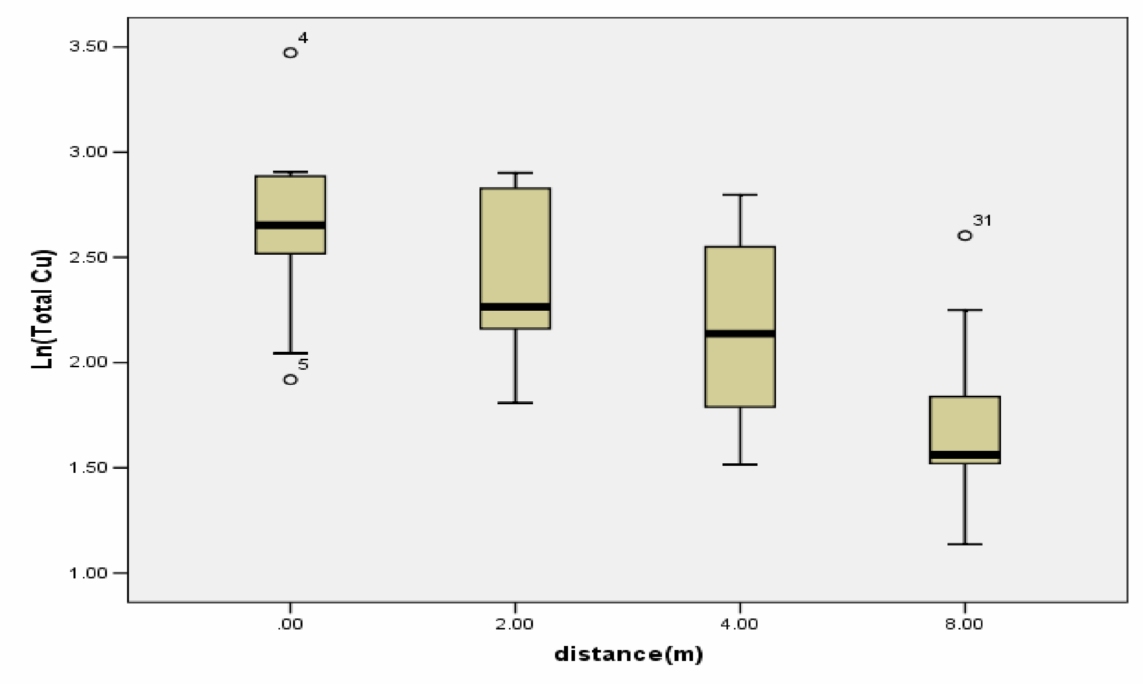


Figure 4.7. Boxplot of total Cu EMCs at College Station Site 3

4.7 Summary statistics at Austin sites

Tables 4.13, 4.14, 4.15, and 4.16 contain the summary statistics (arithmetic mean, range, and standard deviation) of the monitoring data collected at each site for each constituent.

Again, statistics are based on the original data and the ANOVA and post–hoc analyses were performed on the transformed data which is normally distributed. In addition, boxplots were created to examine trends that occurred at each site. Selected boxplots are presented to illustrate some of the trends observed at the research sites. The entire set of plots for each site can be found in Appendix B.

4.7.1 Site 1(Traditional Asphalt Pavement)

The summary statistics and the post hoc analyses results (showing P values) for rainfall events monitored at Site 1(traditional asphalt pavement) are presented in Table 4.13. The tables show that total Cu and total Pb exhibited statistically significant decreases in concentrations between the zero and four meter and zero and eight meter sampling points. Figures 4.8 and 4.9 show the general trend of decreasing concentrations with increasing distance from the edge of pavement for these constituents.

Table 4.13.Summary statistics for Austin Site 1(traditional asphalt pavement)

Constituent	**Sample Location**			
	Edge of Pavement	**2m**	**4m**	**8m**
	Mean **Range** **Std.Deviation** **P-value**	**Mean** **Range** **Std.Deviation** **P-value**	**Mean** **Range** **Std.Deviation** **P-value**	**Mean** **Range** **Std.Deviation** **P-value**
TSS (mg/L)	118 44 – 330 61	121 14 – 330 137 0.857	60 4 – 102 36 0.497	42 17 – 68 21 0.421
TKN (mg/L)	1.13 0.7 – 1.5 0.31	1.86 0.4 – 2.6 0.86 0.822	2.39 0.4 – 5.4 1.81 0.627	2.15 1.1 – 3.7 1.02 0.512
NO3/NO2-N (mg/L)	0.43 0.1 – 1.4 0.55	0.25 0.0 – 0.5 0.19 0.997	0.36 0.0 – 0.9 0.38 0.954	0.27 0.1 – 0.5 0.16 0.997
Total P (mg/L)	0.13 0.1 – 0.2 0.05	0.19 0.1 – 0.3 0.1 0.933	0.316 0.1 – 0.9 0.322 0.574	0.29 0.1 – 0.6 0.22 0.504
Dissolved P (mg/L)	0.04 0.0 – 0.1 0.04	0.1 0.0 – 0.2 0.09 0.85	0.18 0.1 – 0.6 0.23 0.71	0.18 0.0 – 0.4 0.17 0.633
Total Cu (µg/L)	26.84 16.9 – 35.3 6.89	21.46 5 – 44.3 15.69 0.682	10.39 3 – 27.2 9.8 0.04 ⇩	6.62 3.6 – 9.1 2.14 0.016 ⇩
Total Pb (µg/L)	12.57 6.2 – 24.2 7.32	6.54 1.4 – 18.1 6.89 0.171	2.13 0 – 3.7 1.48 0.027 ⇩	1.17 0 – 0.4 0.17 0.017 ⇩
Total Zn (µg/L)	167.4 101 – 209 44.26	114.82 46.5 – 204 71.5 0.6	158.1 42.9 – 385 133.74 0.895	102.42 49.3 – 243 83.48 0.379
Dissolved Cu (µg/L)	5.94 2.1 – 9.9 3.54	8.43 2.8 – 19.7 6.59 0.894	6.73 2.2 – 20.5 7.77 0.995	4.23 2.7 – 5.9 1.23 0.964
Dissolved Pb (µg/L)	0.00 None 0.00	0.00 None 0.00 NA*	0.22 0.0 – 1.1 0.5 NA*	0.00 None 0.00 NA*
Dissolved Zn (µg/L)	47.06 7.5 – 95.1 31.28	61.96 39.2 – 142 44.81 0.856	124.52 39 – 335 121.49 0.282	94.22 36.5 – 223 75.78 0.463
COD (mg/L)	64 29 – 84 20.8	77.2 12 – 176 68.5 0.988	71 15 – 213 80.4 0.958	53.8 36 – 83 17.5 0.989

NA* Not Available

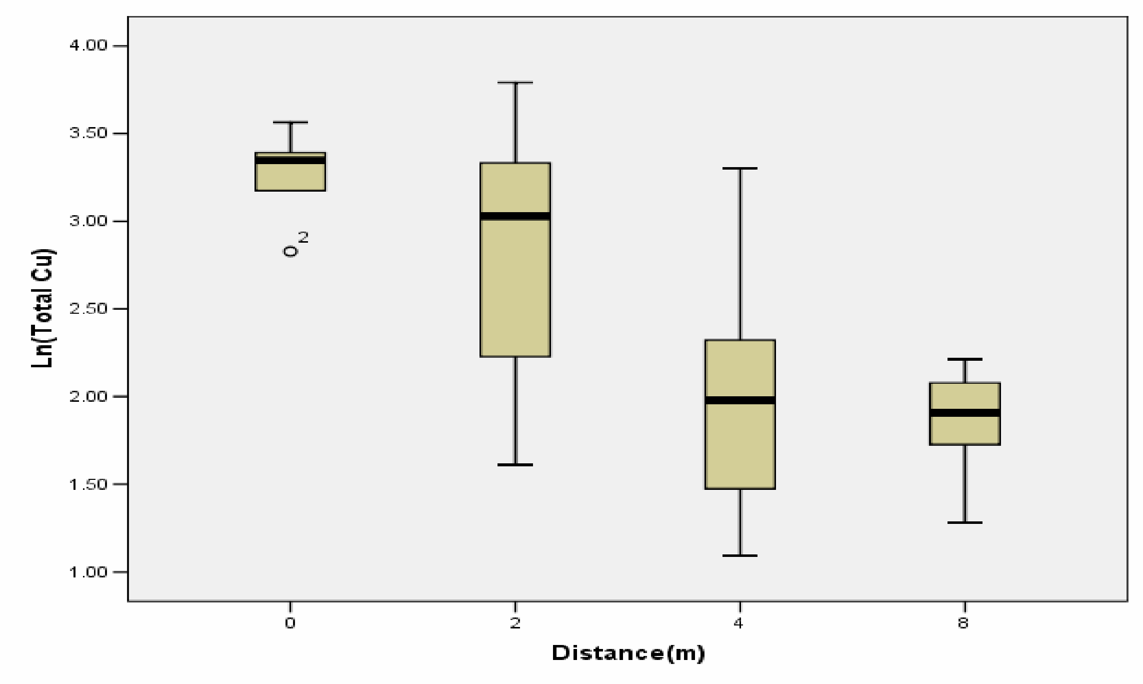


Figure 4.8. Boxplot of total Cu EMCs at Austin Site 1 (traditional asphalt surface)

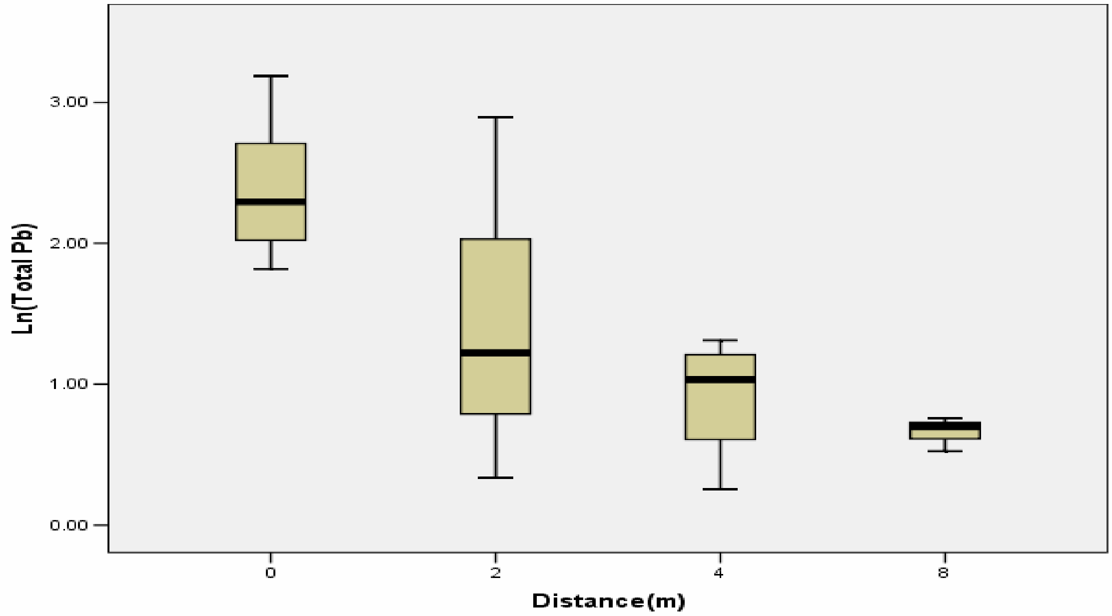


Figure 4.9. Boxplot of total Pb EMCs at Austin Site 1 (traditional asphalt surface)

4.7.2 Site 1(Porous Asphalt Pavement)

The summary statistics and the post hoc analyses results (showing P values) for rainfall events monitored at Site 1(porous asphalt pavement) are presented in Table 4.14. The tables indicate that the only significant changes observed at this site were increases in some constituent concentrations over the vegetated sampling area. The basic trend shows that no significant decreases in constituent concentrations were observed between the edge of pavement and the various sampling distances. The findings based on field observations and site conditions indicate that this trend is due to the extremely clean nature of the runoff leaving the PFC (Kearfott, 2005).

Results from events monitored at this site indicate increases in concentrations for TKN within the first eight meters and for TSS within the first four meters. Figure 4.10 shows a boxplot of TKN concentrations across the vegetation width at this site. Significant increases in both the total and dissolved forms of Zn were also found over almost the entire site. These elevated levels of Zn are believed to be due to leaching of Zn from the galvanized flashing attached to each of the collection pipes. Further discussions can be found in section 4.13.

Table 4.14.Summary statistics for Austin Site 1(porous asphalt pavement)

Constituent	**Sample Location**			
	Edge of Pavement	**2m**	**4m**	**8m**
	Mean **Range** **Std.Deviation** **P-value**	**Mean** **Range** **Std.Deviation** **P-value**	**Mean** **Range** **Std.Deviation** **P-value**	**Mean** **Range** **Std.Deviation** **P-value**
TSS (mg/L)	8 3 – 16 6	14 9 – 19 5 0.485	32 13 – 52 19 0.043 ⇧	25 14 – 46 18 0.127
TKN (mg/L)	0.55 0.4 – 0.9 0.21	1.03 0.5 – 2.1 0.92 0.651	0.95 0.6 – 1.5 0.42 0.449	1.65 1.3 – 2 0.34 0.05
NO3/NO2-N (mg/L)	0.4 0.2 – 0.7 0.22	0.32 0.1 – 0.7 0.3 0.888	0.16 0.0 – 0.5 0.23 0.471	0.16 0.1 – 0.3 0.13 0.481
Total P (mg/L)	0.23 0.0 – 0.5 0.26	0.05 0.0 – 0.1 0.01 0.337	0.22 0.1 – 0.4 0.14 1	0.14 0.1 – 0.2 0.07 0.98
Dissolved P (mg/L)	0.08 0.0 – 0.3 0.13	0.13 0.0 – 0.023 0.01 NA**	0.18 0.0 – 0.2 0.11 NA**	0.06 0.0 – 0.1 0.03 NA**
Total Cu (µg/L)	5.74 2.8 – 11.1 3.89	9.15 3.6 – 19.6 9.05 0.909	5.84 3.2 – 11 3.59 0.999	4.21 3.8 – 4.8 0.5 0.989
Total Pb (µg/L)	0.67 0.0 – 1.5 0.79	1.3 1.2 – 1.6 0.23 NA**	1.29 0.0 – 2.1 0.93 NA**	0.52 0.0 – 1.6 0.91 NA**
Total Zn (µg/L)	45.08 26.7 – 58.5 14.3	63.8 45 – 85.4 20.35 0.362	219.25 183 – 243 27.21 <0.0001 ⇧	281.67 228 – 356 66.46 <0.0001 ⇧
Dissolved Cu (µg/L)	3.94 1.9 – 8.8 3.28	5.9 2 – 13.1 6.25 0.976	3.78 1.5 – 9.8 4.02 0.987	2.97 2.6 – 3.4 0.41 0.999
Dissolved Pb (µg/L)	0.00 None 0.00	0.00 None 0.00 NA*	0.00 None 0.00 NA*	0.00 None 0.00 NA*
Dissolved Zn (µg/L)	33.75 20.3 – 47.2 13.37	56.6 41.1 – 67 13.68 0.165	165.75 109 – 207 41.45 <0.0001 ⇧	225.33 175 – 291 59.5 <0.0001 ⇧
COD (mg/L)	30.5 10 – 77 31.4	54 10 – 122 59.7 0.911	44 22 – 98 36.3 0.836	48 32 – 63 15.5 0.661

NA* Not Available

NA** Post hoc tests could not be performed for Dissolved P and Total Pb, for one group has fewer than two cases.

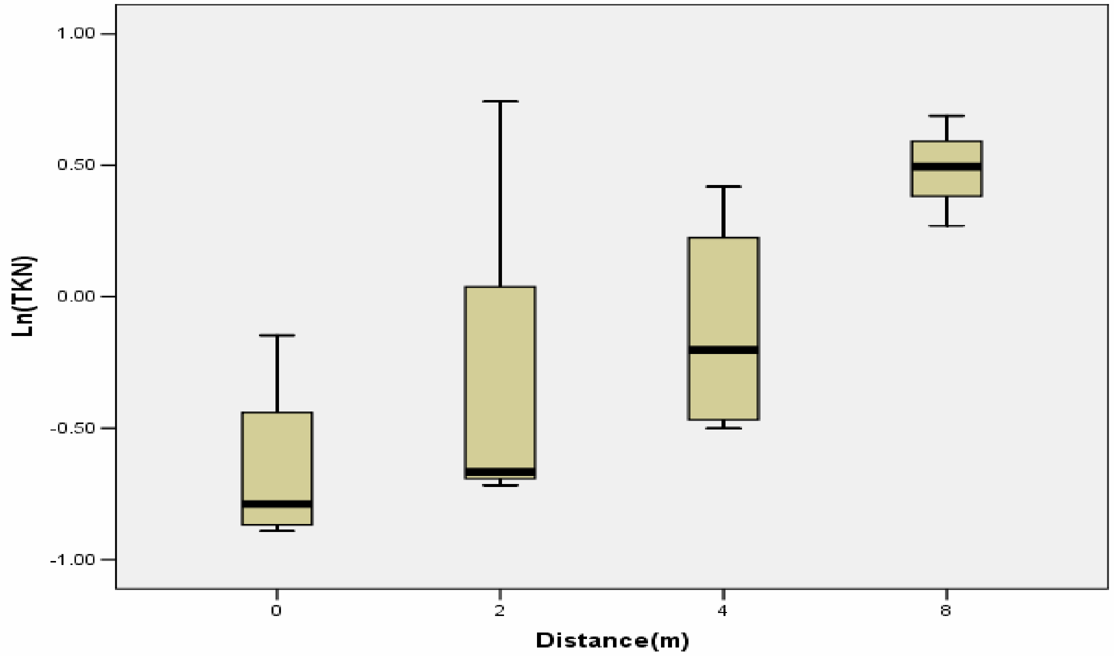


Figure 4.10. Boxplot of TKN EMCs at Austin Site 1 (porous asphalt pavement)

4.7.3 Site 2

The summary statistics and the post hoc analyses results (showing P values) for rainfall events monitored at Site 2 are presented in Table 4.15. The results indicate significant decreases in TSS over the entire width of vegetation at this site. Average EMCs for total Cu also exhibited significant decreases everywhere across the vegetation roadsides from the edge of pavement. Significant decreases also were observed for COD, dissolved Cu, and total Pb, although these decreases were observed only between the zero and eight meter sampling point.

Unlike the TSS and heavy metals, nutrients were often found to increase with increasing distance from the edge of pavement at this site. Both the total and dissolved forms of P exhibited significant increases in average concentrations between the zero and four meter and zero and eight meter sampling point. Figure 4.11 shows a boxplot of the dissolved P concentrations at Site 2. Total and dissolved forms of Zn also showed significant increase over the vegetated area. The reason for higher concentrations is explained in section 4.13.

Table 4.15.Summary statistics for Austin Site 2

Constituent	Sample Location			
	Edge of Pavement	2m	4m	8m
	Mean Range Std.Deviation P-value	Mean Range Std.Deviation P-value	Mean Range Std.Deviation P-value	Mean Range Std.Deviation P-value
TSS (mg/L)	124 49 – 370 96	53 12 – 103 38 0.068	71 15 – 275 88 0.087	39 7 – 185 53 0.003 ⇩
TKN (mg/L)	1.5 0.6 – 2.3 0.6	1.7 0.8 – 4.6 1.1 0.979	2.5 0.8 – 6.9 1.8 0.305	1.6 0.9 – 3.7 0.8 0.986
NO3/NO2-N (mg/L)	0.34 0.0 – 1.5 0.39	0.18 0.1 – 0.4 0.15 0.989	0.33 0.0 – 0.7 0.22 0.759	0.46 0.0 – 1.8 0.55 0.953
Total P (mg/L)	0.13 0.1 – 0.2 0.06	0.24 0.1 – 0.7 0.19 0.351	0.35 0.0 - 1 0.29 0.013 ⇧	0.29 0.1 – 0.5 0.16 0.05
Dissolved P (mg/L)	0.05 0.0 – 0.1 0.03	0.13 0.0 – 0.4 0.14 0.457	0.18 0.0 – 0.5 0.17 0.006 ⇧	0.16 0.1 – 0.3 0.09 0.033 ⇧
Total Cu (µg/L)	21.7 10 – 42.6 8.6	9.54 2.7 – 25.4 6.27 0.001 ⇩	8.24 3 – 23.3 6.01 <0.0001 ⇩	3.07 0.0 – 5.9 1.61 <0.0001 ⇩
Total Pb (µg/L)	9.82 3.1 – 26.2 6.2	10.22 1.9 – 23.2 8.51 0.964	8.53 0.0 – 35.5 10.61 0.823	1.32 0.0 – 3.9 1.6 0.023 ⇩
Total Zn (µg/L)	140.09 82.2 – 229 47.57	198.27 74 – 439 131.94 0.859	286.27 52.7 – 821 249.97 0.388	290.09 81.6 – 825 226.5 0.239
Dissolved Cu (µg/L)	5.55 3 – 8.4 2.13	4.58 1.3 – 9.2 2.46 0.461	4.44 2.5 – 8.3 1.81 0.631	2.01 1.4 – 3.1 0.52 <0.0001 ⇩
Dissolved Pb (µg/L)	0.00 None 0.00	0.93 0.0 – 2.4 1.04 NA*	0.53 0.0 – 2.2 0.89 NA*	0.00 None 0.00 NA*
Dissolved Zn (µg/L)	49.02 16 – 110 24.22	150.7 34.8 – 386 112.26 0.01 ⇧	218.6 54.6 – 650 210.33 0.001 ⇧	209.34 58.6 – 395 127.76 <0.0001 ⇧
COD (mg/L)	80.9 46 – 130 26.3	68.4 19 – 216 55.7 0.563	85.5 15 – 286 78.7 0.84	39.9 19 – 77 19.2 0.026 ⇩

NA* Not Available

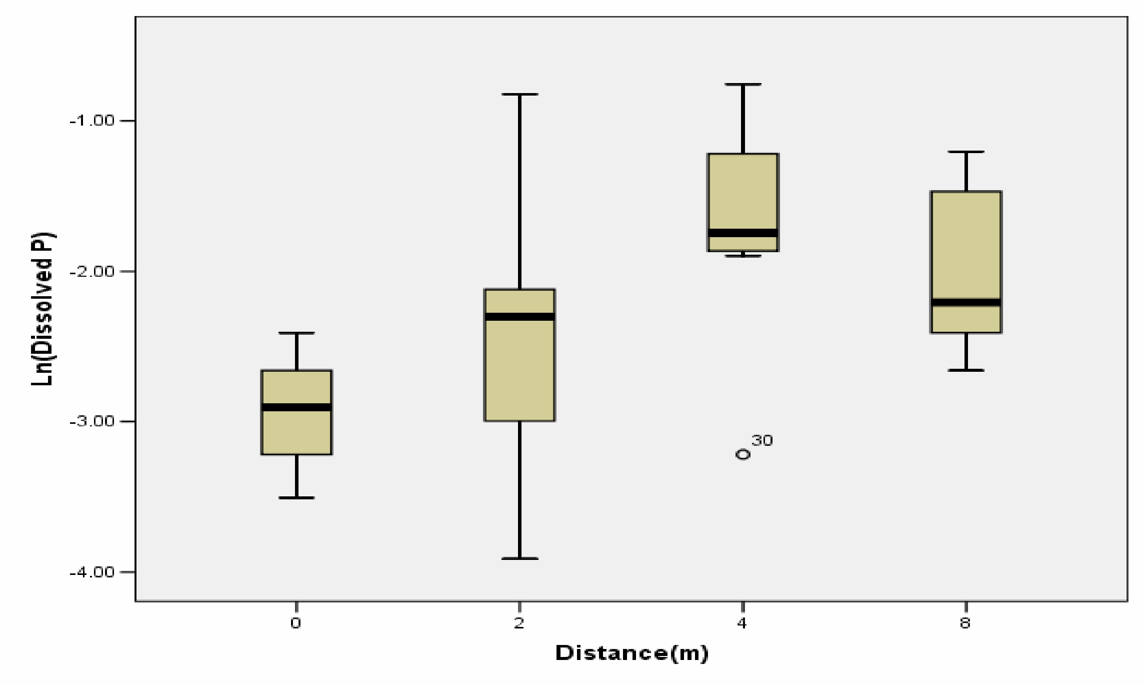


Figure 4.11. Boxplot of dissolved P EMCs at Austin Site 2

4.7.4 Site 3

The summary statistics and the post hoc analyses results (showing P values) for rainfall events monitored at Site 3 are presented in Table 4.16. The results show that 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 shown in Figure 4.12. Total and dissolved P were found to increase with increasing distance from the edge of pavement at this site. Nitrate/nitrite concentrations also were found to significantly increase over the first four and eight meters of vegetation.

Total forms of Cu and Pb were found to significantly decrease over the width of the vegetated area. Unlike Cu and Pb, the total and dissolved forms of Zn indicated significant increases in concentration over the site. Again, this is believed to be due to leaching from the galvanized Zn used in the collection mechanisms and will be addressed in detail in section 4.13.

Table 4.16.Summary statistics for Austin Site 3

Constituent	Sample Location			
	Edge of Pavement	2m	4m	8m
	Mean Range Std.Deviation P-value	**Mean Range Std.Deviation P-value**	**Mean Range Std.Deviation P-value**	**Mean Range Std.Deviation P-value**
TSS (mg/L)	173 64 – 384 100	50 13 – 158 48 <0.0001 ⇩	40 14 – 150 38 <0.0001 ⇩	50 13 – 230 63 <0.0001 ⇩
TKN (mg/L)	1.76 0.8 – 3.4 0.81	1.77 0.6 – 3.5 0.99 0.997	2.45 0.5 – 9.7 2.55 0.989	2.4 0.4 – 6 1.87 0.969
NO3/NO2-N (mg/L)	0.22 0.0 – 0.7 0.17	0.27 0.0 – 0.7 0.25 0.998	0.564 0.0 – 1.7 0.556 0.165	0.72 0.0 – 4.9 1.41 0.116
Total P (mg/L)	0.28 0.1 – 0.9 0.22	0.79 0.2 – 1.7 0.42 0.001 ⇧	1.21 0.4 – 3.4 0.78 <0.0001 ⇧	0.88 0.3 – 2 0.57 <0.0001 ⇧
Dissolved P (mg/L)	0.09 0.0 – 0.2 0.05	0.63 0.1 – 1.5 0.35 <0.0001 ⇧	1.06 0.3 – 2.9 0.66 <0.0001 ⇧	0.72 0.1 – 1.6 0.49 <0.0001 ⇧
Total Cu (µg/L)	29.75 12.3 – 62.2 14.64	9.46 4.3 – 19.8 5.34 <0.0001 ⇩	11.17 5.2 – 32.3 7.53 <0.0001 ⇩	8.23 3.4 – 22.5 5.73 <0.0001 ⇩
Total Pb (µg/L)	14.72 4.8 – 46.5 11.33	8.49 2.3 – 28.6 9.59 0.051	3.54 0.0 – 8.1 2.49 0.001 ⇩	1.55 0.0 – 6.8 2.05 <0.0001 ⇩
Total Zn (µg/L)	175.48 67.7 – 307 75.04	281.92 52.3 – 659 168.54 0.501	324.93 68.2 – 495 146.57 0.156	488.27 116 – 985 271.95 0.004 ⇧
Dissolved Cu (µg/L)	5.11 2.2 – 10.2 2.29	5.45 1.8 – 12.7 3.43 1	6.38 2.6 – 10.4 2.48 0.723	5.03 2.1 – 14.6 3.82 0.956
Dissolved Pb (µg/L)	0.00 None 0.00	0.68 0.0 – 3.8 1.32 NA*	0.00 None 0.00 NA*	0.11 0.0 – 1.2 0.37 NA*
Dissolved Zn (µg/L)	50.15 28 – 88.5 17.46	220.52 53.7 – 553 136.3 <0.0001 ⇧	265.92 35.1 – 450 127.44 <0.0001 ⇧	397.89 74.8 – 927 265.64 <0.0001 ⇧
COD (mg/L)	99.5 42 – 160 38.5	45.8 11 – 107 26.9 0.008 ⇩	75.6 23 – 351 93 0.179	62.9 25 – 149 40.9 0.164

NA* Not Available

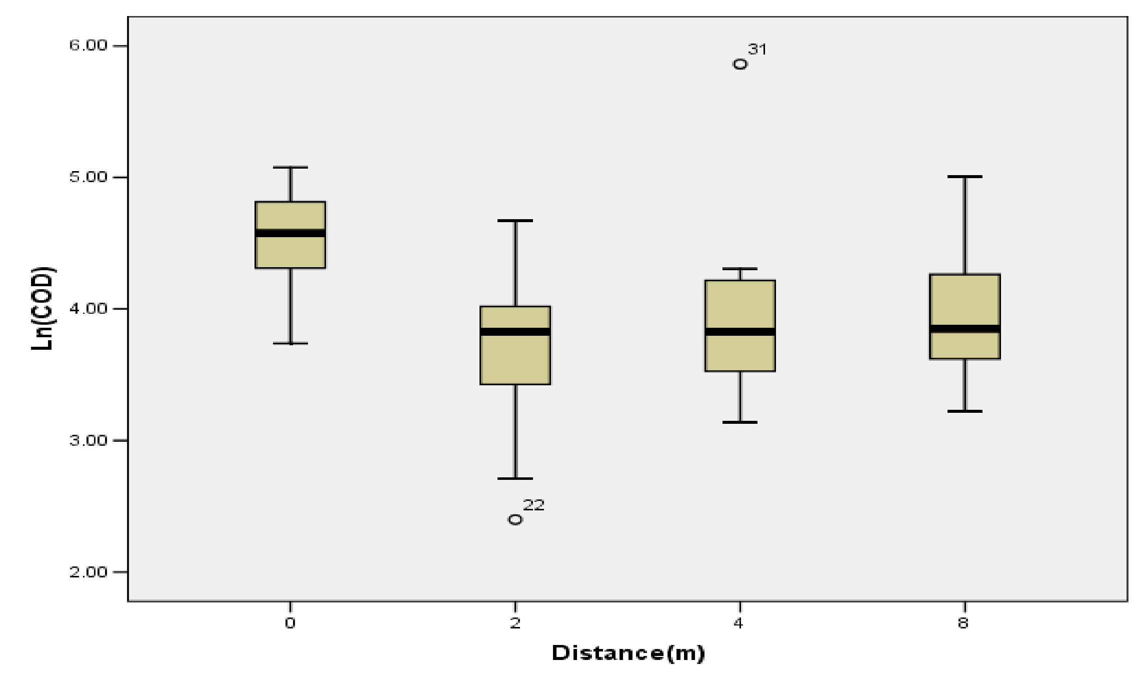


Figure 4.12. Boxplot of COD EMCs at Austin Site 3

4.8 Comparison of edge of pavement concentrations across sites

4.8.1 Comparison at College Station sites

One of the site selection parameters for this study was an ADT of at least 50,000. This high traffic volume was desired so that the runoff associated with the highway set up 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, and there were no differences in the ADT between Site 1, and Sites 2 and 3, for they were located within a stretch of 1.2Km (0.75mile).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.

ANOVA tests were performed on the edge of pavement concentrations measured for each parameter at Site 1, Site 2, and Site 3 to determine if any statistically significant differences existed between the runoff generated at each site. The resulting P- values of ANOVA test are listed in Table 4.17.

Table 4.17. Comparison of edge of pavement EMCs across the College Station sites

Constituent	P Value
TSS	0.668
Total Kjeldahl Nitrogen	0.972
Nitrate/ Nitrite-Nitrogen	0.517
Total P	0.9
Dissolved P	0.705
Total Cu	0.732
Total Pb	0.699
Total Zn	0.995
Dissolved Cu	0.827
Dissolved Pb	NA
Dissolved Zn	0.917
COD	0.383

- NA Not Available

No constituents were found to have P values less than 0.05, thereby satisfying the expectation that the initial quality of the runoff at the edge of pavement at each site would be similar. As an illustration of no statistical differences, a comparison of the TSS concentrations at the edge of pavement at each research site is shown in Figure 4.13.

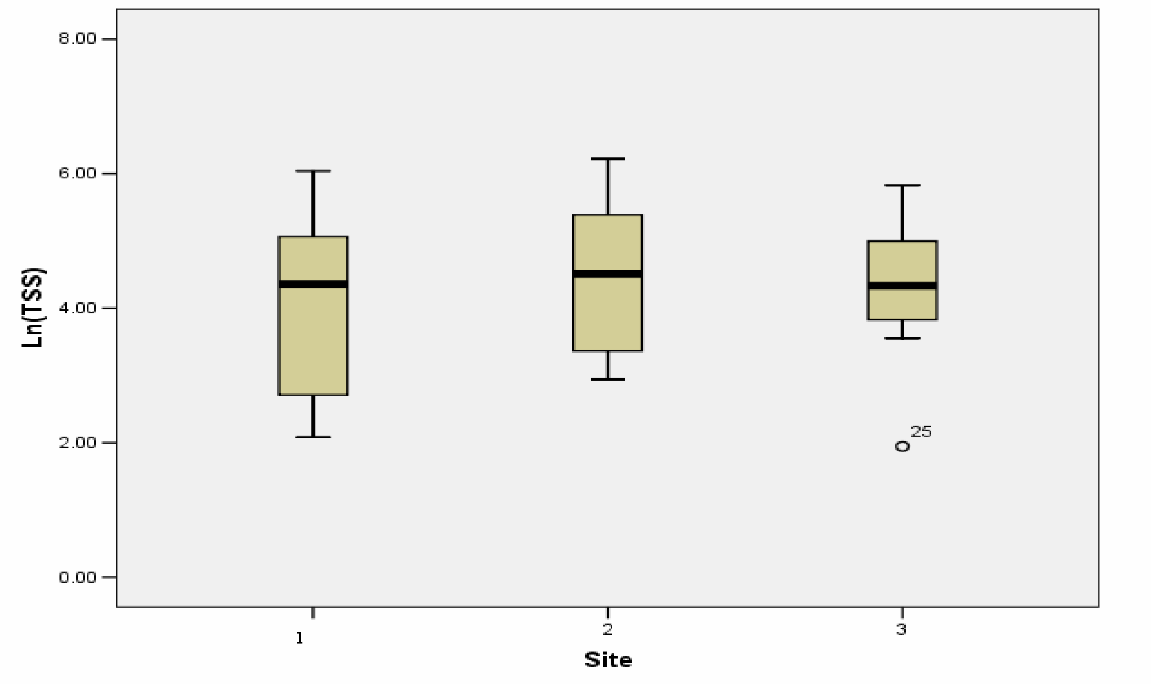


Figure 4.13. Boxplot of edge of pavement TSS EMCs at College Station sites

Another diagnosis on the data regards the concern of the rubber strips installed at zero meter. As mentioned earlier, zero meter flow strips were installed at all the College Station sites. The primary purpose of the flow strips is to direct the runoff to the zero meter sampler. The concern was that it might have caused low levels of TSS in the sampled runoff. The edge of pavement concentrations with and without the zero meter flow strips was compared and the resulting P-values of ANOVA test are listed in Table 4.18.

Table 4.18. Comparison of edge of pavement EMCs with/without flow strip

Constituent	Site 1	Site 2	Site 3
TSS	0.631	0.873	0.89
Total Kjeldahl Nitrogen	0.624	0.806	0.407
Nitrate/ Nitrite-Nitrogen	0.058	0.113	0.411
Total P	0.342	0.776	0.861
Dissolved P	0.897	0.27	0.9
Total Cu	0.409	0.161	0.368
Total Pb	0.469	0.152	0.776
Total Zn	0.663	0.236	0.392
Dissolved Cu	0.876	0.189	0.606
Dissolved Pb	NA	NA	NA
Dissolved Zn	0.886	0.737	0.112
COD	0.851	0.419	0.628

* NA Not Available

No constituent found to have P-values less than 0.05, upon comparing the concentrations at edge of pavement before and after removing the flow strip. Hence it is concluded that the existence of the flow strip at the edge of pavement does not exhibit statistically significant difference in constituent concentrations at any of the College Station sites.

4.8.2 Comparison at Austin sites

One of the site selection parameters for the study at Austin sites was an ADT of at least 35,000, a slightly lower criterion than College Station sites. 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, the hypothesis is that the initial quality of the runoff at the edge of pavement at each site would be similar. The results indicate that with the exception of runoff from the PFC overlay at Site 1 (for reasons explained earlier in section 4.7.2), the above mentioned 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 were observed between the runoff generated at each site. The ANOVA test results showing P values are listed in Table 4.19. The results indicate that no significant differences existed in the concentrations of most constituents at each research site.

Table 4.19. Comparison of edge of pavement EMCs across the Austin sites

Constituent	P value
TSS	0.259
Total Kjeldahl Nitrogen	0.269
Nitrate/ Nitrite-Nitrogen	0.652
Total P	0.022
Dissolved P	0.358
Total Cu	0.233
Total Pb	0.31
Total Zn	0.448
Dissolved Cu	0.883
Dissolved Pb	NA
Dissolved Zn	0.652

Table.4.19 continued

Constituent	P value
COD	0.133

* NA Not Available

The only constituent found to have P value less than 0.05 is the total P, indicating that statistically significant difference in the concentrations existed between the research sites. Further analyses of these datasets indicate that slightly higher concentrations of total P were measured at Site 3 than at Site 1 or Site 2. A boxplot of the total P EMCs at the edge of pavement are presented in Figure 4.14. The reason for higher concentrations of P at the edge of pavement at Site 3 is unknown, but past studies have suggested that the differences may disappear as additional samples are collected (Kearfott , 2005).

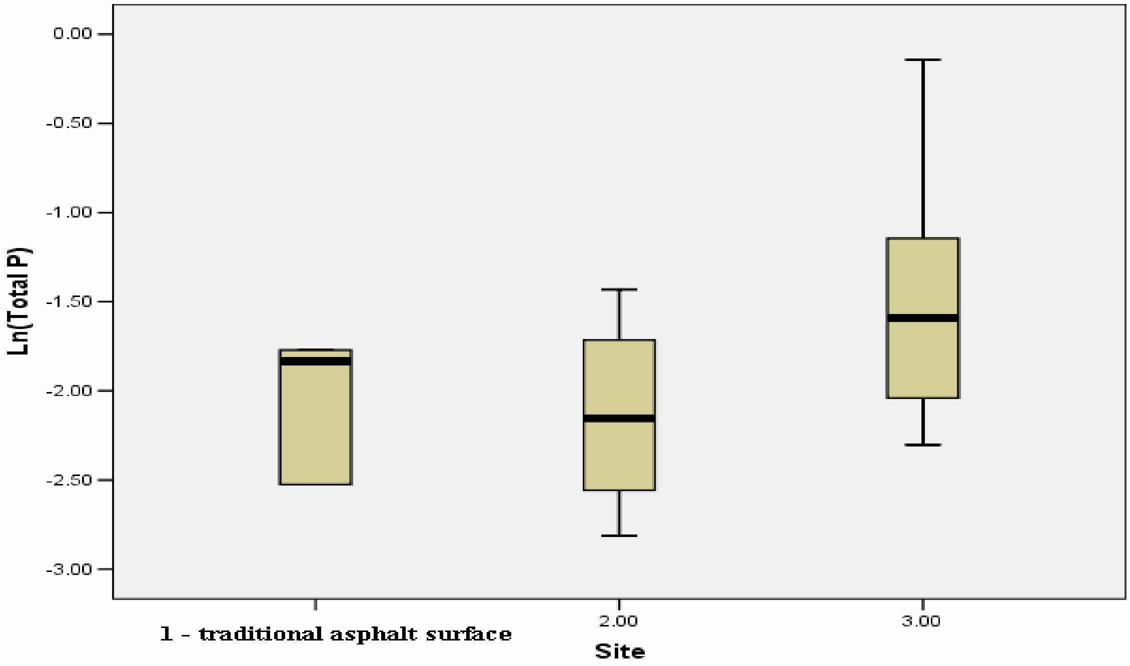


Figure 4.14. Boxplot of total P EMCs at the edge of pavement at Austin sites

Similar to College Station condition, these results indicate that approximately equivalent pollutant levels exist on the road surface at each research site. As an illustration of no statistical differences in edge of pavement concentrations of TSS at each research site is provided in Figure 4.15.These similarities, however, were not found on the PFC overlay surface at Site 1. The observed differences between the runoff quality from the porous pavement and the subsequent site performance are documented in section 4.12.

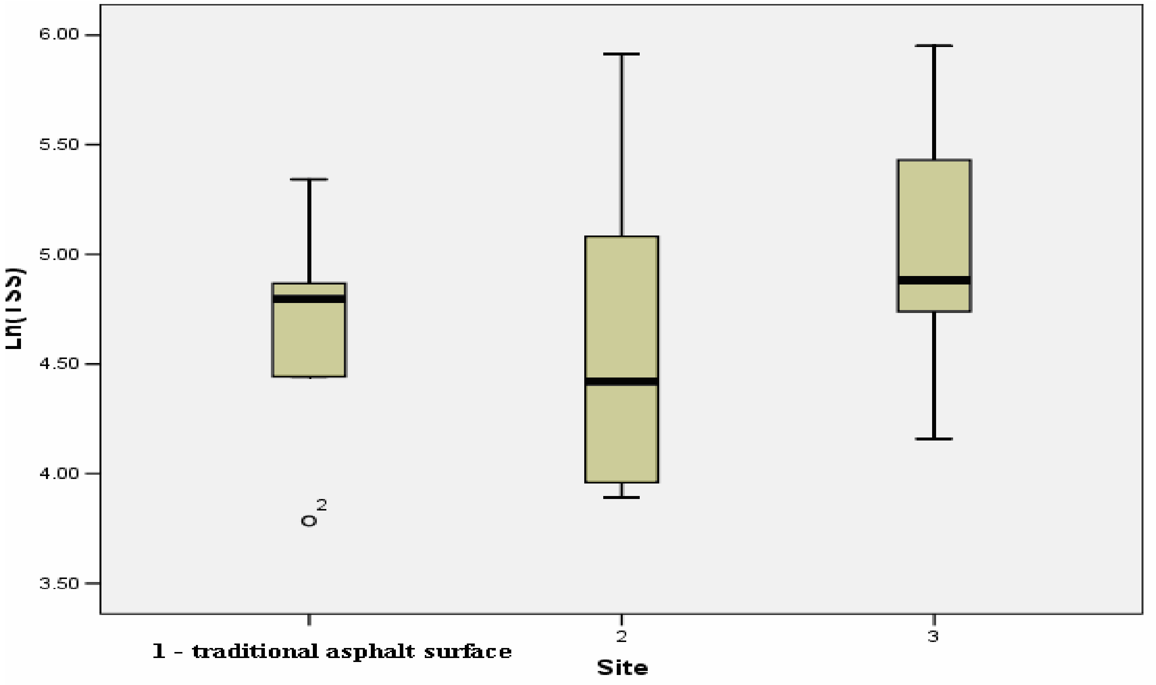


Figure 4.15. Boxplot of edge of pavement TSS EMCs across the Austin sites

4.9 Effects of precipitation characteristics on pollutant concentrations

As mentioned in the literature review, past studies have identified antecedent dry period conditions and runoff intensity during the preceding storm as significant factors that could influence TSS loadings and VSS (Irish et al., 1998). Moe et al. (1982) report that the number of dry days since successive large storm events could have a profound effect on airborne particulate levels as well as water pollutant concentrations. They observed that many water pollutants increase linearly with the number of dry days.

Harrison and Wilson (1985) infer that rainfall effectively removes pollutants from the road surface and that a short antecedent dry period will result in lower pollutant loads. On the other hand, Barrett et al. (1995) argue that changes in the rate of deposition of pollutants on the road surface and removal processes such as air turbulence (natural or the result of vehicles), volatilization and oxidation would reduce the correlation between pollutant load and longer antecedent dry period.

Past reports state that atmospheric dispersion processes dilute the pollutant as it is carried from the road surface (Harrison and Wilson, 1985). They found that deposition processes could appreciably deplete the pollutants that are associated with high deposition velocity. The deposition flux versus distance profiles for Pb indicated that significant proportion of emitted aerosol could be transported out of the immediate vicinity of the road (Harrison and Wilson. 1985). On the other hand, some pollutants such as cadmium and Cu indicated more rapid depletion. Asplund et al. (1980) report that the vehicle turbulence could remove solids and other pollutants from highway lanes and shoulders. Hence the relationship between individual variables, traffic volume, pollutant loads, and concentrations in runoff is obscured.

The less significant performance in pollutant removal in College Station raised the need of further investigation. In order to examine if there is such a trend existing in the selected sites at College Station, a field experiment was conducted. The experiment involved the collection of litter such as paper, beverage cans, torn cloth material, decayed leaves, sediments, and tire pieces, collected over one week period. The test was repeated three times in order to compare the amount (weight) of litter accumulated in the collection pipe (from one end to the other end) at different roadside widths in every site. The results of this experiment are furnished in Appendix H. Though not a testing with rigor, on all the three runs, at all the three sites, the general trend indicated that the collection pipe at two meter collected the maximum amount of litter. However, it cannot be concluded that the two meter sampling point is exposed to more pollutant load than the zero meter sampling point. The reason is that there is no collection pipe at the zero meter sampling point and hence it would not be a fair comparison. This observation gives an idea that pollutants could be removed from highway lanes and thrown at various distances based on the intensity of the wind and the vehicle speed.

Hoffman et al. (1985) indicate that the intensity of the storm could influence the type and quantity of pollutants in runoff. They state that many pollutants are associated with particles, which are more easily mobilized in high intensity storm events. High flow rates are believed to be efficient in transporting the contaminants. However, Barrett et al. (1995) found that peaks in pollutant concentrations occurred due to reduced dilution during lower flow conditions. In this study conducted at College Station, a similar trend was observed. Decrease in concentrations is observed with increasing rainfall volume. This is believed due to reduced dilution during low intense storms. However, low constituent concentrations were measured at low flow conditions. This is because low flow rates may not be efficient in transporting contaminants from the road surface.

4.10 Effects of ADT on pollutant concentrations

As mentioned earlier, motor vehicles have been identified as a major source of pollutant emissions. As mentioned earlier in Chapter III, ADT greater than 50,000 vehicles per day was one of the criteria for choosing the sites at College Station. A sensor detecting the precipitation characteristics and vehicles passing on the SH 6 has been set up by the Transportation Operations Group, TTI, The Texas A&M University System, on the south bound lane on the west shoulder of the right-of-way and it is next to the rain gauge station. The sensor is able to count the number of vehicle and classify the type (class) of the vehicles passing through the 4 lanes on SH6. Lane 1 and Lane 2 account for the traffic count on the north bound lane. Lane 3 and Lane 4 account for the traffic count on the south bound lane. There are 15 different vehicle classes identified by the sensor and the Federal Highway Administration (FHWA) vehicle classification is shown in Figure 4.16.

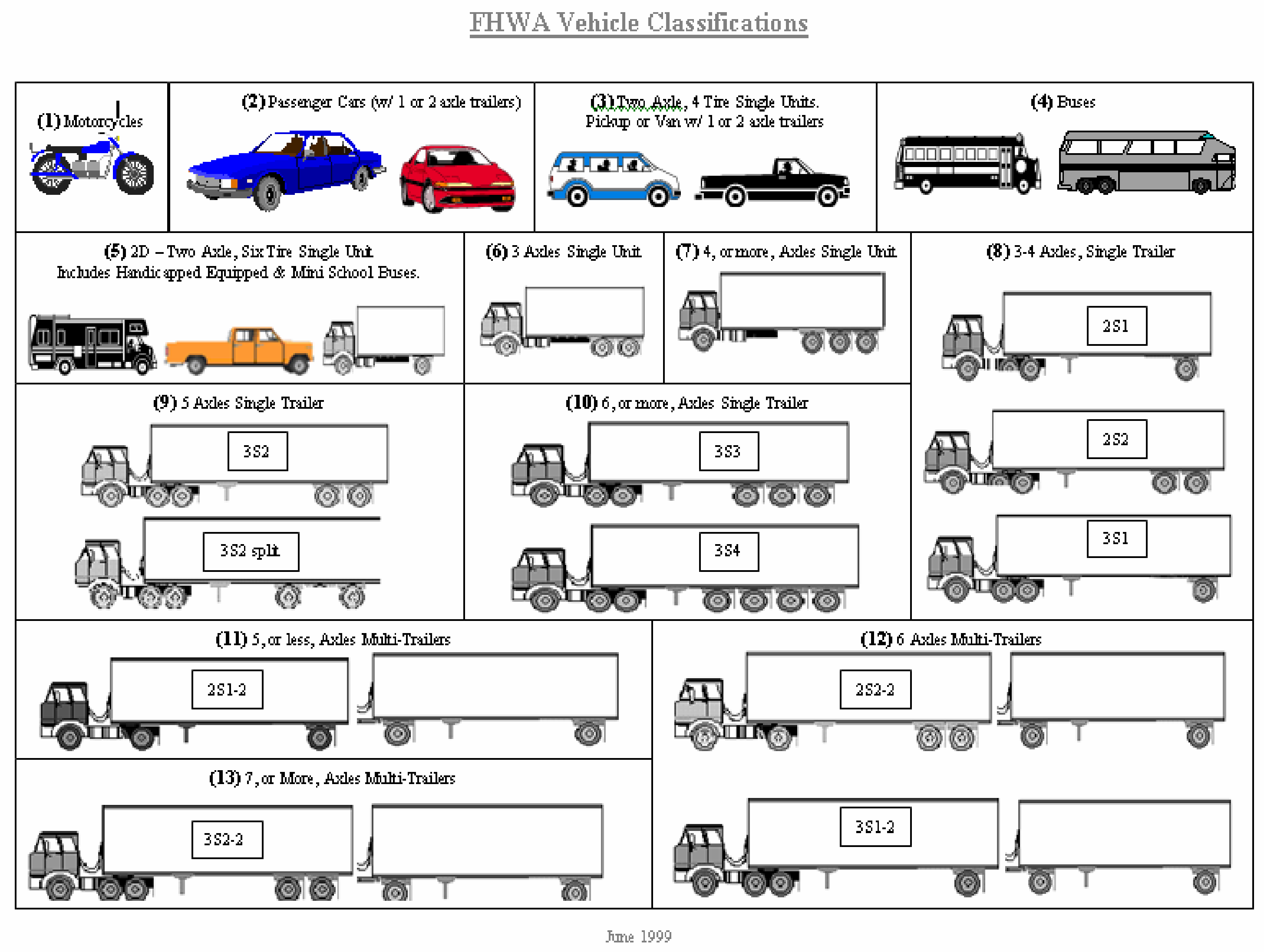


Figure 4.16 Federal Highway Administration (FHWA) vehicle classification (FHWA,2005)

Observation of the data indicates that 90-91% of the traffic count is contributed by Class 1, 2, and 3, i.e., small vehicles, and the remaining 9-10% is contributed by the other classes 4-15, i.e., large vehicles. The data of ADT has been obtained for every month during the sampling period and the information has been consolidated in Appendix F. Table 4.20 shows the VDS recorded during the rainfall event. Table 4.21 shows the average traffic using the highway during the preceding dry period.

Table 4.20 Vehicles during the storm (VDS) and rainfall event dates at College Station sites

College Station	
Rainfall event date	**VDS(No. of vehicles)(all classes)**
3/4/04	21773
3/24/04	22139
5/1/04	18692
8/1/04	17355
8/22/04	16928
10/2/04	19819
11/17/04	21217
1/12/05	20301
1/27/05	21709
5/8/05	16517

Table 4.21 Average daily traffic (during the preceding dry period) and the corresponding dry periods at College Station sites

College Station		
Collection Date	**Dry period (days)**	**Average daily traffic during preceding dry period**
3/4/04	2	22847
3/24/04	6	21630
5/1/04	5	23370
8/1/04	1.5	21597
8/22/04	11	NA*
10/2/04	6	23021
11/17/04	14	21349
1/12/05	4	18321
1/27/05	14	21115
5/8/05	32	20930

- NA Not Available

Harrison and Wilson (1985) found that particulate pollutant emissions cause contamination of roadside vegetation, soils, and surface waters, for a proportion of the total emission was found to be deposited locally. Thus vehicular emissions of metals are well recognized contaminants of the roadside environment. The roadside soils show enrichments of metals such as Pb, cadmium, Cu, and Zn (Harrison et al., 1981; as cited in Harrison and Wilson, 1985). Hewitt and Rashad (1990) report that majority of the Pb carried in the runoff was deposited in soils adjacent to the roadway and about 86% was dispersed by the atmosphere away from the vicinity of the road.

In the past research, there has been a common concern that constituents removed from highway runoff in vegetated roadsides would accumulate in the soil and vegetation that the material could eventually be classified as a hazardous waste. In order to address this concern in the research study at College Station, soil samples were collected from each of the sampling widths at Site 3. The soil samples from Site 3 were transported to the Soil, Water and Forage testing laboratory at the Heep Center, College Station for analysis in April 2005. A complex sample analysis was performed to determine the soil content at the various locations (zero, two, four, and eight meters) of Site 3. The soil analysis report indicates high heavy metal content in the soil. The report indicates that the soil content in Site 3 has excessive amount of Zn and Cu at all the locations and high level of P at two meter sampling area. The results of the soil analysis report are furnished in Appendix G. The normal range of constituent concentrations in the soil was obtained from the soil analysis report (Soil Analysis Report, 2004).

4.11 Correlation and regression analyses

Multiple (stepwise) regression was performed on the natural-log transformed College Station data. The relationship between the various influencing factors such as rainfall volume, dry period, ADT, average daily traffic using the highway during the preceding dry period, and VDS and that of pollutant concentrations is observed from the analyses. The regression analyses show that TSS, total Pb, and COD concentrations in runoff are dependent on dry period. The concentrations of the above mentioned pollutants tend to decrease with longer dry periods. This trend could be explained by the past report that state that atmospheric dispersion processes dilute the pollutant as it is carried from the road surface (Harrison and Wilson, 1985). They found that the pollutants associated with high deposition velocity could be appreciably depleted by deposition processes. However, the results show that the pollutant concentrations in runoff are not highly dependent on ADT. It is believed that the accumulation of pollutants on the highway surface is influenced by the amount of traffic on the road. However, past report indicates that vehicle turbulence could also remove solids and other pollutants from highway lanes, thereby obscuring the relationship between individual variables such as ADT and concentrations in runoff (Asplund et al., 1980). The deposition of pollutants on the highway is not cumulative and they are depleted by natural processes periodically.

The correlation analyses between all sampled constituents were performed and the correlation coefficient R between the sampled constituents is shown in Table 4.22.

Table 4.22 Correlation coefficients (R) between sampled constituents

R	TSS	TKN	Nitrates	Total P	Dissolved P	Total Cu	Dissolved Cu	Total Pb	Total Zn	Dissolved Zn	COD
TSS	1	0.345	0.22	0.084	-0.155	0.491	0.018	0.726	0.225	-0.04	0.455
TKN		1	0.508	0.621	0.47	0.373	0.219	0.217	0.405	0.25	0.63
Nitrates			1	0.24	0.17	0.274	0.091	0.149	0.237	0.141	0.517
Total P				1	0.876	0.283	0.299	0.168	0.544	0.446	0.635
Dissolved P					1	0.139	0.378	-0.13	0.382	0.402	0.464
Total Cu						1	0.48	0.611	0.299	-0.111	0.631
Dissolved Cu							1	-0.021	0.137	0.105	0.433
Total Pb								1	0.496	0.107	0.422
Total Zn									1	0.794	0.592
Dissolved Zn										1	0.351
COD											1

The results show that the concentrations of total Pb and COD are significantly correlated with TSS levels. Hence, we confirm the findings of past report that showed that Pb loadings are significantly correlated with solids (Barrett et al., 1995). It also confirms the correlation observed between solids and COD in past study. (Barrett et al., 1995).

The results indicate that nitrate concentrations in runoff is most dependent on the average daily traffic during the preceding dry period as well as the duration of that dry period. This confirms the finding of past study (Irish et al., 1998). However, the same is not observed with total P concentrations as indicated in past report (Irish et al., 1998).

The results show that the number of vehicles during the storm (VDS) during the storm was evaluated and accepted as a satisfactory independent variable for estimating the loads of total Pb and TSS. The scatter plots shown in Figures 4.17 and 4.18 indicate that the concentrations of TSS and total Pb increase with increasing VDS.

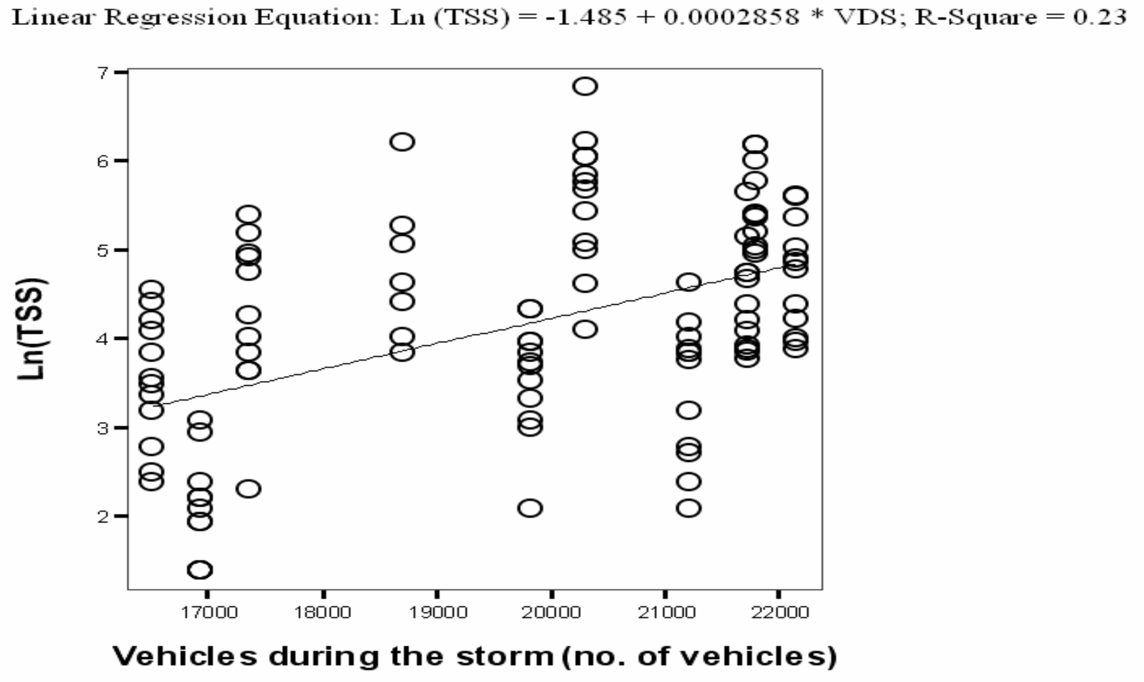


Figure 4.17 Scatter plot of TSS vs. VDS at College Station sites

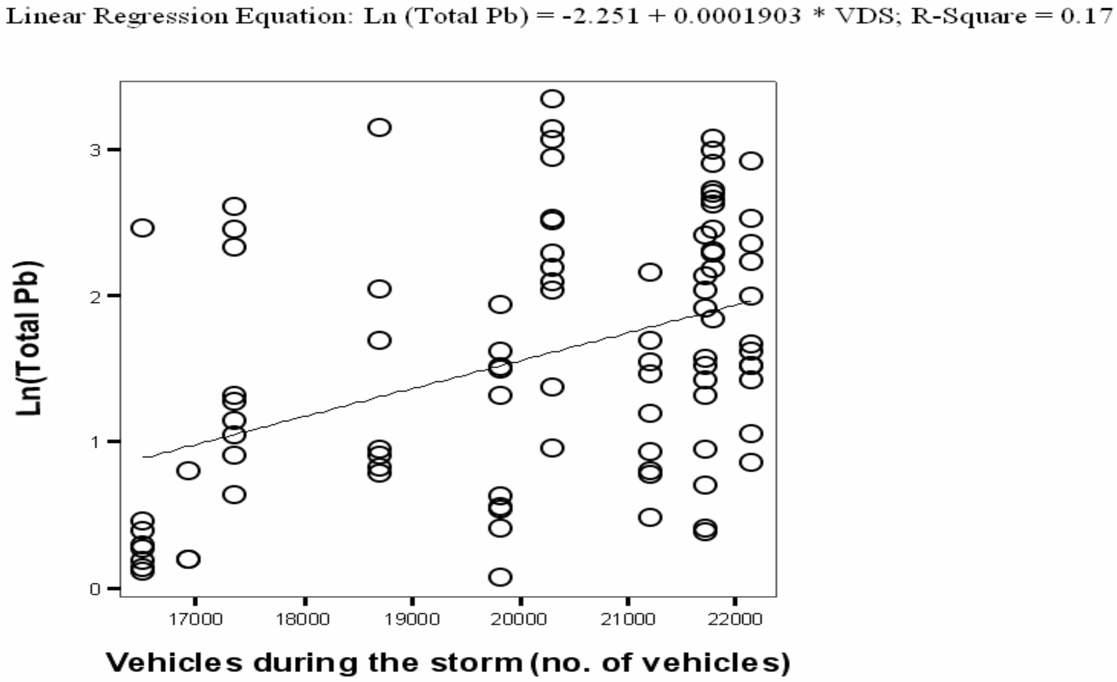


Figure 4.18 Scatter plot of Total Pb vs. VDS at College Station sites

Past study report an association between the antecedent dry period and mean concentration of dissolved Cu (Hewitt and Rashed, 1992). But the analyses on College Station data do not confirm the above finding. It should be noted that collection and sampling of stormwater in a field setting is influenced by many site-specific factors such as slope, soil content, and uncontrollable factors such as fire ant mounds and mal-functioning of the sampling system.

4.12. Comparison of results from traditional and porous pavement

Statistically significant differences in edge of pavement concentrations were observed from the runoff from the PFC surface and from the traditional asphalt surface. ANOVA tests were performed on the edge of pavement concentrations at Site 1 both before and after the installation of the porous asphalt overlay. The results of those tests are presented in Table 4.23.

Table 4.23. P-value for edge of pavement EMCs at Austin Site 1, before and after overlay

Constituent	ANOVA P-Value
TSS	<0.0001*
Total Kjeldahl Nitrogen	0.01*
Nitrate/ Nitrite-Nitrogen	0.565
Total P	0.632
Dissolved P	0.493
Total Cu	0.219
Total Pb	0.004*
Total Zn	<0.0001*
Dissolved Cu	0.363
Dissolved Pb	NA**
Dissolved Zn	0.805
COD	0.058

***** The asterisk denotes that the higher average EMC is contributed by the traditional asphalt pavement

****** NA Not Available

The results show that concentrations of TSS, TKN, and the total forms of Pb, and Zn were found to be significantly lower in runoff generated from the PFC surface than in runoff from the traditional surface. 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 simultaneous decreased concentrations of TSS and total metals concentrations. The species not exhibiting a significant difference between road surfaces are the total Cu, nitrate/nitrite forms of nitrogen and the dissolved forms of Cu, Zn, and P. The reason for total Cu, being a metal species, not exhibiting a significant difference is unknown. Also, it suggests that the porous road surface has no effect upon the concentrations of some stormwater constituents, especially those in the dissolved form.

Boxplots demonstrating the differences between TSS and total Zn concentrations between events monitored from the traditional and porous road surfaces are presented in Figures 4.19 and 4.20 respectively.

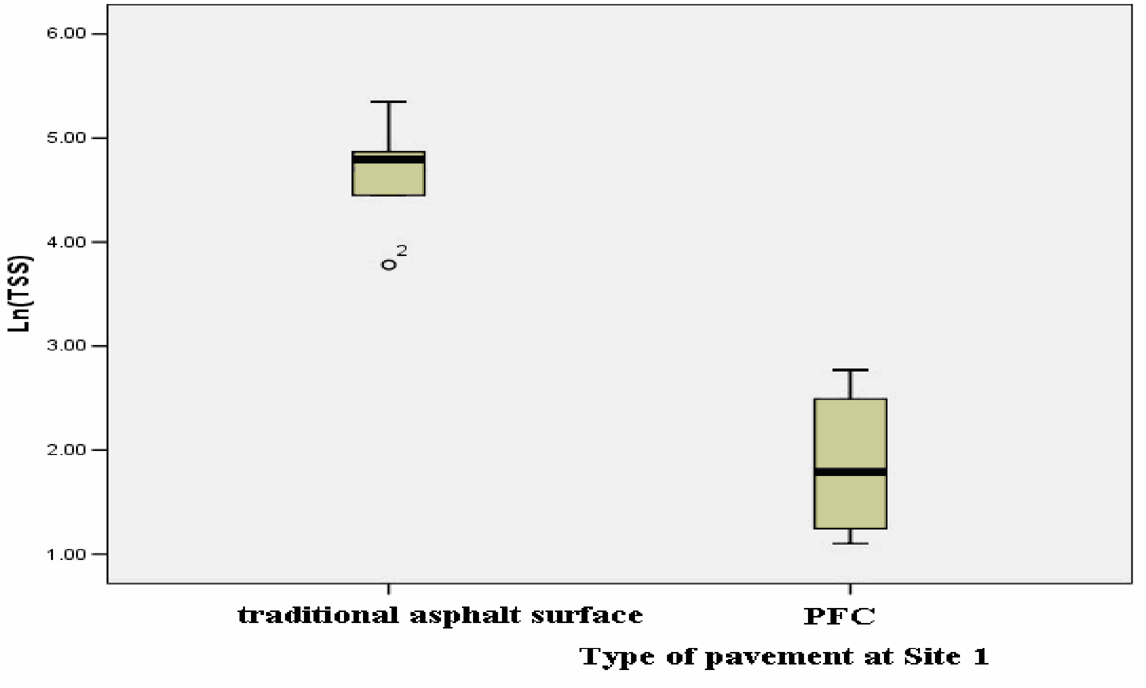


Figure 4.19. Boxplot of edge of pavement TSS EMCs at Austin Site 1

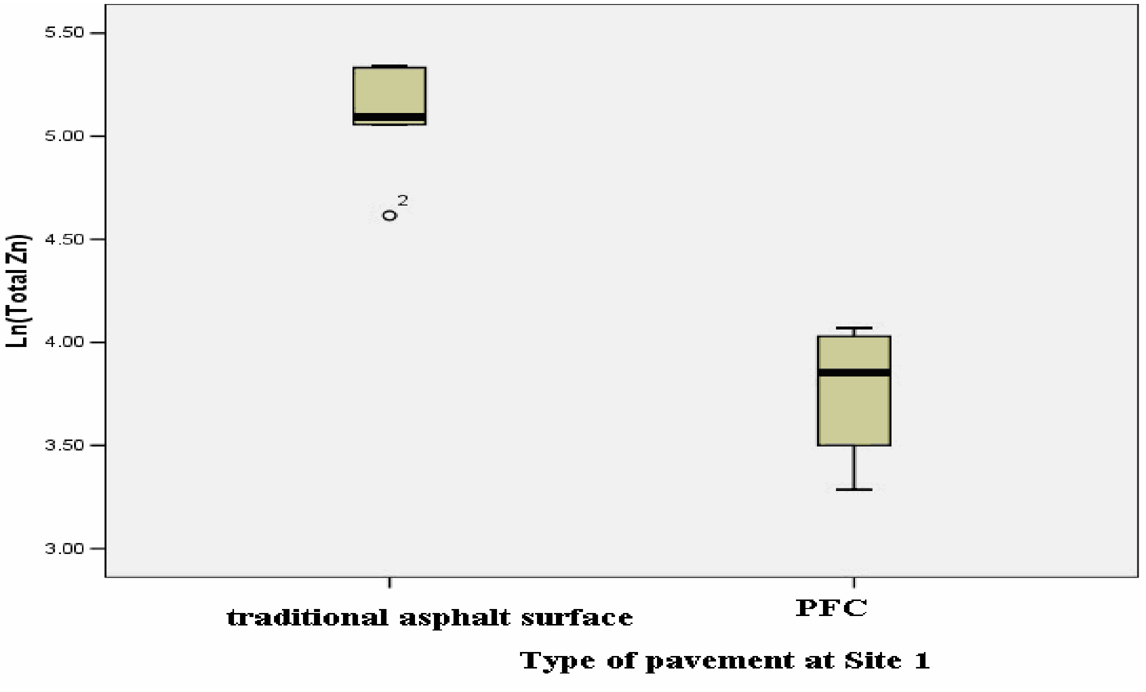


Figure 4.20. Boxplot of edge of pavement total Zn EMCs at Austin Site 1

From these results it is evident that the runoff generated from the PFC surface is of better quality than that from the conventional asphalt surface.

According to Schueler et al. (1987), porous pavement is primarily designed to remove pollutants deposited on the pavement surface from the atmosphere. These pollutants are normally fine grained or are soluble that are transported by atmosphere. Schueler et al. (1987) report that the degree of pollutant removal achieved in porous pavement is closely related to the amount of runoff that is actually exfiltrated into the soil. They report that as water penetrates through the pores, soluble forms of pollutants such as ortho-P and Zn become attached to binding sites on soil particles. Fine grained particles are eventually trapped in the void spaces between soil particles as the runoff percolate through the soil.

The maintenance activities suggested by Schueler et al. (1987) include vacuum sweeping at least four times a year, followed immediately by high pressure jet housing, to keep the asphalt pores free from clogging. According to Schueler et al. (1987), the factors deciding the physical suitability of porous pavement at the site level include soil infiltration rate, type of soil, slope, expected traffic intensity, and vulnerability to wind erosion. Schueler et al. (1987) point out that porous pavement is not feasible for sites with soil infiltration rates less than 0.27 inches per hour (hydrologic soil type “D”), or soil with a clay content greater than 30%. They also suggest that porous pavement should not be constructed over fill soils which form an unstable subgrade, and are vulnerable to slope failure. Schueler et al. (1987) recommend that porous pavement is not suitable for sites with a slope greater than 5%. They also point out that porous pavement is generally used for parking lots and lightly used access roads. They argue that porous pavement is not recommended in areas where wind erosion is expected to supply large quantities of sediment from adjacent barren areas. Additionally, they offer insight into the additional costs incurred in using porous pavement. They report that normal asphalt runs about $1.10 – 1.20 per square foot and the prices for porous asphalt typically run about 10 – 15% higher. The price differential is reflected by the extra costs involved in procuring, producing, transporting and rolling the porous asphalt (Schueler et al.,1987).They offer tips on how potholes and cracks could be repaired using conventional, non-porous patching mixes, as long as the cumulative area repaired does not exceed 10% of the parking lot area.

Schueler et al. (1987) point out the potential savings associated with porous pavement. They include the reduction or elimination of curb and gutters, reduced land consumption because additional land at the site is not needed for stormwater management purposes. Additionally, porous pavements could protect downstream aquatic life (if any exists), as they maintain the pre-development water balance at the site, minimize stream bank erosion and serve as a medium to filter out pollutants (Schueler et al.,1987). They state that high ground water recharge associated with porous pavement facilitates denser perimeter landscape plantings than those adjacent to conventional pavement.

In addition to understanding and quantifying the differences in runoff quality generated from the two different highway surfaces, the evaluation of the subsequent performance of the vegetated roadsides at Site 1 both before and after the installation of the porous asphalt overlay was performed. ANOVA tests were performed to compare the concentrations of each constituent at each sampling distance (two, four, and eight meters) as an initial assessment of differences or similarities in the data. These results are presented in Table 4.24.

Table 4.24. P-value for each sampling distance at Austin Site 1, before and after overlay

Constituent	ANOVA – P Value		
	2m	**4m**	**8m**
TSS	0.116	0.559	0.269
Total Kjeldahl Nitrogen	0.294	0.195	0.538
Nitrate/ Nitrite-Nitrogen	0.722	0.273	0.363
Total P	0.033	0.711	0.275
Dissolved P	0.208	0.419	0.242
Total Cu	0.219	0.453	0.116
Total Pb	0.097	0.253	0.272
Total Zn	0.33	0.201	0.03
Dissolved Cu	0.43	0.413	0.14
Dissolved Pb	NA	NA	NA
Dissolved Zn	0.922	0.241	0.052
COD	0.613	0.642	0.64

* NA Not Available

In spite of the insignificant statistical results, it should be noted that concentrations of most of the pollutants such as TSS, TKN, total and dissolved forms of Cu and total form of Pb, were found to be lower in the runoff generated from the PFC surface than in the runoff from the traditional surface.

Figures 4.21 and 4.22 indicate boxplots of total Cu concentrations at Site 1 in runoff sampled from the conventional and new porous pavement respectively. In events monitored from the conventional road surface, it appears that average Cu concentrations decrease with increasing distance from the edge of pavement. This indicates that the vegetated roadsides are acting as a buffer and is removing Cu from the runoff. On the other hand, in events monitored from the porous road surface, Cu concentrations does not show similar trend, showing slight increases within the first four meters of the edge of pavement and then gradually drop off again. This shows that while the initial runoff is indeed cleaner, the runoff may be picking up Cu from the soil as it travels through the first four meters of the shoulder area. In spite of this increase, the Figure 4.22 shows that the final effluent quality at the eight meter sampling point is as good if not better, with the porous asphalt in place than with the traditional asphalt surface.

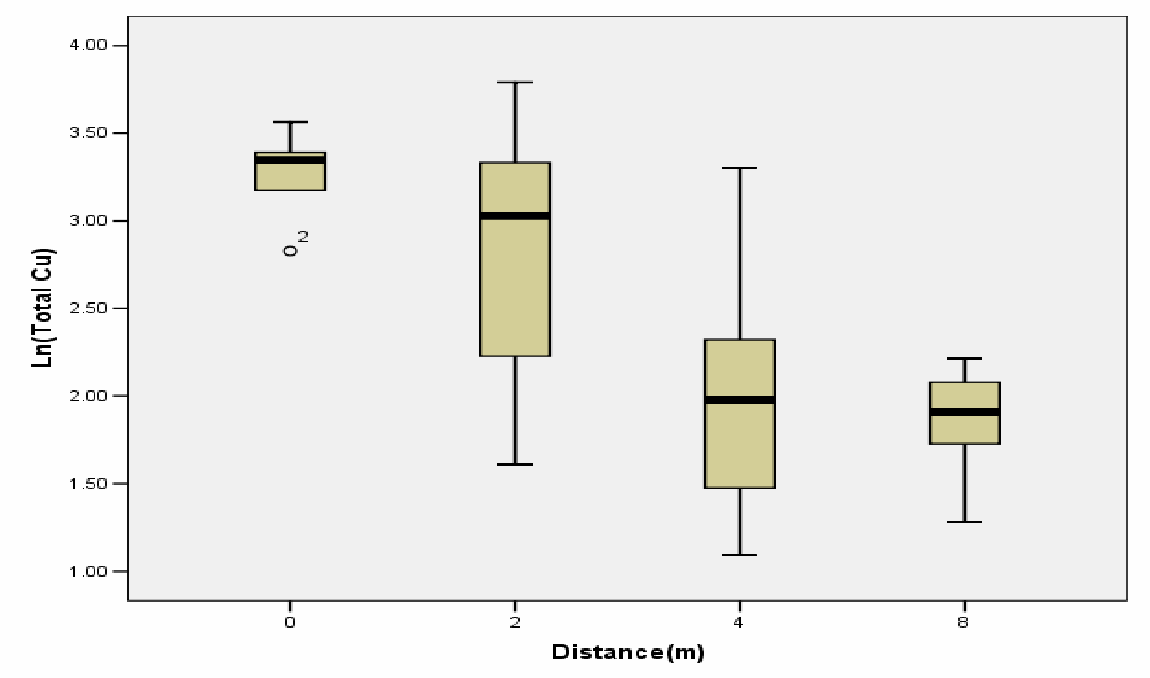


Figure 4.21. Boxplot of total Cu EMCs at Austin Site 1 (traditional asphalt surface)

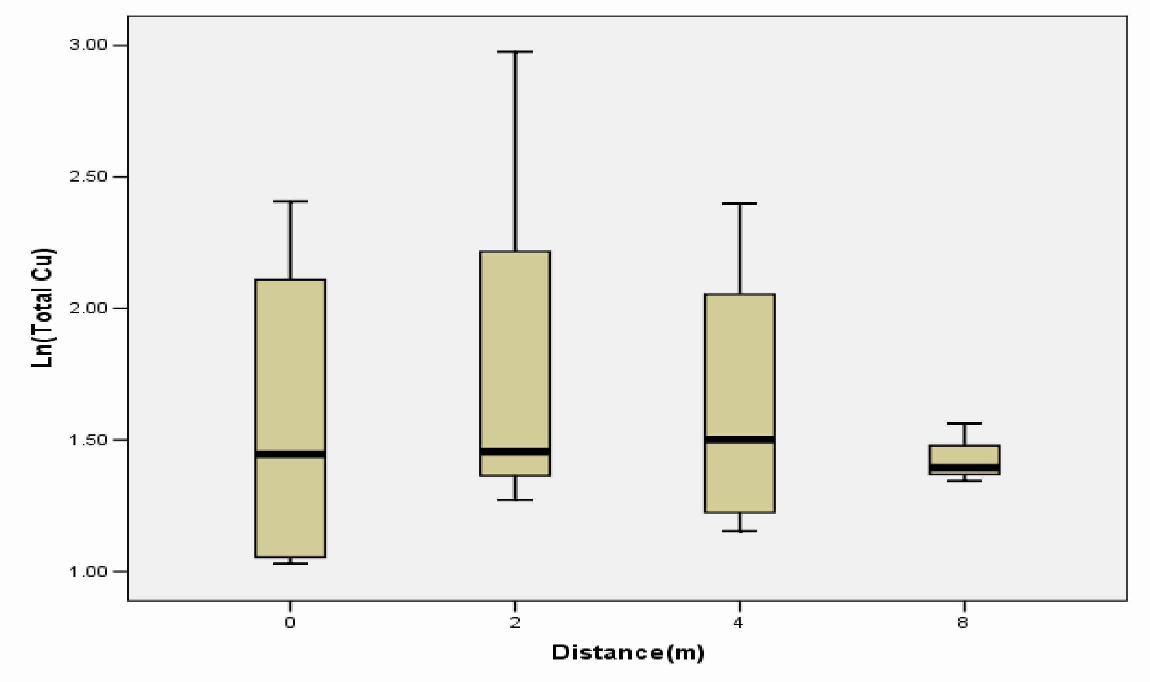


Figure 4.22. Boxplot of total Cu EMCs at Austin Site 1 (porous asphalt surface)

4.13. Site conditions affecting sampling

4.13.1 Fire ants

Fire ant mounds were frequently found at the various locations of the research sites. The negative impact of fire ant mounds on research results could have been the greatest in case of fire ant mounds located upslope of the sampling system. For instance, in case of a rainfall event, as the sheet flow runs through ant mounds, it carries the loose sediments dug out from the underground by the fire ants. This could lead to forming false conclusion that the increased concentration of sediments was carried by the flow, while fire ant mounds contributed to the high level of sediments in the sample. This called for treatment of fire ant mounds in order to avoid incorrect data interpretation.

Treatment of the mounds was performed whenever necessary at each site by using commercially available insecticides, DIAZINON and AMDRO. The chemical mixture used for this purpose cannot be dissolved in water and hence any effect on sample results from the chemical is avoided. These mound materials were cleaned out of each pipe prior to expected rainfall events. However, it is possible that some of these solids were inadvertently collected in the samplers and were counted in the TSS measurements.

4.13.2 Galvanized metal flashing

The concentrations of Zn at the edge of the pavement are much lower than the concentrations reported at the various distances from the edge of the pavement. It is therefore clear that there are other site specific factors affecting the Zn levels. The reason behind the significant increases in both the total and dissolved forms of Zn is believed to be due to the leaching of Zn from the galvanized flashing attached to each of the collection pipes.

Galvanized metal flashing was attached to each collection pipe in order to direct runoff into the pipe and is suspected to be the source of Zn. This mirrors the results from the Austin sites showing higher concentration of Zn. With excessive exposure to the weather and environment, it appears that the galvanized coating on the metal is wearing away and that Zn is leaching out into the runoff.

4.14. Overall performance of vegetated roadsides

4.14.1 Overall performance at College Station sites

The removal efficiency of the vegetated roadsides with respect to various constituents is listed in Table 4.25. The summary table shows the net removal efficiencies for each constituent at each site. The removal percentages were calculated based on rainfall weighted average concentrations measured at each of the sampling distance.

As mentioned earlier, in the study conducted at College Station, a rain gage station set up by the Transportation Operations Group, TTI, on the south bound lane on the west shoulder of the right-of-way (next to Site 1 installation system), records the rainfall volume every 15minutes. Since all the sites are located within a stretch of 1.2Km (0.75mile), it is assumed that all the sites experience the same rainfall intensity.

Table 4.25. Net removal efficiencies (in %) at College Station sites

	Site1 vegetation cover 49% Slope 6 - 8%			**Site 2 vegetation cover 98% Slope 18 - 20%**			**Site 3 vegetation cover 98% Slope 14 - 15%**		
	0-2 m	**0-4 m**	**0 -8m**	**0-2m**	**0-4m**	**0-8m**	**0-2m**	**0-4m**	**0-8m**
TSS	19.3	22.9	12	66	48.3	55.2	-21.3	-91	10.4
TKN	-21.9	-47	-62.9	-55.1	-31	-90.8	-67.9	-68.1	-48.5
NO3/NO2	17.7	57.1	-148	-3.1	51.3	61	-126.9	54.4	-53
Total P	-155.4	-248.5	-163.8	-152	-160	-179	-48.2	-115	-73.5
Diss P	-1174	-408.4	-159.7	-215	-295	-309	-33.3	-78.1	-104
Total Cu	18.5	57.3	40.6	9	45	45.1	28.7	36	62.4
Diss Cu	-3.5	0.8	11.5	3	11.8	29.5	1.1	21.7	34.2
Total Pb	25.2	13.3	51.3	36.4	41.9	58.5	-0.2	-30.5	47.8
Diss Pb	91.6	-3	62.8	NA	NA	NA	NA	NA	NA
Total Zn	-118.1	-314.2	-219.6	-100	-131.2	-176	-170.1	-256	-221
Diss Zn	-284.9	-449.3	-450.1	-230	-280	-371	-303.9	-607	-491
COD	-26.1	-45.8	-74.6	-23.7	-26.2	37.9	19.8	-14	34.3

* NA Not Available

Total Suspended Solids – Negative removal efficiencies were observed at Site 3. Higher removal efficiencies were measured at Site 2 with a maximum of 66% removal within two meters of the edge of pavement, 48.3% removal within four meters, and 55.2% removal within eight meters. Site 1 exhibited lower removal efficiency, achieving 12%

removal between the zero and eight-meter sampling point. This is believed due to the higher amount of dead vegetation that present at Site 1, about 62%, 31%, and 56% of brown patches at two, four, and eight meters respectively from the edge of the pavement.

Total Kjeldahl Nitrogen – Net increases in TKN concentrations were observed at each site, with concentrations consistently increasing with increasing distance from the road surface, which resulted in negative removal efficiency rates.

Nitrate/Nitrite – The majority of removal occurred at Site 2 within first eight meters of vegetation, resulting in a maximum removal efficiency of 61% over this distance. Initial decreases in concentration occurred within the first two meters and further increase in removal efficiency of 57% was measured at Site 1, within first four meters of vegetated roadsides. About 51.3% removal efficiency was observed at Site 2 within the first four meters at Site 2.

Total and Dissolved P – Net increases in P concentrations and negative removal efficiencies were measured at all sites over the width of the vegetated filter strips.

Total Cu – High removal efficiencies were measured at all sites for total Cu, 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 Site 2 (45.1%) and Site3 (62.4%) and at the four meter sampling point at Site 1 (57.3%).

Total Pb – High removal efficiencies for total Pb were observed at all sites. On an average about 52.53% removal occurred within the first eight meters at all sites (Site 1: 51.3%, Site 2: 58.5% and Site 3: 47.8%)

Total and Dissolved Zn – While removal efficiencies indicate that the concentrations of Zn increased at all sites with increasing distance from the edge of pavement. This is believed to be due to the adverse effects of the galvanized metal flashing used on the collection pipes.

Dissolved Cu – Initial increases in dissolved Cu concentrations were observed at Site 1 before achieving a final removal rate of 11.5% by the eight meter point. Moderate removal efficiency for dissolved Cu was measured at Site 3, within the first four meter (21.7%) and eight meter (34.2%).

Dissolved Pb – Concentrations of dissolved Pb 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 Pb originating from the highway surfaces and vegetated strips. Positive removal efficiencies were observed at Site 1.

Chemical oxygen demand – COD removal of 34.3% occurred at Site 3 within the first eight meters of the road surface. Negative removal efficiencies were observed at Sites 1 and 2, except at the eight meter sampling point at Site 2 (37.9%).

The vegetation survey results shown in the Appendix D indicate variation in vegetation density between Site 1, and Sites 2 and 3. The dead vegetation at Site 1 is believed due to the application of fertilizers and pesticides at the roadsides. This shows that the buffer has lost its functional aspect of trapping and removing pollutants. Sites 2 and 3 with higher vegetative cover (98%) outperformed Site 1 in removing stormwater pollutants. This indicates that thick and healthy vegetative cover is needed for effective pollutant removal. Hence, the study suggests that the dead vegetation should be restored in order to increase the ability of roadsides to trap and remove pollutants.

It is believed that vegetated areas with highly dense vegetative covers will result in higher pollutant removal efficiencies than less dense covers. The difference in site performance is evident between the zero and two meters of the road surface for TSS. Figures 4.23 and 4.24 demonstrate this difference with boxplots of TSS concentrations at Site 1 and at Site 2. A comparison of these two graphs indicates that the majority of the removal (66%) at Site 2 occurs between the zero and two meters, whereas lower removal efficiency (19%) is observed at Site 1 within the first two meters from the edge of the pavement. This indicates that the higher vegetation density (98%) between zero and two meters at Site 2 may be facilitating relatively better removal of stormwater pollutants when compared to the removal rate at Site 1 due to poor vegetative cover (37%) between the zero and two meters.

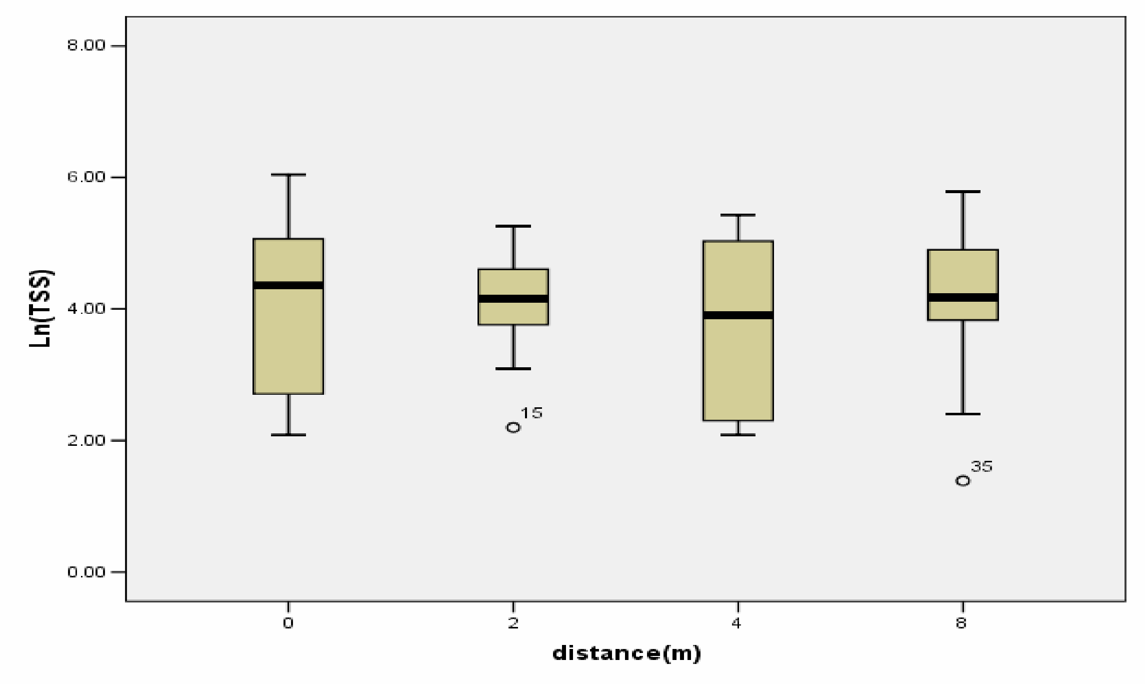


Figure 4.23.Boxplot of TSS EMCs at College Station Site 1

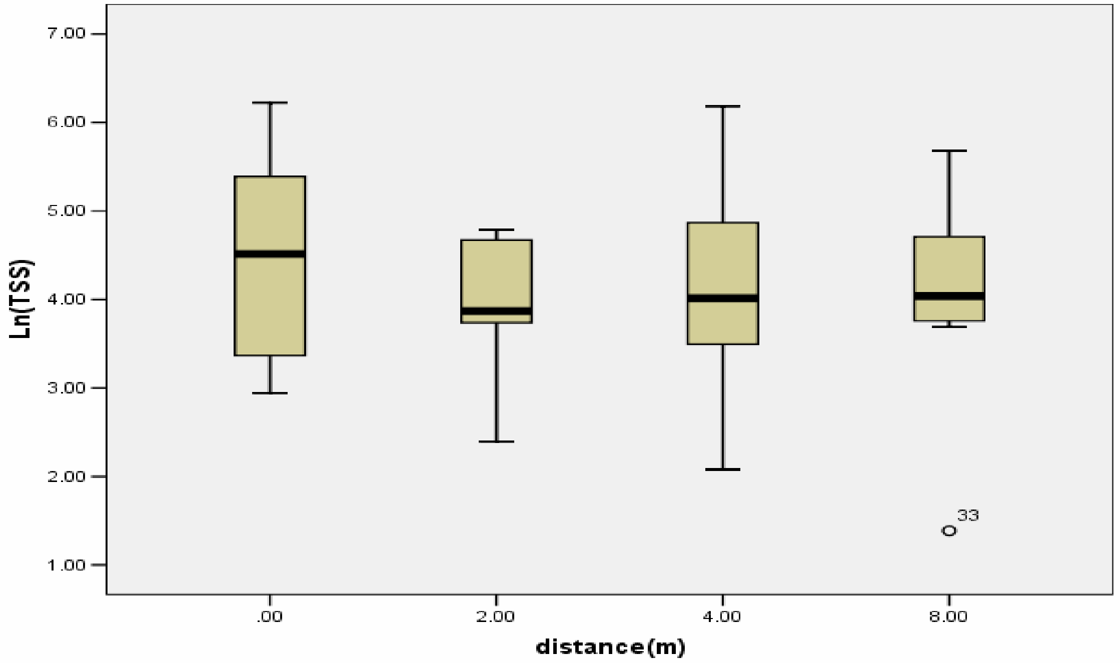


Figure 4.24. Boxplot of TSS EMCs at College Station Site 2

Past studies have indicated that slope could be a factor in the removal efficiencies of the vegetated roadsides. The findings follow the idea reported in past studies stating that grassy swales with shallower slopes exhibited increased pollutant removal efficiencies than swales with steep slopes (Yousef et al., 1987). However, the two steeper Sites (2 and 3) outperformed Site 1 with much flatter slopes. This could be accounted due to poor vegetative cover (brown patches) at Site 1. It appears to be that the grassy roadsides had lost the ability to function as an effective buffer.

4.14.2 Overall performance at Austin sites

The removal efficiency of the vegetated roadsides with respect to various constituents is listed in Table 4.26. Each of the vegetated areas at Austin sites, exhibited similar trends in overall performance with the exception of events monitored at Site 1 with the porous asphalt overlay in place. Table 4.26 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. The events monitored at Site 1 after the installation of the PFC surface are not included as the factors affecting pollutant concentrations and removal mechanisms under this condition differ from the other research sites.

Table 4.26. Net removal efficiencies (in %) at Austin sites

	Site1 vegetation cover 82% Slope 12%			**Site 2 vegetation cover 97% Slope 18%**			**Site 3 vegetation cover 100% Slope 18%**		
	0-2 m	**0-4 m**	**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	29.3	8.58	-21.4
NO3/NO2	32.6	9.4	6.3	60.2	-11.5	-63.9	10.3	-113	-132.6
Total P	-9.4	-1.6	-90.1	33.9	-72	-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
Diss Cu	-41.7	-8.1	12	28.5	17.3	61.1	12.6	-22.9	-6.7
Total Pb	70	88.8	94.9	27.8	70.9	92.7	39.9	62.46	87.75
Diss Pb	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total Zn	48.6	29.3	47.6	7.8	-43.2	-20.7	-5	-22.6	-83.6
Diss Zn	-39.2	-134.4	-111.5	-148	-328.7	-262.7	-247.7	-321.1	-543.9
COD	16.2	55.1	18.6	69.4	64.9	66	70.6	52.05	47.6

*** NA – Not Available**

Total Suspended Solids – Net decreases were observed for TSS over the vegetated roadsides at each research site. Higher removal efficiencies of pollutants were measured at Sites 2 and 3 with a maximum of 89% removal within eight meters of the edge of pavement. Site 1 exhibited lower efficiency at all sampling points when compared to other sites.

Total Kjeldahl Nitrogen – Net increases in TKN concentrations were observed at all sites. Results show that 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 at various sampling distances. Sites 2 and 3 exhibited relatively small increases and occasional decreases in concentrations between sampling distances.

Nitrate/Nitrite – Net decreases in nitrate and nitrate concentrations and positive removal efficiencies were observed at Site 1. The majority of removal occurred at this site within first two meters of vegetated area, resulting in a maximum removal efficiency of 33% over this distance. Initial decreases in concentration occurred within the first two meters at Site 2 followed by increases in concentration with increasing distance from the edge of pavement. A similar trend was observed at Site 3.Maximum removal efficiencies over the first two meters at Sites 2 and 3 were 60.2% and 10.3%, respectively.

Total and Dissolved P – Net increases in total and dissolved P concentrations and negative removal efficiencies were measured at all sites over the width of the vegetated roadsides with the exception of initial decreases within the first 2 meters at Site 2.

Removal efficiencies were observed to be below 35% for both constituents over this distance.

Total Cu – High removal efficiencies were measured at all sites for total Cu, with increasing removal 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%) , 2 (91%), and 3 (80%). High removal efficiency of 80% was measured at Site 3 within the first 2m of vegetation. The removal rate remained relatively consistent over the remainder of the vegetated area.

Total Pb – High removal efficiencies for total Pb 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. Relatively lower removal rates were measured close to the road surface at Sites 2 (28%) and 3 (40%), but total removal of 93% and 88% occurred over the entire vegetated area.

Total and Dissolved Zn – While removal efficiencies show that Zn levels decreased at Site 1, the concentrations of total Zn 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 and has been discussed in the previous section.

Dissolved Cu – Initial increases in dissolved Cu concentrations were observed at Site 1 before achieving a final removal rate of 12% by the eight meter sampling point. The opposite trend was observed 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 Pb – Dissolved Pb concentrations were below the detection limits for the majority of events monitored. Not enough data above detection limits exists to understand any possible pollutant removal trend, but this lack of values over the detection limit also indicates an absence of dissolved Pb originating from the highway surfaces and vegetated roadsides.

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 55% occurred within the first four meters at Site 1 and 52% occurred within the first four meters at Site 3.

These results are consistent with earlier studies, indicating that higher vegetation densities in the vegetated areas result in higher removal efficiencies for most pollutants commonly found in stormwater runoff, especially those found in the particulate form. Past studies indicate that 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 (96.7% and 100% respectively) over both sites, consistently outperformed Site 1, which had 55% cover near the road surface (in between zero and two meters) and an average density of 85% at the bottom of the study area. The vegetation survey results based on visual assessment and quantification are shown in Appendix E. These differences in site performance are evident at various distances from the road surface for various constituents such as TSS, TKN, total Cu, and COD. Figures 4.25 and 4.26 demonstrate these differences with boxplots of TSS concentrations at Site 1 and Site 2.

A comparison of these two graphs indicates that the low TSS removal occurs between the two and four meter sampling points at Site 1, whereas the majority of the removal at Site 2 occurs between the two and four meter sampling points at Site 2; indicating that the higher vegetation density (99.3%) at the bottom of the study at Site 2 may be facilitating better removal of stormwater pollutants.

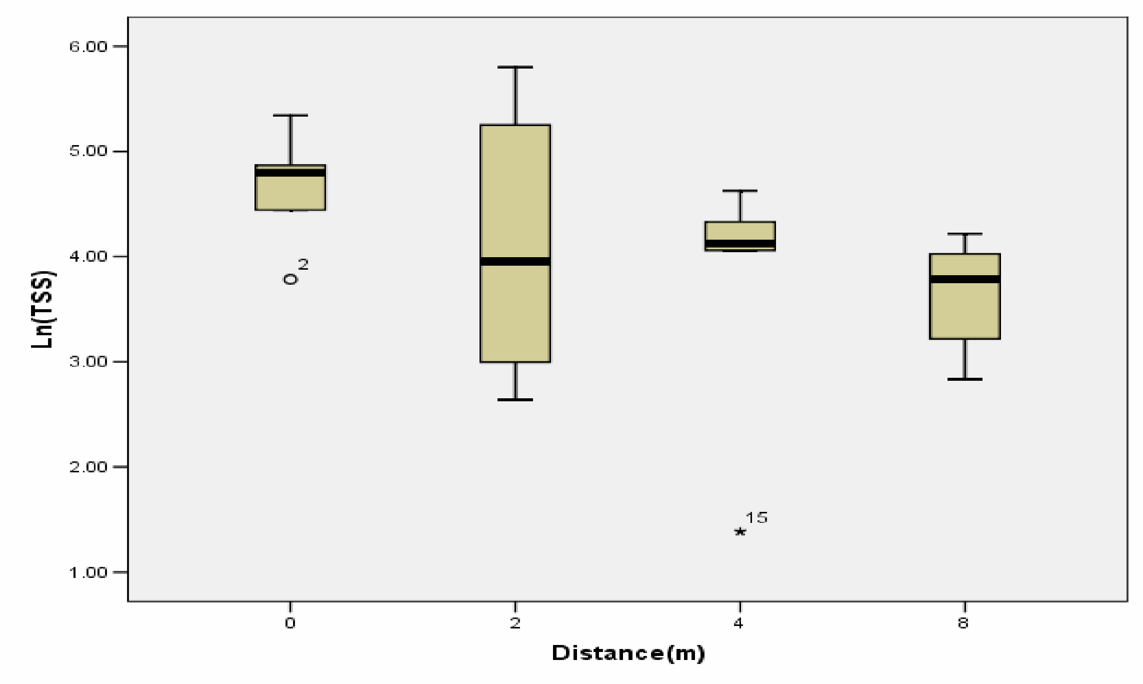


Figure 4.25. Boxplot of TSS EMCs at Austin Site 1 (traditional asphalt surface)

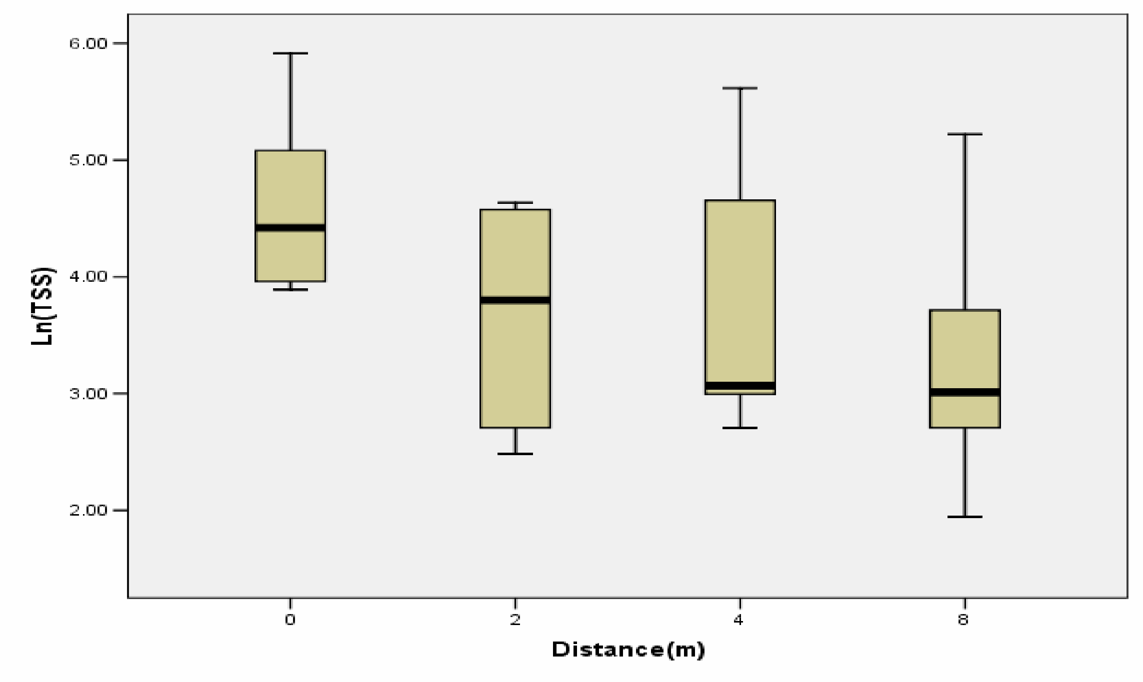


Figure 4.26. Boxplot of TSS EMCs at Austin Site 2

4.14.3 Correlation between vegetation cover and pollutant removal efficiency

Correlation analysis between percentage of pollutant removal efficiency and vegetation cover is performed. The results of the analyses for College Station sites, showing the correlation coefficient (R) are shown in Table 4.27.

Table 4.27. Correlation between pollutant removal and vegetation cover at College Station sites

Constituent	R
TSS	-0.07
TKN	-0.459
Nitrates	0.23
Total P	0.406
Dissolved P	0.671
Total Cu	0.115
Dissolved Cu	0.481
Total Pb	-0.155
Total Zn	0.06
Dissolved Zn	-0.037
COD	0.68

The results indicate that significant correlation exists between Dissolved P, and COD pollutant removal and vegetation cover at College Station sites.

The results of the analyses for Austin sites, showing the correlation coefficient (R) are shown in Table 4.28.

Table 4.28. Correlation between pollutant removal and vegetation cover at Austin sites

Constituent	R
TSS	0.858
TKN	0.542
Nitrates	-0.475
Total P	-0.405
Dissolved P	-0.314
Total Cu	0.812
Dissolved Cu	0.476
Total Pb	-0.072
Total Zn	-0.683
Dissolved Zn	-0.684
COD	0.793

The results indicate that significant correlation exists between TSS, total Cu, and COD pollutant removal and vegetation cover at Austin sites.

4.15. Comparison of College Station and Austin data

The comparisons of College Station and Austin data is reasonable for the similarity observed in aspects such as the nature of collection and sampling systems, sampling procedures, and analytical method adopted to inspect the data. Fire ants and their mounds were persistent problems at all the sites at both of the study areas. The wearing of the galvanized coating on the metal and the leaching out of Zn into the runoff were identified as the factor affecting the Zn levels in both of the study areas. The source of precipitation and traffic data at College Station sites is from the on-site sensor, whereas the rainfall data at Austin sites was obtained from an off-site nearby source.

Similar to College Station condition, the comparison of edge of pavement concentrations at Austin sites indicate that approximately equivalent pollutant levels exist on the road surface at each research site. Thus the expectation of the initial quality of the runoff at the edge of pavement at each site to be similar is satisfied at both of the study areas. One of the site selection parameters for the study at Austin sites was an ADT of at least 35,000, a slightly lower criterion than College Station sites. There is variation observed in the vegetation density at Site 1 between the two study areas, being 49% at College Station Site 1, and 82% at Austin Site 1. This variation reflected in the pollutant removal efficiencies of the roadsides at both of the study areas.

Though less significant performance in pollutant removal was observed at College Station sites, the results provided an opportunity to consider mechanisms other than the traditional method for determining pollutant inputs to the vegetated roadsides. Past study report that the material dispersed through air turbulence will be dominated by fine particles with high metal concentrations (Zanders, 2005). When these particles are blown into the treatment system and become re-suspended in through-flow during a storm, they could contribute to the pollutant load exiting the system without ever having been accounted for as an input. Hence, the pollutant removal by the vegetative roadsides could be underestimated.

In College Station sites, the mean concentrations of TSS are found to decrease with increasing distance from the edge of the pavement at Site 2 and 3. However, this phenomenon is not statistically significant. On the other hand, statistically significant reductions in TSS concentrations were observed at all sites in Austin. Concentrations of total and dissolved Cu exhibited statistically significant reductions at College Station and Austin sites.

CHAPTER V

SUMMARY AND CONCLUSIONS

The objective of this study was to document the stormwater quality benefits of the vegetated sideslopes typical of common rural highway cross sections. A proliferation of research indicates that these roadsides can improve significantly the quality of runoff that enters receiving bodies by reducing pollutant concentrations and loads. It is important that these benefits are documented so that roadsides can be used as a part of the design for meeting stormwater quality requirements.

The remainder of the section will summarize and conclude the key findings of the study conducted at College Station and Austin sites.

The findings of this study are as follows:

1. Similar to College Station condition, the comparison of edge of pavement concentrations at Austin sites indicate that approximately equivalent pollutant levels exist on the road surface at each research site. Thus the expectation of the initial quality of the runoff at the edge of pavement at each site to be similar is satisfied at both of the study areas. There is no significant difference between the edge of pavement pollutant concentrations at each of the research sites. This allows for direct comparisons of the vegetated roadsides and their associated site characteristics (ADT, dry period, and rainfall intensity).

2. There is variation observed in the vegetation density at Site 1 between the two study areas, being 49% at College Station Site 1, and 82% at Austin Site 1. This variation reflected in the pollutant removal efficiencies of the roadsides at both of the study areas. A comparison of TSS removal efficiency at College Station Sites 1 and 2, between the zero and two meters, indicates that the higher vegetation density (98%) between zero and two meters at Site 2 may be facilitating relatively better removal of stormwater pollutants when compared to the removal rate at Site 1 due to poor vegetative cover (37%) between the zero and two meters.

3. The two steeper Sites (2 and 3) outperformed Site 1 with much flatter slopes. This could be again accounted due to poor vegetative cover (brown patches) at Site 1. The grassy roadsides have lost the ability to function as an effective buffer. The results of correlation analyses indicate that significant correlation exists between Dissolved P, and COD pollutant removal and vegetation cover at College Station sites. In Austin sites, significant correlation between TSS, total Cu, and COD pollutant removal and vegetation cover is found.

4. Though less significant performance in pollutant removal was observed at College Station sites, the results provided an opportunity to think about mechanisms other than the traditional method for determining pollutant inputs to the vegetated roadsides. The field experiment conducted to further investigate the less significant performance in pollutant removal in College Station gives an idea that pollutants could be removed from

highway lanes and thrown at various distances based on the intensity of the wind and the vehicle speed. Hence, the pollutant removal by the vegetative roadsides could be underestimated.

5. In College Station sites, the mean concentrations of TSS are found to decrease with increasing distance from the edge of the pavement at Sites 2 and 3. However, this phenomenon is not statistically significant. On the other hand, statistically significant reductions in TSS concentrations were observed at all sites in Austin.

4. No consistent increases or decreases were observed for nutrients (Nitrates and total and dissolved forms of P).

5. Concentrations of total and dissolved Cu exhibited statistically significant reductions at College Station and Austin sites.

6. Total and dissolved concentrations of Zn were elevated at all of the sites in both of the study areas. This is believed to be caused by the leaching of Zn from the galvanized metal flashing used in the collection systems.

7. The influence of various characteristics such as antecedent dry period, ADT, average traffic using the highway during the preceding dry period, and vehicles during the storm on mean concentrations of pollutants is investigated in this study using correlation and regression analyses. The scatter plots of College Station data show that concentrations of

TSS, total Pb, and COD in runoff are dependent on antecedent dry period. The concentrations of the above mentioned pollutants tend to decrease with longer dry periods. However, the results show that pollutant concentrations are not highly dependent on ADT. Also, results show that decrease in concentrations is observed with increasing rainfall volume at the College Station sites. This is believed due to reduced dilution during low intense storms.

8. The results of correlation analysis show that the concentrations of total Pb and Chemical oxygen demand are significantly correlated with TSS levels.

9. The findings indicate that nitrate concentrations in runoff is most dependent on the average daily traffic using the highway during the preceding dry period as well as the duration of that dry period.

10. The results show that the number of vehicles during the storm (VDS) during the storm was evaluated and accepted as a satisfactory independent variable for estimating the loads of total Pb and TSS.

11. In Austin sites, the permeable friction course appeared to have a significant impact on the quality of runoff leaving the road surface. The comparison of pollutant concentrations in runoff sampled from a traditional asphalt-surface 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. On the other hand, no similar studies were performed at the College Station sites.

12. In Austin sites, the finding indicates a concern that the cleaner runoff coming from the PFC is picking up Cu from the soil a sit travels through the first two meters of the shoulder area. However, no soil sample tests were conducted. On the other hand, in College Station, soil analysis was conducted at Site 3. The soil analysis report indicates high heavy metal content in the soil. The report indicates that the soil content in Site 3 has excessive amount of Zn and Cu at all the locations and high level of phosphorus at two meter sampling area. Higher level of Zn and phosphorus concentrations in the soil could have attributed to the significant increases in the Zn and phosphorus concentrations in the sampled runoff.

The results of the study from the two cities in Texas indicate that vegetated roadsides should be utilized as a management practice for controlling and treating stormwater runoff from Texas highways. These roadside slopes 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.

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APPENDIX A

BOXPLOTS OF EACH CONSTITUENT AT COLLEGE STATION SITES

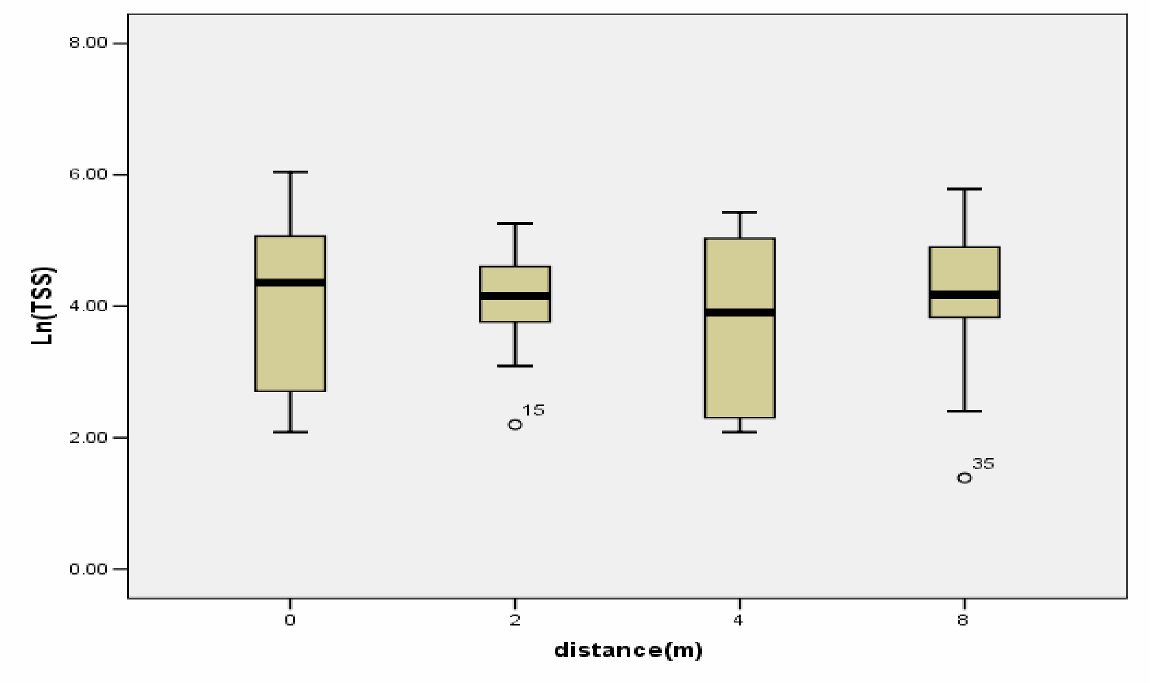


FIGURE A-1 Boxplot of TSS at Site 1

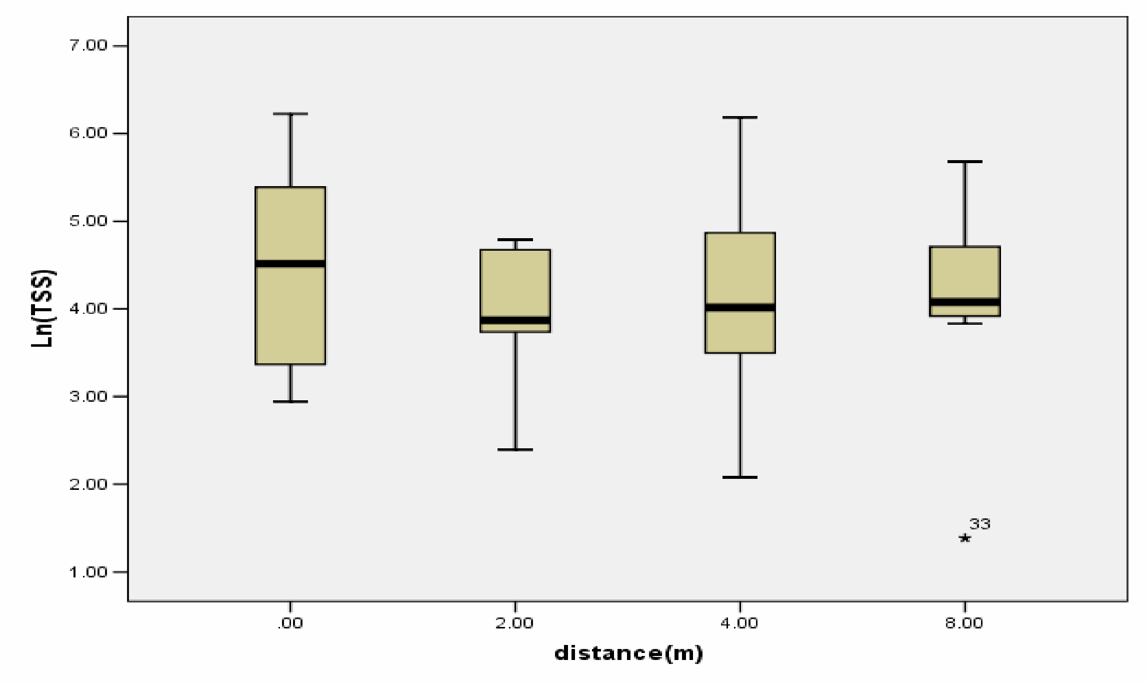


FIGURE A-2 Boxplot of TSS at Site 2

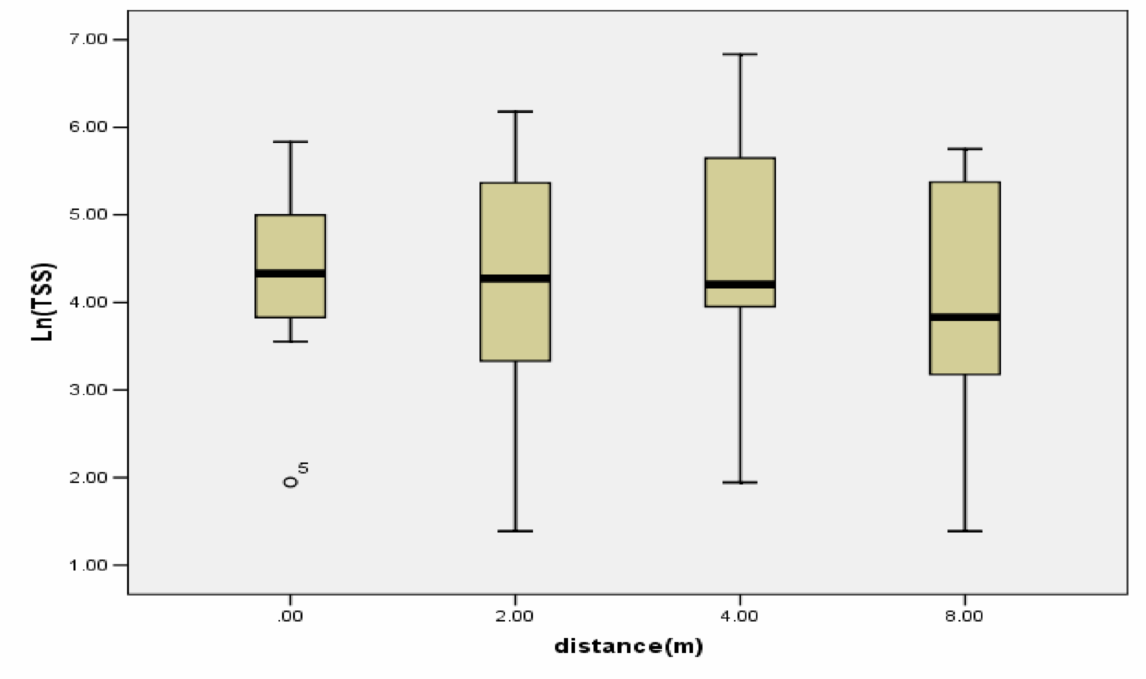


FIGURE A-3 Boxplot of TSS at Site 3

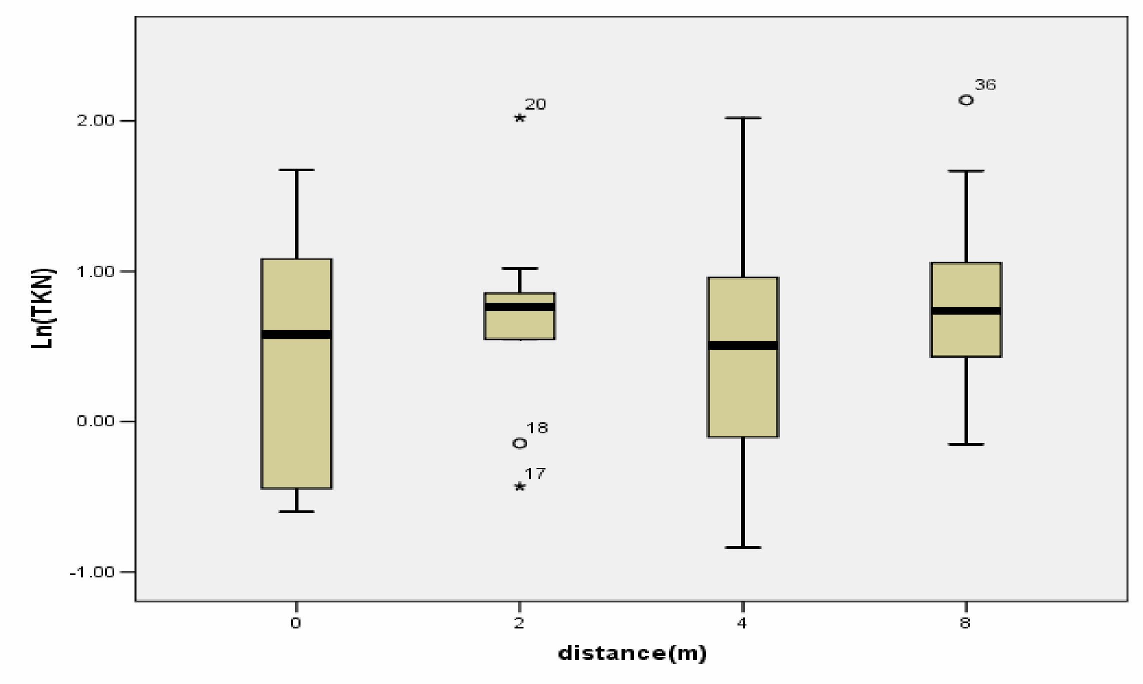


FIGURE A-4 Boxplot of TKN at Site 1

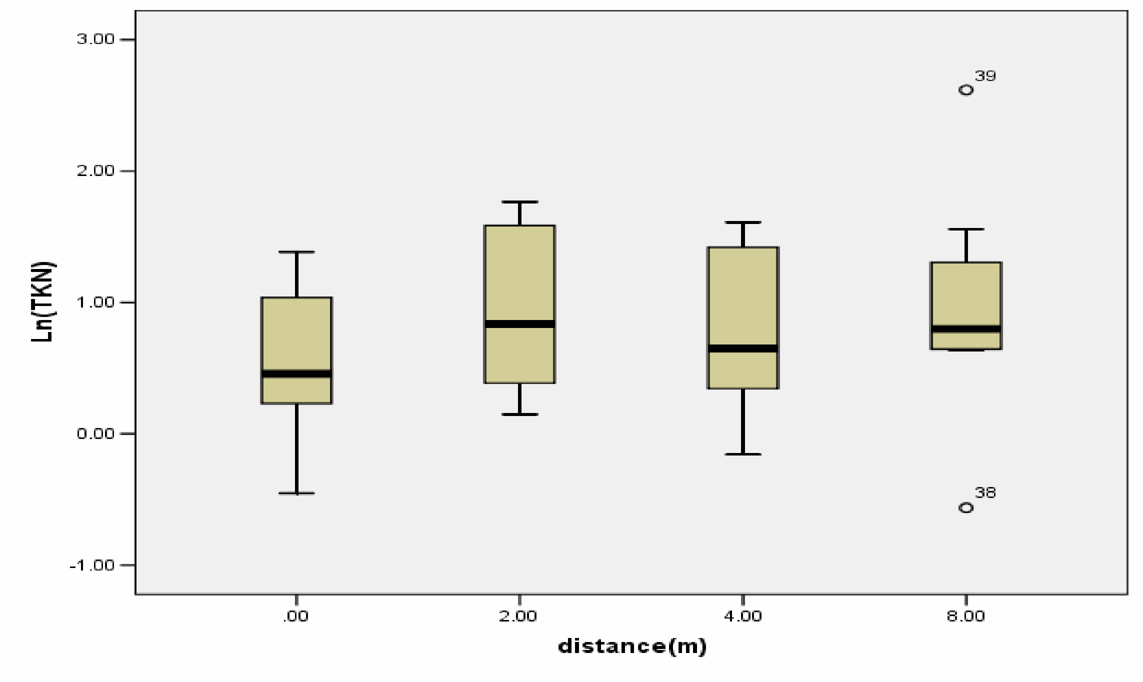


FIGURE A-5 Boxplot of TKN at Site 2

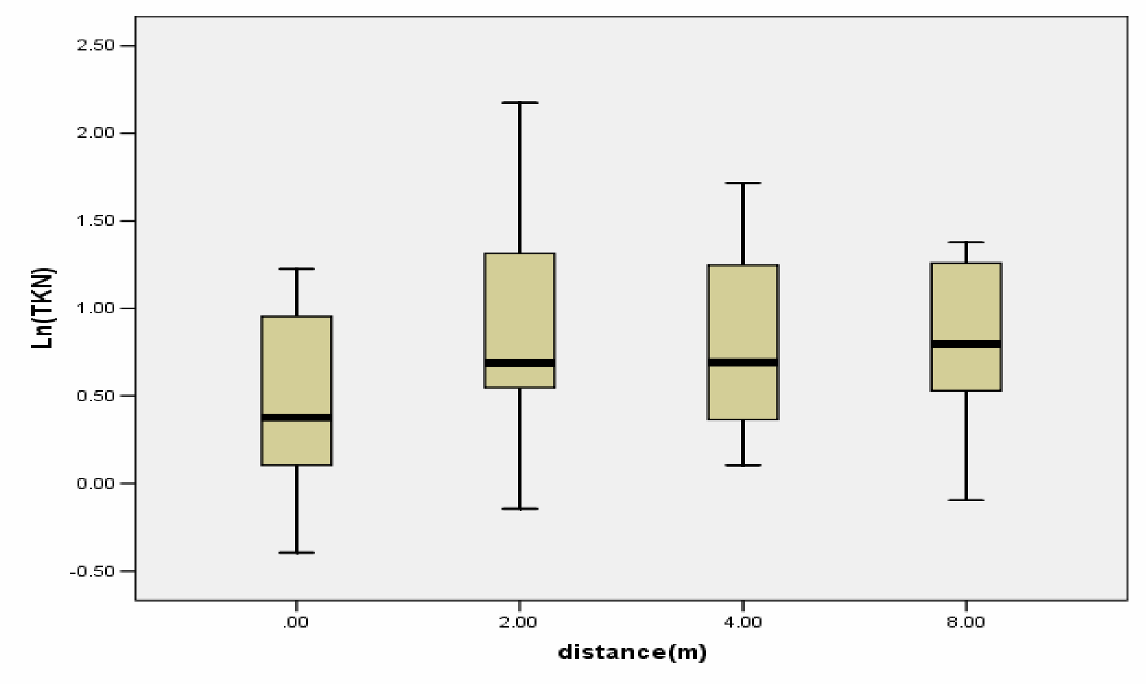


FIGURE A-6 Boxplot of TKN at Site 3

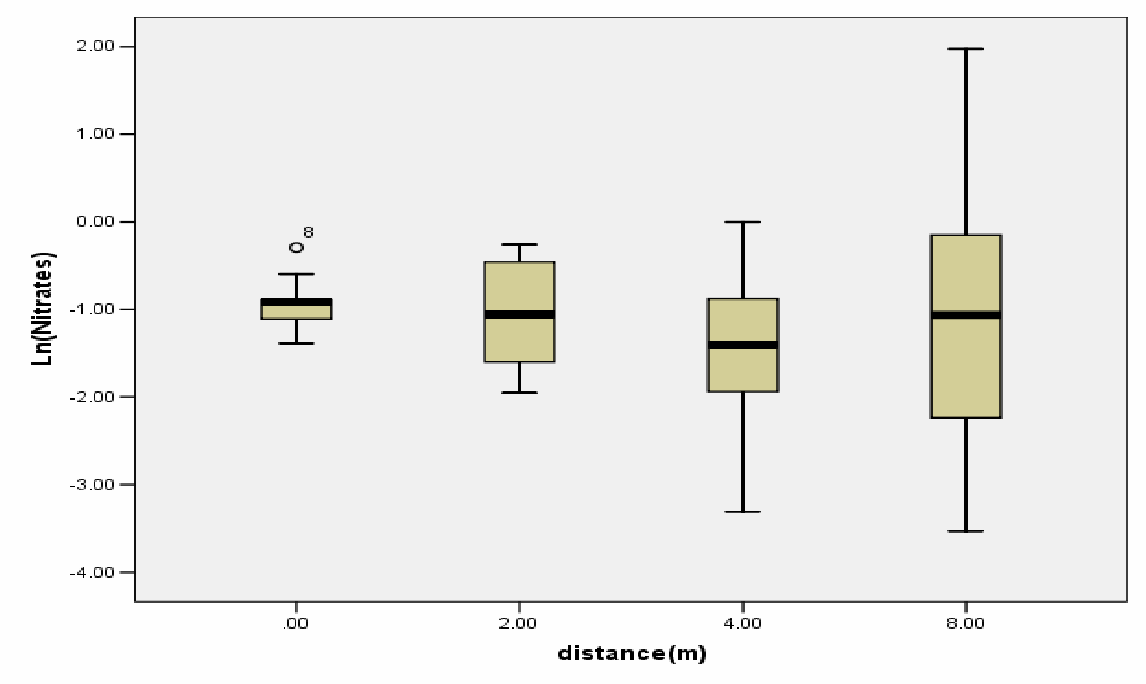


FIGURE A-7 Boxplot of Nitrate/Nitrite at Site 1

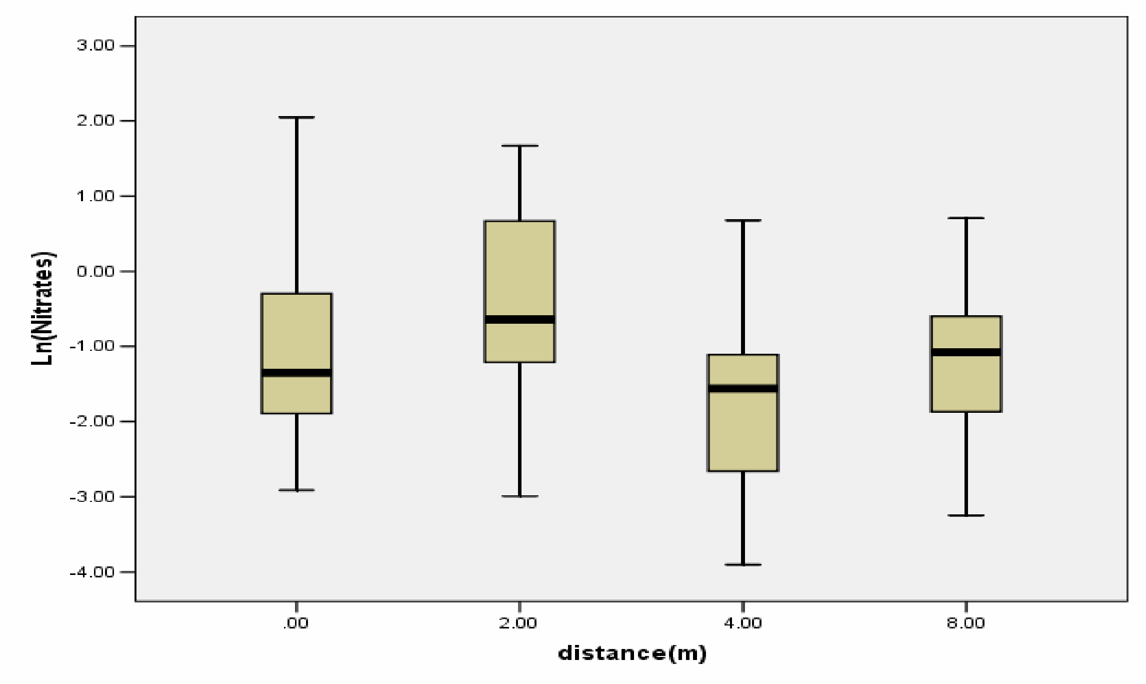


FIGURE A-8 Boxplot of Nitrate/Nitrite at Site 2

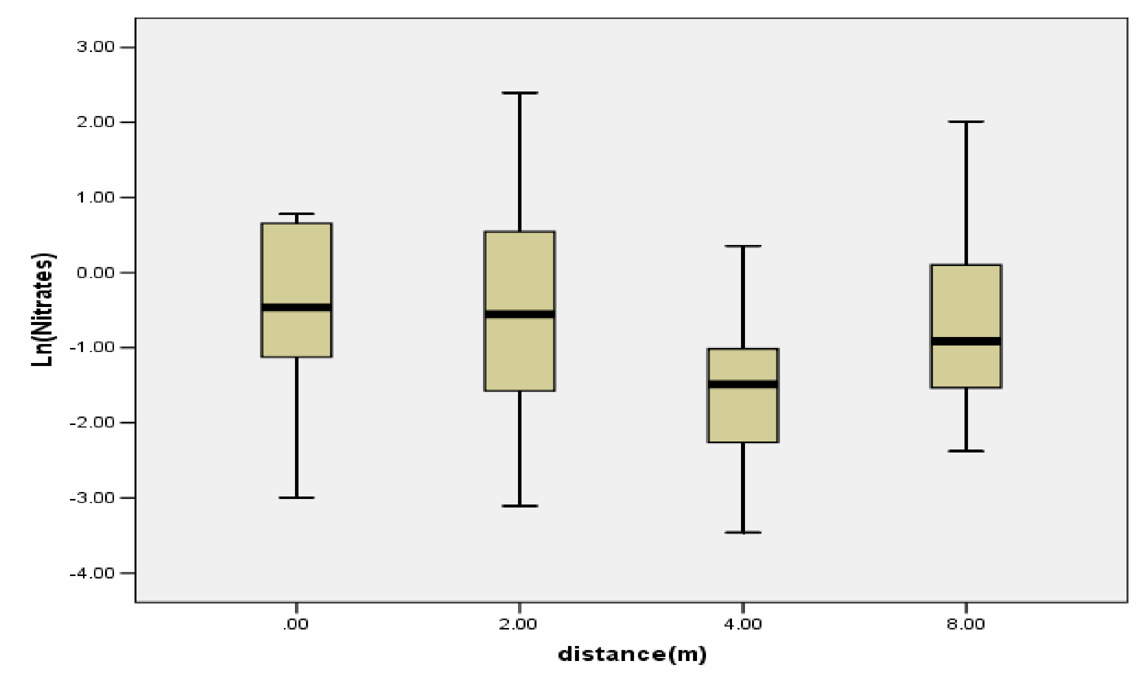


FIGURE A-9 Boxplot of Nitrate/Nitrite at Site 3

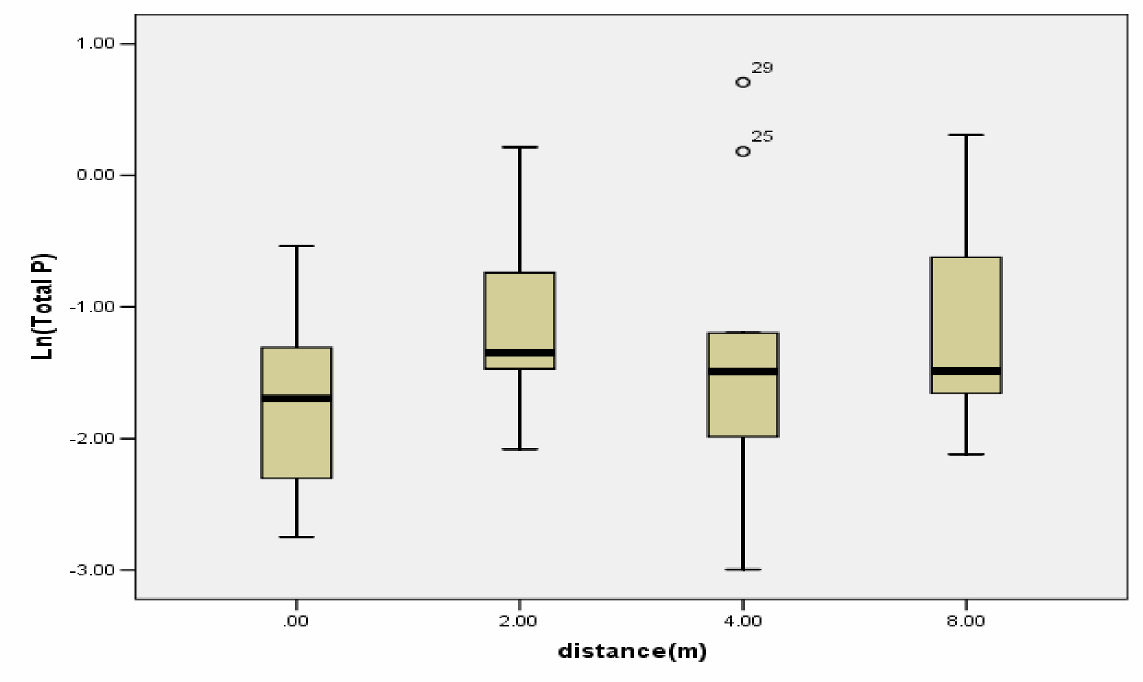


FIGURE A-10 Boxplot of Total P at Site 1

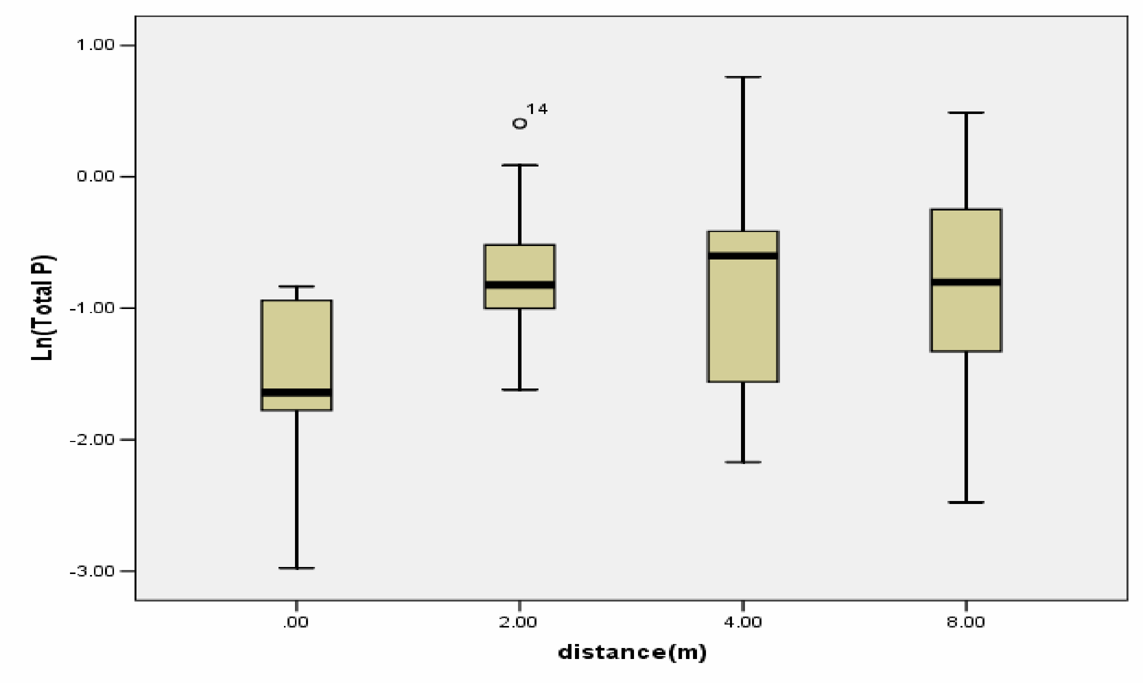


FIGURE A-11 Boxplot of Total P at Site 2

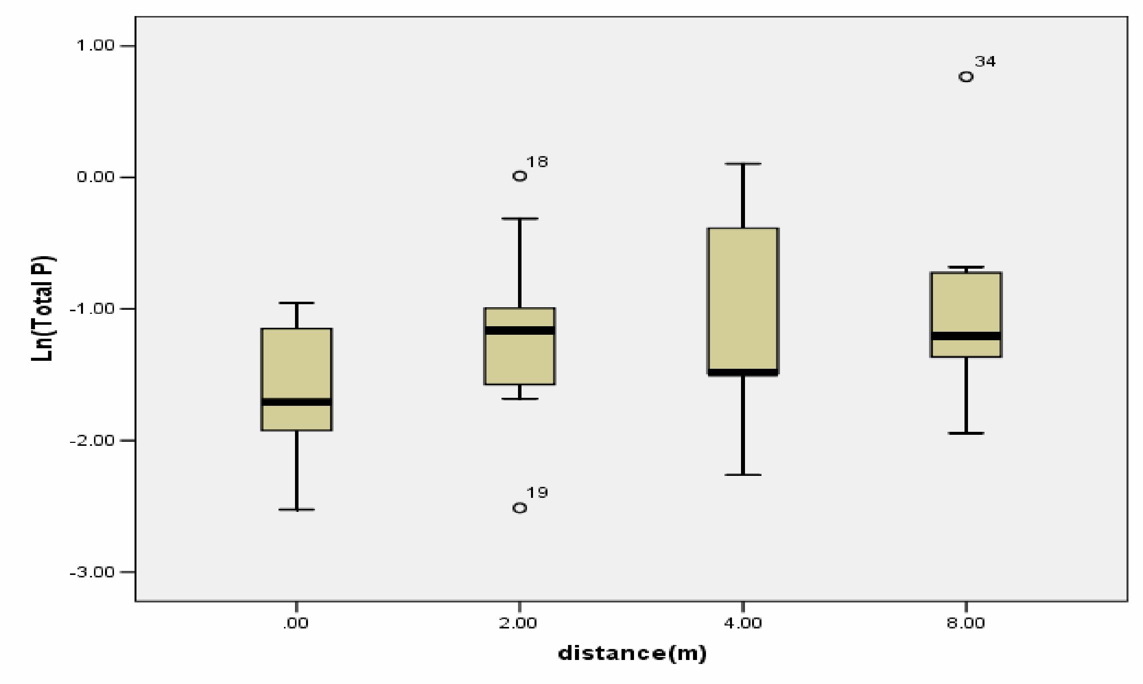


FIGURE A-12 Boxplot of Total P at Site 3

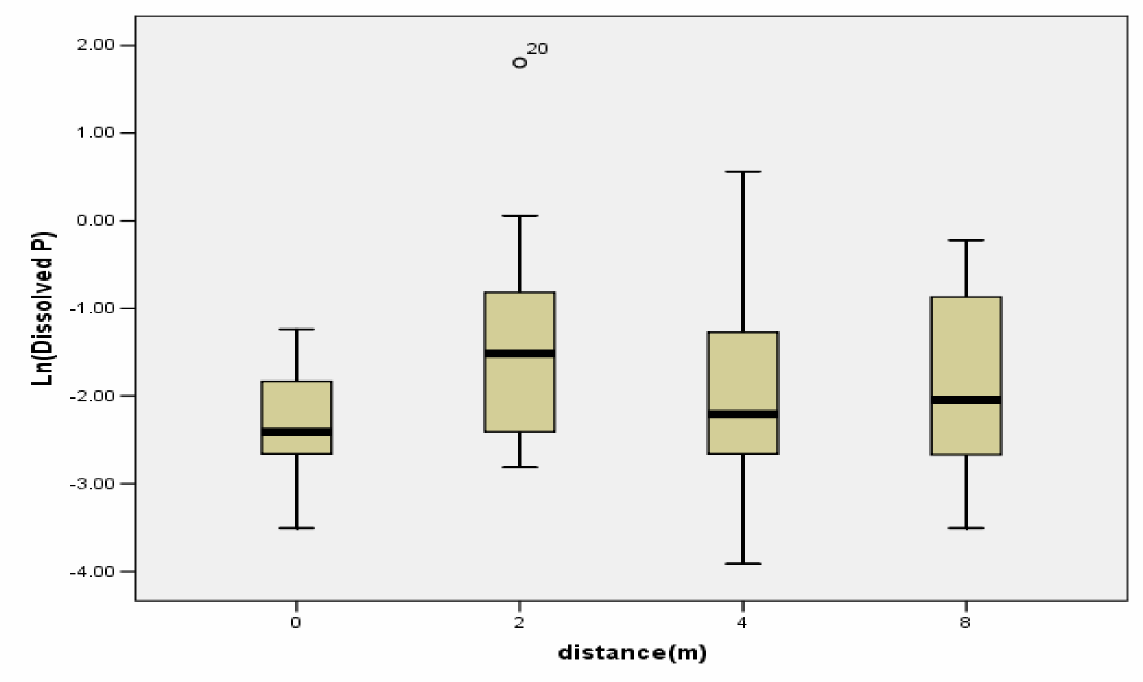


FIGURE A-13 Boxplot of Dissolved P at Site 1

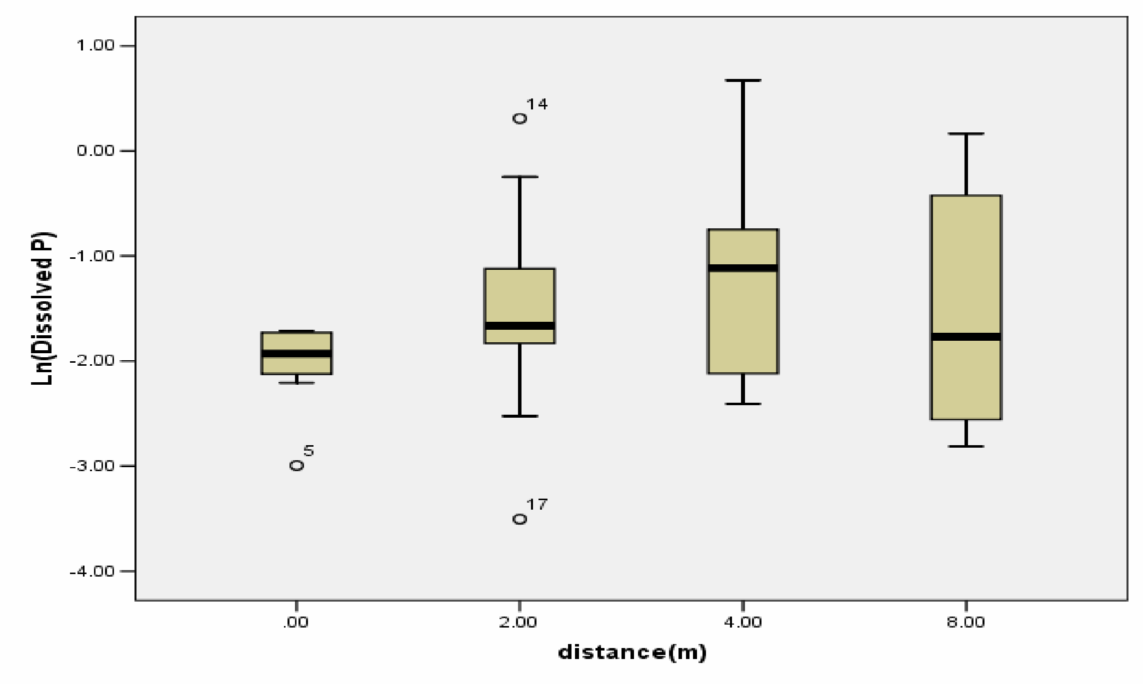


FIGURE A-14 Boxplot of Dissolved P at Site 2

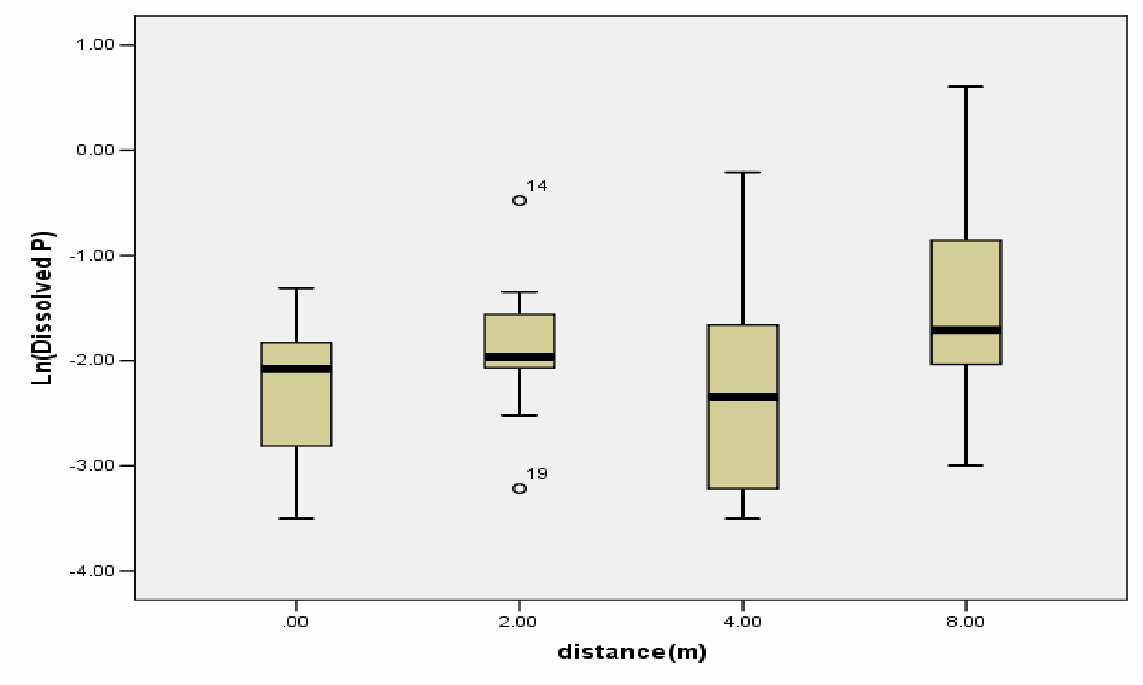


FIGURE A-15 Boxplot of Dissolved P at Site 3

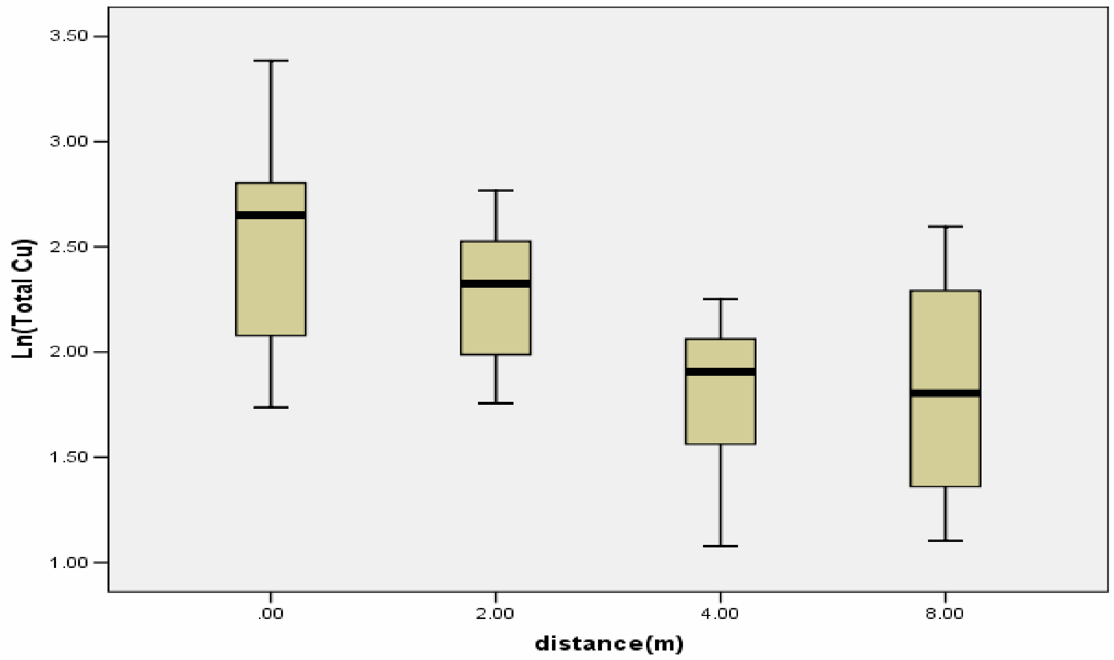


FIGURE A-16 Boxplot of Total Cu at Site 1

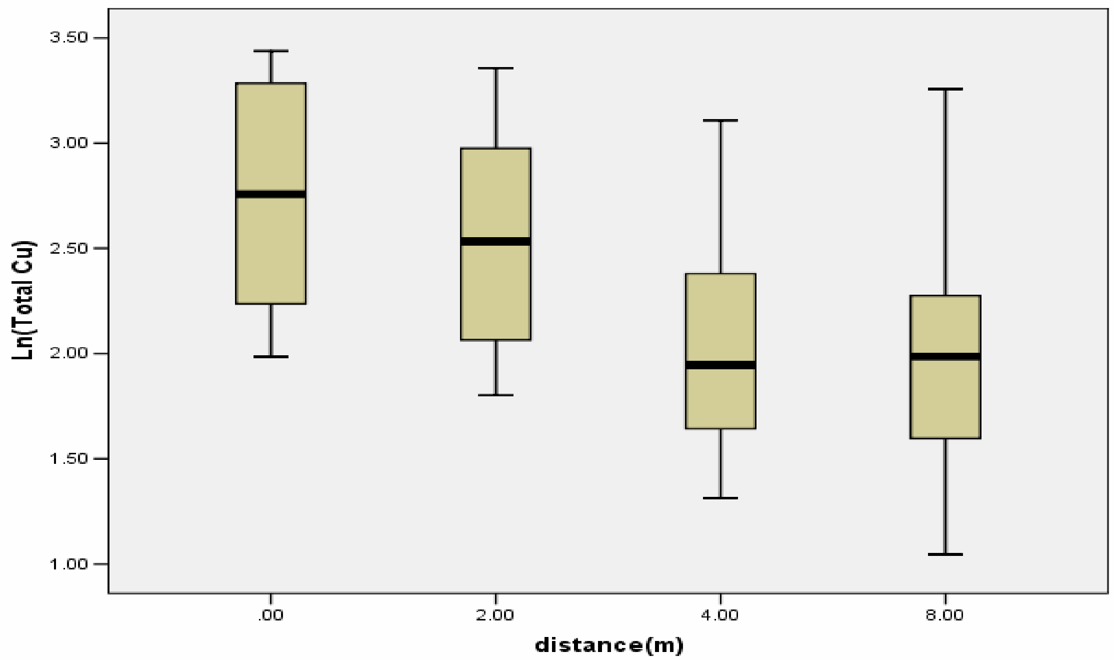


FIGURE A-17 Boxplot of Total Cu at Site 2

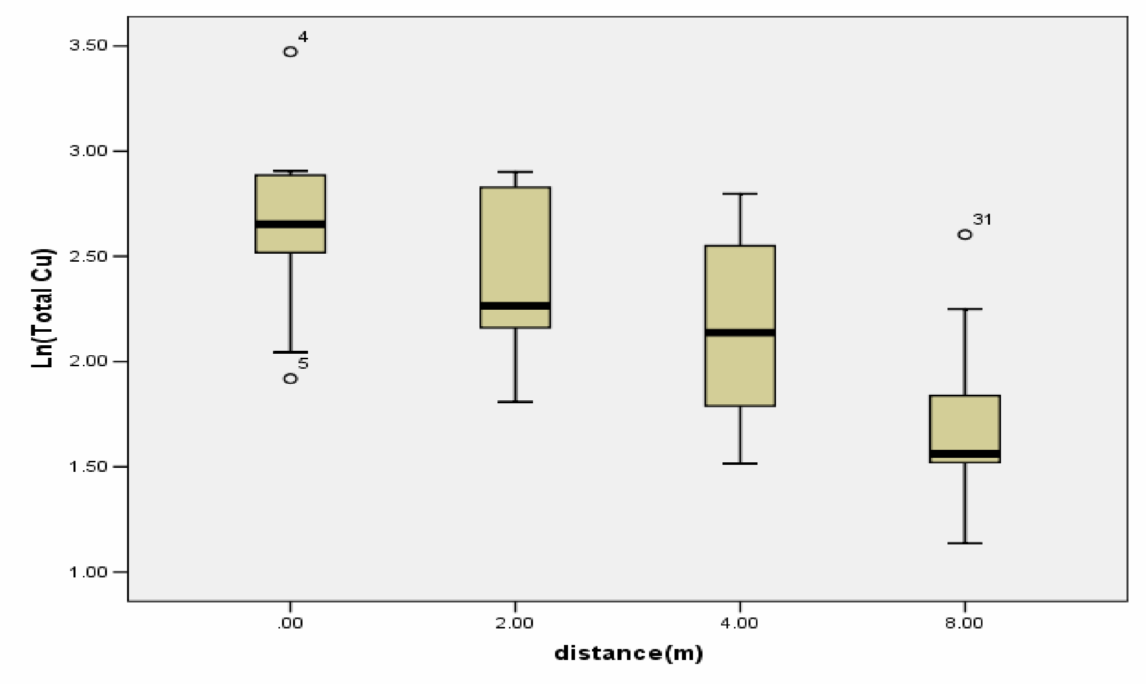


FIGURE A-18 Boxplot of Total Cu at Site 3

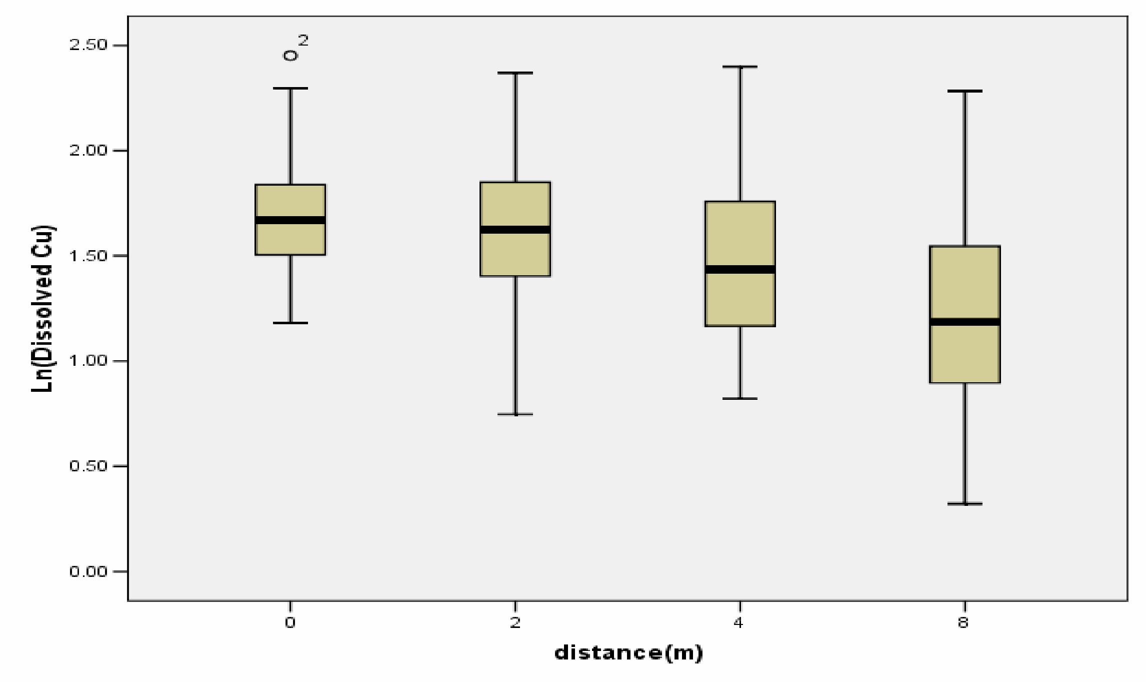


FIGURE A-19 Boxplot of Dissolved Cu at Site 1

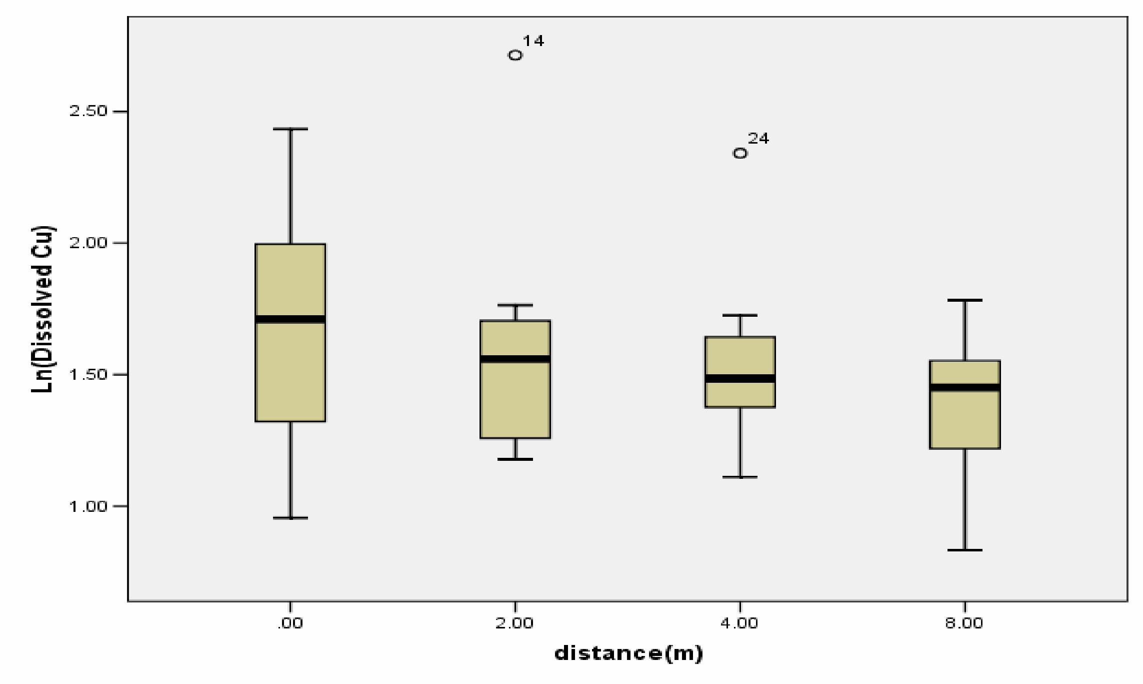


FIGURE A-20 Boxplot of Dissolved Cu at Site 2

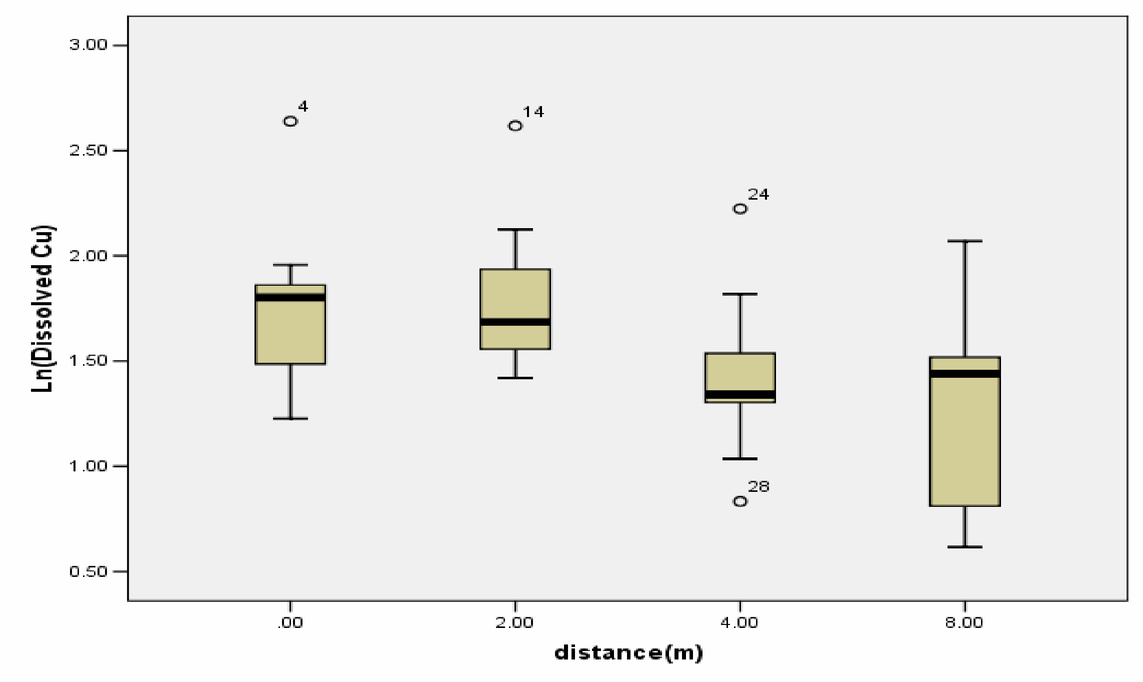


FIGURE A-21 Boxplot of Dissolved Cu at Site 3

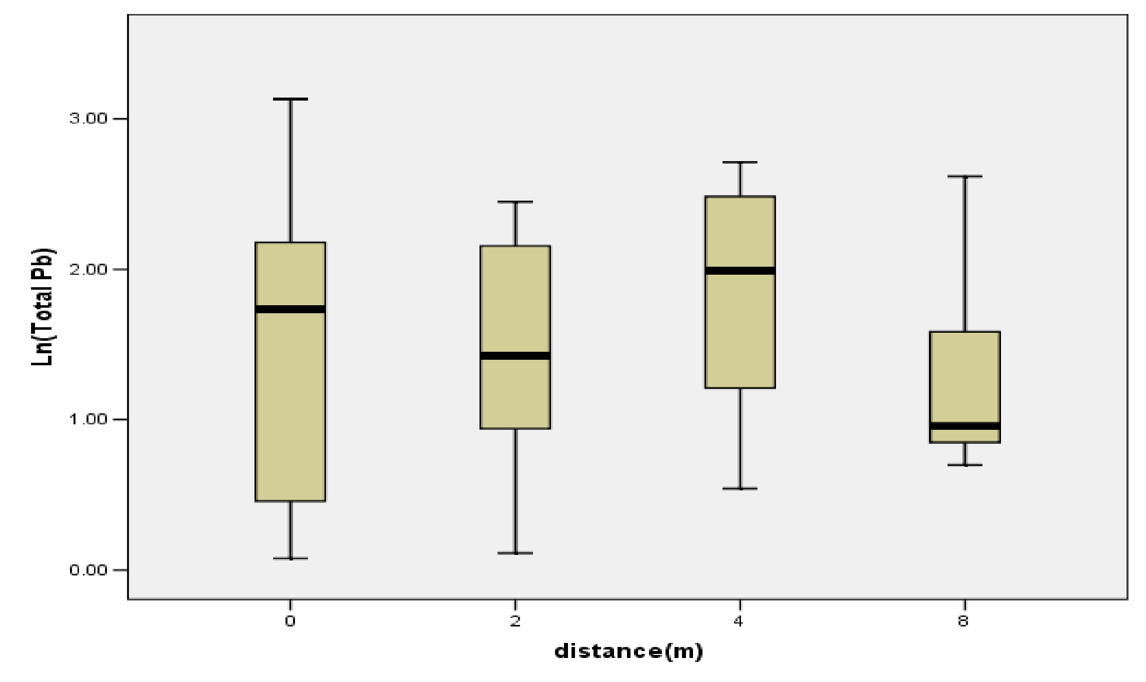


FIGURE A-22 Boxplot of Total Pb at Site 1

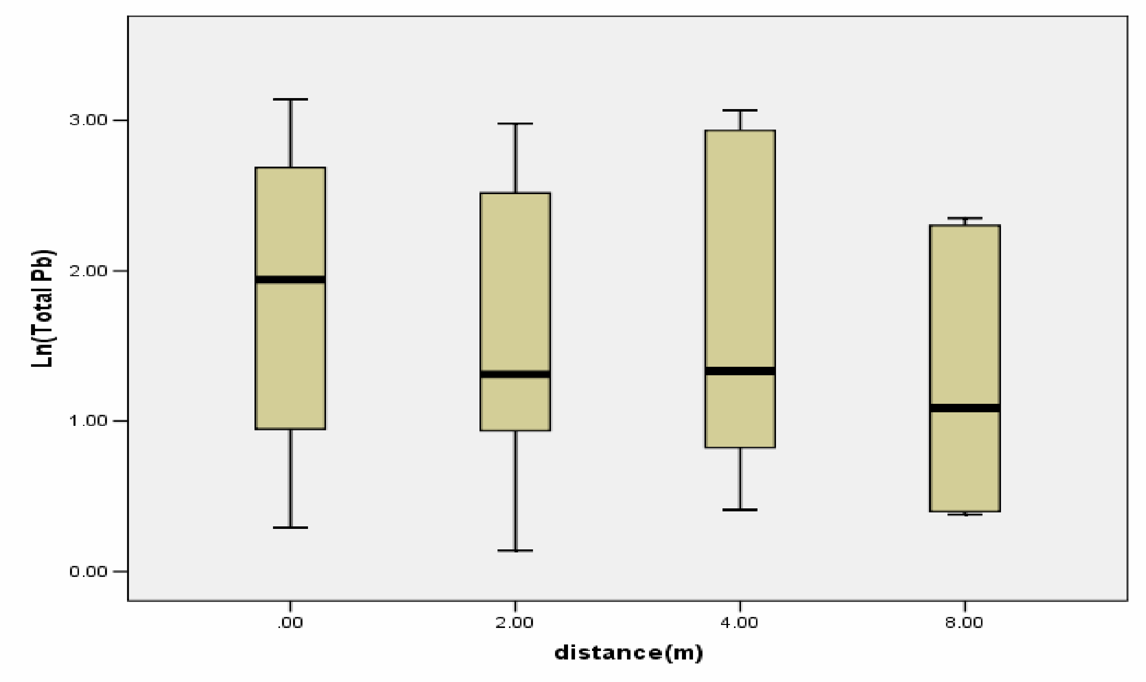


FIGURE A-23 Boxplot of Total Pb at Site 2

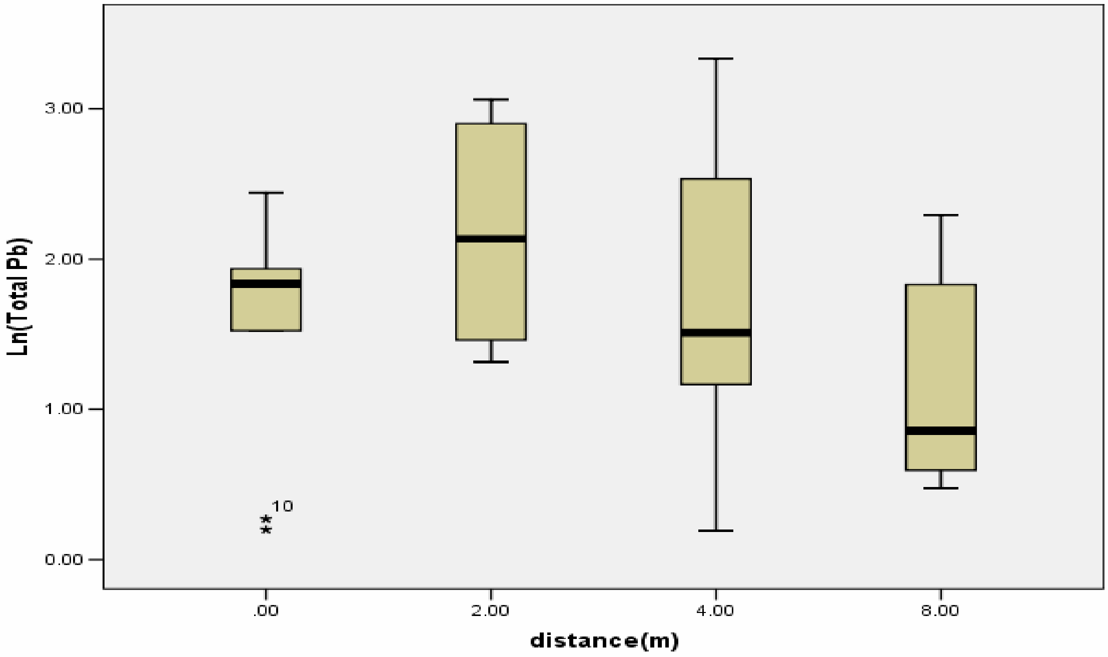


FIGURE A-24 Boxplot of Total Pb at Site 3

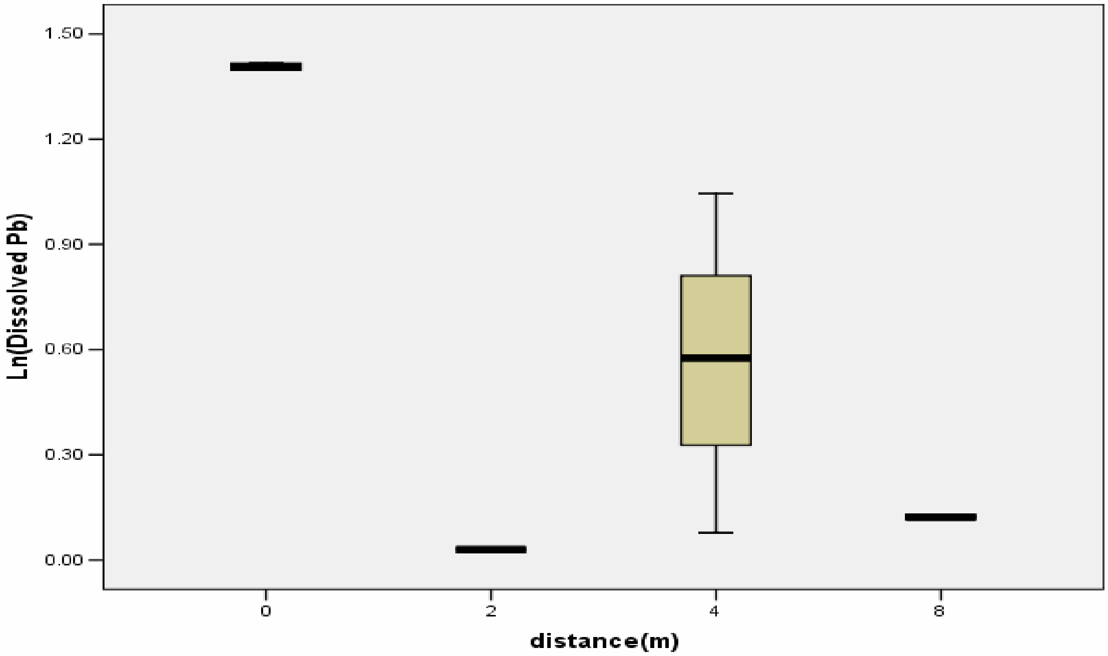


FIGURE A-25 Boxplot of Dissolved Pb at Site 1

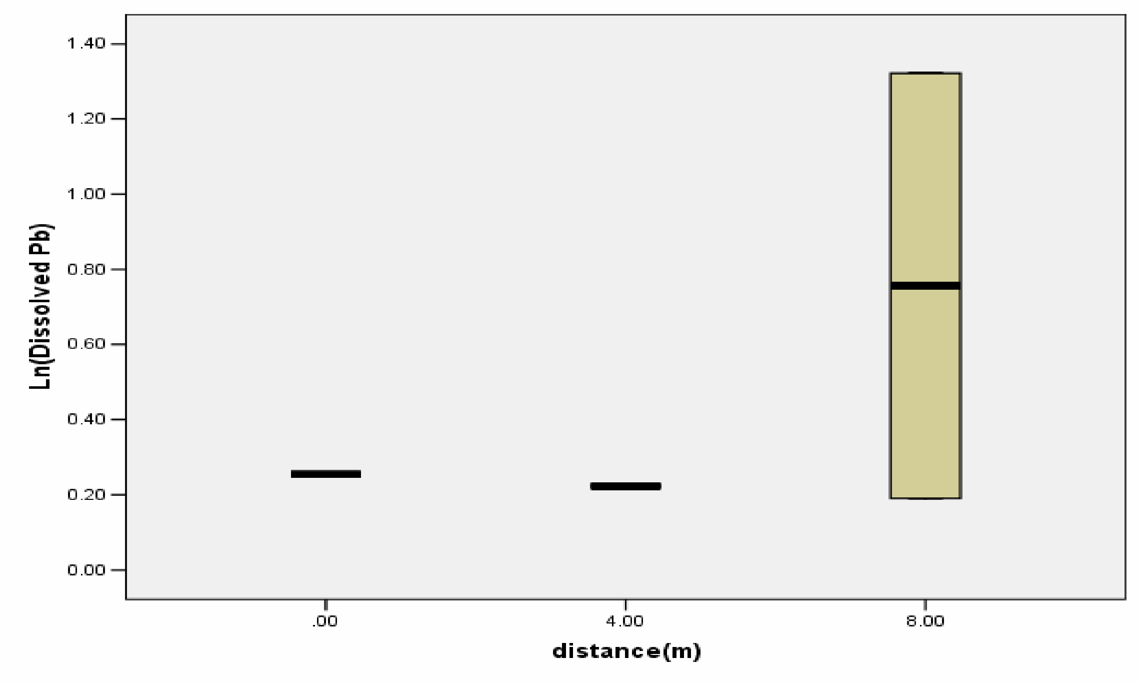


FIGURE A-26 Boxplot of Dissolved Pb at Site 3

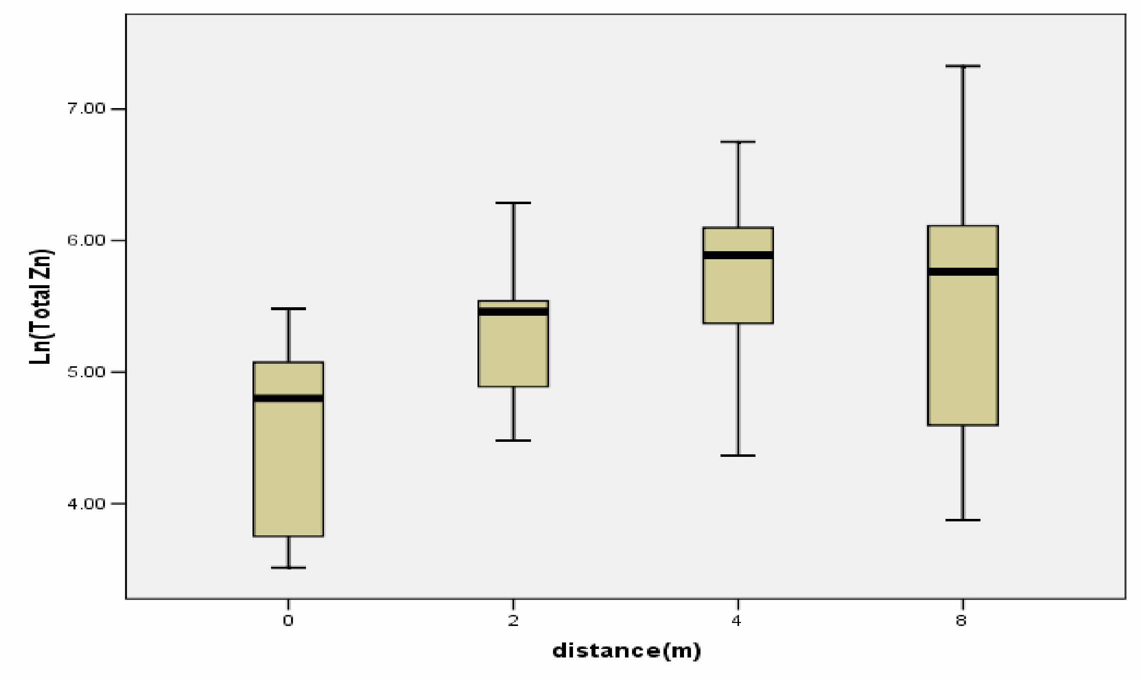


FIGURE A-27 Boxplot of Total Zn at Site 1

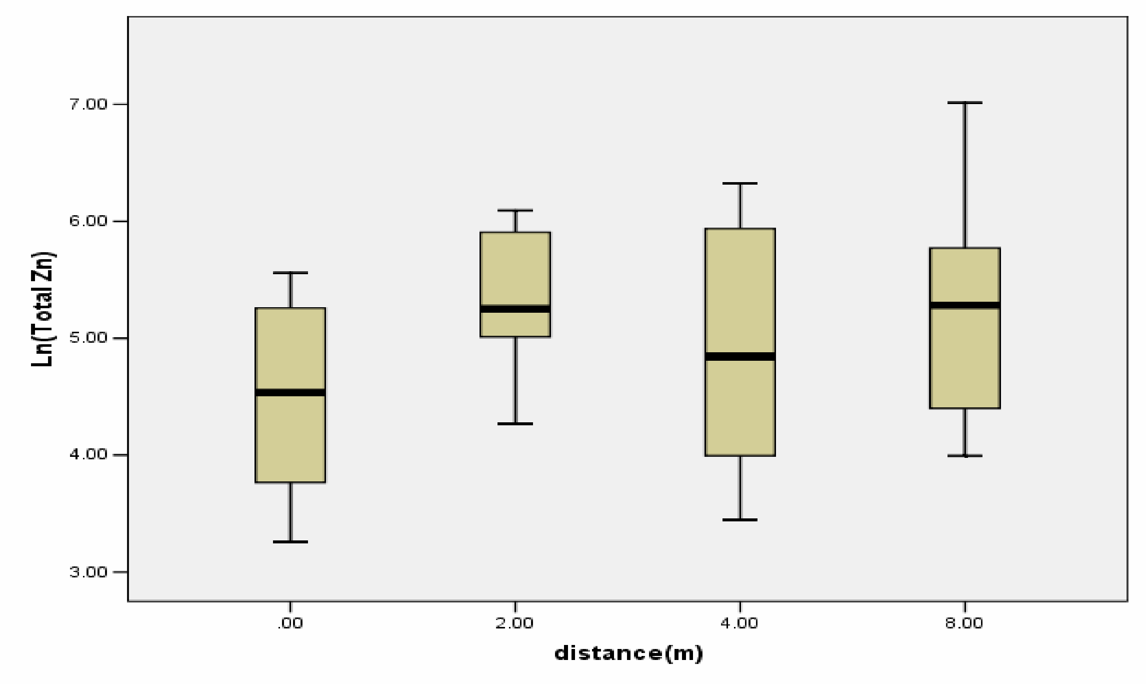


FIGURE A-28 Boxplot of Total Zn at Site 2

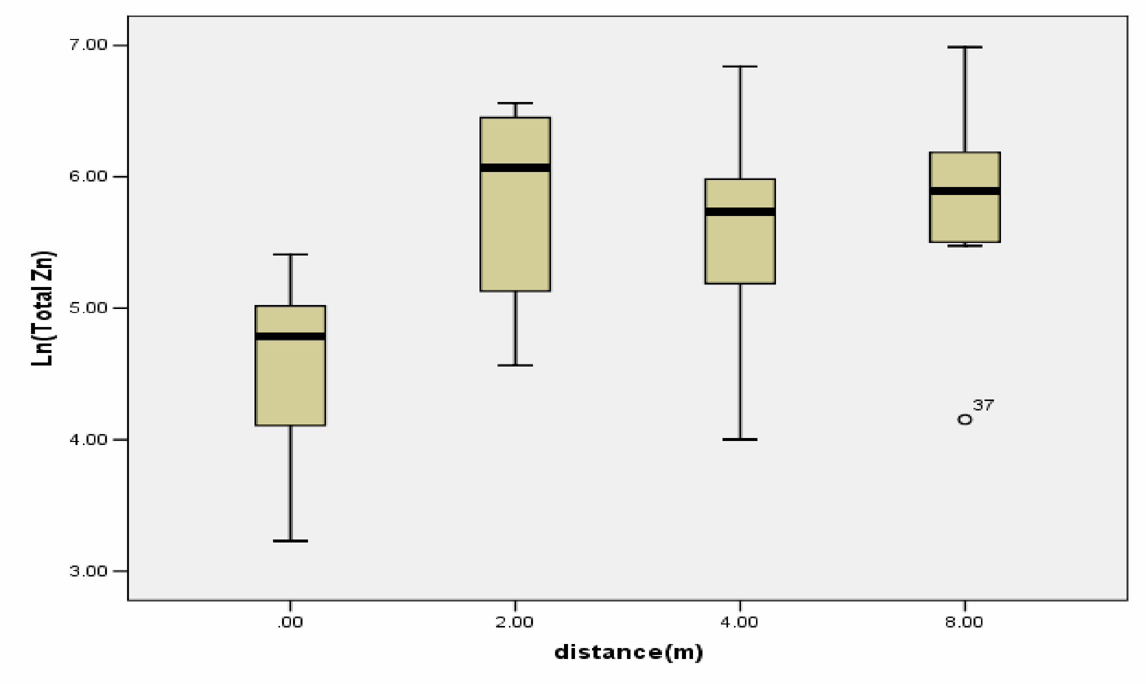


FIGURE A-29 Boxplot of Total Zn at Site 3

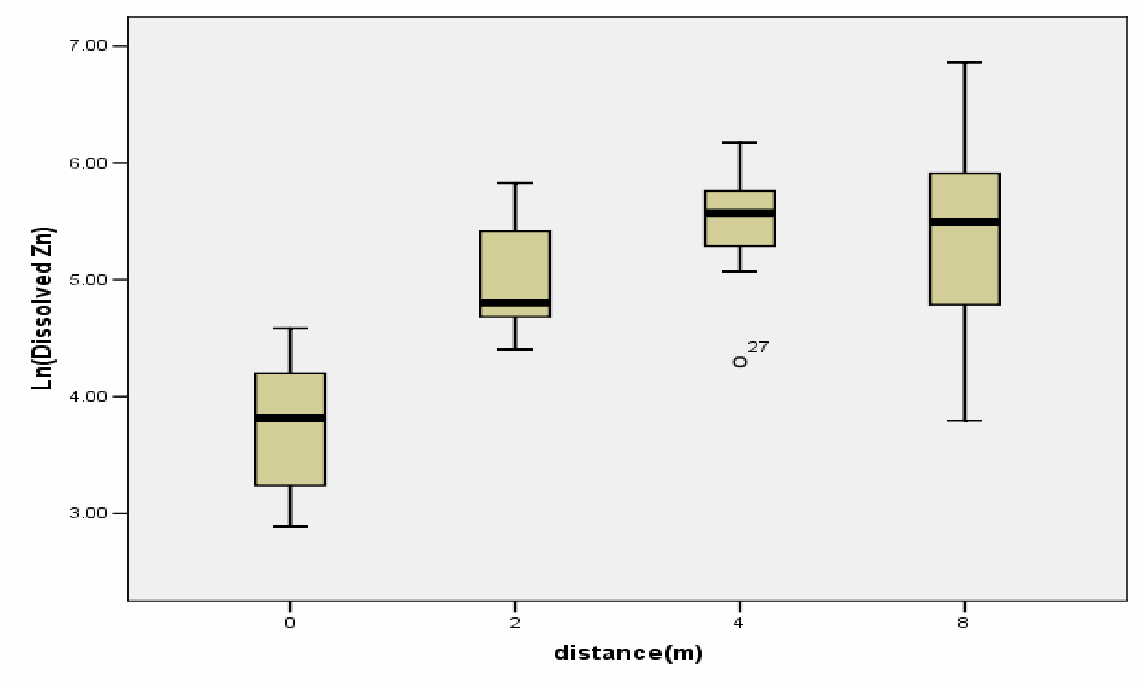


FIGURE A-30 Boxplot of Dissolved Zn at Site 1

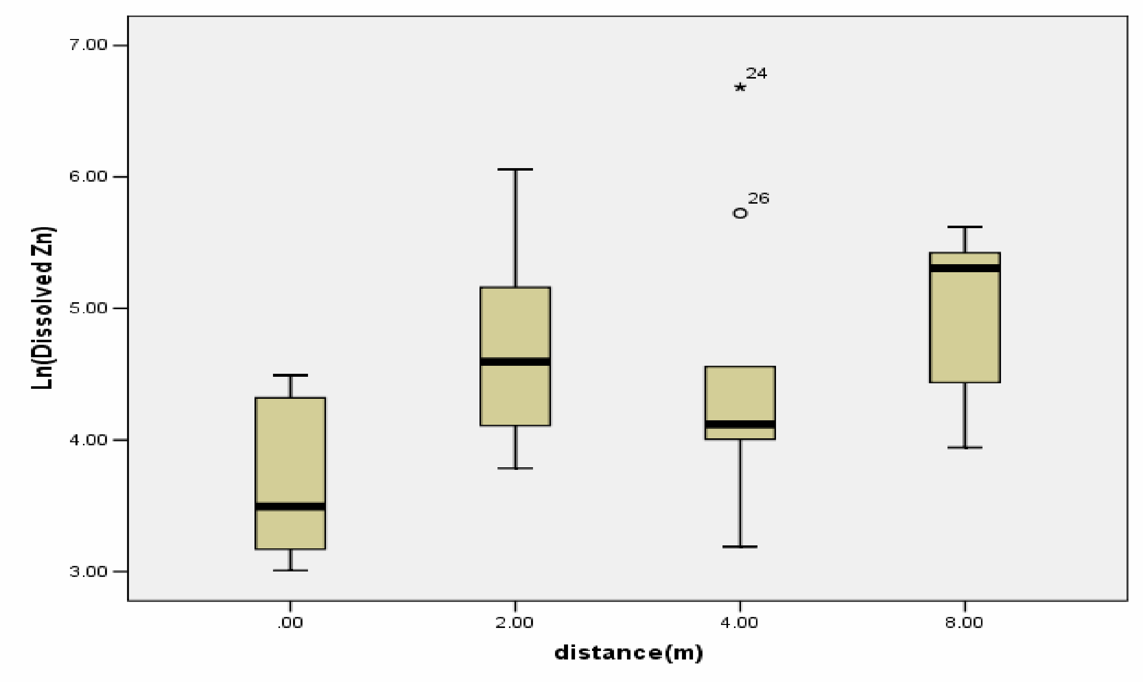


FIGURE A-31 Boxplot of Dissolved Zn at Site 2

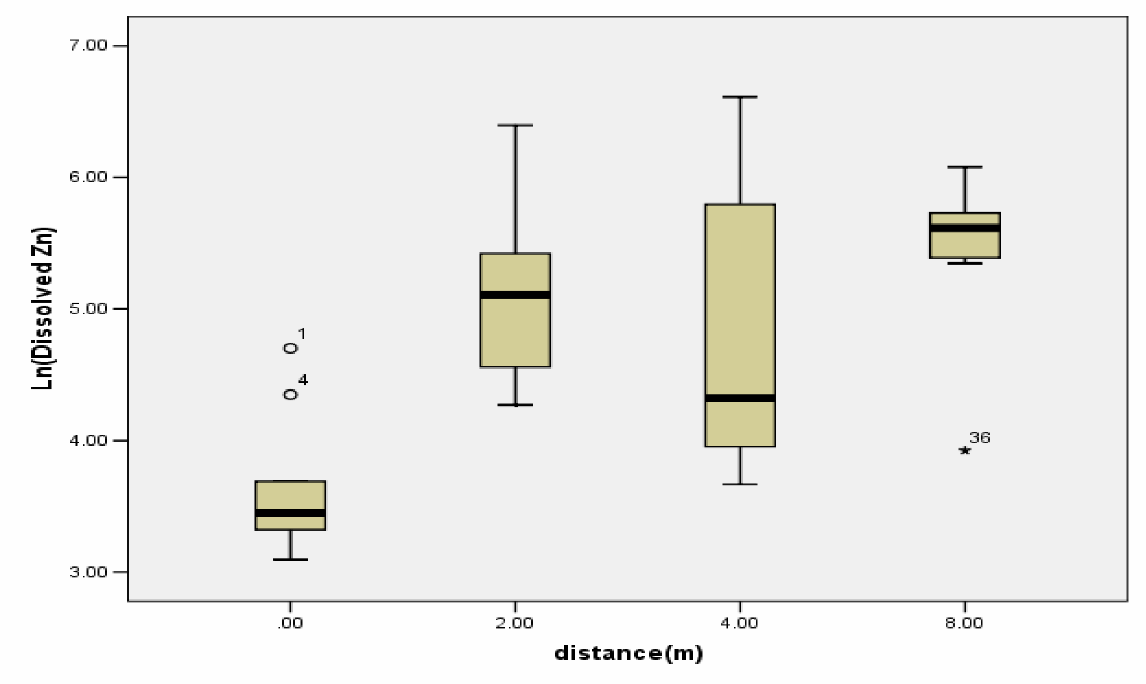


FIGURE A-32 Boxplot of Dissolved Zn at Site 3

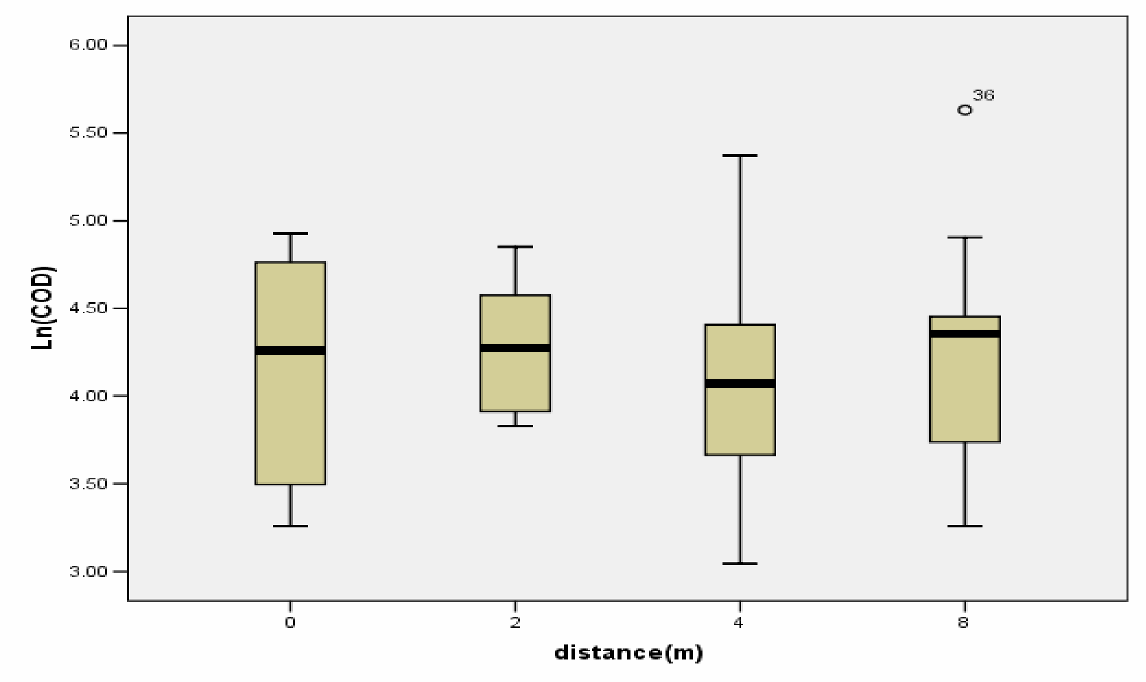


FIGURE A-33 Boxplot of Chemical Oxygen Demand at Site 1

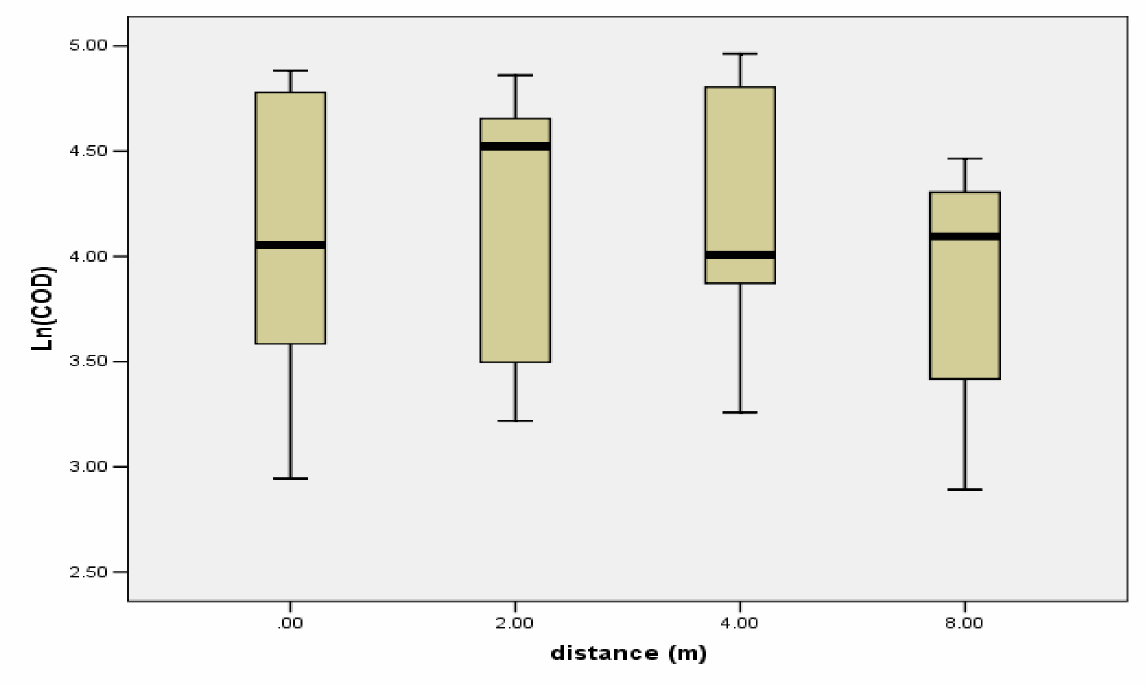


FIGURE A-34 Boxplot of Chemical Oxygen Demand at Site 2

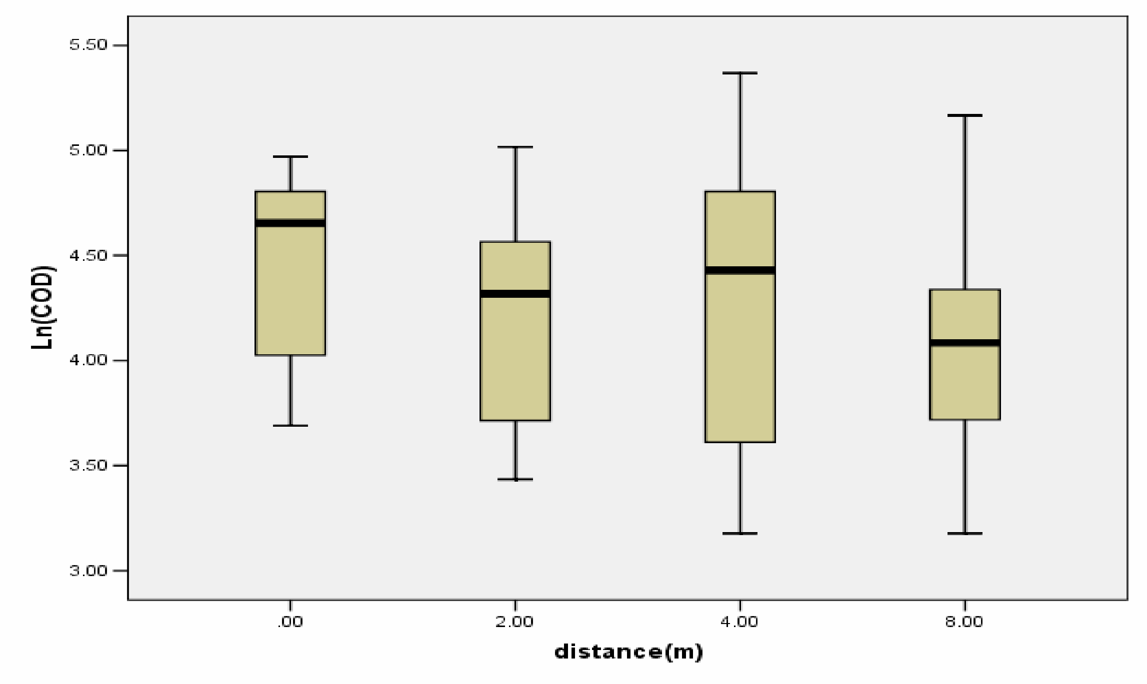


FIGURE A-35 Boxplot of Chemical Oxygen Demand at Site 3

APPENDIX B

BOXPLOTS OF EACH CONSTITUENT AT AUSTIN SITES

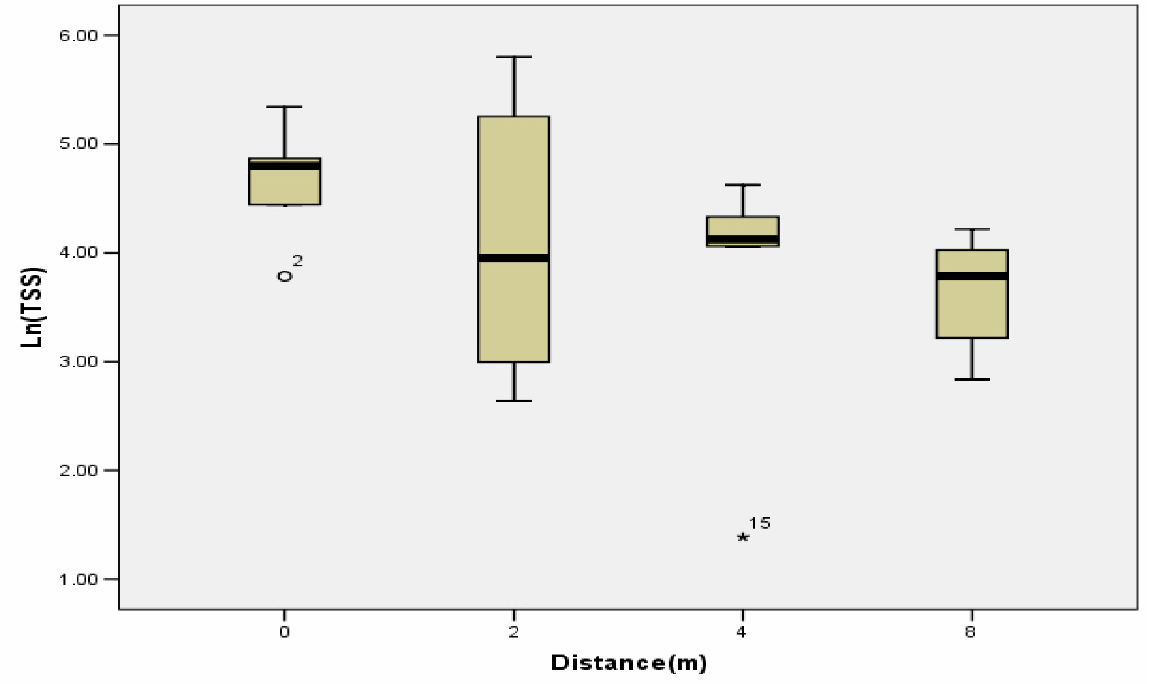


FIGURE B-1 Boxplot of TSS at Site 1, Traditional Pavement

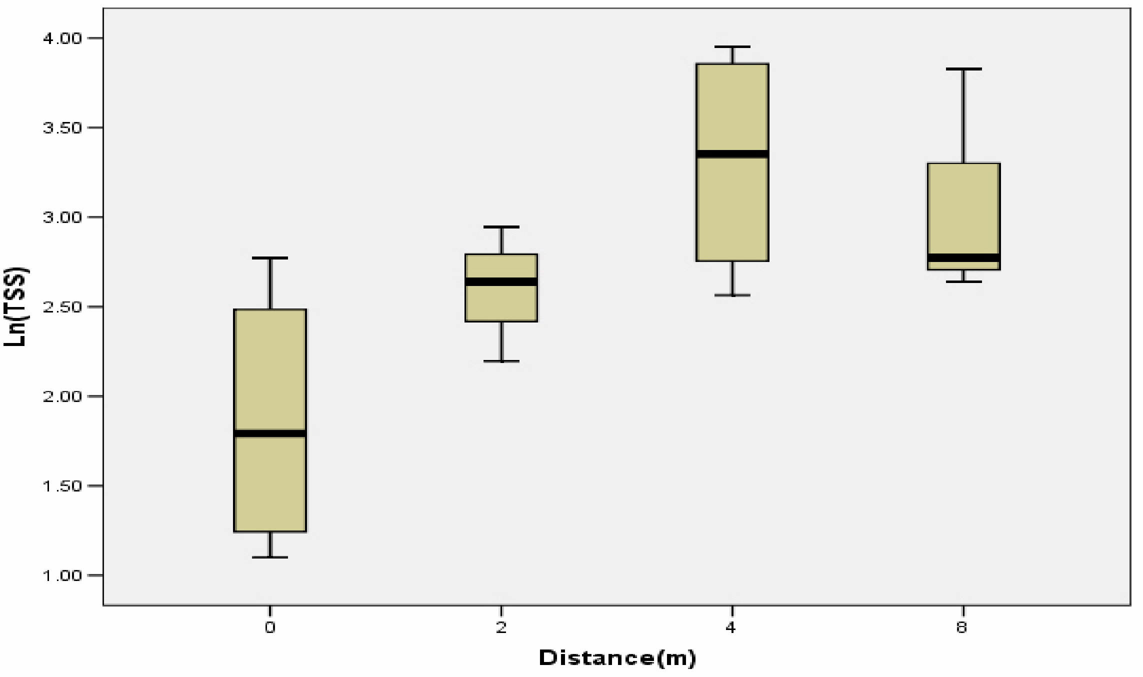


FIGURE B-2 Boxplot of TSS at Site 1, Porous Pavement

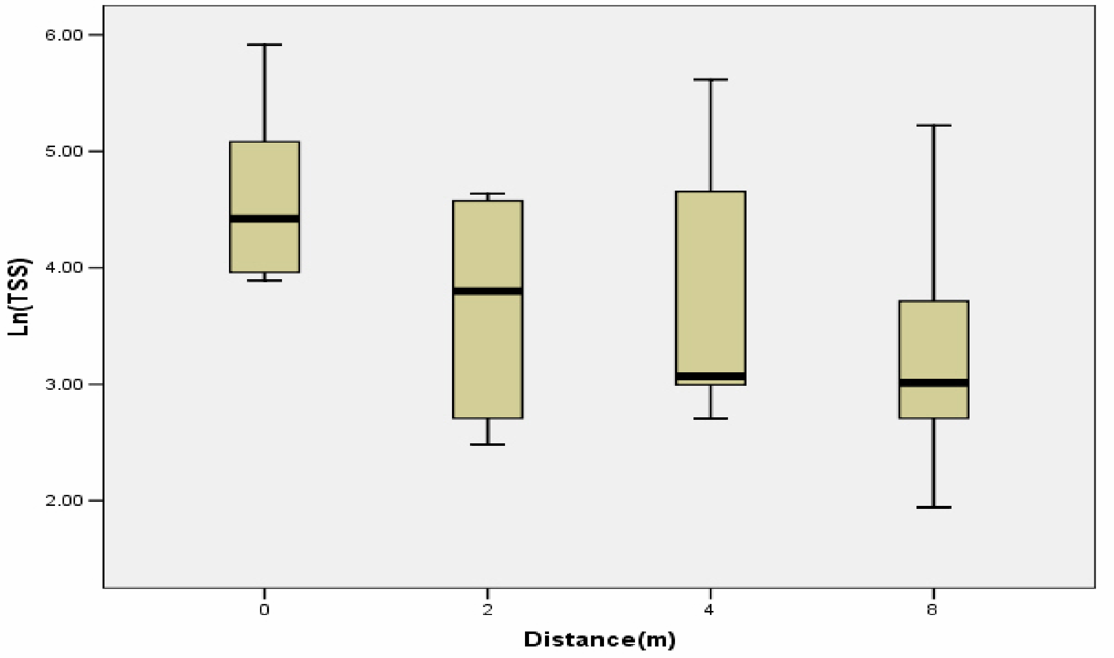


FIGURE B-3 Boxplot of TSS at Site 2

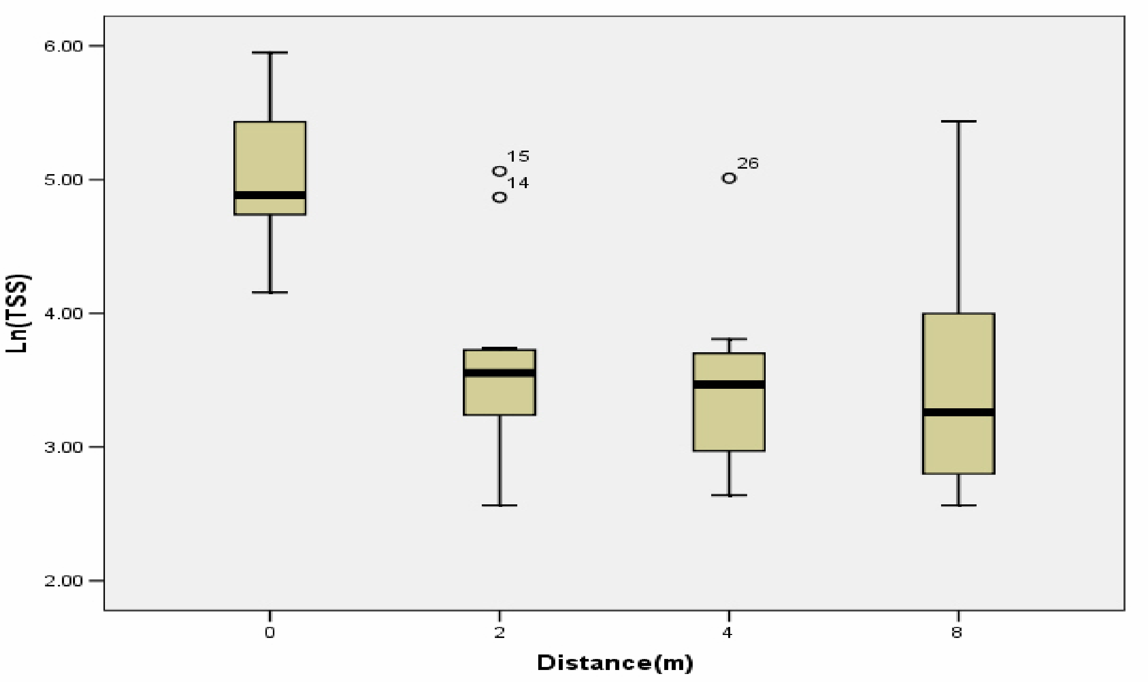


FIGURE B-4 Boxplot of TSS at Site 3

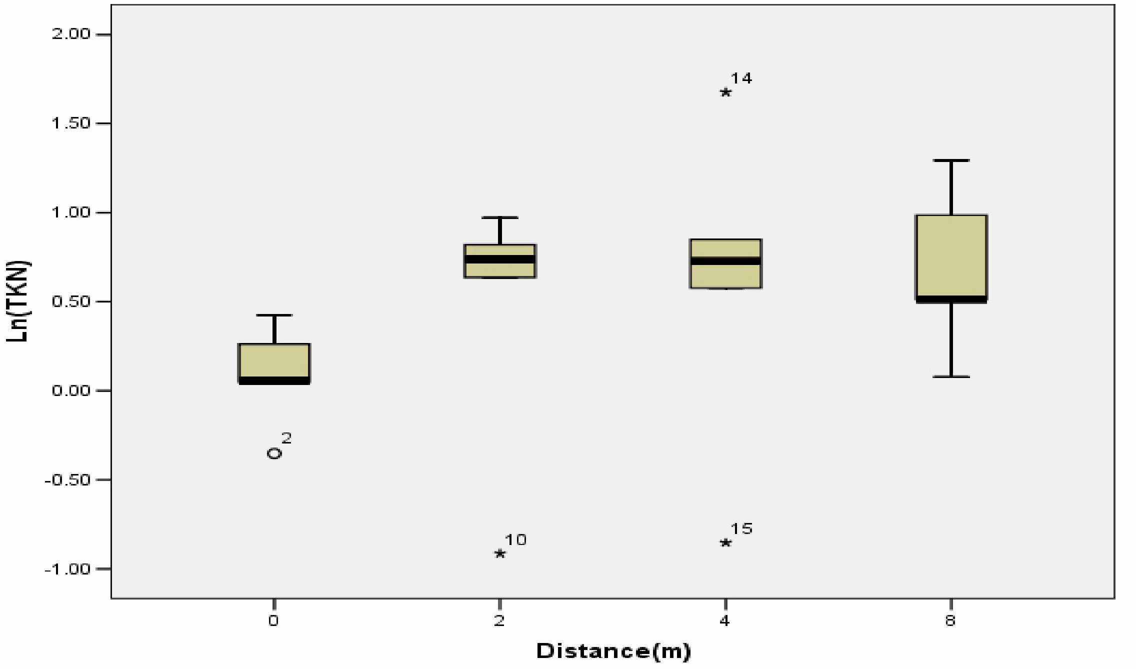


FIGURE B-5 Boxplot of TKN at Site 1, Traditional Pavement

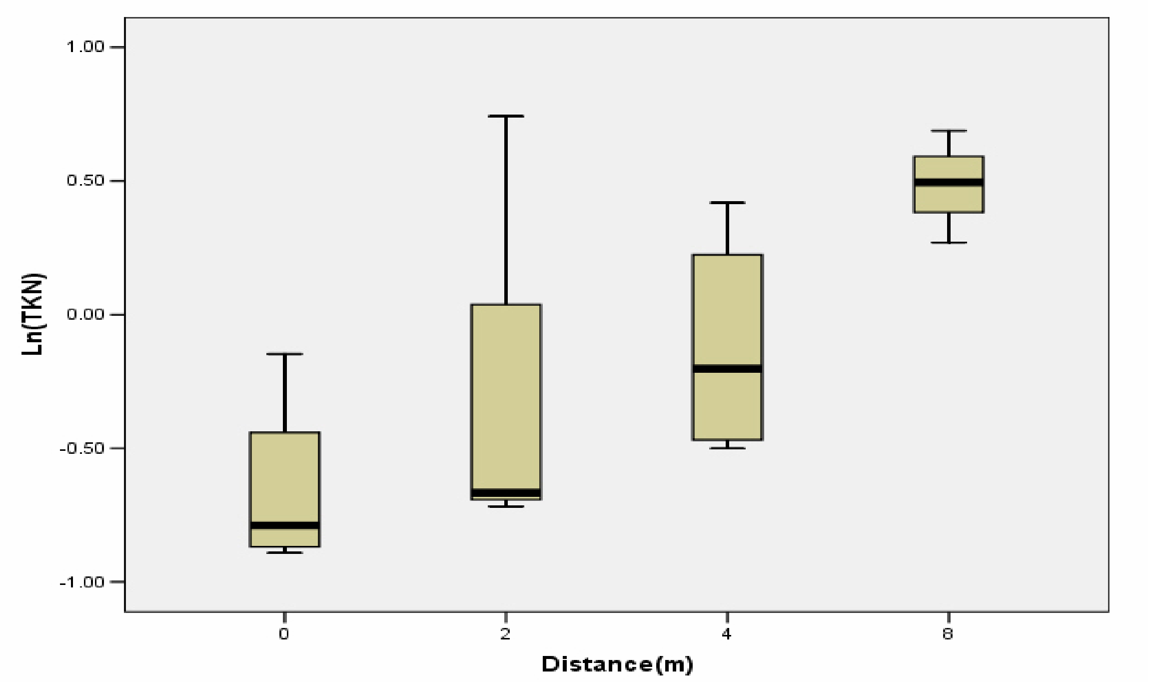


FIGURE B-6 Boxplot of TKN at Site 1, Porous Pavement

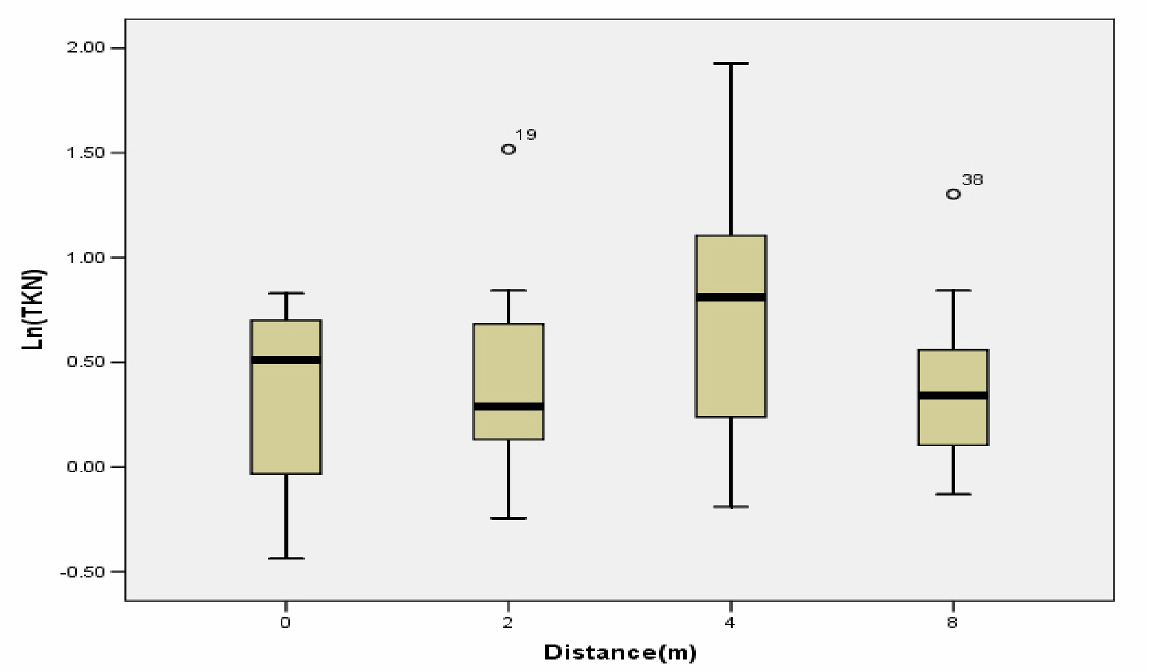


FIGURE B-7 Boxplot of TKN at Site 2

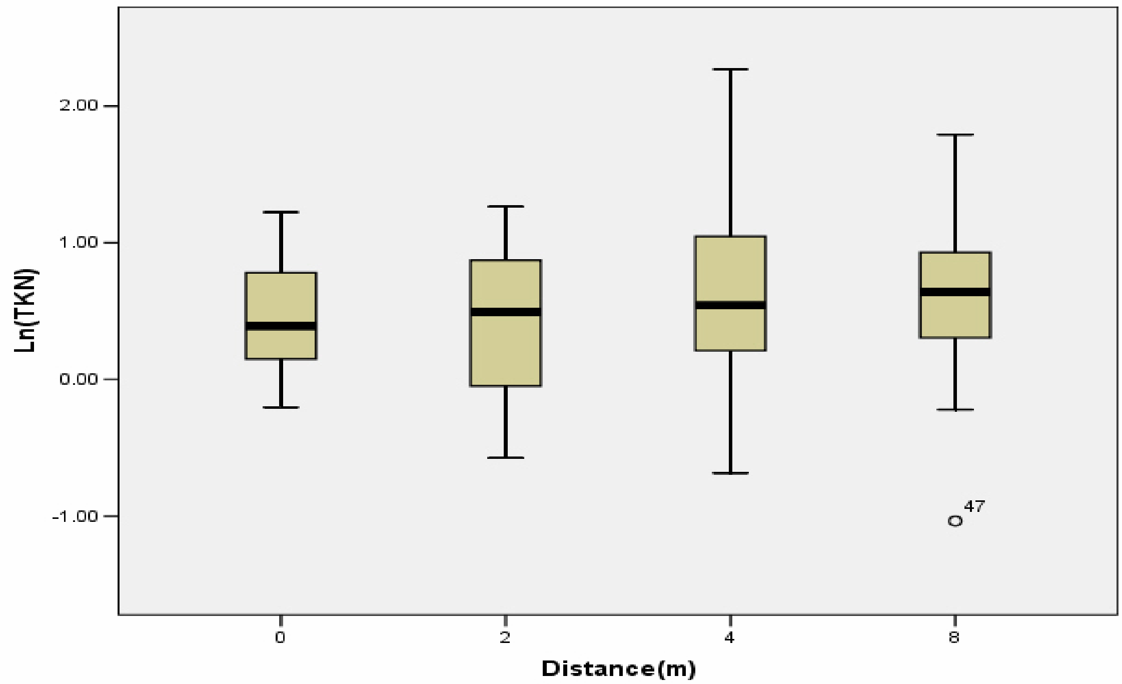


FIGURE B-8 Boxplot of TKN at Site 3

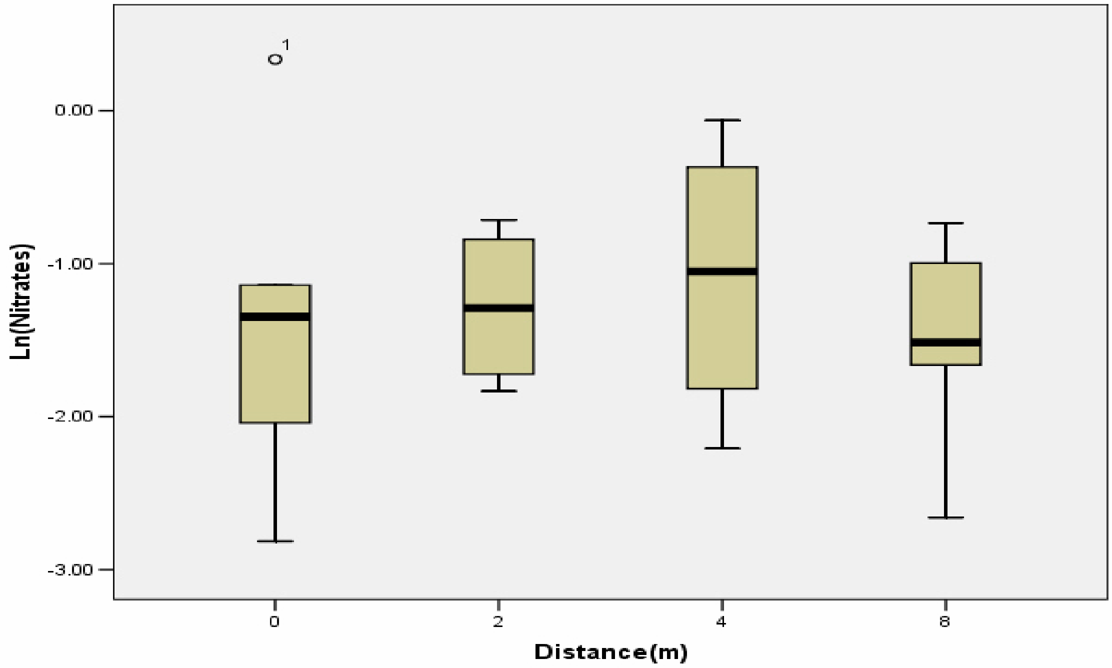


FIGURE B-9 Boxplot of Nitrate/Nitrite at Site 1, Traditional Pavement

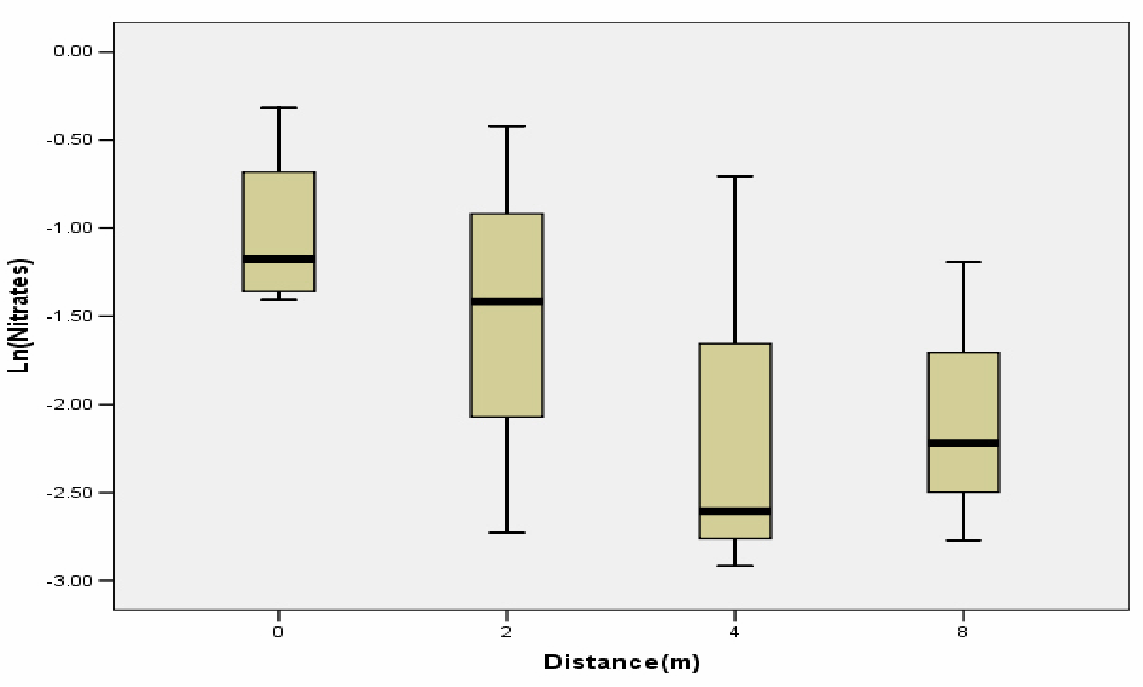


FIGURE B-10 Boxplot of Nitrate/Nitrite at Site 1, Porous Pavement

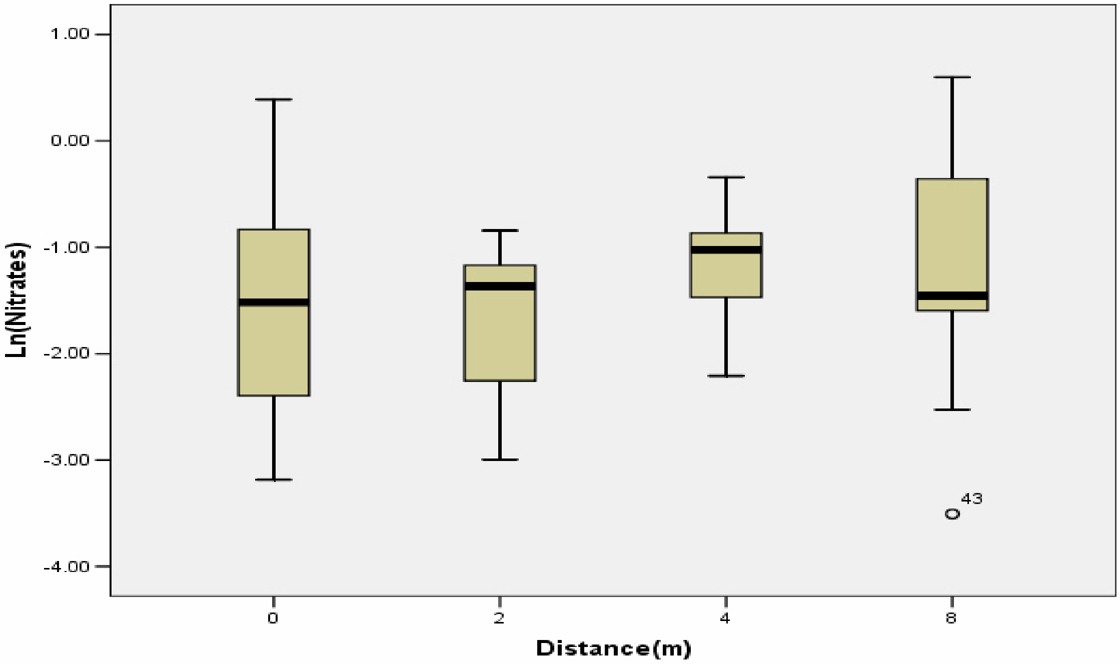


FIGURE B-11 Boxplot of Nitrate/Nitrite at Site 2

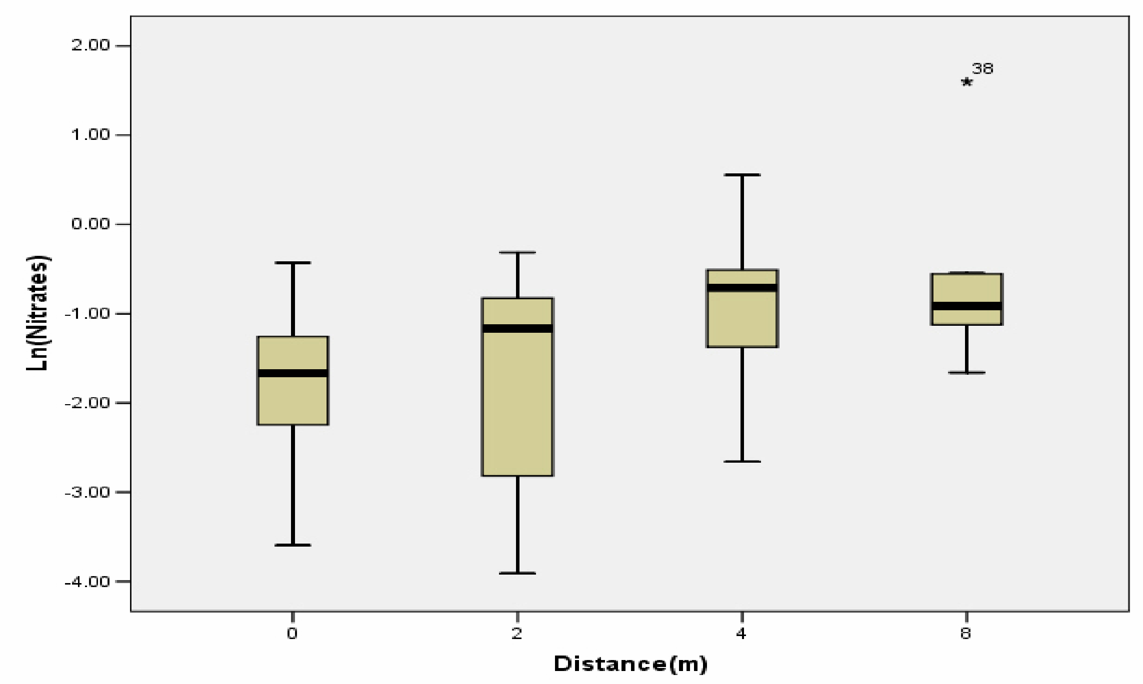


FIGURE B-12 Boxplot of Nitrate/Nitrite at Site 3

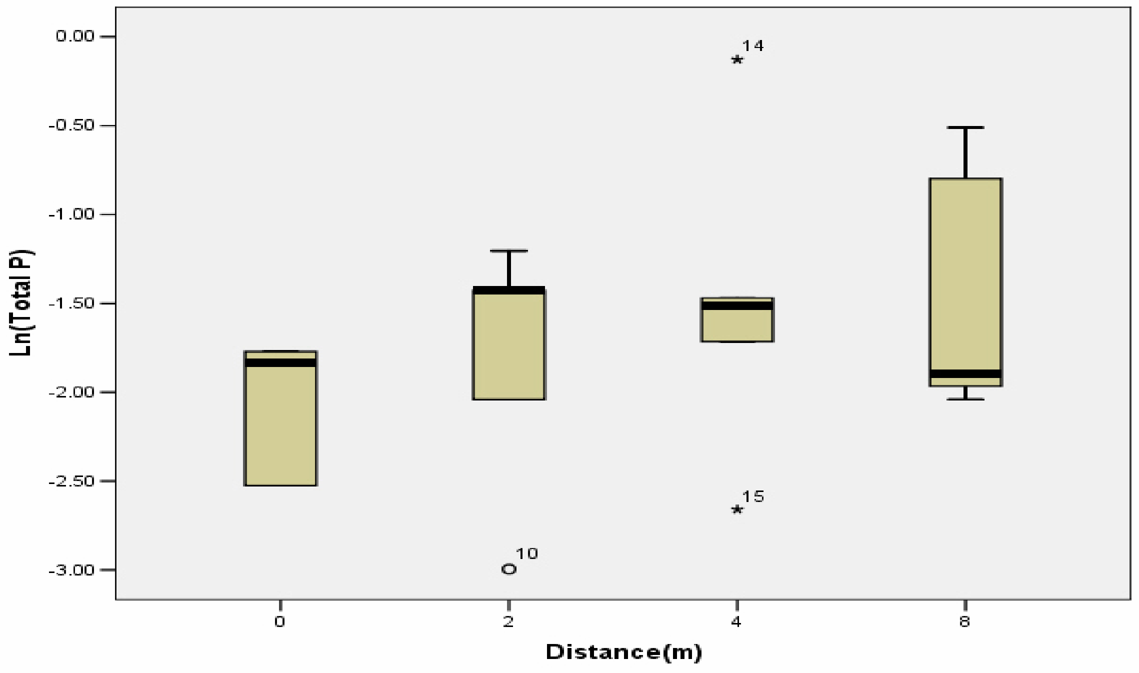


FIGURE B-13 Boxplot of Total P at Site 1, Traditional Pavement

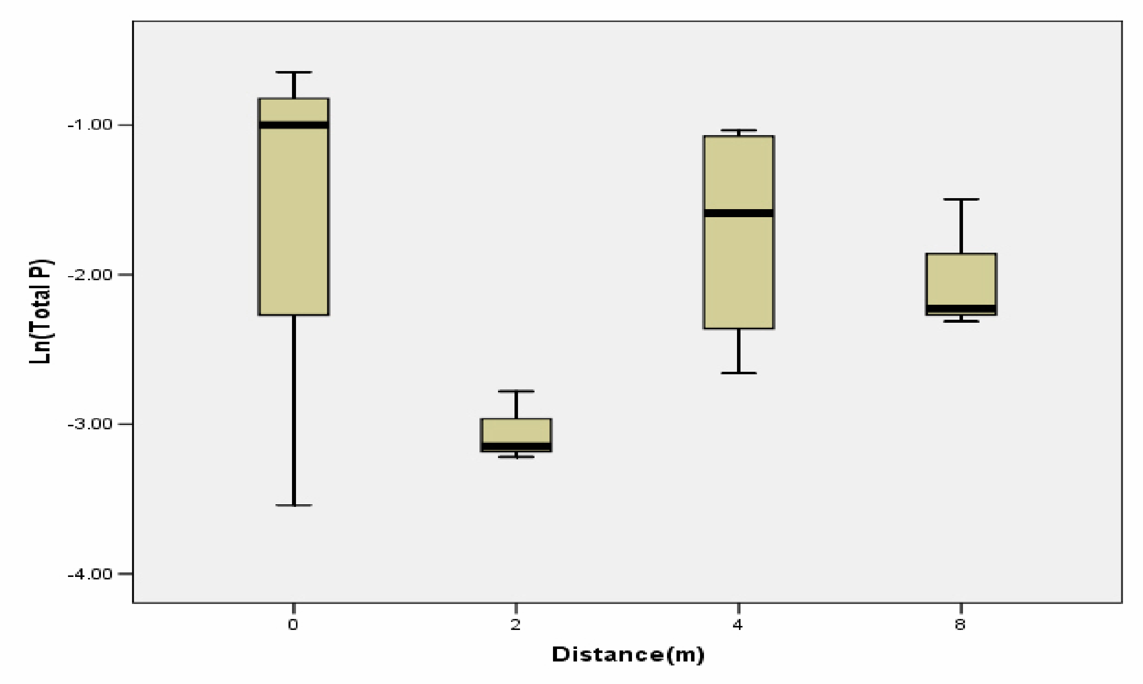


FIGURE B-14 Boxplot of Total P at Site 1, Porous Pavement

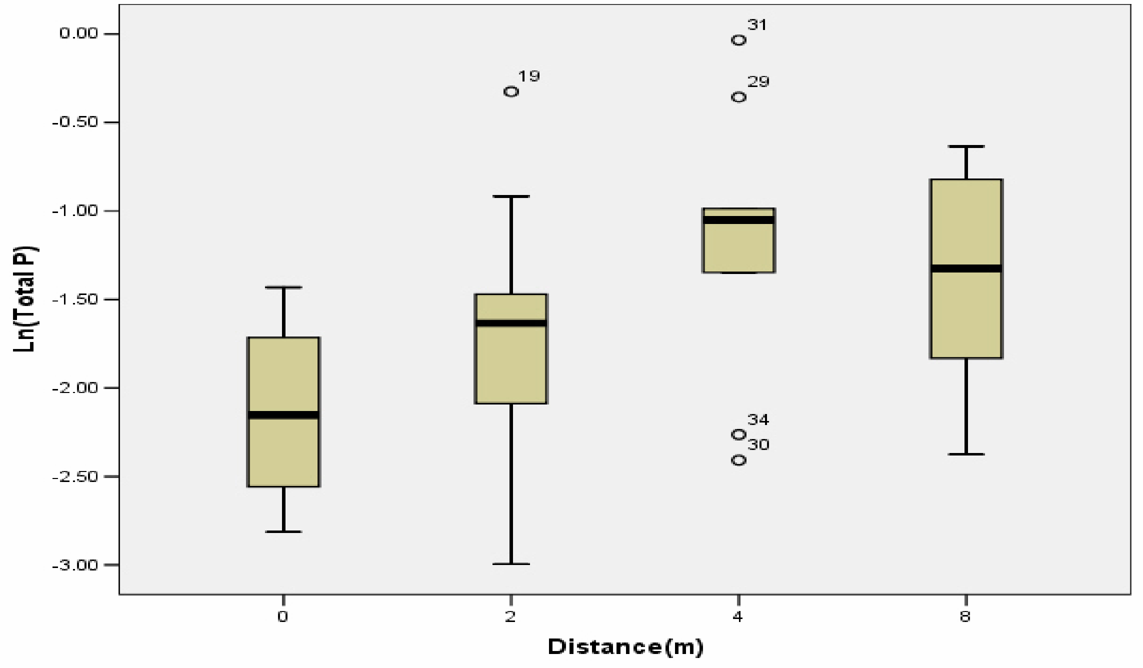


FIGURE B-15 Boxplot of Total P at Site 2

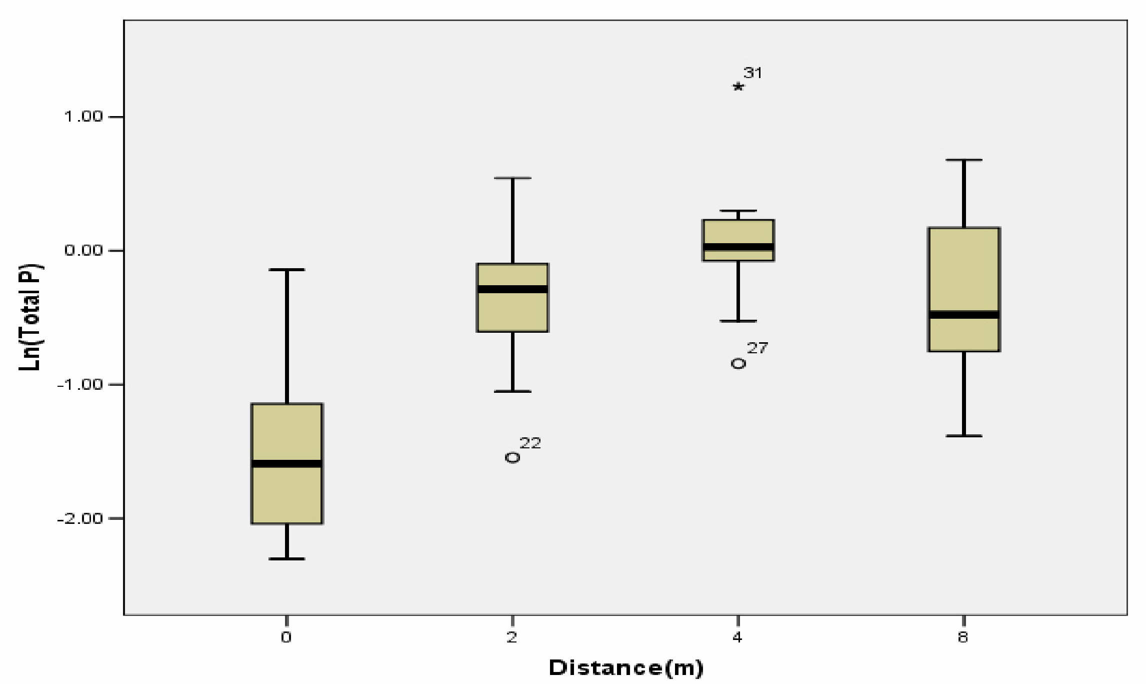


FIGURE B-16 Boxplot of Total P at Site 3

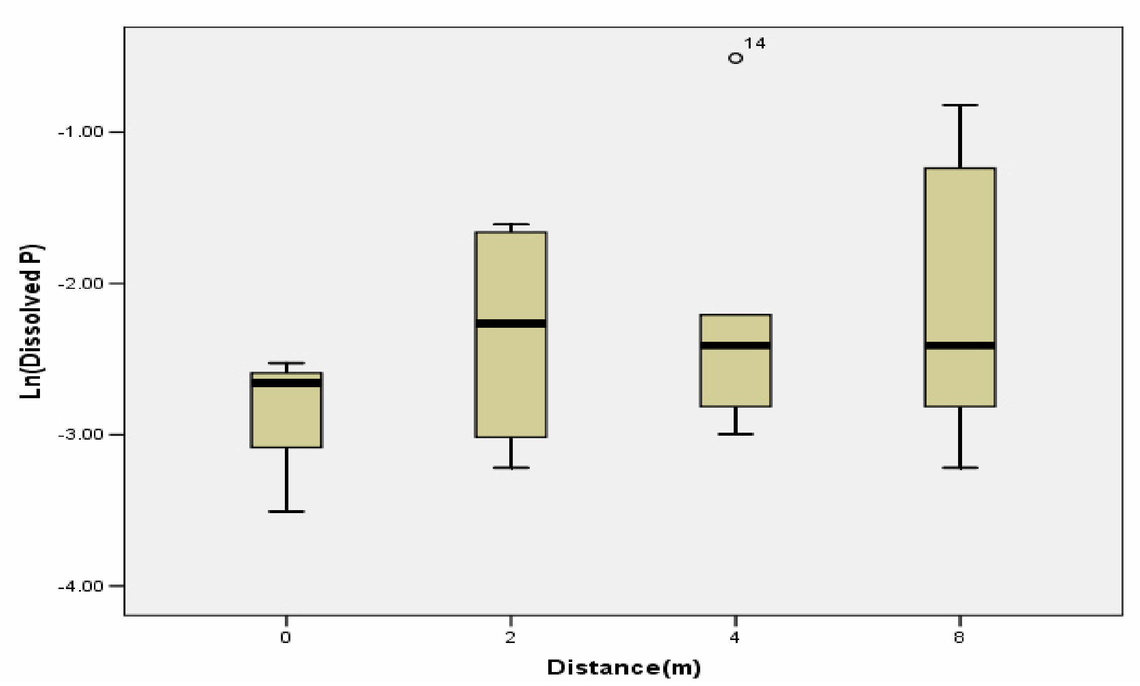


FIGURE B-17 Boxplot of Dissolved P at Site 1, Traditional Pavement

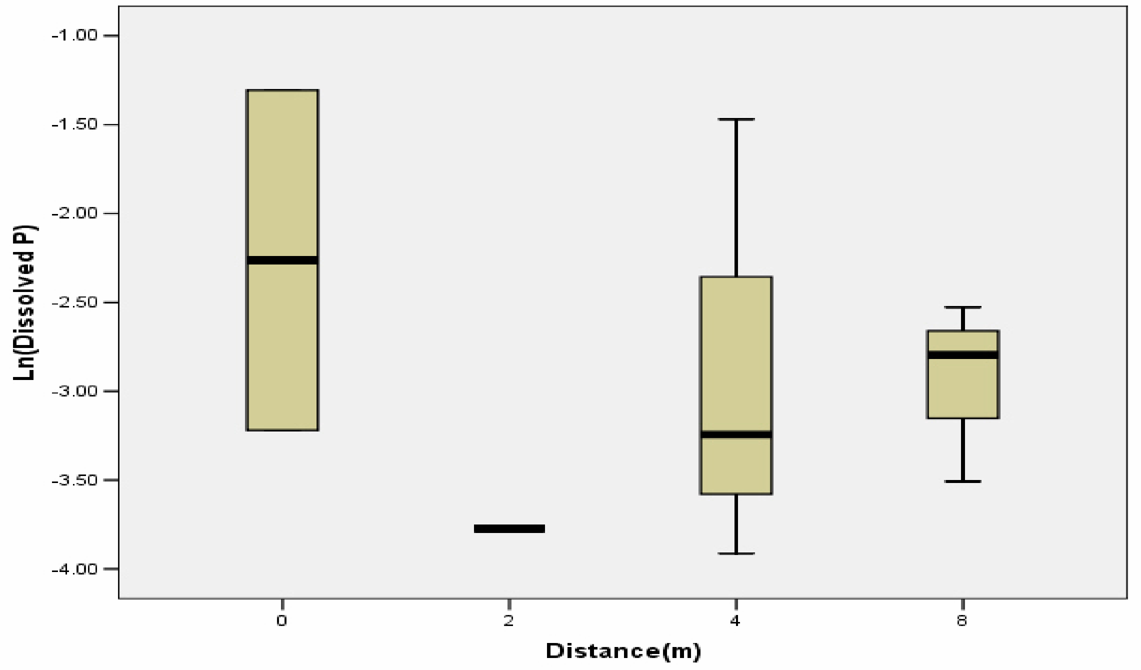


FIGURE B-18 Boxplot of Dissolved P at Site 1, Porous Pavement

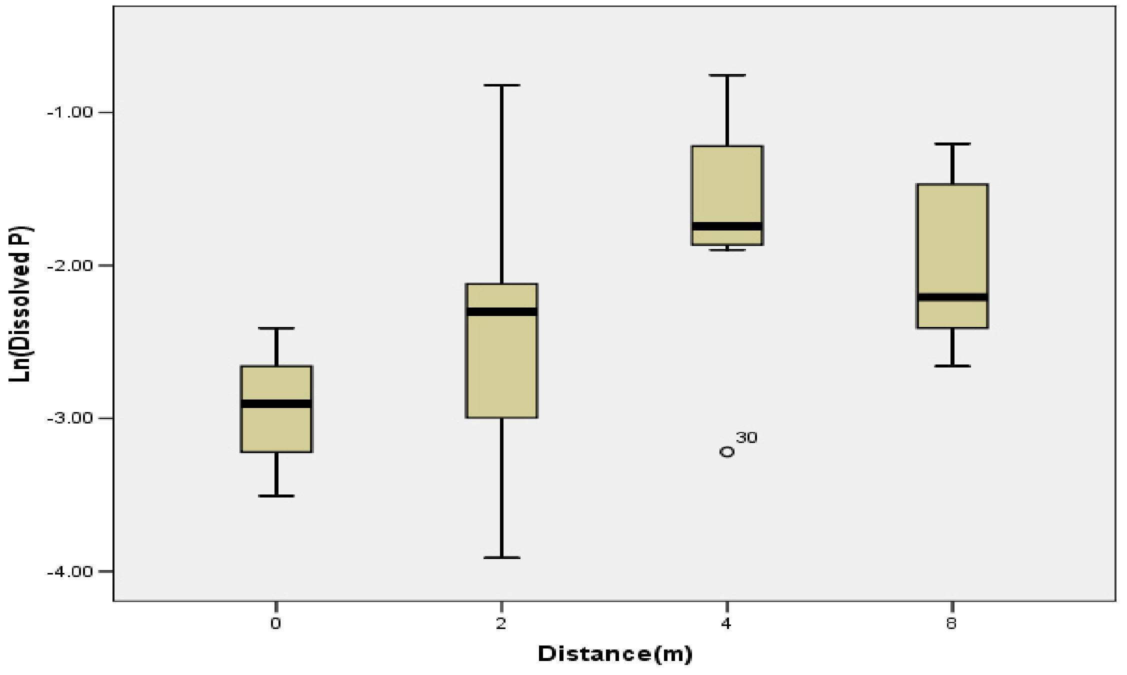


FIGURE B-19 Boxplot of Dissolved P at Site 2

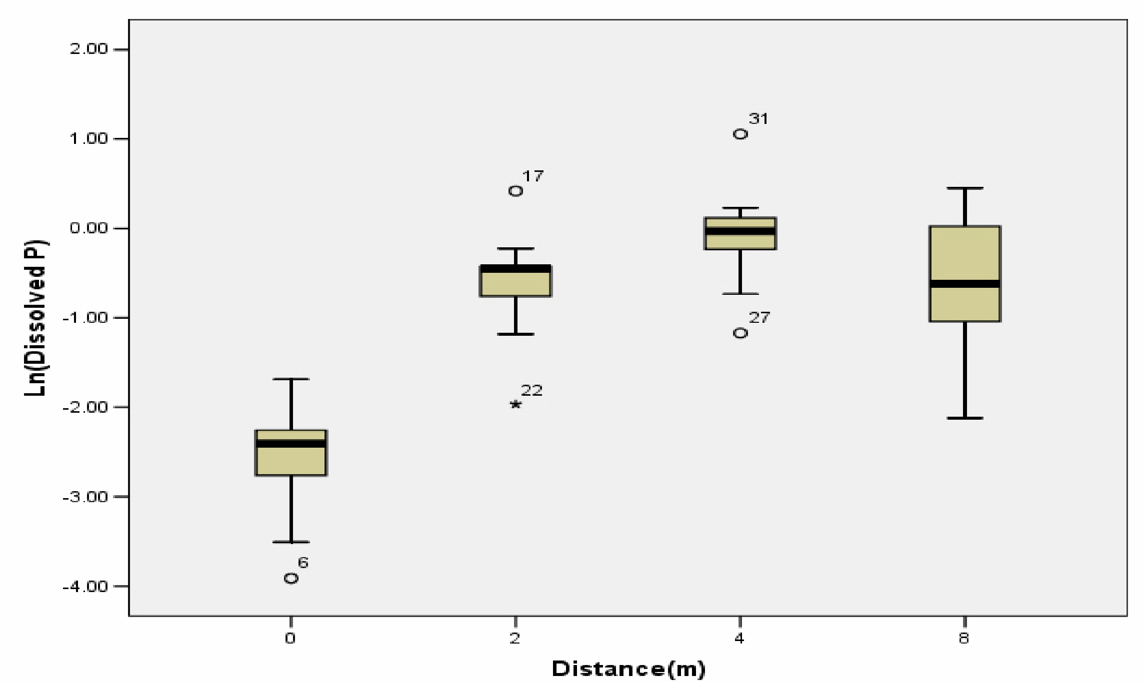


FIGURE B-20 Boxplot of Dissolved P at Site 3

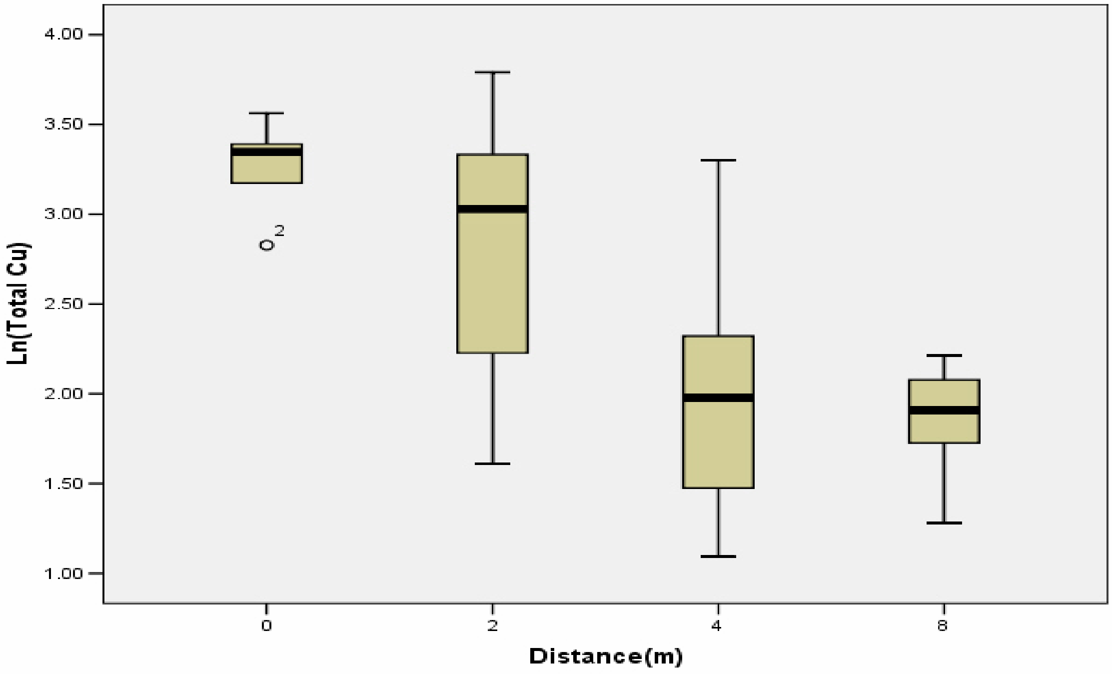


FIGURE B-21 Boxplot of Total Cu at Site 1, Traditional Pavement

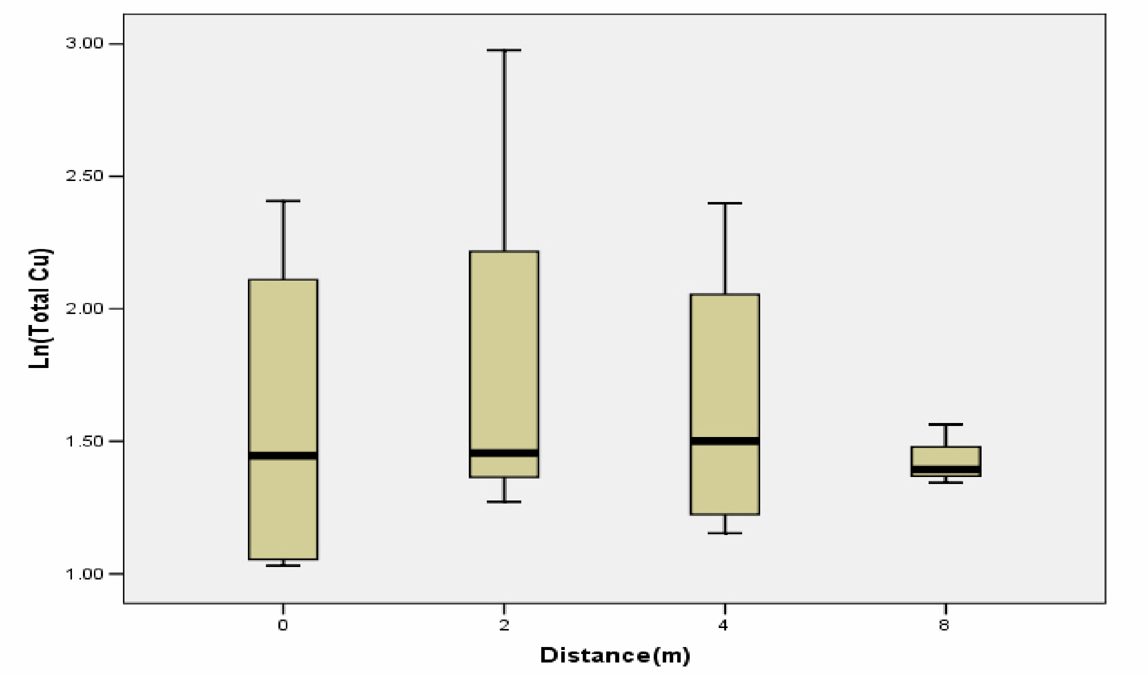


FIGURE B-22 Boxplot of Total Cu at Site 1, Porous Pavement

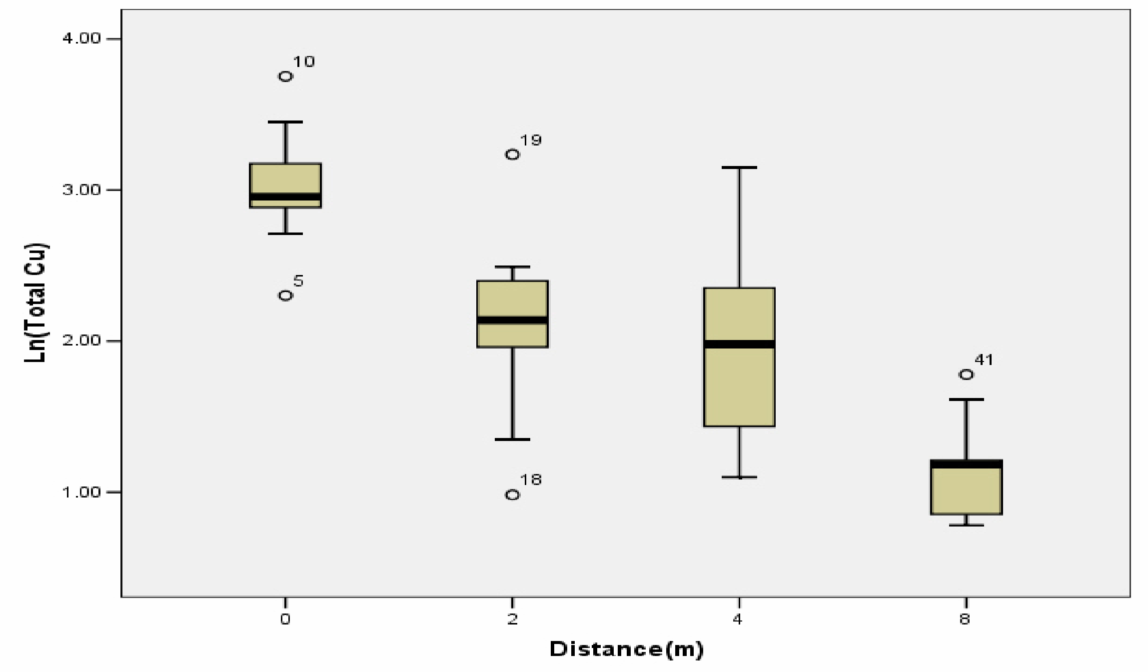


FIGURE B-23 Boxplot of Total Cu at Site 2

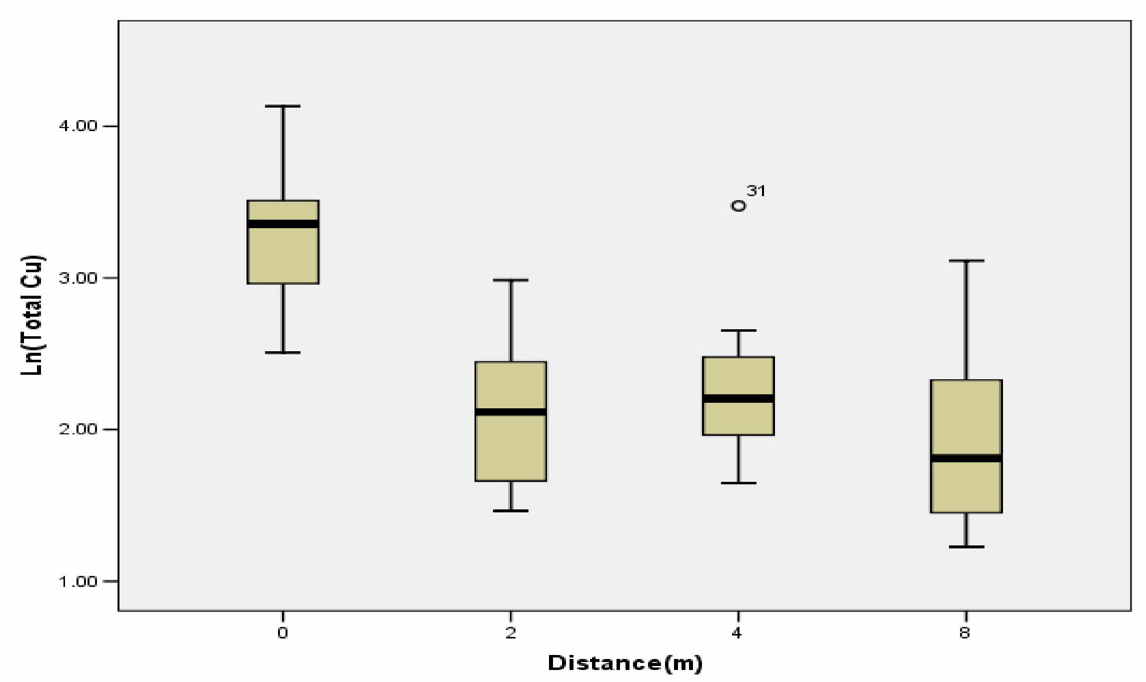


FIGURE B-24 Boxplot of Total Cu at Site 3

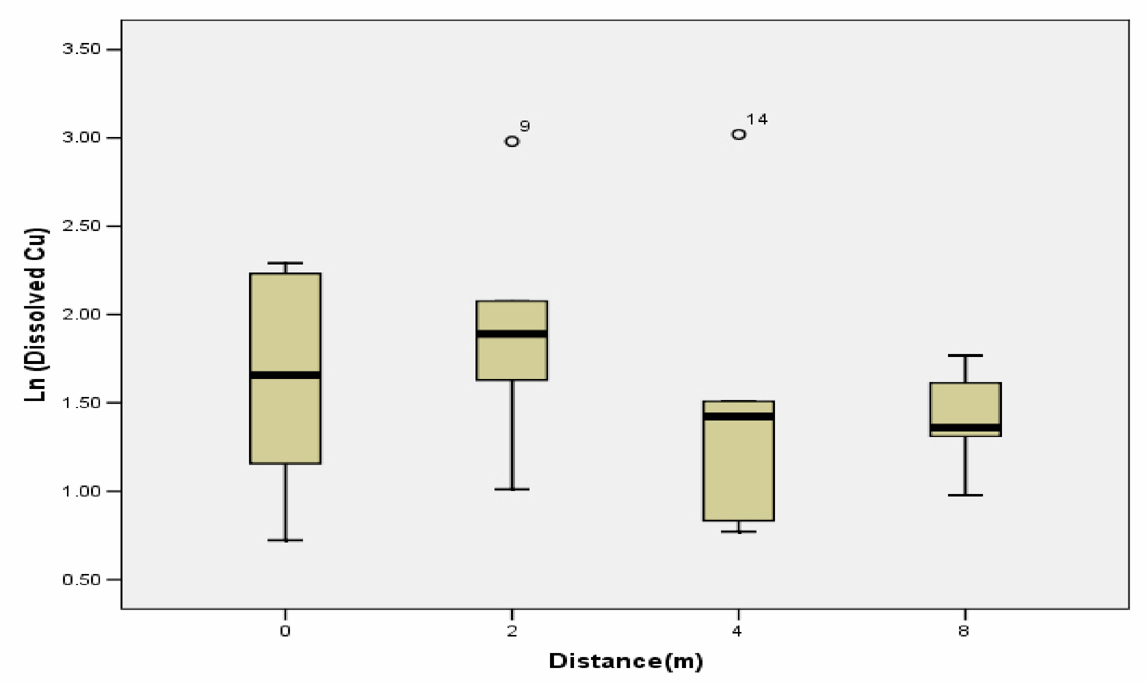


FIGURE B-25 Boxplot of Dissolved Cu at Site 1, Traditional Pavement

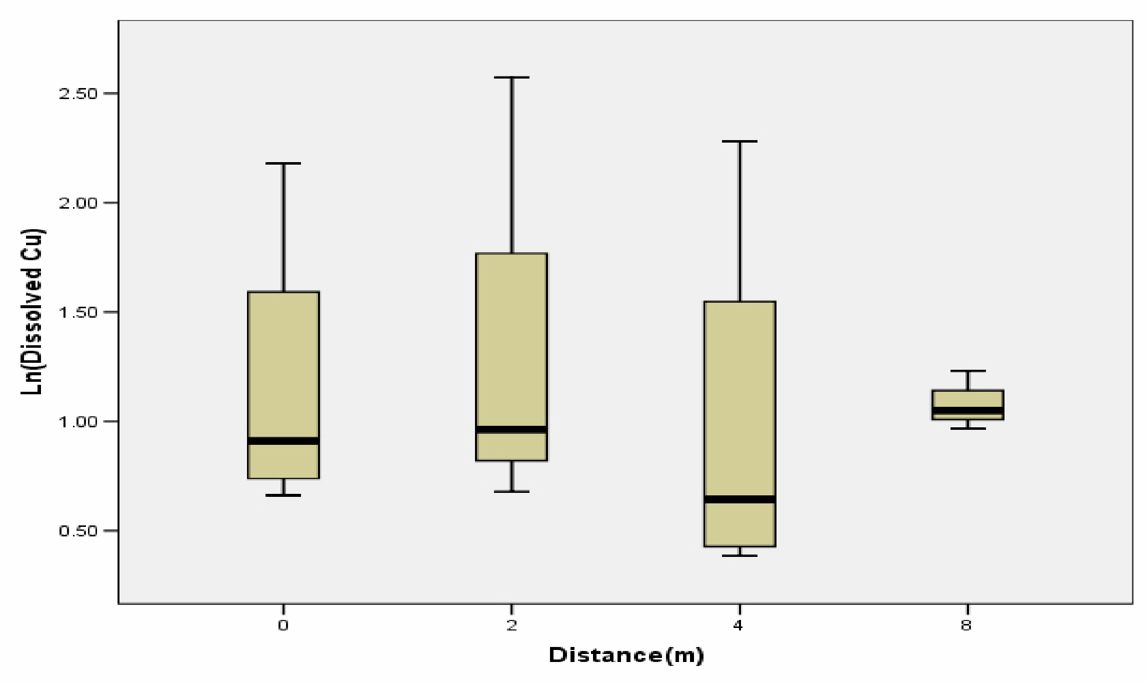


FIGURE B-26 Boxplot of Dissolved Cu at Site 1, Porous Pavement

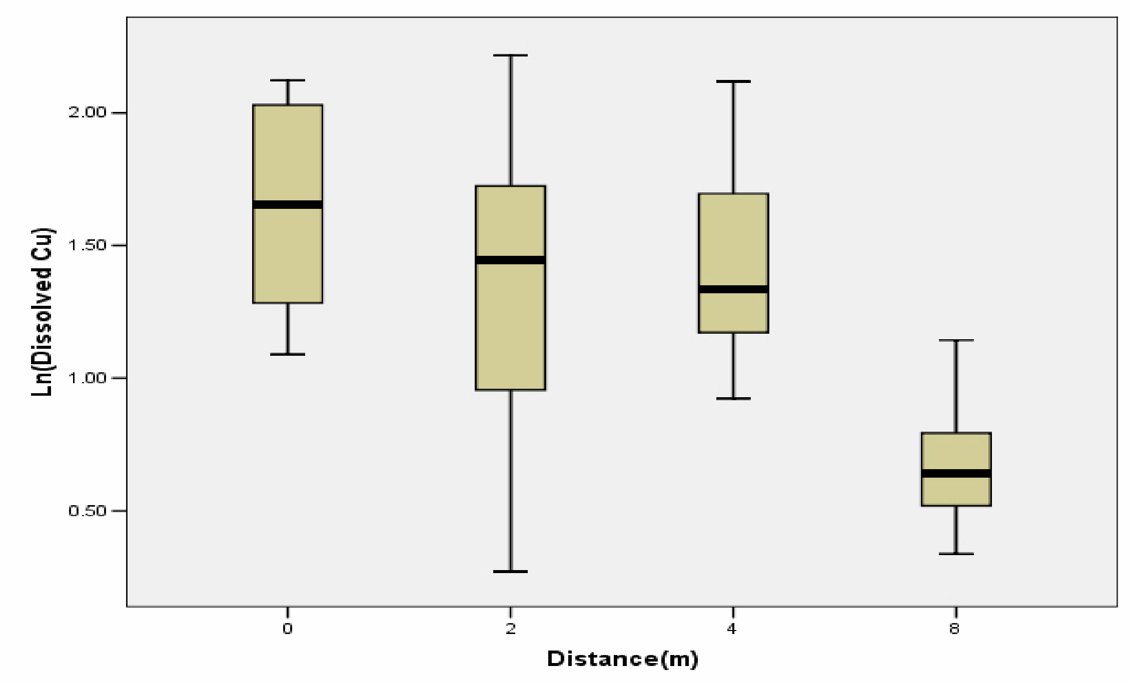


FIGURE B-27 Boxplot of Dissolved Cu at Site 2

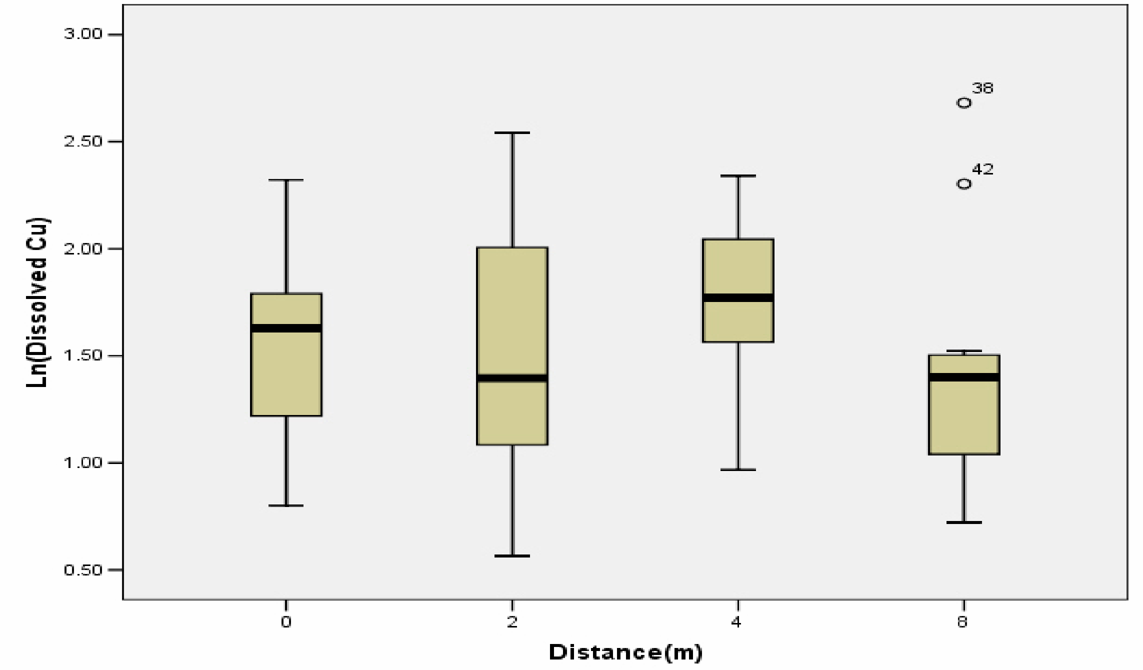


FIGURE B-28 Boxplot of Dissolved Cu at Site 3

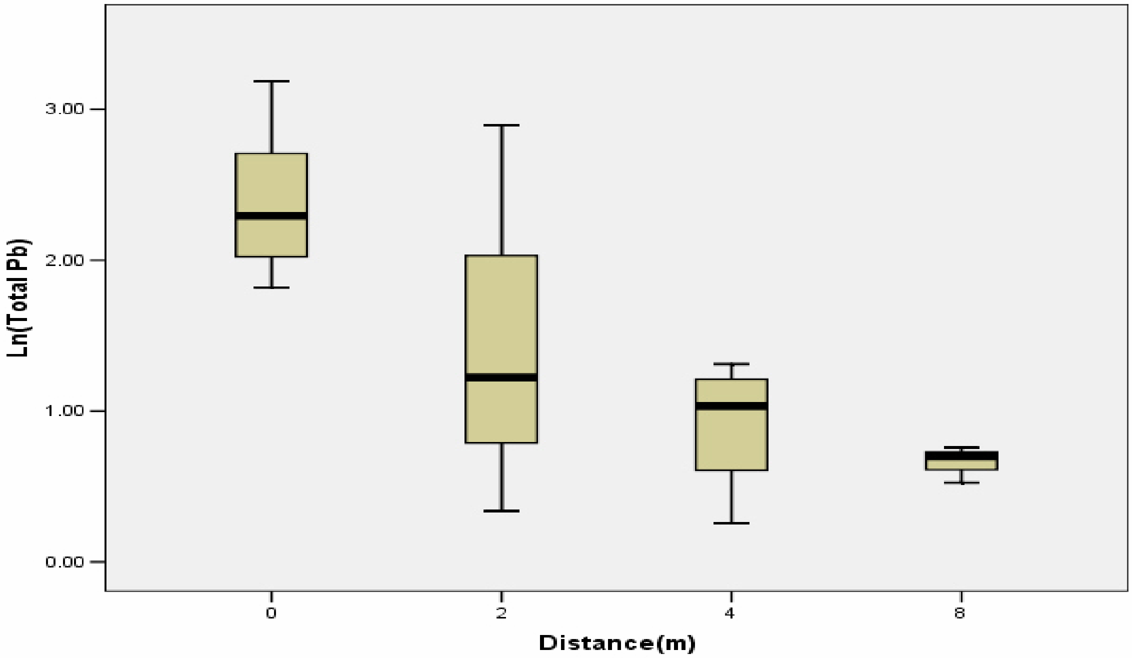


FIGURE B-29 Boxplot of Total Pb at Site 1, Traditional Pavement

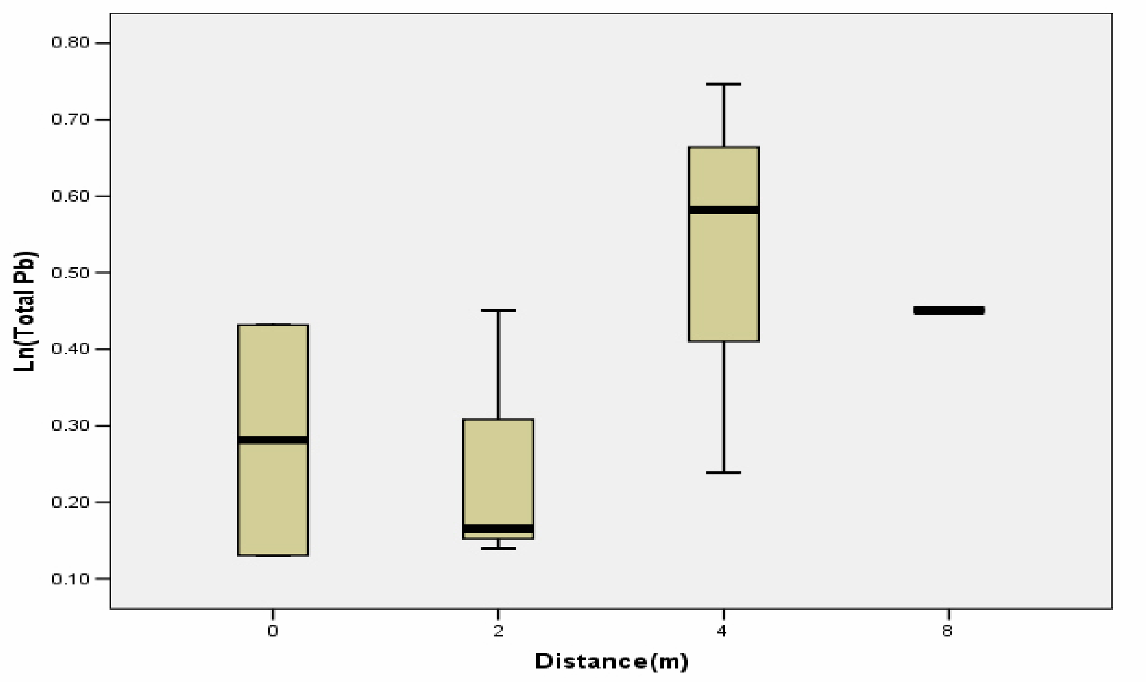


FIGURE B-30 Boxplot of Total Pb at Site 1, Porous Pavement

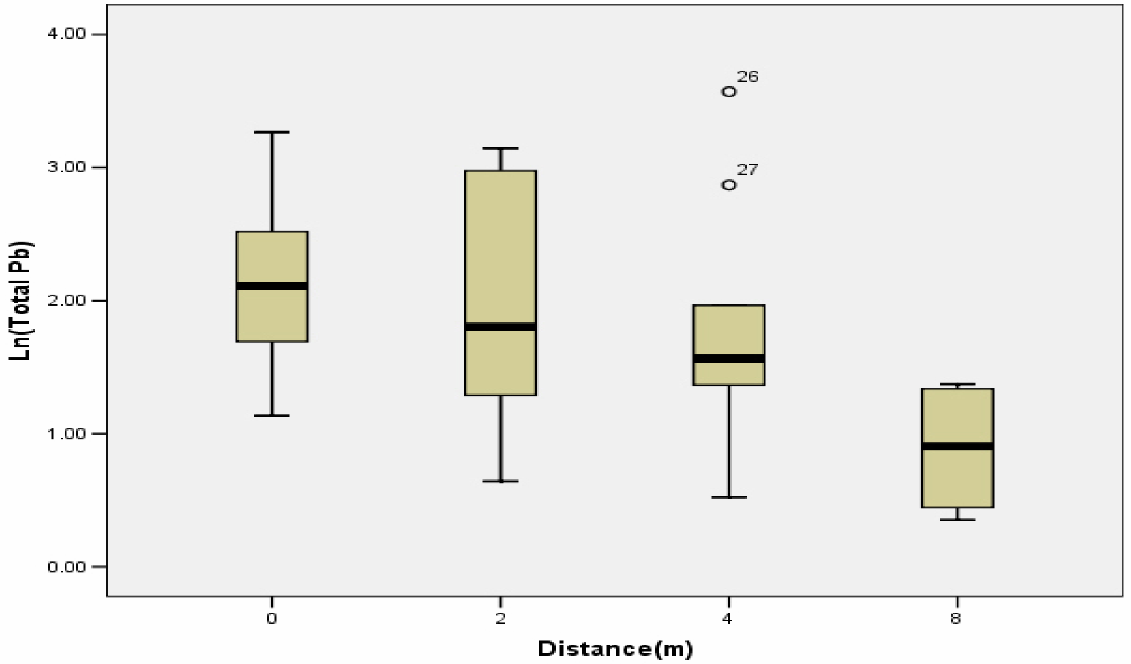


FIGURE B-31 Boxplot of Total Pb at Site 2

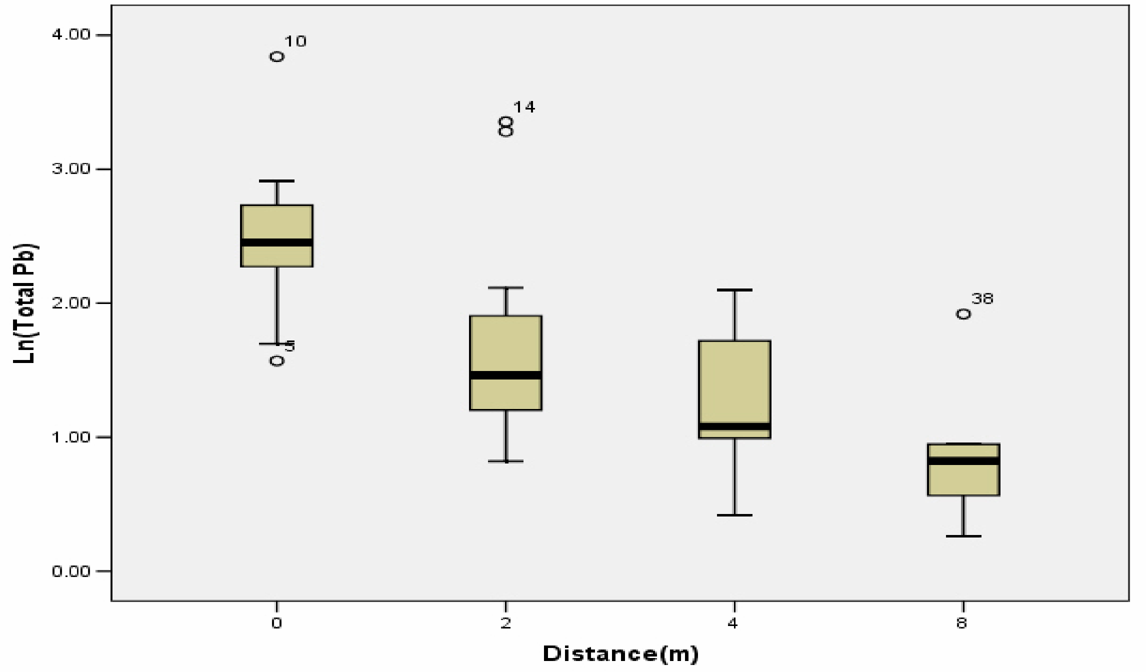


FIGURE B-32 Boxplot of Total Pb at Site 3

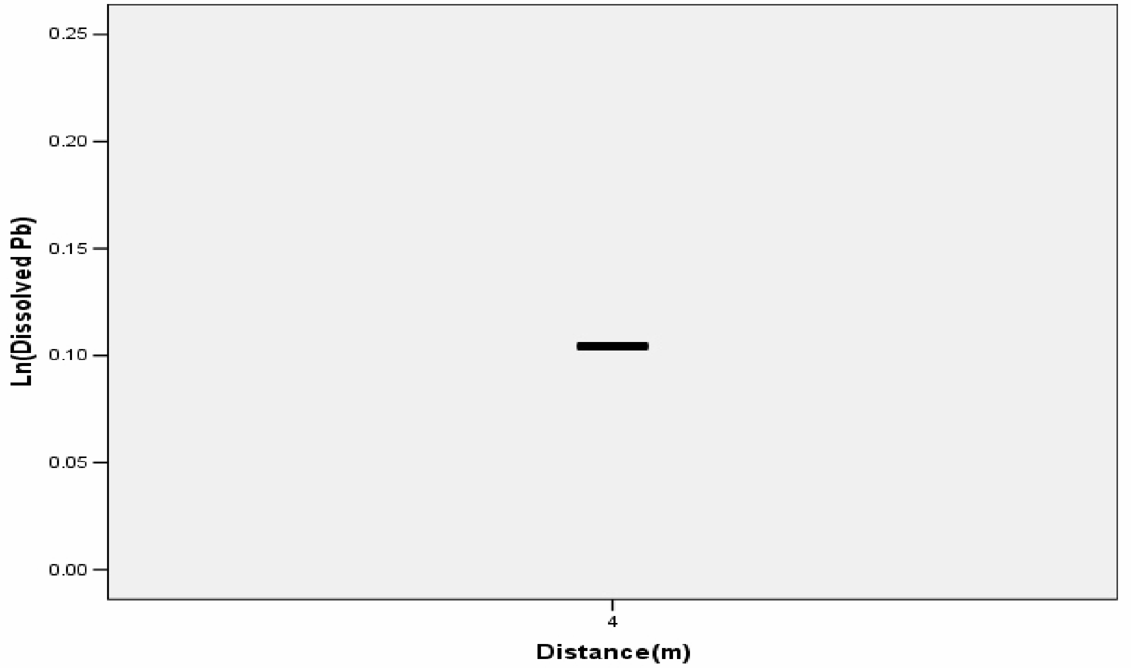


FIGURE B-33 Boxplot of Dissolved Pb at Site 1, Traditional Pavement

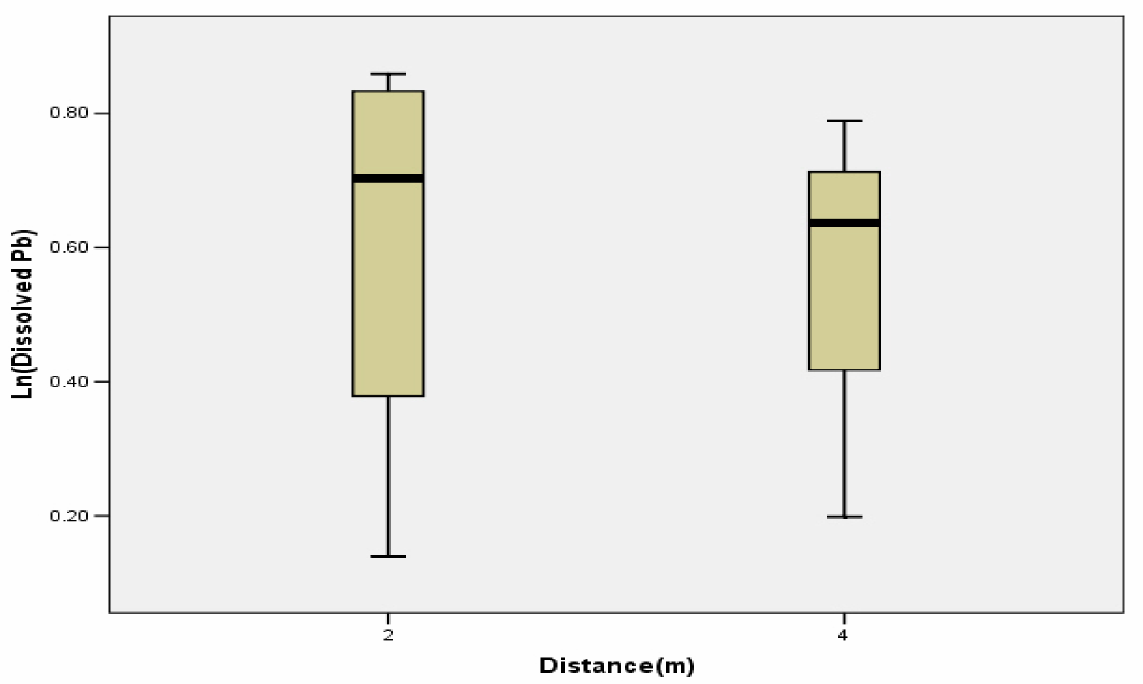


FIGURE B-34 Boxplot of Dissolved Pb at Site 2

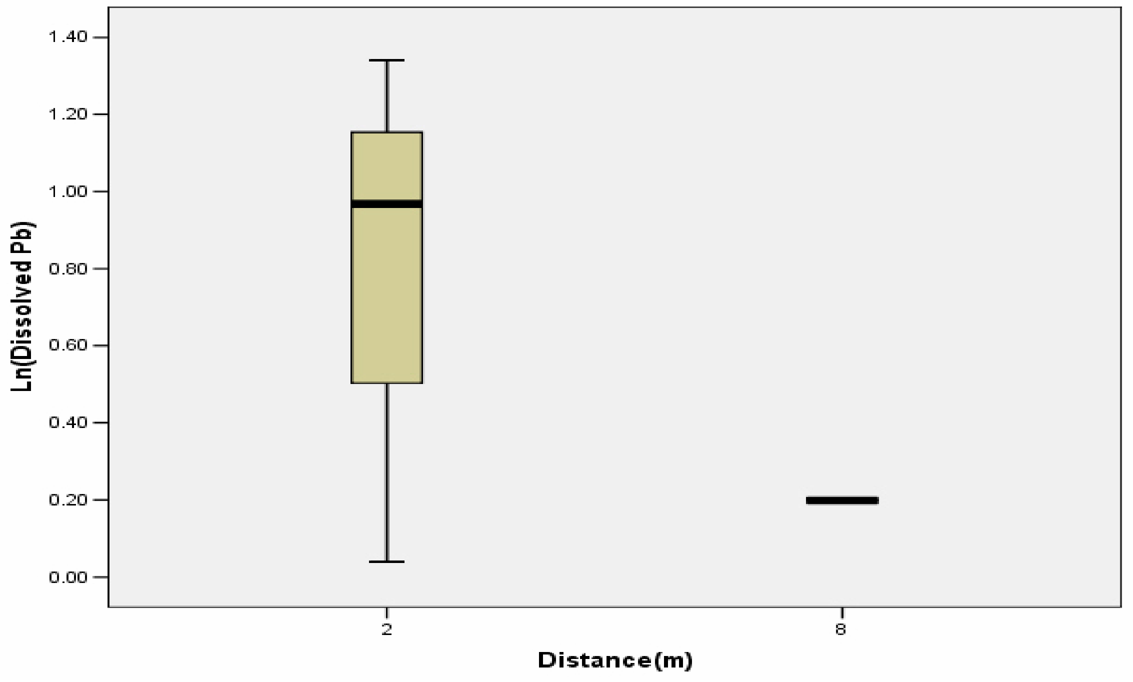


FIGURE B-35 Boxplot of Dissolved Pb at Site 3

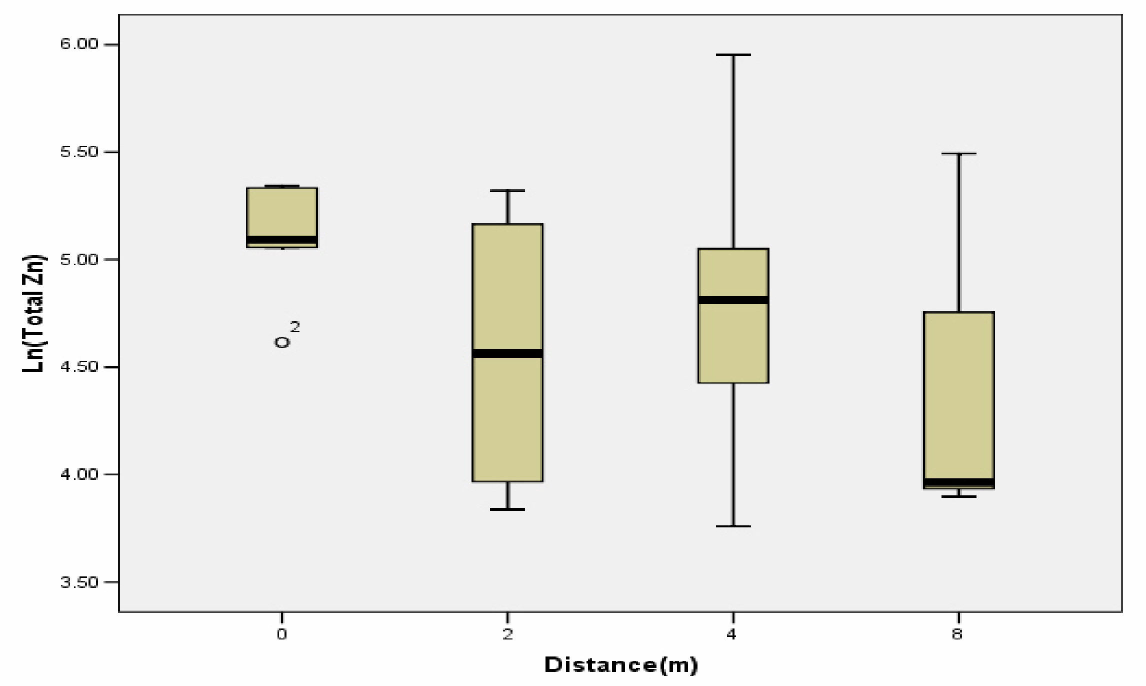


FIGURE B-36 Boxplot of Total Zn at Site 1, Traditional Pavement

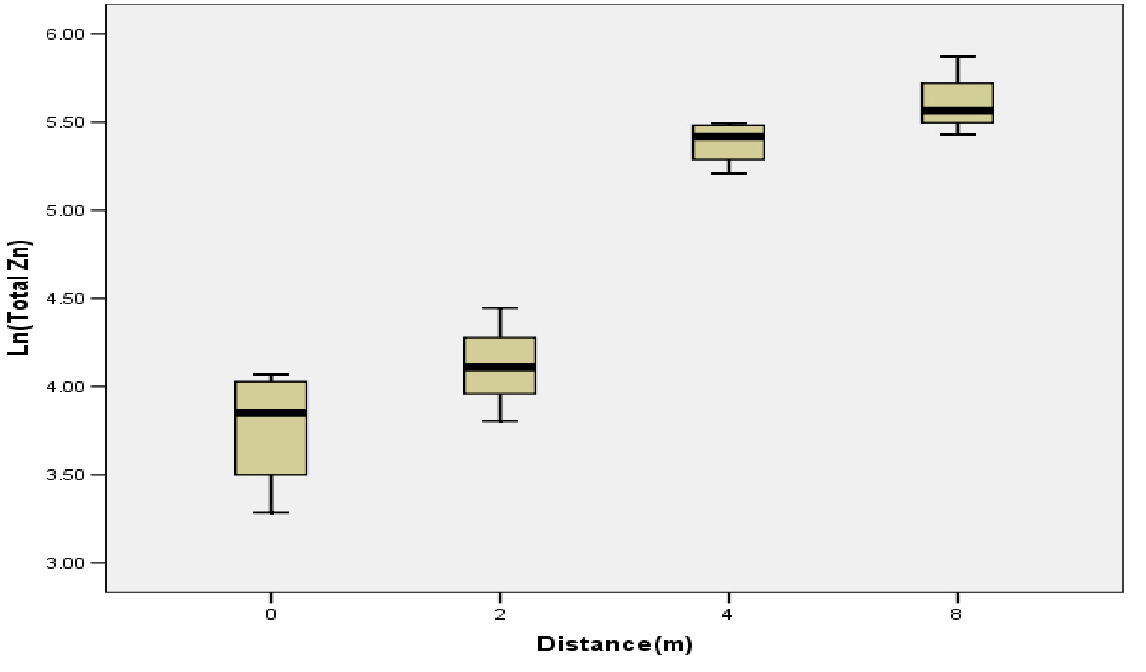


FIGURE B-37 Boxplot of Total Zn at Site 1, Porous Pavement

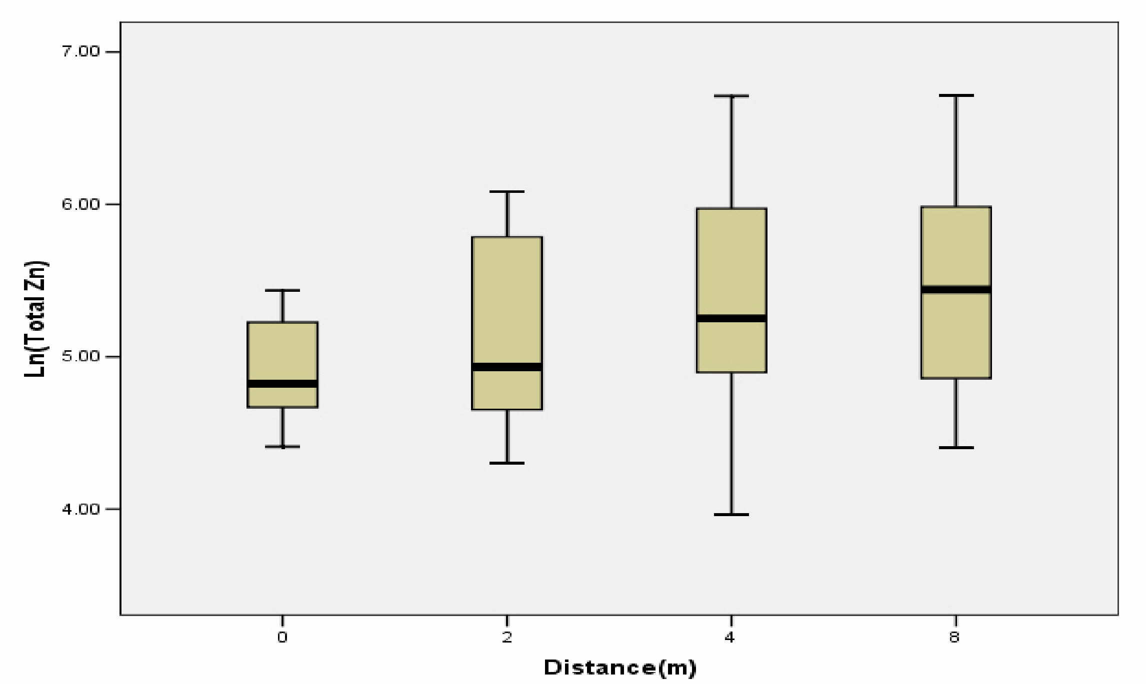


FIGURE B-38 Boxplot of Total Zn at Site 2

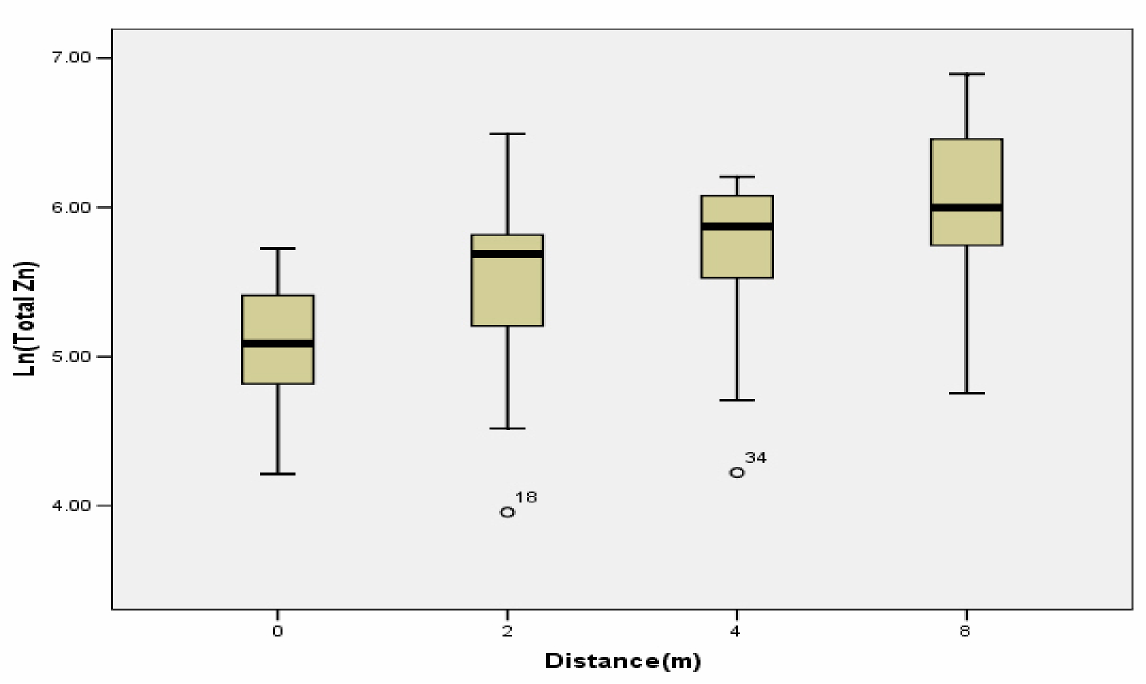


FIGURE B-39 Boxplot of Total Zn at Site 3

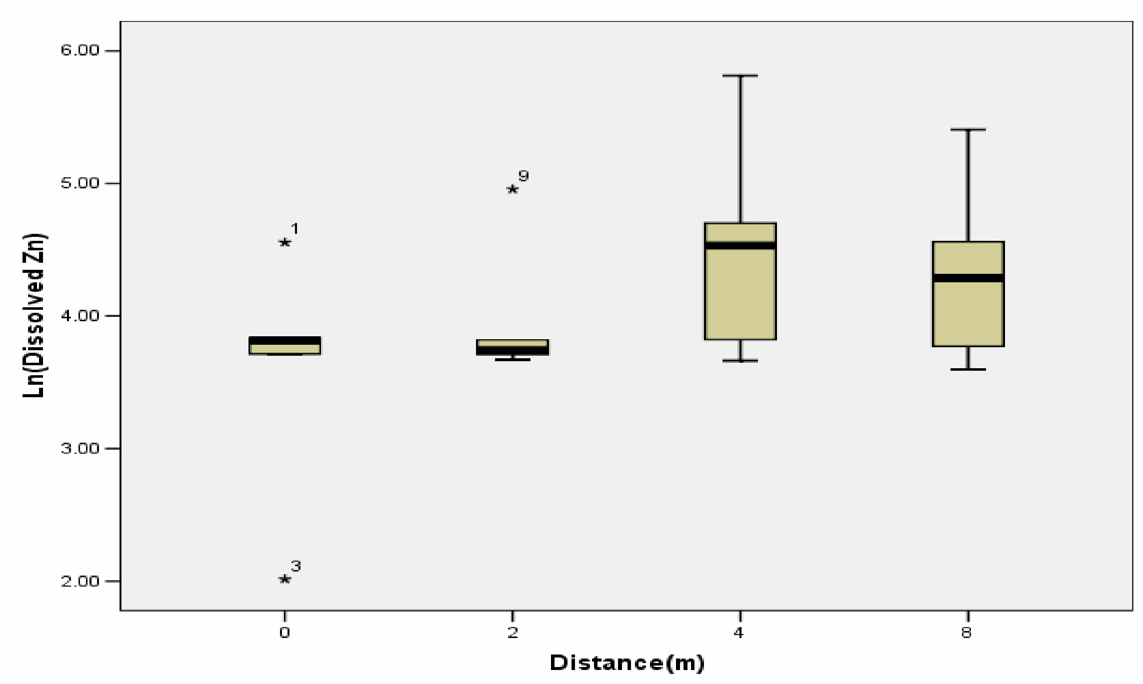


FIGURE B-40 Boxplot of Dissolved Zn at Site 1, Traditional Pavement

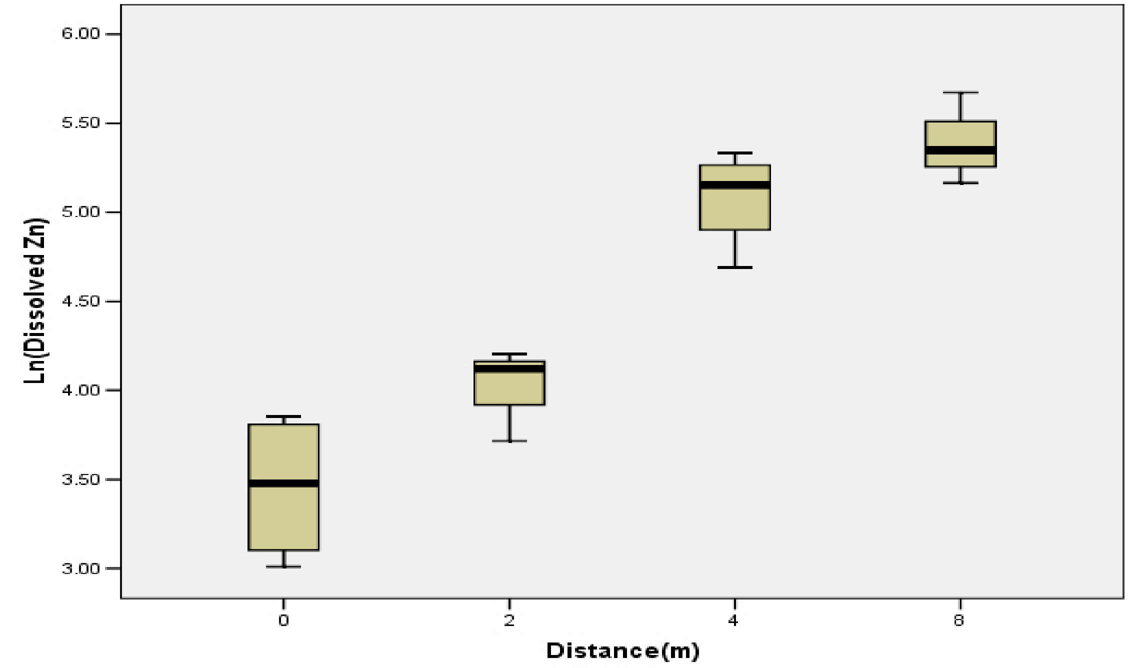


FIGURE B-41 Boxplot of Dissolved Zn at Site 1, Porous Pavement

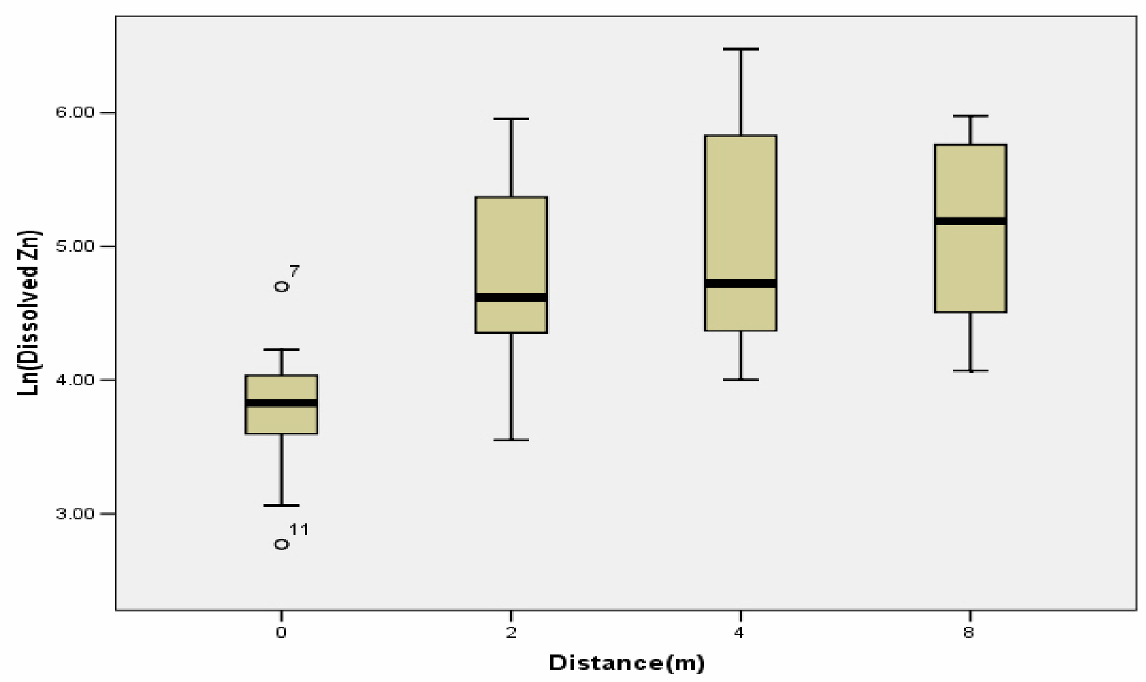


FIGURE B-42 Boxplot of Dissolved Zn at Site 2

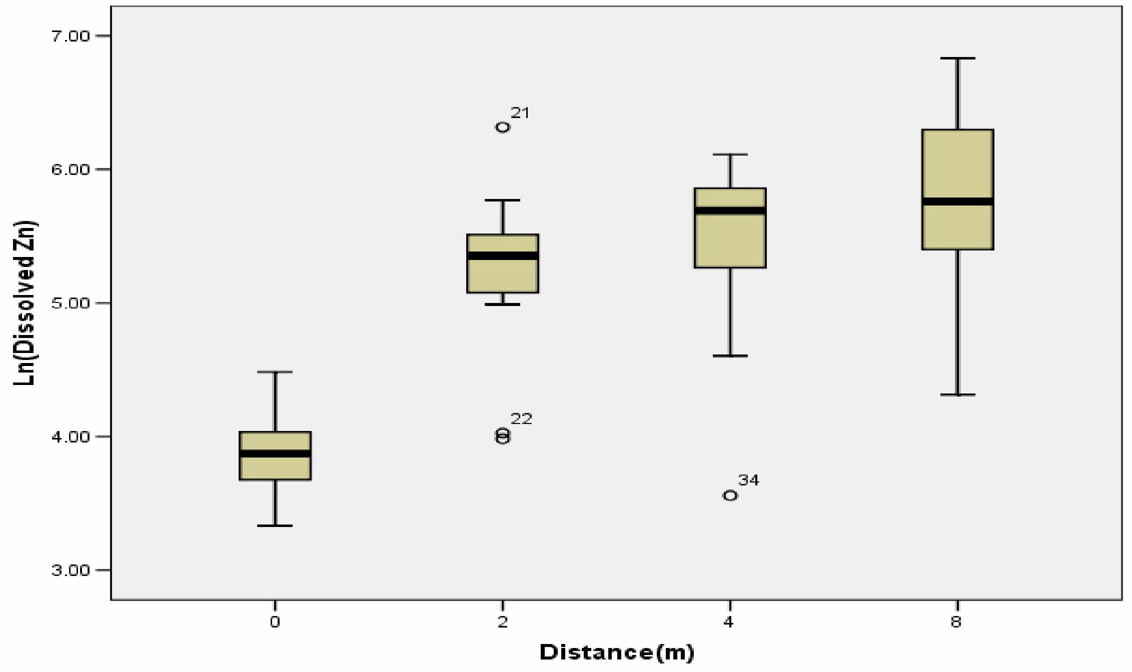


FIGURE B-43 Boxplot of Dissolved Zn at Site 3

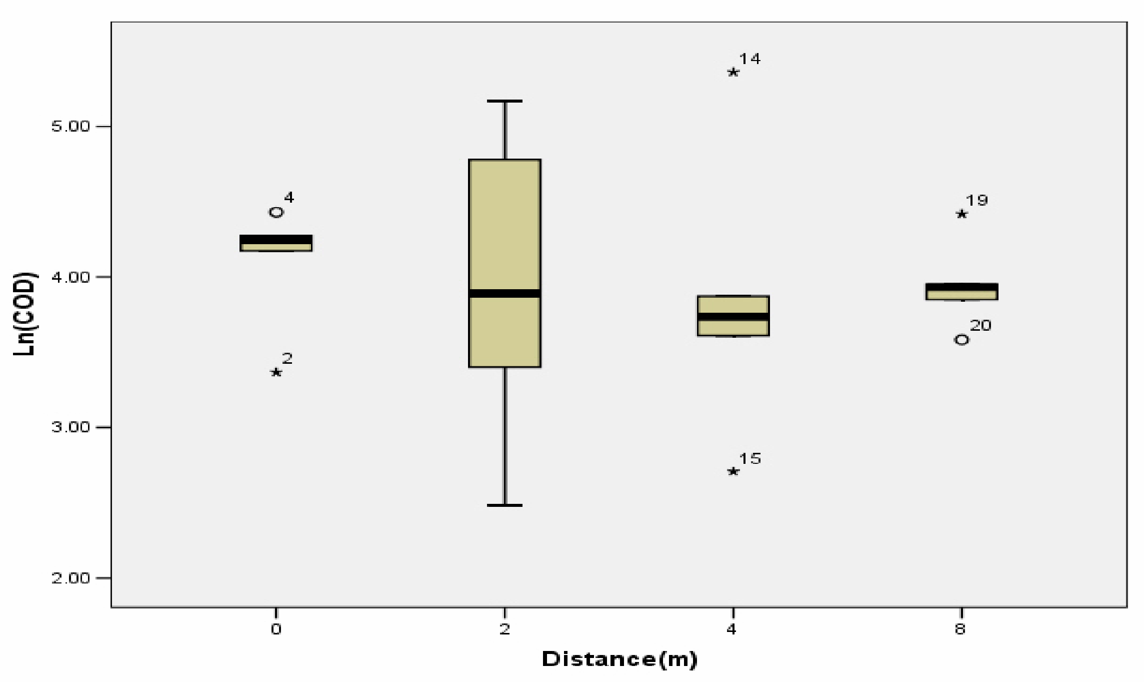


FIGURE B-44 Boxplot of Chemical Oxygen Demand at Site 1, Traditional Pavement

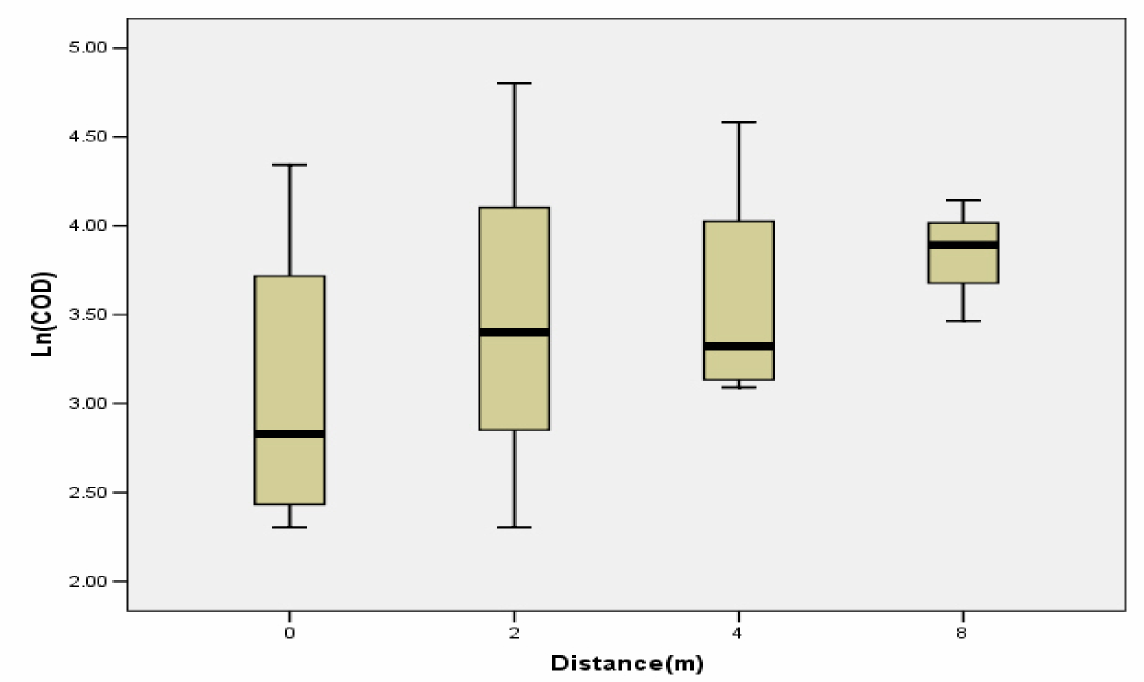


FIGURE B-45 Boxplot of Chemical Oxygen Demand at Site 1, Porous Pavement

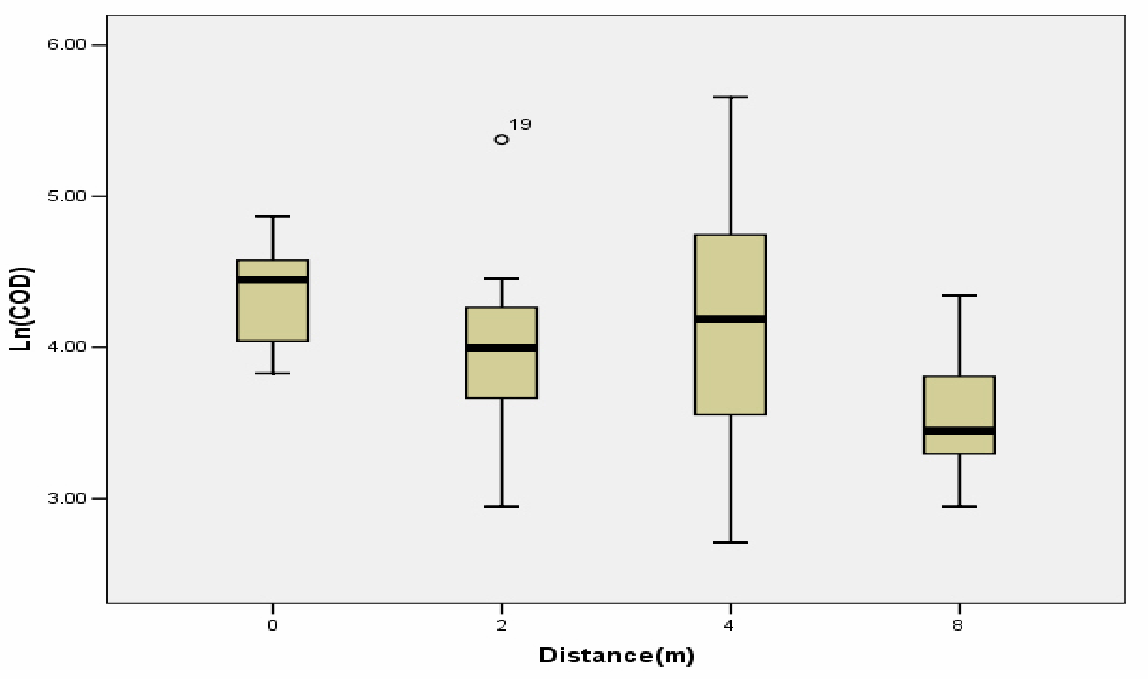


FIGURE B-46 Boxplot of Chemical Oxygen Demand at Site 2

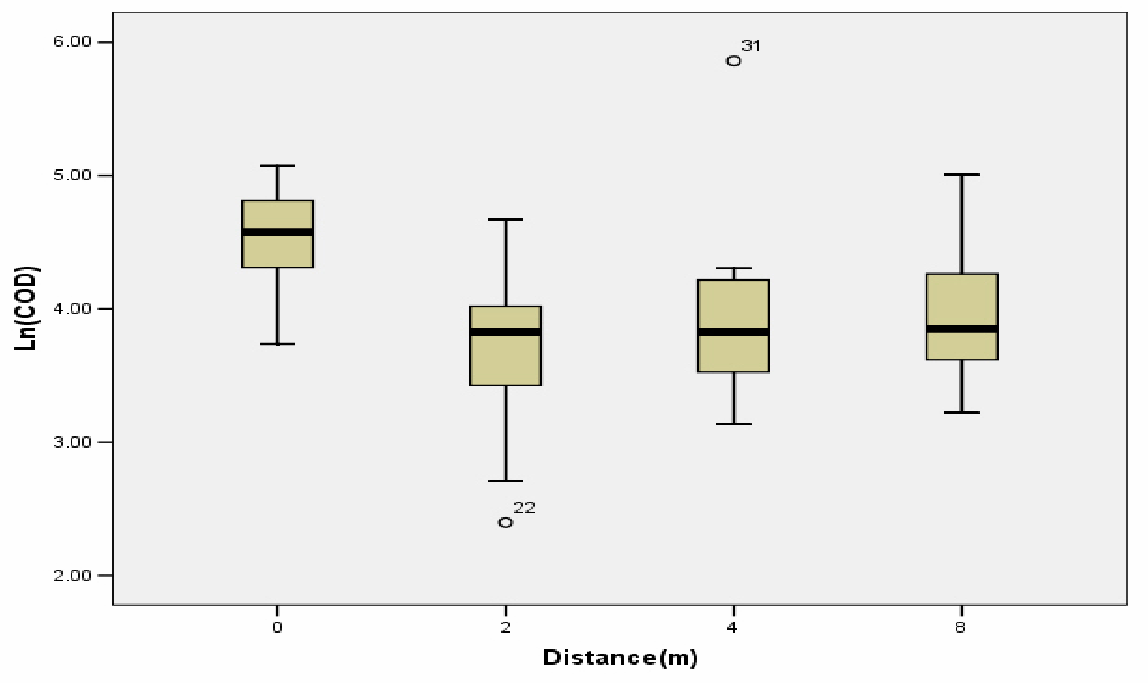


FIGURE B-47 Boxplot of Chemical Oxygen Demand at Site 3

APPENDIX C

STATE OF THE PRACTICE IN TRANSPORTATION SURVEY FINDINGS

Introduction

This survey was conducted to understand the current state of practice among other state department of transportation (DOT). The purpose of this survey is to document the evaluation of the degree to which the vegetated roadsides reduced the adverse impacts that might be caused by discharging untreated runoff directly to the receiving waters. This process involved making selected contacts with the experts in other DOTs which have a strong erosion control program and consider vegetated roadside slopes or grassed embankments as a strategy to improve storm water runoff quality. The summary of the survey provides documentation of the water quality benefits of the vegetated side slopes typical of the common rural highway cross section. The information was collected from a telephone survey and the four questions asked were the following:

(1) Does your agency consider or cite the vegetated roadsides as part of the strategy to control non-point source pollutants in your National Pollutant Discharge Elimination System (NPDES) permits?

If yes,

(2) What are the dominant vegetated species on your roadsides?

(3) Which type of treatment do the vegetated species at your state roadsides provide?

(4) What are the benchmark constituents your department expects to be trapped by the roadside slopes?

Additional questions based on their response evolved and the questions included the following:

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

(6) Have you had projects that documented the efficiency of the vegetated roadsides in trapping pollutants?

The DOTs selected for this survey include:

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

The Summary of Survey

In general all surveyed DOTs (FDOT, MDOT, MNDOT, NYDOT, UDOT, VDOT, and WSDOT) have a positive view about vegetated roadsides in treating the storm water highway runoff. The findings obtained while conducting the survey are the following:

FDOT

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

MDOT

MDOT has recognized vegetated roadsides as part of the strategy to control non-point source pollutants. The department did not cite any specific research or reference publications as the basis for including vegetated roadsides as a storm water quality practice at the time of the survey. The researcher, Raja Veeramachaneni, says that vegetated roadsides are considered as a part of the road design. The department has recognized the utility of vegetated roadsides to be two-folded:

(1) roadsides filtering various constituents as the runoff flows through the swales (sheet flow)

(2) Grassy channels offering pretreatment, filtering most of the pollutant load, before the runoff enters the structural runoff control.

Instead of using the term “vegetated roadsides”, the researcher used the term “grassy channels”. It was unclear whether the researcher referred to the vegetated roadsides in his discussion.

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

MNDOT

MNDOT has also identified vegetated roadsides, bio-swales, bio-retention ditches, and infiltration ditches as an effective means of water quality enhancement. The researcher Dwayne Stenlund says that the department considers plants as an intricate part of the design process. The design process consists of determining the soil recipe in terms of its organic matter content and the soil's ability with respect to infiltration. Lakes in Minnesota have high phosphorus content and additional monitoring revealed that the Switch grass (*Panicum virgatum*) has been found to be extremely efficient with respect to phosphorus removal. The methodology is to engineer a type of soil with a certain amount of activated carbon content which is capable of sequestering certain types of heavy metals. The tie up of metals to the soil could be studied based on the cation exchange. Also, the past studies conducted by the department indicate that compost and peat, when blended with the soil appropriately, can have affinity to certain metals. The plan is to set the soil bed with silt (1/3), clay (1/3), compost (1/3) and develop tree species that can detoxify hydrocarbons, thereby increasing water quality values. In the design of the vegetation matrix, soil type and the resulting infiltration rate are important engineering variables. Grade and water volume are the other parameters in the design specifications for vegetated swales. The researcher referred to the hydraulic engineering center manual (Hydraulic engineering center manual (HEC-11), 2000) mentioning the retardance classes (A-E, where "A" stands for un-mowed tall grass and "E" stands for mowed short turf grass). The theory is that tall plant species offer more retardance to the runoff causing increased settling of solids and vice versa. Mixed species (four types of grass and two types of flowers) were observed to provide better treatment than a monoculture. The department uses both grass species and broad leaved plants on the vegetated matrix and observed better performance than a single type of species. The department is yet to document the roadside manual and is likely to publish one in the coming fall. Maintenance activities include mowing at appropriate intervals but are limited by practical wildlife concerns such as nesting and snake hills and hence shoulder cutting and spot mowing are performed in order to prevent weeds. On the whole, the researcher suggests that the impact of soil chemistry on constituent removal could be better understood by considering vegetation matrix along with the soil recipe.

NYDOT

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

UDOT

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

WSDOT

WSDOT is exploring the water quality benefits of vegetated roadsides in test plots. The department has updated the roadside manual with additional information on using compost as a soil amendment (WSDOT, 2005, and WSDOT, 2004). The researcher, Mark Maurer, believes that the addition of compost should augment the growth of the vegetated species thereby increasing the vegetation density. The Washington state has eight different physical geographic divisions. The type of species used to establish the vegetated areas vary with the geographic region; the most predominant type of species is the Hemlock grass (*Tsuga*). According to Mark Maurer, the short grass species provide better treatment than the broad leafed plants as the sheet of runoff (overland flow) flows through the vegetation matrix. Their dense fibrous roots hold the soil and form numerous root channels that result in increased infiltration. They help to reduce the volume of runoff reaching retention ponds or other water bodies. The high stem count attributes to the denser cover thereby resulting in better filtration. As the sheet of water flows through the vegetative roadside, the primary treatment is provided by the grass species followed by the secondary treatment by the coniferous trees. Furthermore, the grass cover increases the residence time, which in turn reduces the velocity of the flow. Thus the energy in the runoff is blocked by the species and serves as a means for erosion control. Future work includes determining parameters like the soil infiltration rate, soil type and the concentration of various constituents in the runoff after passing through the roadsides. The department is focusing on the removal of heavy metals and the collected samples are sent to a consultant lab for analysis. The maintenance manual includes instructions for appropriate mowing at certain intervals. The researcher referred to the manual called "Roadside Management Study" mentioning the roadside design factors.

Concluding Remarks

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

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

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

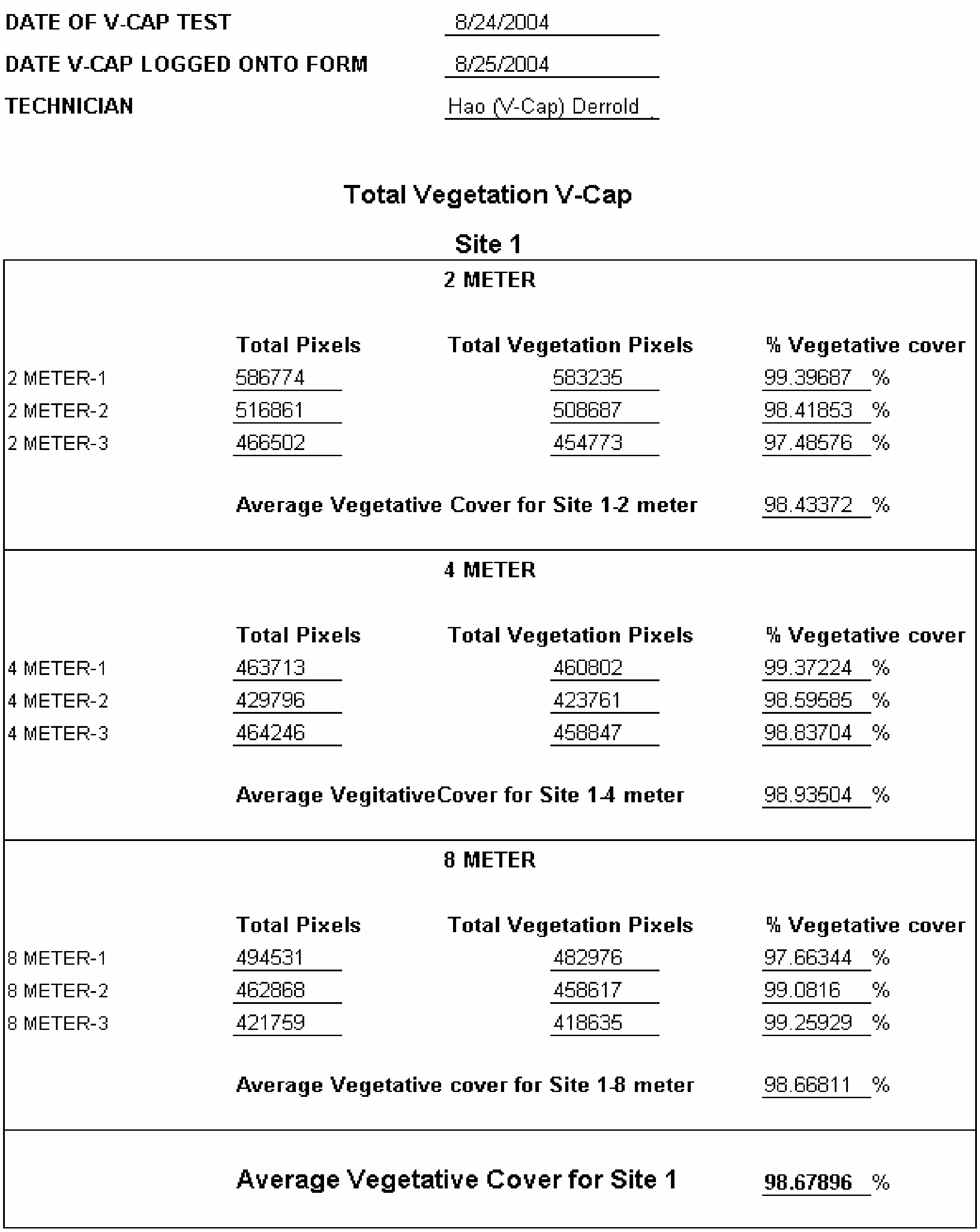
Some DOTs have assessed the water quality and erosion control benefits of vegetated roadsides. The pollution prevention benefits of vegetated roadsides, as identified by the DOTs include, protecting soil from the impact of raindrops, slowing down storm water runoff, anchoring soil in place, intercepting soil before it runs off, and increasing filtration rate of soil. Thus vegetated roadsides could be used as an environmentally sensitive alternative to the conventional storm water sewers. Though no published results are available at this point from the surveyed DOTs, it is reasonable to believe that vegetated roadsides can be effective in reducing the concentration of constituents in highway runoff.

Design of vegetated roadsides with special focus on soil/vegetation matrix is going to pave the way for future research. Additionally, it will provide more insight into the process of treating storm water runoff using roadsides. Moreover, this approach is believed to greatly influence the efficiency of filtration delivered by the roadsides.

APPENDIX D

VEGETATION SURVEY RESULTS AT COLLEGE STATION

Table D-1 Vegetation survey results, Site 1



DATE OF V-CAP TEST 8/24/2004

DATE V-CAP LOGGED ONTO FORM 8/25/2004

TECHNICIAN Hao (V-Cap) Derrold

Total Vegetation V-Cap

Site 1

2 METER

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

4 METER

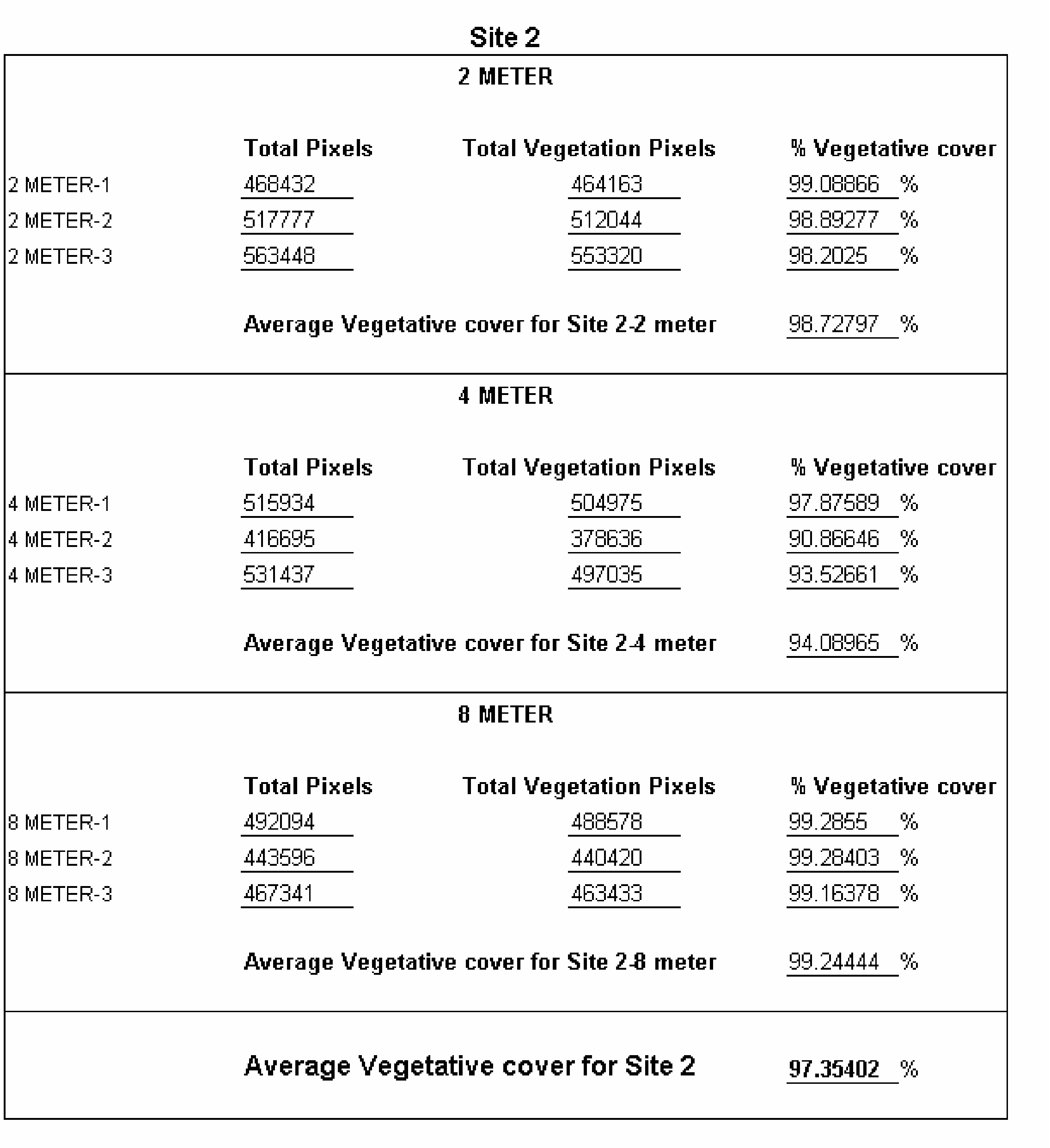
	Total Pixels	Total Vegetation Pixels	% Vegetative cover
4 METER-1	463713	460802	99.37224 %
4 METER-2	429796	423761	98.59585 %
4 METER-3	464246	458847	98.83704 %
	Average VegitativeCover for Site 1-4 meter		98.93504 %

8 METER

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

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

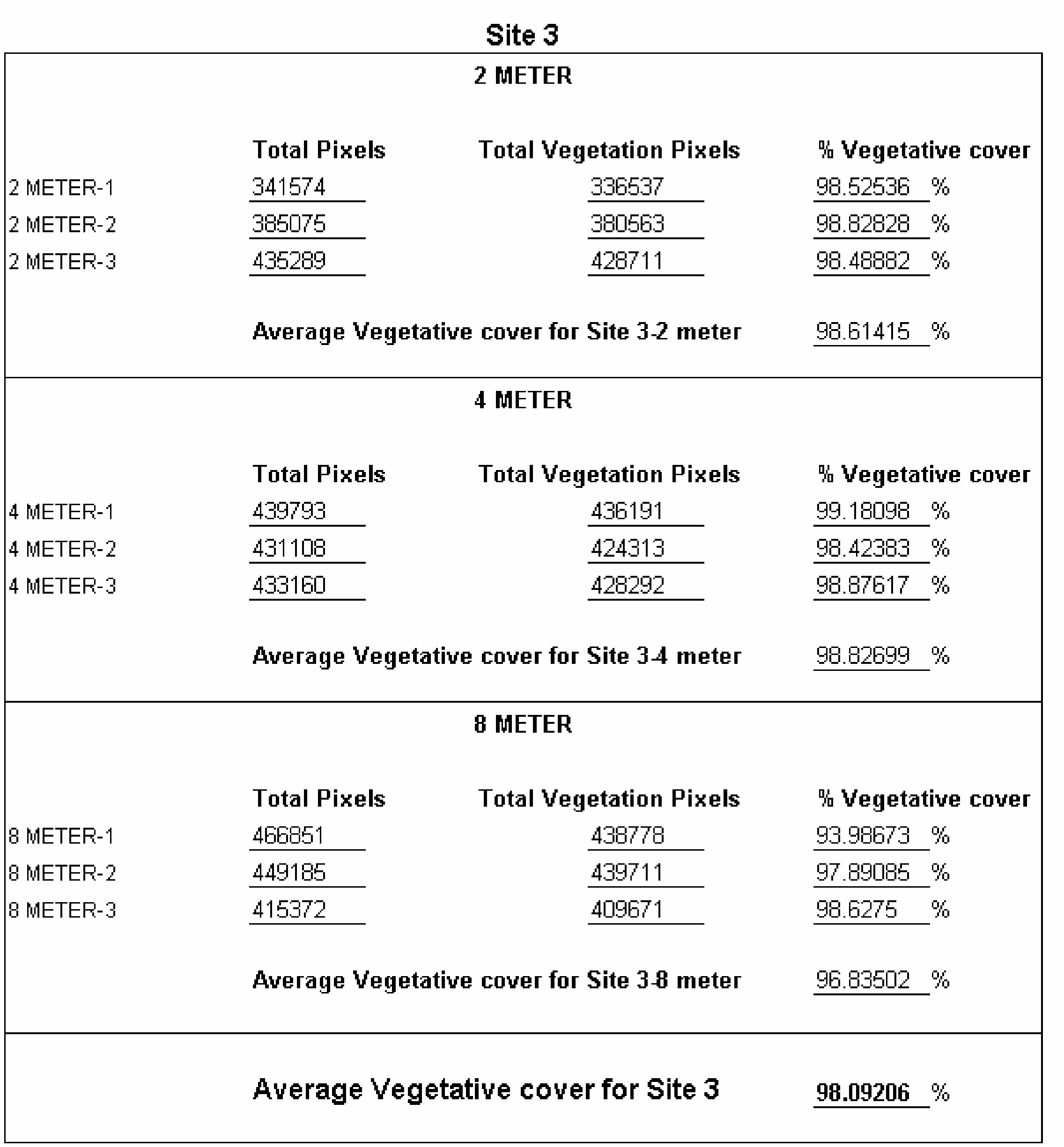
Table D-2 Vegetation survey results, Site 2



Site 2

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

Table D-3 Vegetation survey results, Site 3



Site 3

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

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

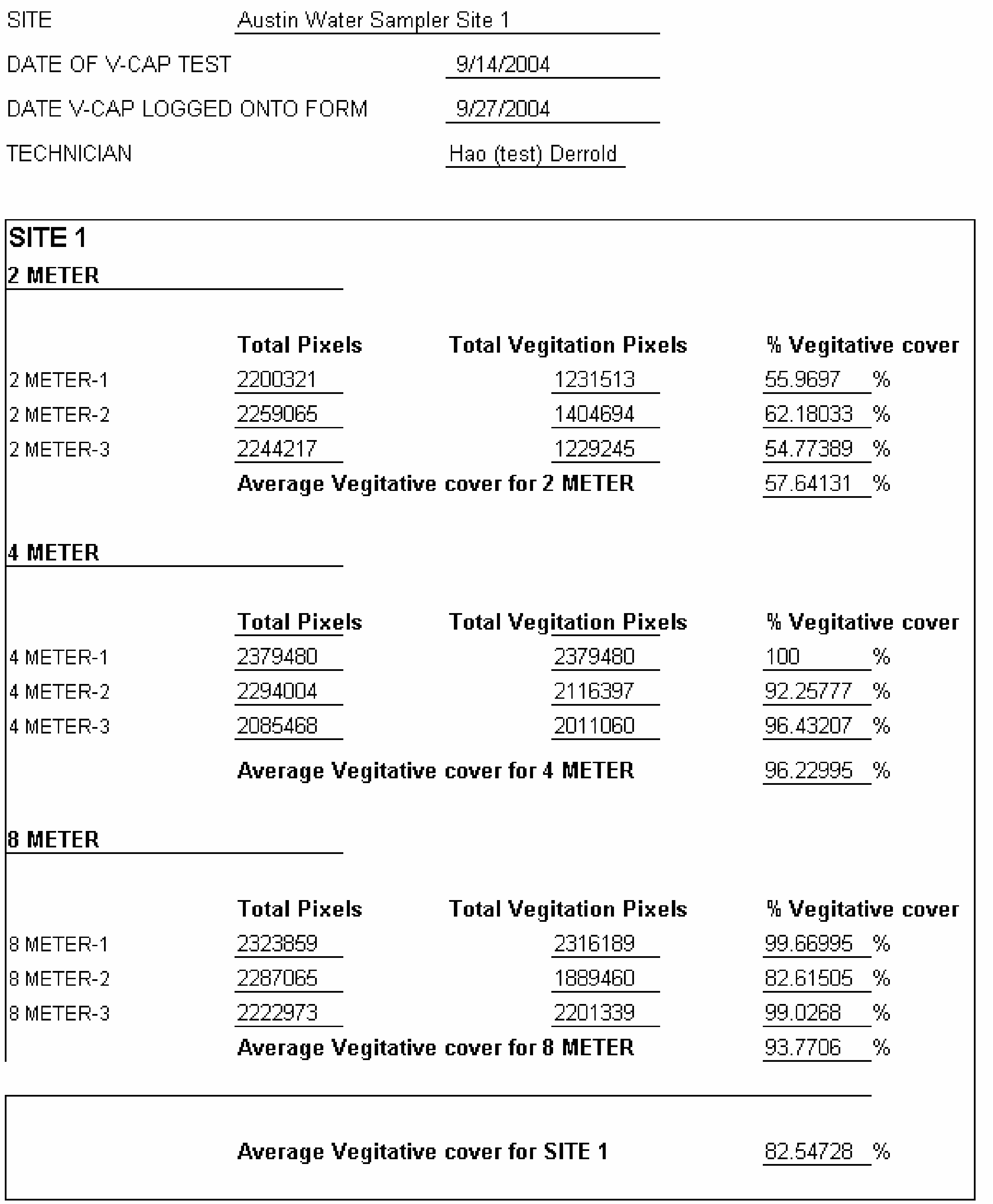
8 METER	Total Pixels	Total Vegetation Pixels	% Vegetative cover
8 METER-1	466851	438778	93.98673 %
8 METER-2	449185	439711	97.89085 %
8 METER-3	415372	409671	98.6275 %
	Average Vegetative cover for Site 3-8 meter		96.83502 %

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

APPENDIX E

VEGETATION SURVEY RESULTS AT AUSTIN

Table E-1 Vegetation survey results, Site 1



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

SITE 1

2 METER

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

4 METER

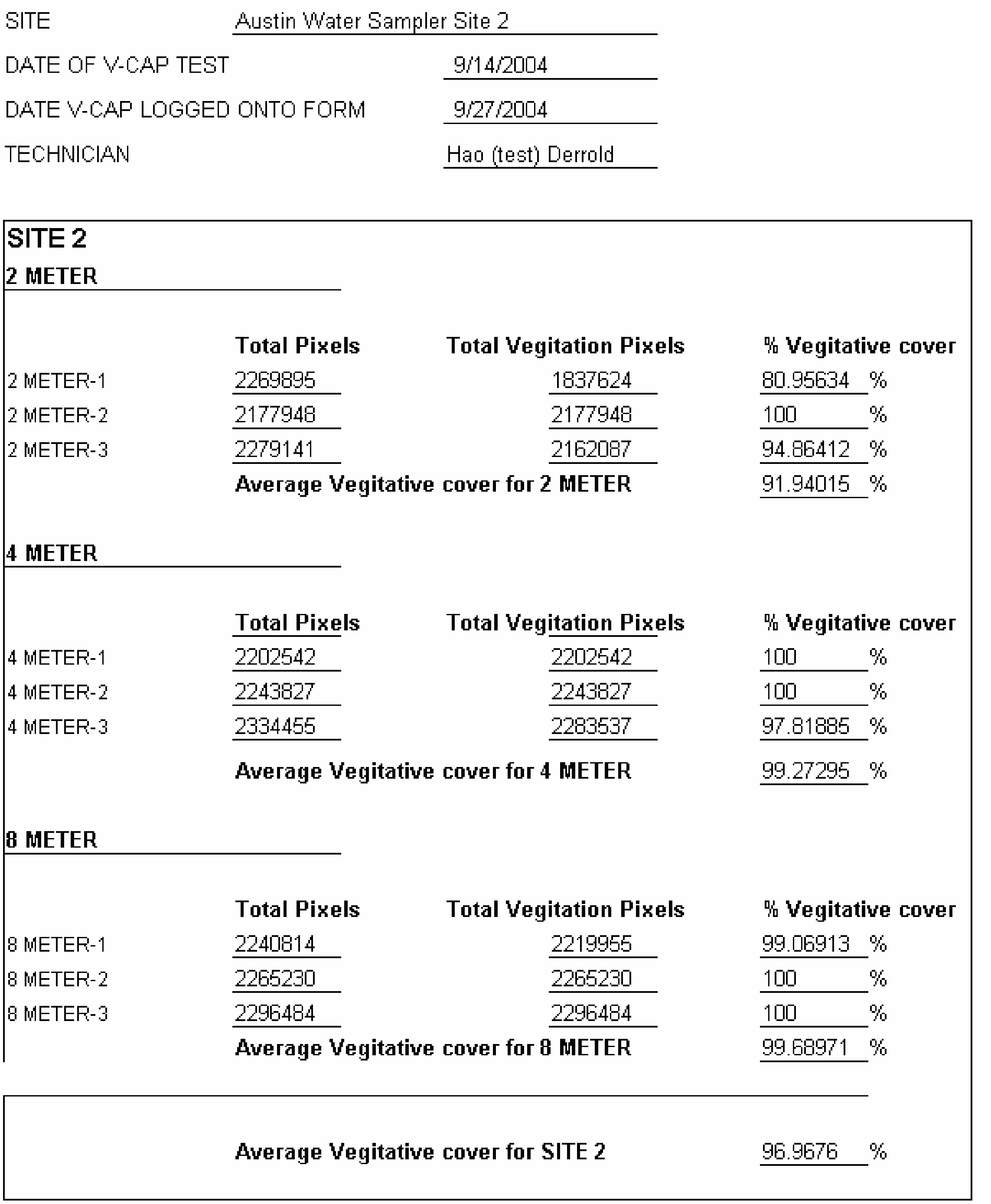
	Total Pixels	**Total Vegitation Pixels**	**% Vegitative cover**
4 METER-1	2379480	2379480	100 %
4 METER-2	2294004	2116397	92.25777 %
4 METER-3	2085468	2011060	96.43207 %
	Average Vegitative cover for 4 METER		96.22995 %

8 METER

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

Average Vegitative cover for SITE 1 82.54728 %

Table E-2 Vegetation survey results, Site 2



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

SITE 2

2 METER

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

4 METER

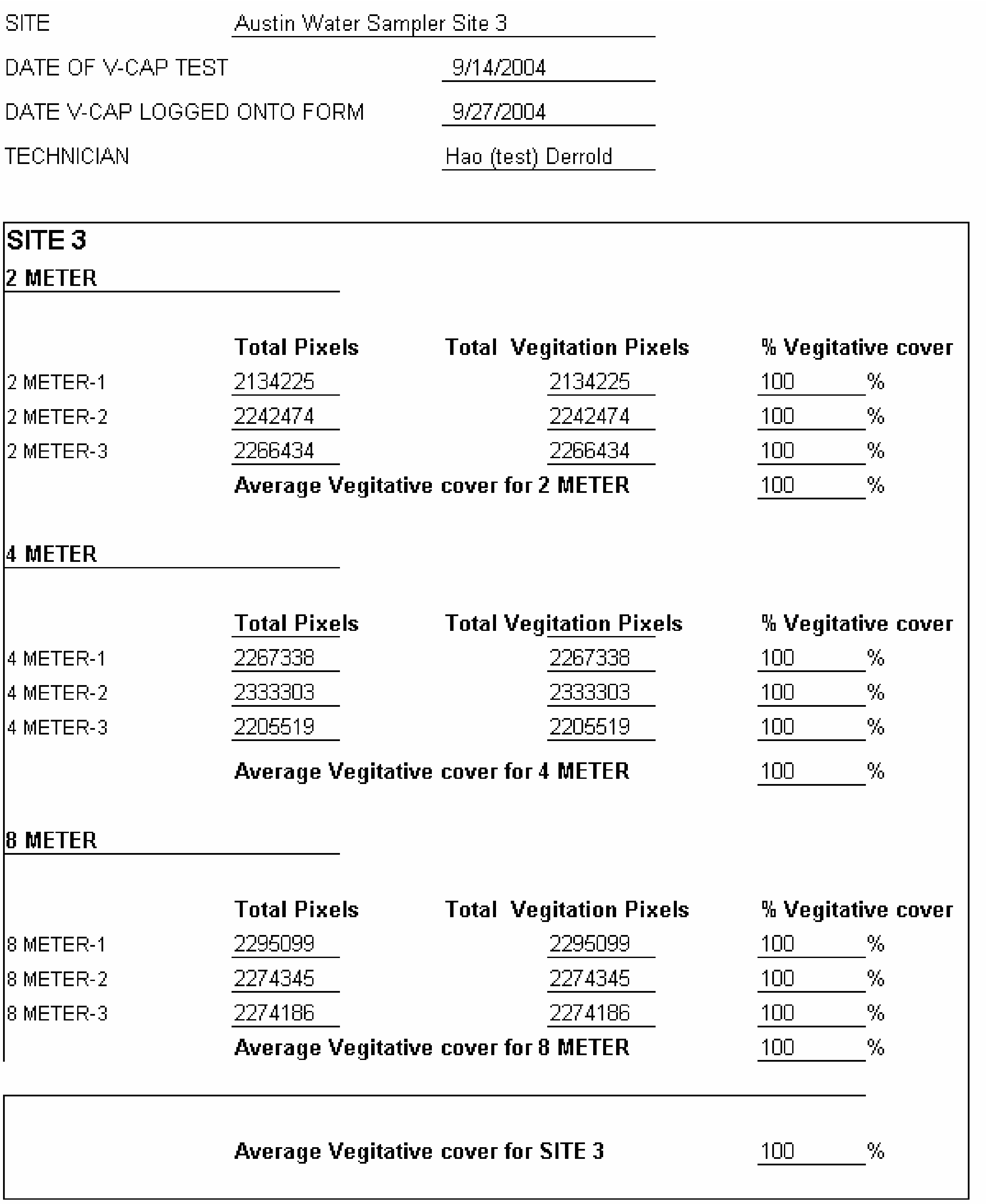
	Total Pixels	**Total Vegitation Pixels**	**% Vegitative cover**
4 METER-1	2202542	2202542	100 %
4 METER-2	2243827	2243827	100 %
4 METER-3	2334455	2283537	97.81885 %
	Average Vegitative cover for 4 METER		99.27295 %

8 METER

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

Average Vegitative cover for SITE 2 96.9676 %

Table E-3 Vegetation survey results, Site 3



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

SITE 3

2 METER

	Total Pixels	Total Vegitation Pixels	% Vegitative cover
2 METER-1	2134225	2134225	100 %
2 METER-2	2242474	2242474	100 %
2 METER-3	2266434	2266434	100 %
	Average Vegitative cover for 2 METER		100 %

4 METER

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

8 METER

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

Average Vegitative cover for SITE 3 100 %

APPENDIX F

TRAFFIC COUNT FOR VEHICLE CLASSIFICATION DURING SAMPLING PERIOD

Sampling Months	**Small Vehicles (Class 1 – 3)**	**Trucks (Class 4 – 15)**	**All Classes (Class 1 – 15)**
March 2004	583051 (91.82%)	51960 (8.18%)	635011 (100%)
April 2004	628624 (92.03%)	54509 (7.98%)	683133 (100%)
May 2004	599782 (92.13%)	51185 (7.87%)	650967 (100%)
June 2004	402955 (90.89%)	40399 (9.11%)	443354 (100%)
July 2004	580187 (91.36%)	54840 (8.64%)	635027 (100%)
August 2004	393617 (91.22%)	37929 (8.78%)	431546 (100%)
September 2004	472112 (91.38%)	44506 (8.62%)	516618 (100%)
October 2004	595148 (91.64%)	54339 (8.36%)	649487 (100%)
November 2004	459258 (91.63%)	41990 (8.37%)	501248 (100%)
December 2004	623838 (91.8%)	55730 (8.2%)	679568 (100%)
January 2005	567249 (91.47%)	52930 (8.53%)	620179 (100%)
February2005	556649 (91.79%)	49832 (8.21%)	606481 (100%)
March 2005	613186 (91.25%)	58746 (8.75%)	671932 (100%)
April 2005	509197 (91.24%)	48933 (8.76%)	558130 (100%)
Total traffic count during sampling period	7584853	697828	8282681

APPENDIX G

SOIL CONTENT ANALYSIS AT COLLEGE STATION SITE 3

Table G 1 Soil Content Analysis at Site 3- 0m

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

Table G 2 Soil Content Analysis at Site 3- 2m

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

Table G 3 Soil Content Analysis at Site 3- 4m

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

Table G 4 Soil Content Analysis at Site 3- 8m

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

*** NA-Not Available**

APPENDIX H

TABULATION OF AMOUNT OF AIRBORNE PARTICULATES

Table H- 1 Tabulation of the weight of airborne particulates collected at the sites

FIELD TEST LOG FORM

SITE: College Station Water sampler sites

Date of Field Test 1: 01/05/2006

Technician: Pavitra
Bret
Arnes

SITE-1

Weight is expressed in grams (g)

0m	2m	4m	8m
NA	72	23	32

SITE-2

Weight is expressed in grams (g)

0m	2m	4m	8m
NA	84	31	50

SITE-3

Weight is expressed in grams (g)

0m	2m	4m	8m
NA	48	50	46

***NA – Not Available**

Table H- 2 Tabulation of the weight of airborne particulates collected at the sites

FIELD TEST LOG FORM

SITE: College Station Water sampler sites

Date of Field Test 2: 01/12/2006

Technician: Pavitra
Bret
Arnes

SITE-1

Weight is expressed in grams (g)

0m	**2m**	**4m**	**8m**
NA	81	69	65

SITE-2

Weight is expressed in grams (g)

0m	**2m**	**4m**	**8m**
NA	214	41	NA

SITE-3

Weight is expressed in grams (g)

0m	**2m**	**4m**	**8m**
NA	97	93	79

***NA – Not Available**

Table H- 3 Tabulation of the weight of airborne particulates collected at the sites

FIELD TEST LOG FORM

SITE: College Station water sampler sites

Date of Field Test 3: 01/20/2006

Technician: Pavitra
Bret
Arnes

SITE-1

Weight is expressed in grams (g)

0m	**2m**	**4m**	**8m**
NA	112	35	49

SITE-2

Weight is expressed in grams (g)

0m	**2m**	**4m**	**8m**
NA	127	56	59

SITE-3

Weight is expressed in grams (g)

0m	**2m**	**4m**	**8m**
NA	49	365	95

***NA – Not Available**

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