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16. Abstract
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- characterization of bridge deck and approach highway stormwater runoff in three different geographical areas of Texas,
- a statistical comparison of the water quality characteristics of stormwater runoff from the bridge surface and the approach highway at each site, and
- an assessment of the impacts of the runoff on the quality of the receiving water at each site.

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Characterization of Stormwater Runoff from a Bridge Deck and Approach Highway and Effects on Receiving Water Quality

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Abstract

Nonpoint source pollution represents one of the largest environmental problems currently facing water quality professionals. A fraction of this pollution is conveyed to receiving waters by stormwater drainage from highways. Some highway runoff is treated by structural or non-structural systems (best management practice [BMPs]) or is diverted to municipal treatment systems, depending on locale. However, much highway runoff and almost all bridge deck runoff enter receiving streams without treatment. Highway runoff may contain suspended solids, metals, oil and grease, fecal coliform, and oxygen-demanding organics. Highway runoff characteristics have been reported in some detail over the years; however, limited data on the characteristics of runoff from bridge decks are available. The objectives of this study are:

- characterization of bridge deck and approach highway stormwater runoff in three different geographical areas of Texas,
- a statistical comparison of the water quality characteristics of stormwater runoff from the bridge surface and the approach highway at each site, and
- an assessment of the impacts of the runoff on the quality of the receiving water at each site.

Texas bridge sites were selected in Austin (Central), Lubbock (High Plains), and Houston (Coastal Zone). The average daily traffic (ADT) count was 58,000 vehicles per day (VPD) at the Loop 360 Bridge crossing Barton Creek in Austin, approximately 10,000 vehicles per day (VPD) at the Loop 289 bridge over the North Fork of the Double Mountain Fork of the Brazos River in Lubbock, and about 15,000 VPD at the bridge on FM 528 crossing Clear Creek near Friendswood, in the Houston area.

Barton Creek is an ephemeral stream with peak flows exceeding 30,000 ft^3/s. Water quality and flow data for Barton Creek at Loop 360 were obtained from the United States Geological Survey (USGS). The North Fork of the Double Mountain Fork of the Brazos River (NFDMFBR) also is an ephemeral stream with peak flows approaching 148 ft^3/s during the study period. The water quality of the stream was monitored for each storm event sampled. Clear Creek is a tidally influenced bayou that is approximately 45 miles long. Clear Creek is one of the largest un-channelized bayous in the city of Houston and supports a variety of river aquatic biota through feeding grounds and nurseries. Peak flows during the course of the study approached 4000 ft3/s

Flow-weighted composite and grab samples of runoff were collected from a bridge and approach highway. The sampling period extended over a period of more than 1 year. ISCO® automatic flow monitoring and sampling equipment was installed to record runoff flow and collect samples from the bridge surface and the approach highway at each site. The samples were analyzed for a suite of constituents including: total and volatile suspended solids (TSS/VSS), total and dissolved metals, phosphorus, nitrogen species, and chemical oxygen demand (COD). Grab samples were collected and analyzed for oil and grease and fecal coliform organisms.

The constituents in the runoff from the bridge deck and approach highway were subjected to paired-event hypothesis testing to establish any significant differences in the concentrations observed for the bridge site and approach highway sites. The average annual loads (lb/yr) of all constituents in the bridge deck runoff were much lower than the annual loads of the respective

constituent in the receiving stream. The difference was several orders of magnitude in most cases. Therefore, the storm water runoff from each of the bridges has very little impact on the water quality of respective receiving stream.

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1. Introduction

1.1 Overview

Non-point source pollution that is discharged into receiving streams is one of the major water quality concerns in the environment today. A large fraction of this pollution is transported in urban stormwater runoff to receiving waters. Population growth and the resulting land development increase urbanization of many watersheds. Urban development results in increases in the amount of impervious cover in a given watershed, which, in turn, results in many changes in the environment. These watershed changes include, but are not limited to decreases in times of concentration of runoff, higher peak flows, altered sedimentation/erosion processes, changes in water quality, reductions in biodiversity, and damage to infrastructure.

Two subsets of urban stormwater runoff are runoff from highway bridge decks and runoff from highway pavements. Extensive efforts have been undertaken to characterize the quality of highway pavement runoff over the last 20 years. Conversely, very little emphasis has been placed on quantifying the concentrations of constituents of bridge deck runoff. The objectives of this study are an evaluation of the characteristics of runoff from a highway bridge deck and adjacent approach highway at three locations that are geographically and climatologically different.

Texas bridge sites at the Loop 360 crossing of Barton Creek in Austin, East Loop 289 Bridge over the North Fork of the Double Mountain Fork of the Brazos River in Lubbock, and the bridge on FM 528 crossing Clear Creek near Friendswood (in the Houston area) were selected. The water quality of paired samples of runoff from the bridge surface and the approach highway were compared statistically. Constituent loadings were calculated using measured flow rates and observed concentration data for specific constituents in the bridge runoff, and historical flow rates and concentration data reported for Barton Creek at the Austin site. The loadings were compared to assess the environmental impact of the bridge runoff on the water quality of the creek.

1.2 Regulatory Framework

Two main permitting issues were addressed by this research, one federal and one state. On a federal level, Clean Water Act Section 404 (CWA) states that "any discharge of dredged or fill material into the navigable waters incidental to any activity having as its purpose bringing an area of the navigable waters into a use to which it was not previously subject, where the flow or circulation of navigable waters may be impaired or the reach of such waters be reduced" is required to have a permit (40 CFR 404). The U.S. Army Corps of Engineers has jurisdiction over the issuance of the "404 permits" that call for the avoidance of negative impacts on wetlands and surface waters where possible and practical, minimization of the remaining impacts, and compensation for any unavoidable impacts. Permit coverage may be obtained through an individual permit or under the Nationwide Permit (NWP). A NWP may be issued for certain classes of activities. The Army Corps of Engineers takes into account the need to maintain the beneficial uses of a particular water body or wetland while allowing for development and progress.

The State of Texas regulates water quality through the Texas Commission on Environmental Quality (TCEQ). TCEQ grants a 401 certification, if the planned development will not impair water quality. A 401 certification is needed prior to the issuance of the 404 permit. A 401 certification is issued, if best management practices (BMPs) are instituted to satisfactorily minimize any impacts on receiving water quality. These controls may be for erosion/sedimentation processes or for the minimization of total suspended solids (TSS) post-construction. Since the TCEQ 401 certification applies to highway bridge projects, the characterization of runoff from highway bridge decks is needed to assess any potential impacts on the receiving waters. Additionally, post construction BMPs for TSS control are required for bridge decks unless a NWP 14 permit is approved. The need to establish the concentrations of constituents in bridge deck stormwater runoff is reinforced further by the fact that many problems could arise from the installation of post construction BMPs on new or existing bridges.

This research project also addresses the Total Maximum Daily Load (TMDL) program, which is another regulatory program that is administered by the United States Environmental Protection Agency (EPA). The TMDL program requires each of the fifty states to submit a list to the EPA of all water bodies within the state that do not meet the designated use and the constituent that causes the impairment. This list is known as the 303(d) list, and is generated every 4 years. Ideally, TMDLs are developed as a means for all stakeholders in the watershed to share equitably in the costs of restoring the water quality of a water body to a level specified by the designated uses. Each stakeholder within the watershed is issued a waste load allocation for the pollutant that causes the impairment. The premise is that controlling the concentration of the designated constituent to a predetermined concentration will result in returning the receiving water to compliance with water quality standards typically within a period of 15 to 20 years depending on the level of impairment. All TMDLs are subject to a period of public comment during which time the stakeholders may weigh in on the stipulations set forth in the TMDL. The TMDL program is designed to be a cooperative effort in which industrial dischargers, agricultural dischargers, regulators, developers, state agencies, municipal governments, environmental groups, academics, and other citizens participate in the planning, data collection, determination of numeric targets, and implementation of the plans.

Few TMDLs have specifically addressed highway pollution as a significant contributor to water quality impairments in the State of Texas. However, as more and more TMDLs are developed, the Texas Department of Transportation (TxDOT) will be included increasingly in these plans. TxDOT is a potential stakeholder in every major watershed in the state. Therefore, TxDOT may be required to participate in all phases of the TMDL program from data collection through implementation of structural BMPs to meet the prescribed waste load allocations. Installation of BMPs on both new and existing highways may be required to meet the load reduction goals of the TMDL. This participation could be costly, but a true assessment of the water quality impacts associated with bridge and highway operations will ensure that TxDOT will not be unduly burdened by the restoration process. An accurate, scientific understanding of the concentrations of pollutants being discharged from bridges and approach highways in Central Texas may result in millions of dollars in savings in construction and delay costs associated with TMDL compliance.

1.3 Scope of Work

The primary objective of this project is the characterization of stormwater runoff from bridge deck, approach highway, and water quality in receiving streams in Central Texas, the High Plains, and the Coastal Zone. Statistical analyses were employed to compare the concentrations of the same constituent in the runoff samples from the bridge and highway approach section. The characterization results were compared with similar data collected locally and regionally to establish the relative quality of the runoff collected at the three bridge sites to the previously monitored runoff quality.

A bridge and associated highway approach section on Loop 360 in Austin, on East Loop 289 Bridge in Lubbock, and on FM 528 near Friendswood (in the Houston area) were selected for this study. An average daily traffic count (ADT) of 58,000 vehicles per day (VPD) was reported for the Loop 360 site in Austin (CAMPO, 2002), approximately 10,000 VPD at the East Deck of the East Loop 289 in Lubbock, and about 15,000 VPD on FM 528 in the Houston area. The bridge deck and approach highway were representative of those in Central Texas, the High Plains and in the Coastal Zone. Flow weighted composite samples were taken to establish event mean concentrations (EMCs). Grab samples also were collected intermittently to analyze for oil and grease and fecal coliform bacteria. The samples were analyzed by an EPA certified lab, Environmental Laboratory Services, a division of the Lower Colorado River Authority (LCRA) located in Austin, Tex. The quality of base flow and storm flow in receiving water for the Austin site were determined from data collected by the United States Geological Survey (USGS), and the changes in concentration and load in the receiving water attributable to storm water runoff from the bridge were assessed. The EMCs observed in the study reported herein were compared to those reported previously for three locations in the Austin area and with data reported in an extensive nationwide study to determine the relative quality of the runoff. The EMCs generated by these sampling efforts were compiled into a database and subjected to a robust statistical treatment to determine whether significant differences exist between the concentrations of specific stormwater constituents at the bridge and approach highway. The statistical analysis also included the generation of 95 percent confidence intervals to quantify the expected differences, if any, between the bridge deck and highway runoff. This analysis led to the identification of those stormwater constituents for which highway runoff could be used as a surrogate for bridge deck runoff.

The annual load of selected constituents were estimated based on the observed concentrations together with measurements of average annual rainfall for the following locations: 1) from the Loop 360 bridge to Barton Creek, 2) from the Loop 289 bridge to the North Fork of the Double Mountain Fork of the Brazos River in Lubbock, and 3) from the FM 528 bridge to Clear Creek near Friendswood (in the Houston area). The observed concentrations were compared to the Texas Surface Water Quality Standards (TAC Title 30, Part 1, Chapter 307) and aggregate eco-region nutrient criteria proposed by the EPA (TCEQ, 1988).

The annual load contributed by the bridge for the constituents sampled was compared to the annual load in the respective receiving stream at each of the three sites. Annual loads in Barton Creek at the Loop 360 bridge were calculated using average concentrations of each constituent in composite samples collected by the USGS from April 1997 until June 2002 and average flows in Barton Creek from 1978 to 2001. An assessment of impacts of the runoff from the Loop 360 bridge on the water quality of Barton Creek was made based on this comparison. Similar assessments of impacts of the runoff from the Loop 289 bridge on the water quality of the North Fork of the Double Mountain Fork of the Brazos River in Lubbock and from the FM 528 bridge on Clear Creek near Friendswood also were completed. The impact of pollutant spills on the quality of the receiving water was not assessed.

2. Literature Review

2.1 Introduction

Nonpoint source pollution has moved to the forefront of concerns regarding maintaining environmental water quality. The Watersheds and Nonpoint Source Section of EPA reports that nonpoint source pollution is the leading cause of water pollution in the United States. Additionally, nonpoint source pollution is the principal source of water quality impairments reported for estuaries (USEPA, 2005). Dramatic increases in the amount and effectiveness of controls placed on industrial and municipal discharges have been seen over the last 20 years. This effort has not always resulted in a proportional increase in receiving water quality. The major reason for this water quality impairment is nonpoint source pollution. Pitt (1991) reported that the annual volume of urban runoff is slightly greater than the annual volume of sanitary wastewater. This fact clearly underscores the need to institute practices that minimize, control, or mitigate these stormwater flows. Nonpoint source pollution is unpredictable; therefore, characterization and subsequent control of nonpoint source pollution is much more complex than typical municipal wastewater discharges (Hvitved-Jacobson and Yousef, 1991).

A subset of nonpoint source pollution is highway runoff. The public road system in the United States consists of approximately 6.3 million kilometers (3.91 million miles) of which 60 percent is paved (Eldin, 2002). Furthermore, the paved area of this system exceeds 50,000 km^2 (19,305 mi^2). Infrastructure for collecting highway runoff varies by locale, but highway runoff may be conveyed by either combined or separate sewer systems. This paper excludes research on highway runoff that drains to combined sewer systems since an entirely different management protocol must be implemented for such flows (Eldin, 2002).

2.2 Sources of Highway Contaminants

There are three major sources of contaminants found in highway runoff: moving vehicles, stationary construction activities including roadway maintenance, and atmospheric deposition. The pavement material also may be a source of particulate matter but to a lesser degree than the other sources. A variety of mechanisms of deposition for each of the major sources has been identified (Hvitved-Jacobson and Yousef, 1991). Constituents in highway runoff may be generated by moving vehicles from fuel combustion products, transmission fluid and coolant losses, transported load losses, oil leaks, fuel leaks, losses of hydraulic steering and braking fluids, and degradation of tires and vehicle moving parts. Motor vehicle exhaust is a major contributor to the pollutants found in highway runoff. Hvitved-Jacobson and Yousef (1991) note that 7.5% of vehicle related particulates are attributable directly to settled particles discharged from vehicle exhaust.

Stationary construction and road maintenance activities also may contribute to the pollutant loadings found in highway stormwater. Eldin (2002) reports that heavy metals such as aluminum, arsenic, lead, and mercury, as well as hydrocarbon compounds may be released by the various construction and maintenance materials that commonly are applied to roadway surfaces. A toxicity-based approach was applied by Huber et al. (2001) to investigate the environmental effects of construction and maintenance chemicals. Acute and chronic toxicity testing was carried out using a freshwater algae species and *Daphnia magna*. The results indicate that aluminum is the principal toxic metal found in the 100 commonly used construction and maintenance materials that were investigated in this study. The presence of soil served as a mitigating factor in these toxicity experiments. Sorption onto the particle surfaces and biodegradation were proposed mechanisms for the reduced toxicity. A regional effect was noted in the toxicity results. A marked difference in the chemical makeup of pavements depending on locale was attributed to the fact that highway pavement surfaces, typically Portland cement concrete (PCC) or asphalt cement concrete (ACC) contain predominantly local materials. This difference also was observed in ecotoxicological analyses in which PCC and ACC pavements from different states were compared (Eldin, 2002).

Atmospheric deposition of pollutants is a key pathway for contaminants to reach highway surfaces. Wanielista and Yousef (1993) reported that the nitrogen, copper, and cadmium found in urban stormwater runoff originated predominantly in the rainwater. The results of 2-year study of five roadways in Minnesota reported by Davis et al. (1999) indicated that concentrations of dissolved nitrate and dissolved ammonia in rainfall were significant sources for those constituents in the highway runoff. Davis et al. (1999) concluded that up to 50percent of the dissolved nitrate and dissolved ammonia in the runoff may be attributed directly to atmospheric sources, i.e. rainwater. An even stronger association between concentrations of nitrogen compounds in rainfall to nutrients in runoff was reported by Irish et al. (1998) who observed that the concentration of nitrate in precipitation accounted for 50 to 100 percent of the concentration in runoff. In addition, up to 22 percent of the total phosphorus load observed in the highway runoff could be attributed directly to phosphorus in rainfall.

The atmospheric processes that result in the formation of acid rain including the cycle of nitrogen-oxide and sulfur-oxide compounds in the highway environment are discussed by Ball et al. (1991). The compounds that are generated by combustion of fossil fuels by motor vehicles are oxidized into strong acids by ozone and hydrogen peroxide in the presence of water vapor, and finally are deposited as sulfuric acid and nitric acid onto the roadway surface. These strong acids have the potential to degrade runoff quality and negatively impact biota in the receiving water. Therefore, site-specific data was gathered when developing a local stormwater management plan because the phenomena are related to local meteorology.

2.3 Factors Affecting Highway Runoff

An exhaustive list of factors that determine the quality of highway runoff is offered by Wanielista and Yousef (1993). This list includes climate, surrounding land use, average daily traffic volume, type of traffic, differences in paving materials, street condition, and level of repair, antecedent precipitation, street sweeping practices, and quantities of air pollution fallout. In their study of Austin, Texas highway runoff, contradictory results regarding the impact of ADT on runoff quality were reported by Barrett et al. (1995a). Other factors such as dust fall, previous storm runoff volume, and pavement maintenance showed good correlation with solids loadings in the highway runoff.

An analysis of gutter systems were incorporated by Davis et al. (1999) who concluded that the concentrations of TSS, total chromium, and total zinc were higher in highway runoff from guttered sites than at non-guttered sites in Minnesota. Reduced time of concentration caused by the installation of gutter systems was cited as the probable reason for increased concentrations. In contrast, concentrations of total phosphorus and fecal *Streptococcus* bacteria were greater at non-guttered sites than at guttered sites. Davis et al. (1999) also investigated the effect of antecedent dry period (or latent period), and ADT on the quality of runoff from highway roadway surfaces. No statistical correlation between most runoff constituents and antecedent dry period was observed. However, concentrations of total phosphorus, dissolved sulfate, and total zinc were significantly correlated with antecedent dry period. Loadings of these parameters were not correlated. The causal link between average traffic volume and loadings of stormwater constituents reported by Davis et al. (1999) concurs with research results reported by Barrett et al. (1996). There is no significant link between ADT and concentrations or loadings of constituents in highway runoff. These findings at first may seem counterintuitive in light of the fact that the apparent source of many of the pollutants found in highway runoff is traffic. However, the average daily traffic volume is not the best variable to use to forecast pollutant loads or concentrations for a given stretch of roadway.

A set of regression equations that may be used to isolate the controlling independent variables for a variety of highway stormwater parameters were developed by Irish et al. (1998). This study is unique in that characteristics of highway runoff from natural storms and simulated storms were incorporated into the analysis of the observed data. Complete control over many of the potentially explanatory variables, e.g. rainfall intensity and total rainfall, was possible for the simulated storms. Solids loading can be described by four independent variables, catchments area normalized volumetric flow, rainfall intensity, antecedent dry period length, and intensity of the preceding storm, as well as an arbitrary intercept term. Solids loading will increase with increased flow, rainfall intensity, and antecedent dry period, and will decrease with more intense preceding storms. Similar analyses were performed for chemical oxygen demand (COD), oil and grease, nutrients, and metals. Traffic loads were adequate predictors for COD and metals while rainfall intensity and antecedent dry period were the main drivers for nutrient loadings.

Similar statistical analyses of highway runoff data collected in California over the four-year period from 1997–2001 were performed by Kayhanian et al. (2003) who reported no direct correlation between annual average daily traffic volume and concentrations of pollutants in stormwater; thus confirming the findings reported by Barrett et al. (1998). Traffic count helped predict concentrations in runoff when used as a variable in a larger multiple regression model. There is some agreement between the multivariate regression analyses that were performed by both research teams. The explanatory variables that had the most influence on concentrations in runoff from California highways were antecedent dry period, seasonal cumulative rainfall, total event rainfall, maximum rain intensity, drainage area, and land use. A model containing annual ADT, total event rainfall, seasonal cumulative rainfall, and antecedent dry period was found to significantly predict 70 percent of the constituents analyzed. The annual average daily traffic count alone may only be used as a general indicator of quality of highway runoff.

2.4 Existing Studies on Bridge Runoff Characterization

During the late1970s and early 1980s, the Florida Department of Transportation funded several studies on highway runoff from bridges. The fate of heavy metals in storm water runoff from highway bridges on Lake Ivanhoe and Lake Lucien near Orlando, Florida was reported by Yousef et al. (1984). Water samples were collected from bridges both with and without scupper drains. Heavy metal concentrations were higher in sediment samples from sites with scuppers than without them. Therefore, the authors recommended that the use of scupper drains in new construction be reduced as much as possible and that the bridge runoff be directed toward either side for maximum removal of heavy metals by overland flow to encourage percolation before the runoff reaches the receiving water. Runoff samples from scupper drains consisted mainly of particulate matter and only 12 percent of total metals in the samples were in dissolved form. Most of the metals in the lake were in the bottom sediment and little metal was in the water column.

A retention/detention pond that receives runoff from Maitland Boulevard Bridge crossing Interstate 4 near Orlando, Florida also was sampled by Yousef et al. (1984). Similar to the findings at Lake Ivanhoe, the sediment at the bottom of the ponds contained 95% of the total heavy metals. Therefore, the data indicate that sediments in bridge runoff carry most of the metals and that retention/detention ponds are effective in the removal of a large fraction of heavy metals in bridge runoff. .

A water quality assessment of storm water runoff from a heavily used urban highway bridge in Miami, Florida was conducted by McKenzie and Irwin (1983) who collected runoff samples from a 1.43-acre bridge section of Interstate 95 during five storm events. Concentrations and loadings of typical water quality parameters were reported and compared to two other previously finished studies to evaluate the effect of average daily traffic on the concentrations of constituents in runoff. Concentrations of nitrate, phosphorus, lead and zinc in runoff from the medium-traffic Interstate 4 site (50,000 ADT) were higher than concentrations observed for the low-traffic U.S. Highway 27 site (4,000 ADT) or the high-traffic Interstate 95 site (70,000 ADT). However, levels of cadmium and copper were about the same at all three sites (McKenzie and Irwin, 1983).

In addition to average traffic, several other factors influence pollutant loads. Among storm events of the same magnitude of runoff, the most significant factor influencing the constituent loads was concentration. Rainfall intensity and runoff volume also affected constituent loadings. Higher intensity storms transported 60 percent of the suspended solids load in the first 4 minutes, whereas lower intensity storms transported only about 15 percent of the TSS load. Loadings of other constituents responded similarly to rainfall intensity (McKenzie and Irwin, 1983).

Irwin and Losey (1978) conducted a water quality assessment of runoff from the Ochlockonee River Bridge on U.S. Highway 27, a rural highway bridge near Tallahassee, Florida. Average traffic count during the study was 4200 vehicles per day. About 15% of the storm water drained directly from the bridge surface to the river, and the rest of the runoff to a grassy floodplain. Samples were collected from the bridge surface using a simulated storm event, bulk precipitation samples, and Ochlockonee River (taken by the USGS). The results of the study indicated that bridge runoff is not a significant annual source of nutrient loadings; however, runoff dominates all other sources during a particular storm event. Therefore, the runoff produces a "shock loading" on an aquatic system.

The impact of the bridge runoff loading on water quality in the receiving water was small. Analyses of the bulk precipitation samples indicated that a significant percentage of the constituent loading from the bridge surface came from atmospheric deposition. This point is well illustrated in the case of suspended solids, for which the annual bulk precipitation load was 138 pounds or 11% of the 1,210 pounds estimated to be in the runoff from the bridge surface. The estimated bridge loads were based on the entire surface area of the bridge (72,800 ft^2); however, only about 10,000 ft^2 of the bridge surface drained directly to the river. The rest of the runoff flowed to a grassy floodplain. The annual loadings contributed by the runoff from the bridge were less than 0.005% of the annual loads in the river for most of the constituents monitored (Irwin and Losey, 1978).

Runoff from the Mopac (Loop 1) Expressway Bridge over Walnut Creek in Austin, Texas drains through vertical openings in the road (Walsh et al., 1997). Runoff samples were collected from the bridge surface via a PVC pipe connected to the vertical openings in the bridge surface. The approximate ADT was 47,000 vehicles per day. Concentrations of TSS, COD, nitrates, zinc, and lead in the bridge runoff were similar to the median concentrations in runoff from highway sites with ADT greater than 30,000 vehicles per day reported by Driscoll et al. (1990).

Griffin et al. (2002) monitored the quality of runoff from the I-220 Bridge, which spans Cross Lake in Shreveport, Louisiana. The bridge was designed with a “closed” drainage system that diverts runoff from the lake, which is a source of drinking water. The runoff is discharged into a concrete lined holding pond. Traffic counts during the study varied from about 30,000 to 42,650 vehicles per day. Approximately 70% of the pollutants, measured as COD, were associated with suspended or settleable solids and could be removed by sedimentation. More than half of the suspended solids were inorganic matter. Therefore, a large portion of the sediment and associated pollutants, e.g. heavy metals, in the bridge runoff could be removed in the holding ponds. The reported average TSS removal was 85% (Griffin et al., 2002). Periodic cleaning of the holding pond and disposal of sediment and associated pollutants would be required in order to keep the process effective.

Runoff from an elevated 1,400-foot long, 1-acre curbed bridge (I-94) over Lower Nemahbin Lake in Wisconsin drained directly into the lake through regularly spaced open scupper drains (Dupuis et al., 1985). The ADT on the eastbound lane alone was 7,500 vehicles per day. The results reported by Dupuis et al. (1985) indicated localized increases in metals and salt concentrations in sediments and aquatic plants near the bridge deck scupper drains. However, no significant adverse effect on aquatic biota near the drains was reported.

Dupuis (2002) summarized the results from six different case studies that specifically addressed impacts on water quality of receiving waters attributed to runoff from bridge decks. Dupuis concluded that the main constituents in bridge runoff of concern and the impact on aquatic life (e.g., acute and chronic toxicity to aquatic life) are particulates (e.g., “carriers” of other constituents and sedimentation effects on aquatic life), nutrients (e.g., eutrophication), and salts (e.g., aquatic life toxicity and drinking water supply taste). More recently, polycyclic aromatic hydrocarbons (PAHs) have also been investigated from a toxicity perspective.

2.5 Effects of Highway Runoff on Receiving Waters and Biota

Potential impacts of stormwater runoff on the environment have been recognized by the EPA. In 1987, the federal government amended the Clean Water Act of 1972 to include provisions to address the potential impacts of stormwater discharges. This amendment requires stormwater permitting for medium and large municipalities. In 1999, the CWA was amended to include the Phase II rules which require some small municipalities (>10,000 people) and all construction sites greater than one acre to obtain a permit (40 CFR 122-3).

The site and time specific nature of the effect of highway runoff on a receiving water body are important considerations in assessing its environmental impacts. The effect of highway runoff on Danz Creek in the Austin, Texas area was evaluated by Barrett et al (1995c) who compared concentrations of TSS, oil and grease, and zinc in 14 paired samples of runoff that were collected upstream and downstream of a newly opened highway right-of-way. The observed concentrations of TSS, oil and grease, and zinc in the creek were higher downstream of the highway; however the concentrations were less than the water quality standards recommended to protect aquatic life.

The most commonly reported contaminants found in highway runoff are lead, cadmium, nickel, zinc, various combustion by-products (PAHs), and oil and grease (Scanlon, 1991). The reported ecological effects of exposure to lead are the potential to bind to calcium sites in animals as well as interfere with the central nervous system, metabolism/growth, and the reproductive system. Lead is bioaccumulative and has been linked to kidney disease as well as impairment of the red blood cells that facilitate oxygen transfer. The removal of lead containing additives from gasoline has drastically reduced the quantity of lead found in highway runoff. The toxic effects of cadmium are similar to those reported for lead with the addition of hypertension as a chronic effect of exposure to high concentrations of cadmium. Nickel and zinc are micronutrients for many species at low concentrations. However, high concentrations of nickel may cause liver problems in animals along with inhibition of reproductive and metabolic rates. Exposure to high concentrations of zinc may result in gastrointestinal disorders, impaired liver enzyme function, reduced bone metabolism, anemia, and interference with copper metabolism (Scanlon, 1991).

Two mechanisms of stormwater creek impairment caused by urban runoff were identified by Pitt (1991) to be the bioaccumulation of lead and zinc associated with polluted sediment and increased stream flows. Bioaccumulation was linked to the die-off or displacement of the native fish species and development of more pollution tolerant non-native species. Peak flows in a creek doubled as a result of the increase in the impervious cover of the drainage area causing alteration of channel morphology and riparian vegetation. These creek changes flushed the majority of contaminated sediments through the creek, but still negatively impacted the local fish population (Pitt, 1991).

Bioassays indicate that highway runoff is strongly inhibitory to algal populations for samples collected from high traffic volume roads with antecedent dry periods of greater than two weeks. Conversely, runoff from roads with lower traffic counts or shorter antecedent dry periods had a stimulatory effect on algal populations (Wanielista and Yousef, 1993). Whole effluent toxicity tests are commonly employed to determine the environmental effects of stormwater pollution because of the potential for antagonistic or synergistic effects of the constituents found in runoff. Factors that influence the overall toxic effects of runoff on receiving water include, but are not limited to pH, temperature, hardness, alkalinity, dissolved oxygen, and the presence of complexing agents (Pitt, 1991).

Pitt (1991) performed extensive bioassay testing to determine the exact mechanism by which highway stormwater induces chronic and acute toxicity. The authors performed tests with water and sediment samples from 15 urban sites in the Toronto, Ontario metropolitan area on a variety of indicator species. The experiment was designed to identify genotoxicity, cytotoxicity, along with more general chronic and acute toxicity. Ecotoxicological effects of sediment in highway runoff, as well as effluents of extended detention ponds and of combined sewer overflows (CSO), were quantified by implementation of the Microdot™ sediment test by Marsalek et al. (1999). The highest frequencies for moderate (24.2%) and severe (19.3%) toxicity were observed for sediment in runoff from multi-lane divided highway sites based on 125 tests. CSO effluent was less toxic than highway runoff (Marsalek et al., 1999).

Assessment of the true toxic effect of these discharges on the ecosystem is difficult because of the ephemeral nature of stormwater runoff. Some organisms can tolerate short-term exposures to highly toxic effluents, but long-term exposure to less toxic concentrations may cause inhibition of the organism. Duration of exposure, dose of potential toxicants, and timing vary in response to changes in hydrology, meteorological conditions, and other environmental factors. Lakes and reservoirs respond to cumulative pollutant loads over an extended period of time, while streams respond more acutely to individual events (Webster et al., 2003).

Consideration of the unique characteristics of each bridge, runoff constituents, and type of water body are essential to accurately evaluate the impacts that a bridge runoff will have on the quality of the receiving water. Specific factors include bridge deck length and width, traffic volume, concentrations of constituents of runoff, and type of receiving water (i.e. river, lake, or estuary).

Storm water runoff generally does not result in acute toxicity in bioassay tests conducted on organisms from streams and lakes that receive highway runoff; however, runoff may produce a toxic response under site-specific conditions. Chronic toxicity that might result from bioaccumulation of metals, sediments, or other constituents in runoff has not been elaborated in much detail. Concentrations of nutrients (i.e., nitrogen and phosphorus) in highway runoff generally are lower than in runoff from undeveloped land (Barrett et al., 1995a).

Characterization of bridge runoff and/or assessment of the impacts of bridge runoff on a receiving water body have not been reported in great detail in the published literature. In contrast, the characterization and impact assessment of highway runoff are discussed in much more detail. Many of the studies on bridge deck runoff were conducted in the late 1970s and the early 1980s when leaded gasoline powered motor vehicles. In addition, much of the observed data that were reported were for sites in Florida. Therefore, the published bridge deck runoff data for the most part are not recent and are geographically limited in scope.

The limited data that are available focus on metals and show that localized increases in pollutant concentrations occur when bridge runoff drains directly into the receiving stream without any pretreatment such as flow over adjacent shoulders or grassy areas. However, no long-term increases throughout the water body and no adverse effects on the stream biota on a large scale have been documented. Most of the published information indicates that heavy metals are critical in assessing the impact on plants and other stream biota; however, most of the metals were associated with the sediments in the water body, rather than the dissolved form, which is more acutely toxic to fish and other organisms.

Dupuis (2002) concluded that,

> "Very few, if any, studies detailing water quality impacts of bridges, or spills from bridges to receiving waters, have been conducted. Several studies have described potential or hypothetical impacts, and a number of measures have been identified to reduce these impacts. Those studies that did specifically address bridge runoff concluded that direct drainage of runoff to certain types of water bodies, especially small lakes, could lead to localized increases in certain pollutant concentrations, such as metals in sediments and/or aquatic biota. However, most of these studies did not consider whether such increases adversely affect aquatic biota as well as other water uses."

Dupuis (2002) also summarized the results of a nationwide survey of environmental managers and bridge design experts in 50 state transportation agencies as well as selected university and other researchers. The results of the survey showed that,

> "Issues of storm water runoff, maintenance activities, and spills associated with bridges are becoming increasingly prominent in many states, especially for larger bridges. State and federal authorities now often advocate the use of some form of containment and/or partial treatment system to be used on storm water runoff from bridges, rather than drain it directly to the receiving stream or lake."

3. Description of Sites

The study project included bridge locations in three areas of Texas that are geographically and climatologically different. Austin is in Central Texas with the Hill Country ranch lands to the west and the coastal plains to the east. The estimated population of the Austin metropolitan area was 859,000 in 2000. The average annual rainfall in Austin is 34.72 inches (88.19 cm) based on a 30-year period of data. Lubbock is in the High Plains and has an annual precipitation of 18.7 inches (National Weather Service). The estimated population of Lubbock was 200,000 in 2000. The third site is in the Coastal Margin region, i.e., within 50 statute miles of the Gulf of Mexico and the annual rainfall is approximately 48 inches. There is no rail commuting system in these areas; therefore, transportation primarily is based on the federal, state, and local roadways.

The Central Texas study site is in south Austin on Loop 360. A GIS image of the project site is presented in Figure 3.1 (see a larger representation in Appendix A, Figure A-1). The location of the project site is Loop 360 west of South Lamar Blvd. and east of Loop 1 (Mopac). The site consists of an approach highway and a bridge that spans Barton Creek. The approach highway is southeast of the bridge. The receiving stream is ephemeral and at times peak flows exceed 30,000 cubic feet per second.

The High Plains study site is located within the city limits of Lubbock on Loop 289. Loop 289 is a section of state highway that completely circles the city of Lubbock. The location of the project site is East Loop 289 north of the 50th Street interchange. The average daily traffic volume is 10,000 vehicles per day. The site consists of an approach highway and a bridge that spans the North Fork of the Double Mountain Fork of the Brazos River (NFDMFBR). The receiving water is an ephemeral stream. However, during the study period peak flows approached 148 cubic feet per second (4 m^3/s). Illustrations of the project site are presented in Figures 3.2 and 3.3.

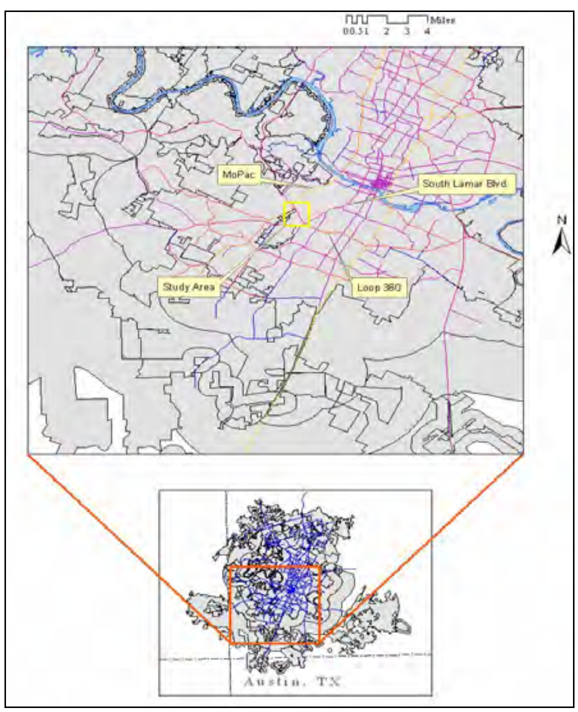

Figure 3.1 Map of Study Area in Austin, Texas

Figure 3.2 Loop 289 Bridge Crosses North Fork of the Double Mountain Fork of the Brazos River in Lubbock, TX

Figure 3.3 Loop 289 Bridge Site in Lubbock, TX

The Coastal Margin site is located is located in Friendswood Texas on F.M. 528, also known as NASA Boulevard. The area recently has been developed and combines a mix of residential, commercial, and light industrial uses. Some agriculture still exists in the area as well.

The bridge deck is located on FM 528, which is a major highway that runs through Harris, Galveston, and Brazoria counties. The location of the site is shown in Figure 3.4. The FM 528 bridge spans Clear Creek, which is a tidally influenced bayou.

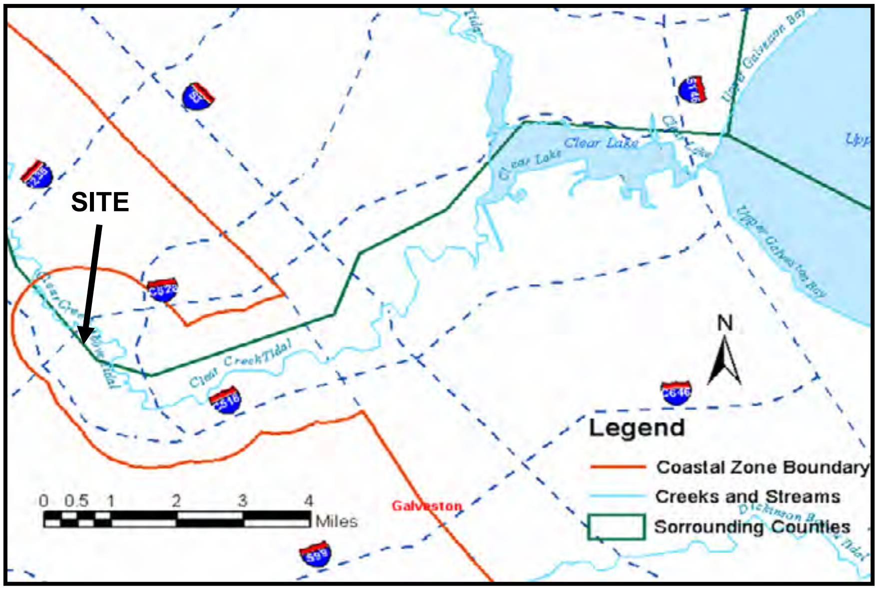

Figure 3.4 Bridge Site Location in Coastal Zone near Friendswood, TX

Specific information about the physical features of the approach highway and bridge as well as the characteristics of the receiving stream at each site is presented in some detail in Appendix A. The instrumentation, flow measurement, and water quality sampling equipment installed at each of the sites is also discussed in Appendix A.

4. Equipment and Methods

4.1 Rainfall, Flow Rates and Volume Measurements

Rainfall was recorded at each site using a tipping bucket rain gauge connected to the flow meter at the approach highway sampling sire for data logging purposes. Rainfall was recorded at 5-minute intervals at the Loop 360 site in Austin and Loop 289 site in Lubbock and 15-minute intervals at the FM 528 site in Friendswood throughout the monitoring period. The flow meters at each site were interrogated using a laptop computer shortly after each rainfall event to ensure that no data were lost or overwritten.

ISCO® 4230 flow meters were installed at the approach roadway site and at the bridge deck to record the volumetric flow rates at the respective sites. The flow meters continuously recorded calculated runoff volumes for each 5-minute interval at the Loop 360 site in Austin and at the Loop 289 site in Lubbock and at 15-minute intervals at the FM 528 site in Friendswood throughout the sampling period. The measured volumes at each time interval were added over the length of the rainfall event to calculate total volume of runoff.

4.2 Analytical Procedures

All runoff samples were delivered for analyses to Environmental Laboratory Services, a division of the Lower Colorado River Authority (LCRA) immediately after collection when laboratory operating hours permitted. When it was not possible to drop off the samples immediately after collection, the bottles were refrigerated at approximately 39^{o}F (4^{o}C) until the lab opened for business. Grab samples were collected at all sites throughout the monitoring period in specified sterile containers that are required for fecal coliform analyses and others in amber glass bottles that are specified for oil and grease samples.

Samples of runoff that were collection from the approach highway and bridge surface at the Loop 360 site in Austin were delivered to the analytical laboratory immediately after the samples were retrieved. Approach highway and bridge deck runoff samples as well as stream samples upstream of the bridge at the Loop 289 site in Lubbock were collected after an appreciable amount of rainfall (usually > 6.4 mm). These samples were stored under refrigeration. The sample bottles were sealed in double Ziploc bags, placed in an insulated chest, and covered with ice prior to shipping overnight. The samples arrived at the analytical laboratory the next morning, usually within 24 hours of sample collection when the samples were collected on weekdays. When the samples were collected on weekends, the bottles were stored in a refrigerator and shipped so that the samples arrived early on Monday morning when the lab reopened after the weekend when the lab did not operate.

However, on some occasions, samples also were collected in Lubbock when the rainfall was less than 6.4 mm when the antecedent number of dry days was very large (usually greater than 2 months). The upstream composite samples from the automatic sampler were mixed in a five-gallon bucket and samples were taken in 250, 500, and 1000 mL polypropylene bottles. The samples in the 250 and 500-mL bottles were preserved with nitric and sulfuric acid, respectively, while the samples in the 1000-mL bottles were not preserved. Grab samples were collected in 1000-mL glass bottles with hydrochloric acid as preservative and 100 mL plastic bottles. All bottles were filled with preservatives prior to sample collection. Nitric acid as a preservative was applicable to metals while sulfuric acid was applicable to COD and nitrogen. Hydrochloric acid was used to preserve the oil and grease.

Each sample of runoff that was collected from the bridge deck and approach highway at the FM 528 site near Friendswood and from Clear Creek was mixed thoroughly, placed in the bottles provided by LCRA, packed in insulated containers that were filled with ice and shipped to the LCRA analytical laboratory in Austin. However, after discussion with LCRA personnel the grab samples that were collected at the FM 528 site were not analyzed for fecal coliform and oil and grease because of the long lag time between sample collection and receipt in Austin.

All applicable QA/QC procedures were followed during the sampling period. The parameters for which the samples were analyzed were recommended by TxDOT and approved by the Texas Commission on Environmental Quality (TCEQ). These parameters are listed in Table 4.1.

Table 4.1 Water Quality Parameters That Were Monitored

Parameter	Units	Method	Practical Quantification Limit
Copper, Total	µg/L	E200.8	1
Copper, Dissolved	µg/L	E200.8	1
Lead, Total	µg/L	E200.8	1
Lead, Dissolved	µg/L	E200.8	1
Zinc, Total	µg/L	E200.8	5
Zinc, Dissolved	µg/L	E200.8	4
Nitrogen, Nitrate (As N)	mg/L	E300	0.01
Nitrogen, Kjeldahl, Total	mg/L	E351.2	0.02
Chemical Oxygen Demand	mg/L	E410.4	7
Phosphorus, Total (As P)	mg/L	E365.4	0.04
Phosphorus, Dissolved (As P)	mg/L	E365.4	0.04
Total Suspended Solids	mg/L	E160.2	1
Volatile Suspended Solids	mg/L	E160.4	1
Fecal Coliform	cfu/100 mL	M9222D	---
Oil & Grease, Total Recoverable	mg/L	E1664	2.58 - 2.74

4.3 Statistical Analysis

The analytical results for each sample were inspected to ensure all appropriate QA/QC procedures were followed by the contracted laboratory. The data were compiled and inspected visually as well as statistically. Box plots were constructed for all runoff constituents at each site to initially characterize the data and identify potential outliers.

The Ryan-Joiner normality test was employed to distinguish normal data sets from non-normal data sets in evaluating the water quality data reported for the runoff collected from the approach highway and the bridge surface at the Loop 360 site in Austin. Overall, the data were distributed normally, but several exceptions were identified where the observed data demonstrated skewed distributions.

A paired t-test was the hypothesis test that was used; therefore, the differences between the bridge and approach highway sites were calculated for each parameter for each storm event. These differences were subjected to the Ryan-Joiner test for normality. All differences, with the exception of nitrate-nitrogen (NO_3-N), were found to be distributed normally at a significance level of 95% (alpha = 0.05). This strong tendency toward normal distribution of data lends further credence to the selection of the paired t-test as the appropriate statistical treatment.

The null hypothesis (H_o) selected for the paired t-tests was:
Approach Highway Concentration (mg/L) – Bridge Concentration (mg/L) = 0

The alternative hypothesis (H_a) for the paired t-tests was:
Approach Highway Concentration (mg/L) – Bridge Concentration (mg/L) ≠ 0

A significance level of 95% was used for these tests. If the alternative hypothesis was acceptable at an alpha level of 0.05, the sign of the difference was inspected to determine whether the data at the bridge demonstrated significantly higher or significantly lower concentrations than the data at the approach highway. If the difference was positive, the bridge concentration was less, and conversely, if the difference was negative, the bridge concentration was greater. The alternative hypothesis for each parameter therefore is positively directional, with respect to the bridge.

The Shapiro-Wilk W. normality test was employed to distinguish normal data sets from non-normal data sets in the evaluation of the water quality data reported for the runoff collected from the approach highway and the bridge surface as well as for the samples of the receiving stream upstream of the bridge at the Loop 289 site in Lubbock. The sampled concentrations were not distributed normally for all three sites with one exception; therefore, the Wilcoxon/ Kruskall-Wallis Tests, a non-parametric test was used to test for significant differences and Tukey-Kramer difference in means to identify which pairs were different. A significance level of 95% was used for these tests. If the alternative hypothesis was acceptable at an alpha level of 0.05, the sign of the difference was inspected to determine whether the data at the bridge demonstrated significantly Fecal Coliform and Oil and Grease data were not tested because of the limited number of samples.

5. Results

5.1 Rainfall and Runoff

Summary data on rainfall amount, peak flow rate, and runoff volume for each storm that was sampled at each of the three sites are presented in Tables 5.1 through 5.4. The data included in Table 5.1 indicate the volume of the runoff that was sampled at the Bridge deck the Approach Highway sampling sites in Austin as a fraction of the total volume of storm runoff that was sampled.

The runoff from the bridge deck and approach highway was measured for a total of 15 rainfall events at the Austin site from June 2003 through February 2004. The rainfall measured at the Loop 360 site at Barton Creek ranged from 0.07 to 2.37 inches and averaged 0.81 inches for the rainfall events that occurred during the study period. The runoff from the approach highway ranged from 0.8 to 16.3 ft^3/s with an average runoff flow rate of 5.26 ft^3/s. The average flow rate of runoff from the bridge deck was 0.077 ft^3/sec and ranged from 0.011 to 0.173 ft^3/s. Barton Creek flow data were obtained from the USGS monitoring station at Loop 360 in Barton Creek (USGS, 2004). Stream flows have been measured daily at the site since 1978 and annual average data were available on the USGS website. Average annual flows recorded at the site are shown in Table 5.2.

The average annual stream flow reported for Barton Creek at Loop 360 during the period from 1978 to 2001 was 48.4 ft^3/s. The average annual base flow was 23.72 ft^3/s and the average annual storm flow was 24.68 ft^3/s (City of Austin, 1996). Therefore, the average annual storm flow is several orders of magnitude greater than the measured bridge deck runoff. Water quality data for Barton Creek also are collected by the USGS from this monitoring station.

Table 5.1 Summary of Rainfall and Runoff Data for the Bridge Site and Approach Highway at Loop 360 at Barton Creek, Austin, TX

			Bridge Site					Approach Highway				
Storm Date	Total Rainfall		Total Runoff Volume		Fraction of Storm Sampled	Peak Flow Rate		Total Runoff Volume		Fraction of Storm Sampled	Peak Flow Rate	
mm/dd/yy	in	mm	ft^3	m^3	%	ft^3/s	m^3/s	ft^3	m^3	%	ft^3/s	m^3/s
06/04/03	0.66	16.8	156.8	4.44	100	0.067	0.002	15,050	426	100	4.4	0.12
06/05/03	1.01	25.7	176.9	5.01	93.6	0.127	0.004	46,150	1306	42.7	6.0	0.17
06/13/03	1.36	34.5	204.4	5.79	81	0.162	0.005	18,267	517	100	6.7	0.19
07/06/03	0.07	1.8	31.8	0.90	100	0.032	0.001					
07/08/03	0.40	10.2	69.9	1.98	100	0.060	0.002					
07/16/03	0.37	9.4	71.0	2.01	100	0.166	0.005					
08/10/03	0.56	14.2	154.7	4.38	100	0.099	0.003	14,318	405	100	9.3	0.26
09/01/03	0.58	14.7						9,893	280	100	1.6	0.05
09/11/03	0.52	13.2						9,502	269	100	2.9	0.08
09/12/03	1.36	34.5	253.2	7.16	65.4	0.028	0.001					
09/21/03	0.49	12.4	91.1	2.58	100	0.011	0.000	4,300	122	100	0.8	0.02
10/09/03	0.44	11.2	67.8	1.92	100	0.042	0.001	6,831	193	100	2.9	0.08
11/17/03	0.81	20.6	134.5	3.81	100	0.173	0.005	18,892	535	100	16.3	0.46
01/15/04	0.63	16.0						14,546	412	100	2.8	0.08
01/16/04	2.37	60.2	431.1	12.20	38.4	0.092	0.003	68,039	1925	29	4.5	0.13
02/04/04	0.80	20.3	137.7	3.90	100	0.035	0.001					
02/05/04	0.98	24.9						24,510	694	80.4	4.5	0.13
02/10/04	0.87	22.1	91.1	2.58	100	0.035	0.001	18,932	536	100	3.6	0.1
02/11/04	0.88	22.4	112.3	3.18	100	0.025	0.001	24,809	702	79.5	4.2	0.12
02/24/04	1.26	32.0						26,996	764	73	7.0	0.2

Table 5.2 Average Annual Stream Flow Barton Creek at Loop 360

Year	ft^3/s	m^3/s	Year	ft^3/s	m^3/s	Year	ft^3/s	m^3/s	Year	ft^3/s	m^3/s
1978	0.036	0.001	**1984**	19.8	0.560	**1990**	4.68	0.130	**1997**	94.8	2.680
1979	60.2	1.700	**1985**	77.7	2.200	**1991**	104	2.940	**1998**	87	2.460
1980	14.6	0.410	**1986**	70.2	1.980	**1992**	157	4.440	**1999**	1.78	0.050
1981	111	3.140	**1987**	129	3.650	**1993**	20.7	0.580	**2000**	14.8	0.419
1982	11.4	0.320	**1988**	0.5	0.014	**1995**	41.3	1.170	**2001**	64.4	1.823
1983	8.14	0.230	**1989**	20	0.560	**1996**	0.08	0.002			

The rainfall and runoff data for the Lubbock site are presented in Table 5.3. These data represent the entire storm event and are not restricted to the portion of the storm that was sampled. The runoff from the bridge deck and the approach highway was measured and sampled for 12 rainfall events during the period of January 2004 through May 2005. The average rainfall during this time period was 0.95 inches and ranged from 0.35 to 1.98 inches. The flow in the receiving stream upstream of the bridge was recorded for seven rainfall events during the course of the study. The average peak stream flow of the North Fork of the Brazos River's Double Mountain Fork upstream of the Loop 289 site during the rainfall events was 72.2 ft^3/s and ranged from 40.8 to 98.5 ft^3/s. It should be pointed out the base flow in the receiving stream is treated municipal wastewater from the City of Lubbock.

Table 5.3 Rainfall and Runoff for the Bridge Deck and Approach Highway at 289 Loop, Lubbock, TX

Storm Date	Rainfall	Runoff Volume				Receiving Stream	
		Bridge Deck		Approach Highway		Peak Flow Rate	
	mm	ft^3	m^3	ft^3	m^3	ft^3/s	m^3/s
01/17/04	50.29	66.8	1.89	2672.3	75.7	83.9	2.4
02/24/04	20.32	30.7	0.87	470.7	13.3	47.7	1.4
02/29/04	23.62	22.7	0.64	288.2	8.2	97.6	2.8
03/04/04	21.08	33.4	0.95	1246.1	35.3	62.2	1.8
04/04/04	22.10	40.1	1.13	95.7	2.7	98.5	2.8
06/18/04	16.51	37.4	1.06	119.3	3.4	75.1	2.1
06/28/04	17.27	33.4	0.95	65.1	1.8	40.8	1.2
08/20/04	13.70	23.2	0.66	119.3	3.4		
09/27/04	44.00	67.7	1.92	319.0	9.0		
11/03/04	22.90	28.9	0.82	142.1	4.0		
02/06/05	8.90	11.9	0.34	10.9	0.3		
05/15/05	30.10	66.8	1.89	186.2	5.3		

The rainfall and runoff data for the site near Houston and the average flow rate in Clear Creek for the period November 2003 through February 2005 are summarized in Table 5.4. The runoff data represent the entire storm event and are not restricted to the portion of the storm that was sampled. Bridge deck and approach highway runoff was recorded and sampled during 16 rainfall events at the FM 528 site on Clear Creek during the study period. The average rainfall for the 16 events for which runoff was sampled was 0.59 inches and ranged from 0.11 to 1.62 inches. Measured runoff from the approach highway ranged from 0.1 to 39.7 ft^3/s with an average flow rate of runoff of 6.1 ft^3/s. The average rate of flow of runoff from the bridge deck was 0.01 ft^3/s and ranged from 0.0003 to 0.0734 ft^3/s. The estimated peak flow in Clear Creek at the FM 528 bridge averaged 1030 ft^3/s for the measured rainfall events and ranged from 517 to 3888 ft^3/s. Therefore, the peak flow rate in the receiving stream at FM 528 was approximately five orders of magnitude greater than the flow rate from the bridge deck.

Table 5.4 Rainfall, Runoff from Bridge Deck and Approach Highway at FM 528, and Average Flow in Clear Creek, Houston, TX

			Bridge Deck				Approach Highway				Clear Creek	
Storm Date	Total Rainfall		Total Runoff Volume		Peak Flow Rate		Total Runoff Volume		Peak Flow Rate		Average Flow	
mm/dd/yy	inch	mm	ft^3	m^3	ft^3/s	L/s	ft^3	m^3	ft^3/s	L/s	ft^3/s	m^3/s
10/26/03	1.23	31.24	111.4	3.15	0.0015	0.04	######	17,488	39.7	1,137.9	517	14.6
11/15/03	0.49	12.45	8.2	0.23	0.0027	0.08	7,754	220	3.9	112.6	984	27.9
01/09/04	0.17	4.32	9.9	0.28	0.0011	0.03	37,893	1,073	1.5	42.2	685	19.4
01/16/04	0.21	5.33	77.9	2.21	0.0028	0.08	######	5,947	13.9	398.1	653	18.5
01/26/04	0.82	20.83	98.8	2.80	0.0035	0.10	34,540	978	3.6	102.7	544	15.4
02/04/04	0.63	16.00	20.8	0.59	0.0008	0.02	75,209	2,130	8.5	244.5	1332	37.7
02/10/04	1.24	31.50	18.2	0.52	0.0036	0.10	3,500	99	0.4	11.4	946	26.8
02/11/04	1.27	32.26	161.8	4.58	0.0063	0.18	######	3,309	7.0	199.8	3888	110.1
02/24/04	0.27	6.86	40.9	1.16	0.0061	0.18	1,306	37	0.1	1.7	750	21.2
03/05/04	0.22	5.59	1,305.1	36.96	0.0114	0.33	15,811	448	0.6	18.4	772	21.9
04/23/04	1.62	41.15	34.4	0.97	0.0003	0.01	68,237	1,932	5.9	169.5	892	25.3
06/08/04	0.56	14.22	57.2	1.62	0.0030	0.09	27,634	782	2.3	66.1	952	27.0
12/14/04	0.74	18.80	49.8	1.41	0.0057	0.16	72,831	2,062	3.8	108.7	----	----
01/25/05	0.11	2.79	45.0	1.27	0.0141	0.40	13,960	395	1.9	54.3	799	22.6
02/11/05	0.11	2.79	98.2	2.78	0.0022	0.06	15,516	439	1.2	33.0	756	21.4
02/25/05	0.13	3.30	122.4	3.46	0.0066	0.19	4,570	129	0.2	6.2	979	27.7
03/17/05	0.21	5.33	807.9	22.88	0.0734	2.10	######	3,856	9.1	261.6	----	----

The rainfall depths for most of the storms sampled was less than 1-inch of rain. Therefore, it was possible to completely sample the storm event of this magnitude without replacing the composite sample bottles mid-storm and mixing the samples at the lab to obtain an EMC (event median concentration). Therefore, the preponderance of the rainfall events was within the selected effective sampling range. The concentrations reported for larger storms overestimate the actual EMCs because the concentrations of most constituents typically are lower in runoff that occurs late in the storm event than those observed at the beginning of the storm; however, the runoff at the end of the storm is not sampled for the largest storms.

5.2 Analytical Results

Flow-weighted composite samples of bridge deck and approach highway runoff composite samples were collected at each of the three sites. These runoff samples were analyzed for the first 14 parameters listed in Table 4.1 on page 25.

Paired grab samples of runoff were collected and analyzed for fecal coliform and oil and grease concentrations. Four and seven grab samples were collected, respectively, at the Austin Loop 360 site at Barton Creek and the Lubbock FM 289 site. The time delay between collecting grab samples at the FM 528 at Clear Creek site in Friendswood and actual analyses in Austin rendered the coliform and oil and grease data unusable.

The reported concentrations of the constituents in the runoff from the bridge deck, approach highway, and receiving stream at each of the three sites are presented in Appendix B, Tables B-1 through B-9. Average and median concentrations for each constituent in the runoff of the bridge deck and approach highway for the entire sampling period for all sites are summarized in Table B-10.

The average concentrations of each constituent that was measured in the runoff from the bridge deck and approach highway at each site are summarized in Table 5.5. The average concentrations reflect the unique meteorological characteristics of the area in which the sampling sites were located. The average concentrations of all the constituents observed in the runoff from the bridge deck and approach highway at the Loop 360 site in Austin, the FM 289 site in Lubbock and the FM 528 site in Houston are of the same order of magnitude with few exceptions. The average suspended solids concentrations in the bridge deck and approach highway runoff collected at the FM 528 sites in Houston was about one half to one third of those observed at the other two sites. A more meaningful way of evaluating the water quality of the runoff is to evaluate concentrations of constituents in runoff samples from the bridge deck and approach highway collected at the same site during the same rainfall event.

Table 5.5 Average Concentration of Constituents in Runoff from Bridge Deck and Approach Highway

Constituent	Units		AUS	LUB	HOUS		AUS	LUB	HOUS
Copper, Total Average	µg/L		16.4	18.7	18.2		23.5	21.8	8.5
Copper, Dissolved average	µg/L		4.2	7.6	11.9		6.5	8.9	4.9
Lead, Total Average	µg/L		9.9	14.3	5.4		13.1	18.1	2.3
Lead, Dissolved Average	µg/L		n/a	1.8	0.4		n/a	2.0	0.1
Zinc, Total	µg/L		166.5	127.6	140.9		134.6	123.5	38.2
Zinc, Dissolved	µg/L		28.8	72.4	77.3		30.7	62.7	17.2
Nitrogen, Nitrate (As N)	mg/L		0.3	0.3	1.4		0.4	0.3	0.6
Nitrogen, Kjeldahl, Total	mg/L		1.0	3.4	1.1		1.5	2.1	1.0
Chemical Oxygen Demand	mg/L		33.3	71.7	40.8		56.2	78.3	27.7
Phosphorus, Total (As P)	mg/L		0.1	1.1	0.1		0.1	0.9	0.1
Phosphorus, Dissolved (As P)	mg/L		0.1	0.9	0.0		0.1	0.7	0.1
Suspended Solids - Total	mg/L		111.8	104.0	53.0		119.2	109.4	30.8
Suspended Solids - Volatile	mg/L		21.3	24.3	11.2		25.0	27.8	9.9
Fecal Coliform	cfu/ 100		5550	650	n/a		4925	1600	n/a
Oil & Grease, Total Recoverable	mg/L		4.79	4.4	n/a		6.24	7.1	n/a

n/a : Indicates that there were insufficient detections of this constituent to allow statistical analyses

5.3 Hypothesis Testing of the Data

Paired runoff samples were collected from the bridge and the approach highway for the same rainfall event at all sites to determine any statistically significant difference between the concentration of a constituent of the bridge deck runoff and the approach highway runoff. A paired test compares the difference between two samples to a reference value (usually 0 or no difference) as opposed to comparing the mean of one sample to the mean of another. A paired test is much more robust than an ordinary t-test because the variability associated with each storm event is factored out. A t-test of concentrations of a given parameter of paired samples ensures that any conclusions regarding the concentrations observed at each are a result of phenomena observed at those sites, and are not a result of differences in storm characteristics.

Results of the null hypothesis testing of concentrations of constituents in paired samples of runoff from the bridge decks and approach highways that were sampled at the sites in Austin, Lubbock, and Houston are presented in Table B-11 in Appendix B. Calculated p-values and 95% confidence levels also are included in the tabular data. A summary of the results of the null hypothesis testing is presented in Table 5.6.

Table 5.6 Summary Results of Null Hypothesis Testing for the Sites Monitored

	Austin		Lubbock	Houston	
Constituent	Hypothesis Accepted?	Bridge Deck Concentration is:	Bridge Deck Concentration is:	Hypothesis Accepted?	Bridge Deck Concentration is:
Copper, Total	Alternative	lower	no difference	Alternative	higher
Copper, Dissolved	Alternative	lower	no difference	Alternative	higher
Lead, Total	Alternative	lower	no difference	Alternative	higher
Lead, Dissolved	Null	no difference	no difference	Null	no difference
Zinc, Total	Null	no difference	no difference	Alternative	higher
Zinc, Dissolved	Null	no difference	no difference	Alternative	higher
Nitrogen, Nitrate (As N)	Null	no difference	no difference	Alternative	higher
Nitrogen, Kjeldahl, Total	Alternative	lower	no difference	Null	no difference
Chemical Oxygen Demand	Alternative	lower	no difference	Alternative	higher
Phosphorus, Total (As P)	Alternative	lower	no difference	Alternative	lower
Phosphorus, Dissolved (As P)	Null	no difference	no difference	Alternative	lower
Suspended Solids - Total	Alternative	lower	no difference	Null	no difference
Suspended Solids - Volatile	Alternative	lower	no difference	Null	no difference
Fecal Coliform	Null	no difference			
Oil & Grease Recoverable	Null	no difference			

The data indicate that the concentrations in the bridge deck runoff of all constituents monitored were lower than or equal to the concentrations measured in the runoff of the approach highway on Loop 360 at Barton Creek in Austin. However, the null hypothesis data for FM 289 in Lubbock indicate that no instance occurred in which the concentration of a constituent in the bridge runoff was significantly different from that of the approach highway. The null hypothesis test was not performed on the Fecal Coliform or Oil and Grease data because of the low number of samples collected at the Lubbock site. Only phosphorus concentrations in the bridge deck runoff were lower than that the concentration in the runoff from the approach highway on FM 528 at Clear Creek in the Houston area. The null hypothesis data indicate no difference in the concentrations of dissolved lead, Total Kjeldhal Nitrogen, Total Suspended Solids and Volatile Suspended Solids in the runoff from the FM 528 bridge deck and the runoff from the approach highway. However, the concentrations of copper, lead, zinc, and nitrate Nitrogen were higher in the runoff from the bridge deck than that observed in the runoff from the approach highway of FM 528 at Clear Creek. The null hypothesis test was not performed on the Fecal Coliform or Oil and Grease data because of the low number of samples collected at the Houston site.

5.4 Annual Loading

The annual loadings (pounds/year) of the constituents that were monitored in the bridge deck runoff at each of the three sites were compared with the loadings (pounds/year) of the same constituents in the respective receiving streams. The loadings are summarized in Table 5.7

Not all storms were sampled during the course of this study and the total rainfall amount was not similar to the yearly average in Austin. Loads for each constituent were estimated from the entire Loop 360 bridge over Barton Creek on an annual basis based on the average concentration of each constituent (Table 5.5), a runoff coefficient = 0.95, the average annual rainfall (34.2 inch/yr) for Austin(NOAA, 2004),and total area of the bridge (30,000 ft^2).

Water quality constituents for Barton Creek at Loop 360 have been measured by the USGS since 1978. However, composite samples were collected only since June 2000. The concentrations reported for these composite samples were used for comparison with results for the composite samples of runoff collected at the Loop 360 bridge in this study. The average base flow and storm flow concentrations for each constituent in Barton Creek are presented in Table B-11 in Appendix B. The Load in Barton Creek is based on an average stream flow of 48.4 ft^3/s (Section 5.1 Rainfall and Runoff) and the concentrations of constituents listed in Table B-11.

Table 5.7 Annual Constituent Loads in Receiving Streams and Annual Constituent Loads in Runoff from Bridge Decks in Austin, Lubbock and Houston

Constituent	Annual Load in Barton Creek	Annual Load in Bridge Runoff	Bridge Runoff Load (% of Load in Creek)	Annual Load in Stream	Annual Load in Bridge Runoff	Bridge Runoff Load (% of Load in Stream)	Annual Load in Clear Creek	Annual Load in Bridge Runoff	Bridge Runoff Load (% of Load in Creek)
	lb/yr	lb/yr	%	(lb/yr)	lb/yr	%	lb/yr	lb/yr	%
Copper, Total	472	0.09	0.018	516	0.03	0.006	4580	0.18	0.004
Copper, Dissolved		0.02		163	0.01	0.007	1520	0.12	0.008
Lead, Total	298	0.05	0.017	616	0.02	0.004	3	0.05	1.742
Lead, Dissolved		ND		34	0.00	0.007	20	0.004	0.020
Zinc, Total	1500	0.84	0.056	2750	0.20	0.007	19100	1.37	0.007
Zinc, Dissolved		0.15		830	0.11	0.014	7020	0.75	0.011
Nitrate (As N)	23424	1.74	0.007	5.1E+07	0.43	0.000	7.5E+05	13.20	0.002
TKN				2.3E+05	5.37	0.002	5.8E+05	10.42	0.002
Total Ntrogen	104962	6.70	0.006						
Chemical Oxygen Demand	2.1E+06	170	0.009	3.0E+06	113	0.004	1.4E+07	395	0.003
Phosphorus, Total (As P)	13591	0.57	0.004	1.7E+04	1.73	0.010	2.3E+05	0.61	0.0003
Phosphorus, Dissolved (As P)	4735	0.42	0.008	4192	1.42	0.034	1.9E+05	0.18	0.0001
Suspended Solids - Total	1.5E+07	568	0.004	6.7E+06	164	0.002	1.1E+08	514	0.0005
Suspended Solids - Volatile	5.8E+05	115	0.020	1.5E+06	38.3	0.003	1.2E+07	108	0.001
Fecal Coliform*	2.5E+16	3E+11	0.001	2.0E+14	1E+09	0.001			
Oil & Grease,		21.5		7E+04	6.4	0.009			

*express as cfu/yr

A comparison of the annual load of each constituent contributed by the Loop 360 bridge runoff to the load present in Barton Creek at Loop 360 indicates that the load contributed by the bridge runoff is several orders of magnitude less than the load in Barton Creek upstream of the bridge. The load of constituents contributed by the runoff from the Loop 360 bridge deck to Barton Creek is minimal (ranging from 0.004% for total phosphorus (as P) and total suspended solids to 0.056% for total zinc). The results indicate that storm water runoff from the Loop 360 Bridge does not result in any substantial adverse impact to the water quality in Barton Creek.

The average loads of constituents contributed by the runoff from the bridge deck for the entire Loop 289 bridge to North Fork of the Double Mountain Fork of the Brazos River were estimated on an annual basis using the average concentration of each constituent (Table 5.5), a runoff coefficient = 0.95, average annual rainfall = 18.7 inch/yr and a total area of the bridge = 16,888 ft^2.

No stream flow or water quality data is available for segment of the North Fork of the Double Mountain Fork of the Brazos River at the FM 289 Bridge. Therefore, the flow measurements observed and the water quality data reported for the stream during this study were used to calculate the mass loadings of the constituents in the stream. The calculated average flow during the time period of September 15, 2003 to May 15, 2005 was 9,560 gallons per minute (21.3 ft^3/s). Concentrations of constituents in flow-weighted samples of the North Fork of the Double Mountain Fork of the Brazos River for all rainfall events monitored, at bridge site, Loop 289 Lubbock, TX are presented in Table B-5 in Appendix B.

A comparison of the annual load of each constituent contributed by the Loop 289 bridge runoff to the load present in the North Fork of the Double Mountain Fork of the Brazos River indicates that the load contributed by the runoff from the FM 289 bridge deck is several orders of magnitude less than the load upstream of the bridge. Therefore, load of constituents to the North Fork of the Double Mountain Fork of the Brazos River is minimal (ranging from 0.002% for total suspended solids to 0.034% for dissolved phosphorus as P). The results indicate that storm water runoff from the Loop 289 bridge does not result in any substantial adverse impact to the water quality in North Fork of the Double Mountain Fork of the Brazos River.

The average annual loadings of constituents from the F.M. 528 bridge deck into Clear Creek was calculated based on the average concentration of each constituent (Table 5.5), a runoff coefficient = 0.95, the average annual rainfall (48inches/yr for the vicinity of Friendswood, TX), and the total area of the bridge, which equaled 40,903 ft^2. The loads were estimated for the entire F.M. 528 bridge over Clear Creek on an annual basis.

The flow measurements from the USGS data indicate an average annual stream flow of 500 ft^3/s for Clear Creek at F.M. 528. The average storm flow was assumed to be approximately fifty percent of the stream flow, thus the average annual storm flow was 250 ft^3/s. The estimated loading of the monitored constituents in Clear Creek were based on the storm flow at F.M. 528 (250 ft^3/s and the concentrations of the constituents in flow-weighted samples of Clear Creek for all rainfall events (Table B-9 in Appendix B).

The data presented in Table 5.7 indicate that the annual load of each constituent contributed by the F.M. 528 bridge runoff is significantly lower than the load in Clear Creek. The load of constituents from the runoff of the FM 528 bridge deck to Clear Creek is minimal (ranging from 0.0001% for dissolved phosphorus (as P) up to 1.74% for total Lead). The exceptionally high concentration of zinc in the bridge runoff is caused by rainwater dripping from the galvanized railings long the walkway on the bridge. Therefore, the results indicate that storm water runoff from the bridge deck on FM 528 at Clear Creek does not result in any substantial adverse impact to the water quality Clear Creek near Friendswood, TX.

6. Conclusions and Recommendations

1. The average concentrations of constituents monitored reflect the unique meteorological characteristics of the area in which the sampling sites were located.
2. The results indicate that bridge deck runoff at the Loop 360, Loop 389 and FM 528 sites does not result in any substantial adverse impact to the water quality in Barton Creek, North Fork of the Double Mountain Fork of the Brazos River and Clear Creek, respectively.
3. The mass loadings of constituents contributed by the runoff from the bridge decks were minimal compared to the mass loads of constituents carried by the respective receiving stream. The mass load contributed by the bridge deck runoff was less than 0.01% of the mass load in the receiving stream.
4. Statistical tests indicate that the concentrations in the bridge deck runoff of all constituents monitored were lower than or equal to the concentrations measured in the runoff of the approach highway on Loop 360 at Barton Creek in Austin.
5. Statistical analysis of the data for Loop 289 in Lubbock indicate that no instance occurred in which the concentration of a constituent in the bridge runoff was significantly different from that of the approach highway.
6. Only phosphorus concentrations in the bridge deck runoff were lower than that the concentration in the runoff from the approach highway on FM 528 at Clear Creek in the Houston area. The null hypothesis data indicate no difference in the concentrations of dissolved lead, Total Kjeldhal Nitrogen, Total Suspended Solids and Volatile Suspended Solids in the runoff from the FM 528 bridge deck and the runoff from the approach highway. However, the concentrations of copper, lead, zinc, and nitrate Nitrogen were higher in the runoff from the bridge deck than that observed in the runoff from the approach highway of FM 528 at Clear Creek.
7. The average suspended solids concentrations in the bridge deck and approach highway runoff collected at the FM 528 sites in Houston were 53 and 31 mg/L, respectively, or about one half those observed at the Loop 360 site in Austin (112 and 119 mg/L) and the Loop 289 site in Lubbock (104 and 109 mg/L, respectively).
8. The average concentrations of the other constituents in the bridge deck and approach highway were of the same order of magnitude at each of the three sites that were monitored.
9. Highway runoff data could be used as a conservative proxy for bridge deck runoff for the constituents monitored in this study, if site-specific bridge deck runoff data were unavailable.

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Appendix A: Description of Sites

This appendix includes specific information about the physical features of the approach highway and bridge, the characteristics of the receiving stream at each site as well as a meteorological description. Instrumentation, flow measurement, and water quality sampling equipment installed at each site also is discussed.

Central Texas Sites, Austin, TX

Loop 360 Bridge Deck, Austin

Loop 360 is a 14-mile stretch of state highway that extends from US 290 southwest of Austin, northward and eastward to US 183 just west of the Missouri Pacific Railroad right-of-way (TxDOT, 2003). The location of the project site is Loop 360 west of South Lamar Blvd. and east of Loop 1 (Mopac). The site consists of a bridge, an approach highway, and a receiving stream. The bridge spans Barton Creek, an ephemeral stream with peak flows exceeding 30,000 cubic feet per second. The approach highway is southeast of the bridge to the. A GIS image of the project site is presented in Figure A-1.

Key criteria for selection of this site are:

1. The runoff from a portion of the bridge deck drains by gravity to a single point.
2. A USGS flow gauging station that records real-time flow data for Barton Creek is located between the two decks of the bridge.
3. There is easy access to the bridge from parking areas, and personnel are protected from traffic by guardrails.

The USGS provides real-time flow data as well as an historical archive of flow data and water quality data that dates back to February 1978. USGS collects composite water quality samples from Barton Creek for four storm events and two baseline events annually (USGS, 2004). The Loop 360 bridge over Barton Creek consists of two separate T-beam concrete decks supported by circular reinforced concrete piers. One deck carries two lanes of traffic to the northwest, and the other deck provides two lanes for travel to the southeast. The surface area of the two decks is 60,000 ft^2. The surfaces of the bridge deck are impervious, and scupper drains are located every 6 linear feet. Some of the scupper drains along each guardrail discharge directly into the creek. The two decks are separate Therefore, only a portion of the surface area of the bridge contributes to the samples collected at the bridge site. Field observations of the volume of runoff during normal rain events indicate that the last two sections of the southbound lanes contribute to the runoff samples during normal rainfall events. The estimated drainage area was approximately 2,357 ft^2 ($219m^2$). The assumed runoff coefficient was 0.95. Photos of the Loop 360 bridge are presented in Figure A-2 and Figure A-3.

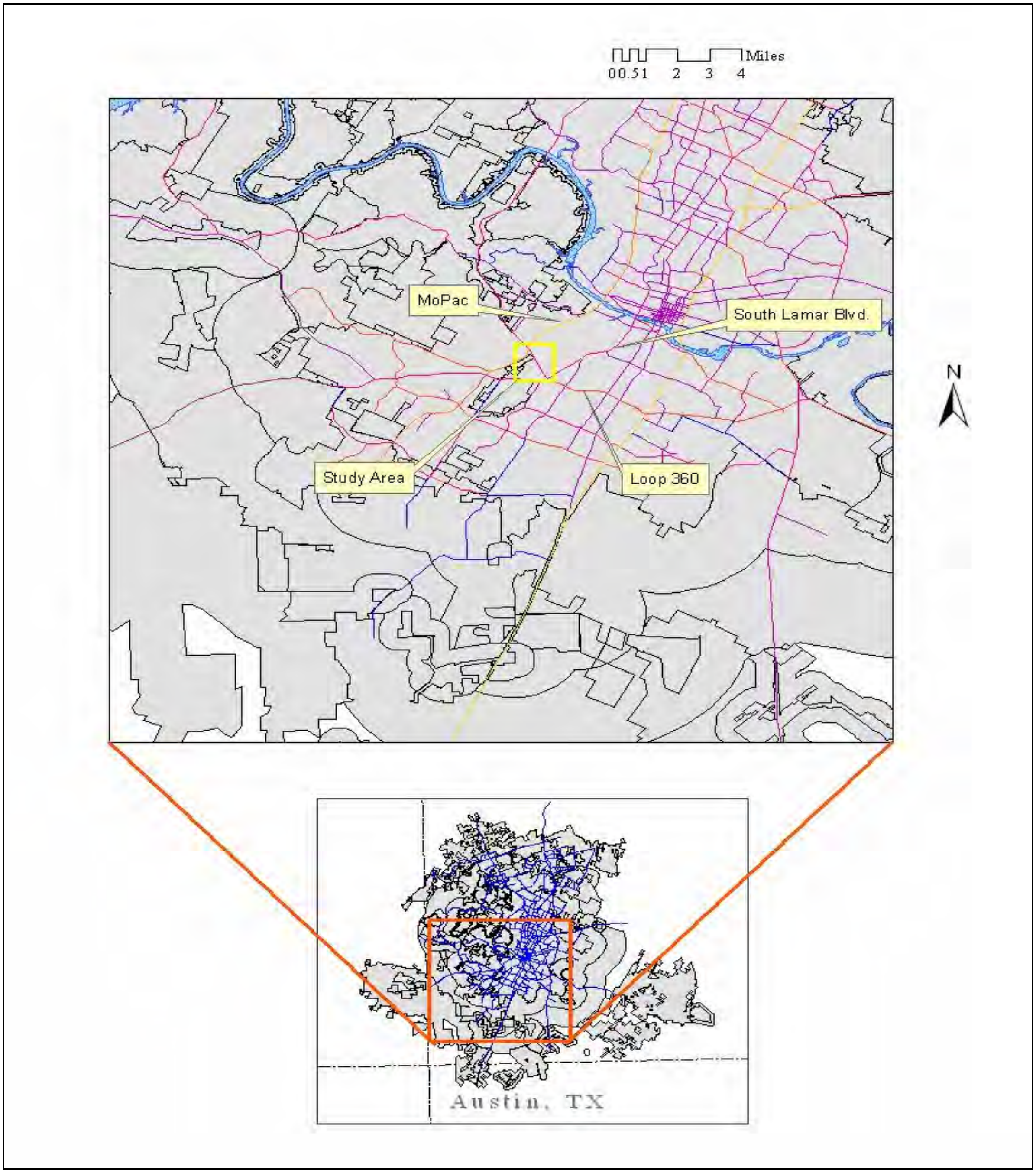

Figure A-1. Map of Study Area in Austin, Texas

Figure A-2. Loop 360 Bridge, Austin, TX

Figure A-3. Security Box at the Loop 360 Bridge, Austin, TX

Loop 360 Approach Highway, Austin

The approach highway is located immediately to the southeast of the Loop 360 bridge. The length of highway that drains to the catchments point extends southeast from the bridge to the crest of the South Lamar overpass. The drainage area for the approach highway is approximately 250,000 ft^2 (23,270 m^2). A photo of the approach highway monitoring point is shown in Figure A-4. Several key requirements were satisfied by this site:

1. All runoff from the roadway surface is captured by curb inlets and conveyed through culverts to a single point.
2. There are no other land uses associated with this drainage area (e.g. no commercial, industrial, or residential inputs).

3. The approach roadway is easily accessible and is situated immediately adjacent to the Loop 360 bridge.

Figure A-4. Flow Monitoring and Runoff Point Approach Highway, Austin, TX

Barton Creek, Austin

Barton Creek is an ephemeral stream with peak flows exceeding 30,000 ft^3/s or 850,000 L/s. However, there are extended periods during the year when there is little or no flow in the creek. The USGS has monitored flows in Barton Creek at several locations since 1978. The average annual stream flow for Barton Creek at Loop 360 from 1978 to 2001 was 48.4 ft^3/s (1,370 L/s). The average stream flow was divided into base flow and storm flow based on the ratio base flow:storm flow = 0.49 (City of Austin, 1996). Therefore, the average annual base flow was 23.72 ft^3/s (671 L/s) and the average annual storm flow was 24.68 ft^3/s (698 L/s). A photograph of Barton Creek flowing underneath the Loop 360 bridge is presented in Figure A-5.

Figure A-5. Barton Creek at Loop 360 Bridge, Austin, TX

Barton Creek drains more than 120 square miles of mostly undeveloped terrain in the Texas Hill Country from the headwaters in Hays County to the confluence with the Colorado River in Austin (City of Austin, 1996). Almost two-thirds of the watershed lies within Travis County. Barton Creek extends over a length of 48 miles (COA, 1996). The geologic characteristics of the Barton Creek Watershed consist of an upper and lower portion separated by the Mount Bonnell Fault. The project site is located within the lower portion of the watershed that is situated on Edwards Limestone, which is characterized as karst formation.

Water quality in Barton Creek is a sensitive environmental issue among the local population. Barton Creek is dammed a few hundred feet upstream of the confluence with the Colorado River to capture water for Barton Springs Pool, which is a popular swimming facility. Barton Springs is the only known location of the Barton Springs salamander; therefore, the quality and quantity of the water at Barton Springs is related to the water quality and flow of Barton Creek (Bio-West, 2002).

About 11 % of the Barton Creek watershed was developed as of August 1996. The majority of this development occurred over a 6,500-acre area in the lower potion of the basin, adjacent to downtown Austin. In 1992, the City of Austin's Planning Department estimated impervious cover northwest of Loop 360 to be 5.5 %. The impervious cover in the watershed including the developed area south of Loop 360 is approximately 6.2 % (COA, 1996).

The Austin City Council directed city staff to evaluate non-point-source pollution control strategies for the Barton Creek watershed. Non-degradation of the water quality in Barton Creek was identified as the goal of the city (COA, 1996).

Meteorological Description

The average annual rainfall in Austin, TX is 34.72 inches (88.19 cm) based on a 30-year period of data. These data were collected at Austin-Bergstrom International Airport (formerly Bergstrom AFB) by the National Oceanic and Atmospheric Association (NOAA). Austin-Bergstrom International Airport is located 6.11 miles to the east of the project site. Historically, the wettest month in Austin is May and the driest month is February. The highest recorded rainfall in a single year was 52.2 inches in 1991 and the lowest annual rainfall was 11.4 inches in 1954 (NOAA, 2004). Snowfall is rare in the Austin area; therefore, highway de-icing rarely is practiced. The average temperature for the area is 79.5^{o}F (26.4^{o}C) (NOAA, 2004).

Runoff Flow Measurement and Sampling

Runoff flow was measured at the bridge site with a 0.5-foot, trapezoidal H-flume constructed of molded fiberglass and an area-velocity meter that was installed at the approach highway site. The rational method was implemented to size the H-flume for the 2-year return frequency storm based on the intensity-duration-frequency curves for the City of Austin. The selected storm duration was 15 minutes based on an estimate of the time of concentration of the bridge catchments. The resulting rainfall intensity was 4.6 in/hr. This rainfall intensity, duration, and estimated catchments area result in a runoff flow rate of 0.25 ft^3/s (7.1 L/s). Manufacturer performance data indicate that a 0.5-foot H-flume can accommodate a flow of 0.331 ft^3/s (9.4 L/s) without overtopping. The selection of the 0.5-foot H-flume provides a safety factor of 1.3 of the design storm assuming that 100% of the rainfall runs off. Pool depth in the flume and accompanying flow were measured by an ISCO ® 4230 bubbler flow meter. Bubbler flow meters measure the air pressure required to push a bubble through an orifice at the bottom of the level pool to determine the depth of water in the control section of the flume. The rate of flow that corresponds to the calculated depth is generated from the stage/discharge relationship provided by the manufacturer. The flume was supported by threaded rod that was anchored in concrete in order to assure the level orientation of the flume that is required for accurate flow measurement. A photo of the flume installation at the bridge site is shown in Figure A-6.

Figure A-6. H-Flume Installation at the Loop 360 Bridge Site, Austin, TX

An ISCO ® 3700 series automatic sampler was used to collect flow weighted composite samples of bridge runoff. A specially designed stainless steel sample strainer was installed in the approach channel of the H-flume to prevent clogging of the intake tube by sediment and debris that could interfere with sampling the runoff. The monitoring equipment was stored in a 3-foot x 5-foot steel security box. Metal conduit was used to convey all tubing from the flume to the sampler to minimize the chances of vandalism or incidental damage. A 12-volt marine battery that was charged by a Solartec® solar module served as a power source for the equipment. Power regulating devices (dampers) were used to prevent overcharging and premature discharge of the battery.

The runoff was measured at the approach highway using an ISCO ® 4250 area-velocity meter. This flow measuring device was selected because the approach highway sample point is in a concrete culvert immediately upstream from an extended detention/sand filtration BMP. Backwater effects may occur upstream of the ponds during large storm events. The area-velocity meter is not affected by backwater effects. The ISCO ® 4250 uses a pressure transducer to gauge depth above the probe and a Doppler anemometer to measure the velocity of particles past the probe. An ISCO ® 3700 automatic sampler, identical to the one installed at the bridge site, was used to collect flow-weighted composite samples of runoff from the approach highway. The probe cable and sampler tube were run through metal conduit to the 3-foot x 5-foot security box that contained the sampler and data collection equipment. The area-velocity meter and accompanying automatic sampler can be seen mounted in the security box in Figure A-7.

A sample strainer and power supply arrangement similar to that used at the bridge site was installed at the approach highway site. The area-velocity probe was anchored to a low profile galvanized metal base plate to withstand the high shear forces resulting from the water velocity through the culvert during large runoff flows from high rainfall events. The base plate was attached to the bottom of the culvert using 5/16" Tapcon® epoxy coated concrete anchors. The sample strainer was mounted normal to the direction of flow immediately adjacent to the area-velocity probe. The sample strainer, area-velocity probe, and base plate installation are shown in Figure A-8. An ISCO® 674 tipping-bucket rain gage was anchored to a concrete retaining wall next to the inflow box culvert at the approach highway site.

Figure A-7. ISCO 4250 A-V Meter and 3700 Sampler installed at the Approach Highway Site on Loop 360, Austin, TX

Figure A-8. Sample Strainer, A-V Probe, and Base Plate Installation in Culvert at the Approach Highway Site, Loop 360, Austin, TX

High Plains Site, Lubbock, TX

Loop 289 Bridge Deck, Lubbock

Loop 289 is a section of state highway that completely circles the city of Lubbock. The location of the project site is East Loop 289 North of the 50th Street interchange. The site consists of a bridge, an approach highway, and a receiving stream. The bridge spans the North Fork of the Double Mountain Fork of the Brazos River (NFDMFBR), an ephemeral stream with peak flows approaching 148 ft^3/s (4 m^3/s) during the study period. An image of the project site is presented in Figure A-9.

Figure A-9. Loop 289 Bridge, Lubbock, TX

The average daily traffic volume is 10,000 vehicles per day. Key criteria for selection of this site are:

1. The runoff from a portion of the bridge deck drains by gravity to a single point.
2. There is easy access to the bridge from parking areas, and the sampling personnel are protected from traffic by guardrails.

The Loop 289 bridge over the NFDMFBR consists of T-beam concrete decks supported by circular reinforced concrete piers. One deck carries two lanes of traffic to the north, while the other deck provides two lanes for travel to the south. Each bridge is 203 (61m) feet long and 41.6 (12.5m) feet wide, resulting in a surface area of 8,444 ft^2 (762.5m^2) per deck. The surfaces of the bridge deck are completely impervious and scupper drains are located every 20.3 linear feet (6.1m). Not all of the surface area of the bridge contributed to the samples collected at the bridge site, since only one scupper drain was sampled. Field observation of the volume of runoff during normal rain events indicated that approximately 800 ft^2 (72m^2) of the middle sections of the northbound lanes contribute to the runoff samples during normal rainfall events. Photos of the Loop 289 bridge are presented in Figures A-10 and A-11.

Figure A-10. Loop 289 Bridge, Lubbock, TX

Figure A-11. The Loop 289 Bridge, Lubbock, TX

Loop 289 Approach Highway, Lubbock

The approach highway is located immediately to the north of the Loop 289 bridge. The length of highway that drains to the catchments point extends north from the bridge to the crest of an adjacent hill. The drainage area for the approach highway is approximately 65,844 ft^2

($7316\ m^2$) while the specific area captured by the flume was estimated at $1588\ ft^2$ ($143m^2$). Several key requirements were satisfied by this site:

1. There is no other land use associated with this drainage area (e.g. no commercial, industrial, or residential inputs).
2. The approach roadway is accessible easily and is situated immediately adjacent to the Loop 289 bridge that was described above.

A photo of the monitoring site for the approach highway is shown in Figure A-12.

Figure A-12. Flow Monitoring and Runoff Sampling Point on the Approach Highway, Lubbock, TX

North Fork of the Double Mountain Fork of the Brazos River, Lubbock, TX

The North Fork of the Double Mountain Fork of the Brazos River is an ephemeral stream with peak flows approaching 148 ft^3/s or 4,000 L/s. However, there are extended periods during the year when there is little or no flow in the creek. A photograph of North Fork of the Double Mountain Fork of the Brazos River flowing underneath the Loop 289 bridge is presented in Figure A-13.

Figure A-13. North Fork of the Double Mountain Fork of the Brazos River

The North Fork of the Double Mountain Fork of the Brazos River drains selected runoff within the city of Lubbock. Runoff is collected in a series of small canyon interconnected lakes within the city and excess flow (above evaporation) is the major source of water. In addition, some wastewater from the Municipal Wastewater Treatment Plant is released to the upstream lakes.

Meteorological Description

Lubbock has an annual precipitation of 18.7 inches/yr, as indicated by the National Weather Service Historically, the wettest month in Lubbock is June, and the driest month is January. The highest recorded rainfall in a single year was 40.55 inches in 1941 and the lowest annual rainfall was 8.73 inches in 1917 (NOAA, 2004). Snowfall is normal a few times a year in the Lubbock area and highway de-icing is practiced. The average temperature for the area is 59.7^{o}F (NOAA, 2004).

Runoff Flow Measurement and Sampling, Lubbock

Runoff flow was measured at the approach highway site with a 0.5-foot, trapezoidal H-flume constructed of molded fiberglass and an area-velocity meter that was installed at the approach highway site. Performance data provided by the manufacturer indicated that a 0.5-foot H-flume can accommodate a flow of 0.331 ft3/s (9.4 L/s) without overtopping.

A photo of the flume installation at the bridge site is shown in Figure A-14.

Figure A-14. H-Flume Installation at the Loop 289 Bridge Site, Lubbock, TX

The selection of the 0.5-foot H-flume provides a safety factor of 1.3 of the design storm assuming that 100% of the rainfall runs off. An ultrasonic level sensor (ISCO 4110) was used to measure the depth of water in the flume and the flow was calculated accordingly, based on the depth. The single-head sensor is sealed in a rugged, corrosion-resistant enclosure and transmits a sound-pulse that is reflected from the surface of the water stream. The elapsed time between sending a pulse and receiving an echo determines the level in the channel. The flume was supported by threaded rod that was anchored in concrete in order to assure the level orientation of the flume that is required for accurate flow measurement. An ISCO ® 3700 series automatic sampler was used to collect flow weighted composite samples of the runoff from the approach highway. A specially designed stainless steel sample strainer was installed in the approach channel of the H-flume to prevent clogging of the intake tube by sediment and debris that could interfere with sampling of the runoff. The monitoring equipment was stored in a 3-foot x 5-foot steel security box. Metal conduit was used to convey all tubing from the flume to the sampler to minimize the chances of vandalism or incidental damage. A12-volt marine battery that was charged by a Solartec® solar module served as a power source for the equipment. Power regulating devices (dampers) were used to prevent overcharging and premature discharge of the battery.

A portion of the precipitation that falls on the east deck of the bridge drains into a 1875-liter polypropylene tank that was located under the bridge deck and was connected to the drain with 50-mm diameter tubing. A photo of the collection tank at the bridge site is shown in Figure A-15.

Figure A-15. Bridge Sampling Tank at the Loop 289 Bridge Site, Lubbock, TX

The average flow rate was determined by measuring the volume of runoff collected in the tank and the duration of the storm event. Composite and grab samples were collected for analysis. The sample collected in the tank was mixed vigorously with the help of a pump connected to the rear of the truck. After mixing the sample collected in the tank for about 15 minutes, a composite sample was withdrawn. Grab samples are collected during the rain event from the drain. The runoff in the tank was drained out after a sample was withdrawn and the tank was cleaned thoroughly by using a jet of water.

A photograph of the stream sampling station is presented in Figure A-16.

(Note the ultrasonic level sensor may be seen on the smaller bridge column at the far right)

Figure A-16. Stream Sampling Station at the Loop 289 Bridge Site, Lubbock, TX

The rate of water flow in the stream was calculated base on the depth of water in the stream and the cross-sectional area of flow. The depth of water was measured using an ultrasonic level sensor (ISCO 4110) that was suspended from the bridge deck (Figure A-16). The cross section of the channel was considered trapezoidal for ease in calculations. The dimensions of the stream cross-section are top width of the channel approximately was 41.6 ft (12.5m) and bottom width approximately was 21.3 ft (6.4m),. The roughness of the channel is 0.067 and the slope of the channel is 0.001097. A tipping-bucket rain gauge (ISCO ® 674) that is shown in Figure A-17 was used to measure rainfall at the site.

Figure A-17. Rain Gauge at Bridge Site, Lubbock, TX

The ultrasonic level sensor and the rain gauge were connected to the flow logger, which was housed in a steel security box along with the automatic sampler (seen in Figure A-16). The flow rate, depth of water and rainfall data were stored in the flow-logger and were retrieved periodically using a field computer. ISCO FLOWLINK 4.15 was used for efficient data storage and management. All equipment was configured so that data were recorded at 5-minute intervals.

A large stainless steel strainer connected to 6.4-mm polypropylene tubing was used to collect water from the stream. The strainer was that was in turn connected to an automatic sampler. The sampler functioned in a similar fashion as the unit that was located at the approach highway, except that the stream sampler was triggered by the intensity of rainfall (>= 1.27 mm). Flow weighted composite samples were collected in four glass bottles each having a volume of 3,800 mL. The samples from the four glass bottles were thoroughly mixed and one sample composite sample was withdrawn and sent for analysis. The glass containers, after withdrawal of a sample, were washed thoroughly with a jet of water and replaced in the automatic sampler

Coastal Site, Friendswood, TX

F.M. 528 Bridge Deck over Clear Creek

The bridge deck is located on FM 528, a major highway that runs through Harris, Galveston, and Brazoria counties. The location of the site is shown in Figure A-18. The FM 528 bridge is shown in Figure A-19 at the crossing of Clear Creek. The bridge is of composite, re-enforced concrete construction and consists of three spans of type 4 pre-stressed pre-cast girders. The bridge deck 8 inches thick. The bridge spans 360 feet in three sections each supported on 36-inch diameter columns on pile foundations and conventional bent cap construction. The bridge deck is approximately 106 feet wide with three 12-foot lanes of traffic in each direction separated by a 14-foot wide center lane. The 10-foot wide sidewalk on each side of the bridge for pedestrian traffic is isolated from the vehicular traffic by a continuous concrete barrier. The pedestrian walkway is shown in Figure A-20.

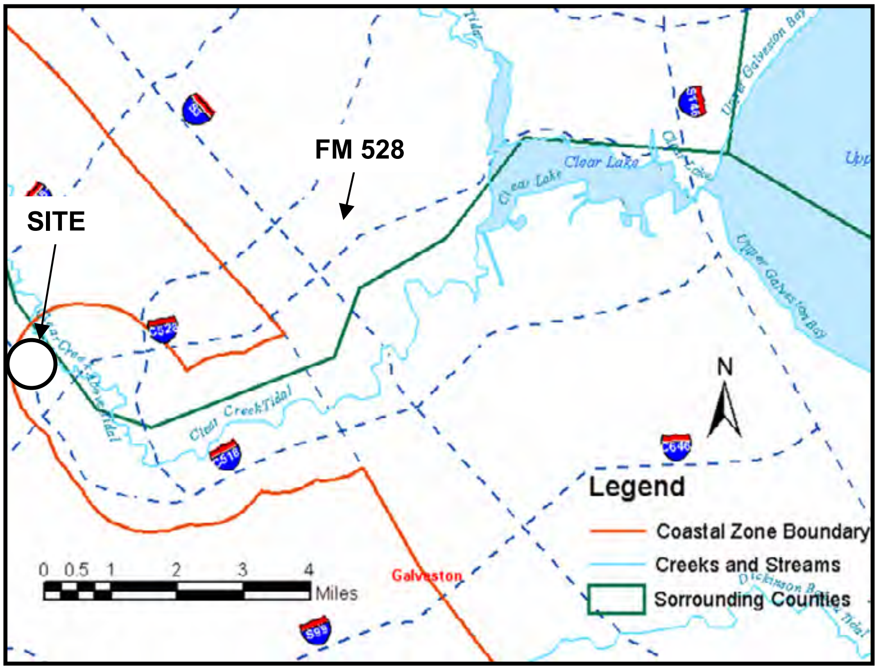

Figure A-18. Bridge Site Location in Coastal Zone near Friendswood, TX

Figure A-19. FM 528 Bridge at Clear Creek near Friendswood, TX

Figure A-20. Pedestrian Walkway & Bridge Deck, FM 528 Bridge at Clear Creek near Friendswood, TX

Stormwater runoff drains from the impervious bridge deck through 4-inch high and 12-inch wide scuppers that are approximately 8 feet apart that are installed in the concrete barrier that separates the pedestrian walkway from the bridge traffic (see Figure A-20). Runoff from the bridge deck flows directly into the creek. Therefore, a collection gutter was suspended along a portion of the brick deck to collect the bridge runoff for sampling. The gutter was connected to a 0.5-foot H-flume to measure the rate of flow of runoff. The gutter and flume installation are shown in Figure A-21 and Figure A-22. A second collection gutter was installed just below the railing on the pedestrian walkway (left side of Figure A-20) as the study progressed. This trough collected rainwater that dripped from the galvanized railing.

Figure A-21. Installation of Gutter to Collect Runoff from Bridge Deck at FM 528 Bridge at Clear Creek near Friendswood, TX

Figure A-22. H-Flume Installation on Gutter to Measure Rate of Flow of Runoff from Bridge Deck at FM 528 Bridge at Clear Creek near Friendswood, TX

Approach Highway Site on FM 528 near Friendswood, TX

The approach highway sampling site is located immediately to the west of the FM 528 bridge at the Clear Creek. The length of highway that drains to the catchment point extends from the FM 528 bridge to approximately 0.5 miles west of the bridge. Runoff from the approach highway flows into 6-foot wide curb opening inlets that are spaced at regular intervals. The inlets on both sides of the roadway drain to separate 24- inch diameter concrete conduits. Runoff from the north side of the roadway is conveyed beneath the roadbed at the point where the approach highway meets the bridge deck to the conduit carrying the runoff from the south side of the approach highway. The runoff from the entire approach highway segment is channeled via a 48-inch diameter culvert into a 105-foot by 160-foot detention pond shown in Figure A-23. Discharge from the detention pond is controlled by a concrete spillway. The drainage area this portion of the approach highway is approximately 320,920 ft^2.

Figure A-23. Detention Pond for Storage of Runoff from Approach Highway at FM 528 at Clear Creek, near Friendswood, TX

Clear Creek

The Clear Creek watercourse is a tidally influenced bayou that is approximately 45 miles long. Clear Creek meanders through Fort Bend, Brazoria, Harris, and Galveston counties and empties into Clear Lake that flows into Galveston Bay. The Clear Creek watershed covers approximately 260 square miles. The relative locations of Clear Creek, Clear Lake, Galveston Bay, F.M. 528, and the project site are shown in Figure A-18. Clear Creek is one of the largest un-channelized bayous in the city of Houston and supports a variety of river aquatic biota through feeding grounds and nurseries.

Meteorological Description, Coastal Margin Site near Friendswood

Climate data for Friendswood was estimated using the weather history of near by Ellington Field airport. The area is subject to abundant rainfall which, combined with favorable temperatures, results in a growing season of more than 290 days. The average monthly temperature in January is from 42 to 62°F and in June from 74 to 90°F. The coldest month is January (52°F average) and the hottest is July (84°F average). The average yearly rainfall is 48 inches. The highest rainfall event recorded in the area occurred in July 25-26, of 1979 when 43 inches of rain fell in a 24-hour period. Prevailing winds are from the southeast.

Runoff Flow Measurement and Sampling, Friendswood

Collection of samples of runoff from the approach highway and bridge deck on FM 528 as well as water quality samples from Clear Creek required two monitoring stations. Each station consisted of security enclosures that contained runoff flow recorders and runoff samplers for analyses of constituents in runoff. The first station was located near the approach roadway runoff outfall of the drainage culvert into the detention basin. A rain gage also was installed at the approach roadway monitoring site. An external solar cell was installed at each station to recharge a 12-volt battery that provided electric power for the equipment. This installation is shown in Figure A-24 and Figure A-25.

(Note: Inset Lower Right shows rain gauge mounted on side and solar panel on top of security enclosure)

Figure A-24. Flowmeter and Automatic Sampler in Security Enclosure at Approach Highway Culvert at FM 528 Site at Clear Creek, near Friendswood, TX

Figure A-25. Sampler Intake and Velocity Probe in Approach Highway Runoff Culvert at FM 528 at Clear Creek

The second station was located at the intersection of the FM 528 bridge and Clear Creek at the western bridge abutment. This station contained two water samplers one for the bridge deck and one for the stream, respectively as well as a flowmeter to measure flow in the flume on the bridge deck gutter. This installation is shown in Figure A-26.

Composite samples of runoff from the approach highway and bridge deck as well of the stream were collected using ISCO 3700 samplers. Flow measurements from the bridge deck and the approach roadway culvert were made using ISCO 4230 flow meters. The rate of flow in Clear Creek was recorded at a USGS monitoring station at the site.

Figure A-26. Automatic Samplers for Bridge Runoff and for Clear Creek and Flowmeter for Bridge Runoff at RM 528 and Clear Creek

Equipment Programming

Flow meter Programming

The first step in programming the flow and rainfall measuring equipment was assignment of partitions in the memory banks of the flow meters for each of the measured parameters. The parameters that were logged by the flow meter are rainfall (mm), depth of runoff (mm), velocity (m/s), and flow (L/s). A reading of each of these parameters was generated every 5 minutes throughout the study period. The memory of the ISCO® flow meters is sufficient to record measurements for approximately 1 month with no data loss. The meter begins overwriting the earliest of the stored data after about one month, depending on amount of data that is recorded at each 5-minute interval. This setup is called the rollover option. This configuration option was most advantageous for the purposes of this study because the chances for data loss on the front end of the monitoring period are minimized by stopping recording after the partitions are filled. The rollover does not stop recording when the partitions are filled, but writes over the first data. A negative effect is missing storms that may occur after the partitions are filled. Frequent downloading and proper archiving of data enables both setups to perform effectively. ISCO Flowlink® database software was utilized to archive all observations.

Automatic Sampler Programming

The variables that need to be defined to program the ISCO® 3700 sampler are the minimum size of the design storm, the number of aliquots required to collect a representative sample, the composite sample bottle volume, and the minimum volume of sample required to perform all analyses. The USEPA mandates that storms must be greater than 0.1 in (0.254 cm) to be considered for NPDES Phase I compliance monitoring. Ten aliquots were sufficient to characterize each storm. The minimum volume of sample required by LCRA Environmental Services for complete parametric analyses was 3 L (0.79 gal). Therefore, each aliquot was set at

300 mL. The capacity of the sample bottles was 9.4 L (2.48 gal) of sample. Therefore, the maximum size storm that may be completely sampled is approximately 3 times the size of the minimum storm (9.4L/3L = 3.133). Therefore, if the minimum storm is fixed at 0.1 inch, the maximum storm would be 3.133 * 0.1 inch = 0.313 inch. This relationship suggests that larger minimum storm sizes lead to wider sampling ranges, which is desirable given the wide variability of rainfall events in the Lubbock area. The minimum storm size that was selected was 0.25 inch (6.35 mm). The largest storm that may be completely sampled without changing bottles is 0.78 inch (19.8 mm). This range simultaneously accommodates

1. the sampling of small events
2. total sampling of the average event
3. minimizing the omission of samples during large events.

Sampler Pacing

One goal of this study was the collection of the most representative samples as practically possible. Therefore, flow-weighted composite samples were chosen. The automatic samplers were enabled when a specified water level condition is met. The approach highway sampler was triggered when the depth of water recorded in the culvert was 0.5 inch (13 mm). The receiving stream sampler was triggered when the rainfall exceeded 1.27mm. Once the samplers were enabled, the equipment remained enabled until the unit was reset upon retrieval of the composite samples. Total volume of the bridge runoff was collected as a single composite; therefore, no pacing was necessary. The ISCO® 3700 samplers automatically sample when enabled; therefore, large numbers of samples may be taken regardless of water level fluctuations. This approach could lead to a sample that was not flow weighted, and therefore not representative of the storm event. This shortcoming was overcome by pacing the samplers.

Runoff volume was used to pace the samplers for the bridge and approach highway sites. A signal was sent to the sampler every time a selected volume of water passes the sample point. The methodology that was chosen to input the initial pacing volume for the approach highway site is shown by the following calculation, which is based on the volume of runoff generated by minimum size storm that fell uniformly over the catchment with an impervious coefficient of 0.95. Following is the calculation of the sample pacing for the Loop 360 site in Austin.

Estimated catchment area = 250,500 ft^2 (23,270 m^2)

250,500 ft^2 (0.25 inch of rainfall) (1 foot/12inch) (0.95) = 4958 ft^3 (140,395 L)

4958 ft^3 / 10 aliquots = **495.8 ft^3 (14,040 L)** per aliquot = initial sample pacing

The same method was utilized to obtain the sample pacing for the bridge site. The only difference was the estimated catchment area. This initial estimate was low as a result of uncertainties associated with the runoff coefficient and catchment area. A value of 6.9 ft^3 (195 L) was used for the bridge site, and a value of 636 ft^3 (18,000 L) was used to pace the approach highway sampler. These figures were decided upon after examination of the hydrographs generated by the first two rainfall events. The samples from these two events were not analyzed.

Sample pacing calculations for the Loop 289 site in Lubbock are

- Estimated catchment area = 1,588ft^2 (143 m^2)
- 1,588 ft^2 (0.25 inch of rainfall) (1 foot/12inch) (0.95) = 31.4 ft^3 (848 L)
- 31.4 ft^3 / 10 aliquots = 3.14 ft^3 (84.8 L) per aliquot = initial sample pacing

A wider flow pacing was used at the Coastal Margin site near Friendswood to accommodate the increased basin area. the wider variation in storm intensity in the coastal area A minimum sample volume that was collected was 3.0 L and frequently the maximum sample volumes was 10 L for any given storm event. The bridge deck and culvert samplers were triggered when the depth of flow was measured at 0.02 feet. The bridge deck sampler also triggered the stream sampler. Flow pacing was accomplished by determining the flow volume between sampling events. The given volumes were 76,218 ft^3 (2,157 m^3) for the culvert and 9,714 ft^3 (275 m^3) by assuming an average rainfall of 0.25 inches and an impervious coefficient of 0.95. The approach highway catchment area was 320,920 ft^2 and the bridge deck area was 40,903 ft^2. Each sample aliquot was 300 mL and no sample pacing time was greater than 15 minutes.

Every sample consisted of nearly simultaneous triggering of all three samplers and was representative of 100% of the storm event. This is a lot of detail that applies only to the Austin site.

Appendix B: Concentrations of Constituents at Sites

Table B-1. Concentrations of Constituents in Flow-Weighted Samples of Runoff at the Bridge Site for All Rainfall Events Monitored, Loop 360 at Barton Creek, Austin, TX

	Date:	6/4/03	6/5/03	6/13/03	7/6/03	7/8/03	7/16/03	8/10/03	9/12/03	9/14/03
Constituent	Units	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n
Copper, Total	µg/L	10.6	12.3	12.9	45.5	21.6	20.6	12.2	12.8	---
Copper, Dissolved	µg/L	4.8	3.24	2.74	7.08	6.34	5.66	3.05	4.77	---
Lead, Total	µg/L	5.95	8.56	9.57	28.3	14.9	13.4	9.35	6.32	---
Lead, Dissolved	µg/L	ND	ND	ND	ND	ND	ND	ND	ND	---
Zinc, Dissolved	µg/L	31.4	15.5	22.3	16.5	25.5	13.3	24.8	16.2	---
Nitrogen, Nitrate (As N)	mg/L	0.520	0.220	0.210	0.350	0.260	0.280	0.760	0.290	---
Nitrogen, Kjeldahl, Total	mg/L	1.09	1.37	0.81	1.88	1.09	1.08	1.15	0.87	---
Chemical Oxygen Demand	mg/L	38.0	17.0	20.0	33.0	24.0	27.0	21.0	22.0	---
Phosphorus, Total (As P)	mg/L	0.140	0.170	0.070	0.280	0.150	0.150	0.040	ND	---
Phosphorus, Dissolved (As P)	mg/L	0.120	0.130	0.050	0.190	0.060	0.110	ND	ND	---
Suspended Solids - Total	mg/L	61.0	91.0	127	340	159	222	91.0	70.0	---
Suspended Solids - Volatile	mg/L	13*	16*	19*	49	32	26	17	19	---
Total Volatile Solids	mg/L	125	125	75	---	---	---	---	---	---
Fecal Coliform	cfu per 100 mL	---	4000	---	---	---	---	---	---	7300
Oil & Grease, Total Recoverable	mg/L	---	4.71	---	---	---	---	---	---	4.81

	Date:	9/21/03	10/9/03	11/17/03	1/16/04	2/4/04	2/10/04	2/11/04	6/9/04
Constituent	Units	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n
Copper, Total	µg/L	5.53	20.8	15.7	8.88	22.7	14.6	9.62	---
Copper, Dissolved	µg/L	3.34	5.99	4.23	2.71	3.46	3.6	2.62	---
Lead, Total	µg/L	1.75	9.57	8.39	4.4	13	8.9	6.66	---
Lead, Dissolved	µg/L	ND	ND	ND	ND	0.21	ND	ND	---
Zinc, Total	µg/L	69.2	200	173	73.3	223	123	77	---
Zinc, Dissolved	µg/L	38.3	30	28	41.1	38.7	51	39.9	---
Nitrogen, Nitrate (As N)	mg/L	0.420	0.410	0.185	0.118	0.577	0.375	0.199	---
Nitrogen, Kjeldahl, Total	mg/L	0.516	1.11	0.766	0.423	1.03	0.829	0.538	---
Chemical Oxygen Demand	mg/L	15.0	72.0	58.0	21.0	68.0	46.0	18.0	---
Phosphorus, Total (As P)	mg/L	0.080	0.120	0.090	0.050	0.130	0.070	0.030	---
Phosphorus, Dissolved (As P)	mg/L	0.040	0.060	ND	0.030	0.080	0.040	ND	---
Suspended Solids - Total	mg/L	11.0	104	108	31.0	158	67.0	37.0	---
Suspended Solids - Volatile	mg/L	8	28	20	20	26	19	7	---
Total Volatile Solids	mg/L	---	---	---	---	---	---	---	---
Fecal Coliform	cfu per 100 mL	---	---	---	3900	---	---	---	7000
Oil & Grease, Total Recoverable	mg/L	---	---	---	3.2	---	---	---	6.44

* : Samples were analyzed past holding time

ND : Not Detected at the Reporting Limit

Table B-2. Concentrations of Constituents in Flow-Weighted Samples of Runoff at the Approach Highway Site for All Rainfall Events Monitored, Loop 360 at Barton Creek, Austin, TX

	Date:	6/4/03	6/5/03	6/13/03	8/10/03	9/1/03	9/11/03	9/14/03	9/21/03	10/9/03
Constituent	Units	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n	Conc'n
Copper, Total	µg/L	9.07	22.5	15.3	32.8	21.2	24.5	---	13.7	47.5
Copper, Dissolved	µg/L	4.07	4.99	5.96	9.54	13.8	9.13	---	6.45	9.05
Lead, Total	µg/L	4.71	16.5	7.56	14.4	5.35	13.3	---	5.69	24.0
Lead, Dissolved	µg/L	ND	ND	ND	ND	ND	ND	---	ND	ND
Zinc, Total	µg/L	59.2	157	84	151	111	149	---	89.5	274
Zinc, Dissolved	µg/L	26.7	36.6	32.0	24.6	46.9	23.5	---	16.1	24.0
Nitrogen, Nitrate (As N)	mg/L	0.27	0.26	0.32	0.46	0.3	0.5	---	0.56	0.439
Nitrogen, Kjeldahl, Total	mg/L	0.58	1.27	0.94	7.08	1.58	1.95	---	1.02	2.03
Chemical Oxygen Demand	mg/L	27.0	11.0	27.0	57.0	60.0	41.0	---	33.0	137
Phosphorus, Total (As P)	mg/L	0.110	0.150	0.020	0.230	0.260	0.110	---	0.110	0.302
Phosph, Dissolved (As P)	mg/L	0.050	0.080	ND	0.080	0.200	0.040	---	0.050	0.156
Suspended Solids - Total (Residue, Non-Filterable)	mg/L	52.0	175	81.0	166	45.0	109	---	38.0	221
Suspended Solids - Volatile	mg/L	13*	23*	17*	36.0	10.0	31.0	---	17	49.4
Total Volatile Solids	mg/L	135	230	90	---	---	---	---	---	
Fecal Coliform	cfu per 100 mL	---	10,000	---	---	---	---	4,000	---	
Oil & Grease, Total Recoverable	mg/L	---	9.5	---	---	---	---	3.59	---	

	Date:	11/17/03	1/15/04	1/16/04	2/5/04	2/10/04	2/11/04	2/24/04	3/4/04	6/9/04
Constituent	Units									
Copper, Total	µg/L	35.6	15.1	15.7	29.1	30.4	20.4	17.7	24.8	---
Copper, Dissolved	µg/L	5.75	6.21	4.18	5.4	5.29	3.65	4.26	5.63	---
Lead, Total	µg/L	26	5.08	7.65	14.1	18.3	12.8	17.8	15.8	---
Lead, Dissolved	µg/L	ND	ND	ND	0.29	ND	ND	1.04	ND	---
Zinc, Total	µg/L	224	75.6	76.8	151	186	121	105	139	---
Zinc, Dissolved	µg/L	11.4	34.7	57.4	25.9	43.2	23.2	34.4	31.4	---
Nitrogen, Nitrate (As N)	mg/L	0.341	0.33	0.288	0.626	0.608	0.228	0.47	0.38	---
Nitrogen, Kjeldahl, Total	mg/L	1.31	0.633	0.757	1.33	1.47	0.813	0.489	1.44	---
Chemical Oxygen Demand	mg/L	84.0	39.0	38.0	73.0	93.0	44.0	64.0	71.0	---
Phosphorus, Total (As P)	mg/L	0.200	0.050	0.070	0.140	0.170	0.090	0.090	0.170	---
Phosph, Dissolved (As P)	mg/L	0.080	0.050	0.030	0.070	0.060	0.040	0.060	0.090	---
Suspended Solids - Total (Residue, Non-Filterable)	mg/L	177	29	68	136	150	90	176	194	---
Suspended Solids - Volatile	mg/L	27.0	9.00	31.0	30.0	28.0	20.0	25	34	---
Total Volatile Solids	mg/L	---	---							---
Fecal Coliform	cfu per 100 mL	---	---	5,300						400
Oil & Grease, Total Recoverable	mg/L	---	---	5.64						ND

* : Samples were analyzed past holding time

ND : Not Detected at the Reporting Limit

++ : Two composite samples were collected on 10-09-03, the results presented here are weighted averages of the two samples based on the volume of flow measured for each sample.

Table B-3. Average Concentration of Water Quality Constituents in Barton Creek at Loop 360 Bridge, Austin, TX (USGS)

Constituent	Average Concentration at Base Flow	Average Concentration at Storm Flow
Copper, Total, µg/L	5.6	4.34
Lead, Total, µg/L	ND	6.11
Zinc, Total, µg/L	4	26.75
Nitrate, as N, mg/L	0.14	0.345
Total N, mg/L	0.35	1.825
COD, mg/L	ND	43
Phosphorus, Total, (as P) mg/L	0.02	0.25
Phosphorus, Dissolved,(as P) mg/L	ND	0.09
TSS, mg/L	12	306
VSS, mg/L		12
Fecal Coliform, cfu/100mL	135	51,383

Table B-4. Concentrations of Constituents in Flow-Weighted Samples of Runoff at Approach Highway Site for All Rainfall Events Monitored, Loop 289, Lubbock, TX

	Date:	1/17/04	2/25/04	2/29/04	3/4/04	4/5/04	6/18/04
Constituent	Units						
Copper, Total	µg/L	7.87	25.5	28.5	31.5	26.7	10.4
Copper, Dissolved	µg/L	7.21	16	8.94	7.79	11.7	5.21
Lead, Total	µg/L	4.87	21.2	21.1	19.7	15.8	13.4
Lead, Dissolved	µg/L	1.73	8.87	ND	ND	2.44	2.75
Zinc, Total	µg/L	45.8	250	129	139	137	50
Zinc, Dissolved	µg/L	54.6	204	46.3	22.8	73.9	38.3
Nitrogen, Nitrate (As N)	µg/L	271	150	130	1330	600	270
Nitrogen, Kjeldahl, Total	mg/L	1.35	1.5	1.13	2.14	2.54	1.87
Chemical Oxygen Demand	mg/L	47	79	55	77	86	64
Phosphorus, Total (As P)	mg/L	0.15	2.07	0.58	0.42	0.34	0.21
Phosphorus, Dissolved (As P)	mg/L	0.05	1.81	0.41	0.21	0.2	0.14
Suspended Solids, Total	mg/L	36	88	170	100	140	70
Suspended Solids, Volatile	mg/L	16	28	48	25	35	12
Fecal Coliform	cfu/100m	50		20	10000		
Oil&Grease, Total Coverable	mg/L	10.9		13.6	7.33		

	Date:	6/28/04	8/21/04	9/27/04	11/3/04	2/6/05	5/15/05
Constituent	Units						
Copper, Total	µg/L	19.9	8.93	11.1	22.9	22.4	45.7
Copper, Dissolved	µg/L	8.78	4.12	3.94	13.4	11.5	8.54
Lead, Total	µg/L	31.2	6.4	10.3	18.7	8.82	45.2
Lead, Dissolved	µg/L	1.52	ND (<1.02)	ND (<1.02)	3.78	ND (<1.02)	ND (<1.02)
Zinc, Total	µg/L	123	46.5	43.2	242	96.4	202
Zinc, Dissolved	µg/L	44.9	24.9	17.2	184	25.1	15.9
Nitrogen, Nitrate (As N)	µg/L	200	250	280	170	420	52
Nitrogen, Kjeldahl, Total	mg/L	3.55	1.09	0.92	1.59	4.93	2.22
Chemical Oxygen Demand	mg/L	153	35	23	69	89	162
Phosphorus, Total (As P)	mg/L	0.38	0.16	0.09	3.34	1.31	2.06
Phosphorus, Dissolved (As P)	mg/L	0.21	0.09	ND	3.08	1.33	1.43
Suspended Solids, Total	mg/L	116	51	50	55	59	378
Suspended Solids, Volatile	mg/L	27	11	11	20	22	78
Fecal Coliform	cfu/100m			79433	10000	1000	1995
Oil&Grease, Total Coverable	mg/L			ND	8.9	4.07	3.47

Table B-5. Concentrations of Constituents in Flow-Weighted Samples of Runoff at the Bridge Deck Site for All Rainfall Events Monitored, Loop 289, Lubbock, TX

Constituent	Date: Units	1/17/04	2/25/04	2/29/04	3/4/04	4/5/04	6/18/04
Copper, Total	µg/L	8.56	29.1	26.1	18.5	8.84	7
Copper, Dissolved	µg/L	5.79	20.9	11.6	6.67	5.26	4.54
Lead, Total	µg/L	4.39	22.7	24.4	13.8	5.67	7.35
Lead, Dissolved	µg/L	1.03	8.37	1.24	ND (<1.00)	2.18	ND (<1.00)
Zinc, Total	µg/L	69.2	353	232	181	72.5	41.2
Zinc, Dissolved	µg/L	70.2	305	112	58.9	51.2	27.9
Nitrogen, Nitrate (As N)	µg/L	202	190	220	330	460	260
Nitrogen, Kjeldahl, Total	mg/L	2.14	3.62	3.5	2.83	1.35	2.3
Chemical Oxygen Demand	mg/L	52	111	108	85	43	53
Phosphorus, Total (As P)	mg/L	0.4	3.25	2	0.9	0.2	0.28
Phosphorus, Dissolved (As P)	mg/L	0.28	3.08	1.4	0.61	0.14	0.2
Suspended Solids, Total	mg/L	22	94	175	112	30	36
Suspended Solids, Volatile	mg/L	13	28	50	18	15	12
Fecal Coliform	cfu/100mL	1259		50	1585		
Oil&Grease, Total Recoverable	mg/L	5.41		3.09	4.14		

Constituent	Date: Units	6/28/04	8/21/04	9/27/04	11/3/04	2/6/05	5/15/05
Copper, Total	µg/L	7.82	7.58	20.4	24.2	24.2	41.7
Copper, Dissolved	µg/L	4.36	5.2	4.04	11.9	3.19	7.41
Lead, Total	µg/L	8.39	3.37	23.8	28.1	16.2	12.9
Lead, Dissolved	µg/L	ND (<1.00)	ND (<1.02)	1.5	3.74	ND (<1.02)	ND (<1.02)
Zinc, Total	µg/L	36.9	32.2	91.1	233	133	56.1
Zinc, Dissolved	µg/L	22.3	30.8	28.8	140	9.33	12.9
Nitrogen, Nitrate (As N)	µg/L	240	360	370	280	160	220
Nitrogen, Kjeldahl, Total	mg/L	2.61	1.39	1.37	1.78	5.32	13
Chemical Oxygen Demand	mg/L	47	75	44	90	84	68
Phosphorus, Total (As P)	mg/L	0.27	0.2	0.2	2.4	2.1	1.12
Phosphorus, Dissolved (As P)	mg/L	0.16	0.12	0.08	2.28	2.08	0.9
Suspended Solids, Total	mg/L	46	27	112	115	118	361
Suspended Solids, Volatile	mg/L	13	10	18	30	30	55
Fecal Coliform	cfu/100mL			10000	158489	1	200
Oil&Grease, Total Recoverable	mg/L			4.82	6.6	5.18	ND (<3.25)

Table B-6. Concentrations of Constituents in Flow-Weighted Samples of the North Fork of the Double Mountain Fork of the Brazos River for All Rainfall Events Monitored, at Bridge Site, Loop 289 Lubbock, TX

	Date:	1/17/04	2/25/04	2/29/04	3/4/04	4/5/04	6/18/04
Constituent	Units						
Copper, Total	µg/L	21.5	12.2	18.2	8.34	7.04	13.8
Copper, Dissolved	µg/L	2.57	5.17	1.99	2.14	2.78	2.82
Lead, Total	µg/L	32.1	8.6	36.9	12.5	6.69	22.1
Lead, Dissolved	µg/L	ND (<1.00)	ND (<1.00)	ND (<1.00)	ND (<1.00)	ND (<1.00)	3.88
Zinc, Total	µg/L	136	52.6	134	57.4	47.4	76.4
Zinc, Dissolved	µg/L	15.1	19.9	15.7	16.7	22.2	35.1
Nitrogen, Nitrate (As N)	µg/L	2,150	2,100	610	1,280	740	1,880
Nitrogen, Kjeldahl, Total	mg/L	5.13	2.28	3.37	2.33	2.51	5.78
Chemical Oxygen Demand	mg/L	126	70	117	49	49	127
Phosphorus, Total (As P)	mg/L	0.61	0.27	0.52	0.26	0.23	0.67
Phosphorus, Dissolved (As P)	mg/L	0.2	0.07	0.14	0.08	0.11	0.23
Suspended Solids, Total	mg/L	358	102	408	116	55	288
Suspended Solids, Volatile	mg/L	110	17	74	26	10	54
Fecal Coliform	cfu/100mL	891		159	891		
Oil&Grease, Total Recoverable	mg/L	ND (<2.68)		ND (<2.57)	ND (<2.53)		

	Date:	6/28/04	8/21/04	9/27/04	11/3/04	2/6/05	5/15/05
Constituent	Units						
Copper, Total	µg/L	6.77	10.2	17.1	7.64	8.03	16.4
Copper, Dissolved	µg/L	2.7	3.81	4.47	3.04	11.2	4.53
Lead, Total	µg/L	4.83	12.1	14.2	6.98	4.97	14.6
Lead, Dissolved	µg/L	ND (<1.00)	ND (<1.02)	ND (<1.02)	ND (<1.02)	ND (<1.02)	ND (<1.02)
Zinc, Total	µg/L	24.9	48.8	59.1	35.9	30.1	84
Zinc, Dissolved	µg/L	11.7	19.6	16.9	10.7	34.7	19.5
Nitrogen, Nitrate (As N)	µg/L	1,430	1,080	240	580	1,800	712
Nitrogen, Kjeldahl, Total	mg/L	2.41	2.77	2.05	1.7	1.58	34
Chemical Oxygen Demand	mg/L	45	53	43	48	37	96
Phosphorus, Total (As P)	mg/L	0.16	0.26	0.2	0.2	0.17	0.69
Phosphorus, Dissolved (As P)	mg/L	0.04	0.07	0.03	ND (<0.02)	0.08	0.28
Suspended Solids, Total	mg/L	58	125	110	72	41	185
Suspended Solids, Volatile	mg/L	17	28	22	14	12	44
Fecal Coliform	cfu/100mL			50119	1995	63	1000
Oil&Grease, Total Recoverable	mg/L			3.81	ND (<2.50)	ND (<2.57)	ND (<2.96)

Table B-7. Concentrations of Constituents in Flow-Weighted Samples of Runoff at Bridge Deck Site for All Rainfall Events Monitored, Clear Creek/FM528, Houston TX

	Date:	10/26/03	11/15/03	1/9/04	1/16/04	1/26/04	2/4/04	2/10/04	2/11/04
Constituent	Units								
Copper, Total	μg/L	15.5	13.9	15.4	23.7	21.4	7.92	16.1	5.2
Copper, Dissolved	μg/L	10.4	7	12	19	14	4.11	13.3	3.45
Lead, Total	μg/L	12.5	8.95	3.21	1.39	6.17	6.19	2.84	4.64
Lead, Dissolved	μg/L	2.16	ND	1.42	ND	ND	0.41	ND	ND
Zinc, Total	μg/L	109	133	108	114	215	117	193	85.4
Zinc, Dissolved	μg/L	76.3	26.2	109	110	102	64.1	165	59
Nitrogen, Nitrate (As N)	mg/L	0.273	0.416	ND	3.37	0.755	0.385	0.913	0.27
Nitrogen, Kjeldahl, Total	mg/L	1.06	0.678	0.952	1.79	1.24	0.332	1.11	0.274
Chemical Oxygen Demand	mg/L	24	26	57	64	46	15	45	27
Phosphorus, Total (As P)	mg/L	0.13	0.04	0.06	0.04	0.06	0.05	0.03	ND
Phosphorus, Dissolved (As P)	mg/L	0.1	ND	ND	ND	ND	0.02	ND	ND
Suspended Solids - Total	mg/L	57	23	8	9	46	27	16	4
Suspended Solids - Volatile	mg/L	17	8	8	8	12	10	4	ND

	Date:	2/24/04	2/10/04	2/11/04	2/24/04	3/5/04	4/23/04	6/8/04	12/14/04
Constituent	Units								
Copper, Total	μg/L	9.08	16.1	5.2	9.08	30.4	17.2	28.5	26.4
Copper, Dissolved	μg/L	6.15	13.3	3.45	6.15	25.7	13.8	19.9	13.8
Lead, Total	μg/L	2.2	2.84	4.64	2.2	2.65	4.1	5.62	10.1
Lead, Dissolved	μg/L	ND	ND	ND	ND	ND	ND	ND	ND
Zinc, Total	μg/L	78.8	193	85.4	78.8	80.8	85.4	98.5	271
Zinc, Dissolved	μg/L	48.3	165	59	48.3	55.6	70.9	44.5	98.2
Nitrogen, Nitrate (As N)	mg/L	0.31	0.913	0.27	0.31	0.94	2.03	3.53	2.71
Nitrogen, Kjeldahl, Total	mg/L	0.11	1.11	0.274	0.11	2.07	0.875	1.8	1.19
Chemical Oxygen Demand	mg/L	20	45	27	20	81	49	59	35
Phosphorus, Total (As P)	mg/L	ND	0.03	ND	ND	0.05	ND	0.12	0.046
Phosphorus, Dissolved (As P)	mg/L	ND	ND	ND	ND	0.03	ND	0.04	0.02
Suspended Solids - Total	mg/L	10	16	4	10	22	21	33	118
Suspended Solids - Volatile	mg/L	5	4	ND	5	13	8	22	24

	Date:	1/25/05	2/11/05	2/25/05	3/17/05
Constituent	Units				
Copper, Total	μg/L	17.1	23.9	15.5	21.7
Copper, Dissolved	μg/L	14	3	10.9	12.4
Lead, Total	μg/L	3.24	4.35	1.38	11.5
Lead, Dissolved	μg/L	1.38	ND	1.1	ND
Zinc, Total	μg/L	125	274	141	167
Zinc, Dissolved	μg/L	113	10.4	93.1	68.4
Nitrogen, Nitrate (As N)	mg/L	0.85	3.64	1.51	1.25
Nitrogen, Kjeldahl, Total	mg/L	0.531	2.07	1.0	1.17
Chemical Oxygen Demand	mg/L	18	44	26	57
Phosphorus, Total (As P)	mg/L	0.027	0.136	0.1	0.175
Phosphorus, Dissolved (As P)	mg/L	0.02	ND	ND	0.088
Suspended Solids - Total	mg/L	48	132	8	319
Suspended Solids - Volatile	mg/L	11	18	ND	22

* : Samples were analyzed past holding time

ND : Not Detected at the Reporting Limit

Table B-8. Concentrations of Constituents in Flow-Weighted Samples of Runoff at Approach Highway Site for All Rainfall Events Monitored, Clear Creek/FM528, Houston TX

	Date:	10/27/03	11/18/03	1/12/04	1/20/04	1/26/04	2/3/04	2/10/04
Constituent	Units							
Copper, Total	μg/L	6.7	10.5	7.0	6.9	10.2	3.18	3.36
Copper, Dissolved	μg/L	0.21	1	ND	1.32	ND	1.87	1.34
Lead, Total	μg/L	6.1	13.0	ND	10.4	6.99	11.7	10.9
Lead, Dissolved	μg/L	4.99	6.35	6.4	4.99	6.73	2.08	2.34
Zinc, Total	μg/L	0.1	ND	ND	ND	ND	0.16	ND
Zinc, Dissolved	μg/L	6.68	4.08	8.81	12.7	5.97	5.96	19.5
Nitrogen, Nitrate (As N)	mg/L	0.4	1.1	0.4	0.661	0.237	0.0816	0.153
Nitrogen, Kjeldahl, Total	mg/L	26	20	15	22	16	37	21
Chemical Oxygen Demand	mg/L	0.1	0.1	0.1	0.05	0.04	0.04	0.09
Phosphorus, Total (As P)	mg/L	0.1	0.21	0.07	0.07	0.07	0.11	0.11
Phosphorus, Dissolved (As P)	mg/L	0.6	1.5	0.4	0.686	0.441	0.94	0.781
Suspended Solids, Total	mg/L	3	16	ND	11	10	26	17
Suspended Solids, Volatile	mg/L	3	8	ND	6	8	9	8

	Date:	2/11/04	2/26/04	3/15/04	4/26/04	6/8/04	12/14/04	1/25/05
Constituent	Units							
Copper, Total	μg/L	ND	5.3	11.1	7.6	12.5	15.3	22.2
Copper, Dissolved	μg/L	1.06	1.69	4.89	3.21	3.81	4.75	6.97
Lead, Total	μg/L	13.2	12.2	32.8	24.3	64.5	59.6	272.0
Lead, Dissolved	μg/L	1.35	2.99	7.2	6.2	4.44	8.54	6.96
Zinc, Total	μg/L	ND	ND	ND	1.1	ND	ND	ND
Zinc, Dissolved	μg/L	7.37	14.9	14.9	53.6	15.6	28	51.7
Nitrogen, Nitrate (As N)	mg/L	0.1	0.6	1	1.2	0.74	1.38	0.6
Nitrogen, Kjeldahl, Total	mg/L	20	37	35	30	47	39	31
Chemical Oxygen Demand	mg/L	0.0	ND	0.09	0.2	0.2	0.27	0.2
Phosphorus, Total (As P)	mg/L	0.05	0.03	0.12	0.16	0.28	0.423	0.195
Phosphorus, Dissolved (As P)	mg/L	0.7	0.4	1.19	0.6	1.47	1.98	1.8
Suspended Solids, Total	mg/L	8	25	37	27	30	144	39
Suspended Solids, Volatile	mg/L	4	8	12	8	18	35	13

	Date:	2/11/05	2/25/05	3/17/05
Constituent	Units			
Copper, Total	μg/L	5.85	9.2	7.4
Copper, Dissolved	μg/L	1.11	3.19	2.94
Lead, Total	μg/L	19.8	45.7	46.1
Lead, Dissolved	μg/L	3.13	4.62	3.34
Zinc, Total	μg/L	ND	ND	ND
Zinc, Dissolved	μg/L	11.4	17.5	14.1
Nitrogen, Nitrate (As N)	mg/L	0.38	0.6	1.2
Nitrogen, Kjeldahl, Total	mg/L	26	33	16
Chemical Oxygen Demand	mg/L	ND	ND	0.1
Phosphorus, Total (As P)	mg/L	0.063	0.265	0.078
Phosphorus, Dissolved (As P)	mg/L	1.12	0.6	1.0
Suspended Solids, Total	mg/L	29	21	80
Suspended Solids, Volatile	mg/L	10	5.0	13

* : Samples were analyzed past holding time

ND : Not Detected at the Reporting Limit

Table B-9. Concentrations of Constituents in Flow-Weighted Samples of Clear Creek for All Rainfall Events Clear Creek/FM528, Houston, TX

	Date:	10/27/03	11/18/03	1/12/04	1/20/04	1/26/04	2/3/04	2/10/04
Constituent	Units							
Copper, Total	μg/L	8.12	6.95	5.21	4.81	4.3	6.34	8
Copper, Dissolved	μg/L	3.73	3.47	3.8	3.09	2.96	2.47	2.14
Lead, Total	μg/L	5.61	2.84	1.73	1.87	2.24	5.17	3.21
Lead, Dissolved	μg/L	0.25	ND	ND	ND	ND	0.44	ND
Zinc, Total	μg/L	27.8	29	19	18.3	15	31	27.9
Zinc, Dissolved	μg/L	9.71	16.3	13.5	13.1	6.76	19.5	9.19
Nitrogen, Nitrate (As N)	mg/L	0.552	1.88	1.73	2.06	1.3	0.31	0.748
Nitrogen, Kjeldahl, Total	mg/L	0.651	1.14	0.593	0.894	0.821	0.913	1.39
Chemical Oxygen Demand	mg/L	18	21	16	17	22	32	27
Phosphorus, Total (As P)	mg/L	0.24	0.64	0.36	0.34	0.31	0.27	0.26
Phosphorus, Dissolved (As P)	mg/L	0.2	0.56	0.34	0.29	0.27	0.15	0.19
Suspended Solids - Total	mg/L	3	23	45	43	43	160	79
Suspended Solids - Volatile	mg/L	ND	8	8	10	13	28	21

	Date:	2/11/04	2/26/04	3/15/04	4/26/04	6/8/04	12/14/04	1/25/05
Constituent	Units							
Copper, Total	μg/L	6.94	6.59	4.06	4.57	7.45	29.8	13.3
Copper, Dissolved	μg/L	2.24	2.46	2	2.68	3.53	4.3	2.89
Lead, Total	μg/L	5.84	4.4	2.2	1.36	2.5	22	8.11
Lead, Dissolved	μg/L	ND	ND	ND	ND	ND	ND	ND
Zinc, Total	μg/L	38.6	24.3	16.2	14.9	80.7	77.6	46.1
Zinc, Dissolved	μg/L	11.6	10.9	7.17	14.6	44.3	9.78	17.7
Nitrogen, Nitrate (As N)	mg/L	0.207	0.18	1.46	2.89	0.81	2.98	4.94
Nitrogen, Kjeldahl, Total	mg/L	1.05	0.203	0.735	0.94	2.68	2.38	1.98
Chemical Oxygen Demand	mg/L	33	25	21	17	48	40	33
Phosphorus, Total (As P)	mg/L	0.23	0.14	0.24	0.51	0.44	0.998	1.26
Phosphorus, Dissolved (As P)	mg/L	0.14	0.11	0.22	0.51	0.33	0.69	1.2
Suspended Solids - Total	mg/L	130	122	48	31	101	792	428
Suspended Solids - Volatile	mg/L	16	16	9	31	37	66	34

	Date:	2/11/05	2/25/05	3/17/05
Constituent	Units			
Copper, Total	μg/L	6.37	21.8	14
Copper, Dissolved	μg/L	4.86	3.0	3.03
Lead, Total	μg/L	4.35	16.2	9.83
Lead, Dissolved	μg/L	ND	ND	ND
Zinc, Total	μg/L	24.3	121.0	48.8
Zinc, Dissolved	μg/L	10.4	15.4	13
Nitrogen, Nitrate (As N)	mg/L	0.85	0.5	2.45
Nitrogen, Kjeldahl, Total	mg/L	1.26	0.8	1.74
Chemical Oxygen Demand	mg/L	33	44.0	35
Phosphorus, Total (As P)	mg/L	0.375	0.6	0.783
Phosphorus, Dissolved (As P)	mg/L	0.202	0.4	0.662
Suspended Solids - Total	mg/L	77	746.0	821
Suspended Solids - Volatile	mg/L	10	62.0	44

* : Samples were analyzed past holding time
ND : Not Detected at the Reporting Limit

Table B-10. Average and Median Concentrations of Constituents in Runoff from Bridge Deck and Approach Highway measured at the Sites in Austin, Lubbock and Houston

			Bridge Deck Runoff				Approach Highway Runoff			
Constituent		Units	AUS	LUB	HOUS	AVE	AUS	LUB	HOUS	AVE
Copper, Total	Average	µg/L	16.42	18.7	18.17	17.76	23.46	21.8	8.48	17.91
	Median	µg/L	12.90	19.5	17.10	1.19	21.85	22.7	7.35	8.21
Copper, Dissolved	Average	µg/L	4.24	7.6	11.94	7.93	6.46	8.9	4.86	6.74
	Median	µg/L	3.60	5.5	12.40	3.86	5.69	8.7	4.99	2.03
Lead, Total Average	Average	µg/L	9.93	14.3	5.35	9.86	13.07	18.1	2.32	11.16
	Median	µg/L	8.90	13.4	4.35	4.47	13.70	17.3	1.69	8.06
Lead, Dissolved	Average	µg/L	n/a	1.8	0.38	1.09	n/a	2.0	0.08	1.04
	Median	µg/L	n/a	0.8	0.00	1.01	n/a	1.0	0.00	1.36
Zinc, Total	Average	µg/L	166.50	127.6	140.94	145.01	134.59	123.5	38.19	98.76
	Median	µg/L	168.00	81.8	117.00	19.77	130.00	126.0	13.20	52.75
Zinc, Dissolved	Average	µg/L	28.83	72.4	77.29	59.51	30.75	62.7	17.22	36.89
	Median	µg/L	28.00	41.0	70.90	26.68	29.05	41.6	14.10	23.35
Nitrogen, Nitrate (As N)	Average	mg/L	0.34	274.3	1.36	92.00	0.40	343.6	0.64	114.88
	Median	mg/L	0.29	250.0	0.91	157.88	0.36	260.0	0.58	198.08
Nitrogen, Kjeldahl, Total	Average	mg/L	0.97	3.4	1.08	1.82	1.54	2.1	0.95	1.53
	Median	mg/L	1.03	2.5	1.06	1.37	1.29	1.7	0.78	0.57
Chemical Oxygen Demand	Average	mg/L	33.33	71.7	40.76	48.60	56.21	78.3	27.71	54.07
	Median	mg/L	24.00	71.5	44.00	20.35	50.50	73.0	26.00	25.36
Phosphorus, Total (As P)	Average	mg/L	0.11	1.1	0.06	0.42	0.14	0.9	0.14	0.39
	Median	mg/L	0.09	0.7	0.05	0.59	0.13	0.4	0.11	0.44
Phosphorus, Dissolved (As P)	Average	mg/L	0.07	0.9	0.02	0.33	0.08	0.7	0.09	0.29
	Median	mg/L	0.05	0.4	0.00	0.49	0.06	0.2	0.06	0.36
Suspended Solids - Total	Average	mg/L	112	104.0	53.00	89.60	119.20	109.4	30.76	86.46
	Median	mg/L	91.0	103.0	23.00	31.94	122.50	79.0	25.00	48.48
Suspended Solids - Volatile	Average	mg/L	21.3	24.3	11.18	18.91	25.02	27.8	9.88	20.90
	Median	mg/L	19.0	18.0	10.00	6.87	26.00	23.5	8.00	9.64
Fecal Coliform [cfu/100 mL]	Average		5550	650	n/a	3100	4925	1600	n/a	3263
	Median		5500	1250	n/a	3465	4650	2000	n/a	2351
Oil & Grease, Total Recoverable	Average	mg/L	4.79	4.4	n/a	4.60	6.24	7.1	n/a	6.67
	Median	mg/L	4.76	4.80	n/a	0.28	5.64	7.3	n/a	0.61

n/a : Indicates that there were insufficient detections of this constituent to allow for statistics to be calculated

Table B-11. Results of Null Hypothesis Testing of Concentrations of Constituents in Paired Samples of Runoff from Bridge Deck and Approach Highway measured at the Sites in Austin, Lubbock and Houston Indicating p-values and 95% Confidence Levels

	Austin				Lubbock		Houston			
Constituent	Hypothesis Accepted?	P-Value	95% Confidence Interval	Bridge Deck Concentration is:	P-Value	Bridge Deck Concentration is:	Hypothesis Accepted?	P- Value	95% Confidence Interval	Bridge Deck Concentration is:
Copper, Total	Alternative	0.000	6.4-16.6	lower	0.040	no difference	Alternative	0.000	-12.9 – -6.4	higher
Copper, Dissolved	Alternative	0.001	1.3-3.6	lower	0.000	no difference	Alternative	0.000	-9.8 – -4.4	higher
Lead, Total	Alternative	0.004	2.3-9.8	lower	0.660	no difference	Alternative	0.004	-5.18 – -0.90	higher
Lead, Dissolved	Null	n/a	n/a	no difference	0.087	no difference	Null	0.058	n/a	no difference
Zinc, Total	Null	0.068	n/a	no difference	0.140	no difference	Alternative	0.000	-148.5 – -57.(	higher
Zinc, Dissolved	Null	0.510	n/a	no difference	0.007	no difference	Alternative	0.000	-78.8 – -41.4	higher
Nitrogen, Nitrate (As N)	Null	0.321	n/a	no difference	0.000	no difference	Alternative	0.011	1.325 – -0.11	higher
Nitrogen, Kjeldahl, Total	Alternative	0.019	0.07-0.67	lower	0.080	no difference	Null	0.241	n/a	no difference
Chemical Oxygen	Alternative	0.007	7.0-34.5	lower	0.910	no difference	Alternative	0.014	-24.43 – -1.6	higher
Phosphorus, Total (As P)	Alternative	0.031	0.006-0.106	lower	0.230	no difference	Alternative	0.006	0.020 – 0.138	lower
Phosphorus, Dissolved	Null	0.664	n/a	no difference	0.008	no difference	Alternative	0.002	0.026 – 0.107	lower
Suspended Solids - Total	Alternative	0.012	11.5-73.0	lower	0.310	no difference	Null	0.085	n/a	no difference
Suspended Solids -	Alternative	0.001	4.8-13.6	lower	0.830	no difference	Null	0.199	n/a	no difference
Fecal Coliform	Null	0.835	n/a	no difference						
Oil & Grease	Null	0.663	n/a	no difference						

n/a indicates that there were no statistically significant results generated for this parameter