Marisa Weber

From:	PUBCOMMENT-OCC
Sent:	Thursday, September 15, 2016 1:44 PM
To:	PUBCOMMENT-OCC2; PUBCOMMENT-ELD; PUBCOMMENT-OPIC; PUBCOMMENT-WQ
Subject:	FW: Public comment on Permit Number WQ0005011000
Attachments:	Request for Contested Case hearing to WQ0005011000_TXDOT_MS41.pdf

eComment = H
Attachment = H

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From: jen.powis@thepowisfirm.com [mailto:jen.powis@thepowisfirm.com]
Sent: Wednesday, September 14, 2016 12:32 PM
To: PUBCOMMENT-OCC <PUBCOMMENT-OCC@tceq.texas.gov>
Subject: Public comment on Permit Number WQ0005011000

REGULATED ENTY NAME TXDOT STATEWIDE MS4 PERMIT

RN NUMBER: RN106645369

PERMIT NUMBER: WQ0005011000

DOCKET NUMBER:

COUNTY: ARANSAS, ARCHER, BELL, BEXAR, BOWIE, BRAZORIA, BRAZOS, CALDWELL, CAMERON, CHAMBERS, CHEROKEE, COLLIN, COMAL, CORYELL, DALLAS, DENTON, ECTOR, EL PASO, ELLIS, FORT BEND, GALVESTON, GRAYSON, GREGG, GUADALUPE, HARDIN, HARRIS, HARRISON, HAYS, HIDALGO, JEFFERSON, JOHNSON, JONES, KAUFMAN, KENDALL, KLEBERG, LAMPASAS, LUBBOCK, MCLENNAN, MIDLAND, MONTGOMERY, NUECES, ORANGE, PARKER, POTTER, RANDALL, ROCKWALL, SAN PATRICIO, SMITH, TARRANT, TAYLOR, TOM GREEN, TRAVIS, UPSHUR, VICTORIA, WALLER, WEBB, WICHITA, WILLIAMSON, WISE

PRINCIPAL NAME: TEXAS DEPARTMENT OF TRANSPORTATION

CN NUMBER: CN600803456

FROM

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MW

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COMMENTS: The following five (5) entities specifically request a contested case hearing on the Texas Department of Transportation's (TXDOT) Permit Application Number WQ0005011000: Galveston Baykeeper, Galveston Bay Foundation, Environment Texas, Turtle Island Restoration Network and Save Our Springs Alliance. The discrete factual and legal challenges asserted are attached.

September 14, 2016

Office of the Chief Clerk, MC-105
Texas Commission on Environmental Quality
P.O. Box 13087
Austin TX 78711-3087

By mail and electronically at: http://www.tceq.texas.gov/goto/comments

RE: Request for Contested Case Hearing on Texas Department of Transportation's NPDES Permit Application No. WQ0005011000

To Whom It May Concern:

The following five (5) entities specifically request a contested case hearing on the Texas Department of Transportation's (TXDOT) Permit Application Number WQ0005011000: Galveston Baykeeper, Galveston Bay Foundation, Environment Texas, Turtle Island Restoration Network and Save Our Springs Alliance. This permit application seeks approval to discharge waters from TXDOT's Municipal Separate Storm Sewer System (MS4) region and is considered a nontraditional MS4 application under the National Pollutant Discharge Elimination Program (NPDES).

Because the Texas Department of Transportation filed this application in 2013, Senate Bill 709's changes to the burden of proof, timeliness of decision, and affected person status do not apply. (*See* SB 709, Section 5(a)(1). "The changes in law made by this Act apply only to: (1) a permit application that is filed with the Texas Commission on Environmental Quality on or after the effective date of this Act."). Regardless, the names and addresses of the primary contacts for all five entities are below and all have dedicated resources and advocacy efforts for decades to improve Texas's water quality. Each member or staff listed below is directly affected through their recreational, scientific, educational, or vocational activities related to these waters across the state and are identified specifically for this purpose. These identified members should receive all future correspondence and will be adversely affected by this permit.

Jen Powis ✓ Galveston Baykeeper ✓ 2010 North Loop West, Suite 275 Houston, Texas 77018	Luke Metzger ✓ Environment Texas 815 Brazos St, Austin, TX 78701	Scott Jones ✓ Galveston Bay Foundation 17330 Hwy. 3, Webster, TX, 77598
Kelly Davis ✓ Save Our Springs Alliance 905 W. Oltorf St., Ste. A Austin, Texas 78704		Joanie Steinhaus ✓ Turtle Island Restoration Network 2228 Broadway St, Galveston, Texas 77550

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These five entities submitted joint comments on this permit application on May 6, 2016, and those comments are incorporated herein by reference. Although not required, all five entities assert that the discrete legal and factual challenges asserted in their comments should be considered during the contested case process. This includes, but is not limited to, (1) the geographic scope of the permit and specifically that it should cover the entire state of Texas, (2) that stormwater discharges will result in exceedances of water quality standards for heavy metals and other pollutants, (3) that the permit fails to adopt explicit timeframes, benchmarks, and best management practices that are applicable to the Edwards Aquifer region as described in the comments, (4) that the permit fails to adopt a cumulative effect analysis in the watershed or require more mitigation for redevelopment areas since roadways are known major polluters, (5) that the permit fails to require wet weather testing, if not numeric limits, and (6) that the permit fails to require additional benchmarking for floatables since roadways are the leading cause of this pollutant.

Specifically, and as will be demonstrated during the contested case, the Executive Director's assertion that stormwater is not capable of hydrologic modeling will be disproven, and had the Texas Commission on Environmental Quality modeled stormwater from linear roadways for pollutants, particularly those listed on the state's 303(d) list, additional provisions within the permit would be necessary to comply with current law. (TCEQ's Response to Comment 13 states in part: "The MS4 permit has been crafted to ensure consistency with TSWQS for stormwater discharges. These discharges are 'intermittent and variable' and do not lend themselves to hydrologic modeling."). Indeed, TXDOT's own hydraulic design manual has computed the discharge rates for stormwater and various pollutants. By TXDOT district, a computation based on roadway miles is possible to benchmark the amount of pollution directly flowing into the state's waters by the stormwater runoff from TXDOT roads. As such, the lack of wet weather testing to benchmark these discharge rates, coupled with the lack of numeric limits within the permit for discharge rates, cannot be said to "reduce the discharge of pollutants from the MS4." Likewise, TXDOT's assertion that oil, grease, and other heavy metals are not discharged from its MS4 but only from adjacent MS4s is inconsistent with three decades of science documenting these pollutants in roadway runoff. Because it appears that TCEQ failed to model appropriately for these pollutants, the permit cannot adequately adopt appropriate minimum control measures for pollution prevention, illicit discharges, and discharges to impaired waters.

Sincerely,

Jen Powis ✓
Galveston Baykeeper

Luke Metzger ✓
Environment Texas

Kelly Davis ✓
Save Our Springs Alliance

Scott Jones ✓
Galveston Bay Foundation

Joanie Steinhaus ✓
Turtle Island Restoration Network

REVIEWED
MAY 10 2016
By [signature] H

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CHIEF CLERKS OFFICE
2016 MAY 10 AM 9:44
TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

May 6, 2016

Office of the Chief Clerk, MC-105
Texas Commission on Environmental Quality
P.O. Box 13087
Austin TX 78711-3087
By mail and electronically at: www.tceq.texas.gov/about/comments/html

RE: Permit No. WQ0005011000

To Whom It May Concern:

I write on behalf of the Galveston Baykeeper (GBK), a 501(c)(3) nonprofit organization working to ensure that every waterway in Texas is swimmable, fishable, and drinkable. GBK's core mission is to ensure the aquatic integrity of the Lower Galveston Bay watershed by focusing on the protection of wetlands and other critical habitats, advocating for adequate mitigation of lost wetland resources, and enforcing all aspects of compliance with the Clean Water Act. These comments are joined by multiple other non-profit organizations concerned with Texas's rivers, streams, bays and estuaries, including Galveston Bay Foundation, Environment Texas, Houston Audubon, Save Our Springs Alliance, and Turtle Island Restoration Network.

Because Texas's Department of Transportation (TXDOT) has the most federal-aid roadways of any state in the nation, stormwater controls and pollution from those roadways are key concerns for our organization. (Attachment 1, Federal Roadway Miles and Estimated Pollution). As such, we submit these comments regarding TXDOT's application and intent to obtain a state-wide NPDES permit from the Texas Commission on Environmental Quality (TCEQ) permit number WQ0005011000. This permit application seeks approval to discharge waters from TXDOT's Municipal Separate Storm Sewer System (MS4) region and is considered a non-traditional MS4 application.

The following four (4) entities specifically request a contested case on this permit application: Galveston Baykeeper, Galveston Bay Foundation, Environment Texas and Save our Springs Alliance. The names and addresses for all four are below and all have dedicated resources and advocacy efforts for decades to improve Texas's water quality. Each member or staff listed below is directly affected through their recreational, scientific, educational, or vocational activities related to these waters across the state and are identified specifically for this purpose. These identified members should receive all future correspondence and will be adversely affected by this permit.

<u>The Geographic Scope for this Permit Improperly Relieves TXDOT of Responsibility</u>

While we applaud TXDOT for recognizing that the educational components of its MS4 must cover the entire state of Texas, we urge TCEQ to amend the geographic scope of the permit to accurately reflect TXDOT's intent, and understanding of how the MS4 permit could appropriately cover a long linear discharge area like that owned and operated by TXDOT.

In its Fact Sheet, TXDOT recognizes that it is a non-traditional MS4 and states "[t]here are no residences, businesses, or commercial and industrial facilities located within TXDOT's right of way – TXDOT regulated area . . . . Since transient users cover such a broad spectrum of society, it is important that TXDOT's educational MCM address as many people as possible with a high level of comprehension." Thus, implying accurately, that its educational program must cover the entire state of Texas. This is then reflected in its Stormwater Management Program (SWMP) when it describes TXDOT's Public Education and Outreach Goals and Objectives. (SWMP at 1.2.1). TXDOT's regulated area, however, is restricted in the definition section of the SWMP (and introductory paragraph of the permit itself) when TCEQ defines the "regulated area" to mean only "areas of the state TXDOT right of way (ROW) within the urbanized areas established by the 2000 and 2010 U.S. Census Bureau Urbanized Area Map – hereafter referred to as 'TxDOT's regulated area.'" (SWMP at 3). This is then directly referenced within the permit itself as the scope of the permit authorizes TXDOT to discharge stormwater "located within the TxDOT Right of Ways (ROW) throughout the State of Texas served by, or otherwise contributing to discharges to the MS4s owned or operated by the permittee, located within the urbanized areas (UAs) in the TxDOT districts listed in Attachment 1 via the regulated MS4 to various ditches and tributaries that eventually reach water bodies listed in Attachment 2." (Permit at 1). The Permit's Attachment 1 lists by zip code the urbanized areas within each TXDOT district, thus improperly limiting the geographic scope of this MS4 permit. This is demonstrated by the attached maps created using the zip codes from the draft permit, highlighting that by using zip codes, TXDOT has improperly avoided responsibility over its roadways within watersheds in the UA's. (Attachment 2, Maps by Zip Code from TXDOT's Permit Application, Attachment 1 including Austin, Houston, Ft. Worth, Dallas, and San Antonio, as well as the entire state). These maps demonstrate that articulating the area of responsibility by zip code fails to account for all the regulated areas within the UAs and improperly relieves TXDOT of responsibility for its roadways that likely see the most miles traveled.

More problematic for the undersigned entities, however, is that by limiting the permit area to the areas that have met the population requirements as an urbanized area, TXDOT has improperly avoided responsibility for its roadways throughout the rest of the state. TXDOT cannot have it both ways—it cannot ask the state for a state-wide permit seeking to cover it as a non-traditional linear municipal separate storm sewer system, but then at the same time, argue that the coverage should only apply to urbanized areas based on population.

This is particularly true as the regulations describing state department of transportations as "small" MS4s do not then limit the geographic scope of those permits by an analysis for urbanized areas based on population. In 40 C.F.R. §122.26(b)(16), a small municipal separate storm sewer system is defined to include "highways and other thoroughfares" as well as other non-traditional MS4s. This is important as it recognizes that certain facilities and governmental agencies, like hospitals or flood control districts would be covered under the proposed "phase II" program precisely because they may not meet urbanized area requirements based on population. Indeed, the federal Environmental Protection Agency's guidance for "small" MS4s recognizes that non-traditional MS4s are not limited by population, but are simply "non-traditional" and designated through regulation as "small" for the purposes of permitting with the National Pollutant Discharge Elimination System. (Attachment 3, EPA Fact Sheet at 1 "The Phase II Rule automatically covers on a nationwide basis all small MS4s located in 'urbanized areas' (UAs) . . . and on a case-by-case basis those small MS4s located outside of UAs that the NPDES permitting authority designates."). It is important to note that EPA's fact sheet on small MS4s also specifically states "[c]ommon pollutants include oil and grease from roadways . . . and carelessly discarded trash, such as cigarette butts, paper wrappers, and plastic bottles." All of which multiple studies have demonstrated occur in great quantities along roadways. (Attachment 4, 2013 Texas Litter Survey conducted for TXDOT).

But even if the "population" of a non-traditional MS4 should be considered, in the Houston-Galveston region alone, more than 170 million miles are traveled each day by the population and while not all of those miles are on TXDOT roadways, the number demonstrates that TXDOT's roads should be considered, in their own right, as a long linear pathway that has more than 100,000 visitors per day.[1] These transient users should be analogized to the population requirements of the permit and thus, TXDOT's permit would still have to cover all of its roadways throughout the state.

The narrowing of TXDOT's regulated area also directly contradicts with its Memorandum of Understanding between it and the predecessor agency of the TCEQ, the Texas Natural Resource Conservation Commission (TNRCC). Under 2.23(e)(ii)(I) of the Memorandum of Understanding with the Texas Natural Resource Conservation Commission entitled "Water Quality", "TXDOT project types to be coordinated with TNRCC include projects which may encroach upon threatened or impaired stream segments designated under §303(d) of the Clean Water Act and/or 5 miles upstream from the designated stream segment." This implies, that at the very least, the geographic scope for this permit would be 5 miles upstream from every stream segment designated as impaired under §303(d) of the Clean Water Act for the state of Texas. This is because TXDOT's first state-wide NPDES permit should not undermine an existing agreement requiring coordination and activity to ensure that all TXDOT programs support TCEQ's efforts on water quality. This demonstrates in part why the geographic scope must in some way be further defined to reflect TXDOT's true programmatic approach both voluntarily agreed to (in the case of state-wide education) or otherwise required by long-standing MOUs and legal authority.

The scope of its responsibility is incredibly important because TXDOT will only spend its budget dollars on areas defined in the permit. Yet, TXDOT has further attempted to limit its responsibility even within the urbanized areas by claiming that other MS4s (presumably the cities and counties) are "discharging" stormwater onto TXDOT's roadways and that TXDOT would have no responsibility to store, clean, or detain that water – instead only being required to alert the separate operator that its discharge is improper. (*See* Fact Sheet at 21 ("TXDOT can better protect the quality of its MS4 by providing increased inspection of third party outfalls. Thus, TXDOT's program to locate and eliminate illicit discharges and improper disposals to the MS4 will focus on third party outfalls."). This improperly shifts the responsibility of roadway pollution to no-man's land. Every municipality will argue that the TXDOT roadway is the ultimate entity discharging

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[1] H-GAC's 2040 RTP System Overview, found at http://www.h-gac.com/taq/plan/2040/system.aspx and last visited on April 27, 2016.

(for example, a bridge)[2] and that such discharge should be covered by TXDOT's MS4. TXDOT appears to be arguing that such discharge would instead be the responsibility of the local municipality or county even though that county or city would have no ability to adopt structural controls or build green infrastructure within TXDOT's right of way in order to slow and clean the discharge. While the data TXDOT has collected may be interpreted as an adjacent MS4 operator illicitly discharging onto a Texas roadway, common sense also suggests that as it rains, water will – as water does – go towards a low point like a ditch next to a road built by TXDOT for precisely that reason. (*See e.g.*, SWMP at 2.2.2. ("Data collected during several permit terms supports the conclusion that the majority of illicit discharges to TXDOT's MS4 come from adjacent third-party MS4s.")). For TXDOT to claim that this is instead an illicit discharge from an adjacent MS4, rather than it being its responsibility to slow, clean, and detain the water as it enters its ditch or basin ignores the science behind how a watershed works.

This highlights a fundamental tension within the permit. TXDOT roads crisscross the state and roadway pollution is significant – from floatables to zinc to lead. Yet, TXDOT would rather be viewed as a mere conduit of water from other places, ignoring its role in creating the changes in the watershed and its design process to keep water off its roads. In *U.S. v. Washington State Dept. of Transportation,* a District Court in Washington found Washington's Department of Transportation liable for hazardous waste in waterways because the department had direct knowledge when designing its roadways—all of its roadways—that it seeks to direct stormwater runoff to the first available ditch, tributary or stream. 716 F. Supp. 2d 1009 (W.D. Wash. 2010). It found:

> It is undisputed that WSDOT designed the drainage systems at issue. Designing is an action directed to a specific purpose. The purpose was to discharge the highway runoff into the environment. WSDOT had knowledge that the runoff contained hazardous substances and there was an actual release of the hazardous substances into the environment. WSDOT argues that it did not have control of the hazardous substances. However, it did have control over how the collected runoff was disposed of. WSDOT did design the drainage system and, as noted by the U.S., WSDOT has the ability to redirect, contain, or treat its contaminated runoff.

Id. at 1015. TXDOT has direct knowledge that it designs roadways to collect water and shift it to man-made or natural ditches and drainages that lead to waters of the U.S. Yet, the current draft permit appears to shift the responsibility of TXDOT's design flaws to the surrounding communities. This is unfair and inappropriate. Instead, the language of the permit describing the geographic scope should be amended to say:

> TXDOT "is authorized to discharge from the Texas Department of Transportation (TxDOT) Municipal Storm Sewer System (MS4) (SIC 9621) including all regulated areas, except for any agricultural lands, located within the TxDOT Right of Ways (ROW)

[2] Similarly, a majority of TXDOT bridges will span rivers and streams in the State of Texas that are waters of the United States. By ignoring these bridges, the permit ignores TXDOT's own design manual that requires the bridge to collect and discharge directly into a stream or river.

throughout the State of Texas served by or otherwise contributing to discharges to the MS4s owned or operated by the permittee."

If the geographic scope is not changed, the undersigned request TCEQ's analysis for why the geographic scope should be more limited than the existing MOU requiring coordination 5 miles upstream from every 303(d) listed stream segment. The undersigned also request TCEQ's analysis for why the geographic scope should be limited to UAs when TXDOT's own numbers show that every linear mile of TXDOT roadways has more than 100,000 "transient" users that should be analogous to population.

Stormwater discharges will result in exceedances of water quality standards for heavy metals

In Attachment 1 to TXDOT's application at page 10 in the paragraph entitled "Oil and Grease," TXDOT maintains that

> Oil and grease that may potentially discharge from the TXDOT MS4 does not originate from any roadway operations; the deposition of oil and grease (other than spills, which are mitigated separately as spill control/emergency response) comes from transient users of the roadway system.

Under 40 C.F.R. 123.35(b)(1)(i), TCEQ is required to develop criteria to evaluate how "storm water discharge results in *or has the potential to result in* exceedance of water quality standards, including impairment of designated uses or other significant water quality impacts, including habitat and biological impacts." [3] Based on a limited review of the following 4 stream segments which have been listed by TCEQ as impaired, it does not appear that this permit would limit the exceedances of heavy metals into impaired waters for these same heavy metals.

We reviewed the following 4 stream segments from TCEQ's 2014 Integrated Report listing impaired waters for the Clean Water Act's 303(d) list:

Segment ID	**Name**	**Parameter**
0402A_01	Black Cypress Bayou	copper in water
0402A_03	Black Cypress Bayou	copper in water
0608A_01	Beech Creek	copper in water
1407A_01	Clear Creek	Aluminum in water

[3] This provision regarding permitting small MS4, also states that any criteria discussed above must be applied to "any small MS4 located outside of an urbanized areas serving a jurisdiction with a population density of at least 1,000 people per square mile and a population of at least 10,000" implying again that limiting a "small" non-traditional MS4 only to "urbanized areas" is not appropriate.

1407A_01	Clear Creek	nickel in water
1407A_01	Clear Creek	zinc in water

Using published and well-accepted concentrations for toxic metals in roadway storm runoff and standard engineering methods to calculate average annual runoff volumes, we then estimated average annual loads for these metals from Texas highways within their watersheds. The results demonstrate that roadways are a significant contributor of these heavy metals within the watersheds of streams listed as impaired based on requirements of federal Clean Water Act.

Pollutant Loads	Inks Lake/Clear Creek	Big Cypress Bayou 0402A_01	Big Cypress Bayou 0402A_03	Beech Creek
Annual Avg. Rain (inches)[4]	28	51	49	57
Average Annual Runoff (cubic Feet/acre/year)	79,381	144,587	138,916	161,597
Copper Load (pounds/acre/year)	0.51	0.93	0.89	1.04
Nickel Load (pounds/acre/year)	49.12	89.47	85.96	100.00
Zinc Load (pounds/acre/year)	2.03	3.70	3.55	4.13
Highway Area (acres)	543	725	1,057	2,2278
Average Annual Load of Copper (pound/year)	277	674	944	2,365
Average Annual Load of Nickel (pound/year)	26,676	64,870	90,893	227,742
Average Annual Load of Zinc (pound/year)	1,103	2,681	3,757	9,413

The undersigned request TCEQ's documentation that supports the determination made by the Executive Director of the TCEQ that the permit and SWMP as implemented and detailed in the application will reduce the discharge of pollutants from the MS4, and in particular for stream segments already listed as impaired waters.

[4] NOAA average precipitation map in GIS for 1981 through 2010.

TXDOT's assertion that oil, grease, and other heavy metals are not discharged from its MS4 but only from adjacent MS4s is inconsistent with three decades of science documenting these pollutants in roadway runoff. If TCEQ supports that assertion, please provide the documentation demonstrating that as well.

In addition, attached is a 1995 report from the Center for Research in Water Resources from The University of Texas at Austin entitled "An Evaluation of the Factors Affecting the Quality of Highway Runoff in the Austin, Texas Area" funded by the TXDOT. (Attachment 7). The Center for Research in Water Resources conducted a four (4) year investigation into the quality of the stormwater runoff from existing highways at the time in and near the recharge zone of the Barton Springs segment of the Edwards Aquifer. Even two decades ago, the engineering community and the Austin community, recognized that to mitigation of copper, lead, oil and grease, iron, zinc and nutrients required "runoff controls." Thus, again, TXDOT's new argument that pollutants of concern, like oil and grease, should be not be regulated under its stormwater permit is counter to established case law and the regulations adopted for non-traditional MS4s.

Assuming Less than Primary Contact for Any Texas Stream Violates the Clean Water Act

TXDOT's application improperly attempts to lower the Clean Water Act standards applied to streams not listed in its application by assuming multiple unclassified waterways in Texas have minimal aquatic life. It assumes that any

> (1) unclassified water body that is intermittent should be presumed only to support minimal aquatic life use with the associated dissolved oxygen criteria of 2.0 mg/L,
>
> (2) unclassified waterbodies that are intermittent with perennial pools should be presumed to support only minimal aquatic life use with the associated dissolved oxygen criteria of 3.0 mg/L, and
>
> (3) unclassified water bodies that are perennial shall be assigned the presumption of high aquatic life use with the associated dissolved oxygen criteria of 5.0 mg/L.

(TXDOT Fact Sheet at 69). First, any perennial water body in the state should be assumed under Texas Water Quality Standards to be primary contact I or at least an exceptional aquatic life standard. According to 30 TAC §307.7(b)(3)(A)(i), this would require as associated dissolved oxygen criteria of 6.0 mg/L. Second, any assumption that even intermittent streams do not support high aquatic life use mistakenly "declassifies" streams throughout the state that may never have been before classified under an existing NPDES. This is because with TXDOT's new "state-wide" approach, it is presumed that additional miles of roadways will now be covered by the NPDES program that were previously not covered by the multiple regional MS4 permits TXDOT had complied with before.[5] Thus, any assumption of a lower water quality standard—especially for perennial waterbodies—violates the Clean Water Act's anti-backsliding provisions.

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[5] This is true even as TXDOT attempts to forego responsibility for its entire linear system and only have this permit apply to the urbanized areas because those urbanized areas recently adopted in the 2010 Census may not have been covered by an existing phase II permit prior to 2015.

The following language in the permit should be amended because it appears the description above utilized the minimum dissolved oxygen contents required for these streams. Section 2.D.2 "Compliance with Water Quality Standards" in the permit should read:

> The requirements in this permit must provide compliance with the Texas Surface Water Quality Standards as specified in 30 TAC §§ 307.1-307.10. This includes the presumption that every unclassified water body that is perennial be assigned an exceptional aquatic life status and meet the mean and minimum dissolved oxygen criteria required by code. This also includes that any unclassified water body that is intermittent or intermittent with perennial pools be assigned an intermediate aquatic life category and meet the mean and minimum dissolved oxygen criteria required by code.

The reason the language should change is to prevent any backsliding or degradation of streams where the water quality currently is higher than presumed, and to meet the Clean Water Act's forward looking mission. This is required under the Clean Water Act. In 1987, two "anti-backsliding" provisions were added to the Clean Water Act, sections 402(o)(2) and 303 (d)(4)(B). [6,7] These provisions were added to further the purpose of the Clean Water Act and ensure that states and the federal government moved towards cleaning up the nation's waterways and that no backtracking on good stewardship would be permitted. It also codified the concept of the environmental rules and regulations being "forward" moving, in that the purpose was to continue to strive towards ensuring every waterway met drinking water standards. TCEQ and TXDOT would violate the Clean Water Act by creating a programmatic approach that implicitly allows more pollution in a variety of Texas streams. This is particularly true as TXDOT has not provided any evidence, nor supported any of these changes with a cumulative review of how the various watersheds would be impacted.

If this language is not amended, the undersigned requests TCEQ's analysis or case studies on unnamed streams that support adopting a minimum aquatic life standard instead of a more

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[6] Clean Water Act of 1972, 33 U.S.C. § 1342 402(o)(2). Section 402(o)(2) allows for less stringent water quality standards in six situations:

1) Where there have been material and substantial alterations or additions to the permitted facility which justify this relaxation;
2) Where good cause exists due to events beyond the permittee's control (e.g., Acts of God) and for which there is no reasonably available remedy;
3) Where the permittee has installed and properly operated and maintained required treatment facilities but still has been unable to meet the permit limitations (backsliding may only be allowed to the treatment levels actually achieved);
4) Where new information (other than revised regulations, guidance, or test methods) justifies backsliding from water quality-based permit limitations and other 301(b)(l)(C) limitations; and
5) & 6) technical mistakes and mistakes of law and permit modifications or variances (these exceptions do not apply to water quality based effluent limitations.)

[7] Clean Water Act of 1972, 33 U.S.C. § 1313 303 (d)(4)(B). (Section 303(d)(4)(B) provides that a permittee may backslide from a water quality-based effluent limitation where water quality meets or exceeds applicable water quality standards. Only two of these would be applicable to the TCEQ downgrade.)

robust standard and how that adoption does not violate the Clean Water Act's anti-backsliding provisions.

<u>Additional Needs to Comply with Existing Regulations Regarding the Edwards Aquifer</u>

As mentioned above, the current draft permit impermissibly narrows the geographic scope of TxDOT's regulated areas. In addition to leaving large swaths of land unregulated, the draft permit fails to cover areas within the recharge zone of the Barton Springs portion of the Edwards Aquifer, as the previous MS4 permit for the Austin District did. That permit, issued on October 7, 2008, specifically states that the MS4 includes areas "within rights-of-way owned and operated by the Texas Department of Transportation located within the corporate boundary and the five mile extra-territorial jurisdiction (ETJ) of the City of Austin, **within all rights-of-way located outside of the corporate boundary of the City of Austin but within the recharge zone of the Barton Springs portion of the Edwards Aquifer,** and within additional rights-of-way that are located within the Austin, Texas urbanized area, in Hays, Travis, and Williamson Counties, Texas." (emphasis added).

Thus, the 2008 MS4 covered the Barton Springs portion of the Edwards Aquifer on a watershed basis, ensuring coordinated regulation of pollutants entering the Aquifer. By contrast, the current draft permit only covers MS4s located "within the TxDOT right-of-way within the urbanized areas established by the 2000 and 2010 U.S. Census Bureau Urbanized Area Maps," and lists the cities and corresponding zip codes in the Austin District, but not including the non-urban portions of the recharge zone.

To ensure the new permit covers the same permits as the past permit, as well as compliance with the Edwards Aquifer Rules, the draft permit should at least include those areas within the recharge zone of the Barton Springs portion of the Edwards Aquifer. Should TCEQ refuse to adopt the above proposed language providing for a statewide geographic scope, TCEQ should at least revise the draft permit to include the italicized language from the 2008 Austin MS4 permit.

1. *<u>Endangered Species</u>*

The Fact Sheet and Executive Director's Preliminary Decision, at page 49, identifies stream segments and endangered species within those stream segments for urbanized areas to be covered by the permit. For the Austin District, several endangered species are listed as occurring in the Colorado River Basin (1400), thus requiring EPA review and potential consultation with the U.S. Fish and Wildlife Service (FWS). However, the list fails to include three salamander species that have recently been listed as federally endangered or threatened. These species are:

- Austin blind salamander, *Eurycea waterlooensis*
- Jollyville Plateau salamander, *Eurycea tonkawae*
- Georgetown salamander, *Eurycea naufragia*

The listing of the Austin blind and Jollyville Plateau salamanders thoroughly discusses how highway construction and operation threaten the survival of the salamander. *Determination of Endangered Species Status for the Austin Blind Salamander and Threatened Species Status for the*

Jollyville Plateau Salamander Throughout Their Ranges, U.S. Fish & Wildlife Service, 78 Fed. Reg. 51,278, 51,302-51,307 (Aug. 20, 2013).[8]

The draft permit should be amended to include the Austin blind salamander, Jollyville Plateau salamander, and Georgetown salamander as species occurring in the Colorado River Basin (1400) of the Austin District.

2. *Edwards Aquifer Protection Program*

The draft permit and Fact Sheet only briefly mention the Edwards Aquifer Rules, asserting that TxDOT must comply with these rules. The section on Edwards Aquifer Rules should be revised and expanded to include specific performance measures that are required of TxDOT under these rules. At a minimum, the permit should include the language regarding Best Management Practices and Measurable Goals under the Edwards Aquifer Rules discussion contained in TxDOT's MS4 application. Requiring these measures in the draft permit does not impose an undue burden, because TxDOT has agreed to abide by these terms, but including them in the draft permit ensures that the terms are legally binding[9] and can help inform future permit renewals.

3. *Spill Prevention and Response*

The draft permit, at page 25, includes "Additional Requirements for Previous TxDOT-Austin District Phase I Permit (WQ0004645000)" and sets out Spill Prevention and Response requirements. Among other things, TXDOT is required to, in coordination with FWS, identify potential projects to prevent spills from entering the Edwards Aquifer, and report any coordination of projects identified in an annual report. Likewise, the 2008 Austin District MS4 Permit required identification of such projects, but additionally required TXDOT to "submit an implementation schedule for those projects identified, not to exceed Year Five of the permit term." There are likely still many projects that need to be implemented, especially given ongoing road construction, and the draft permit should include specific responsibilities for TXDOT to implement spill-prevention programs. Therefore, the draft permit Part III, section B.2 (j)(1) should be revised to include the requirement that TXDOT submit an implementation schedule for projects identified with the FWS as potential projects to prevent spills from entering the aquifer.

TCEQ Should Examine the Cumulative Effect in the Watershed and require more for Redevelopment

[8] See also *Determination of Threatened Species Status for the Georgetown Salamander and Salado Salamander Throughout Their Ranges*; U.S. Fish & Wild. Serv., 79 FR 10,235 (Mar. 26, 2014).

[9] While the undersigned believe the SWMP are legally enforceable, similar to the permit, the reality is that the permit will be examined more frequently when determining water quality compliance measures and thus mirroring the language in the permit places no undue burden on TXDOT.

TXDOT manages the most highway miles of any state in the nation (Attachment 1). Yet, the draft permit fails to correct past mistakes in roadway siting, or design, by not requiring redevelopment to examine the cumulative effect. This draft permit also purports to begin moving towards a watershed approach, yet does not require numeric benchmarking to ensure that a watershed approach is done cooperatively with adjacent permittees. In EPA's August 2007, Watershed Based NPDES Permitting Guidance, EPA attempted to showcase why a watershed approach would be particularly helpful, whereas here, there are multiple point sources contributing high volumes of run-off from impermeable surfaces:

> To understand the first issue, the presence or absence of far-field effects, it is important to consider the difference between localized effects and far-field effects. Localized effects, or nearfield effects, are impacts that are evident within a smaller, more immediate area close to the source of the pollutant or stressor. On the other hand, far-field effects are those impacts felt in a wider area and where there potentially are cumulative impacts from multiple sources. In most cases one could address pollutants with localized effects (e.g., acute and chronic effects of pollutants such as cyanide or chlorine) by controlling and monitoring them through individual permits or nonpoint source controls that apply effluent limitations or practices reflecting individual controls designed to ensure attainment of water quality standards in the immediate Watershed-based Permitting Technical Guidance vicinity of the discharge. Where several point source dischargers experience problems with localized effects of specific pollutants, however, a watershed permitting approach might be helpful. For instance, a monitoring consortium could be established to quantify pollutant sources, assess the impacts of pollutant discharges, and develop site-specific water quality criteria for the waterbody.[10]

Again, a cumulative approach for redevelopment should require TXDOT to re-examine pre-existing siting issues and address the issue of water quality from a watershed perspective (not just the incremental 1 acre or 5 acre redeveloped site).

<u>TCEQ Should Require Wet Weather Testing, if not Numeric Limits</u>

TXDOT's own hydraulic design manual has computed the discharge rates for stormwater and various pollutants. By TXDOT district, a computation based on roadway miles is possible to benchmark the amount of pollution directly flowing into the state's waters by the stormwater run-off from TXDOT roads. (Attachment 6). As such, the lack of wet weather testing to benchmark these discharge rates, coupled with the lack of numeric limits within the permit for discharge rates, cannot be said to "reduce the discharge of pollutants from the MS4," nor does there seem to be support for the idea that the discharges into waters already impaired by sediment, zinc, phosphorous or nitrogen would be eliminated by this permit and corresponding SWMP. Fact Sheet at 17. The SWMP has no numeric limits. It has no benchmarks for reduction in pollution. It has

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[10] The guidance document can be found here: https://www3.epa.gov/npdes/pubs/watershed_techguidance.pdf and was last viewed on April 27, 2016.

no description of impaired waters for criteria pollutants and how those waters would be further protected by TXDOT. It is not enough to maintain the status quo – this new permit application must work to address pre-existing conditions.

While the undersigned applauds TXDOT for implementing an Advanced Outfall Tracking System prior to this permit, it appears that TXDOT has already begun this work and mapped a significant portion of its regulated area. Thus, permitting it to take an additional 5 years to complete the mapping process only delays advancement towards implementing better control measures regarding those outfalls to improve water quality.

The undersigned request a copy of the hydrologic models and research performed by TCEQ in determining that the draft permit, with SWMP, would not further degrade impaired waters in the Houston District.

In addition, if only dry weather testing is required, then at the very least adequate benchmarking must be required. In both the permit and SWMP, TXDOT recites that in lieu of wet weather monitoring it will "evaluate the watershed using existing stormwater characterization data collected by" a variety of regional quasi-governmental entities. Yet, EPA's guidance document on implementing a watershed approach for a permit requires instead, benchmarking for improvement on, for example, aquatic life by examining the "percentage of river miles and lake acres identified as having a fish consumption advisory in 2002 for which water and sediment quality have improved and allow for increased consumption of safe fish." Or by examining within a watershed, the "percent of days of the beach season that beaches monitored by beach safety programs will be open and safe for swimming."[11] Thus, to allow a watershed approach in lieu of wet weather monitoring but to not require adequate benchmarking regarding the watershed approach appears to violate the Clean Water Act's requirement to monitor under 40 C.F.R. § 122.26(d)(2)(i) (Adequate Legal Authority) because the applicant does not have the ability by ordinance or contract to ensure the other entities continue collecting data. Moreover, it is unclear why TXDOT's "analysis and interpretation of this data" to be submitted to TCEQ should act to meet the primary objectives of the permitting program to monitor and benchmark, when other MS4 operators will presumably be charged with paying for and analyzing that same data. (SWMP at 2.6 (In lieu Stormwater Monitoring Program Implementation Overview)).

The following language in the permit should be added:

> Section 2(g)(1) should be amended to state:
> Minimum Investigation Requirements – The permittee shall inspect no less than 25% of the TXDOT MS4 regulated area yearly including inspection for dry weather discharges per year to ensure an adequate monitoring and IDDE program. Such program to inspect may correspond with the prior requirements under Section 2(i)(4) (Identification of Priority Areas) or, as feasible, be in addition to such other requirements.

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[11] EPA Guidance document entitled Watershed-Based National Pollutant Discharge Permitting Technical Guidance EPA 833-B-07-004 August 2007 at Exhibit 1.6 found at https://www3.epa.gov/npdes/pubs/watershed_techguidance.pdf and last viewed on 4/22/16.

Then the prior (g)(1) should be renamed: "Requirements for Known Illicit Discharges." This language is directly taken from TXDOT's proposed SWMP, attachment 3 entitled measurable goals for MCMs in the Stormwater Management Program. The reason it is more appropriately placed in the permit is because (1) the SWMP is only proposed, (2) the SWMP is easily amended without public input, and (3) the SWMP provides an alternative that eliminates a yearly requirement to detect or inspect a certain amount of regulated area, thus providing too much flexibility for TXDOT staff to lower the percentage of road miles actually inspected. This is especially important as TXDOT's SWMP also states that it will "screen all areas of the MS4 at least once during the permit term" thus implying that at the very least 20-25% of every road mile will be inspected each year under this 5 year permit. This type of minimum testing requirements are found in other MS4 permits for departments of transportations and because it does not seem to be any more burdensome to include it in the permit, the language should be amended. (For example, Arizona's Department of Transportation must inspect half of its major outfalls each year. ADOT Permit; Section 3.2.3.2.d.).

Floatables

Finally, language similar to that found in the regional permits that TXDOT is rolling off of related to floatables should be included as it requires a program to actually reduce the discharge rate of floatables in the MS4 by utilizing source controls or structural controls. These types of facilities are directly relevant to TXDOT and should be required by TXDOT as its users – the transient users traveling along the roadways throughout Texas—are direct contributors to litter, and thus, pollution in the state's waters. The language can mirror that found, for example, in Corpus Christi's permit number WQ0004200000 when it describes the storm water management program.

> III.B.6(c): Floatables The permittees shall ensure the implementation of a program to reduce the discharge of floatables (e.g. litter and other human generated solid refuse) into the MS4 which shall include source controls and where necessary structural controls and other appropriate controls

In support, attached is the most recent litter survey conducted by TXDOT and demonstrating that all parties are only too aware of the problem Texas has with floatables and litter from roadways. Should TXDOT be permitted to completely ignore this issue, it places an unmanageable burden on the counties throughout the state and improperly shifts the financial burden from the entity that created the pollution source (the roadway) to cities and counties, and ultimately, Texas's rivers and streams.

Summary

We urge TCEQ to consider adopting the changes recommended above to ensure that Texas's rivers and streams are not only protected but improved with this new state-wide permit.

Jen Powis Galveston Baykeeper	Luke Metzger Environment Texas	Scott Jones Galveston Bay Foundation

2010 North Loop West, Suite 275 Houston, Texas 77018	815 Brazos St, Austin, TX 78701	17330 Hwy. 3, Webster, TX, 77598
Kelly Davis Save our Springs Alliance 905 W. Oltorf St., Ste. A Austin, Texas 78704	Helen Drummond Houston Audubon 440 Wilchester Blvd Houston, Texas 77079	Joanie Steinhaus Turtle Island Restoration Network

Attachment 1

Estimated Stormwater and Direct Pollution from Federal-Aid Highways in Selected States

	All Federal Aid Roads (including National Highway System)						
State	(Miles)*	Runoff from 1 in of rain (gallons)	Acres**	Nitrogen (lbs/yr)	Phosphorous (lbs/yr)****	Sediment (tons/yr)*****	Zinc (lbs/yr)******
AL	55280	2,183,399,874	80,407	1,125,702	123,023	24,926	104,529
AK	9124	360,371,571	13,271	185,798	20,305	4,114	17,253
AZ	36080	1,425,055,489	52,480	734,720	80,294	16,269	68,224
AR	46352	1,830,769,735	67,421	943,895	103,154	20,901	87,647
CA	149111	5,889,452,579	216,889	3,036,442	331,840	67,236	281,955
CO	41856	1,653,190,758	60,881	852,340	93,149	18,873	79,146
CT	15101	596,445,758	21,965	307,511	33,607	6,809	28,555
DE	4103	162,056,615	5,968	83,552	9,131	1,850	7,758
DC	1446	57,112,811	2,103	29,446	3,218	652	2,734
FL	75481	2,981,280,859	109,791	1,537,068	167,980	34,035	142,728
GA	74360	2,937,004,606	108,160	1,514,240	165,485	33,530	140,608
HI	3880	153,248,761	5,644	79,011	8,635	1,750	7,337
ID	24441	965,348,703	35,551	497,708	54,392	11,021	46,216
IL	83385	3,293,465,964	121,287	1,698,022	185,570	37,599	157,673
IN	51171	2,021,106,276	74,431	1,042,028	113,879	23,073	96,760
IA	58614	2,315,083,216	85,257	1,193,594	130,443	26,430	110,834
KS	74959	2,960,663,371	109,031	1,526,438	166,818	33,800	141,741
KY	33882	1,338,240,856	49,283	689,961	75,403	15,278	64,068
LA	33017	1,304,075,862	48,025	672,346	73,478	14,888	62,432
ME	13721	541,939,755	19,958	279,409	30,535	6,187	25,945
MA	21733	858,390,547	31,612	442,563	48,366	9,800	41,095
MD	26147	1,032,730,762	38,032	532,448	58,189	11,790	49,442
MI	84722	3,346,273,591	123,232	1,725,248	188,545	38,202	160,202
MN	72412	2,860,064,249	105,327	1,474,572	161,150	32,651	136,925
MS	48556	1,917,821,351	70,627	988,777	108,059	21,894	91,815
MO	68956	2,723,562,259	100,300	1,404,195	153,458	31,093	130,390
MT	32073	1,266,790,596	46,652	653,123	71,377	14,462	60,647
NE	44098	1,741,743,264	64,143	897,996	98,138	19,884	83,385
NH	16396	647,594,507	23,849	333,882	36,489	7,393	31,003
NJ	7808	308,393,383	11,357	158,999	17,376	3,521	14,764

NM	27414	1,082,773,592	39,875	558,249	61,009	12,361	51,837
NV	29093	1,149,089,228	42,317	592,439	64,745	13,118	55,012
NY	68362	2,700,100,980	99,436	1,392,099	152,137	30,825	129,266
NC	54487	2,152,078,671	79,254	1,109,553	121,258	24,569	103,030
ND	38649	1,526,523,548	56,217	787,034	86,012	17,427	73,082
OH	73402	2,899,166,381	106,767	1,494,732	163,353	33,098	138,797
OK	71248	2,814,089,620	103,633	1,450,868	158,559	32,126	134,723
OR	39925	1,576,921,852	58,073	813,018	88,851	18,003	75,495
PA	66378	2,621,738,727	96,550	1,351,697	147,721	29,930	125,515
RI	4203	166,006,325	6,113	85,588	9,354	1,895	7,947
SC	49053	1,937,451,411	71,350	998,897	109,165	22,118	92,755
SD	42111	1,663,262,520	61,252	857,533	93,716	18,988	79,628
TN	45208	1,785,585,049	65,757	920,599	100,608	20,385	85,484
TX	197828	7,813,632,964	287,750	4,028,497	440,257	89,202	374,075
UT	20504	809,848,607	29,824	417,536	45,631	9,245	38,771
VT	8533	337,028,783	12,412	173,763	18,990	3,848	16,135
VA	54845	2,166,218,634	79,775	1,116,844	122,055	24,730	103,707
WA	46039	1,818,407,142	66,966	937,521	102,458	20,759	87,056
WI	22940	906,063,551	33,367	467,142	51,052	10,344	43,377
WV	64178	2,534,845,099	93,350	1,306,897	142,825	28,938	121,355
WY	17719	699,849,174	25,773	360,823	39,433	7,990	33,505
Total	2350384	92833359784	3418740.4	47862365.09	5230672.8	1059809.5	4444362.47

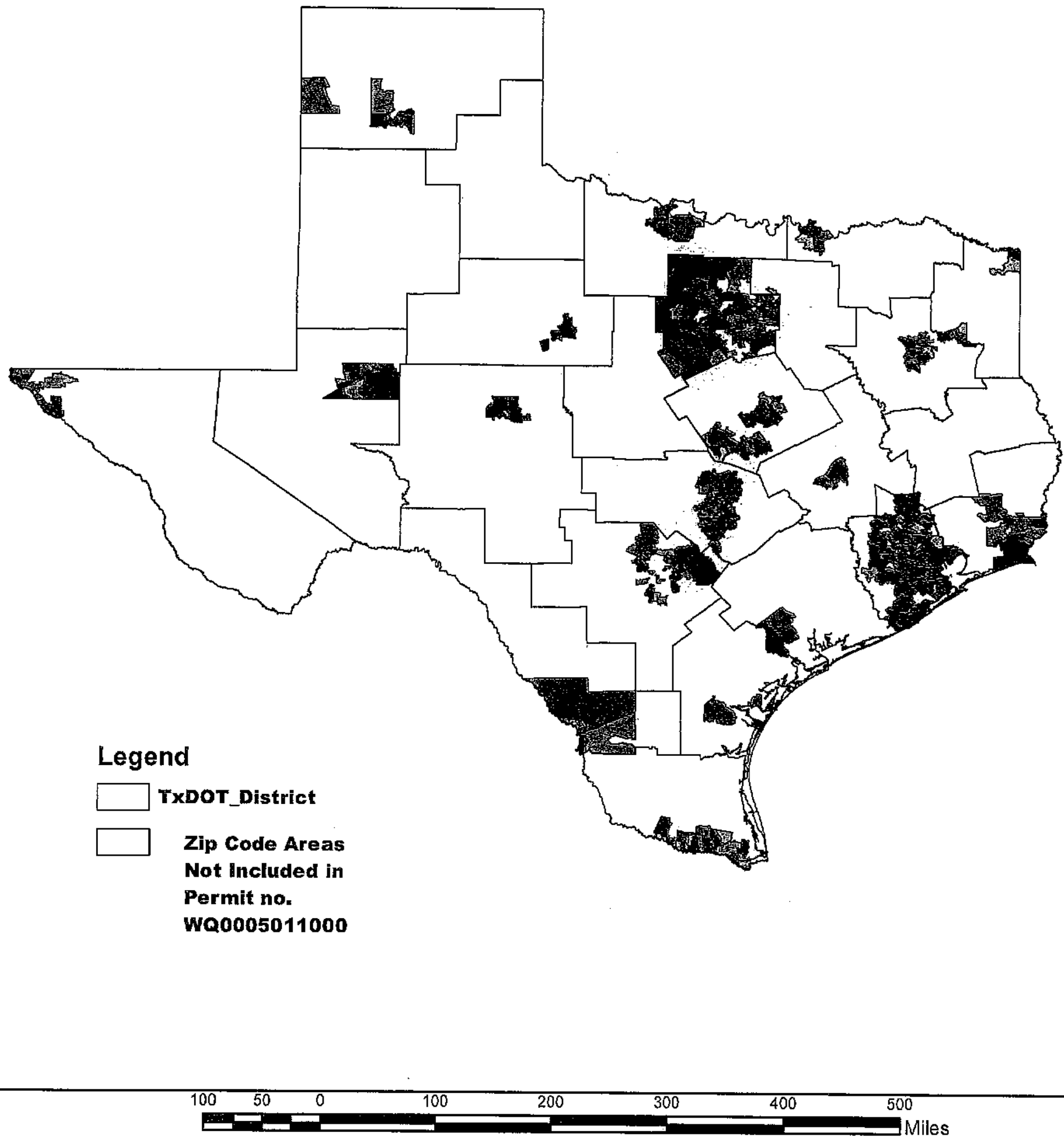
***From the US Department of Transportation Federal Highway Administration Highway Statistics 2006 (Lane miles used)**

**** Acres calculated using an average of a 12 foot wide highway lane.**

Loading rates used are based on national averages computed by the Center for Watershed Protection
*****Nitrogen loading rate: 14 lb/ac/yr.**
******Phosphorous loading rate: 1.53 lb/ac/yr.**
*******Sediment loading rate: 0.31 ton/ac/yr.**
********Zinc loading rate: 1.3 lb/ac/yr.**

prepared by
American Rivers

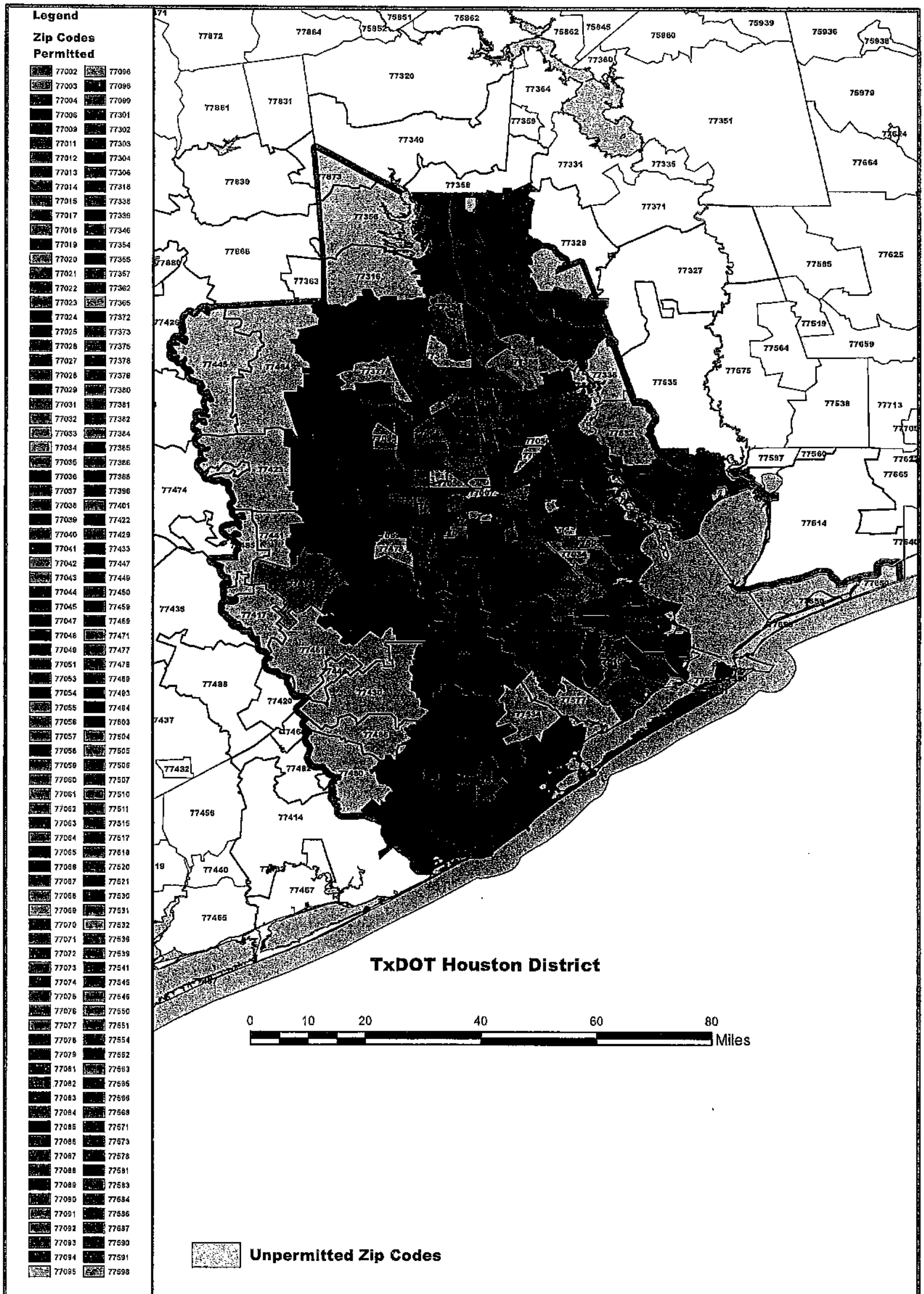
Attachment 2



PERMIT TO DISCHARGE UNDER THE TEXAS POLLUTANT DISCHARGE ELIMINATION SYSTEM

PERMIT No. WQ0005011000

Texas Department of Transportation



PERMIT TO DISCHARGE UNDER THE
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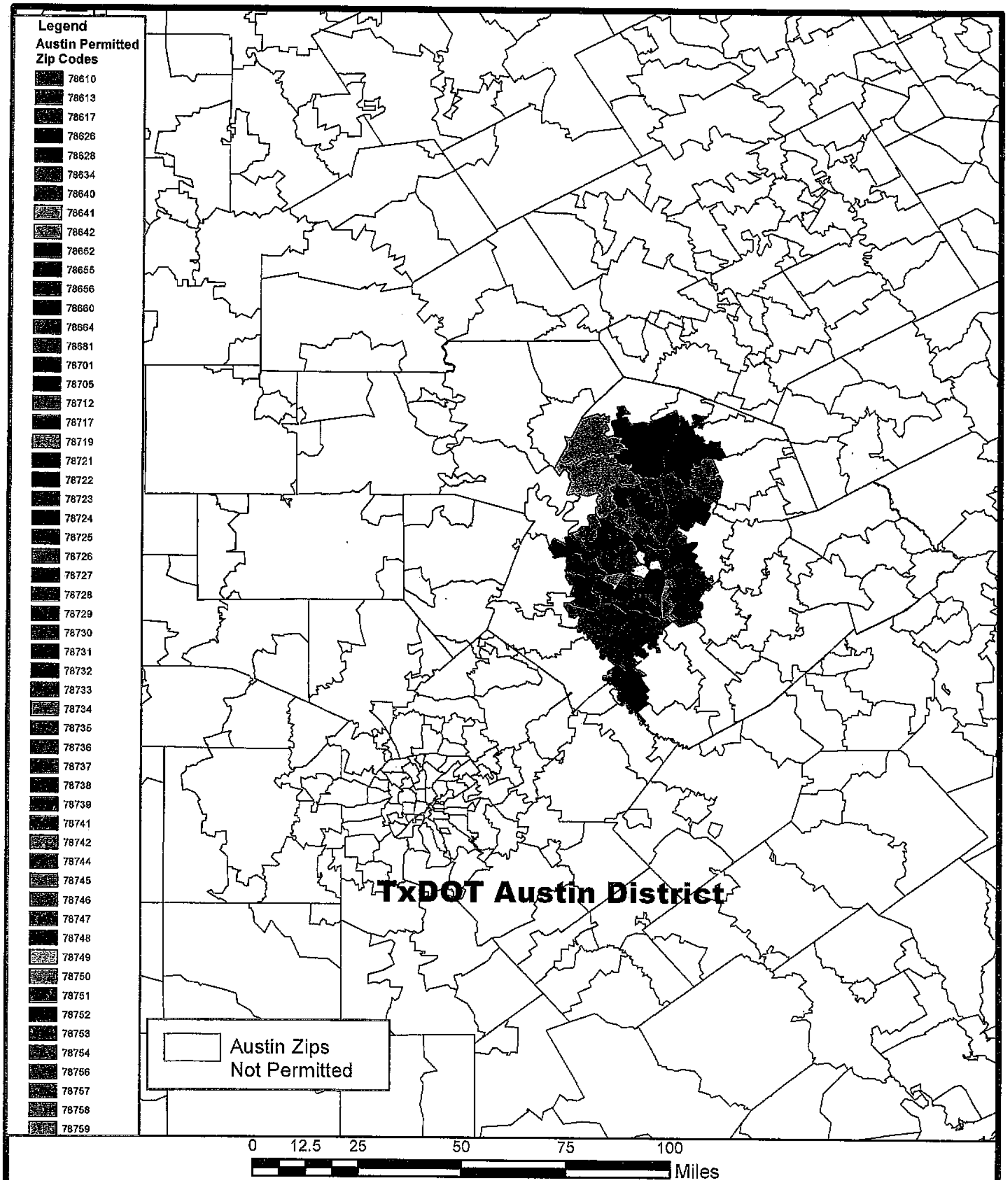
Texas Department of Transportation



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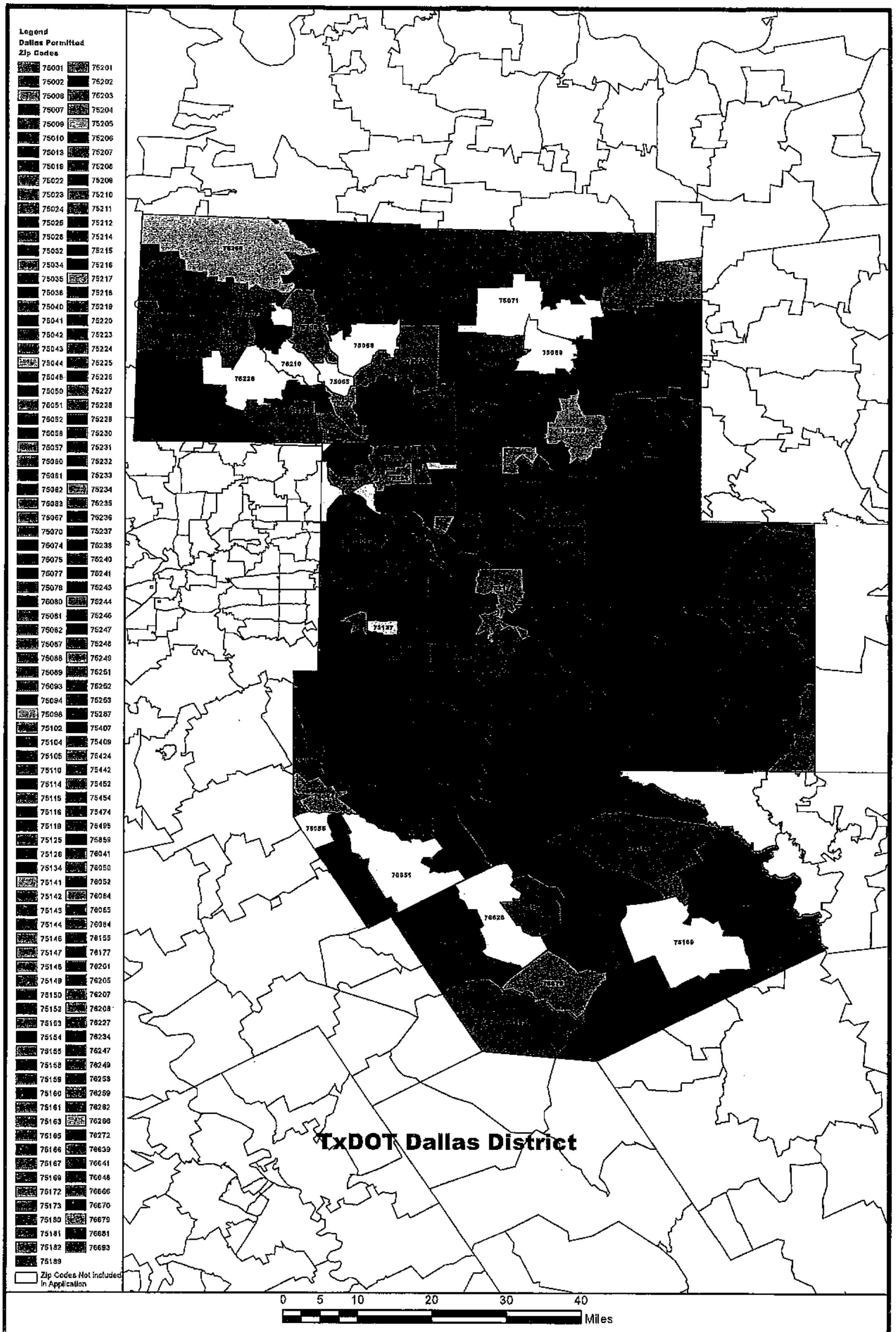

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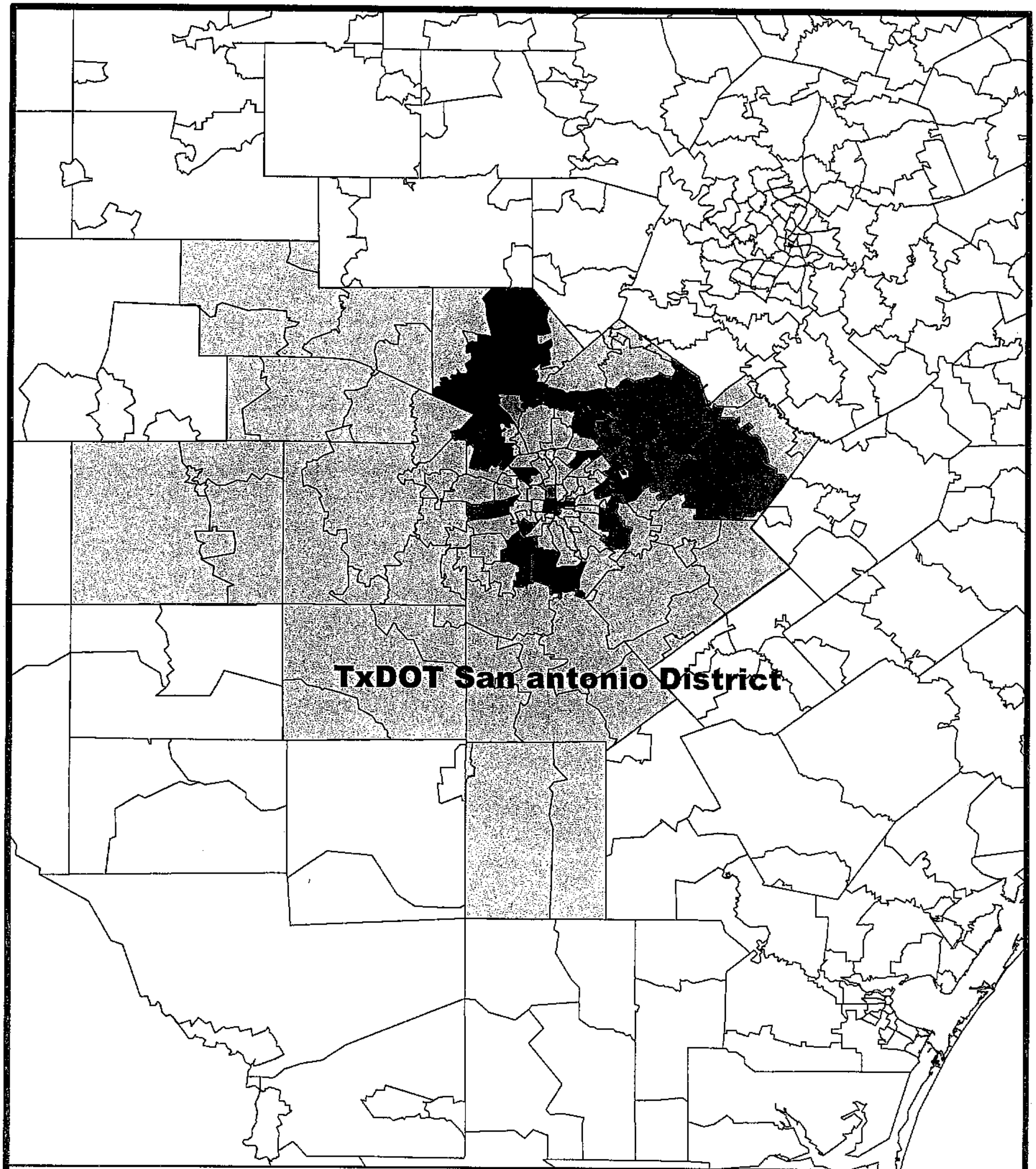

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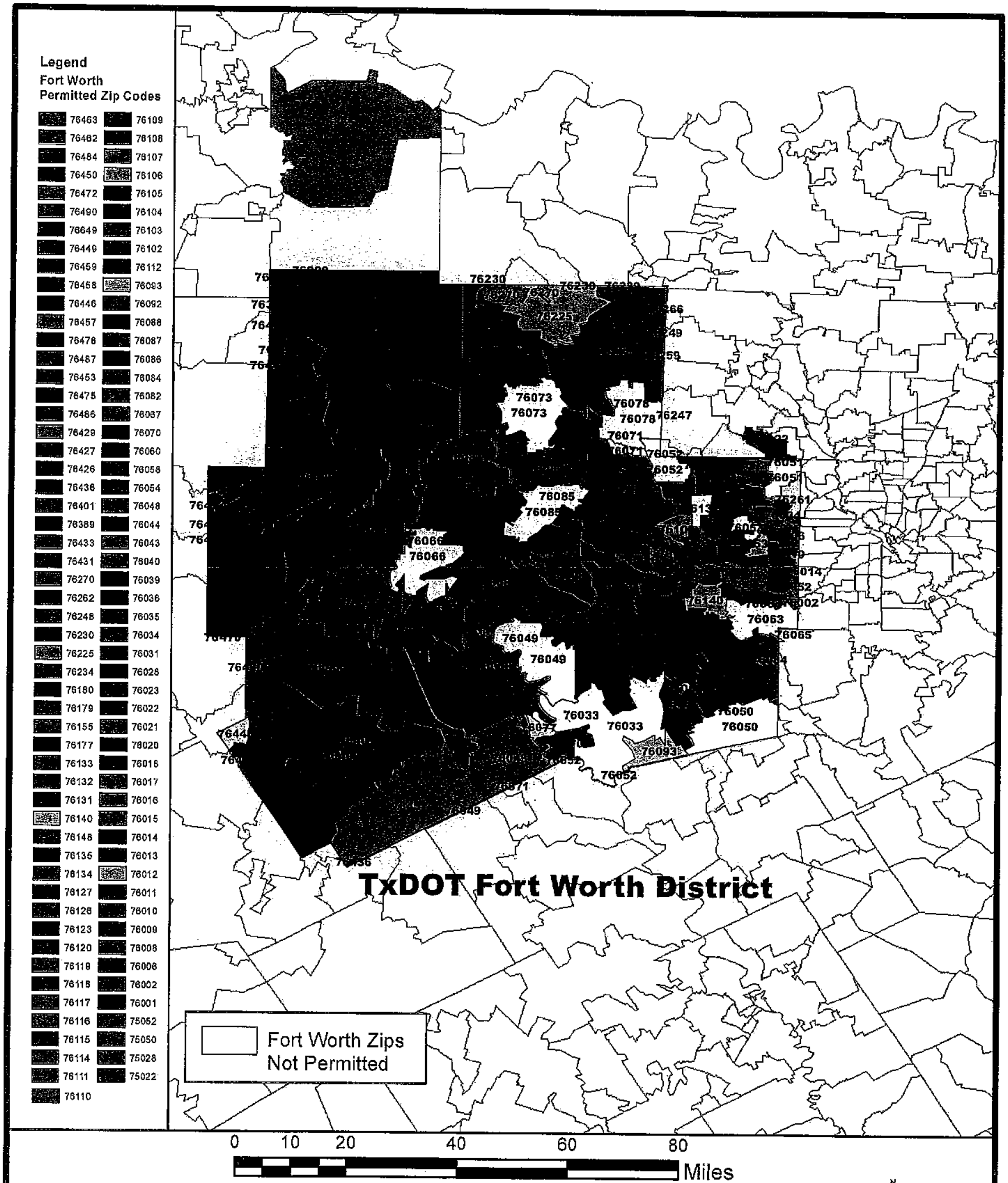

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PERMIT No. WQ0005011000
Texas Department of Transportation

Attachment 3

United States Environmental Protection Agency
Office of Water (4203)
EPA 833-F-00-002
January 2000 (revised December 2005)
Fact Sheet 2.0

Stormwater Phase II Final Rule

Small MS4 Stormwater Program Overview

Polluted storm water runoff is often transported to municipal separate storm sewer systems (MS4s) and ultimately discharged into local rivers and streams without treatment. EPA's Stormwater Phase II Rule establishes an MS4 stormwater management program that is intended to improve the Nation's waterways by reducing the quantity of pollutants that stormwater picks up and carries into storm sewer systems during storm events. Common pollutants include oil and grease from roadways, pesticides from lawns, sediment from construction sites, and carelessly discarded trash, such as cigarette butts, paper wrappers, and plastic bottles. When deposited into nearby waterways through MS4 discharges, these pollutants can impair the waterways, thereby discouraging recreational use of the resource, contaminating drinking water supplies, and interfering with the habitat for fish, other aquatic organisms, and wildlife.

In 1990, EPA promulgated rules establishing Phase I of the National Pollutant Discharge Elimination System (NPDES) stormwater program. The Phase I program for MS4s requires operators of "medium" and "large" MS4s, that is, those that generally serve populations of 100,000 or greater, to implement a stormwater management program as a means to control polluted discharges from these MS4s. The Stormwater Phase II Rule extends coverage of the NPDES stormwater program to certain "small" MS4s but takes a slightly different approach to how the stormwater management program is developed and implemented.

What Is a Phase II Small MS4?

A small MS4 is any MS4 not already covered by the Phase I program as a medium or large MS4. The Phase II Rule automatically covers on a nationwide basis all small MS4s located in "urbanized areas" (UAs) as defined by the Bureau of the Census (unless waived by the NPDES permitting authority), and on a case-by-case basis those small MS4s located outside of UAs that the NPDES permitting authority designates. For more information on Phase II small MS4 coverage, see Fact Sheets 2.1 and 2.2.

What Are the Phase II Small MS4 Program Requirements?

Operators of regulated small MS4s are required to design their programs to:

- ❑ Reduce the discharge of pollutants to the "maximum extent practicable" (MEP);
- ❑ Protect water quality; and
- ❑ Satisfy the appropriate water quality requirements of the Clean Water Act.

Implementation of the MEP standard will typically require the development and implementation of BMPs and the achievement of measurable goals to satisfy each of the six minimum control measures.

The Phase II Rule defines a small MS4 stormwater management program as a program comprising six elements that, when implemented in concert, are expected to result in significant reductions of pollutants discharged into receiving waterbodies.

The six MS4 program elements, termed "minimum control measures," are outlined below. For more information on each of these required control measures, see Fact Sheets 2.3 – 2.8.

❶ ***Public Education and Outreach***
Distributing educational materials and performing outreach to inform citizens about the impacts polluted stormwater runoff discharges can have on water quality.

❷ ***Public Participation/Involvement***
Providing opportunities for citizens to participate in program development and implementation, including effectively publicizing public hearings and/or encouraging citizen representatives on a stormwater management panel.

❸ ***Illicit Discharge Detection and Elimination***
Developing and implementing a plan to detect and eliminate illicit discharges to the storm sewer system (includes developing a system map and informing the community about hazards associated with illegal discharges and improper disposal of waste).

❹ ***Construction Site Runoff Control***
Developing, implementing, and enforcing an erosion and sediment control program for construction activities that disturb 1 or more acres of land (controls could include silt fences and temporary stormwater detention ponds).

❺ ***Post-Construction Runoff Control***
Developing, implementing, and enforcing a program to address discharges of post-construction stormwater runoff from new development and redevelopment areas. Applicable controls could include preventative actions such as protecting sensitive areas (e.g., wetlands) or the use of structural BMPs such as grassed swales or porous pavement.

❻ ***Pollution Prevention/Good Housekeeping***
Developing and implementing a program with the goal of preventing or reducing pollutant runoff from municipal operations. The program must include municipal staff training on pollution prevention measures and techniques (e.g., regular street sweeping, reduction in the use of pesticides or street salt, or frequent catch-basin cleaning).

What Information Must the NPDES Permit Application Include?

The Phase II program for MS4s is designed to accommodate a general permit approach using a Notice of Intent (NOI) as the permit application. The operator of a regulated small MS4 must include in its permit application, or NOI, its chosen BMPs and measurable goals for each minimum control measure. To help permittees identify the most appropriate BMPs for their programs, EPA issued a Menu of BMPs to serve as guidance. NPDES permitting authorities can modify the EPA menu or develop their own list. For more information on application requirements, see Fact Sheet 2.9.

What Are the Implementation Options?

The rule identifies a number of implementation options for regulated small MS4 operators. These include sharing responsibility for program development with a nearby regulated small MS4, taking advantage of existing local or State programs, or participating in the implementation of an existing Phase I MS4's stormwater program as a co-permittee. These options are intended to promote a regional approach to stormwater management coordinated on a watershed basis.

What Kind of Program Evaluation/Assessment Is Required?

Permittees need to evaluate the effectiveness of their chosen BMPs to determine whether the BMPs are reducing the discharge of pollutants from their systems to the "maximum extent practicable" and to determine if the BMP mix is satisfying the water quality requirements of the Clean Water Act. Permittees also are required to assess their progress in achieving their program's measurable goals. While monitoring is not required under the rule, the NPDES permitting authority has the discretion to require monitoring if deemed necessary. If there is an indication of a need for improved controls, permittees can revise their mix of BMPs to create a more effective program. For more information on program evaluation/assessment, see Fact Sheet 2.9.

For Additional Information

Contacts

☞ U.S. EPA Office of Wastewater Management
http://www.epa.gov/npdes/stormwater
Phone: 202-564-9545

☞ Your NPDES Permitting Authority. Most States and Territories are authorized to administer the NPDES Program, except the following, for which EPA is the permitting authority:

Alaska	Guam
District of Columbia	Johnston Atoll
Idaho	Midway and Wake Islands
Massachusetts	Northern Mariana Islands
New Hampshire	Puerto Rico
New Mexico	Trust Territories
American Samoa	

☞ A list of names and telephone numbers for each EPA Region and State is located at http://www.epa.gov/npdes/stormwater (click on "Contacts").

Reference Documents

☞ EPA's Stormwater Web Site
http://www.epa.gov/npdes/stormwater
- Stormwater Phase II Final Rule Fact Sheet Series
- Stormwater Phase II Final Rule (64 *FR* 68722)
- National Menu of Best Management Practices for Stormwater Phase II
- Measurable Goals Guidance for Phase II Small MS4s
- Stormwater Case Studies
- And many others

Attachment 4

2013 Texas Litter Survey

A Survey of Litter at
253 Sites throughout
The State of Texas

Conducted for

Sherry Matthews Advocacy Marketing
Don't mess with Texas

by

Environmental Resources Planning, LLC
Gaithersburg, MD

Final Report

August 23, 2013

Sherry Matthews
Advocacy Marketing

ER PLANNING

Don't mess with Texas®

2013 Texas Litter Survey

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Acknowledgements

ER Planning would like to acknowledge Brenda Flores Dollar, TxDOT and Sherry Matthews Advocacy Marketing for providing the necessary guidance and support to successfully conduct the 2013 Texas Litter Survey.

Thanks to the Science and Operations staff at NOAA's National Weather Office in Lubbock, TX for providing valuable data regarding wind and other weather-related factors critical to understanding how weather affects littering rates in Texas.

Thanks also to all of the field crews and staff at Environmental Resources Planning, LLC for their hard work and dedication to this project.

2013 Texas Litter Survey

Executive Summary

Environmental Resources Planning, LLC (ER Planning), in cooperation with Sherry Matthews Advocacy Marketing and the Texas Department of Transportation (TxDOT), conducted a Visible Litter Study (VLS) to estimate the projected number of pieces and types of litter on Texas roadways in 2013. For this study, two separate litter surveys were conducted in which litter was tallied on 253 sites across Texas, each consisting of a one-tenth mile stretch of TxDOT-maintained roadway. In addition to the 163 original sites sampled in 2009, 90 new sites were also sampled in areas less represented by previous surveys. Data from the *Original Sites* were compared with the same areas surveyed in 2009. Data for the 90 *New Sites* were analyzed separately. This will provide TxDOT with the opportunity to compare changes in litter on *Original Sites* and *New Sites* in future surveys.

The increase in the number of sites in 2013 was designed to provide broader coverage of the state, since areas within sites tend to be more homogeneous than areas of different sites. The Executive Summary includes an overview of the methodology and results of the 2013 VLS. The full report provides an analysis of data from two full litter surveys in addition to the accumulated litter calculated as part of this study with a statistical analysis of the resultant data.

Study Highlights

Highlights from the 2013 VLS are shown below. Comprehensive data can be found in the full report and appendices.

- The results of the 2013 VLS indicate that 434,509,848 items of *Visible Litter* accumulate annually on the TxDOT-maintained roadway system, a reduction of 34% since 2009.
- This decrease in *Visible Litter* occurred despite the rise in both adult population in Texas (5.8%) and an increase in traffic levels statewide (1.5 billion additional miles traveled annually in Texas) between the years in which the 2009 and 2013 VLS studies were conducted.
- Most *Total Litter* (71%) was comprised of *Micro Litter*, items that are not normally visible while driving. *Micro Litter* can result from mowing without prior removal of litter.
- *Cigarette Butts* continued to comprise the largest portion of *Total Litter* in 2013 (31%), similar to 2009 (36%) and 2005 (28%).
- *Automotive Litter (Tire Debris* and *Vehicle Debris*) comprised 24 % of *Total Litter*.
- *Tire Debris* was the second largest component of litter (24%) and was pervasive across all areas of Texas.

- High wind gusts significantly affect how litter accumulation rates are measured in Texas.
- *Total Litter* on new sites, which focused more on roads with lower vehicle traffic, was significantly higher than on original sites.
- Given the portion of *Total Litter* attributable to vehicle debris and the effect of winds, population and traffic, the *Don't mess with Texas* program is likely more effective than is realized.
- Statistical tests show only a mild correlation between litter and the proximity to fast food establishments, convenience stores and schools. This suggests that litter cleanups are becoming culturally ingrained even in the face of continuing littering.
- Littered beverage containers (especially beer cans, water bottles and soda cans) were a larger component of *Visible Litter* (items larger than two square inches) than normally found in statewide litter surveys, but were reduced substantially since 2009.
- The number of adult Texans (16 years or older) as part of the population grew by more than 1 million (6%) since the previous survey. This population growth has generated higher traffic levels, which tends to correlate with higher rates of littering.

2013 Texas Litter Survey

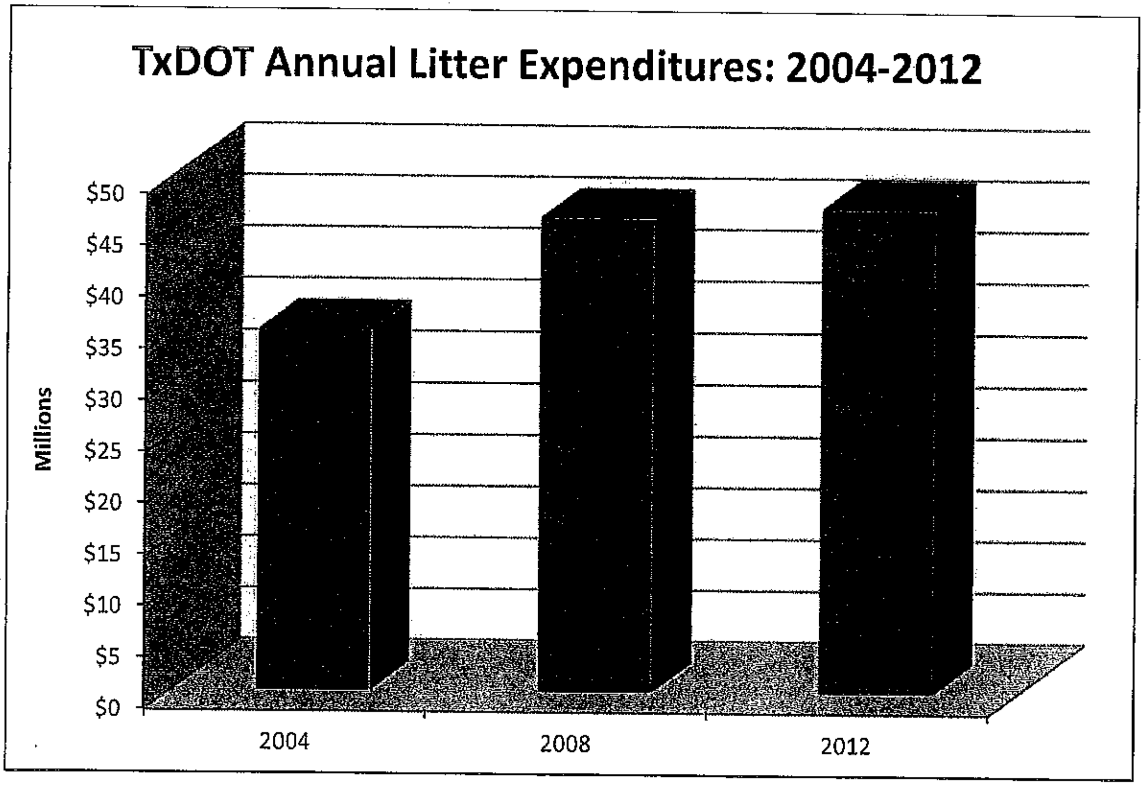
Introduction

Environmental Resources Planning, LLC (ER Planning) conducted two statewide litter surveys throughout the State of Texas in 2013 to gauge the rate, extent and composition of litter along roadways maintained by TxDOT. TxDOT has sponsored such statewide litter surveys since 1985. The methodology used for conducting these litter surveys has consisted of quantifying and characterizing *Visible Litter* (items two square inches and larger) and *Micro Litter* (items smaller than two square inches).

Cost of Litter

The cost to deal with roadside litter in Texas, as shown in Figure 1, is substantial: $47 million to TxDOT alone in 2012. This figure continues to grow. Research conducted by ER Planning staff shows that cities, counties, institutions and businesses in Texas likely expend an amount greater than this for their part in dealing with litter.

Figure 1 – TxDOT Litter-Related Costs



Source: TxDOT (2013)

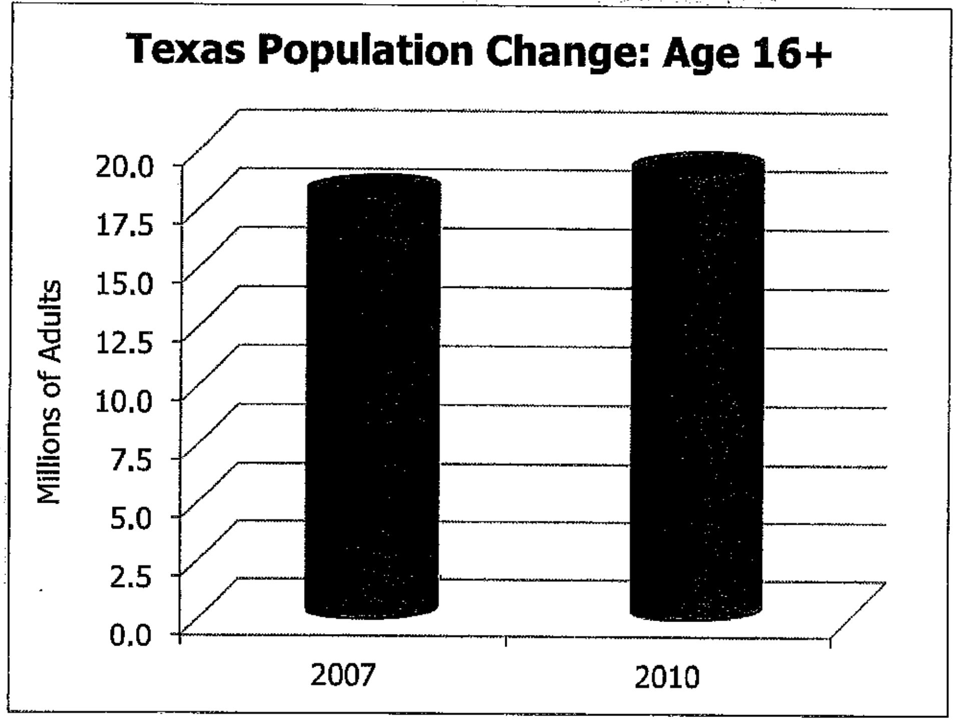
The State of Texas has a significant infrastructure of litter cleanups and educational efforts through TxDOT, Keep Texas Beautiful and its local affiliates and the Adopt-A-Highway program, which covers approximately 10% of Texas roadways.

No other state in the U.S. has consistently monitored roadside litter and provided high-profile litter abatement programs as Texas has done and continues to do. Yet, as in other areas, roadside litter continues to provide challenges.

Traffic Data

The adult driving population in Texas increase 5.8% from 17.9 million in 2007 to 19 million in 2010 as shown in Figure 1. Population growth generates higher traffic levels, which tends to correlate with higher rates of littering. Studies conducted by the Institute for Applied Research have shown that litter rates follow traffic levels and population growth.

Figure 2 – Texas Population Change: 2007 - 2010



Source: TxDOT (2013)

Daily Vehicle Miles Traveled (DVMT) measures the average daily traffic on TxDOT-maintained roadways. Increases in DVMT tend to correlate with higher rates of littering. Traffic levels increased on FM Roads (1.4%) and Interstates (5.9%) between 2008 and 2012, but decreased on State Highways (-1.8%) and U.S. Highways (-3.4%). Overall, the traffic levels statewide increased by 4.1 million miles per day (0.9%) as shown in Table 1. This equates to an increase of 1.5 billion miles annually. This increase was lower than the increase in adult population, suggesting less travel on a per capita basis; however the traffic levels would be expected to rise if economic conditions continue to improve.

Table 1 – Daily Vehicle Miles Traveled

System	Daily Vehicle Mileage		Percent
	2008	*2012*	*Change*
FM/RM Roads	68,509,267	69,407,935	1.3%
Interstates	162,209,757	171,808,165	5.9%
State Highways	116,169,088	114,133,600	-1.8%
U.S. Highways	127,970,392	123,634,294	-3.4%
Total:	**474,858,505**	**478,983,993**	**0.9%**

Source: TxDOT (2013)

Table 2 shows the change in Average Daily Traffic (ADT) counts for the roadway segments sampled on the 163 Original Sites. The overall ADT decreased by 7%, while Large Litter decreased 34% between 2009 and 2013. Although the ADT data sets are from 2007 and 2011, this may still suggest a relationship between traffic levels and the amount of Large Litter observed along Texas roadways (Table 9).

The changes in ADT by roadway type generally correlated with changes in Total Litter. FM Roadways showed the largest increase in daily traffic (+22%) and the largest increase in Total Litter (Table 13). Interstates and US Highways both showed reductions in ADT and Total Litter. State Highways were the only roadway type that did not show a correlation between ADT (which decreased) and Total Litter (which increased).

The reader should keep in mind that 2011 was the most recent ADT data available, while the survey data reflects 2013 conditions. This is consistent with previous Texas litter surveys and was followed in 2013 to be comparable with data from these previous surveys.

Table 2 – ADT for Sampled Roadway Segments by Roadway Type

Roadway Type	Avg. Daily Traffic		
	2007	*2011*	*Percent Change*
FM Roadways	160,480	195,150	22%
Interstates	3,838,911	3,757,700	-2%
State Highway	732,419	574,990	-21%
U.S. Highway	1,101,587	891,000	-19%
Total:	**5,833,397**	**5,418,840**	**-7%**

Source: TxDOT (2013)

Methodology

The 2013 Texas Litter Survey was conducted by surveying 253 sites including the 163 *Original Sites* surveyed in the previous 2009 litter study along with 90 *New Sites*, which focused on areas less represented in previous surveys. These sites were added to provide more data for certain target areas.

Each site was surveyed twice for *Visible Litter* to help ensure accuracy. Taking into account both surveys conducted, field crews surveyed about 4.8 million square feet along Texas roadways. *Micro Litter* was surveyed on three 3′ x 18′ transects and then extrapolated to the length of the site. Details regarding the methodology are included in the Appendix.

In order to be comparable to previous litter surveys conducted in Texas, the first litter survey was conducted between February 26, 2013 and March 9, 2013, while the second litter survey was conducted between April 9, 2013 and April 18, 2013.

The following approach was used for conducting the two litter surveys in 2013:

1. Quantifying and characterizing litter in an initial survey,
2. Quantifying and characterizing litter in a follow-up survey conducted an average of 42 days later;
3. Analyzing data from each survey separately; and
4. Analyzing the change in litter between surveys.

Litter was classified as either *Visible Litter* (two square inches or more) or *Micro Litter* (less than two square inches.) All sites were one-tenth mile in length and a maximum width of 18 feet.

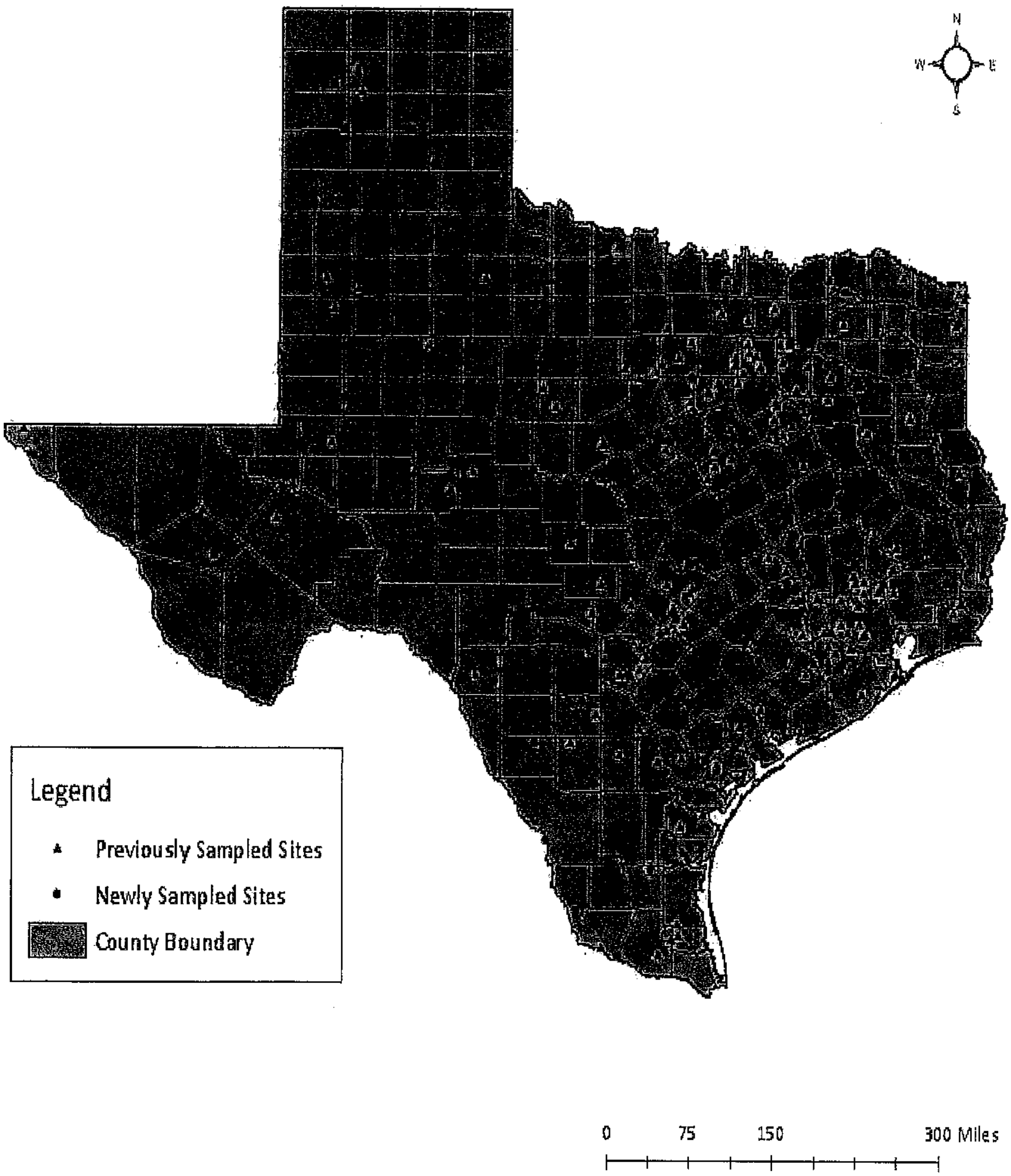
Micro Litter was sampled on three transects of each site. Each of the three transects comprised a 3′ x 18′ area. The area of the three transects totaled 162 square feet. The data from these transects were extrapolated to the size of the entire site.

Litter was characterized using 106 categories (89 for *Visible Litter* and 17 for *Micro Litter*). These categories were consistent with those used in previous Texas litter surveys and other recent litter surveys. Brand names of items were recorded when visible.

Once the two litter surveys were conducted, the net accumulated litter (*Total Litter*) was calculated. The resultant data is shown in the sections below. The data sets for each of the two surveys were examined separately and compared. All percentages are rounded in the report.

Two sites were removed from the survey. Major road construction had begun on one of the *New Sites* between the first and second surveys. Data for a second site (one of the *Original Sites*) was removed as it was deemed an extreme outlier. Thus, this report is based on data from 162 *Original Sites* and 89 *New Sites*. Section 1 reports the findings for *Visible Litter*, those items visible while driving along roadways. Section 2 reports the findings for *Total Litter*: *Micro Litter* and *Visible Litter*. The map in Figure 3 shows the color-coded locations of the *Original Sites* and *New Sites*.

Figure 3 – Sites Distribution Map



Section 1: Analysis of Visible Litter Only

2013 Texas Litter Survey

First Survey

The largest component of *Visible Litter* on both the *Original Sites* and *New Sites* during the first survey was *Tire & Rubber Debris*, as shown in Table 3. *Tire & Rubber Debris* was slightly higher at the *New Sites.* This was followed by *Misc. Paper* and *Misc. Plastic,* two categories representing weathered items not otherwise classifiable. The top 10 components of *Visible Litter* were similar portion on the *Original Sites* and *New Sites.*

The top 10 of the 89 components of litter comprised 64% of *Visible Litter* on the *Original Sites* and 62% of *Visible Litter* on the *New Sites.* The remaining 79 components comprised 36% of *Visible Litter* on the *Original Sites* and 38% of *Visible Litter* on the *New Sites.* All other components not listed comprised less than 3% of *Visible Litter.*

Table 3 – First Litter Survey: Top 10 Components

Visible Litter Items	*Original Sites*	*Rank*	*New Sites*	*Rank*
Tire & Rubber Debris	16%	1	18%	1
Misc. Paper	13%	2	12%	2
Misc. Plastic	8%	3	9%	3
Beer Cans	5%	4	4%	6
Vehicle & Metal Road Debris	4%	5	5%	4
Plastic Packaging - Film	4%	6	3%	7
Construction Debris	4%	7	3%	8
Water Bottles (Plastic)	4%	8	4%	5
Cup Lids, Pieces Lids, Straws *	3%	9	-	-
Tobacco Packaging	3%	10	3%	10
Foil Materials and Pieces *	-	-	3%	9
Subtotal - Top 10 Items	**64%**		**62%**	

** Percentages are not shown for items that were not part of the top 10 ranking.*

Second Survey

The largest components of *Visible Litter* found on both the *Original Sites* and *New Sites* in the second survey were *Tire & Rubber Debris,* followed by Misc. Paper and Misc. Plastic, as was true in the first survey. The other major components of *Visible Litter* were also similar on both the *Original Sites* and the *New Sites* as shown in Table 4. Significantly more *Tire & Rubber Debris* was observed on *New Sites* in the second survey, although most other components comprised a similar percentage of *Visible Litter.* The top 10 components of *Visible Litter* were exactly the same at *Original Sites* and *New Sites.*

The top 10 components comprised 59% of *Visible Litter* on the *Original Sites* and 64% on the *New Sites.* The remaining 79 components comprised 41% of *Visible Litter* on the *Original Sites* and 36% on the *New Sites.* All other components not listed in Table 4 comprised less than 3% of *Visible Litter.*

Table 4 – Second Litter Survey: Top 10 Components

Visible Litter Items	*Original Sites*	*Rank*	*New Sites*	*Rank*
Tire & Rubber Debris	18%	1	27%	1
Misc. Paper	7%	2	7%	3
Misc. Plastic	7%	3	7%	2
Vehicle & Metal Road Debris	6%	4	6%	4
Beer Cans	5%	5	4%	5
Construction Debris	4%	6	3%	10
Water Bottles (Plastic)	4%	7	3%	6
Cup Lids, Pieces Lids, Straws	3%	8	3%	7
Tobacco Packaging	3%	9	3%	8
Soft Drink Cans	3%	10	3%	9
Subtotal - Top 10 Items	***59%***		**64%**	

Accumulated Litter

The largest component of *Accumulated Litter* was *Tire & Rubber Debris* on both the *Original Sites* (18%) and the *New Sites* (27%) as shown in Table 5.

Table 5 – Accumulated Litter: Top 10 Components

Visible Litter Items	Original Sites	Rank	*New Sites*	*Rank*
Tire & Rubber Debris	13%	1	29%	1
Vehicle & Metal Road Debris	7%	2	5%	2
Construction Debris	5%	3	3%	5
Misc. Plastic	4%	4	5%	3
Misc. Paper	4%	5	3%	6
Beer Cans	3%	6	4%	4
Non-Brand Napkins *	3%	7	-	-
Snack Food Packaging *	3%	8	-	-
Tobacco Packaging	2%	9	2%	9
Soft Drink Cans	2%	10	2%	7
Cup Lids, Pieces Lids, Straws *	-	-	2%	8
Water Bottles (Plastic) *	-	-	2%	10
Subtotal - Top 10 Items	**46%**		**59%**	

** Percentages are not shown for items that were not part of the top 10 ranking.*

The top 10 components of *Accumulated Litter* continued to be similar on both the *Original Sites (46%)* and the *New Sites (59%)*, although *Tire & Rubber Debris* was significantly higher on *New Sites (29%)*. A list detailing all components of *Visible Litter* is included in the Appendix.

Since Farm to Market (FM) Roads comprise 56% of the TxDOT roadway system mileage (Table 6), it is not surprising that 58% of the *Visible Litter* accumulates on FM Roads.

Table 6 - Litter Accumulation Rates by Roadway

Road Type	Visible Litter	Percent of Visible Litter
FM Roads	251,831,329	58%
Interstates	32,900,711	8%
State Highways	114,966,303	26%
U.S. Highways	34,811,505	8%
Total	**434,509,848**	**100%**

The physical composition of littered items is shown in Table 7. *Other* includes items made from multiple materials. The composition of items was generally similar, except that *Rubber*, which includes *Tire Debris*, was a higher component of *Visible Litter* on *New Sites*.

Table 7 – Visible Litter Composition

Physical Composition	Percent of Total		
	Original Sites	New Sites	All Sites
Paper & Paperboard	22%	16%	20%
Plastic	24%	20%	22%
Metal	8%	9%	8%
Rubber/Leather	13%	29%	20%
Glass	3%	4%	3%
Textiles	4%	3%	3%
Wood	<1%	<1%	<1%
Other	26%	19%	23%
Total	**100%**	**100%**	**100%**

Table 8 compares the most littered items in 2013 by roadway, showing that *Rubber* was much higher on Interstates than on any other roadway in 2013 causing the percentage of *Paper and Paperboard* items to be lower. The higher incidence of *Rubber* is likely due related to the large volume of eighteen-wheelers and the high speed of traffic on Interstates.

Table 8 – Litter Composition by Roadway

Physical Composition	Percent of Total by Road Type - 2013				
	Interstates	US Highways	State Highways	FM Roads	All Roads
Paper & Paperboard	19%	25%	26%	25%	22%
Plastics	21%	23%	24%	30%	24%
Metals	6%	11%	7%	10%	8%
Rubber/Leather	24%	<1%	5%	4%	13%
Glass	2%	7%	2%	3%	3%
Textiles	4%	3%	3%	2%	4%
Wood	<1%	<1%	<1%	<1%	<1%
Other	23%	31%	32%	25%	26%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

A comparison of changes in *Visible Litter* on the *Original Sites* between 2009 and 2013 (Table 9) indicates an overall reduction of 34% in Visible Litter. This is based on an examination of all litter components in 2009 compared with 2013 and deriving an assessment of the portion likely attributable to *Visible Litter*.

Table 9 – Visible Litter Change Estimate

Visible Litter Change Estimate		
2009	**2013**	**Change %**
662,842,933	435,067,590	-34%

This decrease in *Visible Litter* occurred despite the rise in both adult population in Texas (5.8%) and an increase in traffic levels statewide (1.5 billion additional miles traveled annually in Texas) between the years in which the 2009 and 2013 VLS studies were conducted.

Section 2: Analysis of Combined Visible & Micro Litter

For comparison of 2013 survey data with 2009 survey data, *Micro Litter* and *Visible Litter* were analyzed together in Section 2 as *Total Litter*.

First Survey

Table 10 shows that the largest components of *Total Litter* found on both the *Original Sites* and *New Sites* during that survey were *Cigarette Butts* and *Automotive Litter*. Other components were also a similar portion of *Total Litter* on both the *Original Sites* and *New Sites*. *Tire & Rubber Debris* was much higher at the *New Sites*, causing *Cigarette Butts* to comprise a lower percentage of *Total Litter*. All other components comprised 2% or less of *Total Litter*. The top 10 of the 106 components of litter comprised 68% of *Total Litter* on the *Original Sites* and 71% of *Total Litter* on the *New Sites*. The remaining 96 components comprised 32% of *Total Litter* on the *Original Sites* and 29% of *Total Litter* on the *New Sites*.

Table 10 – First Survey: Top 10 Components of Total Litter

Total Litter Items	***Original Sites***	***Rank***	***New Sites***	***Rank***
Cigarette Butts	26%	1	19%	2
Tire & Rubber Debris (Micro)	8%	2	19%	1
Tire & Rubber Debris (Visible)	8%	3	7%	4
Misc. Paper	6%	4	5%	5
Paper (Micro)	6%	5	8%	3
Misc. Plastic	4%	6	4%	7
Plastic Hard (Micro)	3%	7	2%	8
Glass (Micro)	3%	8	-	-
Beer Cans	2%	9	-	-
Vehicle & Metal Road Debris	2%	10	2%	9
Plastic Water Bottles	-	-	2%	10
Polystyrene Food Service (Micro)	-	-	4%	6
Subtotal - Top 10 Items	**68%**		**71%**	

Second Survey

The largest components of *Total Litter* on *Original Sites* and *New Sites* during the second survey were *Cigarette Butts* and *Automotive Litter*, similar to the first survey. The other major components of *Total Litter* were also similar on both *Original Sites* and *New Sites* (Table 11). More *Tire & Rubber Debris* was observed on *New Sites* in the second survey, causing *Cigarette Butts* to comprise a lower percentage of *Total Litter*. Otherwise, the major components of *Total Litter* were similar on *Original Sites* and *New Sites*.

All other components comprised 2% or less of *Total Litter*. The top 10 of the 106 components of litter comprised 78% of *Total Litter* on the *Original Sites* and 83% of

Total Litter on the *New Sites*. The remaining 96 components comprised 22% of *Total Litter* on the *Original Sites* and 17% of *Total Litter* on the *New Sites*.

Table 11 – Second Survey: Top 10 Components of Total Litter

Total Litter Items	*Original Sites*	*Rank*	*New Sites*	*Rank*
Cigarette Butts	34%	1	22%	2
Tire & Rubber Debris (Micro)	14%	2	31%	1
Paper (Micro)	7%	3	7%	3
Tire & Rubber Debris (Visible)	5%	4	6%	5
Glass Pieces	4%	5	7%	4
Plastic Hard (Micro)	4%	6	3%	7
Misc. Plastic	2%	10	2%	9
Polystyrene Food Service (Micro)	3%	7	3%	6
Plastic Film (Micro)	3%	8	2%	8
Misc. Paper	2%	9	2%	10
Subtotal - Top 10 Items	***78%***		**83%**	

Accumulated Litter

Table 12 lists the top 10 components of *Total Litter* for the *Original Sites*. Together they comprise 78% of this category. As was true in both surveys, tire-related debris, as a component of *Accumulated Litter*, was much higher on *New Sites* (39%) compared to the *Original Sites* (17%).

Table 12 – Accumulated Litter: Top 10 Components

Total Litter Items	Original Sites	Rank	New Sites	Rank
Cigarette Butts	31%	1	17%	2
Tire & Rubber Debris (Micro)	12%	2	31%	1
Tire & Rubber Debris (Visible)	5%	3	8%	4
Glass (Micro)	5%	4	8%	3
Paper (Micro)	4%	5	4%	5
Plastic Film (Micro)	3%	6	2%	8
Plastic Hard (Micro)	3%	7	3%	7
Vehicle and Metal Road Debris	2%	8	2%	9
Polystyrene Food Service (Micro)	2%	9	3%	6
Aluminum (Micro)	2%	10	-	-
Other Items (Wood)	-	-	1%	10
Subtotal - Top 10 Items	**69%**		**80%**	

2013 Texas Litter Survey

The highest portion of *Total Litter in 2013* was *Cigarette Butts* (31%), similar to 2009 (36%). *Total Tire Scraps* (pieces of blown tires) were significantly higher in 2013. *Micro Tire Scraps* were 12%, while *Tire & Rubber Debris comprised 5*7% for a total of 17% compared with 5% in 2009. The remaining top 10 items were all components of *Micro Paper.*

Similar to previous litter surveys in Texas, *Cigarette Butts* were the predominant item found in litter. Table 13 clearly shows this impact – more than half a billion cigarette butts are littered on Texas roadways each year, a significant growth compared with 2009.

Table 13 - Littered Items by Roadway Type (with and without Cigarette Butts)

Roadway Type	Center line Miles	*Including Cigarette Butt Litter*			*Excluding Cigarette Butt Litter*		
		2009	2013	% Change	2009	2013	% Change
FM Roadways	40,965	528,823,879	954,821,303	81%	339,565,496	536,357,634	58%
Interstate Highway	3,233	94,121,255	77,614,712	-18%	52,839,405	57,582,066	9%
State Highway	16,331	260,656,708	291,159,745	12%	192,921,872	215,378,430	12%
U.S. Highway	12,104	218,168,944	157,019,311	-28%	154,866,269	101,245,795	-35%
Total:	72,633	1,101,770,786	1,480,615,070	34%	740,193,042	910,563,925	23%

As shown in Table 14, almost two-thirds of all litter is found on FM roads. This is due, in part, to the fact that FM Roads comprise 56% of the TxDOT roadway system mileage.

Table 14 - Litter Accumulation Rates

Road Type	Visible Litter	Micro Litter	Total Litter
FM Roads	251,831,329	702,989,974	954,821,303
Interstates	32,900,711	44,714,002	77,614,712
State Highways	114,966,303	176,193,442	291,159,745
U.S. Highways	34,811,505	122,207,805	157,019,311
Total	**434,509,848**	**1,046,105,223**	**1,480,615,070**

Just as importantly, Table 14 shows that *Micro Litter* items are consistently a high portion of *Total Litter* on all Texas roadways.

Comparisons to Previous Surveys

The physical composition of littered items is compared in Table 15. For consistency with previous surveys, cigarette butts were classified with paper items. *Paper and Paperboard* was a lower percentage of litter in 2013 mainly due to the higher percentage of *Scrap Tires*, a component of *Rubber*. The percentage of *Metal* and *Plastic* items in 2013 was very similar to 2009.

Table 15 – Litter by Composition

Physical Composition	Percent of Total		
	2005	**2009**	**2013**
Paper & Paperboard	61%	63%	43%
Plastic	25%	19%	17%
Metal	10%	7%	7%
Rubber/Leather	<1%	6%	17%
Glass	1%	2%	6%
Textiles	1%	1%	1%
Wood	<1%	<1%	2%
Other	1%	<1%	7%
Total	**100%**	**100%**	**100%**

When the composition of litter is broken out by roadway type, it is clear that *Tire Scraps* were much higher on Interstates than on any other roadway in 2013 causing the percentage of *Paper and Paperboard* items to be lower, as shown in Table 16.

Table 16 – Litter Composition by Roadway

Physical Composition	Percent of Total by Road Type								Percent of Total	
	Interstate Highway		US Highway		State Highway		FM Roadway			
	2009	2013	2009	2013	2009	2013	2009	2013	2009	2013
Paper & Paperboard	68%	37%	57%	46%	56%	39%	72%	55%	63%	43%
Plastics	19%	13%	19%	22%	22%	19%	14%	20%	19%	17%
Metals	5%	7%	9%	7%	9%	10%	5%	6%	7%	7%
Rubber/ Leather	5%	30%	9%	9%	7%	12%	4%	4%	6%	17%
Glass	2%	4%	3%	7%	2%	5%	3%	7%	2%	6%
Textiles	<1%	2%	2%	1%	2%	1%	<1%	1%	1%	1%
Wood	<1%	2%	<1%	3%	<1%	3%	<1%	2%	<1%	2%
Other	<1%	6%	1%	6%	<1%	10%	1%	6%	<1%	7%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 17 compares the most littered items in 2013 with the most littered items in the two most recent surveys (2005 and 2009). *Cigarette Butts* were the most littered item in each of these surveys. *Tire & Rubber Debris* was also significant in both 2009 and 2013. Pieces of paper and plastic were dominant in both 2009 and 2013, suggesting that some littered items are likely mowed and broken into multiple pieces.

Table 17 – Comparison of Most Littered Items: 2005-2013

Comparison of VLS Item Rank by Survey Year		
2005	**2009**	**2013**
Cigarette Butts (28%)	Cigarette Butts (36%)	Cigarette Butts (31%)
Wrap (7%)	Paper Pieces (7%)	Tire & Rubber Debris (Micro) (12%)
Tissues/Towels/Napkins (5%)	Tire Parts (5%)	Tire & Rubber Debris (Visible) (5%)
Beer Cans (5%)	Cigar Butts (4%)	Glass (Micro) (5%)
Beverage Cups (4%)	Paper (4%)	Paper (Micro) (4%)
Cigarette Packs (4%)	Plastic Pieces (4%)	Plastic Film (Micro) (3%)
Soda Cans (3%)	Beer Cans (3%)	Plastic Hard (Micro) (3%)
Cup Lids (3%)	Cup Pieces (2%)	Vehicle & Metal Road Debris (2%)
Drinking Straws (3%)	Food Wrap (3%)	Polystyrene Food Service (Micro) (2%)
Lottery Tickets (2%)	Soda Cans (2%)	Aluminum (Micro) (2%)

Table 18 compares the top components of *Total Litter* by product use found in *Total Litter*. As in 2009, *Tobacco* remains the most littered item. *Construction/Industrial* and *Automotive* litter have continued to grow between 2005 and 2013.

Table 18 - Comparison of Litter by Use: 2005-2013

Litter by Product Use	Percent of Total		
	2005	**2009**	**2013**
Tobacco	33%	43%	33%
Household/Personal	4%	9%	4%
Food	29%	7%	6%
Non-Alcoholic Beverages	11%	13%	8%
Alcoholic Beverages	6%	6%	2%
Construction/Industrial	8%	10%	15%
Printed	8%	4%	8%
Other	0%	1%	1%
Automotive	1%	7%	24%
Total	**100%**	**100%**	**100%**

The breakdown of product use by roadway shows a significant reduction of *Tobacco* litter on Interstates (from 50% to 27%) and a slight reduction on FM Roads. The reduction of *Beverage-related* litter was likely influenced, in part, by the higher percentage of *Automotive* litter, as shown in Table 19.

Table 19 - Comparison of Litter Use by Roadway: 2009-2013

Use	Percent of Total by Road Type								Percent of Total	
	Interstate Highway		US Highway		State Highway		FM Roadway			
	2009	2013	2009	2013	2009	2013	2009	2013	2009	2013
Tobacco	50%	27%	34%	37%	31%	28%	55%	45%	43%	33%
Household/ Personal	8%	6%	11%	4%	10%	6%	8%	4%	9%	4%
Food	6%	4%	8%	6%	9%	9%	5%	4%	7%	6%
Non-Alcoholic Beverages	14%	7%	14%	13%	13%	9%	9%	7%	13%	8%
Alcoholic Beverages	5%	2%	7%	2%	7%	2%	6%	2%	6%	2%
Construction/ Industrial	9%	10%	9%	17%	15%	18%	7%	17%	10%	15%
Printed	3%	7%	5%	7%	4%	8%	5%	8%	4%	8%
Other	<1%	1%	2%	0%	2%	1%	<1%	<1%	1%	1%
Automotive	6%	37%	10%	16%	9%	19%	5%	12%	8%	24%
Total:	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

The ranking of littered items by use, in Table 20, shows similarities in *Tobacco* and *Construction/Industrial* litter. Both categories were significant portions of litter in all three surveys. Viewing litter through this ranking sheds light on the types of litter found without regard to size.

Table 20 - Comparison of Litter Rank by Use: 2005-2013

Comparison of VLS Use Rank by Survey Year		
2005	2009	2013
Tobacco (33%)	Tobacco (43%)	Tobacco (33%)
Food (29%)	Non-Alcoholic Beverages (13%)	Automotive (24%)
Non-Alcoholic Beverages (11%)	Construction/Industrial (10%)	Construction/Industrial (15%)
Construction/Industrial (8%)	Household/Personal (9%)	Printed (8%)
Printed (8%)	Food (7%)	Non-Alcoholic Beverages (6%)
Alcoholic Beverages (6%)	Automotive (7%)	Household/Personal (7%)
Household/Personal (4%)	Alcoholic Beverages (6%)	Food (6%)
Automotive (1%)	Printed (4%)	Alcoholic Beverages (2%)
Other (0%)	Other (<1%)	Other (<1%)
Agricultural/Garden (0%)	Agricultural/Garden (<1%)	Agricultural/Garden (<1%)

Comparing the monthly projections of litter by roadway type, in Table 21, littering on FM Roads has grown significantly, while littering on State Highways has grown at a lower rate. Littering on Interstates and U.S. Highways dropped closer to 2005 levels.

Table 21 – Monthly Litter Projection by Roadway: 2005-2013

Roadway Type	Monthly Litter Projections			% Change
	2005	2009	2013	2009-2013
FM Roads	876	1,076	1,942	81%
Interstates	1,881	2,426	2,001	-18%
State Highways	877	1,330	1,486	12%
U.S. Highways	1,054	1,502	1,081	-28%

The annualized litter projection changes over the past nine years (Table 22) show the impact of these monthly littering rate projections, particularly on FM Roads. Although *Total Litter* grew 34 % since 2009, two-thirds of *Total Litter* is *Micro Litter*, items that are less than two inches in size. These items are typically more difficult to clean up compared with *Visible Litter*.

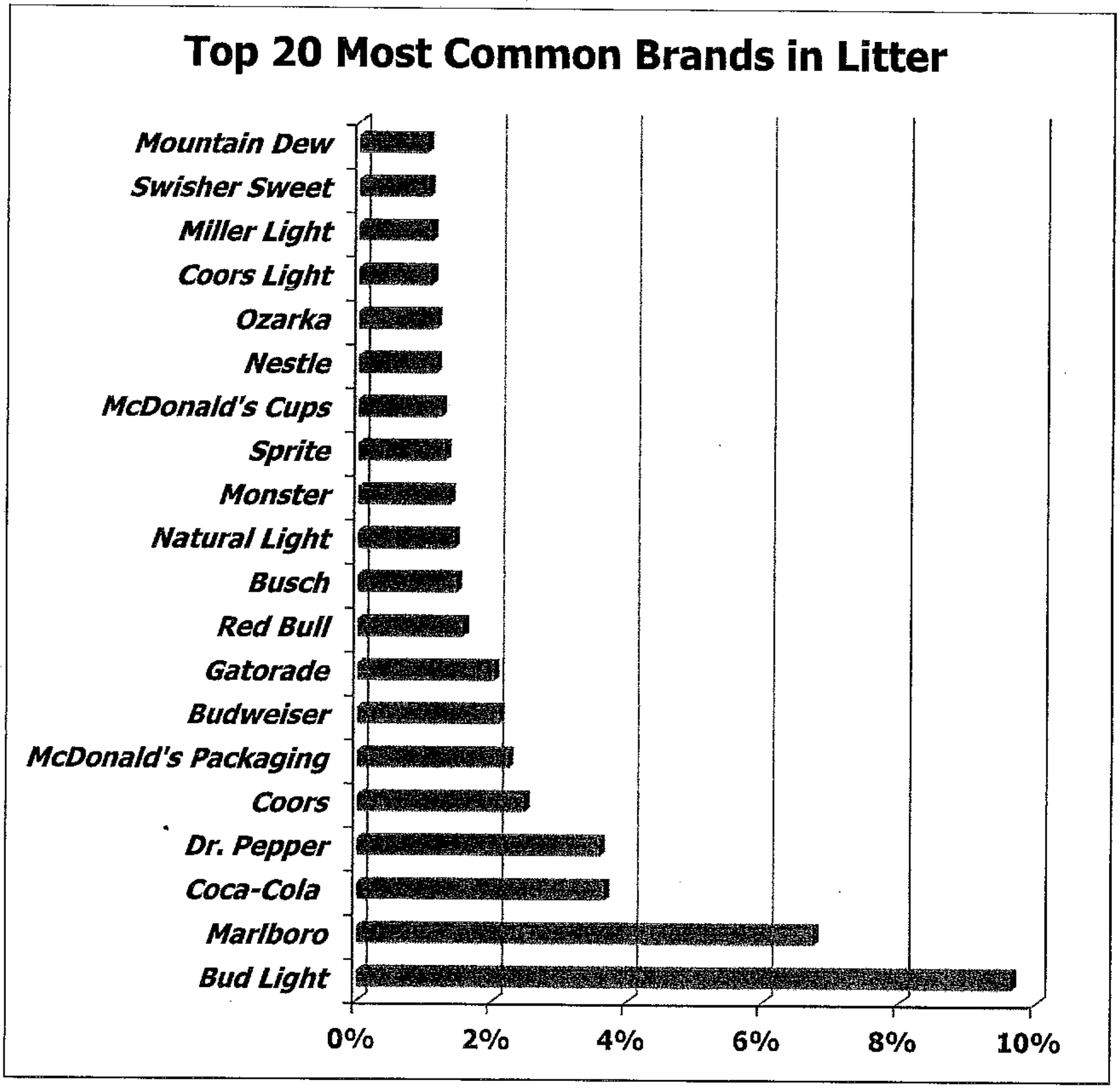
Table 22 – Estimated Littered Items by Roadway: 2005-2013

Roadway Type	Centerline Miles	Number of Littered Items			% Change
		2005	2009	2013	2009-2013
FM Roads	40,965	430,709,842	528,823,879	954,821,303	81%
Interstates	3,233	72,971,697	94,121,255	77,614,712	-18%
State Highways	16,331	170,488,104	260,656,708	291,159,745	12%
U.S. Highways	12,104	153,035,881	218,168,944	157,019,311	-28%
Total:	**72,633**	**827,205,524**	**1,101,770,786**	**1,480,615,070**	**34%**

Branded Litter

Prior visible litter studies performed in Texas have recorded both the brand name as well as the quantity of items within that brand name to provide a better understanding of which brands contribute most to litter. In 2001, 2005 and again in 2009, field crews noted the brand name of each item of litter collected where recognizable. In the 2013 study, field crews also made note of both small and large items of litter.

Figure 4 – Branded Litter



In the 2013 survey, brand names were recorded on over 450 unique brand types. The most pervasive brand name observed in litter, as shown in Figure 4, was Bud Light, which accounted for approximately 10% of all identified branded items. This is not surprising as Bud Light containers made up the majority of alcoholic beverages recorded in the 2009 study. Marlboro (including Marlboro Lights) was the second most identified brand, accounting for approximately 7% of all branded items.

This was followed by Coca-Cola (4%), and Dr. Pepper (4%) containers. In total, the top 20 most common brand names comprised 47% of all brand name items counted.

In 2009, tobacco products comprised 9 of the top 10 most commonly found branded items. Brand names of *Micro Litter* components such as *Cigarette Butts* were recorded when their brand names were readily identifiable. Table 23 displays the top ten brand name litter between the studies. As the table indicates, there was more of a relationship between the 2013 study and the 2005 study.

Table 23 – Branded Litter Comparisons

2005 VLS Brand Rank	***2009 VLS Brand Rank***	***2013 VLS Brand Rank***
Marlboro Light (18%)	Marlboro (7%)	Bud Light (10%)
Marlboro (13%)	Marlboro Light (5%)	Marlboro (7%)
Texas Lottery (3%)	Marlboro 100's (3%)	Coca-Cola (4%)
Doral (3%)	Doral (2%)	Dr. Pepper (4%)
McDonald's (3%)	Camel (2%)	Coors (2%)
Bud Light (2%)	Bud Light (2%)	McDonald's (2%)
Marlboro Menthol (2%)	Virginia Slims (2%)	Budweiser (2%)
Coca-Cola (2%)	Salem (2%)	Gatorade (2%)
Burger King (2%)	Newport (1%)	Red Bull (2%)
Dr. Pepper (2%)	Winston (1%)	Busch (2%)

2013 Texas Litter Survey

Statistical comparisons refer to the *Original Sites* surveyed for comparability to previous surveys unless otherwise noted. Findings based on surveying the *New Sites,* which were selected to provide data on special study areas, are reported separately.

Conclusions

- The results of the 2013 VLS indicate that 434,509,848 items of *Visible Litter* accumulate annually on the TxDOT-maintained roadway system, a reduction of 34% since 2009.
- This decrease in *Visible Litter* occurred despite the rise in both adult population in Texas (5.8%) and an increase in traffic levels statewide (1.5 billion additional miles traveled annually in Texas) between the years in which the 2009 and 2013 VLS studies were conducted.
- Most of *Total Litter* (71%) was *Micro Litter* (items smaller than two square inches).
- *Cigarette Butts* continued to comprise the largest portion of *Total Litter* in 2013 (31%), similar to 2009 (36%) and 2005 (28%).
- *Automotive Litter (Tire Debris* and *Vehicle Debris*) comprised 24 % of *Total Litter.*
- *Tire Debris* was the second largest component of litter (24%) and was pervasive across all areas of Texas.
- High wind gusts significantly affect how litter accumulation rates are measured in Texas.
- *Total Litter* on new sites, which focused more on roads with lower vehicle traffic, was significantly higher than on original sites.
- Given the portion of *Total Litter* attributable to vehicle debris and the effect of winds, population and traffic, the *Don't mess with Texas* program is likely more effective than is realized.
- Statistical tests show only a mild correlation between litter and the proximity to fast food establishments, convenience stores and schools. This suggests that litter cleanups are becoming culturally ingrained even in the face of continuing littering.
- Littered beverage containers (especially beer cans, water bottles and soda cans) were a significant component of *Visible Litter* (items larger than two square inches) in both surveys, similar to 2009 and 2005.
- The number of adult Texans (16 years or older) as part of the population grew by more than 1 million (6%) since the previous survey. This population growth has generated higher traffic levels, which tends to correlate with higher rates of littering.

Recommendations

- High wind gusts affect how litter accumulation rates along Texas roadways are measured. The way and extent to which these occur should be studied further as litter prevention efforts are based on these accumulation rates.
- Areas identified by new sites should be evaluated for focused litter reduction efforts.
- *Tire Debris*, although not an intentional form of litter, deface Texas roadways. Working with the appropriate gatekeepers and strategically placed signage showing the benefits of proper tire inflation can help reduce this form of litter.
- Programs focusing on reducing cigarette butts can reduce litter along Texas roadways significantly.
- Littered beverage containers, a large component of litter on certain sites, present an opportunity for focused litter prevention.
- Focusing on the progress made by the *Don't mess with Texas* program will help provide momentum for future efforts.

Appendices

Appendix A – Branded Litter

Table 24 contains a summary of the top classes of litter and the top brand name within that category as identified by brand type. As the table details, Marlboro cigarettes and packaging comprised 50% of all tobacco items found in the survey, while McDonalds packaging[1] contained the most identifiable brand name items found within food and food packaging. As indicated previously, Coca-Cola and Bud Light beverage containers were the most frequently found brand name items for non-alcoholic and alcoholic containers respectively. The most identifiable retail bag found in 2013 was from Wal-Mart stores.

Table 24 – Branded Litter by Use

Use	Brand Name	Percent within Litter Use
Tobacco	*Marlboro*	50%
	Swisher Sweet	8%
	Camel	6%
	Newport	4%
	Pall Mall	4%
	Copenhagen	3%
	Winston	3%
	Kool	2%
	Doral	2%
	Grizzly	2%
	All other brands	16%
Food & Food Packaging	*McDonald's Packaging*	12%
	Sonic	4%
	Jack in the Box	3%
	Whataburger	3%
	Doritos	3%
	Snickers	3%
	Lays	2%
	Taco Bell	2%
	Wrigley's	2%
	Frito Lay	2%

[1] *Excludes fast-food cups, which were categorized under non-alcoholic beverages to be consistent with the 2009 study.*

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Use	Brand Name	Percent within Litter Use
	Little Debbie	2%
	All other brands	61%
Non Alcoholic Beverages	*Coca-Cola*	10%
	Dr. Pepper	10%
	Gatorade	6%
	Red Bull	4%
	Monster	4%
	Sprite	4%
	McDonald's Cups	3%
	Nestle	3%
	Ozarka	3%
	Mountain Dew	3%
	All other brands	50%
Alcoholic Beverages	*Bud Light*	38%
	Coors	10%
	Budweiser	8%
	Busch	6%
	Natural Light	6%
	Coors Light	4%
	Miller Light	4%
	Keystone	4%
	Miller	4%
	Dos Equis	2%
	All other brands	15%
Printed	*my SA*	7%
	Bud Light Label/Box	6%
	McDonalds	6%
	Sunkist	6%
	7-11	5%
	Other	5%
	HEB	4%
	Home Depot	4%
	Taco Bell	4%
	All other brands	55%
Construction/ Auto	*NAPA*	12%
	All other brands	88%

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Use	Brand Name	Percent within Litter Use
Household/ Personal	*Halls*	9%
	Nike	9%
	Oakley	6%
	All other brands	76%
Agricultural/ Garden	*Lyssy & Eckel Feed*	33%
	Red Chain	33%
	Scotts	33%
Plastic/ Paper Bags	*Wal-Mart*	23%
	HEB	15%
	Reddy Ice	8%
	Ziploc	8%
	99-Cent Store	5%
	Valero	5%
	Unknown	5%
	All other brands	32%

Appendix B – Methodology

The methodology used for the 2013 Texas Litter Survey is based on statistically-based methodologies that have been used in litter surveys throughout North America.

Conducting the Litter Survey

Each survey team was comprised of two people. Upon arriving at a site, the team safely parked their vehicle. Large worker signs were posted and traffic cones or flags were used to define site parameters. Team members were required to wear fluorescent orange/yellow traffic vests to increase visibility. The optimal site size was one-tenth mile (528 feet) x 18 feet. Conditions limiting access to a site's optimal width (e.g. walls or fences) were so noted.

Paint provided by TxDOT was used to mark the beginning, midpoint and end of each site. This helped identify sites that should not be cleaned and helped the survey teams return to the same survey points for the second survey.

The width of each site was measured from 1.5 feet inside the curb or the start of the pavement, towards the outer edge of the site, up to a maximum width of 18 feet and marked to indicate the boundary. This rule was set to include 1.5 feet into the street since curbs are normal catchment structures, for which DOTs typically ensure litter cleanup.

Litter Classification

For the 2013 Texas Litter Survey, litter was classified as *Visible Litter* (>= two square inches) and *Micro Litter* (< two square inches). This breakdown helps define and clarify the extent to which litter item size is a factor in the evaluation of resultant data.

The litter tallies were recorded into 89 categories of *Visible Litter* and 17 categories of *Micro Litter*. Utilizing these categories will allow comparison to litter in other areas and will for future litter surveys in Texas. A detailed description of each litter category is included in the Appendix.

Micro Litter was examined in three segments of each site: at the beginning, middle and end of each site. Each of these segments comprised a 3′ x 18′ area. The resultant data was extrapolated to the total site area.

Survey Count

At each site, the ambient site information was recorded on the appropriate form, describing the site number, size and proximity to conditions (e.g. traffic signal, fast food or convenience stores, etc.) and providing a subjective visual rating.

Appendix C – Visible Litter Components

All components of *Visible Litter* are shown in Table 25. This represents the data for the *Original Sites,* which are statistically comparable to data in the 2009 and 2005 surveys. Almost 25% of all *Visible Litter* is debris related to vehicle and construction. These items were also a significant portion of litter observed at the *New Sites* as well.

Table 25 – Visible Litter Components

Visible Litter Item	Percent
Tire & Rubber Debris	13.4%
Vehicle & Metal Road Debris	7.0%
Construction Debris	4.5%
Misc. Plastic	4.2%
Misc. Paper	3.8%
Beer Cans	3.1%
Non-Brand Napkins	2.8%
Snack Food Packaging	2.5%
Tobacco Packaging	2.4%
Soft Drink Cans	2.4%
Composite Materials - Other	2.3%
Cup Lids, Pieces Lids, Straws	2.3%
Other Cloth	2.2%
Printed Material (Newspapers, Etc.)	2.2%
Plastic Packaging - Film	2.0%
Polystyrene Cups (Foam)	2.0%
Water Bottles (Plastic)	2.0%
Sweet Snack Packaging	1.8%
Polystyrene Block Pieces	1.5%
Home Articles	1.5%
Misc. Cardboard	1.4%
Condiment Package (Salt, Etc.)	1.4%
Soft Drink (Plastic)	1.4%
Clothing Or Clothing Pieces	1.3%
Plastic Drink Cups	1.3%
Receipts (Business, Transfers, Etc.)	1.3%
Plastic Retail Bags - No Brand Name	1.3%
Paper Cups (Cold)	1.3%
Broken Glass Container	1.1%
Paper/Foil Wraps (Burger Wrappers)	0.8%

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Visible Litter Item	Percent
Container Lids	1.1%
Paper Packaging - Other	1.1%
Sport/Energy Drink (Plastic)	1.0%
Misc. Paperboard	0.9%
Foil Materials/Foil Pieces	0.8%
Gum Wrappers	0.8%
Plastic Jars/Bottles/Lids (Non Beverage)	0.7%
Paperboard (Cereal Type)	0.7%
Corrugated Boxes/Box Material	0.7%
Beer Bottles (Glass)	0.7%
Misc. Glass	0.7%
Plastic Retail Bags - Branded	0.7%
Paper Food Wrap (Meat Wrap)	0.7%
Paper Bags - Fast Food	0.6%
Polystyrene Clamshells/Pieces	0.5%
Other Plastic Shells/Boxes	0.5%
Milk/Juice (Plastic)	0.5%
Sport/Energy Drink (Cans)	0.5%
Zipper Bags/ Sandwich	0.5%
Lottery Ticket Debris	0.5%
Paper Cups (Hot)	0.4%
Paper Retail Bags - No Brand Name	0.4%
Paper Beverage Cases	0.4%
Plastic Wrap	0.4%
Plastic Bags - Not Retail (Leaf, Trash)	0.4%
Cigarettes/Butts	0.3%
Food Items	0.3%
Utensils (Plastic or Otherwise)	0.3%
Cans - Aluminum (Non Beverage)	0.3%
Name Brand FF Towels/Napkins	0.3%
Polystyrene Fast Food Plates	0.3%
Foil Containers	0.2%
Foil Pouches	0.2%
Wine/ Liquor (Plastic)	0.2%
Milk/Juice (Gable Top)	0.2%
Paper Clamshells	0.2%
Six Pack Plastic Rings	0.2%
Paper Retail Bags - Branded	0.1%
Cans - Steel	0.1%
Paper Trays	0.1%

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Visible Litter Item	Percent
Wine/ Liquor (Glass)	0.1%
Soft Drink (Glass)	0.1%
Other Paper Cups	0.1%
Paper Fast Food Plates	0.1%
Other Plastic Fast Food Plates	0.1%
Milk/Juice (Glass)	0.1%
Aerosol Cans (Paint, Oils, Etc.)	0.1%
Aseptic (Box)	0.0%
Other Material Trays	0.0%
Cigar Butts/Tips	0.0%
Tea (Glass)	0.0%
Paper Bags - Not Retail	0.0%
Plates - Other Materials	0.0%
Polystyrene Trays	0.0%
Water (Glass)	0.0%
Glass Jars/ Bottles Misc.	0.0%
Tea/Coffee (Can)	0.0%
Tea (Plastic)	0.0%
Total Visible Litter	**100.0%**

Appendix D – Micro Litter: All Components

All components of *Micro Litter* are shown in Table 26. This represents the data for the *Original Sites*, which are statistically comparable to data in the 2009 and 2005 surveys. Two-thirds of all Micro Litter in Texas is either *Cigarette Butts* (almost half of all *Micro Litter*) or *Tire and Rubber* (scraps from blown tires). Other components showed evidence of having been mowed, which creates multiple items of litter from one piece.

Table 26 – Micro Litter Components

Micro Litter Item	Percent
Cigarette Butts	48.0%
Tire & Rubber Debris	18.6%
Glass	6.9%
Paper	6.2%
Plastic - Film	4.9%
Plastic - Hard	4.9%
Polystyrene – Food Service	3.5%
Aluminum	2.4%
Metal	1.1%
Other	1.0%
Bottle Caps	0.7%
Candy Wraps	0.5%
Polystyrene - Packaging	0.4%
Straws	0.2%
Tobacco Packaging	0.2%
Cigar Butts	0.2%
Food	0.1%
Total	**100.0%**

Appendix E – Most Common Items within Use Categories

For comparability to the litter surveys conducted in 2009 and 2005, Table 27 shows each component of *Total Litter* as a percentage of its *Litter Use* category. Under Construction/Industrial, small pieces of both hard and film plastic yielded the same total.

Cigarette Butts (96.6%) were a higher percentage of Tobacco Litter compared to 2009 (84%). Tire Debris (71%) was similar to 2009 (68%). Although some category details differed slightly, there were a number of similar findings compared to 2009. Non-Alcoholic beverage containers (34%) were similar to the results for Soda in 2009 (30%). Beer Cans (55%) were virtually the same as 2009 (56%). When added together, Beer Bottles and Broken Glass Containers, typically attributed to broken Beer Bottles, were also similar (30%) compared to 2009 (26%).

Table 27 – Components of Litter by Use Category

Use	Item Name	Percent of Use Category
Construction/ Industrial	Plastic Film Pieces (Micro)	20.8%
	Plastic Hard Pieces (Micro)	20.8%
	Aluminum Pieces	10.4%
	Construction Debris	10.4%
	Misc. Plastic	9.7%
	Metal Pieces (Micro)	5.2%
	Composite Materials - Other	5.2%
	Other Items (Wood)	4.5%
	Plastic Packaging - Film	4.5%
	Polystyrene Block Packaging	3.2%
	Polystyrene Packaging (Micro)	1.9%
	Foil Materials/Foil Pieces	1.9%
	Misc. Glass (Visible)	1.3%
	Aerosol Cans (Paint, Oils, Etc.)	0.0%
Tobacco	Cigarette Butt	96.6%
	Tobacco Packaging (Visible)	2.5%
	Tobacco Packaging (Micro)	0.6%
	Cigar Butts and Tips	0.3%

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Use	Item Name	Percent of Use Category
Automotive	Tire and Rubber Debris (Micro)	51.3%
	Tire and Rubber Debris (Visible)	19.7%
	Glass Pieces (Micro)	18.9%
	Vehicle and Metal Road Debris	10.1%
Printed	Paper - Micro	4.0%
	Misc. Paper	1.3%
	Receipts (Business, Transfers, Etc.)	0.5%
	Printed Material (Newspapers, Etc.)	0.8%
	Paper Packaging - Other	0.4%
	Stationary (School, Business Etc.)	0.4%
	Lottery Ticket Debris	0.2%
Non-Alcoholic Beverages	Polystyrene Food Service – (Micro)	27.3%
	Cup Lids, Pieces Lids, Straws	9.5%
	Soft Drink (Cans)	9.5%
	Water (Plastic)	8.3%
	Polystyrene Cups (Foam)	8.3%
	Soft Drink (Plastic)	5.9%
	Plastic Drink Cups	5.9%
	Bottle Caps	5.9%
	Paper Cups (Cold)	4.7%
	Sport/Energy Drink (Plastic)	4.1%
	Sport/Energy Drink (Cans)	2.4%
	Milk/Juice (Plastic)	2.4%
	Paper Cups (Hot)	2.4%
	Straw Pieces (Micro)	2.4%
	Milk/Juice (Gable Top)	1.2%
	Soft Drink (Glass)	0.0%
	Foil Pouches	0.0%
	Water (Glass)	0.0%
	Aseptic (Box)	0.0%
	Tea/Coffee (Can)	0.0%
	Milk/Juice (Glass)	0.0%
	Other Paper Cups	0.0%

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Use	Item Name	Percent of Use Category
	Tea (Plastic)	0.0%
	Tea (Glass)	0.0%
Household/ Personal	Misc. Cardboard	11.4%
	Clothing or Clothing Pieces	11.4%
	Home Articles	11.4%
	Plastic Retail Bags - No Brand Name	11.4%
	Container Lids	9.1%
	Misc. Paperboard	6.8%
	Paperboard (Cereal Type)	6.8%
	Plastic Jars / Bottles/ Lids (Non Beverage)	6.8%
	Corrugated Boxes/ Box Material	4.5%
	Zipper Bags/ Sandwich	4.5%
	Plastic Retail Bags - Branded	4.5%
	Cans-Aluminum (Non Beverage)	2.3%
	Paper Retail Bags - No Brand Name	2.3%
	Plastic Bags - Not Retail (Leaf, Trash)	2.3%
	Cans - Steel	2.3%
	Paper Retail Bags - Branded	2.3%
	Glass Jars/ Bottles Misc.	0.0%
	Paper Bags - Not Retail	0.0%
Food & Food-Related Items	Non-Brand Napkins	18.2%
	Snack Food Packaging	16.4%
	Sweet Snack Packaging	10.9%
	Condiment Package (Salt, Etc.)	9.1%
	Candy Wrapper Pieces	5.5%
	Paper/Foil Wraps (Burger Wrappers)	5.5%
	Gum Wrappers	5.5%
	Other Plastic Shells/Boxes	3.6%
	Polystyrene Clamshells	3.6%
	Food Items	3.6%
	Paper Bags - Fast Food	3.6%
	Paper Food Wrap (Meat Wrap)	3.6%
	Foil Containers	1.8%

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Use	Item Name	Percent of Use Category
	Utensils (Plastic or Otherwise)	1.8%
	Paper Trays	1.8%
	Plastic Wrap	1.8%
	Polystyrene Fast Food Plates	1.8%
	Name Brand FF Towels/Napkins	1.8%
	Paper Clamshells	0.0%
	Paper Fast Food Plates	0.0%
	Other Material Trays	0.0%
	Polystyrene Trays	0.0%
	Other Plastic FF Plates	0.0%
	Plates - Other Materials	0.0%
Alcoholic Beverages	Beer Cans	55.0%
	Broken Glass Container	20.0%
	Beer Bottles (Glass)	10.0%
	Paper Beverage Cases	5.0%
	Six Pack Plastic Rings	5.0%
	Wine/ Liquor (Plastic)	5.0%
	Wine/ Liquor (Glass)	0.0%
Agricultural/ Garden	Other Cloth	100.0%

Appendix F – Statistical Analysis of Litter Audit Results

Confidence levels use statistical tests to show the probability that data in a survey represent actual conditions. The confidence levels for the 2013 litter survey were wider than 2009, as shown in Table 28, but narrower than in 2005.

Table 28 - Annual Litter and 90% Confidence Interval Estimate

Survey Year	Annual Litter Estimates (Millions of Items)	Annual Litter Estimates Minus 90% CI Estimate (Millions of Items)	Annual Litter Estimates Plus 90% CI Estimate (Millions of Items)
2005	827	578	1,076
2009	1,102	902	1,302
2013	1,481	1,057	1,905

Statistical tests were conducted to evaluate any potential correlations between litter and the following factors: beautification, convenience stores, fast food outlets, schools and traffic signals/signs. Separate tests were run for *Visible Litter* and *Micro Litter*.

Significance tests are typically conducted at the ".05 level" (95% likely to be true) or ".01 level" (99% likely to be true). Each of these tests was run for the first survey (S #1), the second survey (S #2) and the accumulated litter (Acc.).

As shown in Table 29, *Visible Litter* tended to be lower near any of these factors. This may be due to more frequent cleanups, as businesses and schools have become sensitized to the importance of keeping areas around their facilities clean.

Table 29 - Visible Litter Proximity Test

Factor	Beaut.	Conv. Stores	Fast Food	*School*	*Traffic Signs*
N=	**19**	**42**	**28**	***7***	***38***
S #1	0.04	-0.02	-0.01	-0.13	-0.13
S #2	-0.07	0.01	-0.05	-0.10	-0.16
Acc.	-0.13	0.03	-0.05	0.05	0.00

Colored cells are significant at the:

.05 level
.01 level

The results for Micro Litter (Table 30) were different. Virtually all of the factors showed a mild correlation to higher levels of litter, especially convenience stores and fast food outlets.

This is likely due to the fact that cleanups of *Micro Litter* are difficult and time consuming. Cleanup crews tend to focus on removal of *Visible Litter*, which is more visible than small items.

In addition, many of the positive results for the *Micro Litter* tests (Table 30) were at the .01 level, meaning a stronger likelihood (99%) that they are true than results at the .05 level (95%).

Table 30 – Micro Litter Proximity Test

Factor	Beaut.	Conv. Stores	Fast Food	*School*	*Traffic Signs*
N=	19	42	28	*7*	*38*
S #1	0.09	0.17	0.14	-0.03	0.14
S #2	0.08	0.25	0.27	0.04	0.11
Acc.	0.04	0.18	0.21	0.06	0.03

Colored cells are significant at the:

.05 level
.01 level

Correlations for Sites is a statistical test that analyzes the data and determines whether the amount of litter accumulated at each site was similar between surveys. The data in Table 31 shows that a noticeable similarity did exist at each site.

Table 31 - Correlations for Sites

Correlations for Sites Survey 1 vs. Survey 2	
Visible	0.67
Micro	0.47

Correlations between Surveys is a statistical test that analyzes the data and determines if the most and least littered items were similar between surveys. The data in Table 32 yielded a very strong correlation showing that the most and least littered items were very similar between the two surveys.

Table 32 - Correlations between Surveys

Correlations Between Surveys Survey 1 vs. Survey 2	
Visible	0.94
Micro	0.96

Another statistical test was run to analyze the data and determine if the litter accumulation patterns was similar for *Original Sites* and *New Sites*. There was a very strong correlation (Table 33) showing that litter across the State of Texas tends to be similar, as was true in previous surveys.

Table 33 - Correlations between Original and New Sites

Size	*Survey 1*	*Survey 2*
Visible	0.98	0.96
Micro	0.95	0.99

Impacts of High Wind Gusts

High wind gusts are a significant factor affecting how *Visible Litter* is statistically measured in Texas. Table 34 shows the percentage of days at each weather station that high wind gusts of 30 mph or greater, capable of moving littered items between sites, were recorded. This data is limited to the dates between the start of the first survey (February 26, 2013) and completion of the second survey (April 18, 2013). For instance, high wind gusts were recorded on 71% of those days in Lubbock. This shows that measuring *Visible Litter* in Texas by purging sites and conducting subsequent surveys will likely result in an overstatement of *Visible Litter*.

Table 34 – Recorded High Wind Gusts

Weather Station	*30 mph+*
Amarillo	65%
Abilene	62%
Austin	44%
Beaumont	38%
Brownsville	52%
Corpus Christi	73%
Dallas-Fort Worth	63%
El Paso	50%
Houston	37%
Lubbock	71%
Odessa	50%
San Antonio	31%
San Angelo	60%
Tyler	38%
Waco	46%
Wichita Falls	63%

Appendix G – Litter Categories and Descriptions

Table 35 includes a detailed description of the categories used for *Visible Litter* in the 2013 Texas Litter Survey. These categories and descriptions have been used for a number of recent litter surveys including Texas. Descriptions are also included for the categories of *Micro Litter* although many of those items are identifiable only by material.

Table 35 – Litter Categories and Descriptions

Litter Item	Category	Material	Description
Beer Cans	Beverage	Metal	Beer in aluminum cans
Beer Bottles (Glass)	Beverage	Glass	Beer in glass bottles
Soft Drink (Glass)	Beverage	Glass	Soft drinks in glass bottles
Soft Drink (Cans)	Beverage	Metal	Soft drinks in aluminum cans
Soft Drink (Plastic)	Beverage	Plastic	Soft drinks in plastic bottles
Sport/Energy Drink (Metal)	Beverage	Metal	Sport drinks in aluminum cans
Sport/energy Drink (Plastic)	Beverage	Plastic	Sport drinks in plastic bottles
Tea/Coffee (Metal)	Beverage	Metal	Tea or coffee drinks in aluminum cans
Tea/Coffee (Plastic)	Beverage	Plastic	Tea or coffee drinks in plastic bottles
Tea/Coffee (Glass)	Beverage	Glass	Tea or coffee drinks in glass bottles
Water (Glass)	Beverage	Glass	Packaged water in glass bottles
Water (Plastic)	Beverage	Plastic	Packaged water in plastic bottles
Wine/ Liquor (Glass)	Beverage	Glass	Wine & liquor in glass bottles
Wine/ Liquor (Plastic)	Beverage	Plastic	Wine & liquor in plastic bottles
Milk/Juice (Plastic)	Beverage	Plastic	Milk or juice containers in plastic bottles
Milk/Juice (Glass)	Beverage	Glass	Milk or juice containers in glass bottles
Milk/Juice (Gable)	Beverage	Paper	Milk/juice in gable top cartons
Foil Pouches	Other Bev. Packaging	Composite	Packaged goods and pieces of foil pckg.
Aseptic (Box)	Other Bev. Packaging	Composite	Drink-in-box, juice, fluids, other
Broken Cont. Glass	Other Bev. Packaging	Glass	Glass bottle fragments
Six Pack Plastic Rings	Other Bev. Packaging	Plastic	Retainer plastic for carrying cans
Foil Containers	Other Bev. Packaging	Metal	Foil wraps (e.g., ice cream)
Plastic Drink Cups	Cups	Plastic	Cups, all resin types
Paper Cups (Cold)	Cups	Paper	Cups, all paper types - cold drinks
Paper Cups (Hot)	Cups	Paper	Cups, all paper types - hot drinks
Polystyrene Cups (Foam)	Cups	Plastic	Cups, all polystyrene types - hot drinks

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Other Paper Cups	Cups	Paper	Cups, other materials
Cup Lids, Pieces Lids	Cups	Plastic	Cups, lids, straws and pieces
Plastic Retail Bags - Brand Name	Bags	Plastic	Whole\pieces of branded retail plastic bags
Plastic Retail Bags - No Brand	Bags	Plastic	Whole\pieces of non-branded retail plastic bags
Paper Retail Bags - Brand Name	Bags	Paper	Whole\pieces of branded retail paper bags
Paper Retail Bags - No Brand	Bags	Paper	Whole\pieces of non-branded retail paper bags
Paper Bags - Fast Food	Bags	Paper	Whole\pieces of fast food paper bags
Plastic Bags - Not Retail	Bags	Plastic	Whole\pieces of non-retail plastic bags (e.g., leaf, trash, etc.)
Paper Bags - Not Retail	Bags	Paper	Paper bags & sacks (e.g., leaf debris)
Zipper Bags/ Sandwich	Bags	Plastic	Plastic lunch bags and sacks
Plastic Packaging - Film	Bags	Plastic	Stretch wrap, dry cleaner bags, commercial/industrial non-bag plastic film
Corrugated Boxes & Material	Other Packaging	Paper	All cardboard and box materials
Paperboard	Other Packaging	Paper	Cereal, shoe boxes and pieces etc.
Paper Beverage Cases	Other Packaging	Paper	Paper material outer packaging for beverage products
Polystyrene Clamshells	Other Packaging	Plastic	Whole and pieces of expanded foam containers
Paper Clamshells	Other Packaging	Paper	Whole and pieces of take-away or other paper containers
Other Plastic Shells/Boxes	Other Packaging	Plastic	PET, PVC, HDPE, other material shells
Plastic Jars / Bottles/ Lids	Other Containers	Plastic	Non-beverage plastic jars/bottles, (e.g., detergent bottles)
Glass Jars/ Bottles Misc.	Other Containers	Glass	Glass jars/bottles not described above
Cans - Steel	Other Containers	Metal	Steel food/non-food containers
Cans - Aluminum	Other Containers	Metal	Aluminum food/non-food containers
Container Lids	Other Containers	Plastic	All lids, closures, and pieces > 4 sq. in.
Aerosol Cans	Other Containers	Metal	Aerosol cans, tops, lids for spray paints, oils, etc.
Paper Food Wrap	Food Wraps/Containers	Paper	Commercial/Non-commercial food wrap (e.g., meat wrap)
Paper / Foil Composite Wrap	Food Wraps/Containers	Composite	Wrap for food/non-food (e.g., hamburger paper/foil)
Plastic Wrap	Food Wraps/Containers	Plastic	All retail plastic wrap types, food, non-food
Condiment Package	Take-Out Extras	Plastic	Pouches and containers (e.g., ketchup, salt, creamers, etc.)
Utensils	Take-Out Extras	Plastic	Forks, knives, chop sticks etc.
Branded Fast Food Towels/Napkins	Take-Out Extras	Paper	Towels & napkins with identifiable brand
Paper Fast Food Plates	Take-Out Extras	Paper	Paper Plates used to serve fast food
Polystyrene Fast Food Plates	Take-Out Extras	Plastic	Polystyrene Plates used to serve fast food
Other Plastic Fast Food Plates	Take-Out Extras	Plastic	Other Material Plates used to serve fast food
Plates - Other Materials	Take-Out Extras	Composite	Plates - not fast food (e.g., picnic plates)
Polystyrene Trays	Trays	Plastic	Take-out/non-take out, microwavable, display trays
Paper Trays	Trays	Paper	Take-out/non-take out, microwavable, display trays
Other Material Trays	Trays	Plastic	Take-out/non-take out, microwavable, display trays
Gum Wrappers	Confectionary/ Snack	Composite	Packaging used to seal, sell gum products
Sweet Snack Wraps and Pouches	Confectionary/ Snack	Composite	Packaging used to seal, sell candy and cake products

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Snack Food Packaging	Confectionary/ Snack	Composite	Snack foods such as chips, etc.
Food Items	Confectionary/ Snack	Organic	Apple cores, banana peels, etc.
Clothing Or Clothing Pieces	Cloth	Cloth	All cloth, clothing pieces, and clothing discarded on site
Other Cloth	Cloth	Cloth	Tarps, industrial fabrics etc.
Non-Brand Towels & Napkins	Paper	Paper	Napkins and towels - no brand identification
Paper Packaging - Other	Paper	Paper	Paper packaging otherwise not described
Lottery Ticket Debris	Paper	Paper	Tickets, and gaming items
Printed Materials	Paper	Paper	Commercially printed materials (newspapers, flyers, etc.)
Stationary	Paper	Paper	School papers, business forms, etc.
Receipts	Paper	Paper	Receipts, tickets, bus transfers, invoices, packing slips
Cigarette Debris	Tobacco	Tobacco	Cigarette butts and discarded cigarettes (>= 2 inches^2)
Cigar Debris	Tobacco	Tobacco	Cigar butts, tips and discarded cigars items (>= 2 inches^2)
Tobacco Packaging	Tobacco	Composite	All other tobacco packaging, matches, lighters, matchboxes
Misc. Paper	Other Miscellaneous	Paper	All other paper whole or shredded, unidentifiable
Misc. Plastic	Other Miscellaneous	Plastic	All other plastic whole or shredded, unidentifiable
Misc. Paperboard	Other Miscellaneous	Paper	All other paperboard whole or shredded, unidentifiable
Misc. Cardboard	Other Miscellaneous	Paper	All other cardboard whole or shredded, unidentifiable
Misc. Glass	Other Miscellaneous	Glass	All other glass, whole or broken, unidentifiable
Vehicle & Metal Road Debris	Other Miscellaneous	Composite	Auto parts, debris from auto accidents, other transportation-related
Composite Materials	Other Miscellaneous	Composite	Items made of multiple materials (e.g. metal and plastic, etc.)
Foil Materials/Foil Pieces	Other Miscellaneous	Metal	Foils and pieces, aluminum food foils, industrial foils
Construction Debris	Other Miscellaneous	Composite	Debris associated with construction
Tire & Rubber Debris	Other Miscellaneous	Rubber	Rubber sheets/pieces, tire pieces, shock absorbers
Home Articles	Other Miscellaneous	Composite	All non-described household items, (e.g., lamps, etc.)
Aluminum	Micro Litter	Metal	Micro pieces of aluminum (less than two inches^2)
Bottle Caps	Micro Litter	Composite	Metal or plastic caps for bottles and containers (less than two inches^2)
Candy Wrappers	Micro Litter	Composite	Micro pieces of candy wrappers (less than two inches^2)
Cigar Butts/Tips	Micro Litter	Tobacco	Cigar butts, tips and discarded cigars items (less than two inches^2)
Cigarette Butts	Micro Litter	Tobacco	Cigarette butts and discarded cigarettes (less than two inches^2)
Food	Micro Litter	Organic	Food scraps (less than two inches^2)
Glass	Micro Litter	Glass	Micro pieces of glass (less than two inches^2)
Metal (not Aluminum)	Micro Litter	Metal	Micro pieces of metal other than aluminum (less than two inches^2)
Other Materials	Micro Litter	Composite	Other small materials not otherwise categorized (less than two inches^2)
Tobacco Packaging	Micro Litter	Composite	Micro pieces of tobacco-related materials (less than two inches^2)
Paper	Micro Litter	Paper	Micro paper scraps (less than two inches^2)
Plastic – Film	Micro Litter	Plastic	Micro pieces of plastic film (less than two inches^2)
Plastic – Hard	Micro Litter	Plastic	Micro pieces of hard plastic (less than two inches^2)
Polystyrene Foam - Packaging	Micro Litter	Plastic	Micro pieces of polystyrene packaging (less than two inches^2)

Polystyrene Foam – Food Service	Micro Litter	Plastic	Micro pieces of polystyrene food service items (less than two inches^2)
Tire & Rubber Debris	Micro Litter	Rubber	Micro pieces of rubber (less than two inches^2)
Straws	Micro Litter	Composite	Micro pieces of straws (less than two inches^2)

Appendix H – Sites Locations

Table 36 provides a detailed description of the site locations used for the 2013 Texas Litter Survey. Locations for each of the *Original Sites* were based on the location information provided from the 2009 survey. *New Sites* were selected in conjunction with Sherry Matthews Advocacy Marketing staff.

Table 36 – Site Locations

Type	ID	Tm	District	County	Site Description
Original	Abl01	West	Abilene	Callahan	IH-20: 0.1 mile past intersection with FM-603
Original	Abl02	West	Abilene	Scurry	US-84: 0.1 mile past intersection with FM-612 in Fluvanna, about 8 miles northwest of Snyder
Original	Abl03	West	Abilene	Callahan	SH-36: 0.1 mile past intersection with US-283
New	Abl04	West	Abilene	Nolan	IH-20: 0.1 mile past Exit 241
New	Abl05	West	Abilene	Taylor	IH-20: 0.1 mile past Exit 277
New	Abl06	West	Abilene	Kent	US-380: 0.1 miles past intersection with FM-1081
New	Abl07	West	Abilene	Scurry	SH-350/SH-208: 0.2 miles past intersection with US-180
New	Abl08	West	Abilene	Haskell	FM-617: 0.2 miles past intersection with US-277 before SH-6
Original	Ama02	West	Amarillo	Carson	IH-40: 0.1 mile past intersection with FM-2880
Original	Ama03	West	Amarillo	Potter	US-287: 200 feet past Burlington/Santa Fe RR track about 0.1 mile south of Potter County/Moore County Line
Original	Ama04	West	Amarillo	Moore	SH-152: 0.1 mile past intersection with FM-1284
New	Ama05	West	Amarillo	Oldham	IH-40: 0.2 miles past Exit 49 (in between Vega and Amarillo)
New	Ama06	West	Amarillo	Carson	IH-40: 2.0 miles east past intersection with SH-207
New	Ama08	West	Amarillo	Hartley	US-385: 3 miles north of intersection with US-354/FM-767
New	Ama09	West	Amarillo	Oldham	SH-214: 0.2 miles south of SH 214 & I-40 intersection (off exit 22)
Original	Atl01	North	Atlanta	Bowie	US-59/US-71: 1 mile north of Loop 14/Texas Blvd/Arkansas Blvd, traveling north
Original	Atl03	North	Atlanta	Bowie	SH-93: 0.1 mile northeast of intersection with FM-558/Old Buchanan Road, north of Wagner Creek, traveling northeast
Original	Atl05	North	Atlanta	Bowie	IH-30: 0.1 mile west of intersection with FM-989, traveling west
Original	Atl06	North	Atlanta	Cass	FM-251/S William Street: 0.1 mile south of intersection with SH-77, south of Atlanta, traveling south
New	Atl07	North	Atlanta	Titus	IH-30: 0.1 mile west of Exit 162, near US-271, traveling west
New	Atl08	North	Atlanta	Bowie	FM-44: 0.1 mile west of intersection with US-259, south of De Kalb, west of New Boston, traveling west

New	Atl09	North	Atlanta	Bowie	FM-74 (Houston Street): 0.1 mile east of intersection with Co Rd 3775 about 1 mile past SH-236 in Queens City, traveling east
Original	Aus00	South	Austin	Gillespie	SH-16: 0.1 mile past intersection with Triple Creek Road, past City of Fredericksburg
Original	Aus01	South	Austin	Travis	FM-2244: 0.1 mile past intersection with SH-71
Original	Aus04	South	Austin	Travis	US-183: 0.1 mile past intersection with FM-812
Original	Aus05	South	Austin	Travis	FM-969: 0.1 mile past intersection with FM-973 west of Sh-45/SH-130 near Thunderbird Farms
Original	Aus08	South	Austin	Hays	IH-35: 0.1 mile past SH-4 Loop
Original	Aus10	South	Austin	Travis	SH-71: 0.1 mile past FM-973
Original	Aus11	South	Austin	Williamson	US-79: 0.1 mile past intersection with FM-685
Original	Aus12	South	Austin	Mason	SH-29: 0.1 mile past intersection with FM-1222
Original	Aus15	South	Austin	Williamson	US-79: 0.1 mile past intersection with FM-1460
Original	Aus17	South	Austin	Caldwell	FM-2720: 0.1 mile past intersection with SH-142
Original	Aus18	South	Austin	Blanco	FM-2766: 0.1 mile past intersection with US-281
New	Aus19	South	Austin	Hays	IH-35: 0.5 miles directly past FM-150, past Town of Kyle, TX
New	Aus20	South	Austin	Williamson	US-79: 0.1 mile past intersection with FM-1460 near City of Round Rock
New	Aus21	South	Austin	Hays	SH-21: 0.5 miles past SH-21 and FM-150 intersection near City of Uhland, past San Marcos Municipal Airport
Original	Bmt01	East	Beaumont	Orange	IH-10: 0.1 mile past Neches River Bridge
Original	Bmt02	East	Beaumont	Liberty	US-59: 0.1 mile past the intersection with SH-105 near the MONTGOMERY COUNTY Line
Original	Bmt03	East	Beaumont	Liberty	SH-321: 0.1 mile past intersection with FM-1008
Original	Bmt04	East	Beaumont	Liberty	FM-1960: 0.1 mile past intersection with FM-686 about 6 miles west of City of Dayton and US-90
Original	Bmt05	East	Beaumont	Jasper	US-96: 0.1 mile past intersection with FM-2800
Original	Bmt06	East	Beaumont	Jefferson	IH-10: 0.1 mile past intersection with FM-364
New	Bmt07	East	Beaumont	Tyler	US-69: 0.1 mile past intersection with FM-1013 in Town of Hillister
New	Bmt08	East	Beaumont	Hardin	US-69: 0.4 miles past intersection with SH-327 approaching City of Lumberton
New	Bmt09	East	Beaumont	Newton	SH-87: 0.3 miles past intersection with FM-253
Original	Bry01	East	Bryan	Freestone	IH-45: 200 feet past intersection with SH-179 east of Teague about 42 miles south of Corsicana
Original	Bry02	East	Bryan	Burleson	FM-50: 0.1 mile past intersection with FM-1361, west of SH-6 and Mustang Hills, northeast of Somerville
Original	Bry04	East	Bryan	Washington	US-290: 0.1 mile past Loop 2447
Original	Bry05	East	Bryan	Burleson	FM-1362: 0.1 mile past intersection with SH-21
Original	Bry06b	East	Bryan	Brazos	FM-2038: 0.1 mile past Marker 628
New	Bry07	East	Bryan	Grimes	SH-90: 0.1 mile past intersection with SH-6

New	Bry08	East	Bryan	Madison	SH-75: 0.1 mile past intersection with Old San Antonio Road near IH-45
New	Bry09	East	Bryan	Robertson	US-79: 0.3 miles past intersection with FM-46 in Town of Franklin
New	Bry10	East	Bryan	Washington	FM-50: 0.5 miles past intersection with FM-390, north of SH-105 in between Brenham and Navasota
Original	Bwd01	North	Brownwood	Brown	US-67/US-377: 0.1 mile northwest of intersection with FM-1467, traveling northwest
Original	Bwd02	North	Brownwood	Comanche	SH-16: 0.1 mile southeast of intersection with FM-R 3200, traveling southeast from Comanche
New	Bwd03	North	Brownwood	Brown	US-183: 0.4 miles north of intersection with US-67, traveling north from Brownwood
New	Bwd04	North	Brownwood	Comanche	FM-587: 0.5 miles east of intersection with Co Rd 679 in COMANCHE COUNTY traveling east toward De Leon Municipal Airport
Original	Chs01	West	Childress	King	US-82/SH-114: 0.1 miles past US-83 traveling east
New	Chs02	West	Childress	Knox	US-277: 0.1 mile past intersection of FM-266 at Town of Goree
New	Chs03	West	Childress	Childress	SH-256: 0.5 miles west of intersection with US-62/US-83
Original	Crp01	South	Corpus-Christi	Live Oak	IH-37: 0.1 mile past intersection with FM-799
Original	Crp02	South	Corpus-Christi	Nueces	SH-358: 0.1 mile past intersection with IH-37
Original	Crp04	South	Corpus-Christi	Nueces	US-77: 0.1 mile past intersection with FM 892 (Lincoln Ave), about one mile southwest of NUECES COUNTY Airport
Original	Crp05	South	Corpus-Christi	Refugio	US-183: 0.1 mile past intersection with SH-202
Original	Crp06	South	Corpus-Christi	Bee	SH-359: 0.1 mile past intersection with US-181
New	Crp07	South	Corpus-Christi	Live Oak	IH-37: 0.1 mile past Mile Marker 48
New	Crp08	South	Corpus-Christi	Goliad	US-183/US-77: 0.3 miles past intersection with SH-239
New	Crp09	South	Corpus-Christi	Refugio	US-77: 0.1 mile past intersection with FM-774 at Town of Refugio
New	Crp10	South	Corpus-Christi	Bee	SH-202: 0.4 miles past intersection with FM-2441
New	Crp11	South	Corpus-Christi	Kleberg	FM-771: 0.3 miles past intersection with US-77 traveling towards Riviera Beach
Original	Dal01	North	Dallas	Collin	SH-121/Sam Rayburn Hwy: 0.3 miles north of intersection with FM-2933/Co Rd 1116, 2-3 miles traveling northeast from US-75 and Melissa
Original	Dal02	North	Dallas	Collin	SH-78: 0.3 miles west of intersection with SH-205, north of Lake Ray Hubbard and I-30, west of Plano, traveling west

Original	Dal03	North	Dallas	Dallas	IH-35E/US-77: 1.0 miles north of IH-635 loop, north of downtown, near Valley View Lane traveling northward
Original	Dal04	North	Dallas	Dallas	IH-20: 0.1 mile west of intersection with FM-1382, about 6.5 miles west of US-67, traveling east from Fort Worth
Original	Dal05a	North	Dallas	Dallas	IH-20: 0.1 mile east of intersection with IH-45, traveling east
Original	Dal06	North	Dallas	Ellis	US-287: 0.6 miles southwest of intersection with US-67, traveling southeast, south of Midlothian, near Crossroads Lake
Original	Dal08	North	Dallas	Kaufman	IH-20: 0.3 miles east of intersection FM-2932, near FM-741, about 15 miles west of IH-635, traveling east
Original	Dal09	North	Dallas	Kaufman	IH-20: 0.3 miles southeast of intersection FM-2965, traveling northwest toward Dallas, about 11 miles southwest of Terrell Airport
Original	Dal10	North	Dallas	Kaufman	US-175: 0.3 miles southeast of intersection with US-175 Business, north of Mabank, east of Cedar Creek Reservoir, traveling southeast
Original	Dal11	North	Dallas	Kaufman	SH-274: 0.3 miles south of intersection with FM-148, traveling north toward Kaufman
Original	Dal12	North	Dallas	Navarro	IH-45: 2 miles south of exit 242, traveling south
Original	Dal13	North	Dallas	Navarro	US-287: 0.3 miles east of intersection with FM-3243, traveling southeast from Corsicana, near Campbell Field-Corsicana Airport
Original	Dal14	North	Dallas	Navarro	SH-22: 0.1 mile west of intersection with FM-1839, traveling west from Corsicana (about 5-6 miles)
Original	Dal15	North	Dallas	Rockwall	IH-30: 0.1 miles east of intersection with FM-740 on left-hand side of road
Original	Dal16	North	Dallas	Ellis	IH-45/US-287: 0.1 mile north of intersection with FM-1182, near ELLIS/NAVARRO COUNTY lines, traveling south toward Corsicana
Original	Dal17	North	Dallas	Denton	US-380: 0.1 mile west of intersection with FM-156, 7.5 miles west of Denton, traveling west
Original	Dal18	North	Dallas	Denton	FM-720 (El Dorado Pkwy)/FM-2934: 0.1 mile west of intersection with FM-423, south of US-380, west of City of Frisco, east of Dallas North Tollway, traveling west
Original	Dal19	North	Dallas	Navarro	IH-45: 0.1 mile southeast of intersection with FM-1394/Ranch RD-1934, traveling about 12.5 miles south from Corsicana
Original	Dal21	North	Dallas	Dallas	US-175: 0.1 mile south of intersection with IH-45, traveling south, between Warren Street and Metropolitan Ave
Original	Dal22	North	Dallas	Dallas	SH-356: 0.1 mile south of intersection with SH-183, traveling south
Original	Dal23	North	Dallas	Rockwall	SH-276: 0.1 mile east of intersection with FM-548, about 6.5 miles east of IH-30/US-67, traveling east from Dallas
New	Dal24	North	Dallas	Dallas	IH-30: 0.1 mile east of Exit 34, traveling west
New	Dal25	North	Dallas	Collin	US-75: 0.1 mile north of intersection with SH-121 near Fairview past intersection with US-380, traveling north
New	Dal26	North	Dallas	Denton	FM-455/Chapman Road: 0.2 miles west of intersection with IH-35/US-77, traveling west, near Lake Ray Roberts, about 11.5 miles north of Denton

Original	Elp01	West	El Paso	Reeves	IH-10: 0.1 miles past intersection with IH-20
Original	Elp02	West	El Paso	El Paso	US-54: 0.1 mile before Texas-New Mexico State line
Original	Elp04	West	El Paso	El Paso	IH-10: 0.1 mile past Spur 375
Original	Elp05	West	El Paso	Jeff Davis	SH-17: 0.1 mile past intersection with Front Street in area of Fort Davis
New	Elp06	West	El Paso	El Paso	IH-10: 0.1 mile past Exit 42
New	Elp07	West	El Paso	Hudspeth	US-180/US-62: 0.1 mile past intersection with Ranch Rd 659
New	Elp08	West	El Paso	Presidio	US-67: 0.2 miles past intersection with US-90 in Town of Marfa
New	Elp09	West	El Paso	Brewster	SH-118: 0.4 miles past intersection with US-67/90
New	Elp10	West	El Paso	Jeff Davis	SH-17: 0.5 miles past intersection with US-118
Original	Ftw01	North	Fort Worth	Johnson	US-67: 0.1 miles west of FM-2331, traveling about 7.5 miles west from Cleburne.
Original	Ftw02	North	Fort Worth	Johnson	SH-171: 0.1 mile south of JOHNSON COUNTY Line traveling south
Original	Ftw03	North	Fort Worth	Johnson	FM-2331: 0.1 mile south of intersection with FM-4, southwest of SH-171 and northwest of US-67 and City of Cleburne
Original	Ftw04	North	Fort Worth	Palo Pinto	IH-20: 0.1 mile east of intersection with SH-193 traveling east
Original	Ftw05	North	Fort Worth	Parker	IH-20: 0.1 mile northeast of intersection with FM-113/Fannin St./N Plum St about 5 miles south of Millsap, traveling north
Original	Ftw06	North	Fort Worth	Parker	SH-199: 0.1 mile south of intersection with FM-2257 traveling south
Original	Ftw07	North	Fort Worth	Parker	SH-171: 0.1 mile south of intersection with FM-51 traveling south
Original	Ftw08	North	Fort Worth	Tarrant	IH-30 East: 0.1 mile east of intersection with SH-360, east of Fort Worth traveling east (exit 30)
Original	Ftw09	North	Fort Worth	Tarrant	IH-20 East: 0.1 mile east of intersection with SH-360, east of Fort Worth traveling east
Original	Ftw10	North	Fort Worth	Johnson	IH-35 west: 0.2 miles north of intersection with FM-917 traveling north
Original	Ftw11	North	Fort Worth	Somervell	US-67: 0.1 mile west of intersection with FM-199 traveling west.
Original	Ftw12	North	Fort Worth	Palo Pinto	IH-20: 0.1 mile west of intersection with US-281 traveling southwest
Original	Ftw13b	North	Fort Worth	Jack	FM-2210: 0.1 mile north of intersection with SH-199 traveling north
Original	Ftw14	North	Fort Worth	Palo Pinto	SH-16: 0.1 mile north of intersection with FM-207 traveling north
New	Ftw15	North	Fort Worth	Johnson	IH-35W: 0.1 mile north of intersection with US-67 in Alvarado, Exit 26 A, traveling north toward Fort Worth
New	Ftw16	North	Fort Worth	Johnson	IH-35E: at intersection with Exit 391
New	Ftw17	North	Fort Worth	Hood	US-377: 0.2 miles south of intersection with SH-171 traveling south
Original	Hou03	East	Houston	Harris	SH-529: 0.1 mile past intersection with SH-6
Original	Hou04r	East	Houston	Harris	IH-10: 0.1 mile past Exit 741 near intersection with Katy Fork Bend Road
Original	Hou05	East	Houston	Harris	IH-45: 0.1 mile past intersection with W Parker Road and E Little York
Original	Hou06	East	Houston	Harris	IH-45: 0.1 mile past intersection with FM-2920
Original	Hou07	East	Houston	Harris	IH-10: 0.1 mile past HARRIS/CHAMBERS COUNTY Line
Original	Hou08	East	Houston	Harris	US-59: 0.1 mile past intersection with SH-288, before IH-610 Loop

Original	Hou09	East	Houston	Harris	SH-288: 0.1 mile past intersection with US-90A past Houston
Original	Hou11	East	Houston	Montgomery	FM-2854: 0.1 mile past intersection with SH-105
Original	Hou12	East	Houston	Harris	IH-10: 0.1 mile past SH-8, past Houston, before IH-610 Loop
Original	Hou13r	East	Houston	Harris	IH-10: 0.1 mile past intersection with SH-99 near Mason Creek Park
Original	Hou14	East	Houston	Harris	US-90: 0.1 mile past intersection with SH-8, near FM-2100
Original	Hou15	East	Houston	Waller	IH-10: 0.1 mile past WALLER COUNTY Line
Original	Hou16	East	Houston	Waller	US-290: 100 past WALLER/WASHINGTON COUNTY Line
Original	Hou17	East	Houston	Montgomery	SH-249: 0.1 mile past HARRIS/MONTGOMERY COUNTY Line
Original	Hou18	East	Houston	Montgomery	IH-45: 0.1 mile past the HARRIS/MONTGOMERY COUNTY line, near The Woodlands
Original	Hou21	East	Houston	Montgomery	FM-1314: 0.1 mile past intersection with SH-242
Original	Hou22	East	Houston	Montgomery	FM-2090: 0.1 mile past intersection with US-59 near Splendora
Original	Hou25	East	Houston	Fort Bend	SH-36: 0.1 mile past intersection with between FM-361, near City of Needville
Original	Hou26	East	Houston	Galveston	IH-45: 0.1 mile past intersection with FM-646, near HARRIS COUNTY Line
Original	Hou27	East	Houston	Montgomery	IH-45: 0.1 mile past intersection with FM-830/1097
Original	Hou28	East	Houston	Fort Bend	US-59: 0.1 mile past Williams Way to FM-762
Original	Hou29	East	Houston	Fort Bend	US-59: 0.1 mile past intersection with FM-2919/Main Street southwest of Houston
Original	Hou30	East	Houston	Harris	IH-10: 0.1 mile past intersection with SH-99
Original	Hou31	East	Houston	Galveston	IH-45: 0.1 mile past intersection with SH-275
Original	Hou32	East	Houston	Montgomery	SH-105: 0.1 mile past intersection with Millmac Rd in City of Cut and Shoot
Original	Hou33	East	Houston	Galveston	SH-146: 0.1 mile past intersection with SH-197/25th Avenue North adjacent to Moses Lake
Original	Hou34	East	Houston	Fort Bend	FM-723: 0.1 mile past intersection with FM-359, south of IH-10 near Katy/Memorial Parkway, north of US-59 near City of Rosenberg
Original	Hou35	East	Houston	Brazoria	FM-2004: 0.1 mile past intersection with FM-523, several miles east of SH-288, north of City of Angleton
Original	Hou36	East	Houston	Waller	FM-1488: 0.1 mile past intersection with FM-1736, past US-290 and SH-6, near City of Hempstead
New	Hou37	East	Houston	Harris	IH-10: 0.1 mile past intersection with FM-526 near Exit 778
New	Hou38	East	Houston	Montgomery	IH-45: 25 feet past Exit 103 near FM-1375
New	Hou39	East	Houston	Fort Bend	SH-36: 0.5 miles past intersection with FM-442 near City of Needville
Original	Ldo01	South	Laredo	Kinney	US-90: 0.1 mile past intersection with FM-693, about 1-2 miles north of Brackettville
Original	Ldo02	South	Laredo	La Salle	IH-35: 0.1 mile past intersection with FM-469 (near Mile Marker 77)
New	Ldo03	South	Laredo	La Salle	IH-35: 0.1 mile past intersection with SR 44 near LA SALLE/WEBB COUNTY border
New	Ldo04	South	Laredo	Webb	IH-35: 0.1 mile past Mile Marker 25
New	Ldo05	South	Laredo	Kinney	US-90: 0.1 mile past intersection with FM-1572
New	Ldo06	South	Laredo	Val Verde	SH-163: 0.2 miles past intersection with US-90
New	Ldo07	South	Laredo	Dimmit	SH-85: 0.5 miles past intersection with FM-65 in Town of Brundage

Original	Lub01	West	Lubbock	Hockley	SH-114: 0.1 mile past intersection with FM-303 near Levelland
Original	Lub02	West	Lubbock	Lubbock	FM-179/Dowden Ave/Co Rd 1400: 0.1 mile past intersection with US-82/US-62/Brownfield Hwy, in City of Wolfforth
Original	Lub03	West	Lubbock	Terry	US-385: 0.1 mile past intersection with Ranch Road 2196
New	Lub04	West	Lubbock	Lubbock	IH-27: 0.1 mile past exit 14
New	Lub05	West	Lubbock	Swisher	IH-27: 0.1 mile past exit 77
New	Lub06	West	Lubbock	Castro	SH-194: 0.3 miles southeast of intersection with SH-86 (at Town of Dimmitt)
New	Lub07	West	Lubbock	Lynn	FM-1054: 0.4 miles past intersection with FM-213 near Town of Draw
New	Lub08	West	Lubbock	Floyd	FM-788: 0.3 miles east of intersection with FM-2301 about 6 miles east of IH-27/US-87 near Plainview
Original	Luf03	East	Lufkin	San Jacinto	US-59: 0.1 mile past LIBERTY COUNTY Line
Original	Luf04	East	Lufkin	Polk	SH-146: 0.1 mile past City of Livingston ETJ (Extra Territorial Jurisdiction)
Original	Luf06	East	Lufkin	Shelby	US-84: 0.1 mile past intersection with FM-1970 near Timpson
Original	Luf07	East	Lufkin	San Augustine	FM-2213: 0.1 mile past intersection with Texas Avenue south of City of San Augustine Line near US-96 and SH-147
New	Luf08	East	Lufkin	Nacogdoches	US-259: 0.1 mile past intersection with US-59 near Stephen F. Austin University
New	Luf09	East	Lufkin	Houston	US-287: 0.2 miles past intersection with FM-227
New	Luf10	East	Lufkin	Angelina	SH-63: 0.3 miles past intersection with SH-147
Original	Oda01	West	Odessa	Ector	IH-20: 0.1 mile past intersection with US-385
Original	Oda03	West	Odessa	Ward	SH-18: 5.0 miles north of intersection with Ranch Road -1219
Original	Oda04	West	Odessa	Pecos	US-285: 0.1 mile past intersection with FM-1776
New	Oda05	West	Odessa	Midland	IH-20: 0.1 mile past Exit 136
New	Oda06	West	Odessa	Ector	IH-20: 0.1 mile past Exit 101
New	Oda07	West	Odessa	Reeves	US-285: 0.4 miles past intersection with FM-1450
New	Oda08	West	Odessa	Martin	SH-176: 25 feet past intersection with SH-349
New	Oda09	West	Odessa	Pecos	SH-18: 0.3 miles past intersection with IH-10
New	Oda10	West	Odessa	Pecos	US-285: 0.1 mile past intersection with FM-1776
Original	Phr01	South	Pharr	Brooks	US-281: 0.1 mile past intersection with FM-3066 near Brooks County Airport
Original	Phr02	South	Pharr	Hidalgo	SH-107: 0.1 mile past intersection with FM-493
Original	Phr03	South	Pharr	Willacy	FM-1762/Co Rd 3401: 100 past intersection with US-77 about 2-3 miles north of E Hidalgo Ave in Raymondville
Original	Phr04	South	Pharr	Starr	US-83: 0.1 mile past intersection with North Blanca Road south of Rio Grande City
Original	Phr05	South	Pharr	Brooks	US-281: 0.1 mile past intersection with FM-1418
Original	Phr06	South	Pharr	Hidalgo	FM-490: 0.1 mile past intersection with FM-1425 several miles west of US-77
New	Phr07	South	Pharr	Brooks	US-281: 0.1 mile past intersection with FM-755, near Town of Rachal about 53 miles north of McAllen

New	Phr08	South	Pharr	Zapata	US-83: 0.1 miles past intersection with FM-2687 near Town of Lopeno
New	Phr09	South	Pharr	Cameron	US-83: 0.1 mile past Guadalupe Flores Road near Sullivan City, near Town of Lopeno
New	Phr10	South	Pharr	Willacy	SH-186: 0.5 miles past intersection with FM-1420
New	Phr11	South	Pharr	Brooks	FM-755: 0.5 miles past intersection with US-281
Original	Prs01	North	Paris	Lamar	US-82: 0.1 mile south of intersection with FM-38 traveling south
Original	Prs02	North	Paris	Lamar	SH-19: 0.1 mile north of the DELTA COUNTY Line traveling north
Original	Prs04	North	Paris	Hopkins	IH-30W: 0.1 mile east of intersection with SH-19 in Sulphur Springs city limit near Exit 122, traveling east
Original	Prs05	North	Paris	Red River	FM-114: 0.1 mile east of intersection with FM-44, past Town of Annona, near US-82 northwest of New Boston traveling east
New	Prs06	North	Paris	Hopkins	IH-30: 0.1 mile west of Exit 137 traveling east
New	Prs07	North	Paris	Red River	SH-37: 0.5 miles north of intersection with US-82 in Clarksville, about 41 miles north of IH-30 and Mt. Pleasant, traveling south
New	Prs08	North	Paris	Lamar	FM-195: 0.1 miles north of intersection with FM-2648 & FM-906 about 10 miles east of US-271, 10 miles south of SH-109, north of US-82, traveling north from Paris
Original	Sat02	South	San Antonio	Comal	IH-35: 0.1 mile past HAYS COUNTY Line
Original	Sat03	South	San Antonio	Bexar	SH-16: 0.1 mile past IH-410 Loop
Original	Sat05	South	San Antonio	Comal	FM-3009: 0.1 mile past intersection with FM-2252, about 2 miles north of I-35 about 10 miles east of US-281
Original	Sat06	South	San Antonio	Bexar	US-181: 0.1 mile past intersection with SH-122
Original	Sat07	South	San Antonio	Bexar	US-87: 0.1 mile past FM-1628 (Stuart Road), near IH-410 Loop
Original	Sat08	South	San Antonio	Bexar	IH-35: 0.1 mile past intersection with FM-Loop 1604, near BEXAR/ATASCOSA COUNTY Line
Original	Sat09	South	San Antonio	Bexar	IH-10/US-90: 0.1 mile past intersection with FM-1518, near FM-1604 in City of Adkins past San Antonio
Original	Sat10	South	San Antonio	Guadalupe	SH-123: 0.1 mile past HAYS COUNTY Line, past GUADALUPE COUNTY
Original	Sat11	South	San Antonio	Kerr	IH-10: 0.1 mile past Mile Marker 522 near KERR COUNTY Line
Original	Sat12	South	San Antonio	McMullen	SH-72: 0.1 mile past intersection with SH-16
Original	Sat13	South	San Antonio	Guadalupe	IH-10: 0.1 mile past intersection with FM-1104 near GUADALUPE COUNTY Line

Original	Sat14	South	San Antonio	Atascosa	IH-37: 0.1 mile past FM-1099 near Town of Campbellton
Original	Sat15	South	San Antonio	Frio	FM-140: 0.1 mile past FM-472, east of IH-35 east of City of Pearsall
New	Sat16	South	San Antonio	Frio	IH-35: 0.1 mile past Exit 111 near US-57
New	Sat17	South	San Antonio	Bexar	IH-410: 0.1 mile past Southton Road near Exit 42
New	Sat18	South	San Antonio	Frio	US-57: 0.5 miles past intersection with FM-140
Original	Sjt02	West	San Angelo	Tom Green	US-87: 0.1 mile past intersection with FM-2105 past City of San Angelo
Original	Sjt03	West	San Angelo	Irion	FM-853: 0.1 mile past intersection with US-67 about 5 miles west of IRION/TOM GREEN COUNTY Line
New	Sjt04	West	San Angelo	Crockett	IH-10: 0.1 mile past Exit 372
New	Sjt05	West	San Angelo	Irion	SH-163: 0.6 miles past intersection with US-67, past Town of Barnhart
Original	Tyl01	North	Tyler	Cherokee	FM-747: 0.5 miles south of intersection with US-79, traveling north toward Jacksonville, near US-175
Original	Tyl02	North	Tyler	Gregg	SH-300: 3.0 miles north of Spur 281 traveling north
Original	Tyl03	North	Tyler	Henderson	SH-19: 100 south of intersection with FM-2709 traveling about 7 miles north from Athens
Original	Tyl04	North	Tyler	Smith	US-69: 0.1 mile south of intersection with IH-20, about 10 miles north of Tyler, traveling south
Original	Tyl05	North	Tyler	Van Zandt	IH-20: 0.1 mile southeast of intersection with FM-1255, traveling southeast from Canton
Original	Tyl06	North	Tyler	Rusk	US-259: 0.1 mile south of intersection with FM-3310, about 3.5 miles south of US-79/US-259 intersection, traveling south from Henderson
New	Tyl07	North	Tyler	Van Zandt	US-80: 1.5 miles east of intersection with SH-19 about 13 miles north of City of Canton traveling east
New	Tyl08	North	Tyler	Cherokee	FM-241: 0.1 mile north of intersection with SH-21 traveling north toward Rusk, northwest of Nacogdoches
New	Tyl09	North	Tyler	Smith	FM-849: 0.2 miles north of intersection with IH-20 Exit 552 traveling north
New	Tyl10	North	Tyler	Smith	FM-850: 0.1 miles west of intersection with SH-31 near Headache Springs Natural Park traveling west
Original	Wac03	East	Waco	McLennan	US-84: 0.1 mile past intersection with SH-317 near MCLENNAN/CORYELL COUNTY Line
Original	Wac04	East	Waco	McLennan	SH-6: 0.1 mile past intersection with FM-185 near Waco Bridge
Original	Wac05	East	Waco	McLennan	IH-35: 0.1 mile past intersection with FM-308 (West Elm Mott Lane) near FM-3149
Original	Wac06	East	Waco	Bosque	FM-2490: 0.1 mile past intersection with RC Granger Rd/Co Rd 3650 near BOSQUE/MCLENNAN COUNTY Line about 20 miles west of IH-35/US-77
Original	Wac07	East	Waco	McLennan	IH-35: 0.1 mile past N Pecan Street past Town of Hillsboro, past intersection with US-

					77/Abbott Ave
Original	Wac08	East	Waco	Hamilton	SH-22: 0.1 mile past intersection with FM-1602 near Cranfills Gap
New	Wac09	East	Waco	Hill	IH-35: 0.1 mile past intersection with FM-1242 (Pine Street) near Exit 358 and City of Abbott
New	Wac10	East	Waco	McLennan	IH-35: 0.1 mile past intersection with FM-434 near Exit 335A
New	Wac11	East	Waco	Coryell	US-84: 0.3 miles past intersection with FM-116
New	Wac12	East	Waco	Bosque	SH-22: 0.5 miles past intersection with SH-6 and SH-124
Original	Wfs01	North	Wichita Falls	Cooke	IH-35/US-77: 0.1 mile south of intersection with FM-1306/Co Rd 218 near Exit 494 traveling south from Gainesville toward Denton
Original	Wfs02	North	Wichita Falls	Wichita	US-287/Old Iowa Park Rd: 750 feet west of intersection with FM-369, traveling west from Wichita Falls/IH-44 area toward Wichita Valley Airport
New	Wfs03	North	Wichita Falls	Wichita	IH-44: 3 miles north of intersection with US-287, just south of the Texas/Oklahoma border, traveling south
New	Wfs04	North	Wichita Falls	Archer	FM-368: 0.1 mile north of intersection with US-277/US-82, traveling south past City of Wichita Falls
Original	Ykm01	South	Yoakum	Jackson	US-59: 0.1 mile past intersection with FM-234
Original	Ykm02	South	Yoakum	Victoria	SH-185: 0.1 mile past intersection with US-59 southeast side of VICTORIA COUNTY
Original	Ykm03	South	Yoakum	Wharton	FM-102: 0.1 mile past intersection with US-59
Original	Ykm04	South	Yoakum	Austin	IH-10: 0.1 mile past intersection with SH-36
New	Ykm05	South	Yoakum	Fayette	IH-10: 0.1 mile past Mile Marker 670
New	Ykm06	South	Yoakum	Lavaca /Colorado	FM-155: 0.4 miles past intersection with US-90 Alt. near LAVACA/COLORADO COUNTY line
New	Ykm07	South	Yoakum	Victoria	FM-616: 0.1 mile past intersection with US-87 south past City of Victoria

2013 Texas Litter Survey

Company Background

ER Planning's senior staff led Keep America Beautiful's 2008 National Litter Survey, 13 citywide and statewide litter surveys along with other important litter-related projects. These include:

- Texas (2013)
- Toronto (2012)
- Oakland, CA (2011-12)
- San Francisco, CA (2011-12)
- Washington, D.C. (2011-12)
- Maine (2010)
- New Hampshire (2010)
- Vermont (2010)
- KAB National Litter Survey (2008)
- Litter: Literature Review (2007)
- Georgia (2007)
- Tennessee (2007)
- Santa Monica and Malibu (2005)
- New Jersey (2004)

The 2013 Texas Litter Survey was led by Steven Stein. The statistical aspects of this project were overseen by Dr. Ron Visco, who holds a Ph.D. in Research Design and Statistics. The field work planning was overseen by Kristian Ferguson. Emilie Knapp led the field survey on the ground. Each of these senior staff has worked on at least eight litter surveys.

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ER PLANNING

Attachment 5

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Attachment 6

Estimated Stormwater and Direct Pollution from Federal-Aid Highways in Texas							
	All Federal Aid Roads (including National Highway System)						
	(Miles)*	Runoff from 1 in of rain (gallons)	Acres**	Nitrogen (lbs/yr)	Phosphorous (lbs/yr)****	Sediment (tons/yr)*****	Zinc (lbs/yr)******
TxDOT District							
Abilene	8,439.82	333,348,403	12,276	171,865	18,782	3,806	15,959
Amarillo	9395.623	371,099,893	13,666	191,329	20,910	4,237	17,766
Atlanta	6,471.70	255,613,206	9,413	131,787	14,402	2,918	12,237
Austin	9,482.98	374,550,281	13,793	193,108	21,104	4,276	17,931
Beaumont	5,864.05	231,613,028	8,530	119,413	13,050	2,644	11,088
Brownwood	5,855.79	231,286,585	8,518	119,245	13,032	2,640	11,073
Bryan	7,179.37	283,564,477	10,443	146,198	15,977	3,237	13,576
Childress	5,473.38	216,182,616	7,961	111,458	12,181	2,468	10,350
Corpus Christi	7,179.65	283,575,181	10,443	146,204	15,978	3,237	13,576
Dallas	10,624.97	419,655,459	15,454	216,363	23,645	4,791	20,091
El Paso	4,917.21	194,215,394	7,152	100,132	10,943	2,217	9,298
Fort Worth	8,958.51	353,835,156	13,031	182,428	19,937	4,039	16,940
Houston	10,566.86	417,360,243	15,370	215,180	23,516	4,765	19,981
Laredo	5,180.90	204,630,424	7,536	105,502	11,530	2,336	9,797
Lubbock	12,132.18	479,185,967	17,647	247,055	27,000	5,471	22,941
Lufkin	6,532.53	258,016,131	9,502	133,026	14,538	2,946	12,352
Odessa	8,144.01	321,664,963	11,846	165,842	18,124	3,672	15,400
Paris	7,276.89	287,415,918	10,585	148,184	16,194	3,281	13,760
Pharr	6,408.12	253,102,059	9,321	130,493	14,261	2,889	12,117
San Angelo	7,332.89	289,627,875	10,666	149,324	16,319	3,306	13,866
San Antonio	11,036.77	435,920,327	16,053	224,749	24,562	4,977	20,870
Tyler	8,842.25	349,243,420	12,861	180,060	19,678	3,987	16,720
Waco	7,842.34	309,749,753	11,407	159,699	17,453	3,536	14,829
Wichita Falls	6,468.28	255,478,126	9,408	131,718	14,395	2,917	12,231
Yoakum	8,160.33	322,309,397	11,870	166,174	18,160	3,680	15,430

Total	195,767.38	7,732,244,284	284,753	3,986,536	435,671	88,273	370,178

*From the US Department of Transportation FHWA Highway Statistics 2006 (Lane miles used)

** Acres calculated using an average of a 12 foot wide highway lane.

Loading rates used are based on national averages computed by the Center for Watershed Protection

***Nitrogen loading rate: 14 lb/ac/yr.

****Phosphorous loading rate: 1.53 lb/ac/yr.

*****Sediment loading rate: 0.31 ton/ac/yr.

******Zinc loading rate: 1.3 lb/ac/yr.

prepared by Galveston Baykeeper based on American Rivers work for national roadways

Attachment 7

Technical Report

CRWR 264

AN EVALUATION OF THE FACTORS AFFECTING THE QUALITY OF HIGHWAY RUNOFF IN THE AUSTIN, TEXAS AREA

by

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September 1995

CENTER FOR RESEARCH IN WATER RESOURCES

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ACKNOWLEDGMENTS

This research was funded by the Texas Department of Transportation (TxDOT) and the Civil Engineering Department at the University of Texas at Austin through grant number 7-1943, "Water Quantity and Quality Impacts Assessment of Highway Runoff and Construction in the Austin, Texas Area."

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1.0 Conclusions and Recommendations

The Center for Research in Water Resources at The University of Texas at Austin has conducted a four-year investigation of the quality of storm water runoff from existing highway pavements in and near the recharge zone of the Barton Springs segment of the Edwards Aquifer. The two goals of this research project were to identify the variables that affect the build-up and wash-off of constituents from highways in the Austin, Texas area and to develop a water quality model that incorporates these variables. The research was funded by the Texas Department of Transportation and the Department of Civil Engineering at The University of Texas at Austin through grant number 7-1943, "Water Quantity and Quality Impacts Assessment of Highway Construction in the Austin, Texas Area."

Isolation of the variables that influence highway runoff quality is facilitated during "steady-state" storm conditions (e.g., a constant rate of constituent input from rainfall and traffic). A unique rainfall simulator was used to produce steady-state storm events during this research. The rainfall simulator provided a uniform rainfall over a 230-meter length of 3-lane highway during periods of active traffic. The entirety of the runoff drained to a single curb inlet where water quality samples were collected throughout the simulation. The length of highway exposed to the artificial rainfall allowed for collection of water that had washed from the bottoms of the moving vehicles. This project marked the first scientific use of a rainfall simulator in conjunction with active traffic.

Thirty-five rainfall simulations were conducted between July 6, 1993 and July 14, 1994. Additionally, 23 natural storm events were sampled at the same location between September 14, 1993 and April 28, 1994. Statistical analysis showed no significant difference between the runoff generated by the rainfall simulator and the natural runoff. The samples collected during simulated and natural storm events combined to provide 423 storm water runoff observations. Furthermore, 21 variables were identified for each storm event, and multiple regression analysis was used to determine the relationship of each variable to the quality of the highway runoff. The variables found to be statistically significant were retained for use in a constituent-specific regression model.

The majority of variations observed in highway storm water loading in the Austin area may be explained by causal variables measured during the rain storm event, the antecedent dry period, and the previous rain storm event. Significant causal variables during the rainfall event include the duration of the event (min), the volume of runoff per area of watershed (L/m^2), the intensity of the runoff per area of watershed ($L/m^2/min$), and the average volume of traffic per lane. The significant causal variables from the antecedent dry period include the duration of the dry period (hrs) and the average volume of traffic per lane during the dry period. The significant causal variables from the preceding storm event include the duration of the event (min), the volume of runoff per area of watershed (L/m^2) and the intensity of the runoff per area of watershed ($L/m^2/min$).

The identification of the causal variables that significantly influence constituent loading is among the more important findings of this study. There are two major applications of this knowledge. First, recognition of the specific variables that influence a given constituent load may suggest constituent-specific mitigation procedures, and second, the applicability of the model is directly reflected in the causal variables.

Because the dependent variable in the regression analysis is expressed as load (g/m^2), the total volume of flow during the storm event will appear in every constituent model. Similarly, the intensity of the runoff and the duration of the runoff also will frequently appear in the models. The variables flow, intensity, and storm duration, therefore, offer little diagnostic information in the interpretation of the model specification. However, the appearance of the other variables in the model, such as the number of vehicles during the storm, the duration of the antecedent dry period, and the volume of runoff during the previous storm event, are variables that "control" the constituent loading. The examination of the controlling variables in each model adds insight into the applicability of the model and the mitigation of constituent loading. A summary of selected water quality constituents and their relevant causal variables is presented in Table 1.1.

Table 1.1 Variables Affecting Pollutant Runoff Loads

	Storm Duration	Storm Volume	Storm Intensity	Vehicles During Storm	Length of Antecedent Dry Period	Antecedent Traffic Count	Previous Storm Duration	Previous Storm Volume	Previous Storm Intensity
Iron		*	*		*				
TSS		*	*		*				*
Zinc	*	*				*	*	*	*
COD	*	*	*		*	*			
Phosphorus	*	*	*			*			
Nitrate		*	*			*			
BOD_5		*	*	*		*			
Lead		*	*	*					*
Copper	*	*		*					
Oil and Grease		*		*					

As an example, 93% of the variation observed in the storm water loadings of total suspended solids (TSS) is explained by the total volume of storm water runoff (L/m^2), intensity of the runoff ($L/m^2/min$), total duration of the antecedent dry period (hrs), and the intensity of the runoff during the previous storm event ($L/m^2/min$). This model formulation suggests that the conditions during the antecedent dry period (e.g., dustfall, pavement/right-of-way maintenance activities, etc.) and the intensity of the preceding storm event (e.g., the thoroughness of the previous wash-off) have a greater influence on TSS storm water loadings than any of the other variables examined, including the traffic volume during the storm event. Efforts to mitigate the storm water loading of TSS should therefore be directed at activities during the antecedent dry period that deposit dirt and debris on the highway surface. Consequently, street sweeping was found to be effective at reducing TSS loads. Street sweeping on a once every two-week schedule, as compared to no street sweeping, significantly reduced the average loads of TSS observed in the highway storm water runoff. However, no other constituent showed a significant change in loading during the street sweeping period.

Highway runoff constituents, in general, fall into one of three categories: (1) those constituents, such as TSS, which are influenced by conditions during the dry period and may be mitigated by dry period activities such as street sweeping and others; (2) those constituents that are most influenced by conditions during the rainfall event and may only be mitigated through the use of runoff controls; and (3) those constituents that are influenced equally by both periods. The constituents that are significantly affected by conditions during the preceding storm event generally are those constituents that are controlled by the dry period variables.

The variables found to significantly affect the other highway runoff constituents are detailed below:

- **Nutrients:** The total duration of the storm event (min), total volume of storm water runoff (L/m^2), intensity of the runoff (L/m^2/min), and the total volume of traffic during the antecedent dry period (a measure of the length of the dry period) combine to explain 95% of the variation in nitrate load, and 90% of the variation in total phosphorus load, observed in the highway runoff. This regression formulation is strongly influenced by the quantity of these nutrients contained in the rainfall. The concentrations of nutrients observed in rainfall accounted for 50% to 100% of the nitrate load, and up to 22% of the total phosphorus load observed in the highway runoff. The mitigation of nutrients in highway runoff requires the use of runoff controls.

- **Organics:** The total duration of the storm event (min), total volume of storm water runoff (L/m^2), runoff intensity (L/m^2/min), total volume of traffic during the storm, and the total volume of traffic during the antecedent dry period combine to explain 86% of the biochemical oxygen demand (BOD_5) load, 95% of the chemical oxygen demand (COD) load, 94% of the total carbon load, and 91% of the dissolved total carbon load observed in the highway runoff. The mitigation of organics must be accomplished with runoff controls.

- **Oil and Grease**: The total volume of storm water runoff (L/m^2) and the total volume of traffic during the storm combine to explain 94% of the variation in the oil and grease loads observed in the highway runoff. The mitigation of oil and grease must be accomplished with runoff controls.

- **Copper:** The total duration of the storm event (min), total volume of storm water runoff (L/m^2), and total volume of vehicles during the storm combine to explain 90% of the variation in the copper load observed in the highway runoff. The mitigation of copper must be accomplished with runoff controls.

- **Lead:** The total volume of storm water runoff (L/m^2), runoff intensity (L/m^2/min), total volume of vehicles during the storm, and the intensity of the previous storm runoff (L/m^2/min) combine to explain 68% of the variation in the lead load observed in the highway runoff. The mitigation of lead must be accomplished with runoff controls.

- **Iron:** The total volume of storm water runoff (L/m^2), runoff intensity (L/m^2/min) and the total duration of the antecedent dry period (hrs) combine to explain 92% of the variation in the iron load observed in the highway runoff. The mitigation of iron must be accomplished with dry period practices.

- **Zinc:** The total duration of the storm event (min), total volume of storm water runoff (L/m^2), volume of vehicles during the antecedent dry period, total duration of the previous storm (min), and the total volume of storm water runoff in the previous storm (L/m^2) combine to explain 92% of the variation in the zinc load observed in the highway runoff. The mitigation of zinc must be accomplished with both runoff controls and dry period practices.

Although traffic volume during the storm does not appear as a "significant" variable in every model formulation, it is nevertheless an influential factor in all constituent loading. The storm water constituent wash-off patterns for high speed highway pavements were found to be different during periods when traffic is on the highway than during periods when there is no traffic. The runoff from pavements with high speed traffic does not exhibit as pronounced a "first flush" of constituent mass as the runoff of pavements without traffic. The continuous input of material from traffic insures a continual increase in the cumulative constituent load throughout the duration of the storm event. As a result, highway watersheds that contain large shoulder areas or other non-traffic bearing surfaces (e.g., > 35% of the total watershed) can be expected to produce less constituent loading per unit of surface area than other highway pavements.

2.0 Introduction

2.1 Research Area

The State of Texas, through the Texas Natural Resource Conservation Commission (TNRCC), regulates all activities that have the potential to cause pollution in the Edwards Aquifer (Chapter 313 entitled "Edwards Aquifer," Subchapter B, §313.27). This rule applies to any activity that alters or disturbs surface water quality and quantity characteristics within the recharge zone of the aquifer. The construction of highways, railroads, utility services, and residential/commercial developments are all regulated activities under Chapter 313. Consequently, the Texas Department of Transportation (TxDOT) is charged with the responsibility for the control of storm water runoff from highway construction sites and from existing highways located inside the Edwards Aquifer recharge zone. Exercising this responsibility has had a profound impact on the design and construction of area highways. During fiscal year 1993, the Austin District of TxDOT spent more than $10 million on the installation and construction of temporary and permanent runoff control facilities. The cost of storm water control now accounts for as much as 20% of the overall cost of highway construction in the Edwards Aquifer recharge zone. This financial burden has placed a new importance on understanding the role of the urban highway as a non-point source of water pollution in the Austin area.

2.2 Research Objective

Controlling the cost of storm water management along highways in the Edwards Aquifer recharge zone is a major concern of TxDOT. Cost-effective and efficient management practices to mitigate the transport of harmful constituents to the aquifer are dictated by fiscal and environmental concerns. The environmental concerns in the Edwards Aquifer, in conjunction with the high cost of complying with a pollution prevention policy whose goals are not easily understood, have motivated TxDOT to undertake an extensive investigation of the water quality aspects of storm water runoff from highways in or near the Barton Springs segment of the Edwards Aquifer recharge zone. Identification of the variables that determine constituent loads in highway runoff is the first step in determining the most cost-effective mitigation methods. Development of predictive models will further assist cost-effective analyses of highway storm water management practices in the Edwards Aquifer recharge zone.

The objectives of this research are:

- the determination of the variables that affect the build-up and wash-off of constituents from highways in the Austin, TX area,
- the development of a predictive model that incorporates the variables that affect runoff quality.

The methodology of model development is the subject of this report. The underlying theory of the build-up and wash-off of materials from highway surfaces is presented in this chapter. The rationale for data collection and the manner in which data were collected is discussed in Chapter 3. A summary of the data is presented in Chapter 4. The formulation of the model is detailed in Chapter 5; the results of the model presented are given in Chapter 6. Appendices provide supporting data and documentation.

2.3 Highway Runoff Constituents

The bulk of the material on urban roadways consists of inert minerals such as quartz, feldspar, etc. (Sartor and Boyd, 1972). The quantities of these particles correlate well with the average daily traffic count (Hvitved-Jacobson and Yousef, 1991), although atmospheric dustfall also may be a major source (Gupta et al., 1981). Stormwater runoff that carries solids from highway surfaces is undesirable for several reasons:

1. High sediment loads increase the probability of transporting nutrients, pesticides, organic constituents, and microbial forms that may be attached to the particles (Svensson, 1987; Wagner and Mitchell, 1987; Sartor and Boyd, 1972).
2. The deposition of solids can clog recharge features and restrict the flow of water into the aquifer (Guadalupe-Blanco River Authority, 1988)
3. The Edwards Aquifer contains a number of invertebrates and at least one vertebrate. The build-up of silt in submerged caverns may interfere with organism metabolism (Guadalupe-Blanco River Authority, 1988).

Several classifications of solids have been observed for highway runoff. The total solids (TS) content of a sample is defined as the amount of material remaining after evaporation of the water or a steam bath followed by drying the sample to a constant weight at 103° - 105°C. Total suspended solids (TSS) is the fraction of total solids that is retained on a filter with a pore size of about 1.2 micrometers (μm). Volatile suspended solids (VSS) consists of the organic fraction of TSS. Highway runoff studies typically report values for both TSS and VSS.

Organic material is the next most common constituent in highway runoff. Biodegradable organics may stimulate the growth of bacteria in receiving watercourses. In the worse case, the oxygen consumed during the biochemical oxidation of organic matter can deplete the dissolved oxygen in the receiving stream to the point of causing septic conditions and destroying populations of fish and other aquatic species that require dissolved oxygen.

The organic content of runoff may be expressed as BOD, COD, and total organic carbon (TOC). The BOD analysis is a bioassay procedure that provides suitable living conditions for bacteria to function in an unhindered fashion (i.e., all necessary nutrients for bacteria growth must be present and there must be an absence of toxic substances). The test is a direct measure of the oxygen consumed by bacteria during the oxidation of organic matter in a measured time period. Five days is the typical test period, and the results are denoted as BOD_5. Durations of up to 20 days, however, are also employed.

The COD analysis measures the ability of organic material to be reduced by a strong oxidizing agent (potassium dichromate) at an elevated temperature. Organic matter is oxidized during the test regardless of the biological assimilability of the substances. COD values are therefore greater than BOD_5 values for most compounds. The COD may be much greater when the organic matter is resistant to biological degradation.

The TOC is the total amount of organic carbon in the runoff. Carbon in runoff is oxidized to carbon dioxide with a catalyst and oxygen as the carrier gas; carbon dioxide is then measured using an infrared analyzer. The TOC analysis is rapid and is applicable to low concentrations of organic matter.

The dissolved oxygen content in natural surface waters also is affected by the input of nutrients to the water body. Nitrogen and phosphorus are the primary nutrients observed in highway runoff that can stimulate algal blooms in receiving waters. The sources of nutrients typically include atmospheric deposition and the application of roadside fertilizers (Hvitved-Jacobson and Yousef, 1991). The concentration of nitrogen and phosphorus in highway runoff is a concern for two reasons; (1) these compounds stimulate the growth of aquatic plants in surface waters and (2) excessive nitrates (NO_3) in drinking water can cause methemoglobinemia in infants.

The enrichment of a surface water with nutrients, or eutrophication, is a natural aging process that results in the increased growth of planktonic and rooted aquatic plants. During the daylight hours, aquatic plants convert inorganic nutrients and CO_2 into organic plant material through the process of photosynthesis. The process will continue as long as nutrients are available to maintain plant growth. The dissolved oxygen (DO) produced during photosynthesis is generally beneficial to the surface water ecosystem, but an over-abundance of plant growth can result in severe DO problems. Excess vegetation, in the most extreme cases, can produce exaggerated diurnal variations in dissolved oxygen that results in supersaturated levels of DO during daylight hours and extremely low levels of DO as the plants respire at night. An additional oxygen demand is exerted as the plant matter dies and decays. Excessive aquatic plant growth also may be aesthetically objectionable and can interfere with the biological, recreational, and navigational use of the water.

Phosphorus is not known to be harmful outside of stimulating plant growth. The control of phosphorus, however, may be important in areas where natural surface waters contain low concentrations of phosphorus relative to the nitrogen concentration. Both phosphorus and nitrogen are required to sustain maximum growth of aquatic plants and the nutrient that is in short supply therefore limits the growth aquatic plants. If phosphorus is the "limiting" nutrient in the receiving stream, additional discharges of phosphorus may promote new plant growth.

Nitrogen compounds can cause problems other than aquatic plant growth. Un-ionized ammonia is toxic to several species of young freshwater fish (USEPA, 1981), but the greater concern is the contamination of drinking water sources with nitrates.

Excessive nitrates in drinking water can cause methemoglobinemia in very young infants. Nitrates have a negative charge (NO_3) and, therefore, are not attracted to soils, which also have negative charges. It is for this reason that nitrogen in the form of nitrate usually reaches the ground water, where it is very mobile due to its solubility and anionic form.

Metals are the most common toxicants found in highway runoff. The sources of metals in highway runoff include vehicles, atmospheric deposition, naturally occurring metals in soils, and highway-related sources such as paint and corrosion products (Gupta et al., 1981; Yousef et al., 1886). The two major concerns with trace metals are: (1) these elements may move through soils and enter ground water and (2) metals can accumulate in the food chain. It should be noted that metals are not necessarily toxic; however, unless the concentration causes toxicity (e.g., metals at low concentrations are essential to the human diet).

The most common metals found in highway runoff are copper, iron, lead, and zinc (Sartor and Boyd, 1972; Gupta et al., 1981; USEPA, 1983; Driscoll et al., 1990). Chromium, which is found in small concentrations, is most likely in the reduced form of the chromate ion (Cr^{3+}), which is much less toxic than the highly oxidized form (Cr^{6+}) found in plating shop wastes (Driscoll et al., 1990). Arsenic, cadmium, mercury, and nickel are found in relatively insignificant amounts (Sartor and Boyd, 1972; Gupta et al., 1981). Iron is not known to be harmful; however, the iron concentrations normally observed in highway runoff are higher than those reported in natural water systems (Driscoll et al., 1990).

Pathogenic organisms that potentially are responsible for waterborne diseases such as typhoid and paratyphoid fever, dysentery, diarrhea, and cholera, have been observed in highway runoff (Sartor and Boyd, 1972; Gupta et. al., 1981). The Barton Springs segment of the Edwards Aquifer is potentially sensitive to the presence of pathogenic organisms. The aquifer is used as a drinking water source, and Barton Creek is used by the public for swimming and boating.

It is difficult to identify specific pathogenic organisms in a water sample. The number of pathogens in a normal sample usually is very small and it is difficult to isolate the pathogens from the other bacteria in the sample. Water quality samples are analyzed for "indicator organisms" that signify the potential presence of pathogens. Total coliform

(TC), fecal coliform (FC), and fecal streptococci (FS) are indicators used in bacteriological analyses of water. Fecal coliforms and fecal streptococci are bacteria found in the digestive tract of warm-blooded animals. The presence of fecal coliforms and fecal streptococci may be an indication of pathogenic organisms. Additionally, the ratio of fecal coliforms to fecal streptococci may be used to determine the origin of the contamination. Domestic animals have a FC/FS ratio that is less than 1.0, whereas the ratio for humans is typically greater than 4.0 (Metcalf & Eddy, Inc., 1991). A total coliform count includes both the fecal coliforms and the coliforms found in soils.

Coliforms generally die off quite rapidly in receiving waters (Sartor and Boyd, 1972). Bacteria also are removed from runoff streams by filtration, adsorption, desiccation, radiation (sunlight), predation by other bacteria, and exposure to other adverse conditions (USEPA, 1981). Therefore, any relationship between the number of coliforms on the highway surface and the number that may be found in adjacent receiving streams is difficult at best.

Other parameters and constituents of concern in highway runoff include pH, temperature, total dissolved solids, oil and grease, and pesticides and herbicides. Values of pH reported by Driscoll et al. (1990) ranged from 5.5 to 7.5, with an average of 6.5. Discharges within this pH range are not known to cause water quality problems. Temperature is of concern only if runoff volumes are large enough to severely alter the temperature of the receiving stream. Total dissolved solids (TDS) may be a concern if the highway runoff results in an increase in the salinity of the receiving water. TDS could be a concern during snow melt in areas where highways are heavily salted to aid in ice removal.

Oil and grease concentrations reported by Driscoll et al. (1990) ranged from 5 mg/L to 10 mg/L. There is no evidence that oil and grease at these concentrations are harmful to human health and the environment.

Pesticides (chlorinated hydrocarbons) were found in significant quantities in street runoff by Sartor and Boyd (1972). However, this class of constituents was not addressed in this study.

The median constituent concentrations observed in highway runoff are summarized in Tables 2.3.1 and 2.3.2.

2.4 Highway Runoff Constituent Build-Up Mechanisms

Highway runoff characterization studies have been conducted in the United States for over 30 years. A massive amount of data relating to the quality of runoff from urban pavements has been generated. An evaluation of the available literature suggests that the sources of constituents in highway runoff can be categorized as: (1) vehicular contributions, (2) atmospheric deposition, and (3) the road bed material. The relationship of each source to the quality of the storm water runoff is very complex and not well understood.

Table 2.3.1 Reported Median Constituent Concentrations in Urban Runoff

Constituent	Median Concentration
pH	5.5 - 7.5 [(a)]
TSS	142 mg/L (0.62) [(a)]
VSS	39 mg/L (0.58) [(a)]
BOD_5	5 mg/L - 25 mg/L [(a)]
COD	114 mg/L (0.58) [(a)]
Total Carbon	25 mg/L (0.62) [(a)]
Kjeldahl Nitrogen	1.83 mg/L (0.45) [(a)]
$NO_2 + NO_3^-$	0.76 mg/L (0.56) [(a)]
PO_4 - P	0.40 mg/L (0.89) [(a)]
Total Coliform	260/100ml - 180,000/100ml [(b)]
Fecal Coliform	20/100ml - 1,900/100ml [(b)]
Fecal Streptococci	940/100ml - 27,000/100ml [(b)]
Oil & Grease	5 mg/L - 10 mg/L [(a)]

Number in parenthesis is the reported coefficient of variation
(a) - Driscoll et al. (1990); (b) - Gupta et al. (1981)

Table 2.3.2 Metals in Highway Runoff

Metal	Concentration in Highway Runoff (μγ/Λ)	% Dissolved	Drinking Water Standard (μγ/Λ)
Cadmium	1 - 30 [c]	72% [e]	10 [a]
Chromium	15 - 35 [c]	65% [e]	(Cr6+) 50 [a]
Copper	54 (0.68) [c]	70% [e]	1,000 [b]
Iron	3,000 - 12,000 [c]	27% [e]	300 [b]
Lead	400 (1.46) [c]	21% [e]	50 [a]
Mercury	0.001 - 1.5 [c]	Not Reported	2 [a]
Nickel	150 [d]	76% [e]	Not Established
Zinc	329(0.44) [c]	57% [e]	5,000 [b]

Number in parenthesis is the reported coefficient of variation
(a) USEPA Primary Drinking Water Standards
(b) USEPA Secondary Drinking Water Standards
(c) Driscoll et al. (1990). A single value represents the site median EMC for all urban highway sites.
(d) Gupta et al. (1981)
(e) Yousef et al. (1986)

The source of the constituents in highway runoff is influenced by environmental conditions that are often difficult, if not impossible, to measure. Some of the constituents can be traced to more than one source, in which case it is often difficult to distinguish the dominant source. The build-up process of constituents in highway runoff is further complicated by a continuous and complex removal process. During dry weather, materials are continually blown on and off the highway, as well as on and off of vehicles by natural and vehicle induced winds. During wet weather, storm water washes constituents from both the highway surface and the vehicles. Although physical transport is thought to be the primary method of constituent removal, there is certainly some chemical or biological removal that occurs on the highway surface (i.e., volatilization, chemical decay, biodegradation, etc.).

Highway constituent loads are thought to be closely related to the average daily traffic (ADT) count of the highway. Sartor and Boyd (1972) identified the following list of vehicle contributions:

1) Leakage of fuel, lubricants, hydraulic fluids, and coolants;
2) Fine particles worn off of tires and clutch and brake linings;
3) Particulate exhaust emissions;

4) Dirt, rust, and decomposing coatings that drop off of fender linings and undercarriages;

5) Vehicle components broken by vibration or impact (glass, plastic, metals, etc.).

ADT is a measure of highway usage. The high ADT highways, such as urban expressways, typically produce higher constituent concentrations than the low ADT highways that are normally located in rural areas. Driscoll et al. (1990) found a statistically significant difference in the constituent concentrations at sites with an ADT greater than 30,000 and those with an ADT less than 30,000. However, it is difficult to segregate the influence of traffic from that of the surrounding land use since lighter traffic sites tend to be more rural than heavier traffic sites. A lack of a clear correlation with ADT within each group led Driscoll et al. (1990) to the conclusion that surrounding land use is a more important influence than traffic. Stotz (1987) and Mar et al. (1982) also reached the same conclusion.

ADT should not be confused with the number of vehicles that use the highway between storms, which for most highway traffic patterns is indistinguishable from the duration of the antecedent dry period (ADP) of a storm. Although not a true "source," the ADP is a commonly cited variable thought to affect runoff quality (Sartor and Boyd, 1972; Moe et al., 1978; Howell, 1978; Kent et al., 1982; Lord, 1987; Hewitt and Rashed, 1992). The ADP provides the opportunity for material to accumulate on the highway surface. The pattern of constituent build-up during the ADP is an important relationship used in many highway runoff models. Although linear build-up patterns have been observed (Moe et al., 1978), it is obvious that accumulations are limited by some upper bound. Sartor and Boyd (1972) and Pitt (1979) observed non-linear build-up patterns that approached asymptotic values.

Ordinary least squares (OLS) regression analysis is often used to identify the factors that influence constituent accumulation during the ADP. Correlation coefficient values for curves fit to the duration of the ADP are typically less than 0.30 (Sartor and Boyd, 1972; Driscoll et al., 1990), which suggests that there are additional parameters that influence material accumulation other than the duration of the ADP. The poor correlations may also reflect the difficulty involved in accurately measuring the amount of material that has accumulated on the highway surface during the ADP. Since the ADP build-up washes off early in the rainfall event (during that time both vehicles and rainfall are contributing materials to the runoff), it is difficult to measure the dry period build-up during a natural rainfall event. Sartor and Boyd (1972) attempted to remedy this problem by using a rainfall simulator to wash the highway surface during a period of no traffic. The use of the simulator allowed the collection of runoff samples under ideally controlled conditions, which should have minimized the sampling error.

Some researchers (Horner et. al., 1979; Kerri et. al., 1985; Harrison and Wilson, 1985) have reported a weak correlation with ADP, which suggests that a net accumulation of material need not occur during a dry period. Constituents are continually being removed from the highway surface during the ADP. Natural and vehicle-induced winds have been observed to blow materials off the highway during dry weather. Constituents may also be removed during the ADP by volatilization, biodegradation, and chemical decay. Kerri et al. (1985) concluded that there is no statistical significance between the constituent load of a storm and the duration of the ADP of a storm. This finding was attributed to the traffic-generated winds that continually sweep the surface of the highway and the pick-up of materials by tires. Their study established a better correlation with the number of vehicles *during* the storm (VDS). It was suggested that constituents are more likely to be washed from vehicles during a storm than blown from vehicles during dry weather. Harrison and Wilson (1985) and Horner et al. (1979) also found a weak correlation between the duration of the ADP and constituent concentration in the storm runoff.

VDS is the total count of vehicles that actually travel the highway section during the rain storm. A related parameter, vehicle intensity during the storm (VIDS), is a density measure reported as number of vehicles per unit time or unit of discharge. Driscoll et al. (1990) suggests that neither VDS nor VIDS should be estimated from ADT counts. Traffic counts recorded on a 1 hour interval or less should be matched as close as possible to the duration of the runoff event.

The relationship between VDS and water quality suggest that vehicles are the major source of runoff constituents during a storm event, whereas VIDS may account for less obvious vehicle contributions. Both tires and undercarriage winds apply substantial energy to the surface of the road. These forces may dissolve or suspend many of the constituents that have accumulated on the highway. Particulates in exhaust emissions are "scrubbed" from the air during a rain storm, adding constituents to the runoff that otherwise may have drifted from the highway (Gupta et al., 1981). Both of these phenomena are better represented with a density measure.

Regression analysis that uses VDS or VIDS as the single explanatory variable would be expected to fail for the same reasons as with ADP, described above. But many researchers have found a correlation between VDS and contaminate loading (Chui et al., 1981; Chui et al., 1982; Asplund et al., 1982; Horner and Mar, 1983). Vehicular traffic may dominate other sources under certain storm duration or intensity situations. Therefore, the concentrations of constituents would be expected to reach a "steady state" during a lengthy storm event with steady traffic flow. Gupta et al. (1981), however, observed decreasing concentrations of constituents after over two hours of rainfall. The average vehicle speed and vehicle mix (i.e., the distribution of cars, buses, tractor trailers, etc.) also would be expected to have an influence on runoff quality, but these parameters have not been widely studied.

Atmospheric fallout can contribute a considerable amount of constituents to the highway. Gupta et al. (1981) reported that typical dustfall loads in U.S. cities range from 2,600 to 26,000 kg/km^2-month. Solids, nutrients, metals, and biodegradable organics also may be contributed by atmospheric fallout (Sartor and Boyd, 1972; Gupta et al., 1981). The type and amount of constituents that collect on highways are influenced by the surrounding land use. Driscoll et al. (1990) concluded that surrounding land use is the most important factor that influences constituent loads in highway runoff. In general, the constituent loading in industrial areas is substantially higher than residential or commercial areas (Sartor and Boyd, 1972; Gupta et al., 1981; Driscoll et al., 1990).

The characteristics of the highway surface also may influence runoff quality. Such characteristics include the materials of construction, curbs and gutters, guard walls, age, configuration, and drainage features. There is little evidence to suggest that asphalt highways produce more or less constituents than concrete pavements. The age and condition of the pavement seems to be a more dominant factor than the material of construction (Sartor and Boyd, 1972; Driscoll et al., 1990). An older highway, or one in need of repair, can be expected to release a larger amount of aggregates regardless of the base material. The presence of guard walls, curbs, and gutters tend to trap constituents that otherwise would be blown from the highway during dry periods (Wiland and Malina, 1976; Gupta et al., 1981; Driscoll et al., 1990).

2.5 Constituent Removal Mechanisms

Material is continually being removed from the highway surface by natural and vehicle-induced winds that constantly "sweep" the highway surface (Aye, 1979; Asplund, et al., 1980). This phenomenon clearly is demonstrated on curbed highways by the build-up of dirt and debris along the gutter and shoulder and the noticeable lack of material in the traffic lanes. Stormwater runoff also has been observed to deposit material along the curb. Therefore, it is not surprising that the majority of material on the highway surface is found within 3 feet of the curb (Sartor and Boyd, 1972; Laxen and Harrison, 1977).

Street sweeping is a commonly used municipal practice for the control of dirt, debris, litter, etc. along urban streets and highways. A regular schedule of street sweeping not only has the potential for reducing storm water constituent loads, but also has the additional benefits of improving air quality, aesthetic conditions, and public safety (Pitt, 1979). Unfortunately, street sweeping is not very effective in reducing the organic, nutrient, and metal loading in storm waterss because the largest percentage of these constituents is associated with materials less than 48 microns in size (Sartor and Boyd, 1972; Pitt, 1979; Gupta et al., 1981; USEPA, 1983). Modern street sweeping equipment is not a very effective collector of material this small.

Constituents are removed via storm water wash during rainfall events. The extent of constituent removal during a runoff event depends primarily on runoff volume, which is a function of rainfall intensity and duration. A positive correlation between rainfall intensity and highway runoff volume is expected and well documented (Driscoll et al., 1990). It is also reasonable to expect that a higher intensity rain storm would wash more constituents from the highway surface, in less time, than a smaller storm. Therefore, it is generally accepted that constituent loading (i.e., mass of constituent removed from highway per unit time and/or area) is positively correlated with rainfall intensity (USEPA, 1983). This correlation is important because the ultimate constituent concentration in a receiving stream is determined by the constituent mass loading to that stream.

It would seem logical that the large amounts of water produced by high-intensity storms would dilute the finite amount of material present on the highway. However, intuition fails with respect to constituent concentrations within the storm event. Research has shown that constituent concentrations (i.e., mass of constituent per unit volume of runoff) are not only variable within a particular storm, but also from one storm to the next. Varying rainfall patterns result in runoff flows that vary considerably within the storm events. The work of Harrison and Wilson (1985) and Hoffmann et al. (1985) show that constituent concentrations generally follow the same trend as rainfall intensity during long-duration, light-intensity storms (i.e., storm duration to 8 hours with peak intensities less than 8 mm/hr). The National Urban Runoff Program (NURP) data analysis (USEPA, 1983) considered over 300 samples and found no correlation between concentration and storm volume or intensity. The NURP analysis is supported by over 250 samples collected during a Federal Highway Administration study (Shelley and Gaboury, 1986) and by the work of Driscoll et al. (1990).

There is also substantial evidence to suggest that a period of high concentration typically occurs early in the runoff event (Howell, 1978; Horner et al., 1979) This period is known as the "first flush" and has lead to the speculation that the majority of constituents are removed early in the event. It should be noted that some literature refers to "first flush" in terms of constituent loading, whereas others define "first flush" in terms of concentration.

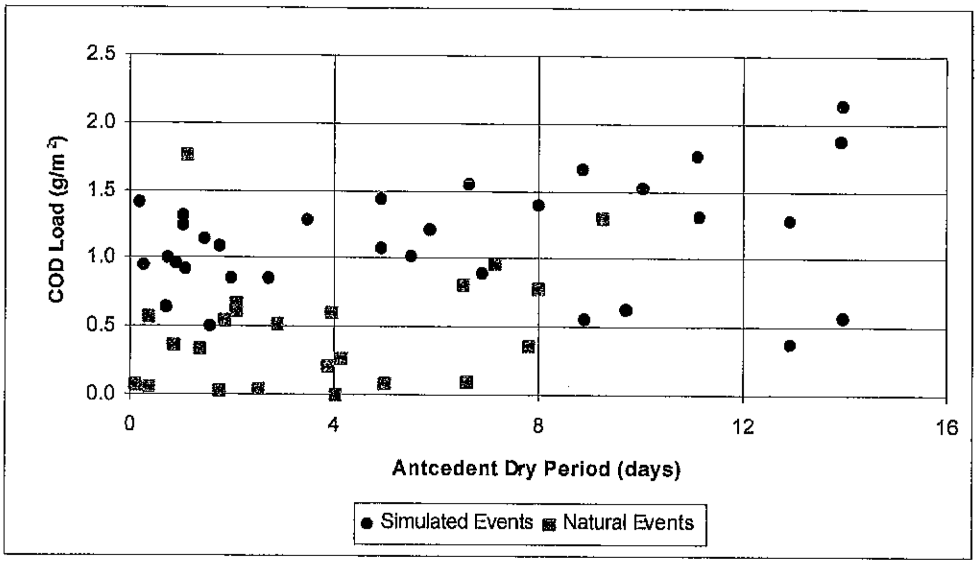
The phenomenon of "first flush" was first demonstrated by Sartor and Boyd (1972) with the use of a rainfall simulator. The magnitude of the "first flush" was a function of rainfall intensity and the particle size of the constituent. Others have shown that dissolved constituents and the constituents associated with the smaller solids are more likely to show a "first flush" pattern (McKenzie and Irwin, 1983; Harrison and Wilson, 1985; Hewitt and Rashed, 1992).

Although the period of "first flush" is easily recognized by looking at a constituent loadograph (i.e., a plot of load vs. time), few researchers have attempted to define the boundaries, either time or magnitude, that constitute "first flush." This ambiguity has lead to disagreement among the designers of water quality control structures regarding the volume of runoff that should be captured to meet a desired treatment level. The City of Austin has defined the "first flush concentration" as the mean concentration of a constituent in the first 0 to 3 mm of runoff. This concentration is generally found to be higher than the event mean concentration (Chang et al., 1990). It has also been shown in Austin that a water quality control structure that collects the first 13 millimeters of runoff will effectively capture 73% - 100% of the total annual load, depending on the degree of watershed imperviousness (Chang et al., 1990). However, the "13 millimeter rule" is highly site specific and dependent on the characteristics of the local annual rainfall.

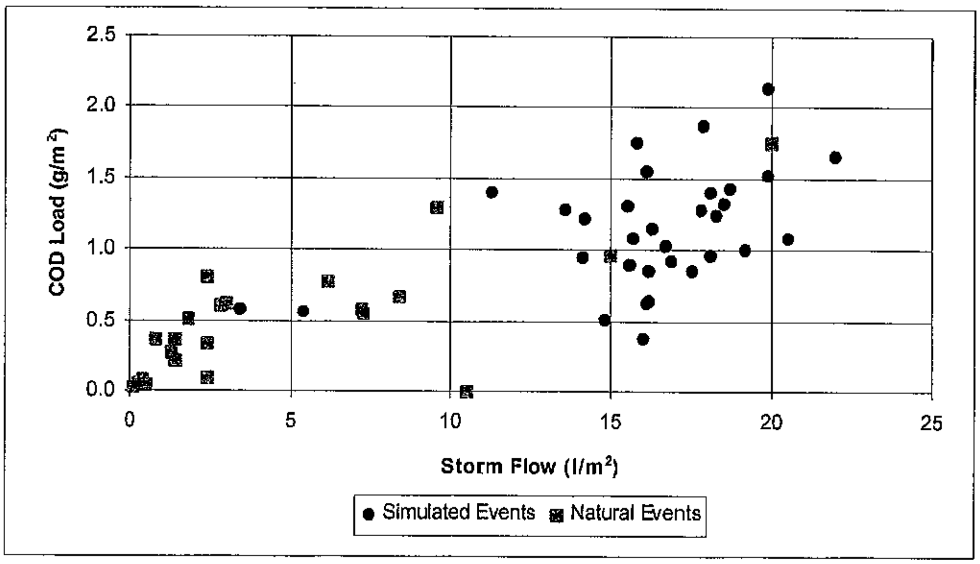
2.6 Highway Constituent Discharge Theory

Analysis of the preceding literature review indicates the complexity of the constituent build-up process on the highway surface. During the dry period between storm events, material is continually being deposited onto the highway surface by vehicles and through atmospheric deposition. At the same time, many substances are removed from the road by natural and vehicle-induced winds, volatilization, biodegradation, and chemical decay. The complexity of constituent build-up on highway surfaces is illustrated in Figure 2.6.1a, using data collected during this research

Wash-off of accumulated substances, shown in Figure 2.6.1b, is more predictable than build-up. The materials accumulated during the dry period are removed early in the storm during the "first flush." Traffic and rainfall continue to introduce new substances throughout the storm. Rainfall may also "scrub" vehicle exhaust and other sources



(a) Observed COD Build-Up



(b) Observed COD Wash-Off

Figure 2.6.1

associated with the highway environment. The commonly observed correlation between total storm runoff and constituent load is a result of the continual input of material throughout the storm and, of course, the inclusion of flow in the load calculation.

All rainfall events do not result in a net removal of constituents from the highway surface. Many storm events produce light rainfall (i.e., less than 0.25 mm in 15 min) that will produce little or no runoff; however, enough moisture is available to wash the bottoms of vehicles. Storm events of this magnitude, many lasting 6 hours or longer, frequently occur in the Austin area. Furthermore, storms are followed by a time of no rainfall during that vehicle bottoms continue to be washed but the runoff is insufficient to remove any material. Therefore, most naturally occurring storm events are not capable of completely removing all material from the surface of busy highways.

Constituent loads vary between storm events because each individual storm event is different. However, even if two storms were perfectly alike, the pollutant loads would differ. The fact that the two storms occurred at different times would cause the storms to be different. An endless number of differences between storm events is possible; however, only a few variables actually affect the quality of the runoff. The major variables that affect the constituent loading are the total volume of runoff, the average intensity of the runoff, the length of antecedent dry period, and the number of vehicles traveling through the storm. Ideally, holding these variables constant between storms should result in similar loads.

The total constituent load (or mass), M, produced during a storm event, is the product of the flow-weighted mean concentration of the constituent, $\bar{c}$, and the total volume of runoff, V, given as:

$$M = \bar{c}V = \int c(t)Q(t)dt \qquad (2.6.1)$$

where c is the instantaneous concentration and Q is the volumetric rate of runoff. Furthermore, the total volume of runoff, V, is equal to the total volume of rainfall, P, on the watershed, less any losses, L, such as storage, evaporation, infiltration, drift, etc. given as:

$$V = P - L = \int Q(t)dt \qquad (2.6.2)$$

Any two storm events of equal rainfall intensity and duration, over the same section of highway, under equivalent weather conditions (e.g., temperature and wind) *should* produce similar volumes of runoff. Since *L* is expected to be small and approximately constant for a 100% impervious surface, the total volume of runoff from any given storm should be predictable.

The flow-weighted mean concentration of a constituent is the amount of constituent mass, *M*, available during the storm divided by the volume of storm water runoff, *V*. The volume of runoff, *V*, varies primarily with the rainfall. However, the amount of constituent mass, *M*, that is available during the storm is considerably more complex. The total storm load can consist of the mass that has accumulated on the highway surface at the instant the storm begins, plus any pollutant mass introduced during the storm, plus or minus any production/decay of pollutant mass during the storm. However, the amount of dry material that has accumulated on the highway prior to the start of the storm, is influenced only by variables that precede the rainfall. These variables occur during the antecedent dry period (ADP), although the extent of pollutant wash-off (or accumulation) during the preceding storm event also may be important. Similarly, the amount of material input from traffic and rainfall is completely independent of the ADP and preceding storm. Finally, any production/decay (including settling) of material during the storm will depend on the total amount of material present, which, in turn, is a function of variables of the pre-rainfall and rainfall periods.

The changes in constituent load during a storm may be illustrated by considering a rainfall event over a segment of highway as analogous to the flushing of a dry stream bed. In this system, the pavement segment is the "stream bed," with rainfall providing the inflow and the point of outflow being at the curb inlet box. The stream bed is dry at the beginning of the storm but contains a specific mass of a constituent. As rain water enters the system, the available mass of constituent is mobilized and moved downstream toward the curb inlet. If there is no change in the inflow of water (i.e., the inflow is at steady state) a hydrograph recorded at the curb inlet will show a rising leg over the time of concentration, a plateau throughout the remainder of the storm, and a falling leg that is similar to the rising leg after the end of the rainfall. To an observer at the curb inlet, there is a "time release" of the dry mass of constituent that accumulated on the highway surfaces. If the traffic across the highway segment is constant throughout the storm, and the storm completely flushes the dry accumulation from the highway, the outflow of constituent mass ultimately will equal the input of mass from the rainfall and the vehicles. The principal statement for the mass balance is:

Rate of change of mass of constituent =

the rate of input from rainfall into the system

\+ the rate of input from traffic into the system

\+ the mobilization rate of the dry accumulation

\+ the sum of all rates of output from the system

± rate of production/decay within the system

The mass balance is expressed mathematically as:

$$\frac{d(Vc)}{dt} = W + R - Qc \pm K_1 Vc \qquad (2.6.3)$$

Where the mass entering the system is:

$$W = Q_P c_P + M_v \qquad (2.6.4)$$

and the outflow Q at the curb inlet is:

$$Q = Q_P - Q_L \qquad (2.6.5)$$

where:

Qp = flow provided by rainfall (L^3/T)

cp = concentration of the constituent in rainfall (M/L^3)

M_v = mass input from vehicles (M/T)

QL = loss of flow resulting from watershed storage, evaporation, etc.

K_1 = constituent decay rate within the system

and

$$R \equiv \text{ mobilization rate of the dry accumulation} = f\left(P, \frac{dP}{dt}, \text{traffic rate}\right)$$

where during the storm:

$$\frac{dM}{dt} = -R \qquad (2.6.6)$$

(R would probably be first order, e.g., K_2M with $K_2 = f$[P, dp/dt, traffic rate])

and during the dry build-up period:

$$\frac{dM}{dt} = W_a + W_t + W_m - W_s \tag{2.6.7}$$

and

$$M = \int_{t_0}^{t_s} (W_a + W_t + W_m - W_s)dt \tag{2.6.8}$$

where:

W_a	=	net atmospheric load = f(wind, temperature, humidity, land use)
W_t	=	net traffic load = f(traffic rate, traffic mix, temperature)
W_m	=	net load from maintenance activities = f(guard rail repair, grass cutting, bridge sanding)
W_s	=	removal of constituent mass by street sweeping
t_0	=	end of previous storm
t_s	=	start of current storm

Some rainfall is going to accumulate on the pavement during the early stages of the storm; therefore:

$$\frac{dV}{dt} = A\frac{dh}{dt} \tag{2.6.9}$$

and expanding the derivative in equation 2.6.3 gives:

$$\frac{dVc}{dt} = V\frac{dc}{dt} + c\frac{dV}{dt} = V\frac{dc}{dt} + cA\frac{dh}{dt} \tag{2.6.10}$$

that yields the general case equation:

$$cA\frac{dh}{dt} + V\frac{dc}{dt} = W + R - Qc \pm K_1Vc \tag{2.6.11}$$

The maximum amount of time that a particle is mobilized on the highway segment (i.e., the time of concentration) is probably too short for any chemical transformation of the constituent to occur; therefore the decay/production rate, K_1, is approximately equal to zero. Furthermore, once all of the inputs have reached steady state (e.g., flow-in is equal to flow-out and the traffic flow is constant) then the mobilization rate, R, is constant. Therefore, if the rainfall and traffic provided no constituent input into the system (i.e., $W = 0$), the only mass output of the system is the flushing of the material that originally resided on the dry road surface, and the concentration of constituent in the runoff, c_F, is given by:

$$c_F = c_0 \exp\left[-\left(\frac{Q}{V} + R\right)t\right] \tag{2.6.12}$$

If the constituent input from both the rainfall and the traffic is assumed constant (i.e., there is no variation over the duration of the storm), each source would be considered as a single step input into the system. The concentration of constituent in the runoff attributable to the step input, c_S, is given by:

$$c_S = \frac{W}{Q}\left\{1 - \exp\left[-\left(\frac{Q}{V}\right)t\right]\right\} \tag{2.6.13}$$

that describes the build-up of concentration to an equilibrium level given by:

$$c_S = \frac{W}{Q} \tag{2.6.14}$$

The lack of volume, or "shallowness" of the highway stream bed, results in the instantaneous and complete mixing of the constituent mass contributed by rainfall and vehicles. Therefore, Equation 2.6.14 best describes the steady state input of material from rainfall and traffic.

Finally, the total response of the storm to an initial accumulation of material on the highway surface and a constant input from rainfall and traffic is the sum of Equations 2.6.12 and 2.6.14 and is expressed mathematically as

$$c = c_F + c_S = \frac{W}{Q} + c_o \exp\left[-\left(\frac{Q}{V} + R\right)t\right] \tag{2.6.15}$$

Plots of Equations 2.6.12, 2.6.14, and 2.6.15 are presented in Figure 2.6.2. At the start of the storm the amount of dry material that has accumulated on the highway, plus the amount contributed by traffic/rainfall, yields an initial runoff concentration c_0. If the storm continues indefinitely, the initial accumulation of dry material is removed completely by the runoff. Simultaneously, new constituent mass from the traffic and/or rainfall is added to the system at a constant rate. Note that even in the presence of a constant constituent input, the combined response shows the familiar first flush pattern.

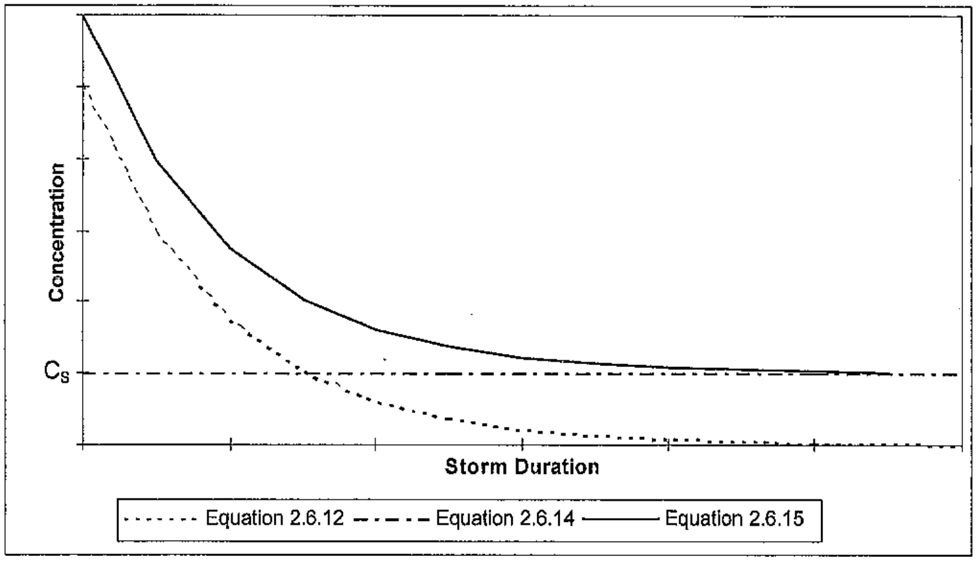


Figure 2.6.2 Theoretical Wash-Off Pattern

The variables that influence dry weather build-up and the traffic/rainfall input rate must be identified to predict the storm load. The response to these variables is easily distinguishable if the storm maintains a steady state condition over a prolonged period. Of course, this is never the case in nature. However, if a designed series of "steady state" storms could be created, it may be possible to identify the causal variables of storm load. The use of a rainfall simulator to create such a storm is the subject of Chapter 3.

2.7 Summary

The cost of storm water control accounts for as much as 20% of the overall cost of highway construction in the Barton Springs segment of the Edwards Aquifer recharge zone. Because of concern that the current runoff control structures are not constructed in the "best" (either environmentally or cost-effective) manner, TxDOT initiated research that would (1) determine the variables that affect the build-up and wash-off of constituents from highways in the Austin area and (2) develop a predictive model that incorporates the variables which affect runoff quality.

A review of highway runoff literature indicates that (1) the build-up and wash-off of materials from highway pavements is a very complex process, (2) there is considerable disagreement over the importance of the "first-flush" effect, and (3) street sweeping is generally not effective for the removal of the smaller sized particles that are associated with the majority of the constituents. However, constituent runoff patterns would be distinguishable if a steady-state storm event (i.e., constant rainfall and constant traffic input) is sampled at regular intervals throughout the duration of the event.

3.0 Data Collection

3.1 Introduction

The development of the highway runoff predictive model is supported by data collected at two sampling sites along Loop 1 (MoPac Highway) in Austin. The principal sampling site was located near the West 35th Street overpass. A rainfall simulator was erected at this site, and between July 6, 1993 and July 14, 1994, a total of 35 simulated storm events were conducted for the purpose of measuring storm water loading during "controlled" rainfall events. All of the simulated storms were performed over active traffic with the exception of three "no-traffic" storms. In addition, 23 natural storm events were sampled at the West 35th Street site between September 14, 1993 and April 28, 1994.

The second sampling site was located on a MoPac expressway overpass near Convict Hill Road. The major differences at this site are the watershed size (approximately 10% of the West 35th Street site), the low traffic count (average daily traffic volume at the site is approximately 20% of that at the West 35th Street site) and the high guardrails along the overpass that possibly trap contaminants as they move along the highway. Otherwise, the surrounding land use, traffic mix, and prevailing weather conditions are all similar to the West 35th Street site. A site comparison is presented in Table 3.1.1. Twenty natural storm events were sampled at the Convict Hill site between April 29, 1994 and November 5, 1994. The primary use of these data was the verification of the model, that was formulated using the West 35th Street data.

3.2 Rainfall Simulation

Rainfall simulation has been used in highway runoff research since the mid-1960's (Hamlin and Bautista, 1965; Sartor and Boyd, 1972; Wiland and Malina, 1976; Irwin and Losey, 1978). The rainfall simulator is used to produce an artificial rainfall event during that certain parameters thought to affect highway runoff loading are "controlled." The most commonly controlled parameters during a highway rainfall simulation include the storm intensity, storm duration, and the antecedent dry period. The influence of average daily traffic count, surrounding land use, seasonal variations and street maintenance operations may also be determined with the use of a rainfall simulator. Two different methods have been used to produce the artificial runoff: (1) a sprinkler system set up over the road surface and (2) a pressurized wash.

Table 3.1.1 Highway Characteristics at the MoPac Test Sites

Highway Characteristic	MoPac & West 35th Street	MoPac & Convict Hill
Number of Lanes	3	2
Inside Shoulder Width	2.4 m	3.0 m
Outside Shoulder Width	3.0 m	6.4 m
Length of Watershed	300 m	30 m
Impervious Area	4,358 m^2	511 m^2
Percent Watershed in Active Traffic Lanes	77%	44%
Percent Impervious	100%	100%
Time of Concentration	12 minutes for a storm intensity of 31 mm/hr	NA
Highway Construction	Asphalt with 15 cm Curb	Asphalt with 1 m Retainer Walls
Speed Limit	88 km/hr	88 km/hr
Local Land Use	Residential/Light Commercial	Residential/Undeveloped

The sprinkler system approach attempts to simulate natural rainfall by using a series of spray nozzles set up to sprinkle water onto the highway surface. Experiments are designed to determine the constituent loads that result from different storm patterns. Although rain droplet size and impact energy may vary considerably from actual rainfall, it is important that the simulator be able to reproduce a spatially uniform rainfall intensity (Reed and Kibler, 1989). The section of roadway exposed to the "rain" is typically 40 to 85 square meters in size (Sartor and Boyd, 1972; Reed and Kibler, 1989) and the highway must be closed to traffic during the experiment.

The pressurized wash method is designed to remove all accumulated material from the highway surface. A high-pressure stream of water is used to dislodge material residing on the highway surface and wash it to a sampling station. The wash is accomplished by using a fire hose supplied by a water hydrant or water tank, and no attempt is made to simulate natural rainfall. Similar to the sprinkler system approach, the highway is closed to traffic during the experiment. The total amount of material residing on the highway surface may be determined using this method; however, no relationship can be established between the quality of the runoff and the temporal variations in rainfall and traffic. This approach is typified by the work of Hamlin and Bautista (1965); Wiland and Malina (1976); and Irwin and Losey (1978).

A "sprinkler" type rainfall simulator was constructed at the MoPac & West 35th Street site to facilitate data collection for this research. The West 35th Street site was selected because of site-specific hydrologic, traffic, and safety characteristics that allowed the design of a rainfall simulator that could be operated over active traffic. The simulator was set up along a 300-meter section of highway that drained to a single curb inlet box. This condition greatly simplified sample collection during the artificial storms. Furthermore, spray from the simulator covered approximately the entire natural watershed for the curb inlet box, which allowed a direct comparison of natural events to simulated events at the site.

The average daily volume of traffic at the West 35th Street site is approximately 60,000 vehicles per day. The high traffic volume allowed for a significant variation in the number of vehicles exposed to the "storm," depending on the time of day the simulator was operated. Traffic variations during daylight hours ranged from 3,000 vehicles/hr (between 10:00 am and 11:00 am) to 6,000 vehicles/hr (between 7:00 am and 8:00 am).

Safety considerations, however, were the most important aspect in the rainfall simulator site selection process. The West 35th Street site proved an excellent choice because of the excellent traction characteristics of the pavement in the wet zone. A high-speed service road also provided a convenient by-pass around the simulator for motorists who did not want to drive through the artificial rain storm.

Finally, the commitment and support of the staff of the TxDOT made it possible to operate the rainfall simulator over high-speed highway traffic. This simulator provided the unique opportunity to study a design storm under actual highway conditions.

The major advantages of using a rainfall simulator under these conditions are:

1. Control of the parameters that affect highway runoff, such as:

- Rainfall intensity
- Rainfall duration
- Antecedent dry period
- Traffic intensity during the storm
- Pavement maintenance operations

2. Execution of a precise water quality sampling scheme based on a pre-known storm event during ideal sampling conditions.

3. The ability to generate a large number of runoff events for statistical analysis.

4. The ability to generate "rainfall" during extended periods of dry weather (a common summertime occurrence in the Austin area).

5 Provide a "steady-state" storm, with respect to rainfall and traffic intensity, in which to measure the response of storm loading to different causal variables.

3.3 Rainfall Simulator Design

The objective of the rainfall simulator design was to produce a system capable of simulating natural rainfall over a section of highway during actual traffic conditions. The system must operate to produce highway runoff that can be collected and evaluated to determine constituent loads that result from various combinations of climatological conditions and vehicle use patterns. Specifically, the rainfall simulator had to meet the following criteria:

1. provide rainfall of varied and controlled intensities;
1. produce a rain that falls uniformly over a 3-lane width of traffic;
1. produce rainfall over the entire length of the highway watershed serviced by a curb inlet drain;
1. provide rainfall from above a 14-foot height in order to clear tractor trailer traffic;
1. operate within the normal 10-foot width of a highway shoulder because no structure could be built over or across the highway;
1. be portable, but structurally stable and secure to safely withstand the wind forces resulting from high-speed traffic turbulence.

Natural rainfall consists of numerous water droplets of varying sizes. These droplets are constantly changing mass as they fall through the atmosphere as a result of evaporation, shear stresses, and collisions with other droplets. Furthermore, the droplets travel with varying downward velocity components as a result of the effects of wind, lift, and air drag. Light rainfall events will produce small droplets and mist, whereas heavy rainfall events will produce a wide range of droplet sizes including mist. The success of a rainfall simulator design depends on the ability of the simulator spray head to produce a variety of water droplet sizes and distribute them over a large area. A simulator that must deliver rainfall from outside the target sampling area, such as from the shoulder of a highway, can only accomplish this by creating a water droplet size distribution at the spray head with a velocity distribution spread over each droplet size. The simulator must produce droplets of various sizes and throw each droplet size through a wide range of velocities. The velocity of the droplet will determine the distance of travel, and the droplets having the greatest velocity must travel across the entirety of the sampling zone. A large amount of energy is required to propel droplets, as opposed to a stream, a given distance from the spray head. The smaller the droplet, the more energy is required to throw the droplet a given distance. An illustration of this principle is shown in Appendix C.

The spray head is the most critical operating part of the rainfall simulator. The spray head is responsible for the application and even distribution of water over the highway surface. It must be adjustable, light-weight, and capable of continuous operation for the duration of the sampling session. Furthermore, the design of the spray head drives the design of the water supply and distribution lines and the support stands. During the initial part of the research, spray head design concentrated on investigating the applicability of agricultural irrigation equipment. However, modern irrigation spray heads are designed to provide small water droplet size to prevent damage to crops and soils. Conversely, the rainfall simulator is designed to produce large droplets, capable of damaging soils (as in erosion studies) or dislodging materials from the surface of vehicles as required in this study. This fundamental difference played a major role in the final design of the spray head.

Irrigation spray heads generally fall into two categories. The first category is the mist application spray head. These spray heads are most commonly seen on center-pivot irrigation equipment. A spray nozzle directs a stream of water toward a splash plate that diffuses the water in all directions. The design of the splash plate determines the size of the droplet and the pattern of spray. Spray coverage is a full 360 degrees, but a deflector may be used to limit the direction of the spray pattern. These spray heads are capable of evenly distributing a continuous spray over a 21-meter-diameter circular area. These designs are most likely to have applications in studies simulating drizzles, mists, or heavy fogs, where the application area is under 353 square meters per spray head (177 square meters for non-centered spray heads). The Nelson R30 Series is representative of this type of spray head.

The second category of irrigation spray head is the impact sprinkler. This type of spray head is most commonly seen on golf courses, parks, and other turf areas where a large water droplet size will not cause damage to the soil. Impact sprinklers are capable of throwing large droplets of water over 185 meters. These spray heads use a nozzle similar to that of mist spray heads; however, instead of hitting a 90 degree splash plate, the water stream glances off a spring-loaded or levered splash plate mounted tangent to the stream. The water that hits the splash plate breaks into small droplets or mist. However, if the splash plate has a long lever arm, the majority of the water stream will not collide with the splash plate. The water that does not collide with the splash plate will break-up into large droplets as the unimpeded stream of water travels through the air. The unbroken stream of water results in the great throw distances achieved by the impact sprinkler. The width of continuous coverage of the impact sprinkler is only as large as the dispersion of water stream. Therefore, the impact sprinkler is commonly swivel-mounted in order to obtain 360-degree spray coverage. The Rainbird Model 35A-TNT is representative of the impact sprinkler type of irrigation spray head.

Neither type of spray head is suitable for use in a large-area simulator where the spray head and associated support structures have to be mounted outside of the area of rainfall. The impact sprinkler can spray a great distance, but the width of spray is extremely narrow. The mist spray head is capable of providing a large area of continuous spray, but the water droplet is small and the throw distance is short. A rainfall simulator for an active highway requires a spray head that can throw large drops of water a great distance, yet continuously cover as wide an area as possible. It is therefore necessary to design a spray head that combines the characteristics of both the impact sprinkler and the mist spray head.

An analysis of water droplet formation in the various different irrigation spray heads provides insight into how this objective can be reached. Surface tension is the mechanism that holds the water droplet together and subsequently controls the size range of droplets that can be produced. If surface tension is uncontrollable, the water droplet size produced by a simulator is a function of (1) the type of splash plate used, (2) the angle of approach of the water stream, and (3) water pressure. Any droplet size can be obtained by holding two of the variables constant, and varying the third. A specific splash plate, for example, set at a constant angle can produce a range of droplet sizes from very large (low pressure) to very small (high pressure) by only changing the pressure. Similarly, if pressure and angle of attack are held constant, droplet size can be regulated by changing the type of splash plate (i.e., a rough or rotating splash plate will yield small drops, and a smooth or yielding splash plate will provide large drops). A graphical illustration of these parameters is shown in Figure 3.3.1.

Experiments were conducted at the Center for Research in Water Resources (CRWR) to evaluate the performance of various splash plates. The "best" rainfall, judged by observation, was produced by a large, smooth splash plate mounted tangent to the exiting water stream. This design allows the water stream to spread out across the surface of the plate with a minimum loss of velocity. The water leaves the plate at all edges, giving width to the spray pattern. Additionally, the splash plate is flexible, which allows some droplets to leave the plate sooner and with higher velocity than others. Because droplets of all sizes are being produced on the plate, all droplet sizes are subject to leaving the plate at varying velocities.

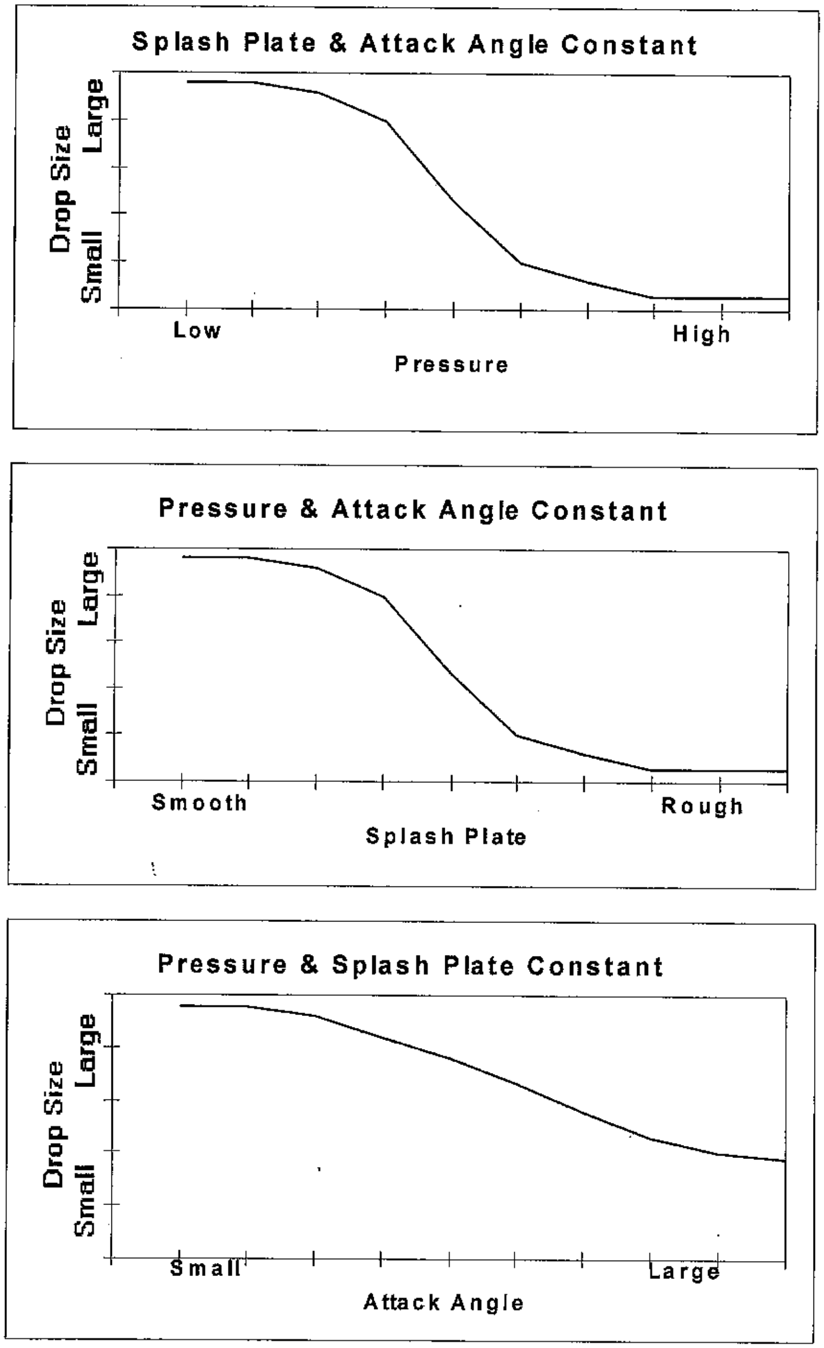


Figure 3.3.1 Relationship Between Nozzle Pressure, Splash Plate Design, Attack Angle, and Droplet Size

Experiments also were conducted to determine the optimal water pressure and nozzle diameter required to drive the water stream across the splash plate. Nozzle diameters up to 16 mm and pressures up to 586 kpa were tested. It was observed that if the water pressure is too high with respect to the nozzle diameter, atomization occurred at the nozzle. If the water pressure is too low, there is not enough energy to break the water stream into smaller drops as it crosses the splash plate. Water pressure in the range of 310 to 450 kpa worked the best with most nozzle diameters. Pressures above 500 kpa will atomize the water stream in the range of nozzle diameters tested at CRWR. Pressures below 175 kpa generally resulted in insufficient throw distance, depending on nozzle diameter. Holding pressure constant at 450 kpa, a 3-meter increase in throw distance was observed for each 0.8 mm increase in nozzle diameter through the range of 3 mm to 6 mm in diameter.

The simulator spray heads must be mounted on the highway shoulder within 2 to 3 meters of the first lane of traffic. The spray heads must also be mounted at a 4.3-meter height so the spray can clear tractor trailer traffic. This arrangement presented the challenge of creating water droplets that will fall both 2 meters and 15 meters from a 4.3-meter elevation. Experiments at CRWR showed that a single nozzle would not satisfactorily perform this task. The simulator spray head was therefore designed with two vertically mounted nozzles. The top nozzle was used to spray water droplets across the center and far lanes of traffic. The lower unit was a smaller diameter nozzle used to cover the near to center lanes. The splash plate for each nozzle was the same size and was set at the same angle of attack. Exit pressure was also the same for both nozzles. The shorter throw distance was achieved by using a smaller orifice, resulting in a smaller flow rate.

The departure angle of the water droplets is also an important consideration. Commercial irrigation equipment manufacturers generally set impact spray heads at a 23-degree angle. However, tests at CRWR during calm conditions indicated that throw distance increased as nozzle angle increased to 45 degrees. The outdoor tests indicated that different nozzle angles could off-set the effects of some wind speeds and directions. The simulator nozzle was therefore swivel mounted to allow for infinite control of nozzle angle to accommodate various weather conditions. A simple pull-string arrangement allowed the spray head to be set at any angle from the ground.

The nozzle angle may also be used to shorten the throw distance in situations where high rainfall intensities are simulated. Rainfall intensities greater than 75 mm/hr require a nozzle diameter/water pressure combination that produces a throw distance greater than 15 meters (i.e., the width of the highway segment). This situation is remedied by increasing the nozzle angle greater than 45 degrees to obtain the appropriate throw distance.

Figure 3.3.2 shows the assembly of the simulator spray head. The entire head is constructed of PVC in order to reduce weight. No special machining or assembly techniques are required to produce the spray heads, and the nozzles are easily changed for different operating conditions and maintenance.

The spray stand is the structure that supports, and delivers water to, the elevated spray head. The stand has to be lightweight and portable, yet steady and safe when subjected to roadside turbulence and vibrations. A tripod configuration was selected for the stand. Two collapsible swivel legs were forward mounted to support a riser pipe that delivers water to the spray head. The legs can be positioned and locked anywhere along the length of the riser pipe to accommodate for uneven ground. Additionally, the legs swivel in all directions, allowing for various set-up possibilities. Further flexibility is gained from using rubber hose to connect the riser pipe to the distribution piping. Quick-disconnect fittings are used to attach the stand supply hose to the distribution piping. A safety cable is secured to a ground anchor that is placed in the center of the tripod footprint. The entire stand and spray head assembly can be set up and positioned by a single person.

The spray head is the forward-most component of the spray stand, and the legs are as far removed from the traffic lane as possible. The rear-most component of the stand is the bottom of the riser. This configuration insures that all water delivery hardware is as far off the road as possible. The spray stand is illustrated in Figure 3.3.3.

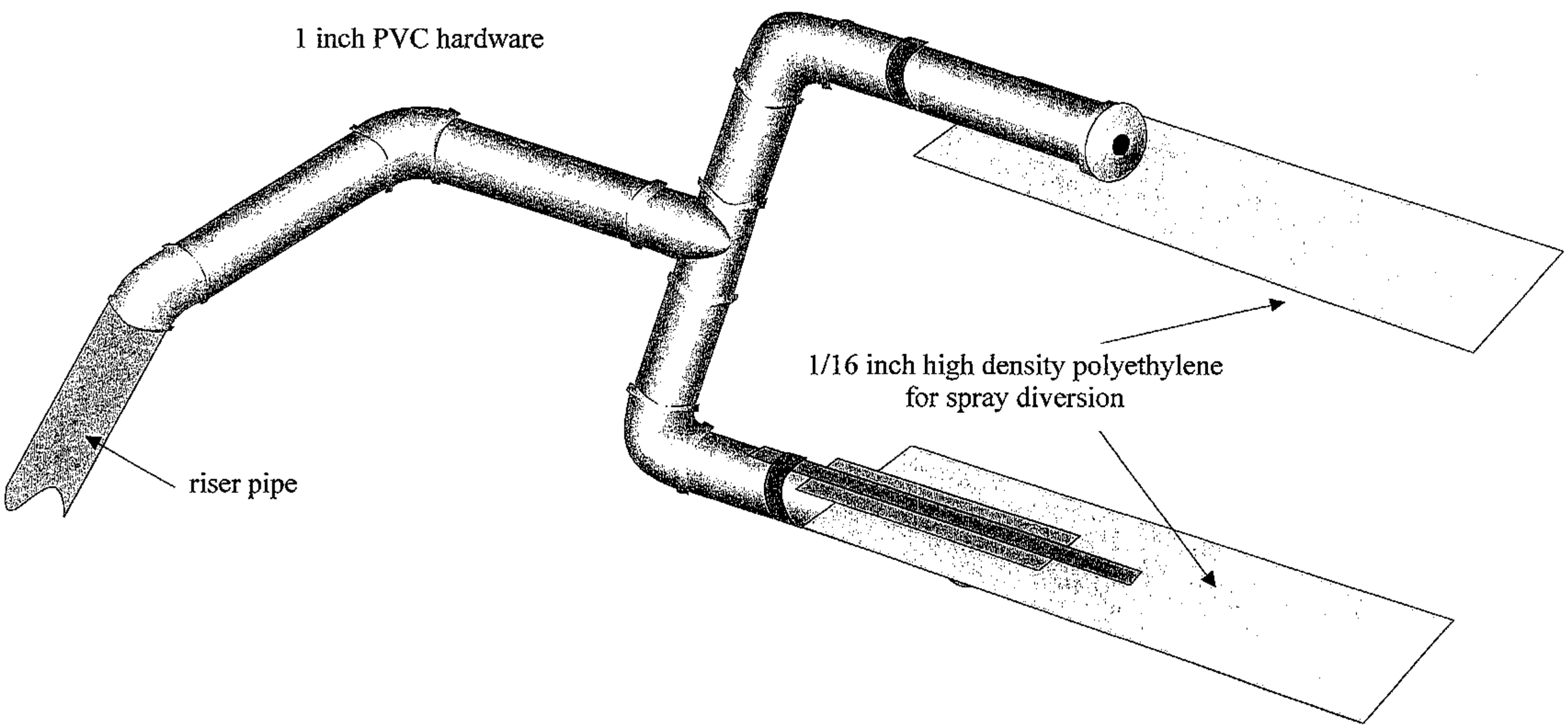


Figure 3.3.2 Spray Head Assembly

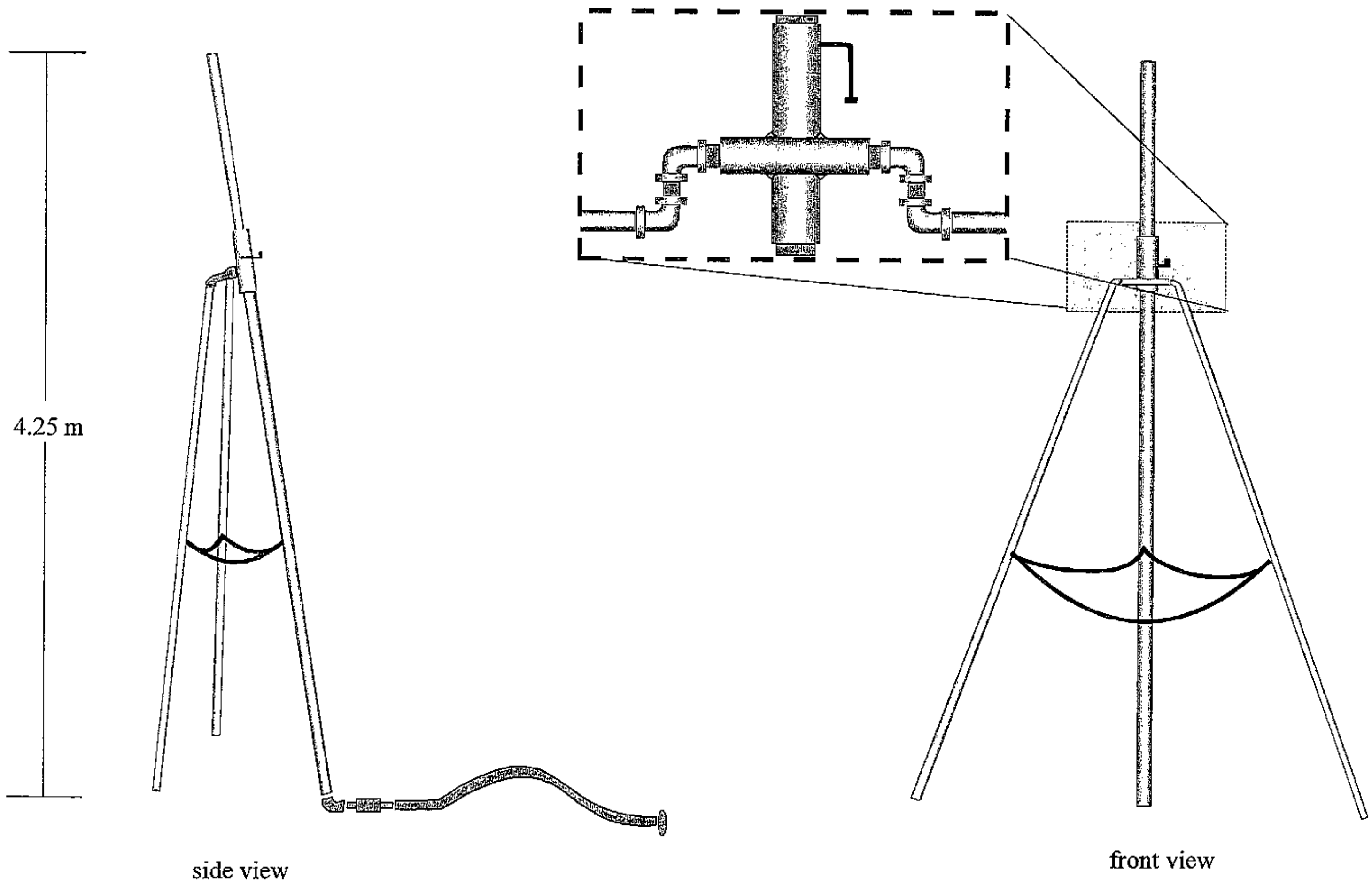


Figure 3.3.3 Spray Stand Assembly

The water supply at the West 35th Street sampling site is a City of Austin fire hydrant. The water must be transported a distance of more than 300 meters to the rainfall simulator. High-pressure aluminum irrigation piping was selected for this task because it is lightweight, sturdy, and easily assembled. The pipe string was assembled by use of a cam lock connection at the end of each joint.

The main design consideration for the delivery and distribution piping was choosing a pipe diameter that would minimize water hammer in the system. Good engineering practice is to keep the water velocity under 1.5 m/sec. The anticipated water flow rate in the system was 56 L/s, based on 67 spray heads (each spray head has a 4-mm diameter nozzle and a 5-mm nozzle) with an operating pressure of 415 kpa. The minimum pipe diameter allowed by this flow rate is calculated as:

$$Diameter = 2\sqrt{\frac{Flow}{(\pi)(Velocity)}} = 2\sqrt{\frac{(56)}{(3.1416)(1.5)(1000)}} = 0.22m \qquad (3.3.1)$$

The supply piping chosen for the initial simulator was 204-mm nominal diameter by 1.6-mm wall thickness. A 6-meter joint length was selected to facilitate handling.

The water supply piping must also distribute water to each spray stand along the sampling zone. If the stands are located every 4.6 meters, 67 stands are required in a 300-meter sampling zone. High-pressure aluminum irrigation piping was again chosen for this task. An outlet was installed every 4.6 meters along the length of the pipe string to facilitate water distribution to the spray stands. Each outlet was threaded and equipped with a quick-disconnect fitting for ease in connection to the stand.

The flow rate through the piping is reduced as water is distributed to the spray stands and is a function of the number of remaining stands (RS) and the flow per stand (FS). A smaller diameter pipe can therefore be employed and not violate the 1.5 m/sec maximum velocity rule. The point where the nominal pipe diameter can be reduced to 153 mm was determined as follows:

$$\begin{aligned} \text{Total Remaining Flow (TRF)} &= \text{RS x FS} \\ &= \text{(RS)(0.8 L/s)} \end{aligned} \qquad (3.3.2)$$

The nominal diameter of the piping can be reduced to 153 mm at the point where the following number of stands remain in the system:

$$RS = \frac{(Velocity)(Area)}{(13.28)(0.0022)} = \frac{(1.5)(0.018)(1000)}{(0.84)} \cong 32 \qquad (3.3.3)$$

Equation 3.3.3 suggests that the nominal piping diameter can be reduced to 153 mm for the last 152 meters of the sampling zone. Therefore, if the sampling zone is 300 meters long, the first 150 meters should be 204-mm nominal diameter while the last 150 meters can be 153-mm nominal diameter. The 153-mm nominal diameter pipe selected for this section of the system has a wall thickness of 1.5 mm with distribution outlets every 4.6 meters similar to the 204-mm distribution piping. Pipe lengths for the 153-mm nominal diameter pipe was six meters.

The total system assembly is illustrated by the diagram in Figure 3.3.4. The City of Austin provided a 153-mm nominal diameter turbine meter with screen filter to account for water usage. The meter had a maximum delivery of 126 L/s. The meter, screen filter, and a 153-mm nominal diameter resilient wedge gate valve were trailer-mounted to provide a single operating unit that could easily be connected to both the hydrant and the supply piping by flexible hoses. The gate valve provided the main on/off valve for the system. An 204-mm nominal diameter supply line delivers water to the distribution section. The length of the area draining to the sampling point was 225 meters. The initial 150 meters of the distribution piping is 204-mm nominal diameter, and the final 75 meters is 153-mm nominal diameter. Flexible 32-mm nominal diameter hose connected the distribution piping to the main 25.4-mm nominal diameter riser of the spray stand. The spray head was mounted at the top of the spray stand riser. Each spray stand was positioned along the shoulder of the highway to minimize overlapping of spray from each stand.

3.4 Rainfall Simulator Operation

The simulator was engaged by opening the gate valve located on the meter trailer. The use of this valve was preferable to that of the hydrant since the hydrant could be

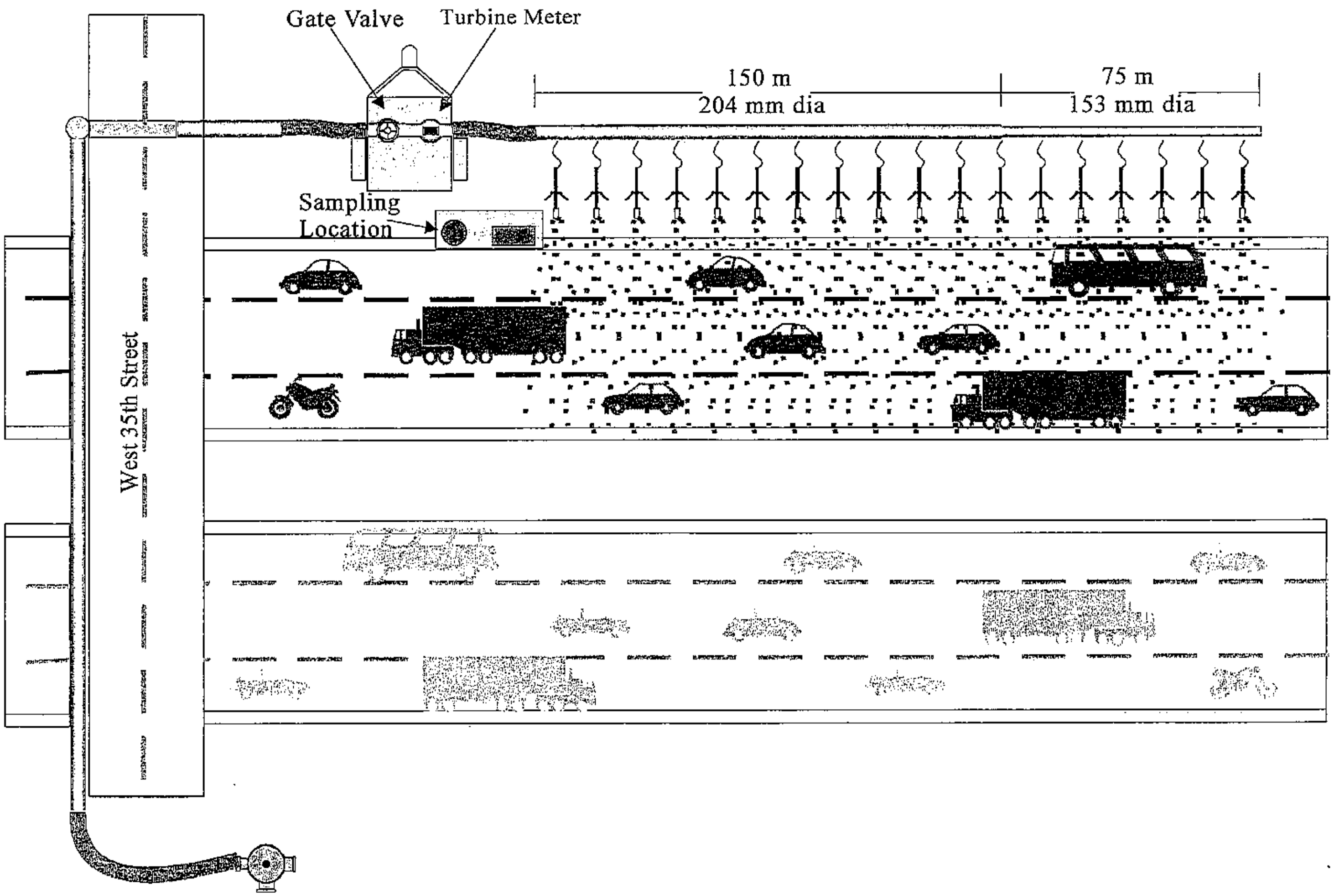


Figure 3.3.4 Total Rainfall Simulator Assembly

damaged as a result of numerous openings and closings. The initial opening of the gate valve was always performed very slowly, allowing the supply piping, distribution piping, and spray stands the opportunity to fill with water and bleed all air before full pressure of the hydrant was applied to the system. Similarly, the valve was always closed slowly to prevent a shock wave that could damage the hydrant.

Water usage by the system is a function or nozzle diameter, water pressure, and number of nozzles. The relationship between nozzle diameter, water pressure, and flow rate is shown in Table 3.4.1. Accordingly, different rainfall intensities are simulated by applying more or less water to the sampling zone, which is regulated by different combinations of nozzle sizes and nozzle pressures. The selection of the correct nozzle size and pressure for a given rainfall intensity was a trial and error process. Table 3.4.2 shows the observed rainfall intensities that resulted from selected nozzle diameters and pressures. The values given in Table 3.4.2 are only used as a guide and assume that there is no loss of water to evaporation or other means, and that all of the water falls evenly over the sampling zone. Following the selection of a nozzle size and pressure combination, the nozzle angle was adjusted to keep the spray within the sampling zone or offset wind effects. The rainfall simulations at the West 35th Street site used 5.2-mm and 4.0-mm diameter nozzles under a pressure of 207 kpa to produce a 28 mm/hr rainfall. The nozzle angle was set at approximately 45 degrees.

Table 3.4.1 Flow Rate (L/s) Given Nozzle Diameter (mm) and Pressure (kpa)

	Nozzle Diameter (mm)					
Pressure (kpa)	3.6	4	4.4	4.8	6.4	9.5
207	0.20	0.24	0.29	0.35	---	1.84
241	0.21	0.26	0.32	0.38	---	1.98
276	0.23	0.28	0.34	0.40	0.73	2.12
310	0.24	0.30	0.36	0.43	0.77	2.25
345	0.25	0.31	0.38	0.45	0.81	2.38
379	---	0.33	0.40	0.47	0.86	2.50
414	---	0.34	0.41	0.49	0.90	2.61

Source: Rainbird Irrigation Equipment (metric conversion made by the author)
Example: A 4-mm diameter nozzle under 207 kpa pressure produces 0.24 L/s flow

Table 3.4.2 Rainfall Intensities Produced by Selected Spray Head Nozzle Sizes and Pressures

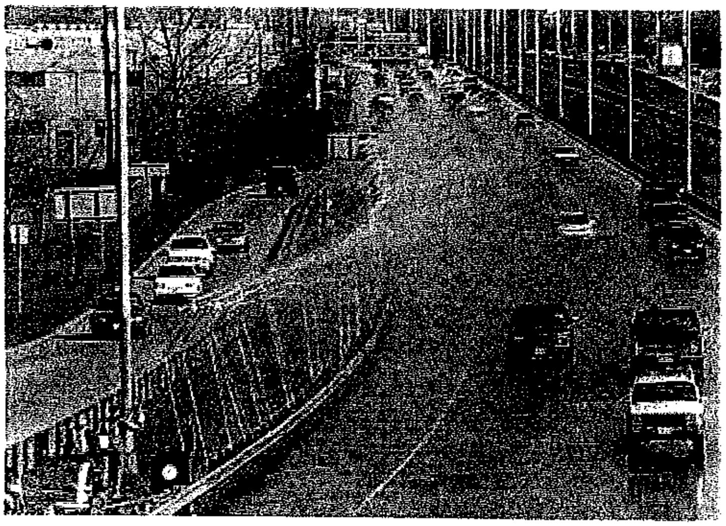
Rainfall Intensity (mm/hr)	Diameter of Small Nozzle (mm)	Diameter of Large Nozzle (mm)	Nozzle Pressure (kpa)	Nozzle Flow Rate (L/s)
38	3.6	4.8	207	35
51	3.6	4.8	345	47
64	4.0	5.2	414	56
76	4.0	6.4	310	72
89	4.0	6.4	414	83

Calculations showed that there was only a 14 to 21 kpa pressure loss across the 67 spray stands. There is negligible performance change in the spray head from this small amount of pressure change, so there was no need for more precise control (e.g., placing pressure regulators at the riser pipe of each stand).

The rainfall simulator is shown in Figure 3.4.1a, and the sampling station set-up at the curb-inlet is shown in Figure 3.4.1b. The actual operating parameters of the simulator are listed in Table 3.4.3. A more extensive description of the rainfall simulator is described by Irish (1992).

3.5 Water Quality Sampling

The characterization of a storm water runoff event is entirely dependent upon the design of the sampling program since constituent concentrations and storm water flow rates must be determined from water quality samples that are collected throughout the runoff event. Furthermore, a complete characterization will only be obtained if the sampling interval is short enough, as compared to the total storm duration, to provide an accurate "picture" of the event. This is a difficult task during natural storm events since it is impossible to predict the duration and intensity of the rainfall and subsequently the discharge of the storm. An automatic sampler that is programmed to collect on a predetermined schedule with limited sample jars will inevitably miss the entirety of an event (e.g., either the early part of a light storm or the latter part of a heavy storm will be missed). It is for this reason that the researcher must be at the site with an adequate



(a) View of the rainfall simulator in operation

(b) The storm water sampling station

Figure 3.4.1 The rainfall simulator at MoPac and West 35th Street, Austin, Texas

Table 3.4.3 Rainfall Simulator Actual Operating Parameters

Length of Spray	228.6 m
Maximum Spray Distance	15.2 m
Maximum Spray Height	Approximately 9 m
Maximum Flow @ Pressure	38 L/s @ 206.9 kpa
Maximum Rainfall Intensity	30.5 mm/hr

supply of sampling jars if a true representation is to be obtained of a natural storm. The major advantage of a simulated runoff event is that the researcher knows in advance both the duration of the event and the total volume of runoff that will be produced. With this knowledge, the sampling plan can be designed to precisely capture any desired runoff characteristic.

A selected "grab" sample will yield the instantaneous constituent concentration at a precise moment in the event. The temporal changes in concentration during the event are determined by the comparison of a set of regularly collected grab samples. Furthermore, any number of grab samples may be mixed to yield a single average, or "composite," sample. The intervals at that grab samples are collected may be time-paced, flow-paced, or a combination of both. The time-paced method schedules sample collections at specified time intervals throughout the storm (e.g., every 5 minutes). The flow-paced method collects the sample following the passage of a specified volume of runoff. The decision of that protocol to use depends largely upon the runoff characteristic of interest. Temporal changes in concentration, such as the magnitude and duration of the first flush, can only be determined from a series of grab samples that are collected frequently throughout the storm. The event mean concentration, however, can be determined from a single flow-paced composite sample.

The rainfall simulation sampling protocol was based on the time-paced method. The first sample was collected as soon as runoff was established at the curb inlet box, typically about 3 minutes after the start of the spray. Subsequent samples were collected on 5-minute intervals throughout the remainder of the storm. Observations during the first six storms revealed that the sharpest reduction in constituent concentrations occurred within the first 30 minutes of wash-off. The sampling interval was therefore extended to 10 minutes during the latter half of all subsequent simulations. All samples were collected manually by laboratory technicians on-site during the rainfall simulation. The storm sampling scheme, shown in relation to the simulated storm hydrograph, is illustrated in Figure 3.5.1. The rainfall simulator was turned off immediately following the collection of the 48 minute sample and the final runoff sample was collected 10 minutes later, or approximately 58 minutes from the start of the spray. Because the time of concentration for the site was approximately 12 to 14 minutes, this sampling scheme yielded two samples from the "rising leg" of the hydrograph, a sample at the beginning and end of the hydrograph "plateau," and a sample from the "falling leg" of the hydrograph.

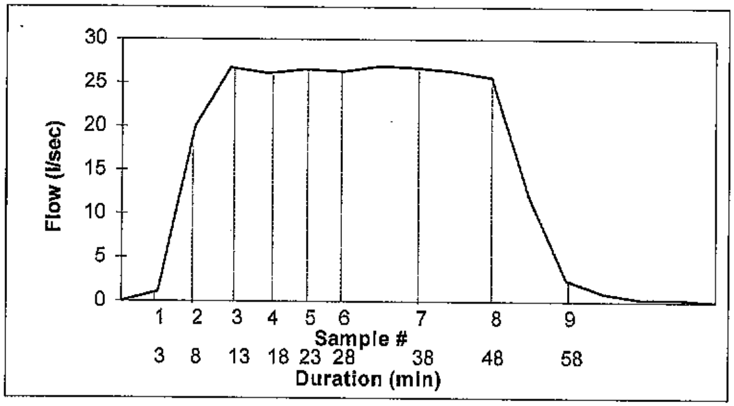


Figure 3.5.1 Simulated Storm Sampling Scheme

The sampling protocol for natural storm events was initially designed to imitate the simulator sampling plan. An automatic sampler was programmed to collect the first grab sample on the detection of runoff along the curb, collect two successive grab samples on a 5-minute interval, and collect a fourth composite sample based on 5-minute intervals over the following 20 minutes. This sampling scheme would yield three grab samples over the first 10 minutes of the storm and a composite sample of the next 20 minutes for a total of 30 minutes of sampling coverage. The plan was based on the observation that once flow was established at the sampling site, the flow normally lasted for at least 30 minutes. This protocol was used to sample all natural storms through November 2, 1993. After this date, the fourth (composite) sample was changed to a flow-weighted composite with collections occurring every 1,900 liters of runoff.

The protocol was changed once more on June 1, 1994 to a schedule which collected four flow-weighted composite samples over the first 10 mm of rainfall during the storm. Each composite consisted of six samples collected every 1900 liters of flow. A full composite therefore represented approximately 2.5 mm of rainfall on the watershed.

Many waste stream constituents are found in the receiving stream prior to the waste outfall, because they either occur naturally in the surface water or they have originated from other waste discharges further upstream. In either case, a blank sample is usually collected to determine the upstream concentration of constituents, or "background," that exists prior to the influence of the subject waste source.

Highway runoff can only occur during and after a rain storm (or snow melt, which was not considered by this study); therefore, the background concentration is the constituent concentration in the rain water. Constituents such as nitrate, phosphate, and metals in rainfall are common in highway runoff. Therefore, an attempt was made to collect a rainfall sample during each natural runoff event. The concentrations of constituents measured in the rainfall sample were subtracted from the concentrations measured in the samples collected at the curb inlet box to determine the true contribution of the highway. Unfortunately, a full sample of rain water could not be collected for each runoff event. At least 10 to 13 mm of total rainfall was required to collect a full sample using the rainfall/atmospheric dust collectors available to this study. Runoff at the West 35th Street site was observed following 0.25 mm of rainfall in a 15-minute period. The median concentration measured of all rainfall samples collected was used as the rainfall blank values. These values are reported in Table 3.5.1.

Highway runoff constituents are also found in the City of Austin tap water that is used for rainfall simulations. Nitrates, phosphates, carbon, and iron are common in the city water. A blank sample was collected near the beginning and end of each simulation. The two samples were averaged to determine a value for background concentrations during each rainfall simulation. These values are reported in Table 3.5.1

Table 3.5.1 Median Background Constituents

Constituent	Austin Tap Water (mg/L except pH)	Natural Rainfall (mg/L except pH)
pH	9.5	NA
TSS	ND	ND
VSS	ND	ND
BOD_5	2 (0.3)	2 (1.1)
COD	5 (0.5)	15 (0.8)
Total Carbon	10 (0.4)	7 (0.8)
Dis. Total Carbon	11 (0.4)	7 (0.8)
Nitrate	0.15 (0.5)	0.47 (0.8)
Total Phosphorus	0.3 (0.4)	0.05 (0.9)
Oil and Grease	0.2 (1.1)	ND
Copper	0.006 (1.3)	0.007 (0.9)
Iron	0.067 (1.0)	0.080 (0.9)
Lead	< 0.042 (1.6)	0.011 (1.1)
Zinc	0.025 (2.8)	0.022 (0.9)

Number in parenthesis is the coefficient of variation;
ND (Non-Detectable); NA (Not Available)

3.6 Runoff Constituents

The primary measure of the quantity of a constituent contained in storm water is *concentration.* Concentration, C, is defined as the amount of mass of constituent contained in a unit volume of runoff. Mathematically,

$$C = \frac{\text{Mass of Pollutant}}{\text{Volume of Fluid}} \quad \frac{[M]}{[L^3]} \qquad (3.6.1)$$

Concentration is reported for most constituents in either milligrams per liter (mg/L) or micrograms per liter (μ g/L). The exceptions are bacteria counts ("colony-forming units" per 100 mL, CFU/100 mL), turbidity ("nephelometric turbidity units," NTU), and conductivity (microsiemens per cm, μS/cm).

The water quality samples collected during the simulated and natural storm events were analyzed for constituents listed in Table 3.6.1. The laboratory methodology is presented in Appendix A. Microbiology work was not performed on the simulated samples since the Austin tap water contained chloramine for disinfection purposes. Dissolved oxygen measurements also were suspended during simulated storms since the value was near 100% saturation for all measurements.

Table 3.6.1 Highway Runoff Constituents

Field Measurements	pH, Dissolved Oxygen, Conductivity, Water Temperature
Laboratory Analysis	
Bacteriological	Total Coliforms, Fecal Coliforms, Fecal Streptococci
Solids	Total Suspended Solids, Volatile Suspended Solids, Turbidity
Oxygen Demand / Organics	Biochemical Oxygen Demand, Chemical Oxygen Demand, Total Carbon, Dissolved Total Carbon, Oil and Grease
Nutrients	Nitrate, Total Phosphorus
Metals	Cadmium, Chromium, Copper, Iron, Lead, Nickel, Zinc

Dissolved oxygen, conductivity, water temperature, and pH were measured for natural storms only when a technician was on site at the start of the storm. Natural storm event samples were collected using an ISCO Model 3700 Portable Sampler and ISCO Model 3230 flow meter. Simulation grab samples were collected manually on-site during the simulation. All field measurements were made using the Ciba Corning Analytical Checkmate Modular Testing System.

3.7 Flow Measurement

The primary measure of storm water discharge is *flow*. The flow rate, Q, is defined as the volume of runoff per unit time. The units reported in this research are liters per second (L/s). Mathematically, the flow rate is:

$$Q = \frac{\text{Volume of Runoff}}{\text{Time}} \; \frac{[L^3]}{[T]} \tag{3.7.1}$$

It is important to measure the total storm discharge since both a pollutant mass balance and flow balance must be performed to predict the final concentration of a constituent in the receiving stream (Thomann and Mueller, 1987). During the storm, the rate at that constituent mass is discharged is termed the *load*, W, and is expressed mathematically as:

$$W = \text{(Concentration)(Flow)} \quad \left[\frac{M}{T}\right] \qquad (3.7.2)$$

Load commonly is expressed in units of kilograms per day (kg/d). However, there are many variations adapted to describe a particular process, and units of mass per time-related property (i.e., rainfall or runoff volume) are not unusual. Highway runoff loading often is expressed as mass/time/length of road, mass/time/area of road, or mass/area of road/millimeters of runoff (Barrett et al., 1993). Load is reported in this research as grams per square meter of highway surface (g/m^2).

Instantaneous flow rates were recorded every 5 minutes using an ISCO Model 3230 flow meter with plotter. This flow meter is a "bubbler" type. The meter determines the depth of water in a channel by measuring the amount of air pressure required to force an air bubble from a submerged tube. As the depth of water increases, the pressure required to emit a bubble increases. The meter has an accuracy of ± 1.5 mm in the range of water levels possible in highway curbs and gutters. The flow meter will convert the level measurements to flow with a user-defined equation or interpolate a flow value from a known rating curve.

Installation of a weir or flume along the curb of the highway at the West 35th Street site was not practical. The height of the curb is too low, and the device would extend onto the highway shoulder, causing a hazard to traffic. Any attempt to measure the flow of water inside the curb inlet box would require the installation of a weir or flume and a stilling basin for accurate measurements. This equipment would restrict the drainage capacity of the inlet box, causing a hazard of roadway flooding during heavy flows. Measuring the water level in the discharge pipe of the inlet box is also impossible because of the steep angle of descent of the pipe. Furthermore, flow measurements inside the curb inlet box are complicated because the curb inlet box at this location also functions as a junction box (i.e., flows from other watersheds move through the box during natural rain events). The only practical way to measure the storm water discharge rate at this site was to measure the level of water along the highway curb. These measurements can subsequently be converted to flow rates using either Manning's equation (Urbonas and Roesner, 1992) or the stage-discharge relationship of the gutter. The stage-discharge relationship, or rating curve, for the gutter at the West 35th Street site was developed using the metering equipment of the rainfall simulator and is presented in Figure 3.7.1. This curve provided the basis for flow measurement at the West 35th Street site.

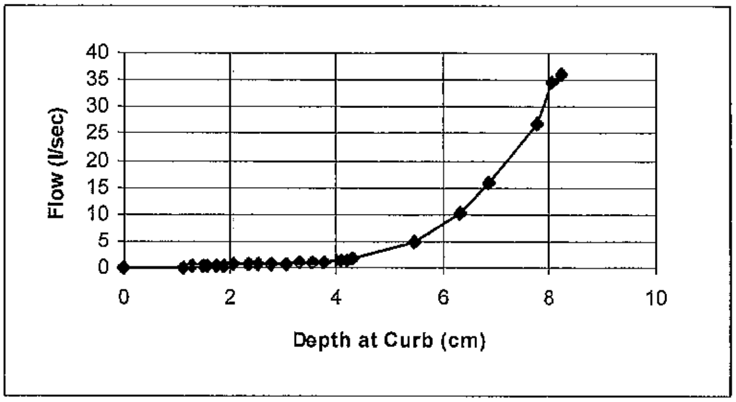


Figure 3.7.1 Rating Curve for Highway Curb at MoPac & 35 Street

Flow measurement at the Convict Hill site presented a different challenge. The highway runoff flowed off the Convict Hill overpass to ground below via a down-spout. A weir or flume could not be installed along the curb for the same reasons as at West 35th Street, and there was no practical way to rate the curb. A catch box with a weir was installed at the bottom of the down-spout to measure descharge. The depth of water in the box was measured with an ISCO Model 3230 flow meter, and the flow conversion was made using a weir formula.

3.8 Event Mean Concentration

The event mean concentration (EMC) is commonly used to describe storm water runoff events. The EMC is defined as the total constituent mass discharged during an event divided by the total volume of discharge during the event (Huber, 1992). Mathematically,

$$EMC = \frac{M}{V} = \frac{\int C(t)Q(t)dt}{\int Q(t)dt} \qquad (3.8.1)$$

The EMC is a flow-weighted average of the constituent concentration and is reported in units of mg/L. The total mass loading of a constituent during the storm may be obtained by multiplying the EMC by the total volume of storm runoff.

The EMC is the concentration of a constituent in a single composite sample collected on a flow-paced interval throughout the storm. However, if only concentration data are available for sequential grab samples collected at discrete time intervals, the hydrograph (plot of flow vs. time) and the pollutograph (plot of constituent concentration vs. time) of the storm must be known in order to calculate the EMC. Furthermore, the concentration measured at a specific time, *T*, is the average concentration in the sample collected during the interval that begins one-half way between *T* and the time of the previous sample, and that ends one-half way between *T* and the time of the next sample. The mass load is obtained by multiplying this "average" concentration by the total flow accumulated during the interval and the length of the interval. This procedure is described mathematically by the trapezoidal rule and the calculation proceeds as follows:

1) $$EMC = \frac{M}{V} = \frac{\sum_i C_i Q_i \Delta t_i}{\sum_i Q_i \Delta t_i} \qquad (3.8.2)$$

2) $$M = \int C(t)Q(t)dt = \sum_i C_i Q_i \Delta t_i \qquad (3.8.3)$$

3) $$V = \int Q(t)dt = \sum_i Q_i \Delta t_i \qquad (3.8.4)$$

4) The concentration, C(i), at time t(i), is equal to the average concentration for a period Δ T(i) beginning at time t(i) - 0.5[t(i) - t(i-1)] and ending at time t(i) + 0.5[t(i+1) - t(i)].

5) Q(i) is equal to the total volume of flow during period Δ T(i) divided by the duration of period Δ T(i).

3.9 Rainfall Measurement

Rainfall was measured at each site using an ISCO Model 674 rain gage equipped with a "tipping bucket" that measures rainfall in 0.25 mm increments. A pulse signal is sent to the ISCO flow recorder on each tip of the bucket. The rainfall hyetograph was recorded in 5-minute intervals throughout the duration of a storm. Rainfall measurements are reported in millimeters.

3.10 Miscellaneous Measurements

The traffic count during both wet and dry periods was measured using a StreeterAmet traffic data system installed at the MoPac test site by TxDOT. Wind speed (m/s) and direction were measured during rainfall simulations with a Kahlsico hand-held anemometer at the test site. Air temperature (^{0}C) was obtained from the National Weather Service Office, Austin, TX. Simulator duration time (minutes) and sampling intervals were measured with a stop watch.

3.11 Detection Limit Data

Concentrations of highway runoff constituents are often near the detection limit of analytical equipment. For example, metal concentrations typically are in the micrograms-per-liter range. For cases where the concentration of constituents are below the detection limit of the analytical methodology or equipment in use, the constituent concentration is reported as below the "limit of detection" (LOD) or "non-detectable" (ND). Specifically, the LOD for a particular method is defined in 40 CFR Part 136 as the "...lowest concentration of the analyte that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero."

Concentrations less than the LOD are reported in a variety of ways, such as "non-detectable," "0," or "less than values." In this report, the notation used is the LOD proceeded by a "<" sign. Although the true concentration of the constituent is unknown, it is recognized that the concentration is greater than zero but less than the LOD.

The are several common methods of treating ND values (Gilbert, 1987). The method selected for this research is to replace ND with a value of one half the LOD. This substitution yields an unbiased estimate of the true population mean as long as the analytical procedure does not yield a value of less than zero. However, estimate of the variance is biased. The expected value, or mean, of a ND observation is an appropriate substitution in most cases, but it cannot be made universally.

The application of the term ND requires care and consideration of the type of sample and the constituent in question. A sample of tap water or rainfall provides the background concentration that exists before the influence of the highway and is considered to be the blank. The highway contribution is established by subtracting the background concentration measured in the blank sample from the instantaneous concentration measured in the runoff samples. An approximation of the true mean of the background concentration is appropriate for this calculation. Therefore, ND values are replaced by a value of one half the LOD. However, in the case of oil and grease, which are not expected to be in the blank sample, a reported ND value is assigned a zero since oil and grease are not be expected to be in either the City of Austin drinking water or in the natural rainfall.

A value of ND may also be reported for a runoff sample. The runoff sample can be a single sample collected at a particular instant during the event, or a composite of collections from several intervals during the event. Since all of the constituents listed in Table 3.6.1 are expected to be in the highway runoff, any ND value in a runoff sample is replaced by one half of the LOD value, and the EMC for the event will be calculated using this value. However, if a large number of ND values are reported for a pollutant during a single event, the value of the EMC could be less than the value of the LOD. The most extreme case is a ND value reported for all samples collected during the runoff event in which the expected value for the constituent is one half the LOD.

3.12 Summary

A rainfall simulator was constructed to aid in the collection of highway runoff data. The simulator covered nearly 4,400 m^2, which was the entirety of the watershed that drained to a single curb inlet, and was operated over active highway traffic. The advantages of the simulator were (1) the control of parameters that affect highway runoff, (2) the execution of a precise water quality sampling scheme during ideal sampling conditions, (3) the generation of storm events during extended periods of dry weather, (4) the generation of a large number of runoff events for statistical analysis, and (5) the production of a steady-state storm event.

The highway runoff constituents measured during this research included TSS, VSS, turbidity, BOD_5, COD, TOC, dissolved TOC, oil and grease, nitrate, total phosphorus, cadmium, chromium, copper, iron, lead, nickel, zinc, pH, dissolved oxygen, conductivity, water temperature, total coliforms, fecal coliforms, and fecal streptococci. The sampling protocol for simulated storm events was based on time-paced grab samples. Natural event sampling protocol was based on flow-weighted composite samples. Blank samples of Austin tap water and rainfall were collected to provide background concentrations. Runoff volume was measured using rating curves established for the street curbs at the sampling site.

4.0 Data Summary

4.1 Introduction

A total of 35 simulated rainfall events were sampled at the West 35th Street site between July 6, 1993 and July 14, 1994. A total of 23 natural storm events were sampled at the West 35th Street site between September 14, 1993 and April 28, 1994, and 20 events were sampled at the Convict Hill site between April 29, 1994 and December 9, 1994. An analysis of the data is presented in this chapter and includes the characteristics of each sampled storm event, an analysis of the underlying distribution of the data, the computation of descriptive statistics, analysis of constituent wash-off patterns, and an analysis of daily and seasonal trends.

Total suspended solids (TSS), nitrate, and oil and grease were selected for detailed analysis because (1) there is local concern regarding the input quantities of these constituents into the Edwards Aquifer and (2) these constituents best represent the wash-off patterns of all constituents in highway runoff. The characteristics of other highway runoff constituents are presented in the appendices noted throughout the chapter.

4.2 Storm Event Characteristics

Thirty-two rainfall simulations were conducted over active traffic during the study period and the characteristics of each event are presented in Table 4.2.1. Samples of runoff were collected over a 60 minute time period, and variations in the event duration were a result of equipment failure and other unforeseen circumstances. The variations in the measured flow are a result of adverse wind conditions that carried the spray outside of the sampling zone. Traffic volume during the simulated storm event ranged from 1,358 to 3,733 vehicles and varied with the time of day the simulation was conducted. The temperature during the simulated events varied with the season.

The duration of the antecedent dry period varied as a result of the simulator spray schedule. The Austin area experienced no rainfall from June 23, 1993 through August 31, 1993, which allowed for several simulations to be preceded by a 14-day dry

Table 4.2.1 Characteristics of Simulated Storm Events (Traffic Sessions)

Date	Event Duration (min)	Event Flow (l/m^2)	Vehicles During the Event	Temp (^0C)	Antecedent Dry Period (hrs)	Antecedent Traffic Count	Preceding Storm Flow (l/m^2)
7/6/93	60	19.9	3,132	30	241	548,020	58.5
7/12/93	50	14.2	3,637	30	141	328,670	20.9
7/20/93	35	11.3	1,673	30	192	473,380	14.9
7/27/93	50	15.6	2,521	31	166	405,540	11.8
8/10/93	65	19.9	3,361	31	335	811,060	16.3
8/24/93	25	3.4	1,358	32	335	811,060	20.9
9/23/93	60	15.5	3,610	31	268	578,260	22.6
10/7/93	60	15.8	3,733	26	267	644,990	1.8
11/4/93	60	18.3	3,092	21	25	68,060	9.3
11/17/93	60	18.5	3,618	12	25	66,120	3.3
12/1/93	60	17.9	3,406	12	334	734,000	19.5
12/10/93	45	5.4	2,709	12	214	547,260	18.8
12/16/93	60	13.6	3,989	12	83	230,750	4.2
1/4/94	60	16.0	2,689	11	310	610,250	16.4
1/11/94	60	18.1	2,910	17	21	50,710	0.5
1/13/94	60	18.1	2,879	14	4	16,090	3.9
2/3/94	60	16.7	2,956	7	132	282,170	0.3
2/17/94	60	16.1	3,139	14	160	365,750	10.3
2/24/94	60	17.5	2,995	10	47	85,410	22.9
3/1/94	60	14.1	3,282	12	6	32,860	12.6
3/10/94	60	16.9	3,352	9	26	77,920	36.2
3/17/94	60	14.8	3,352	19	37	78,240	13.9
4/8/94	60	16.2	3,337	19	65	168,396	10.4
4/13/94	60	15.7	3,116	19	42	112,264	1.8
4/20/94	60	16.2	3,116	22	17	42,099	2.9
5/12/94	60	16.1	3,116	27	233	561,320	9.0
5/26/94	60	22.0	3,116	26	213	505,188	0.3
5/31/94	60	16.3	3,282	28	35	112,264	26.3
6/8/94	60	20.5	3,238	31	118	280,660	18.6
6/16/94	60	19.2	3,433	29	18	84,198	10.3
7/1/94	60	18.7	3,190	30	118	304,420	48.6
7/14/94	60	17.8	3,050	31	310	733,620	20.8

period. At least one simulated storm event was produced having an antecedent dry period of each daily interval between 1 and 14 days. The total natural rainfall during the period of operation of the simulator was 444 mm, that is approximately one-half the average annual rainfall of 856 mm.

Three simulated storm events were conducted under "no-traffic" conditions, and the characteristics of these events are presented in Table 4.2.2. The no-traffic experiments were conducted by closing the sampling site to traffic and operating the rainfall simulator in the same manner as during a traffic event. The no-traffic events occurred on early Sunday morning's, as soon after sunrise as possible, to minimize disruption of highway use.

Table 4.2.2 Characteristics of Simulated Storm Events (No-Traffic Sessions)

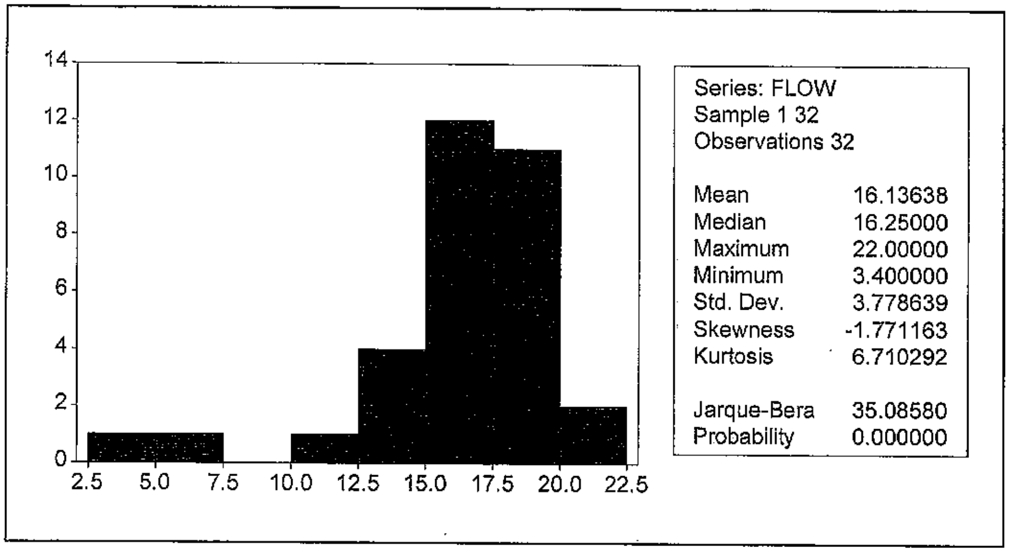
Date	Event Duration (min)	Event Flow (l/m^2)	Temp. (^0C)	Antecedent Dry Period (hrs)	Antecedent Traffic Count	Preceding Storm Flow (l/m^2)
9/12/93	60	21.5	28	283	668,550	19.8
2/6/94	60	22.5	17	68	167,090	18.8
6/26/94	60	22.4	31	53	140,330	1.0

A primary reason for using a rainfall simulator in highway runoff research is the control of all, or at least most, of the parameters that influence constituent loads in highway runoff. However, there are many factors beyond the control of the experiment that cause variation among the parameters that are suppose to be under "control." For example, the total volume of water sprayed during the simulated event was held constant for all simulated storm events; however, there was considerable variation in the volume of runoff recorded between simulated events because the spray was affected by "wind drift" and "traffic drag-out" differently during each simulation. The best the experimenter can do is repeat enough runs so that the variation in the "uncontrolled" parameters exhibit a normal distribution. The total volume of runoff, the total volume of traffic during the storm, and the total volume of flow during the preceding storm were all uncontrolled variables during the rainfall simulations. However, enough simulated storm events were conducted so that the probability of occurrence of each uncontrolled parameter is normally distributed. The normal distribution of uncontrolled parameters is illustrated in Figure 4.2.1. The units of the abscissa are the same units indicated in Table 4.2.1 and the frequency of occurrence is shown on the ordinate.

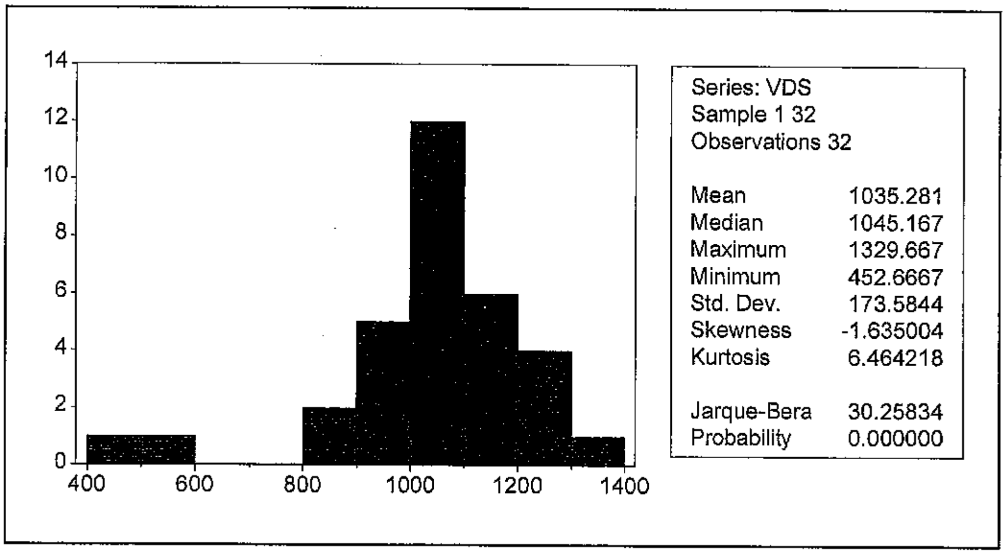
There are certain variables that affect the loading of constituents in highway runoff that the rainfall simulator was able to control. One of these is the duration of the antecedent dry period (ADP), which is controlled by the choice of the time and day that the simulated event is conducted. The volume of traffic during the antecedent dry period (ATC) was controlled by the ADP because of the nature of the traffic pattern. The experiments were designed to obtain a number of repetitions for each ADP between 1 and 14 days in length. Therefore, the frequency distribution for these variables is more rectangular than the distribution of the uncontrolled variables.

The frequency distributions for ADP and ATC are shown in Figure 4.2.2. The units of the abscissa are the same units indicated in Table 4.2.2, and the frequency of occurrence is shown on the ordinate.

Twenty-three natural storm events were sampled using automatic samplers at the same site as the simulated storm events (West 35th Street) between September 14, 1993 and April 28, 1994. The characteristics of these natural storm events are reported in Table 4.2.3. The second column of Table 4.2.3 titled "Event Duration (min)" reflects the total time interval that samples were collected during the storm and not necessarily the total duration of the storm. Sampling intervals during the natural storm events at the West 35th Street site ranged from 25 minutes to 830 minutes (13.8 hrs). The third column titled "Event Rainfall (mm)" is the volume of rainfall recorded during the sampling interval. Sampled rainfall volumes ranged from 0.25 mm to 19.28 mm. The fourth column titled "Vehicles During the Event" is the total number of vehicles recorded during the sampling interval. The average temperature recorded during the storm event by the National Weather Service Office, Austin, is reported in degrees Celsius. The duration of the antecedent dry period (hrs), the traffic count during the antecedent dry period, and the total volume of storm flow during the preceding storm event (L/m^2) also are reported in Table 4.2.3.

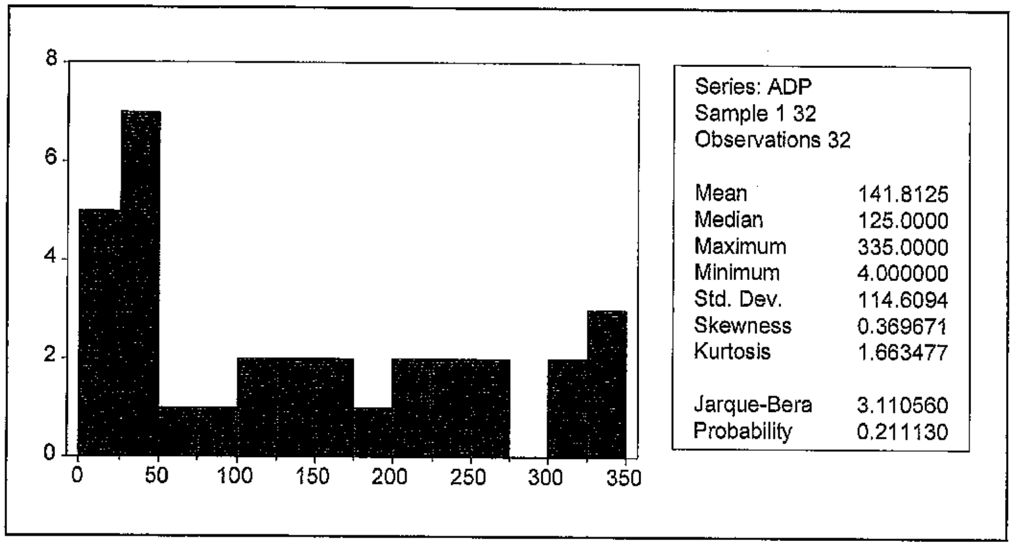


(a) Storm Event Runoff (L/m²)

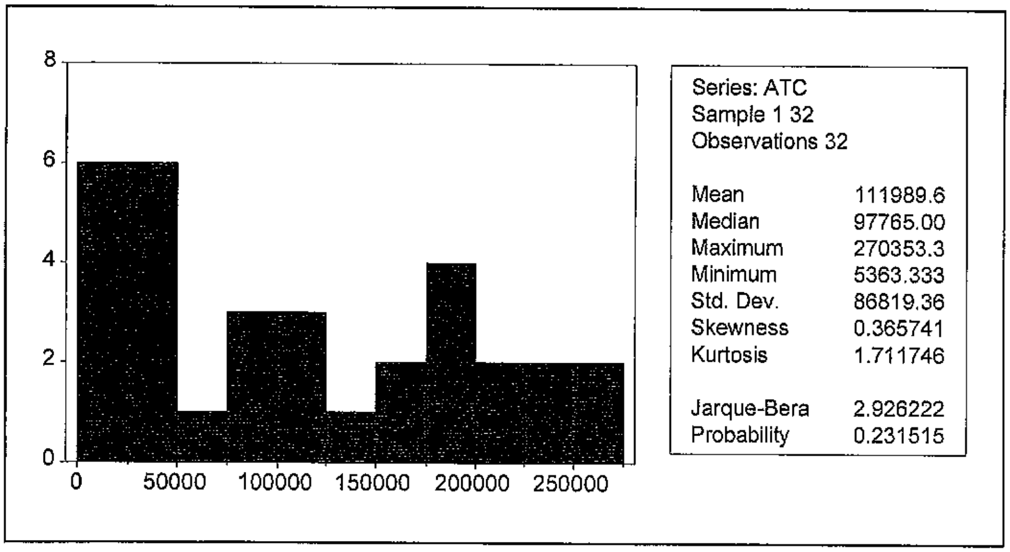


(b) Number of Vehicles during the Storm Event

Figure 4.2.1 Distribution of Uncontrolled Variables during Rainfall Simulations



(a) Duration of the Antecedent Dry Period (hrs)



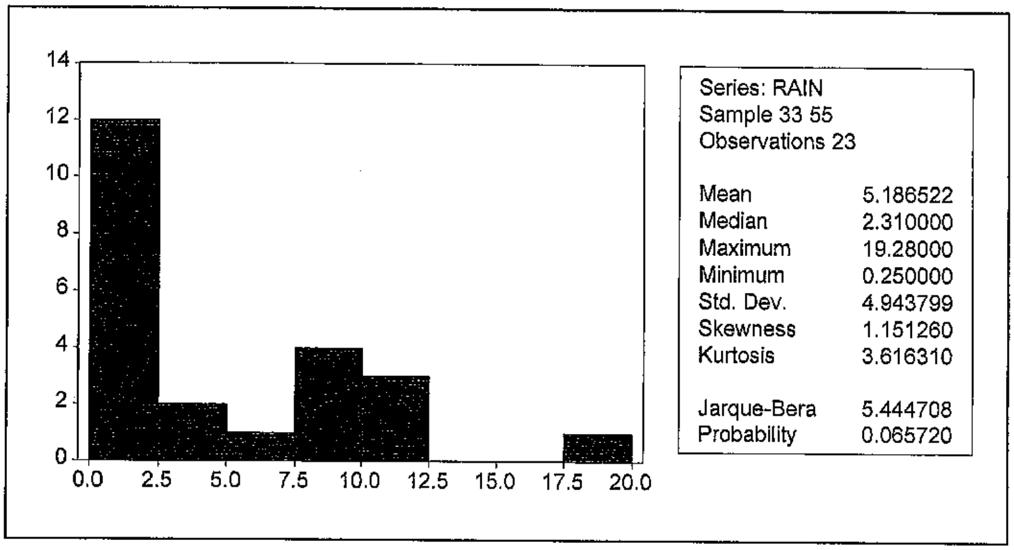
(b) Traffic Count during the Antecedent Dry Period

Figure 4.2.2 Distribution of Controlled Variables during Rainfall Simulations

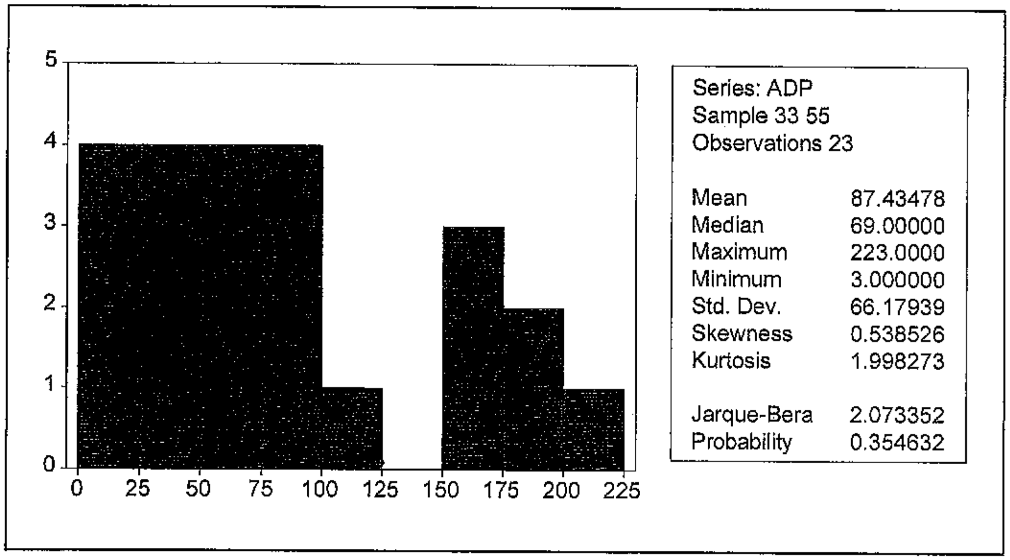
Table 4.2.3 Characteristics of Sampled Natural Storm Events (West 35th St. Site)

Date	Event Duration (min)	Event Rainfall (mm)	Vehicles During the Event	Temp. (^{0}C)	Antecedent Dry Period (hrs)	Antecedent Traffic Count	Preceding Storm Flow (l/m^2)
9/14/93	45	0.25	110	26	42	124,660	22.6
10/13/93	60	1.52	120	19	120	270,580	0.3
10/20/93	40	11.68	162	18	159	398,750	0.8
10/20/93	45	1.27	1,470	20	9	18,740	7.6
10/20/93	60	1.52	1,695	20	3	9,950	0.3
10/29/93	175	6.86	9,940	13	192	480,710	0.5
11/2/93	50	1.52	720	12	99	221,630	6.6
12/22/93	135	1.40	9,140	5	93	214,730	0.2
1/13/94	55	2.31	210	9	33	75,150	19.5
1/20/94	620	2.31	22,190	9	157	375,890	19.1
1/22/94	190	1.32	6,205	8	20	43,530	11.4
2/21/94	800	19.28	13,610	19	27	63,800	1.2
2/28/94	830	10.13	25,510	14	97	226,110	18.5
3/9/94	25	8.13	190	7	172	437,490	14.3
3/13/94	595	7.62	31,230	16	44	115,570	17.9
3/15/94	85	8.38	1,430	17	50	93,620	9.0
3/27/94	30	1.02	95	9	60	149,670	1.1
4/5/94	30	12.19	1,975	19	223	500,200	2.3
4/11/94	205	1.78	10,460	22	69	173,320	17.2
4/15/94	25	4.32	2,425	23	50	146,180	16.7
4/19/94	25	3.05	2,400	23	95	231,740	3.3
4/28/94	50	1.52	3,620	28	188	483,980	17.4
4/28/94	170	9.91	7,190	19	9	31,220	1.0

The distribution of the sampled rainfall volumes and the duration of the antecedent dry periods are shown in Figure 4.2.3. The distribution of the rainfall exhibits normality, as evidenced by a 94% confidence level using the Jarque-Bera test (refer to Section 4.3 for details of the Jarque-Bera test). The distribution of the duration of the antecedent dry period is expected to be exponential (Chow et. al., 1988). However, the distributions of the recorded duration of the antecedent dry periods for the sampled natural events at the West 35th Street site are rectangular, similar to what would be expected if the duration of dry period had been controlled. This is a result of the rainfall simulations, which were conducted during the dry period between natural storms.



(a) Event Rainfall (mm)



(b) Antecedent Dry Period (hrs)

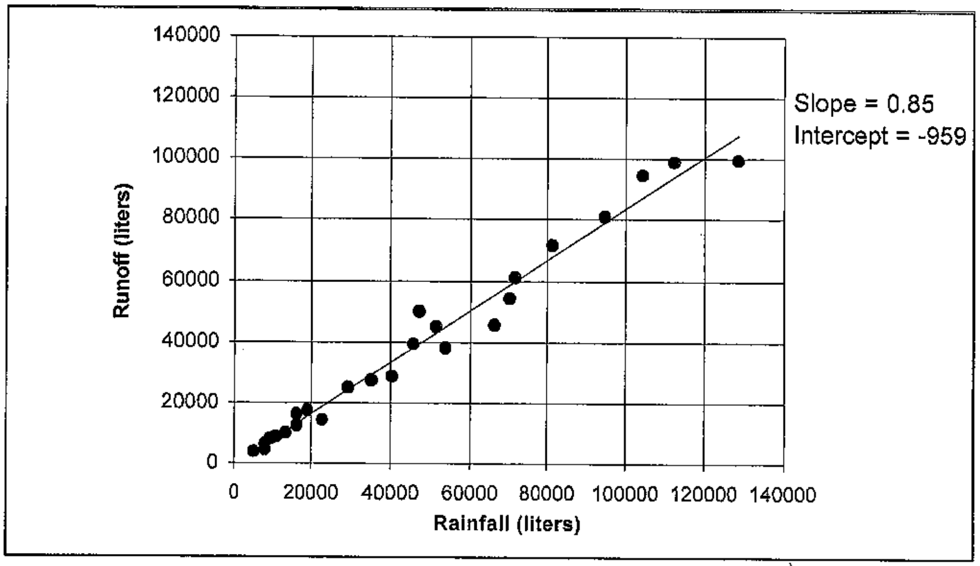
Figure 4.2.3 Distribution of Natural Rainfall Event Variables

Twenty natural storm events were sampled at the Convict Hill site between April 29, 1994 and December 9, 1994. The characteristics of these storms are reported in Table 4.2.4. Similar to the characteristics reported in Table 4.2.3, the event duration, event rainfall, vehicles during the storm, and average temperature reported in Table 4.2.4 each represent observations during the sampling interval of the storm.

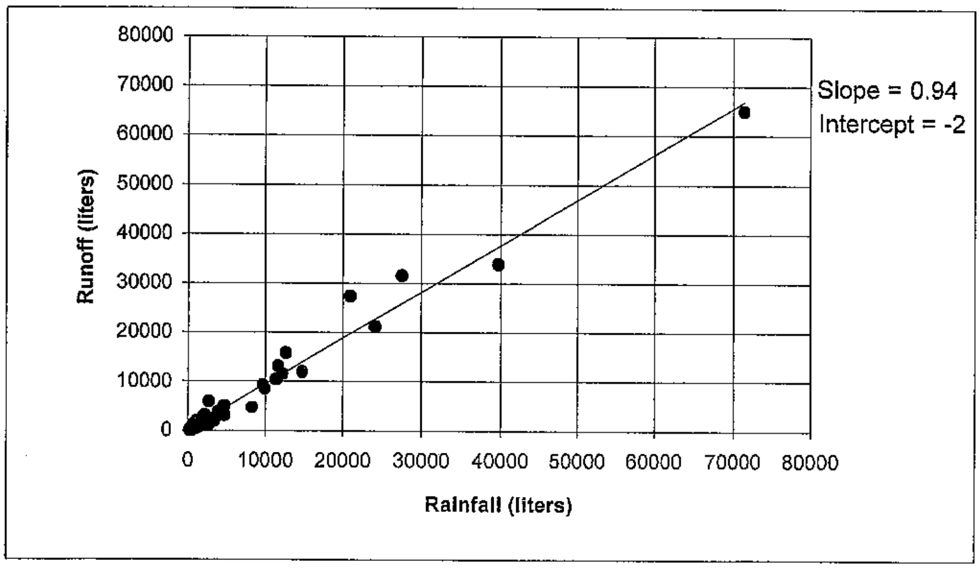
The relationship between rainfall volume and runoff volume is presented in Figure 4.2.4 for the West 35th Street watershed and the Convict Hill watershed. The reported rainfall volume and runoff volume are for the entirety of the storm event, not the

Table 4.2.4 Characteristics of Sampled Natural Storm Events (Convict Hill)

Date	Event Duration (min)	Event Rainfall (mm)	Vehicles During the Event	Temp (^{0}C)	Antecedent Dry Period (hrs.)	Antecedent Traffic Count	Preceding Storm Flow (l/m^2)
4/29/94	27	2.29	5	24	12	3,528	4.6
5/2/94	228	2.79	1388	17	6	1,764	1.5
5/13/94	40	11.68	382	21	261	76,734	3.8
5/14/94	10	6.35	39	23	30	8,820	28.7
5/16/94	112	1.78	109	23	24	7,056	19.3
6/10/94	20	4.32	115	29	152	44,688	3.6
6/19/94	12	5.84	39	28	24	7,056	5.1
6/21/94	16	4.06	24	28	43	12,642	6.9
8/8/94	15	4.57	39	31	48	14,112	0.5
8/9/94	75	9.14	102	26	6	1,764	6.1
8/16/94	52	7.62	357	28	175	51,450	78.2
8/22/94	94	6.86	514	27	19	5,586	1.5
9/7/94	27	4.32	173	29	166	48,804	2.0
9/8/94	7	6.86	2	24	12	3,528	4.3
9/9/94	37	11.94	354	24	16	4,704	44.4
10/7/94	133	9.40	452	24	75	22,050	0.5
10/14/94	195	6.10	500	18	155	45,570	140.2
10/25/94	68	14.22	11	18	159	46,746	22.1
10/27/94	503	5.33	2975	12	43	12,642	41.1
11/5/94	34	12.45	6	19	193	56,742	5.3
11/15/94	308	3.81	1956	14	240	70,560	24.6
12/2/94	48	7.62	362	13	333	97,902	1.5
12/9/94	139	2.29	109	10	150	44,100	7.4



(a) West 35th Street Sampling Site



(b) Convict Hill Sampling Site

Figure 4.2.4 Rainfall / Runoff Relationship water quality sampling interval. The runoff coefficient is 0.85 at the West 35th Street site and 0.94 at the Convict Hill Site. This difference is possibly a result of the West 35th Street watershed being ten times longer than the Convict Hill watershed (Table 3.1.1).

4.3 Distribution of Highway Runoff EMCs

The lognormal distribution is the most commonly used probability density model for environmental contaminant data (Gilbert, 1987). The event mean concentrations (EMCs) of constituents in urban runoff, and highway runoff in particular, have been described by the lognormal distribution (USEPA, 1983; Driscoll et. al., 1990). The shape of the underlying distribution must be known in order to select the statistics that will best estimate the parameters of the population. Methods that are used to evaluate distributional shape include (1) probability plotting, (2) examination of the coefficient of variation, (3) skewness, (4) kurtosis, and (5) normality testing with the Jarque-Bera statistic.

Probability plotting is commonly used to determine the shape of an underlying distribution. Probability plotting methods exist for normal, lognormal, Weibull, gamma, and exponential distributions (Gilbert, 1987). Driscoll et al. (1990) extensively used log probability plots to demonstrate the lognormality of the EMCs of highway runoff constituents. Probability plotting can provide a quick determination of whether the data are likely to have come from a specific type of distribution; however, the principal application of the method is the determination of the mean and variance of the distribution once the shape is known.

Normal and lognormal probability plots were constructed for all highway runoff constituents in this study. The results indicate that each constituent is best represented by a skewed distribution. It is risky, however, to rely on the "straightness" of the plotted points to determine the normality or non-normality of the distribution. Although a probability plot can detect a skewed distribution, the plot cannot evaluate the amount of skewness, a factor that is imperative in the selection of descriptive statistics. Therefore, probability plots have limited value for the determination of distributional shape. The normal and lognormal probability plots for the TSS data collected at the West 35th Street site are presented in Figures 4.3.1.

The properties of skewness and kurtosis each measure an aspect of non-normality. Skewness (S) is the standardized third cumulant defined as:

$$S = \frac{\frac{1}{N}\sum_{n=1}^{N}(y_n - \bar{y})^3}{\sigma^3} \qquad (4.3.1)$$

where: N = sample size;

y = value of the observation;

$\bar{y}$ = sample mean;

σ = standard deviation of the sample.

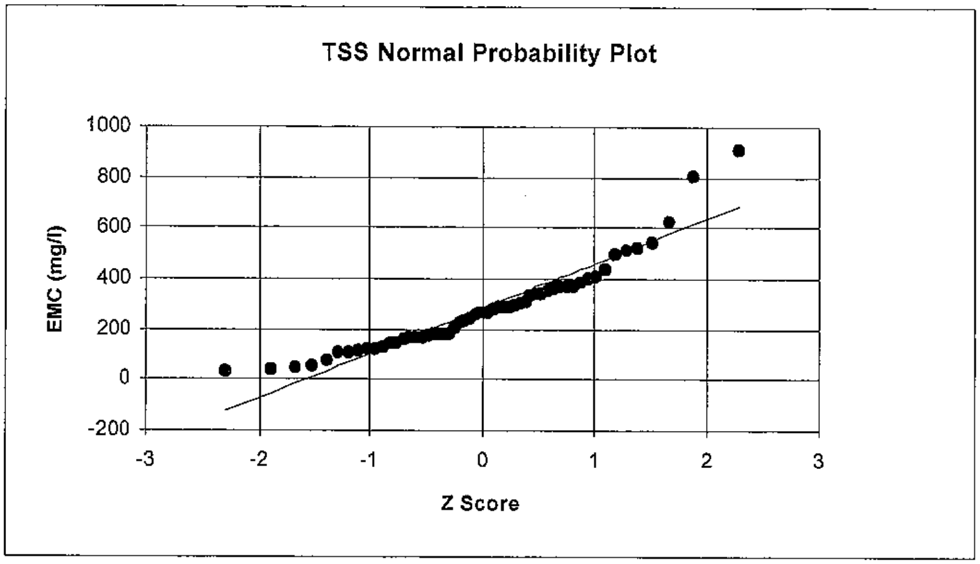
If the distribution is skewed to the left, then S is negative and if the distribution is skewed to the right, then S is positive. For a symmetrical distribution, S is equal to zero.

Kurtosis (K) is the standardized fourth cumulant defined as:

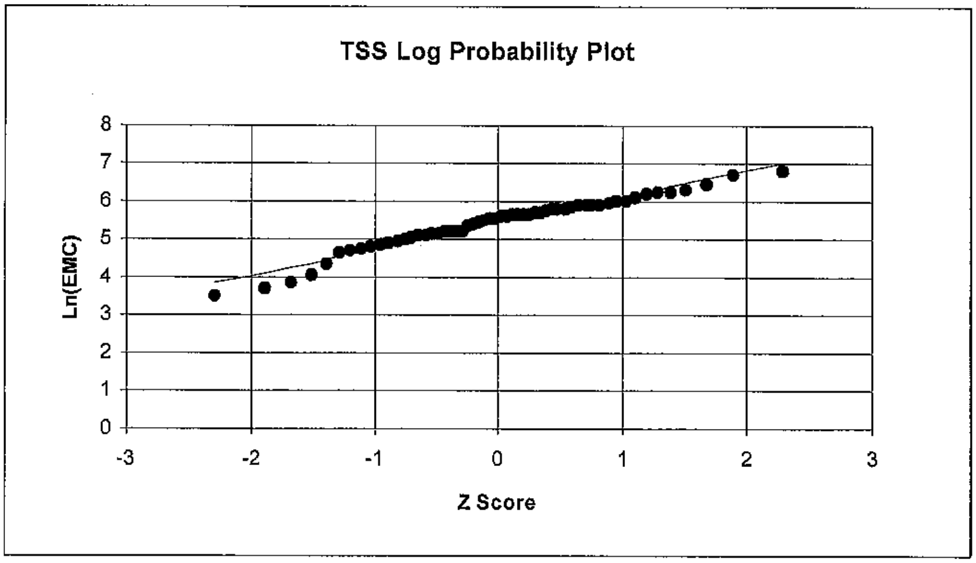
$$K = \frac{\frac{1}{N}\sum_{n=1}^{N}(y_n - \bar{y})^4}{\sigma^4} - 3 \qquad (4.3.2)$$

For a normal distribution, K is equal to zero. If K is positive, the distribution is said to be leptokurtic and typically has less pronounced "shoulders" and heavier "tails" than the normal distribution. If K is negative, the distribution is said to be platykurtic and typically has squarer shoulders and lighter tails than the normal distribution (Box and Tiao, 1973).

Histograms of the event mean concentrations for TSS, nitrate, and oil and grease are presented in Figures 4.3.2, 4.3.3, and 4.3.4 respectively. The skewness and kurtosis are given in each figure. These plots were produced using MicroTSP Econometric Views software (Quantitative Micro Software, Irvine, CA). The equation used by this software to calculate kurtosis does not subtract three from the standardized fourth cumulant as shown in Equation 4.3.2. Therefore, the kurtosis of a normal distribution is equal to three



(a)



(b)

Figure 4.3.1 Normal and Lognormal Probability Plots for the TSS Data

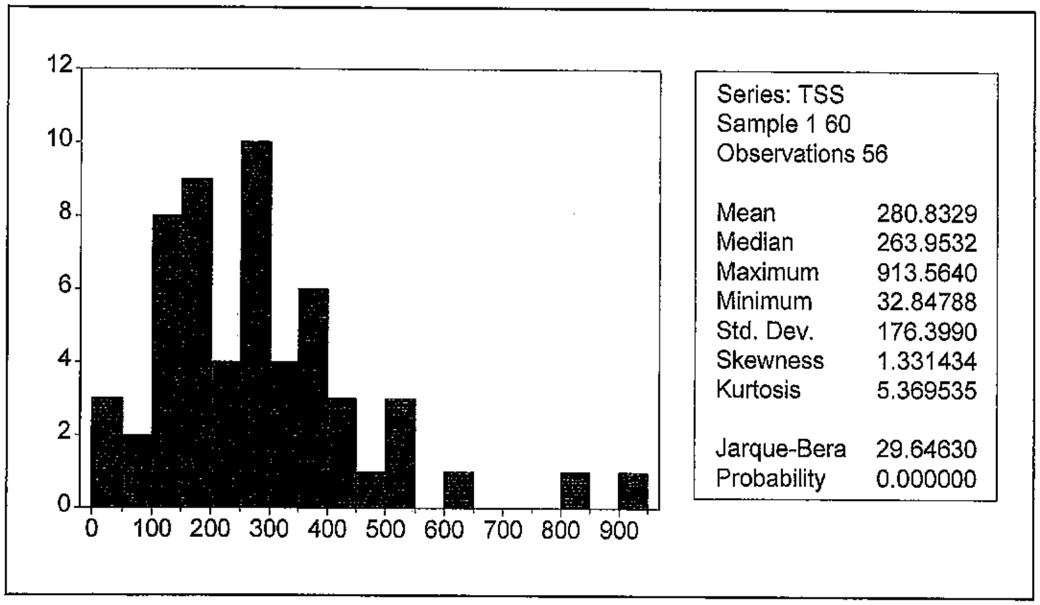


Figure 4.3.2 Histogram of TSS Observations

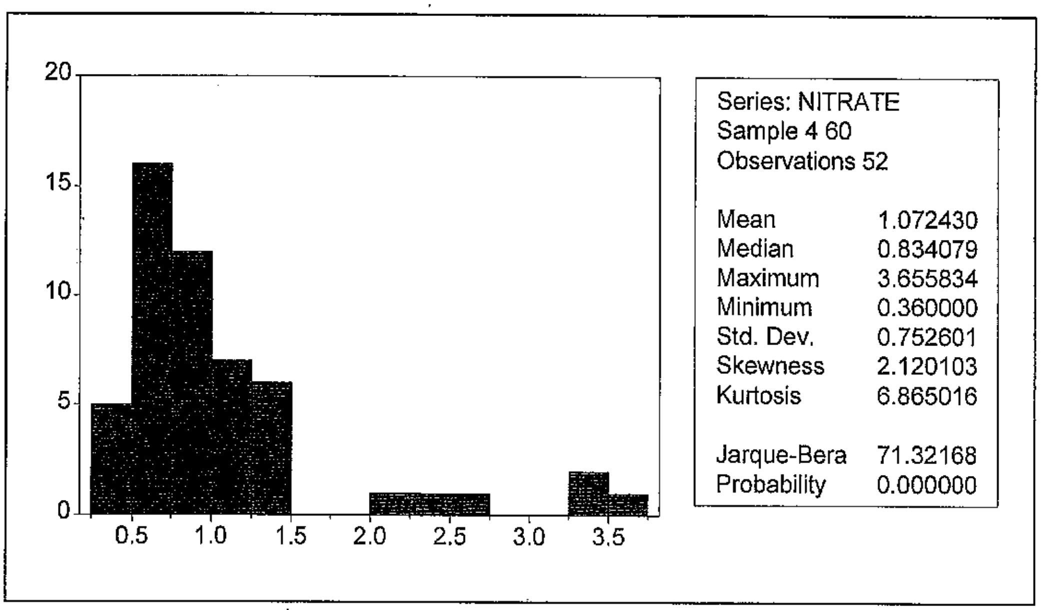


Figure 4.3.3 Histogram of Nitrate Observations

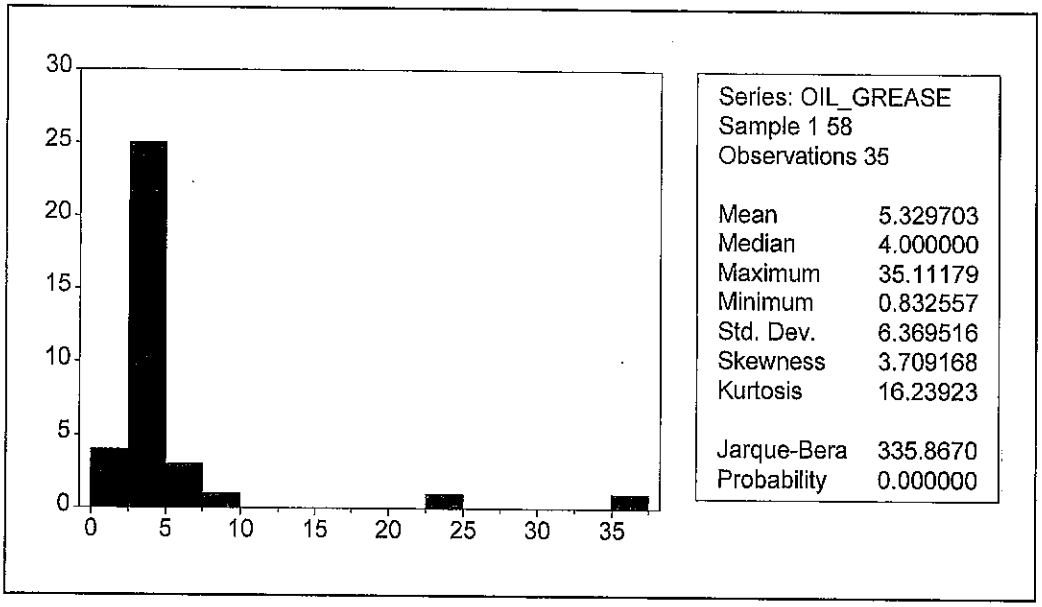


Figure 4.3.4 Histogram of Oil and Grease Observations

in these results. The skewness and kurtosis results presented in Figures 4.3.2, 4.3.3, and 4.3.4 indicate that there is positive skew, or lognormality, in the underlying distributions of highway constituent EMCs.

The Jarque-Bera statistic tests whether a series is normally distributed (Quantitative Micro Software, 1994). The Jarque-Bera statistic is distributed chi-squared (χ^2) with two degrees of freedom under the null hypothesis of normality. The critical value of χ^2 is 5.99 at a 0.95 confidence level. The Jarque-Bera statistic, J, is calculated as:

$$J = \frac{N}{6}[S^2 + 0.25(K)^2] \qquad (4.3.3)$$

The value of the Jarque-Bera statistic and associated probability is included in the histograms presented in Figures 4.3.2, 4.3.3, and 4.3.4. The results of the Jarque-Bera test indicate that the skew in the underlying distributions of the highway constituent EMCs is not statistically distinguishable from a normal distribution.

The amount of skew in the distribution is an important measure in the selection of descriptive statistics. The arithmetic mean, median, and variance of a sample is statistically an unbiased estimator of the true population parameters regardless of the shape of the underlying distribution; however, it is the minimum variance unbiased (MVU) estimator only if the underlying distribution is normal. The MVU estimators can be derived for a lognormal distribution and are presented in Gilbert (1987). Since the normal distribution is a special case of the skewed distribution (i.e., skewness = 0), the normal MVU estimators will provide better estimates if the distribution has little or no skew, whereas the lognormal MVU estimators will be a better estimate if there is a large amount of skew in the distribution. The relative amount of variation in the distribution determines that estimators are the best to use. The normal estimators are preferred if the coefficient of variation is believed to be less than 1.2 (Koch and Link, 1980). All of the data collected during both simulated and natural events had coefficients of variation less than 1.2, which suggests the use of the normal estimators. This result is consistent with the result of the Jarque-Bera test.

The probability plots for all highway runoff constituents are presented in Appendix D, and the histograms for all highway runoff constituents are presented in Appendix E. The units of the abscissa are mg/L and the frequency of occurrence is shown on the ordinate.

4.4 Descriptive Statistics

The event mean concentration for each storm event sampled is shown in Tables 4.4.1 through 4.4.4. The median values of the event mean concentrations (EMC) measured during all sampled storm events are presented in Table 4.4.5. The values reported for all natural storm events are the EMCs observed during the event and have not been corrected for any of the constituents in the rain water. The EMCs for simulated storm events have been corrected for the background constituents in Austin tap water.

The relative variation observed in EMCs among different storm events is given by the coefficient of variation (i.e., the standard deviation divided by the mean) enclosed by

Table 4.4.1 Event Mean Concentrations for Simulated Rainfall Events with Traffic

DATE	Flow (liters)	TSS (mg/L)	VSS (mg/L)	BOD (mg/L)	COD (mg/L)	TC (mg/L)	DTC (mg/L)	N (mg/L)	TP (mg/L)	O&G (mg/L)	Cu (mg/L)	Fe (mg/L)	Pb (mg/L)	Zn (mg/L)
7/6/93	86773	522	54	4.1	92	44	18	N/A	0.34	2.5	0.020	4.2	N/A	0.84
7/12/93	61839	352	45	5.3	101	63	23	N/A	0.39	3.8	0.007	5.4	N/A	0.26
7/20/93	49054	291	23	9.2	139	88	46	N/A	0.54	4.7	0.010	4.0	N/A	0.25
7/27/93	67801	298	23	8.4	72	48	24	0.73	0.28	4.7	0.010	3.2	N/A	0.08
8/10/93	86797	260	24	N/A	122	64	28	0.75	0.38	4.9	0.010	2.8	N/A	0.14
8/24/93	14858	622	55	27.7	182	113	74	1.38	0.84	4.0	0.009	6.7	N/A	0.51
9/23/93	67372	264	38	12.5	100	60	32	N/A	0.41	4.0	0.069	4.2	N/A	0.27
10/7/93	68843	509	41	8.2	126	74	26	1.24	0.51	2.3	0.040	5.5	N/A	0.49
11/4/93	79702	499	54	9.5	83	62	21	0.57	0.37	4.2	0.009	6.6	0.036	0.05
11/17/93	80837	264	29	3.8	86	42	16	0.55	0.12	2.5	0.018	4.5	0.065	0.05
12/1/93	78187	337	38	4.9	120	28	21	0.81	0.42	2.6	0.027	3.9	0.040	0.21
12/10/93	23719	364	40	5.4	118	55	24	1.24	0.35	3.4	0.015	4.7	0.110	0.23
12/16/93	59355	335	25	5.2	109	60	20	0.88	0.30	5.4	0.029	5.3	0.058	0.14
1/4/94	69708	400	59	5.4	39	102	25	0.79	0.20	3.7	0.029	7.6	0.181	0.05
1/11/94	79077	170	33	2.4	68	37	16	0.68	0.23	3.0	0.033	3.6	0.021	0.03
1/13/94	78793	337	41	2.2	93	54	18	0.64	0.35	3.9	0.021	4.9	0.048	0.17
2/3/94	72964	371	45	4.5	76	54	17	0.69	0.21	3.0	0.024	5.1	0.153	0.21
2/17/94	70200	441	61	4.7	111	76	18	0.61	0.33	4.5	0.029	7.8	0.183	0.29
2/24/94	76389	299	22	3.7	64	46	17	N/A	0.25	2.9	0.025	4.9	0.106	0.19
3/1/94	61626	225	17	3.2	81	61	16	N/A	0.28	4.0	0.021	5.1	0.116	0.17
3/10/94	73683	280	32	3.6	70	42	14	0.55	0.21	3.0	0.015	4.1	0.082	0.12
3/17/94	64314	409	42	3.7	49	62	12	0.55	0.33	N/A	0.022	5.7	0.092	0.15
4/8/94	70692	165	25	4.1	68	38	15	0.78	0.09	N/A	0.033	3.2	0.084	0.12
4/13/94	68251	237	17	5.6	84	40	16	0.64	0.24	N/A	0.023	2.9	0.063	0.15
4/20/94	70749	208	22	3.0	54	25	9	0.58	0.16	N/A	0.018	2.2	0.057	0.11

Table 4.4.1 Event Mean Concentrations for Simulated Rainfall Events with Traffic (Continued)

DATE	Flow (liters)	TSS (mg/L)	VSS (mg/L)	BOD (mg/L)	COD (mg/L)	TC (mg/L)	DTC (mg/L)	N (mg/L)	TP (mg/L)	O&G (mg/L)	Cu (mg/L)	Fe (mg/L)	Pb (mg/L)	Zn (mg/L)
5/12/94	70162	N/A	N/A	3.6	54	30	13	0.71	0.25	N/A	0.022	2.2	0.011	0.08
5/26/94	95733	143	14	5.4	91	37	24	1.08	0.23	N/A	0.019	2.8	0.024	0.13
5/31/94	70938	242	37	3.0	85	47	13	0.90	0.32	N/A	0.023	6.3	0.120	0.17
6/8/94	89222	166	23	3.9	68	59	13	0.80	0.16	N/A	0.027	4.1	0.086	0.19
6/16/94	83619	183	19	2.7	67	33	15	0.65	0.16	N/A	0.023	3.5	0.084	0.14
7/1/94	81575	180	34	6.2	92	44	18	1.03	0.14	1.0	N/A	N/A	N/A	N/A
7/14/94	77771	182	32	6.2	87	33	19	0.99	0.27	3.2	0.011	3.1	0.014	0.16

Table 4.4.2 Event Mean Concentrations for Simulated Events without Traffic

Date	Flow (liters)	TSS (mg/L)	VSS (mg/L)	BOD (mg/L)	COD (mg/L)	TC (mg/L)	DTC (mg/L)	N (mg/L)	TP (mg/L)	O&G (mg/L)	Cu (mg/L)	Fe (mg/L)	Pb (mg/L)	Zn (mg/L)
9/12/93	93689	26	2	2.1	19	14	14	0.73	0.08	0.0	0.009	0.9	0.141	0.027
2/6/94	98023	67	6	2.1	24	15	13	0.55	0.07	0.4	0.009	1.5	0.023	0.050
6/26/94	97720	81	7	2.1	30	14	12	0.56	0.08	0.0	0.009	1.2	0.022	0.060

Table 4.4.3 Event Mean Concentrations for Natural Rainfall Events at the West 35th Street Sampling Site

DATE	Flow	TSS	VSS	BOD	COD	TC	DTC	N	TP	O&G	Cu	Fe	Pb	Zn
	(liters)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
9/14/93	450	58	26	19	248	N/A	N/A	2.74	0.61	4.2	0.04	0.3	0.02	N/A
10/13/93	1832	106	26	25	190	84	72	3.26	0.61	3.2	0.04	1.2	0.44	0.28
10/20/93	10243	385	36	12	42	32	15	0.52	0.30	0.8	0.05	2.0	0.12	0.18
10/20/93	1264	157	42	28	195	79	33	1.11	0.50	4.3	0.08	5.6	0.24	0.36
10/20/93	1601	116	47	28	185	68	31	1.07	0.47	4.7	0.08	4.4	0.23	0.34
10/29/93	26957	147	33	18	126	53	33	0.84	0.33	9.6	0.06	2.5	0.09	0.24
11/2/93	5620	175	44	21	209	82	45	2.11	0.39	5.0	0.07	2.7	0.19	0.29
12/22/93	6271	48	8	0	149	66	38	1.32	0.30	5.9	0.06	3.5	0.13	0.22
1/13/94	10408	123	24	6	142	35	33	1.41	0.15	4.1	0.01	0.7	0.03	0.06
1/20/94	10444	286	81	40	336	145	80	3.44	1.04	35.1	0.05	5.7	0.04	0.36
1/22/94	5988	79	40	43	264	128	85	2.36	0.51	24.0	0.04	5.3	0.05	0.30
2/21/94	87156	370	40	5	88	16	11	0.37	0.33	N/A	0.12	3.1	0.12	0.23
2/28/94	45877	N/A	N/A	N/A	N/A	39	10	0.43	N/A	N/A	0.04	7.7	0.27	0.59
3/9/94	65514	N/A	N/A	7	64	33	13	0.49	0.27	N/A	N/A	4.7	0.15	0.31
3/13/94	31975	40	20	9	75	26	19	1.08	0.12	N/A	N/A	N/A	N/A	N/A
3/15/94	36692	313	37	9	79	46	14	0.41	0.30	N/A	0.02	4.4	0.10	0.21
3/27/94	1964	131	57	15	90	N/A	N/A	1.03	N/A	N/A	N/A	N/A	N/A	N/A
4/5/94	41803	808	86	23	135	79	20	0.73	0.70	N/A	0.05	9.7	0.23	0.26
4/11/94	7627	540	114	23	292	153	53	0.96	0.73	N/A	0.07	7.8	0.21	0.51
4/15/94	13203	914	130	22	203	80	20	0.00	0.93	N/A	0.05	7.5	0.18	0.40
4/19/94	12084	N/A	N/A	N/A	217	61	28	1.39	0.76	N/A	N/A	N/A	N/A	N/A
4/28/94	3471	126	44	56	452	123	89	3.66	1.09	N/A	N/A	N/A	N/A	N/A
4/28/94	31525	266	49	10	80	39	18	0.62	0.39	N/A	0.02	2.0	0.06	0.16

Table 4.4.4

Event Mean Concentrations for Natural Rainfall Events at the Convict Hill Sampling Site

Date	Flow (liters)	TSS mg/L	VSS mg/L	BOD mg/L	COD mg/L	TC mg/L	DTC mg/L	N mg/L	TP mg/L	O&G mg/L	Cu mg/L	Fe mg/L	Pb mg/L	Zn mg/L
4/29/94	1420	239	39	10	72	49	28	1.47	0.062	NA	0.015	NA	NA	0.063
5/2/94	1420	86	23	6	78	41	23	0.89	0.109	NA	0.020	2.9	NA	0.081
5/13/94	3975	403	42	5	92	39	17	0.71	0.260	NA	0.010	8.9	0.141	0.174
5/14/94	1325	348	20	7	NA	29	11	0.78	0.358	1.5	0.009	4.0	0.090	0.099
5/16/94	1514	6	6	7	46	24	21	0.75	0.078	2.0	0.002	1.0	0.033	0.053
6/10/94	1514	512	50	24	174	89	43	NA	0.380	NA	0.032	11.8	0.223	0.310
6/19/94	1514	4	0	5	75	20	20	0.60	NA	1.9	0.011	4.5	0.100	0.292
6/21/94	2271	40	12	6	68	31	22	1.61	0.112	2.4	0.001	0.5	0.171	0.033
8/8/94	2271	176	68	13	114	NA	NA	NA	0.200	8.1	0.003	2.2	0.021	0.042
8/9/94	3407	42	14	3	32	11	5	0.21	0.048	1.6	0.001	0.9	0.007	0.010
8/16/94	3407	80	8	10	39	23	21	1.80	NA	1.7	0.001	1.1	0.007	0.028
8/22/94	3407	40	12	3	15	14	11	0.43	0.060	0.8	0.002	0.8	0.012	0.017
9/7/94	1703	292	44	16	49	22	19	1.02	0.080	1.8	0.009	1.8	0.017	0.079
9/8/94	3407	0	0	5	17	5	5	0.53	0.025	0.4	0.003	0.3	0.016	0.022
9/9/94	6814	3	2	3	10	5	5	0.40	0.025	1.3	0.008	0.5	0.007	0.028
10/7/94	5110	68	7	8	49	21	16	0.60	0.077	0.9	0.003	0.8	0.011	0.019
10/14/94	4826	24	16	6	43	32	14	0.78	0.030	2.4	0.003	0.9	0.021	0.055
10/25/94	6814	146	15	4	19	18	8	NA	0.041	0.9	0.003	0.7	0.009	0.016
10/27/94	5962	68	16	4	40	24	10	NA	0.113	1.8	0.007	2.5	0.014	0.215
11/5/94	6814	192	24	3	29	19	8	NA	0.078	0.9	0.007	1.5	0.013	0.045
11/15/94	1136	12	4	5	33	20	17	NA	0.060	1.7	0.006	1.2	0.014	0.081
12/2/94	3407	156	28	5	39	21	5	0.39	0.070	7.6	0.007	1.4	0.007	0.052
12/9/94	1420	136	28	3	29	13	12	0.55	0.005	NA	NA	NA	NA	NA

Table 4.4.5
Median Event Mean Concentrations (mg/L)

	West 35th St. Traffic Simulation*	West 35th St. No-Traffic Simulation*	West 35th St. Natural Event	Convict Hill Natural Event
TSS	291 (0.4)	67 (0.5)	157 (0.9)	83 (1.1)
VSS	33 (0.4)	6 (0.5)	42 (0.6)	16 (0.9)
BOD_5	4.7 (0.8)	2.1 (0.0)	15.3 (0.7)	5.4 (0.8)
COD	86 (0.3)	24 (0.2)	142 (0.6)	44 (1.0)
Total Carbon	51 (0.4)	14 (0.02)	57 (0.6)	22 (0.7)
Dis. Total Carbon	18 (0.6)	13 (0.1)	28 (0.7)	16 (0.6)
Nitrate	0.74 (0.3)	0.56 (0.2)	1.00 (0.8)	0.73 (0.6)
Total Phosphorus	0.28 (0.5)	0.08 (0.1)	0.41 (0.5)	0.08 (1.0)
Oil & Grease	3.7 (0.3)	0.4 (1.7)	5 (1.2)	2 (1.0)
Copper	0.022 (0.5)	0.009 (0.03)	0.049 (0.6)	0.006 (1.0)
Iron	4.2 (0.3)	1.2 (0.2)	3.5 (0.8)	1.4 (1.2)
Lead	0.082 (0.6)	0.023 (1.1)	0.123 (0.8)	0.016 (1.3)
Zinc	0.16 (0.8)	0.050 (0.4)	0.263 (0.7)	0.053 (1.1)

* West 35th St. simulation data has been corrected for the background in Austin tap water; Number in parenthesis is the coefficient of variation.

parentheses. The relative variation for most constituents is less during the simulated events than during natural events. This phenomenon is a result of the "steady-state" nature (e.g., a constant rainfall, runoff, and traffic rate) of the simulated rain storm. The similar event duration and sampling protocols among the simulated storms also contributed to the lower variations observed in the simulated EMCs.

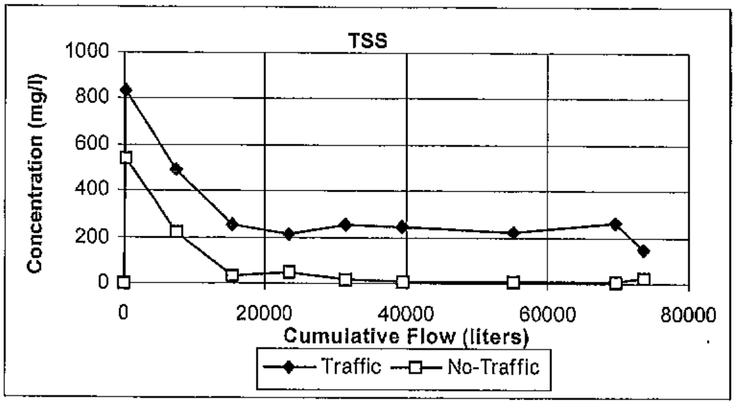
The EMCs for natural storm events are higher than the simulated storm event EMC values for every constituent except TSS. These results are attributed to a lack of adequate sampling coverage over the entire duration of most of the natural storm events. The automatic sampler was programmed with a predetermined sampling sequence to sample the duration of the expected storm. However, if the rainfall intensity is higher than anticipated, only the first part of the storm is sampled. Concentrations of constituents were observed to be higher in the earlier stages of the runoff event, and in particular during the rising leg of the hydrograph, for all of the constituents under study. The values for natural storm EMCs would have been smaller had the entirety of each natural storm been sampled. Likewise, sample collection during the simulated events always lasted the entirety of the simulated storm event.

The higher concentrations of TSS observed during the simulated events are explained by the intensity of the simulated rainfall. The simulated storms were, on average, a higher intensity rainfall than the natural storms. The higher flow rates associated with the simulated events moved more of the heavier dirt particles than the smaller natural storms.

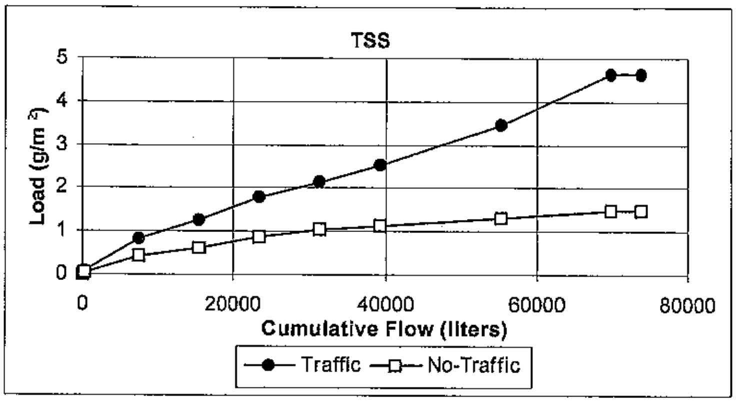
4.5 Constituent Wash-Off Patterns

The wash-off patterns observed during the simulated storm events for TSS, nitrate, and oil and grease are shown graphically in Figures 4.5.1a-c, 4.5.2a-c, and 4.5.3a-c, respectively. Part A of these figures shows the variation in the concentration of the constituents during the simulated storm events. A period of high concentration is evident at the beginning of the storm for each constituent. The period of high concentration, however, occurs simultaneously with the rising leg of the hydrograph and ends at the time of concentration for the watershed. It is difficult to ascertain from the graph if the high concentration in the beginning of the storm results from a large amount of material being washed from the highway early in the storm event (e.g., a true first flush) or from the smaller volume of water on the watershed at the start of the storm.

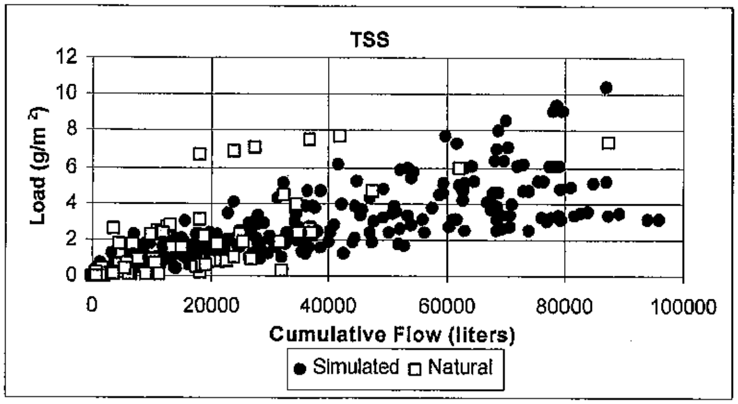
The loads for TSS, nitrate, and oil and grease observed during the simulated events are shown in Figures 4.5.1b, 4.5.2b, and 4.5.3b, respectively. These plots indicate that load increases linearly with increased flow volume for each constituent as long as there is traffic to provide an input of constituent mass. The cumulative load curve becomes relatively flat for the no-traffic simulations, which is a result of the lack of constituent mass in the runoff. The single exception is nitrate. The cumulative load curve for nitrate continues to increase even under no-traffic conditions. This phenomenon is explained by (1) the mobility of nitrate, because of its anionic form (NO_3), does not require the energy associated with vehicles (i.e., the forces resulting from tires and vehicle-induced winds) to mobilize in the runoff and (2) the amount of nitrates in the tap water used for the rainfall simulations.



(a) Median TSS Concentration During a Simulated Storm Event

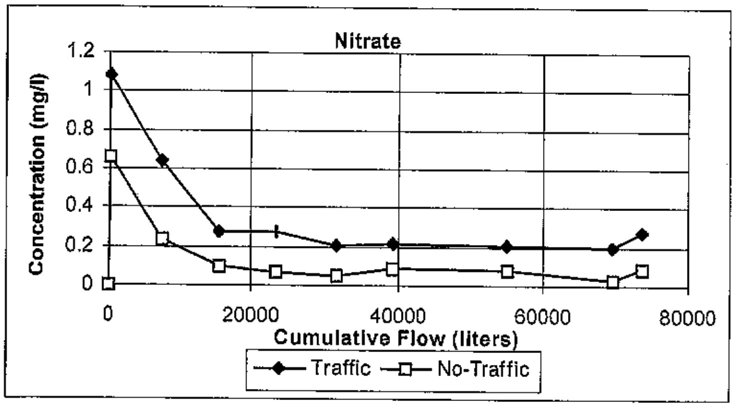


(b) Median TSS Load During a Simulated Storm Event

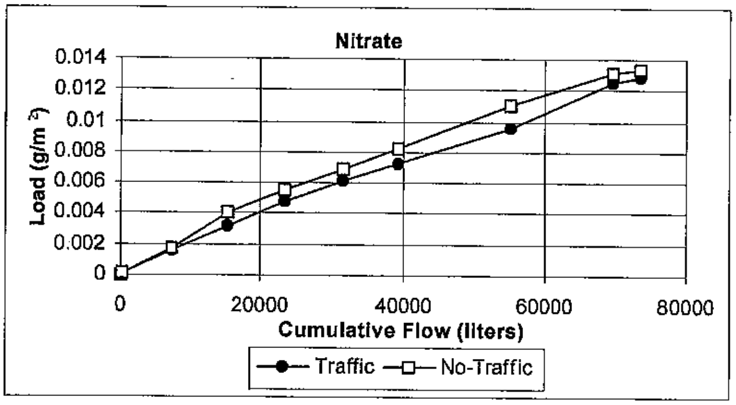


(c) TSS Load During Natural and Simulated Storm Events

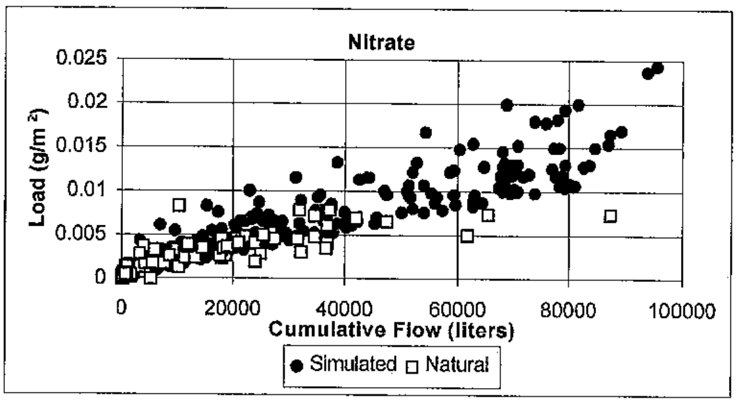
Figure 4.5.1



(a) Median Nitrate Concentration During a Simulated Storm Event

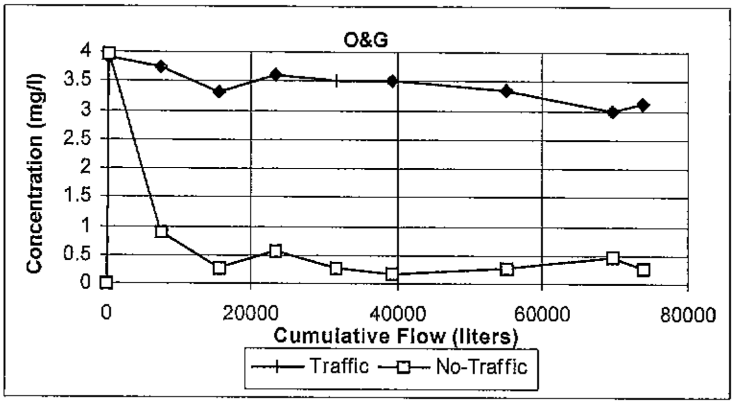


(b) Median Nitrate Load During a Simulated Storm Event

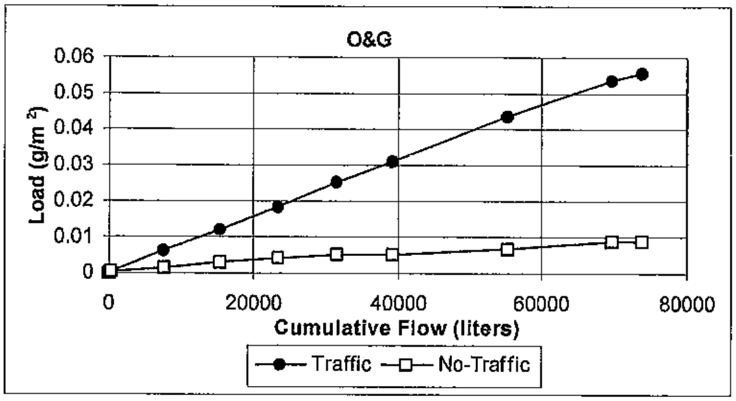


(c) Nitrate Load During Natural and Simulated Storm Events

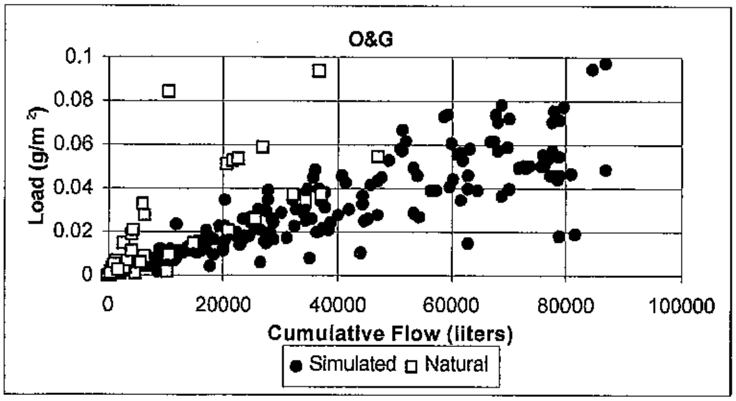
Figure 4.5.2



(a) Median Oil and Grease Concentration During a Simulated Storm Event



(b) Median Oil and Grease Load During a Simulated Storm Event



(c) Oil and Grease Load During Natural and Simulated Storm Events

Figure 4.5.3

A plot of the total observed load in relation to the total volume of flow is shown in Figures 4.5.1c, 4.5.2c, and 4.5.3c for TSS, nitrate, and oil and grease, respectively. Observations for both natural events and simulated events are plotted. No statistical difference was found between the data observed for simulated events and the natural events; this is visually evident from the graphs.

The wash-off patterns for all highway runoff constituents are presented in Appendix F.

4.6 First Flush

The "first flush" of constituents in highway runoff is examined in Figures 4.6.1a-c and 4.6.2a-c. The percent of the total storm load in relation to the percent of the total storm flow is shown in Figure 4.6.1a-c. First flush of constituent mass is not strongly pronounced on pavements with high speed traffic. The percentage of total mass discharged is only slightly higher than the percentage of the total runoff volume discharged. The results of Figure 4.6.1a-c are shown numerically in Table 4.6.1.

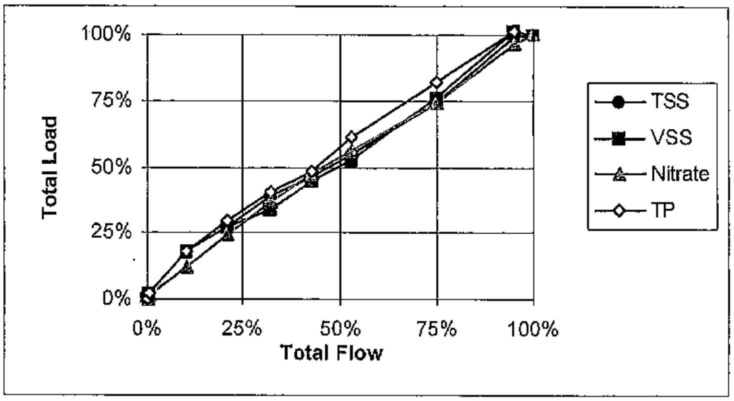
The fraction of percent mass discharged to percent runoff discharged is plotted in relation to storm volume in Figure 4.6.2a-c. A value of one indicates the percentage of the total storm load that has passed is equal to the percentage of the total volume of storm flow that has passed. The value of this fraction rapidly approaches one and becomes approximately equal to one shortly after the half-way point in the storm.

4.7 Daily and Seasonal Variations

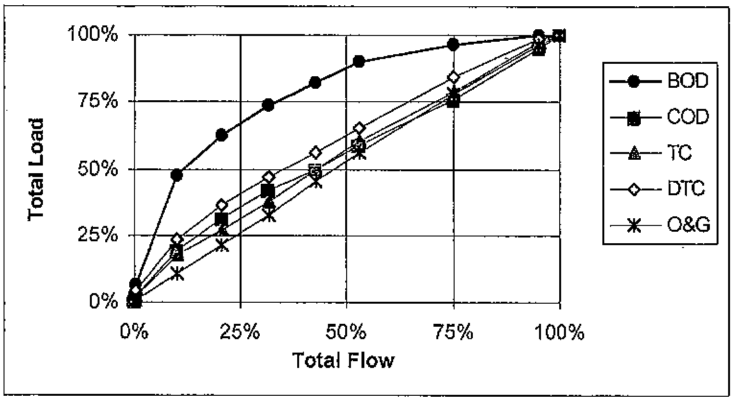
There is no evidence that any constituents exhibited daily or seasonal trends. A time-series plot of the TSS and nitrate data collected during the period July 1993 through July 1994 is presented in Figure 4.7.1. The variation during the day for TSS and nitrate for the same time period is plotted in Figure 4.7.2.

4.8 Street Sweeping Variations

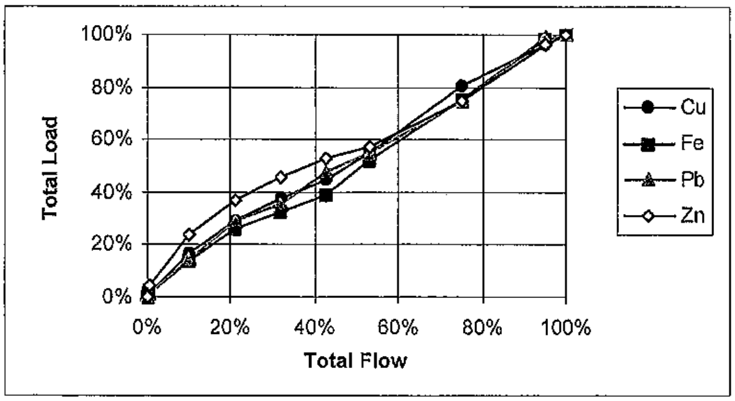
Street sweeping operations were suspended at the West 35th Street sampling site during the first 7 months of the study period, and resumed during the last months of the



(a) Load vs. Flow for Solids and Nutrients

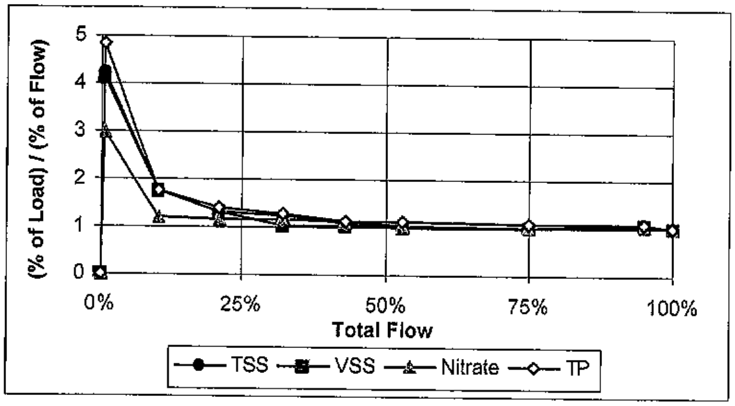


(b) Load vs. Flow for Organics and Oil and Grease

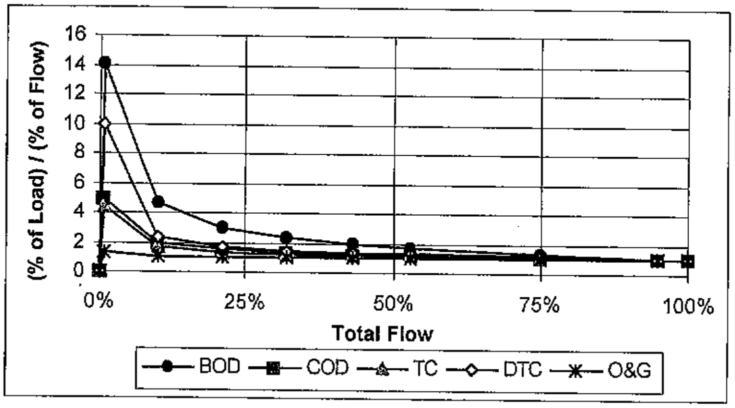


(c) Load vs. Flow for Metals

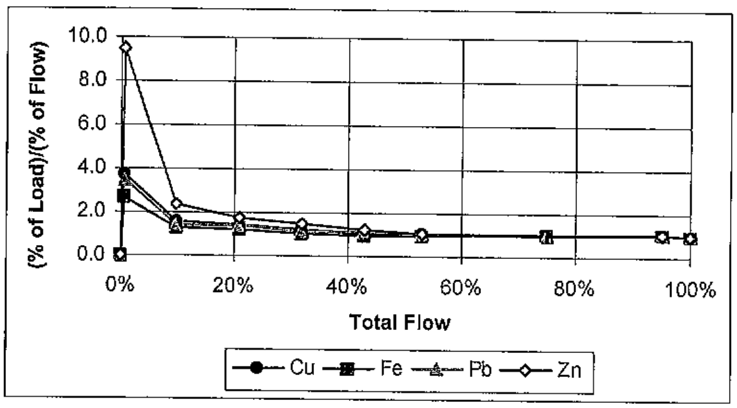
Figure 4.6.1



(a) Percent Load vs. Flow for Solids and Nutrients



(b) Percent Load vs. Flow for Organics and Oil and Grease



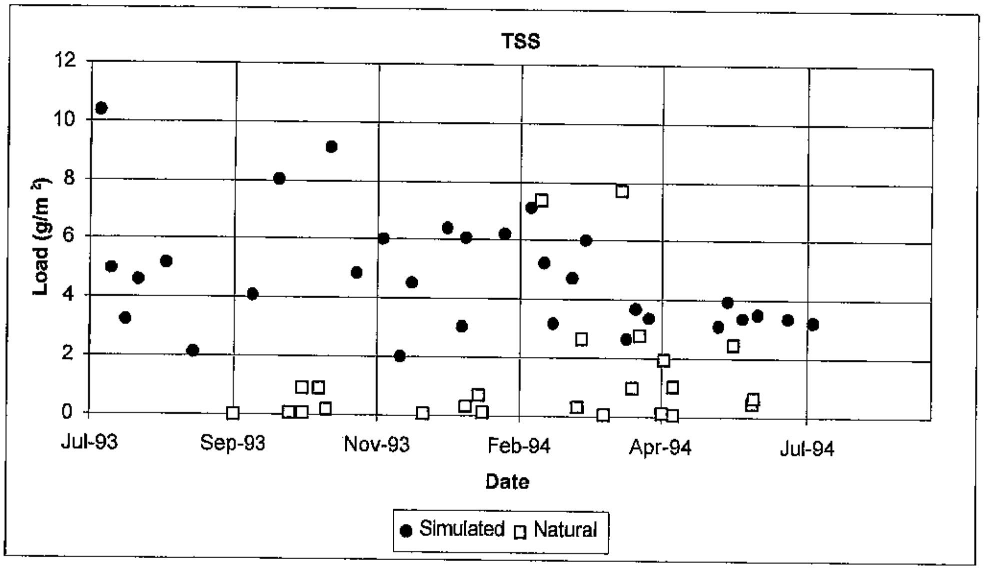
(c) Percent Load vs. Flow for Metals

Figure 4.6.2

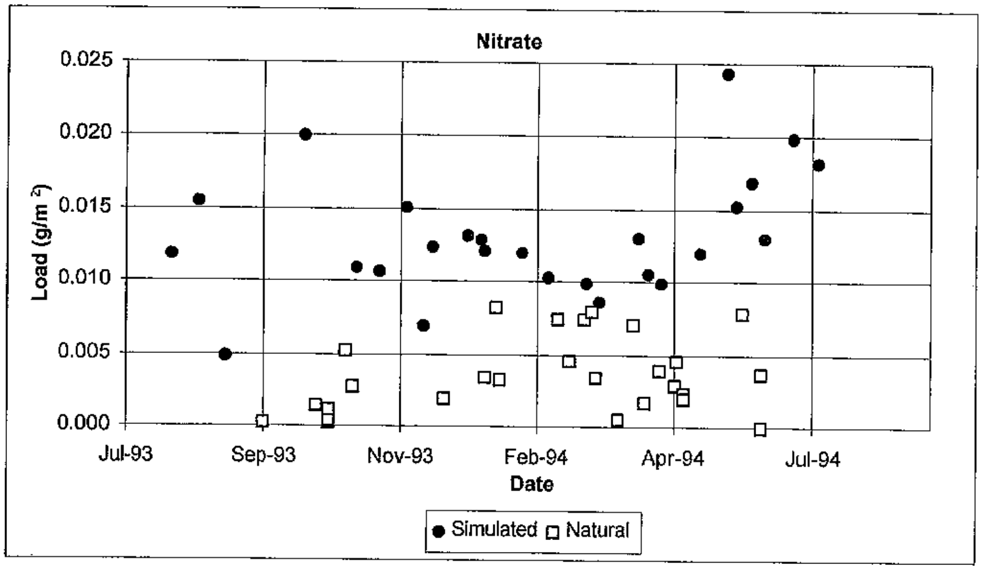
Table 4.6.1 First Flush of Highway Runoff Constituents (percentage of constituent load versus percentage of total runoff*)

	Traffic Conditions Total Storm Runoff = 21 mm			No-Traffic Conditions Total Storm Runoff = 28 mm		
% of Runoff	21%	53%	75%	19%	53%	75%
Volume of Runoff	(4.3 mm)	(11.2 mm)	(15.7 mm)	(5.3 mm)	(15.0 mm)	(21.1 mm)
TSS	27%	55%	74%	42%	75%	87%
VSS	28%	52%	76%	44%	65%	73%
BOD_5	63%	90%	97%	100%	100%	100%
COD	32%	59%	76%	51%	93%	95%
Total Carbon	27%	60%	79%	45%	72%	90%
Dis. Total Carbon	36%	66%	85%	31%	59%	79%
Nitrate	25%	56%	74%	31%	62%	83%
Phosphorus	29%	61%	82%	63%	82%	94%
Oil and Grease	21%	56%	78%	33%	60%	73%
Copper	29%	55%	80%	70%	74%	74%
Iron	26%	52%	75%	80%	96%	98%
Lead	29%	55%	75%	84%	96%	96%
Zinc	37%	57%	75%	56%	85%	93%

* Based on the median of all loads and flows recorded during the simulated storm events.

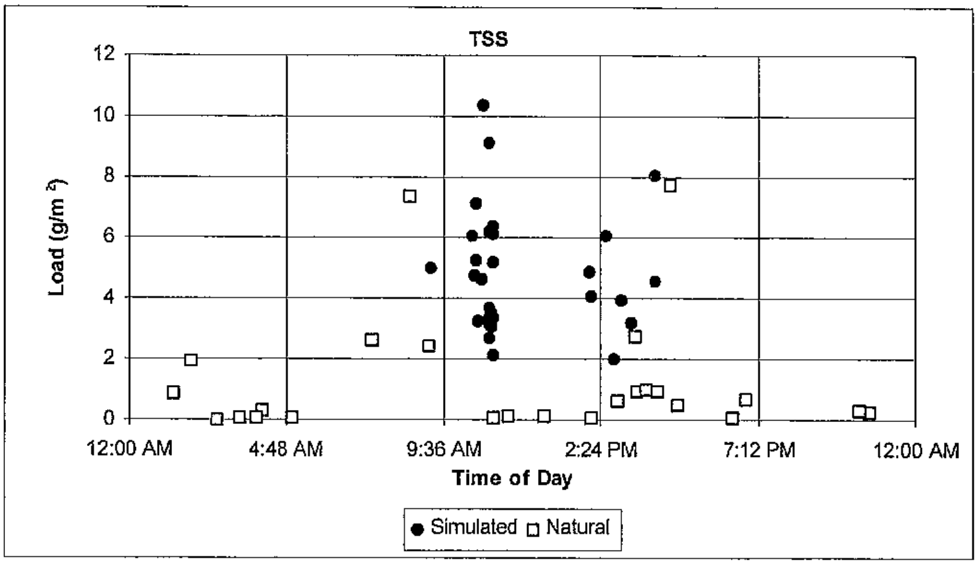


(a) Seasonal Variation (July 1993 - July 1994), TSS

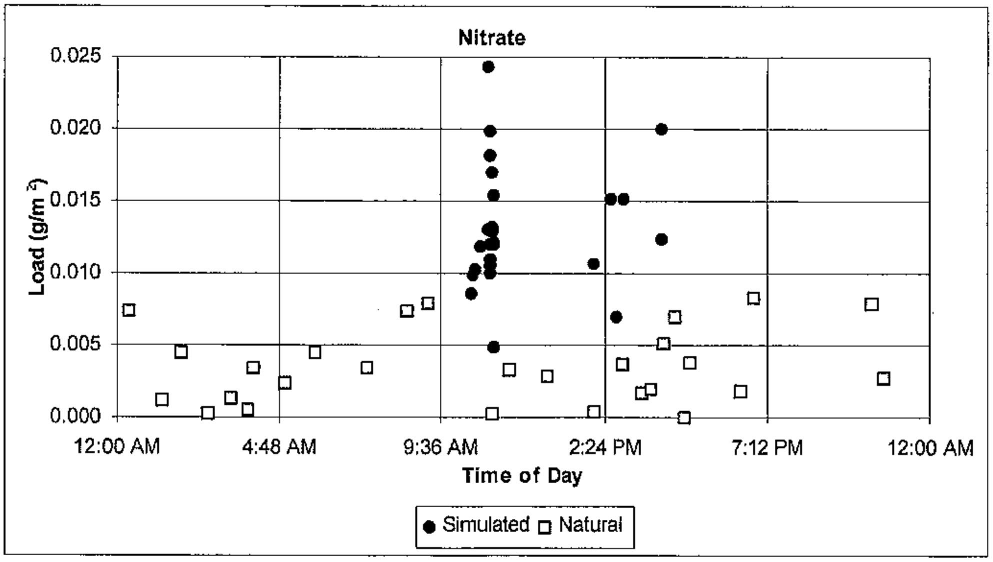


(b) Seasonal Variation (July 1993 - July 1994), Nitrate

Figure 4.7.1



(a) Hourly Variation (July 1993 - July 1994), TSS



(b) Hourly Variation (July 1993 - July 1994), Nitrate

Figure 4.7.2

study at a sweeping frequency of once every 2 weeks. There were a total of 18 simulated storm events and 11 natural events sampled during the no-sweep period. Fourteen simulated events and 12 natural events were sampled during the sweeping period. Two of the three no-traffic simulated events were conducted during the no-sweeping period.

Using the simulated data only, the median load for the no-sweep period was compared to the median load for the sweeping period for each constituent. Statistical difference between the two groups was determined using a *t*-test. The only constituents that showed a significant difference between the sweeping periods were the solids. The storm water loading of both TSS and VSS was reduced as a result of sweeping once every 2 weeks. The computed values the *t*-statistic are shown in Table 4.8.1. A negative sign in front of the *t*-statistic in Table 4.8.1 indicates that the median load of the constituent increased during the sweeping period. However, no constituent showed a significant increase during the sweeping period.

Table 4.8.1 Computed Street Sweeping *t*-Statistics

Constituent	Computed *t*-Statistic
TSS	3.53[a]
VSS	2.19[b]
BOD_5	0.01
COD	1.14
Total Carbon	1.57
Dissolved Total Carbon	1.58
Nitrate	-1.29
Total Phosphorus	1.80
Oil and Grease	-0.91
Copper	0.43
Iron	-0.79
Lead	-1.40
Zinc	1.80

(a) $|t| > t_{0.01,} = 2.326$; (b) $|t| > t_{0.05,\infty} = 1.960$

4.9 Summary

A total of 35 simulated rainfall events and 23 natural storm events were sampled at the West 35th Street sampling site. The distribution of EMCs at this site were positively skewed; however, the degree of skewness was not enough to justify the use of lognormal estimators to calculate the sample parameters.

Constituent wash-off patterns during the simulated events were similar to those predicted by the wash-off theory presented in Chapter 2. A first flush of constituent mass was evident during all simulated events; however, it was much more pronounced during the no-traffic simulations because of the absence of the traffic input.

A street sweeping frequency of once every 2 weeks was found to significantly reduce the loading of solids (TSS and VSS) in the highway runoff. Street sweeping did not significantly change the loading of other constituents.

5.0 Model Development

5.1 Introduction

Predictive modeling of storm water quality is used to provide insight and analysis into the control of storm water constituents. Storm water models range from simple screening equations that can be solved on a hand-held calculator to complex simulation methods that require considerable computer time to complete. The three most common types of storm water predictive models include regression models, statistical techniques, and deterministic simulation models.

The regression model is a mathematical equation that defines the line of average relationship between a dependent variable and one or more independent, or causal, variables. Storm water regression models commonly identify constituent concentration or load as variables that are dependent upon runoff volume, rainfall intensity, traffic intensity, antecedent dry period, surrounding land use, etc. The mathematical approach used to formulate the regression model is the method of least squares. The method of least squares minimizes the sum of the squared differences, or residuals, between the values predicted by the regression equation and the observations. If correctly specified, the method least squares will provide the best linear and unbiased estimate of the population parameters.

Regression equations are easy to use and provide a quick method for screening storm water quality. The storm water regression model can be formulated to predict total storm load and inner-event loads. Regression models especially are well suited for predicting the cumulative constituent load that results from a continuous series of storm events. Regression models have been criticized as poor predictors when applied beyond the original data set or region from that they were created (Driscoll et al., 1990); however, this statement is universally true of all water quality modeling methods. Site-specific quality data is critical for the calibration and verification of urban runoff quality simulation models (Huber, 1986).

The National Urban Runoff Program (NURP) employed a statistical method for storm water quality modeling (Driscoll et al., 1990). The NURP statistical method is based on the assumption that rainfall, runoff volumes, and runoff event mean concentrations (EMC) are all independent, random variables that vary between storm events. The NURP study concluded that EMCs are random variables that are best described by a lognormal distribution (USEPA, 1983). Rainfall data historically have been considered to be represented by a gamma distribution (Chow et al., 1988).

The storm event is assumed to be independent of previous events if the time span between event midpoints is greater than some minimum time period. This minimum inter-event time (MIT) is typically in the range of 3 to 24 hours. The MIT is selected by making use of the assumption that MITs are exponentially distributed (Chow et al., 1988) and therefore have a coefficient of variation (COV) equal to one. Trial values of the MIT are chosen until the COV of the time between event midpoints in equal to one (Driscoll et. al., 1990).

Runoff volumes are calculated using rainfall and runoff statistics. The mean runoff volume is computed by multiplying the mean volume of a rainfall event by the ratio of average runoff to rainfall. The mean constituent load is determined by multiplying the mean EMC by the mean runoff volume (Eq. 3.8.2). All variation in the constituent loads is assumed to be attributable to the variation in the runoff volume.

The NURP statistical method is relatively easy to apply and can provide a quick screening like regression equations. The method has also been successfully applied as part of the NURP program. A shortcoming to the method is that temporal changes in concentration or load cannot be predicted during the storm. Therefore, the method has limited use in the evaluation of highway runoff control structures.

Physically based deterministic simulation models represent the most complex tools available for storm water analysis. Modern computers allow these models to time-step through the build-up and wash-off of highway constituents, as well as the change in runoff quantity and quality throughout a drainage system, including storage and treatment facilities. Most simulation models are capable of performing both single and continuous event simulations. Build-up and wash-off functions are used to determine the amount of material removed from the highway surface, and either the nonlinear reservoir method or kinematic wave method is used to route the runoff throughout the remainder of the drainage system. Several of the more common simulation models include:

1. Storm Water Management Model (SWMM)

2. FHWA Urban Highway Storm Drainage Model
3. Storage, Treatment, Overflow, Runoff Model (STORM)
4. Hydrological Simulation Program - FORTRAN (HSPF)

These models are considered "operational" water quality models and each one has (1) a user's manual and documentation, (2) is in use by someone other than the model developer, and (3) has continued support (Huber, 1986).

Simulation models typically consider constituent build-up as a function of the length of the antecedent dry period and consider constituent wash-off as a function of the storm duration. Linear equations are sometimes used to describe specific regions of correlation, but intuition suggests that neither build-up nor wash-off should be entirely linear. The most common curve forms used to describe constituent build-up are power, exponential, and Michaelis-Menton expressions. Wash-off curves are generally a variation of the first-order decay formulation (Huber, 1986). However, a special case of the regression equation known as a rating curve is also used to describe wash-off. The rating curve expresses the relationship between load or concentration and flow rate. Rating curves are almost always power functions, although other forms are sometimes used (Huber, 1986). Runoff flow routing downstream of the highway pavement is accomplished using the nonlinear reservoir method or the kinematic wave method.

Simulation models have been designed to model extensive storm water collection and transfer systems. The models are best applied to urban storm sewer designs that include extensive pipelines, channels, storage elements, treatment elements, etc. Simulation models produce the most varied output of any of the modeling methods and provide the detailed analysis required for the extensive evaluation of comprehensive storm water controls.

5.2 Selection of an Appropriate Modeling Technique

The selection of a storm water quality modeling technique must consider the objective of the task at hand. The objective of this research is the development of a model that predicts the amount of material that is washed from the highway surface during either a design storm event or a design series of storm events. The model output is the predicted constituent load at the edge of the pavement, at any point during the storm. All three of the previously mentioned modeling techniques can accomplish this goal; however, there are several important factors that must be considered in model selection.

The model should be applicable to both single-event and continuous-event design scenarios. The model should be capable of producing a single storm event loadograph for the evaluation of the effectiveness of storm water controls. However, receiving waters respond relatively slowly to constituent inputs. The total load input over an extended period of time (i.e., weeks to years) is required to estimate response of receiving waters. All three modeling techniques are capable of single-event and continuous-event modeling.

The modeling technique also must be capable of estimating the cumulative amount of load produced at any specific instance during the storm. The ability to predict cumulative edge-of-pavement loads throughout the storm is an important aspect if the model is to be used to evaluate control structure efficiency. The amount of constituent mass captured by a fixed-capacity control structure will be the amount of mass that has washed from the highway at the time the structure is filled. Subsequently, the amount of constituent mass released to the receiving stream will be that portion that is washed from the highway after the structure is full. As shown by the data presented in Chapter 4, the amount of constituent that is washed from the highway surface varies throughout the duration of the storm (Figures 4.6.1 and 4.6.2). The concentration of the constituent will be greater early in the storm than later due of the effect of "first-flush." The model must therefore predict the fraction of constituent mass captured by the control structure and the mass of constituent released by the control structure based on load rate variations during the storm. Both regression models and physically-based deterministic simulation models can accomplish this task. However, this condition eliminates the NURP statistical technique from consideration.

A final consideration is the amount of information that the model uses to determine constituent loading. The more commonly used simulation models (e.g., SWMM) determine constituent build-up in terms of elapsed time since the last cleaning (either by rain or sweeping). Although the available build-up functions include linear, power, exponential, and Michaelis-Menton, the only information utilized by the model is the duration of the dry period. The best fit of an exponential function to the TSS data collected during sampling at the 35th Street site is presented in Figure 5.2.1. The correlation coefficient (R^2 = 0.0013) in Figure 5.2.1 suggests that there are other variables that influence the build-up of TSS. If the dry period duration was calculated from a continuous rainfall record, other known variables would include the intensity of the preceding storm. This new information will indicate the extent of the previous wash-off and subsequently the amount of residual material remaining on the highway from the previous storm event. The improved explanatory power that results from using both dry period duration and previous storm intensity to predict TSS loading at the West 35th street site is illustrated in Figure 5.2.2

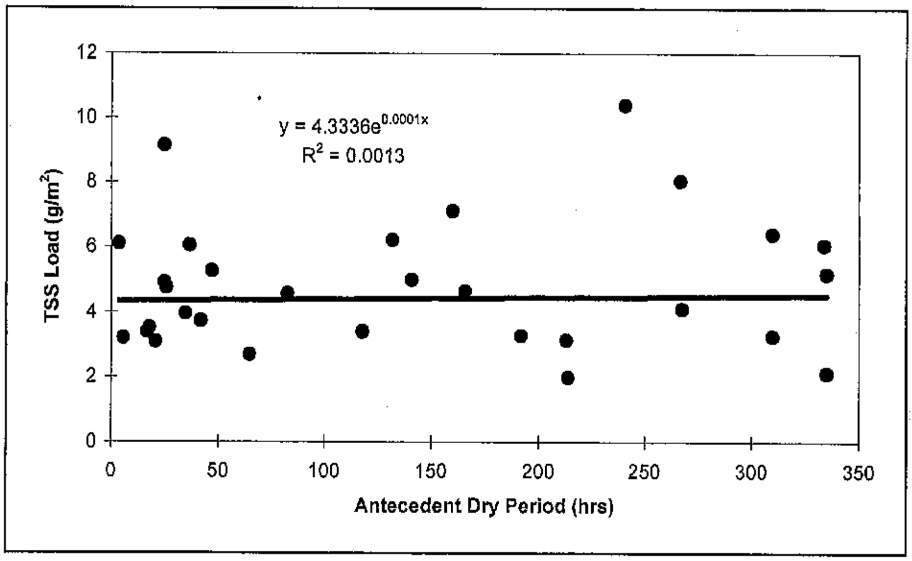


Figure 5.2.1 Exponential Function Fit to the Data Collected at the West 35th St. Sampling Site

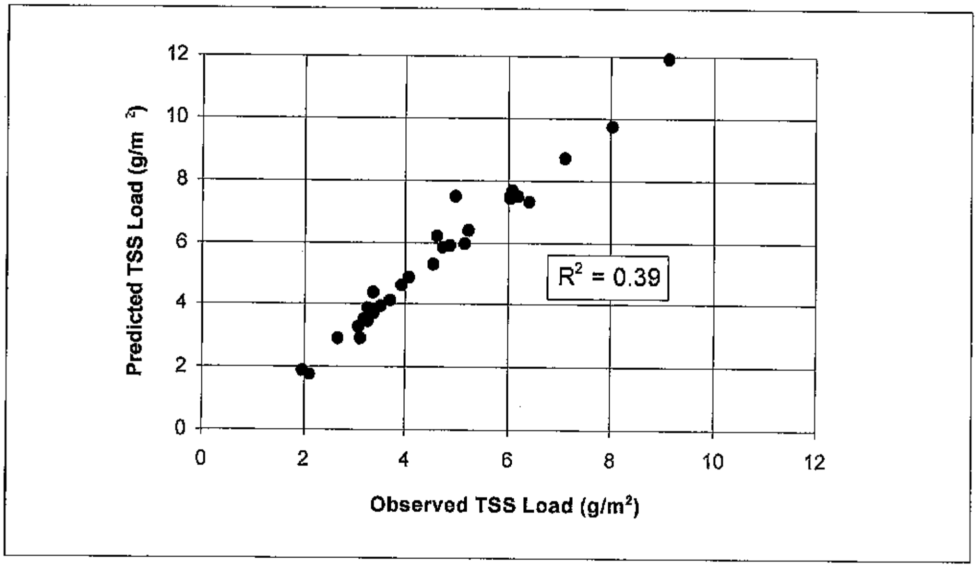


Figure 5.2.2 Observed TSS Load vs. Predicted TSS Load using Duration of the Antecedent Dry Period and the Intensity of the Preceding Storm as Causal Variables

Regression analysis can determine the relationship between numerous causal variables and the constituent load. Regression analysis will also indicate the statistical significance of each causal variable as it relates to a specific constituent, which in turn may suggest possible mitigation procedures or model applicability scenarios. Furthermore, the formulated regression equation may be used as input to a physically based deterministic simulation that might model a much broader system.

In summary, regression analysis was chosen as the modeling technique best-suited for edge-of-the-pavement load calculations because of the following:

- Regression equations can be used to calculate both single-event and continuous storm loading patterns.
- Regression models make use of multiple causal variables (e.g., runoff intensity, traffic volume, duration of the dry period, etc.).
- The regression analysis will evaluate the statistical significance of all causal variables in relation to a specific constituent. This information can suggest mitigation procedures or model applicability situations.
- The regression model can be attached as the input to a larger model simulating a much broader system.

5.3 Identification of Relevant Model Variables

The most important step in the development of an empirical model is the identification of the relevant explanatory variables. The term "relevant" has two distinct meanings in regression analysis: scientific relevance and statistical relevance (Johnson et al., 1987). Scientific relevance is based on the underlying theory guiding the process. Variables are included in the model because scientific theory suggests inclusion. Statistical relevance is based on hypothesis tests that suggest whether a coefficient is "statistically" different from zero. This section describes the process that is used to identify the set of relevant highway storm water quality causal variables. Note that it may not be necessary, nor desirable, to use all of the relevant variables in the final storm water model. The process of selecting the "model variables" from the identified set of "relevant variables" is discussed Section 5.7.

The mass of constituent that is washed from the highway surface during a storm event is related positively to the total volume of runoff (Eq. 3.7.2). Scientific theory suggests that a regression of constituent load against storm runoff will result in the sign of the runoff coefficient being positive. Furthermore, the computed *t*-ratio for the runoff coefficient should be greater than the critical *t*-ratio at the 0.95 level, which suggests statistically a 95% confidence level in any decision to reject the null hypothesis that the runoff coefficient is actually equal to zero. It is possible for scientific theory to suggest variable relevancy yet be contradicted by statistics, which is the case when the exclusion of a relevant variable from the model has led to a bias in the statistical analysis. Likewise, statistical relevance can be established between variables that are correlated only by happenstance. These inconsistencies make it difficult to distinguish between the truly relevant explanatory variables and those with only circumstantial correlation. There are certain traits, however, that are exhibited by all relevant explanatory variables. These traits include:

(1) some underlying scientific theory explains the response of the dependent variable to a change in the independent variable;

(2) the variable, when included with all of the other independent variables, must add some explanatory information to the model (i.e., the variable cannot be perfectly collinear with any other variable);

(3) the variable is known with certainty or at least capable of being measured with a high degree of accuracy.

The process of identifying relevant variables must be based on scientific theory, otherwise there is no way to distinguish between true causation and circumstantial correlation. A detailed discussion of correlation and causation is reserved for Section 5.5. It should be noted here that a high degree of correlation between two variables in no way implies causation. There is a high degree of correlation, for example, between the yearly number of publications by Professor Sydney Chapman and the yearly means of sunspot relative numbers for the years 1910 through 1967 (Campbell, 1968). This correlation is curious, especially considering that Dr. Chapman worked in fields of research related to solar changes, but there is absolutely no evidence of causation. The correlation coefficient is only a measure of the degree of covariation between Dr. Chapman's productivity and the sunspot cycle and nothing more. The correlation coefficient, or the more commonly used square of the correlation coefficient (R^2), is a measure of the "explanatory" power of the regression equation only if the variables that are selected for use in the regression are derived from some guiding theory that bestows the equation with causality.

A variable that is "relevant" also must add explanatory information that is independent of the information collectively added by all other relevant variables in the model. The "independence" of the explanatory variable must be considered in the selection process because many variables in the storm water runoff process tend to move together. The size of a storm event, for example, may be expressed in terms of rainfall volume, runoff volume, duration of the storm, or the number of vehicles that traveled through the storm. The lack of independent movement among the explanatory variables is a condition known as multicollinearity.

Multicollinearity affects every storm water runoff data set. A precise estimate of the effect of single variable is difficult since all of the variables move together. This results in is high values for the variance of the estimated coefficients which increases the standard error of the regression and reduces the t-ratio. A small t-ratio is not necessarily a problem as long as the analyst is not mislead by a small t-ratio that is the result of the presence of multicollinearity. However, multicollinearity causes the statistical significance of the computed variable coefficient to vary depending on what other variables happen to be present in the equation. This situation is interpreted as "instability" in the regression coefficients. Scientific theory provides only general guidelines for the selection of specific empirical variables (e.g., a general mass balance says that the amount of material contained in the output of a storm water system is determined by the amount of material input into the system, plus or minus any decay or production of the material within the system; the mass balance does not indicate what the specific inputs might be for a particular system); therefore, it is customary when working with highway runoff data to experiment with alternative specifications of the same basic equation. A number of formulations of the runoff model are developed that differ only by the specific causal variables used, such as storm duration, rainfall volume, runoff volume, traffic during the storm, duration of the antecedent dry period, traffic during the dry period, etc. A correlation among the variables in the sample exists; therefore, the coefficients of some variables will be significant in some formulations and not significant in others. The coefficients will appear to be "unstable" under these conditions.

Multicollinearity does not effect the predictive performance of a regression equation (Anselmi, 1987). The reason is that multicollinearity only obscures the individual effects of each explanatory variable on the dependent variable. The regression results will remain valid in terms of the effects on the dependent variable by the collective action of the explanatory variables as long as the conditions that originally caused the multicollinearity remain constant.

A perfect correlation between variables is seldom the case in storm water data sets, if for no other reason than measurement error. However, perfect correlation may occur, if the regression model is used to predict storm loading. For example, if the predictive model uses both rainfall volume and runoff volume as explanatory variables, and rainfall totals are the only data available, the user of the model would have to estimate runoff as a function of rainfall. Runoff volume, in this case, would be perfectly correlated to rainfall volume and would therefore not add any new information to the model.

A trait of a relevant variable is measurability. The regression equation assumes that there is measurement error associated with the value of the dependent variable. This error is one of the primary reasons for the existence of a disturbance term associated with each regression equation (refer to Appendix G). However, the regression assumes that there is no measurement error in the independent variables. Any measurement error on the right-hand side of the equation will invalidate the regression. Therefore, any variable selected for use as an independent variable in the model should be one that is known or can be measured with certainty. For example, consider the variables total rainfall and total runoff. If there is no variation in the rainfall over the highway watershed, which is a reasonable assumption for short highway watersheds between curb inlets, the total rainfall can be measured more accurately than the total runoff from the watershed. All other factors equal, total rainfall would make a better explanatory variable than total runoff.

In summary, ordinary least squares regression will determine the correlation between any two variables, but sound scientific principles determine if the response of one variable is truly attributable to a change in another. Once a variable is determined to have scientific significance, other factors such as multicollinearity and measurability should be considered in order to establish the relevancy of the variable. The final variables used in the model are selected using statistical procedures outlined in Section 5.7.

The causal variables that influence constituent loading in highway storm water runoff were determined to originate during three different time periods: (1) the current storm, (2) the antecedent dry period, and (3) the preceding storm. Mathematically, the general population regression equation is given as:

$$\begin{aligned} Y = \beta_0 &+ (\beta_{s1} X_{s1} + \beta_{s2} X_{s2} + \ldots + \beta_{si} X_{si}) \\ &+ (\beta_{a1} X_{a1} + \beta_{a2} X_{a2} + \ldots + \beta_{ai} X_{ai}) \\ &+ (\beta_{p1} X_{p1} + \beta_{p2} X_{p2} + \ldots + \beta_{pi} X_{pi}) \\ &+ U_i \end{aligned} \tag{5.3.1}$$

where the subscripts s, a, and p refer to variables from the storm, the antecedent dry period, and the preceding storm respectively, and U is the uncertainty term. Table 5.3.1 lists the relevant variables identified during this study.

Table 5.3.1 Relevant Model Variables

Variable	Example of Effect
Date of the Storm	Seasonal trends
Time of Day of the Storm	Atmospheric conditions may change during periods of industrial activity
Storm Duration	Potential for further constituent input
Total Rainfall or Total Runoff	Directly related to constituent loading
Intensity of Runoff	Higher kinetic energy in runoff may flush more material
Traffic Count during the Storm	Traffic is the source of certain constituents
Traffic Mix during the Storm	Construction vehicles, diesel-powered vehicles, and others may be "dirtier" than the normal population of vehicles
Traffic Speed during the Storm	Scour from tires and vehicle-induced wind forces increase with speed
Surrounding Land Use	Industrial areas are "dirtier" than rural areas
Curb / Guardrail Height	Taller guardrails trap constituents along the highway
Duration of Antecedent Dry Period	Provides the opportunity for the build-up of constituents
Antecedent Traffic Count	Increased opportunity for dry vehicle contributions
Weather Conditions	Heavy winds during the dry period could remove constituents from the highway surface
Maintenance Activities	Grass cutting, bridge sanding, and guardrail maintenance add dirt and debris to the highway surface
Street Sweeping	Potential to remove constituents from highway surface
Previous Storm Characteristics	The degree of removal during the previous storm event will affect the amount of material available for the current storm event.

5.4 Worksheet Development

The worksheet is a systematic way to organize and record the values of all variables used in the regression analysis. The columns of the worksheet identify the variables that are used in the analysis, and the rows contain the respective values of the variables for each observation. This task was accomplished with an *Excel* spreadsheet, that is compatible with the MicroTSP Econometric software used for the regression analysis.

The values of all variables for each observation were recorded as cumulative values from the beginning of the storm event so that each observation could be considered the end of the current runoff. Therefore, the 450 observations recorded during the 35 simulated rainfall events and 23 natural storm events each represent an individual runoff event. The advantages to organizing the data in this manner are (1) an increase in the available number of storm events for the regression analysis and (2) the regression equation formulated from the data set will be able to predict inner-event loading patterns. The disadvantage, however, is the introduction of autocorrelation, into the data set. Autocorrelation results when the value of a variable is dependent on the preceding value of the variable. A data set can be transformed, however, to account for the autocorrelation prior to the formulation of the regression equation. The method used to transform the data in this research is presented in Appendix G.

The constituent loads are adjusted for background concentrations of the constituent prior to the formulation of the regression equation. Background concentrations for the rainfall simulations are the constituent concentrations measured in the tap water, and background concentrations for the natural storm events are the constituent concentrations measured in the rainfall. In the worksheet, only the observations recorded during the rainfall simulations were adjusted for background concentrations of the constituents. The difference between the constituent concentration measured in the tap water and the average concentration measured for the constituent in the natural rainfall was added/subtracted to the constituent concentration measured in the simulated runoff sample. This method essentially "normalized" the simulated runoff samples to match the natural runoff samples.

Scaling of the variables is also identified in the worksheet. The objective of the regression analysis is to formulate a predictive equation that is applicable to highway watersheds other than the West 35th Street site. Constituent loads recorded in the worksheet are in units of grams per square meter of highway surface (g/m^2) to account for differences in watershed areas. Likewise, runoff discharge rates were recorded in liters per minute per square meter of highway surface ($l/m^2/min$). Vehicle counts during the wet and dry periods were recorded as the average count per lane of traffic in order to be compatible with watersheds with a different number of traffic lanes.

5.5 Covariance, Correlation, and Causation

Covariance is the measure of linear dependence between two variables. The covariance is given by:

$$Cov(x,y) = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{n-1} \tag{5.5.1}$$

where: x_i = i^{th} observation of variable x;

y_i = i^{th} observation of variable y;

$\bar{x}$ = mean of x;

$\bar{y}$ = mean of y;

n = number of observations.

A large value of covariance indicates a strong linear relationship between two variables and is equal to zero if the two variables are independent. The covariance also could equal zero if the two variables are related by a non-linear function such as a quadratic or exponential. The covariance, however, has little application to highway storm water quality because the covariance is dependent on the scales chosen for the two variables. This makes it impossible to know whether the value of the covariance is truly large or small.

The problem is solved by converting the covariance to a scaleless covariance by dividing by the standard deviations of the two variables. The scaleless covariance is called the correlation coefficient, r, and is shown mathematically as:

$$r(x,y) = \frac{\dfrac{\sum (x_i - \bar{x})(y_i - \bar{y})}{n-1}}{S_x S_y} \tag{5.5.2}$$

where: S_x = standard deviation of x;

S_y = standard deviation of y.

The value of the correlation coefficient ranges from -1 to +1, and values that approach -1 or +1 indicate a strong correlation between x and y. If the sign of the correlation coefficient is positive, the value of x increases with an increase in y, and if the sign is negative, the value of x decreases with an increase in y.

The coefficient of multiple determination, or R^2, is the square of the correlation coefficient and is often used in regression analysis to measure the percent of variation in the dependent variable associated with, or explained by, variation in the independent variable. The degree of correlation between two variables in no way implies causation. However, the correlation coefficient can be used to measure the degree of causation if there is reason to believe the two variables are related in the system under study. Furthermore, R^2 is only a measure of the linear association between two variables. Two variables may be related according to a nonlinear function and have a low value of R^2.

The correlation coefficients between suspected causal variables and highway runoff constituents are presented in Table 5.5.1.

Table 5.5.1 Correlation Coefficients Between Suspected Causal Variables and Constituent Load (g/m^2)

	TSS	VSS	BOD_5	COD	Total Carbon	Dis. Total Carbon	NO_3	TP	Oil & Grease	Cu	Fe	Pb	Zn
Duration	0.07	0.05	0.24	0.30	0.07	0.12	0.11	0.31	0.42	0.49	0.12	0.17	0.32
Flow	0.91	0.92	0.76	0.87	0.87	0.96	0.94	0.82	0.86	0.59	0.91	0.51	0.67
Intensity	0.79	0.79	0.61	0.67	0.72	0.77	0.77	0.64	0.60	0.38	0.74	0.37	0.54
VDS	0.15	0.13	0.39	0.43	0.18	0.27	0.25	0.40	0.56	0.40	0.23	0.23	0.40
Air Temp.	-0.04	0.04	0.14	0.09	-0.07	0.06	0.10	0.14	-0.01	-0.01	0.03	-0.09	0.06
ADP	0.14	0.21	0.28	0.16	0.16	0.27	0.31	0.21	0.09	0.06	0.12	0.05	0.22
ATC	0.11	0.18	0.28	0.18	0.13	0.25	0.31	0.21	0.09	0.05	0.09	0.03	0.23
ADP Temp.	-0.18	-0.12	0.02	-0.03	-0.19	-0.05	0.01	0.00	-0.12	-0.06	-0.12	-0.17	-0.04
P-Duration	0.14	0.16	0.05	-0.16	0.27	0.05	-0.05	-0.10	0.04	0.01	0.17	0.12	-0.12
P-Flow	0.11	0.10	0.19	0.16	0.10	0.16	0.22	0.21	0.07	-0.04	0.13	0.05	0.20
P-Intensity	0.03	0.03	0.18	0.29	-0.08	0.15	0.27	0.32	0.04	-0.02	0.04	-0.02	0.32
P-VDS	0.06	0.12	-0.01	-0.17	0.20	0.01	-0.09	-0.16	-0.01	0.03	0.12	0.10	-0.12
P-Temp.	-0.30	-0.29	-0.05	-0.07	-0.34	-0.15	-0.07	-0.05	-0.19	-0.12	-0.27	-0.28	-0.12

Duration of storm is in units of minutes; Flow = L/m^2; Intensity = volume of runoff / duration;
VDS = Vehicle count during the storm; ADP = Duration of the antecedent dry period;
ATC = Vehicle count during the antecedent dry period; Temperature in °C;
P prefix indicates previous storm characteristic.

5.6 Model Misspecification

There are four assumptions regarding the residuals that must be made for ordinary least squares (OLS) regression to be valid. The implications of these assumptions and the remedies used to satisfy misspecifications are discussed in Appendix G. A fifth assumption, which of multicollinearity, is made when formulating a multiple regression model. The effects of multicollinearity have been described in Section 5.3.

5.7 Variables Included in the Model

Theoretically, all of the variables identified in Table 5.3.1 influence the constituent load in highway runoff and should be included in any empirical model used to predict the constituent loading in highway runoff. Unfortunately, it is not possible to include all of the identified variables in the model, nor is it particularly desirable. Some of the variables, such as surrounding land use, traffic speed, and traffic mix cannot be used in the model because their values are fixed in the data set. There are other variables that influence constituent loading in highway runoff that have not been identified because of a lack of knowledge of the build-up/wash-off process. Furthermore, the inclusion of all relevant variables in the model, or model overfitting, can be harmful because the prediction error of the model is proportional to the number of parameters in the model (Berthouex and Brown, 1994). The goal is to determine an adequate model with the fewest possible terms. Unfortunately, the method of selecting the final model is strictly trial and error and dependent on the subjectivity of the analyst.

A three-phase approach was used to search for the simplest, "adequate" model. The first phase begins with an overfit of the model. The regression equation is formulated using every known causal variable and each coefficient is examined for statistical relevance (a computed t-ratio greater than the critical t-ratio for rejecting the null hypothesis at the 0.95 level) and scientific relevance (the coefficient has the expected sign) to determine that variables are candidates for discard. The variables that fail both tests are eliminated one at a time, the regression equation is reformulated, and the new coefficients are examined for relevance. The procedure is repeated until there are no longer any variables that are statistically insignificant *and* display the wrong sign.

The second phase of the search involves making a judgment on the variables that show statistical significance and not scientific significance, or vise versa. If the variable is statistically significant and scientifically relevant, but does not have the expected sign, it is allowed to remain in the model since the probable cause of the sign change is multicollinearity with an included or excluded variable. The decision is not as straightforward if the variable is scientifically relevant and has the expected sign, but is not statistically significant. In most cases, the variable is eliminated from the model.

However, there are some circumstances in which the variable should be allowed to remain in the model. Multicollinearity may have reduced the value of the computed t-ratio below the critical t-ratio, which could lead to the wrong conclusion.

The final phase of the search involves a reconsideration of the discarded variables since scientific theory suggests that all of the variables should be included in the model. It is possible for a variable that was discarded early in the process to become statistically relevant in a new model formulation with a fewer number of variables. All discarded variables, therefore, should be individually reinserted into the trimmed model and tested for relevance.

The model development included the testing of different functional forms of the major independent variables. For example, it is not scientifically appealing to use the duration of the antecedent dry period in a linear form. Intuitively, the build-up of material on the highway surface is not linear throughout the range of possible dry period durations, but becomes asymptotic at some level. In this case, it is more appealing to specify the reciprocal of the dry period duration in the model.

During model development, the linear, reciprocal, and quadratic forms of the major independent variables were specified in model. The log-log [i.e., $\mathrm{Ln}(y) = C + \beta \mathrm{Ln}(x)$] and linear-log [i.e., $y = C + \beta \mathrm{Ln}(x)$] model forms also were specified. Interestingly, a linear-linear specification showed the greatest explanatory power for all constituents in the West 35th Street data.

It is tempting to rank the independent variables in order of their relative importance during the selection process. Methods used to rank variables include comparing the magnitudes of the variable coefficients, comparing simple correlation coefficients, and comparing t-ratios. None of these methods, however, are particularly attractive.

The absolute values of the coefficients should not be used to make statements about the relative importance of the variables in the equation. The magnitude of the coefficient is meaningless since the variables are scaled in different units. Simple correlation coefficients, such as those in Table 5.5.1, also should not be used to rank the importance of variables. Correlation coefficients are computed without regard for the effect on the dependent variable of the other relevant variables in the equation.

A third basis for assigning importance to model variables is ranking by the magnitude of the respective t-ratio. The t-ratio cannot be used to rank variables. If a variable has a t-ratio that is twice the size of the t-ratio of another variable, it does not follow that the variable is twice as important. All it suggests is that the relative variance of one estimated coefficient is smaller than the relative variance of the other. If the computed t-ratio exceeds the critical t-ratio for the confidence level of the test, all that can be stated is that the null hypothesis can be rejected.

The methods of beta coefficients and elasticities offer the best possibilities for ranking model variables. A description of these methods may be found in most texts on regression analysis including Johnson et al. (1987). However, there are no compelling reasons to rank the variables of the highway constituent runoff model.

5.8 Summary

The regression model was found to have the most applicability for predicting edge-of-pavement constituent loads in highway runoff. Regression equations can (1) be formulated that calculate both single-event and continuous storm loading patterns, (2) make use of multiple causal variables, (3) provide information that can suggest mitigation procedures or model applicability situations, and (4) be attached as the input to a larger model simulating a much broader system.

The model was developed using a three-stage approach to examine the applicability of suspected causal variables. The goal was to formulate the model with the fewest explanatory variables in order to reduce prediction error. Because the explanatory variables selected for use in the model are based on both scientific and statistical relevance, the calculated correlation coefficient is an effective measure of the explanatory power of the equation. The linear forms of the explanatory variables were found to have greater explanatory power than other functional forms such as reciprocal and quadratic.

6.0 Model Results

6.1 Introduction

The results of the regression equations that were formulated using the data collected at the West 35th Street sampling site are presented in this chapter. Although data were collected during both simulated and natural rainfall events, no statistical difference was detected among the data generated with the rainfall simulator and those collected during the natural storm events. Therefore, no attempt was made to segregate simulated from natural data during model formulation. The regression equations were formulated using the combined data for storm events sampled at the West 35th Street site.

A statistical difference was detected among the street sweeping data. Street sweeping was not conducted at the West 35th Street during the first 7 months of the study period, but resumed during the last 5 months of the study at a sweeping frequency of once every 2 weeks. No significant correlation was detected among the constituent loads and the amount of time since the street sweeping activity. However, a statistical difference was detected among the data collected for each period. Therefore, two sets of regression equations were formulated. The first set applies to highway pavements where no street sweeping activity occurred and the other to highway pavements that are swept on a frequency of approximately once every 2 weeks. Examples of each equation are given in the chapter. The results of all regression analysis are presented in Tables 6.2.1, 6.2.2, and 6.2.3, and in Figures 6.2.1 through 6.2.4. Additional data also are presented in Appendix I.

6.2 Results of the Regression Analysis

The numerical results of the regression formulation are presented in Tables 6.2.1 and 6.2.2. The first column lists the constituents that were modeled. The second column, N, is the size of the sample used to formulate the regression. The differences in sample size among the constituents is mostly a result of missing data. The maximum sample size possible is 422, which is the result of the 423 observations recorded less 1 observation

Table 6.2.1 Summary of Model Coefficients (Non-Metals)

Constituent (g/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Flow (L/m^2)	Intensity (L/m^2min)	VDS	ADP (hrs)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2min)
TSS	402	0.5482	0.93	0.2556*		0.3068	2.0181		0.0037				-2.9865
				(0.2721)		(0.0140)	(0.8077)		(0.0007)				(0.6989)
VSS	401	0.0630	0.93	-0.0186*		0.0348	0.1649		0.0005			0.0069	-0.6721
				(0.0322)		(0.0016)	(0.0932)		(0.0001)			(0.0013)	(0.1336)
COD	420	0.1169	0.95	-0.0613*	0.0007	0.0773	0.7785		-0.0041	6.0E-6			
				(0.0343)	(7.8E-5)	(0.0025)	(0.1156)		(0.0009)	(1.2E-6)			
Phosphorus	411	0.0005	0.90	-0.0005	3.3E-6	0.0002	0.0032			5.1E-9			
				(0.0002)	(3.6E-7)	(1.1E-5)	(0.0005)			(8.0E-10)			
Nitrate	351	0.0010	0.95	-0.0015		0.0006	0.0086			1.2E-8			
				(0.0004)		(2.8E-5)	(0.0016)			(1.6E-9)			
Total Carbon	404	0.0766	0.94	-0.0657*	-0.0011	0.0411	0.7307	1.1E-4		6.7E-7			
				(0.0322)	(1.6E-4)	(0.0015)	(0.0965)	(1.7E-5)		(1.3E-7)			
Dis. TC	402	0.0265	0.91	-0.0306		0.0073	0.3585	2.2E-5		1.3E-7			0.1983
				(0.0108)		(0.0005)	(0.0324)	(2.8E-6)		(5.5E-8)			(0.0585)
BOD_5	398	0.0145	0.86	-0.0081*		0.0035	0.0619	1.1E-5		1.5E-7			
				(0.0046)		(0.0004)	(0.0228)	(1.6E-6)		(2.3E-8)			
Oil and Grease	263	0.0054	0.94	-0.0004*		0.0030		1.0E-5					
				(0.0020)		(8.9E-5)		(5.8E-7)					

N = # of observations.; S = std. error of regression (g/m^2); R^2 = correlation coefficient adjusted for degrees of freedom; C = intercept;
Duration = duration of storm event (min); Flow = total volume of runoff per unit area of watershed (L/m^2);
Intensity = Flow divided by Duration ($L/m^2/min$); VDS = single-lane vehicle count during storm; ADP = duration of antecedent dry period (hrs);
ATC = single-lane vehicle count during ADP; PDUR = duration of the previous storm event (min);
PFLOW = total volume of runoff per unit area of watershed during the previous storm event (L/m^2); PINT = PFLOW divided by PDUR ($L/m^2/min$);
An asterisk indicates the coefficient is not statistically different from zero; Numbers in parenthesis are the standard error of estimate of the coefficients;
Example: TSS (g/m^2) = 0.2556 + 0.3068(*Flow*) + 2.0181(*Intensity*) + 0.0037(*ADP*) - 2.9865 (*PINT*)
This table is applicable only to highway pavements with no street sweeping activity. Refer to Table 6.2.3 for street sweeping adjustments.

Table 6.2.2 Summary of Model Coefficients (Metals)

Constituent (g/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Flow (L/m^2)	Intensity ($L/m^2 min$)	VDS	ADP (hrs)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT ($L/m^2 min$)
Iron	399	0.0084	0.92	-0.0028*		0.0042	0.0282		2.3E-5				
				(0.0028)		(0.0002)	(0.0082)		(1.0E-5)				
Zinc	399	0.0007	0.92	0.0002*	2.5E-6	0.0001				4.9E-9	-3.2E-6	0.0003	-0.0241
				(0.0002)	(4.2E-7)	·(7.9E-6)				(1.1E-9)	(3.0E-7)	(1.5E-5)	(0.0016)
Lead	319	0.0004	0.68	0.0008		6.5E-5	-0.0020	8.0E-8					-0.0023
				(0.0002)		(8.9E-6)	(0.0006)	(2.4E-8)					(0.0008)
Copper	398	8.1E-5	0.90	1.9E-5*	3.8E-6	2.4E-5		-2.4E-7					
				(2.0E-5)	(1.5E-7)	(9.6E-7)		(1.6E-8)					

N = # of observations.; S = std. error of regression (g/m^2); R^2 = correlation coefficient adjusted for degrees of freedom; C = intercept;
Duration = duration of storm event (min); Flow = total volume of runoff per unit area of watershed (L/m^2);
Intensity = Flow divided by Duration ($L/m^2/min$); VDS = single-lane vehicle count during storm; ADP = duration of antecedent dry period (hrs);
ATC = single-lane vehicle count during ADP; PDUR = duration of the previous storm event (min);
PFLOW = total volume of runoff per unit area of watershed during the previous storm event (L/m^2); PINT = PFLOW divided by PDUR ($L/m^2/min$);
An asterisk indicates the coefficient is not statistically different from zero; Numbers in parenthesis are the standard error of estimate of the coefficients;
Example: Iron (g/m^2) = $-0.0028 + 0.0042(Flow) + 0.0282(Intensity) + 0.000023(ADP)$
This table is applicable only to highway pavements with no street sweeping activity. Refer to Table 6.2.3 for street sweeping adjustments.

lost due to the first-order autocorrelation adjustment. The third column, *S*, is the standard error of the regression. Ninety-five percent of the regression predictions fall within plus or minus two standard errors of the regression. The fourth column is the coefficient of multiple determination, R^2, adjusted for degrees of freedom.

The following terms/acronyms are used in Table 6.2.1 to identify the variables used in the regression equations:

C	=	the constant (*y*-intercept) term in the equation;
Duration	=	total duration of storm in minutes;
Flow	=	the total volume of flow per unit area of watershed during the storm (L/m^2);
Intensity	=	Flow divided by Duration ($L/m^2/min$);
VDS	=	average number of vehicles traveling through the storm in a single lane;
ADP	=	total duration of the antecedent dry period in hours;
ATC	=	average number of vehicles using the highway during the ADP in a single lane;
PDUR	=	the total duration of the preceding storm in minutes;
PFLOW	=	the total volume of flow per unit area of watershed (L/m^2) the preceding storm event;
PINT	=	PFLOW divided by PDUR ($L/m^2/min$)

Columns 5 through 14 of Tables 6.2.1 and 6.2.2 list the coefficients of the independent variables of the equation. The number in parentheses is the standard error of the coefficient. A coefficient marked with an asterisk indicates that the coefficient is not statistically different than zero as determined by the *t*-statistic (i.e., one cannot be 95% confident the coefficient is not zero since ± 2 standard errors include zero). The only coefficients included in the final regression equation that failed the *t*-test are those of the *y*-intercept term C. The combination of high adjusted R^2 values with the statistically significant coefficients indicate that the equations are a "good fit" of the West 35th Street data (further evidence of a good model fit is the normality of the residuals exhibited in Appendix H).

The constituents listed in both Tables 6.2.1 and 6.2.2 are listed in ascending order according to the importance of the traffic count during the storm (VDS) in the regression equation. For example, the first constituent listed in Table 6.2.1, TSS, has the regression equation comprised of the fewest number of explanatory variables of that VDS is not included. The last constituent listed, oil and grease, has the regression equation comprised of the fewest number of explanatory variables of that VDS is included. Traffic count during the antecedent dry period was considered to be less important than traffic during the storm in this order system.

The interpretation of Tables 6.2.1 and 6.2.2 is presented below using TSS for an example. The predictive equation for the edge-of-pavement loading for TSS is determined using the coefficients shown in line 1 of Table 6.2.1, columns 5 through 14. The predictive equation for TSS is therefore:

$$\begin{aligned} TSS(\text{g/m}^2) = {} & 0.2556 + 0.3068(Flow) + 2.0181(Intensity) \\ & + 0.0037(ADP) - 2.9865(PINT) \end{aligned} \qquad (6.2.1)$$

The positive (+) sign preceding the coefficients of *Flow, Intensity,* and *ADP* indicates that an increase in the value of any of these variables will result in an increase in the load of TSS. Likewise, the greater the intensity of the preceding storm event (*PINT*), the less the TSS load (i.e., there is less material remaining on the highway following a larger storm event). The values given in parenthesis under each coefficient in Table 6.2.1 are the standard errors of the coefficients. There is a 95% probability that the true value of the variable coefficient is within +/- 2 standard errors (the given coefficients are not necessarily the "true" values since there is uncertainty, or a lack of knowledge, regarding the underlying build-up and wash-off processes of TSS in nature). For example, there is a 95% probability that the true value of the coefficient for *ADP* is between 0.0023 and 0.0051. Note that if there is no storm event at all (i.e., *Flow, Intensity, ADP*, and *PINT* are all equal to zero), the load of TSS is not equal to zero, but rather 0.2556 g/m^2. However, the standard error for the constant term, *C*, is 0.2721, and there is a 95% chance that the true value of the constant term is between -0.2886 and 0.7998. Since this range includes the value of zero, the equation actually states that there is a 95% probability that the true load of TSS is zero if there is no storm at all.

The TSS equation was formulated from a data set consisting of 402 observations (shown in column 2 of Table 6.2.1). This information is helpful in determining the degrees of freedom of the regression analysis (i.e., the number of linear independent pieces of information in *n* observations). For example, the TSS regression has 397 degrees of freedom, which is the result of 402 (number of observations) less 5 (the number of estimated parameters, or the coefficients of the three explanatory variables plus the constant term).

The standard error of the TSS regression is 0.5482 (shown in column 3 of Table 6.2.1). This number is an estimate of the uncertainty (i.e., lack of knowledge) that exists within the West 35th Street TSS data. During the fit of the West 35th Street TSS data, 95% of the equation predictions were within +/- 1.0964 g/m^2 (i.e. two standard errors) of the observed value. Note that this is not the same as the standard error of the forecast, which is almost always larger than the standard error of the regression.

The adjusted R^2 of the TSS regression is 0.93 (shown in column 4, Table 6.2.1). This number indicates that 93% of the variation in the TSS loading observed at the West 35th Street sampling site is explained by the variables *Flow*, *Intensity*, *ADP*, and *PINT*.

Table 6.2.3 gives the set of "street sweeping shifts" determined from the analysis of the West 35th Street data. These coefficient shifts should be added to the coefficient values given in Tables 6.2.1 and 6.2.2 if the regression equations are to be used for highway pavements where street sweeping is performed approximately once every 2 weeks. The following equations demonstrate the use of the street sweeping shifts for iron:

The predictive model for iron from Table 6.2.2 (i.e., used if there is no sweeping):

$Iron(g/m^2) = -0.0028 + 0.0042(Flow) + 0.0282(Intensity) + 0.000023(ADP)$

The predictive model for iron if there is once every two week sweeping:

$Iron(g/m^2) = -0.0028 + (0.0042-0.0006)(Flow) + 0.0282(Intensity) + 0.000023(ADP)$

Table 6.2.3 Street Sweeping Shifts (once every 2 weeks sweeping schedule)

Constituent (g/m^2)	C	Duration (min)	Flow (L/m^2)	Intensity (L/m^2min)	VDS	ADP (hrs)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2min)
TSS	-0.8225		-0.1484	2.6652						
	(0.3031)		(0.0190)	(1.0463)						
VSS	-0.0574		-0.0142	0.2724		-0.0003			-0.0034	0.1236
	(0.0413)		(0.0022)	(0.1231)		(0.0002)			(0.0018)	(0.2120)
BOD_5			-0.0014	0.0728	-7.6E-6					
			(0.0006)	(0.0278)	(0.0000)					
COD			-0.0181							
			(0.0023)							
Total Carbon		0.0011		-0.6375	-0.0001					
		(0.0002)		(0.0877)	(1.9E-5)					
Dis. Total Carbon				-0.2597	-1.5E-5		3.3E-7			-0.1916
				(0.0302)	(2.9E-6)		(8.9E-8)			(0.0737)
Nitrate	0.0017		0.0002	-0.0096						
	(0.0005)		(3.7E-5)	(0.0020)						
Phosphorus			-8.0E-5							
			(1.1E-5)							
Oil and Grease			-0.0009							
			(0.0002)							
Copper		-3.5E-6			2.2E-7					
		(2.1E-7)			(1.9E-8)					
Iron			-0.0006							
			(0.0002)							
Lead	-0.0010			0.0031						0.0028
	(0.0002)			(0.0006)						(0.0012)
Zinc								2.7E-6	-0.0003	0.0233
								(3.7E-7)	(2.1E-5)	(0.0024)

Shifts should *only* be used with coefficients in Tables 6.2.1 and 6.2.2. Refer to Tables 6.2.1 and 6.2.2 for acronym descriptions.
Example: Iron (g/m^2) = -0.0028 + (0.0042 - 0.0006)(*Flow*) + 0.0282(*Intensity*) + 0.000023(*ADP*)

The values shown in parentheses in Table 6.2.3 are the standard errors of the estimates of the sweeping shifts. All of the shifts in Table 6.2.3 have been determined to be statistically different from zero by using the *t*-test.

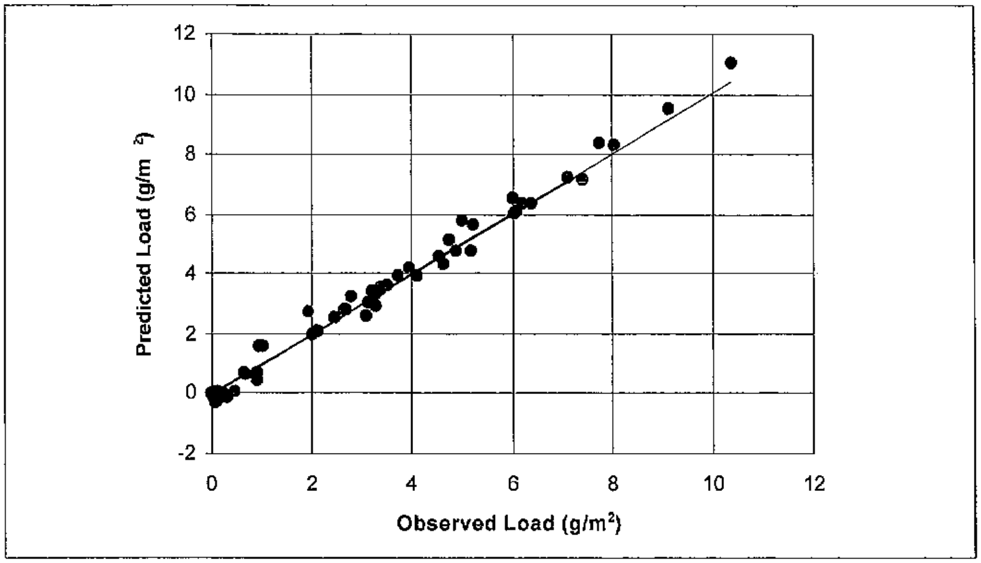
As shown in Table 4.8.1, not all constituent loads were reduced during the period of street sweeping. The street sweeping shifts reflect these results. The highway runoff model was used to calculate the expected storm water loading for each constituent during a design storm under two assumptions: (1) a street sweeping program with a once every 2 weeks schedule was currently being conducted and (2) no street sweeping program was being conducted. The results are presented in Table 6.2.4. The parameters of the design storm are footnoted in Table 6.2.4.

The results of the regression analysis are shown graphically in Figures 6.2.1 through 6.2.4 for TSS, COD, nitrate, and zinc, respectively. Similar figures are presented

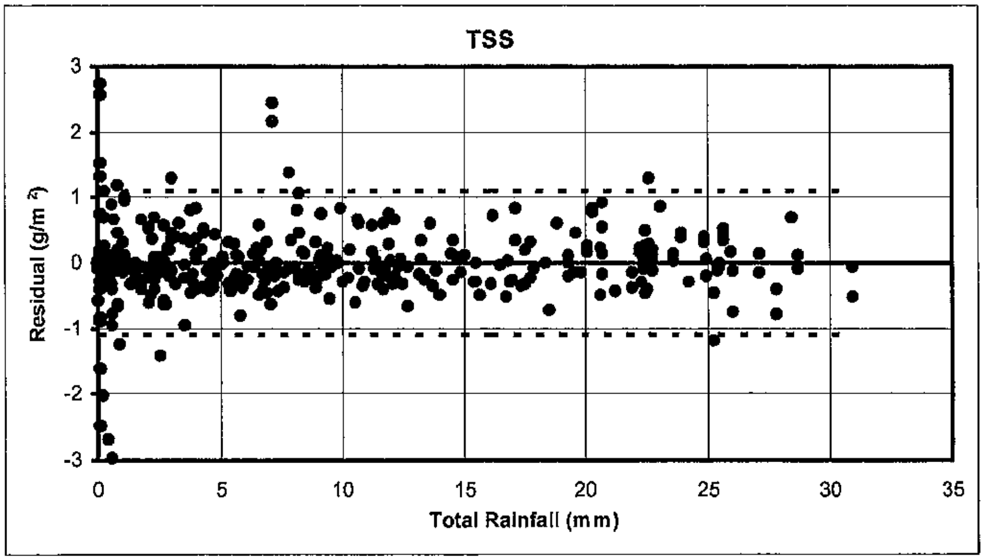
Table 6.2.4 Expected Loads based on MoPac Street Sweeping Program

Constituent	Expected Load with Street Sweeping (g/m^2)	Expected Load without Street Sweeping (g/m^2)
TSS	3.2	5.8
VSS	0.4	0.6
BOD_5	0.09	0.10
COD	1.3	1.6
Total Carbon	0.7	1.0
Dissolved Total Carbon	0.19	0.29
Nitrate	0.014	0.012
Total Phosphorus	0.003	0.005
Oil and Grease	0.07	0.07
Copper	0.0004	0.0004
Iron	0.07	0.08
Lead	0.0014	0.0007
Zinc	0.003	0.001

Storm duration = 60 minutes; Rainfall intensity = 25.4 mm/hr (1 in/hr);
Vehicles during the storm = 3,136; Antecedent dry period = 7 days;
Traffic count during dry period = 131,396; Previous storm duration = 60 minutes
Previous storm intensity = 25.4 mm/hr (1 in/hr); Watershed size = 4358 m^2 (46,910 ft^2)
Traffic lanes = 3

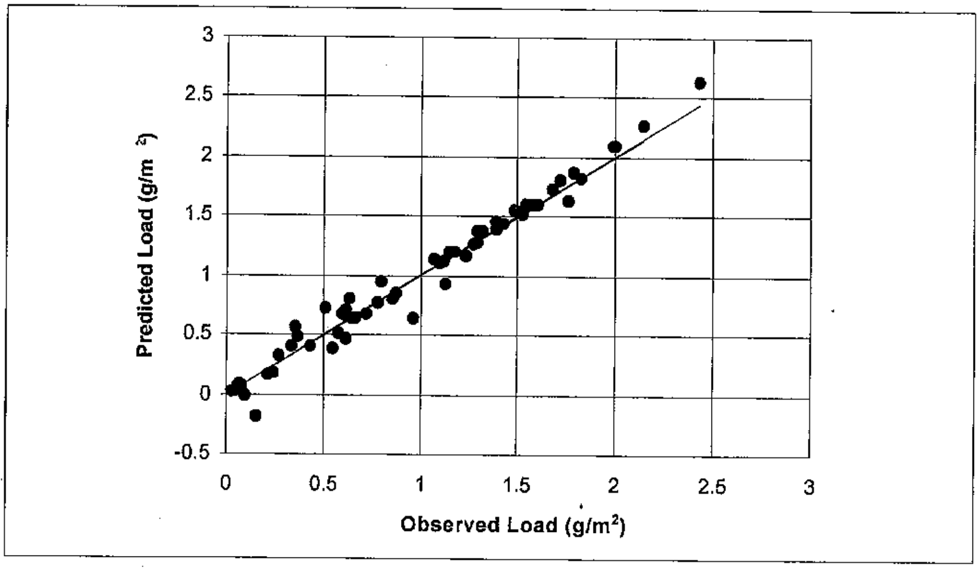


(a) Fit of Data from West 35th Street Site

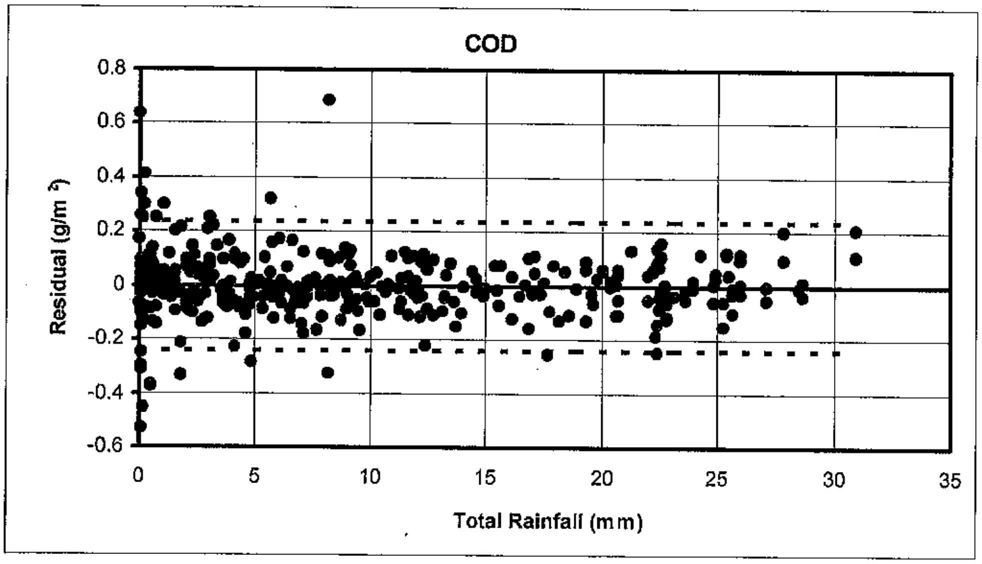


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure 6.2.1 TSS Model Results

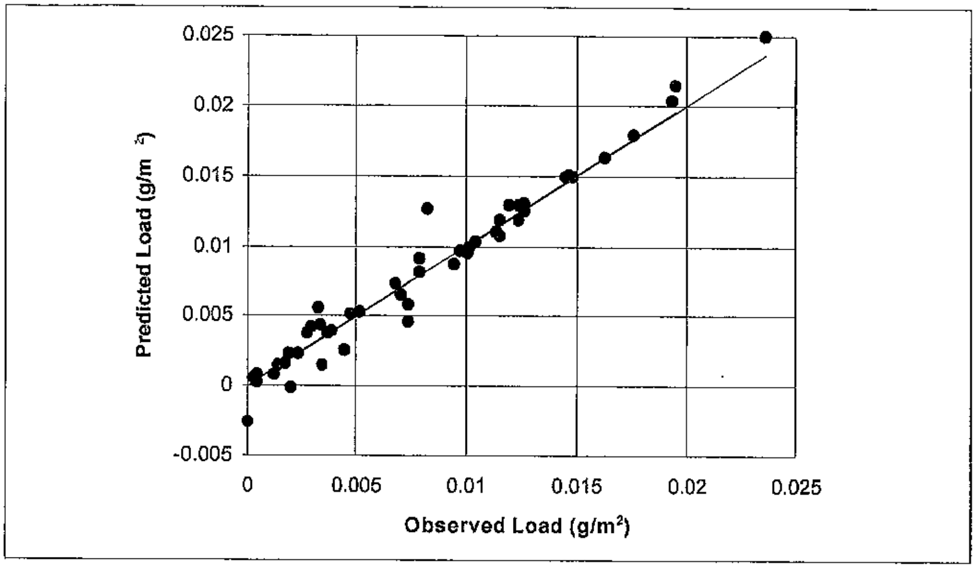


(a) Fit of Data from West 35th Street Site

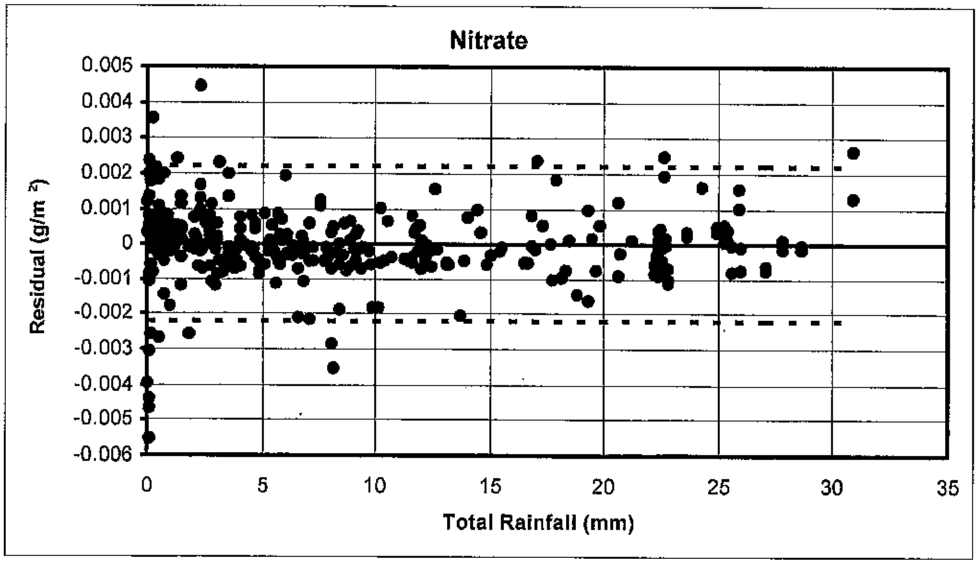


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure 6.2.2 COD Model Results

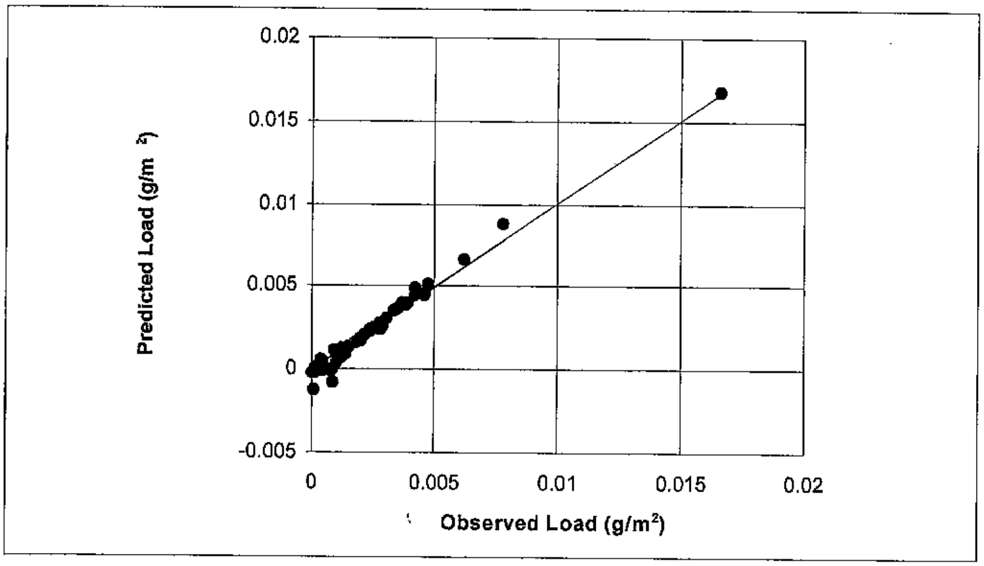


(a) Fit of Data from West 35th Street Site

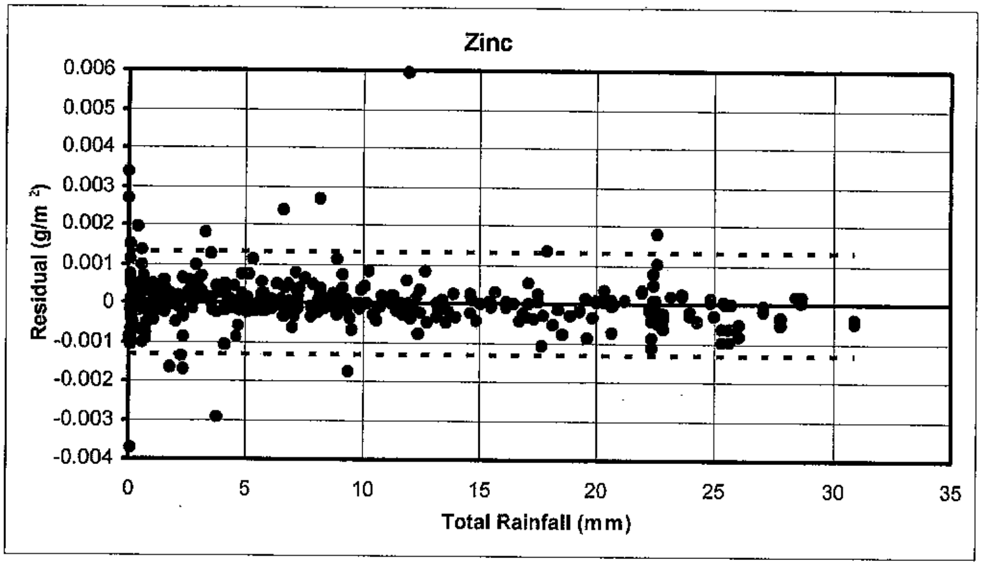


b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure 6.2.3 Nitrate Model Results



(a) Fit of Data from West 35th Street Site



(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure 6.2.4 Zinc Model Results

for all other highway runoff constituents in Appendix I. Part A of Figures 6.2.1 through 6.2.4 shows a plot of the observed total load versus the predicted total load for each storm recorded at the West 35th Street site. The solid line represents a perfect prediction, and the distance the predicted point is away from the line is a measure of the prediction error. Part B of each figure shows a plot of all of the residuals from the fit of the West 35th Street site data versus the total rainfall amount at the time of the observation. The dashed lines represent ± 2 standard errors of the regression.

Note in Part B of Figures 6.2.1 through 6.2.4 that the variation of the residuals is similar for storms of all magnitudes and that there is a normal distribution of residuals about the zero axis. This is graphic evidence that two fundamental ordinary least squares assumptions are satisfied: (1) homoscedasticity (at least with respect to runoff magnitude), and (2) a normal distribution of residuals (refer to Appendix G).

6.3 Model Verification with Data from the Convict Hill Site

The 20 storms that comprise the Convict Hill data were the only storm events available with which to verify the model. Unfortunately, there are many inaccuracies in the measurement of the explanatory variables at the Convict Hill site (relative to the West 35th Street site). Hourly traffic counts, for example, are measured at the site by TxDOT one day a year, and therefore, the number of vehicles that use the highway during both wet and dry periods must be estimated from these annual traffic counts (at West 35th Street, hourly traffic counts are recorded year around). The weekend traffic count, which is known to be much less than the weekday count, is complicated because the annual traffic count is conducted on a weekday. The Convict Hill site also has experienced a traffic growth rate of approximately 10% per year since 1993 because of increased residential development, which further complicates the traffic estimate. The predictive ability of each model that has traffic as an explanatory variable is adversely effected by the inaccuracy of the traffic counts.

The estimate of storm water discharge also is subject to errors. The Convict Hill sampling site is an overpass from that storm water drains via a downspout. Storm flow is directed from the downspout to a box that has a V-notch weir for one side. The water level is measured in the box using a bubbler flow meter and converted to flow using a weir formula. The box has been known to overflow on several occasions, resulting in the loss of accurate flow data. Any inaccuracy in the flow measurements will adversely affect the predictive ability of all constituent models.

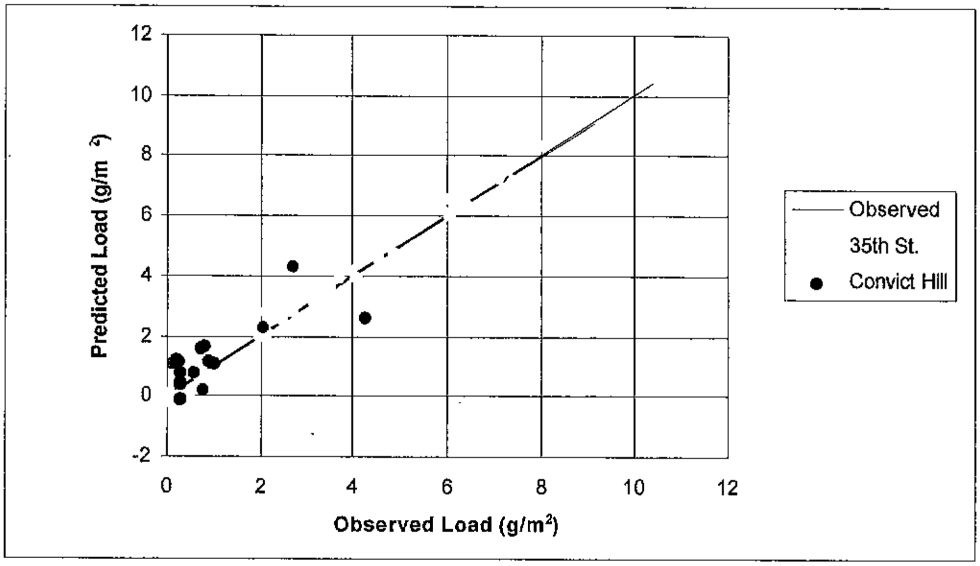
The model predictions for the Convict Hill storms are illustrated in Figures 6.3.1 through 6.3.4. The results from the fit of the West 35th Street data are shaded in the background to give a "feel" for the prediction error for storms occurring at the Convict Hill site.

The over-prediction tendency exhibited by the models at the Convict Hill site also can be attributed to the large area of pavement in the Convict Hill watershed that is not exposed to traffic (the loading differences observed for highway pavements under traffic and no-traffic conditions is shown in Figures 4.5.1, 4.5.2, and 4.5.3). Approximately 44% of the Convict Hill site watershed is exposed to traffic, compared to 77% at the West 35th Street site.

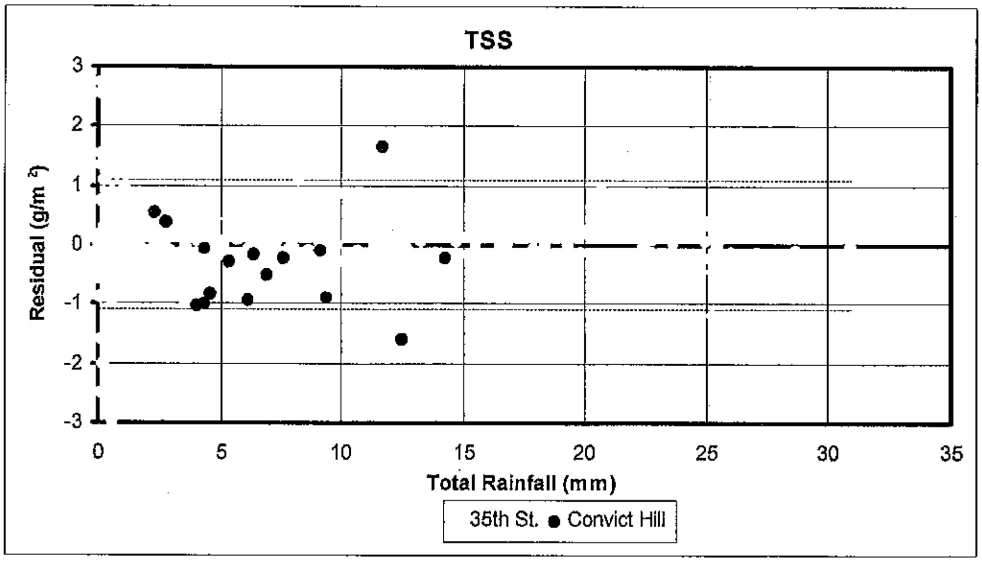
6.4 Interpretation of the Regression Results

The identification of the causal variables that influence constituent loading is among the more important findings of this study. There are two major applications of this knowledge. First, recognition of the specific variables that influence a given constituent load may suggest constituent-specific mitigation procedures, and second, the applicability of the model is directly reflected in the causal variables.

Because the dependent variable in the regression is expressed as load (g/m^2), the total volume of flow during the storm event will appear in every constituent model. Similarly, the intensity of the runoff and the duration of the runoff also will frequently appear in the models. The variables flow, intensity, and storm duration, therefore, offer little diagnostic information in the interpretation of the model specification. The appearance of the other variables in the model, such as VDS, ADP, and the previous storm event are the variables that "control" the constituent loading. The examination of the controlling variables in each model adds insight into the applicability of the model

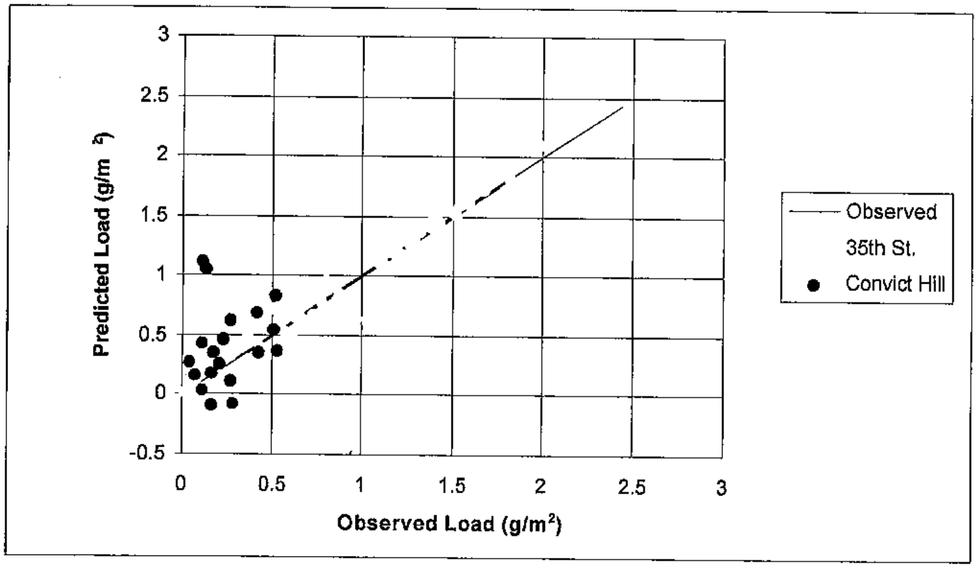


(a) Model Predictions at the Convict Hill Site

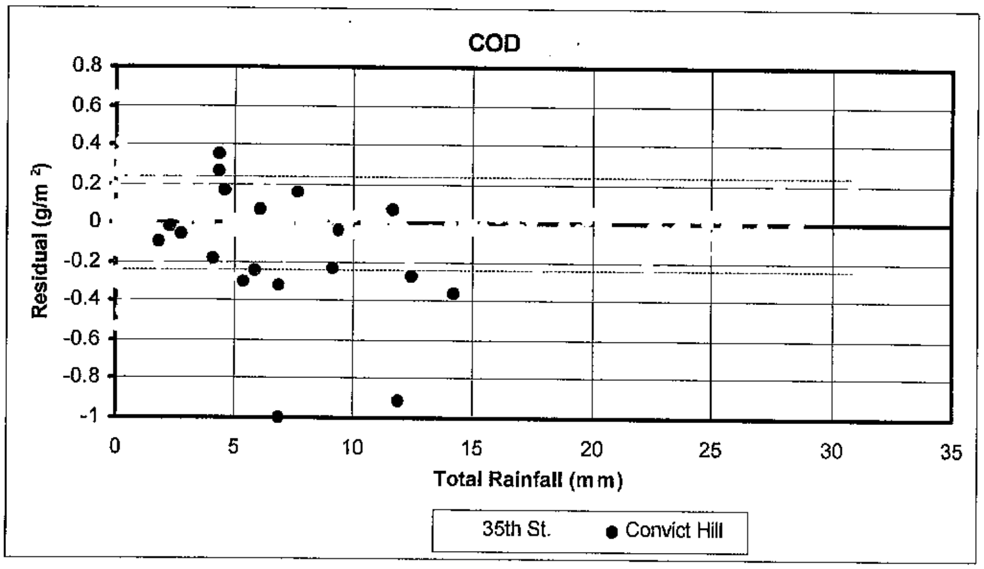


(b) Prediction Error vs. Total Rainfall

Figure 6.3.1 TSS Model Predictions

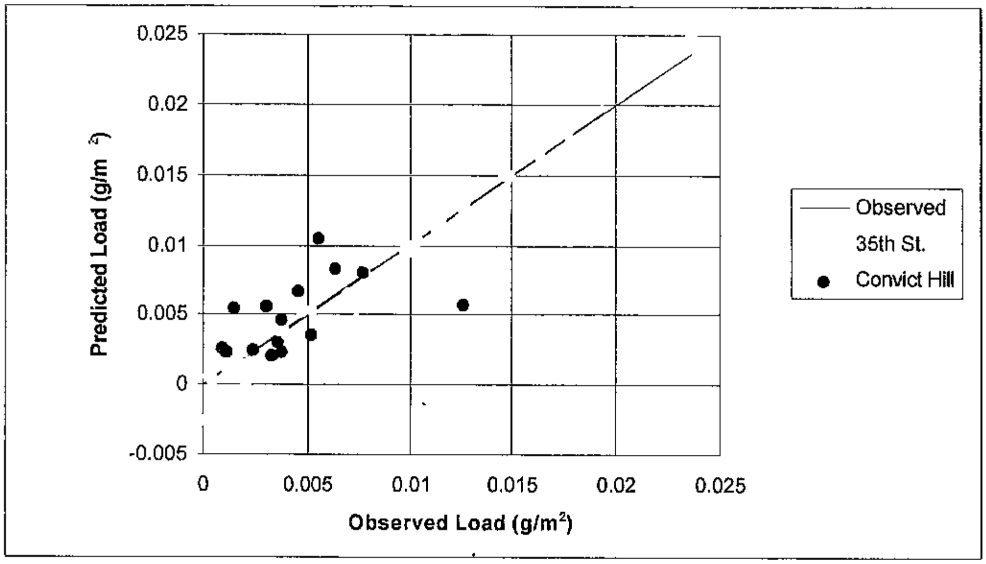


(a) Model Predictions at the Convict Hill Site

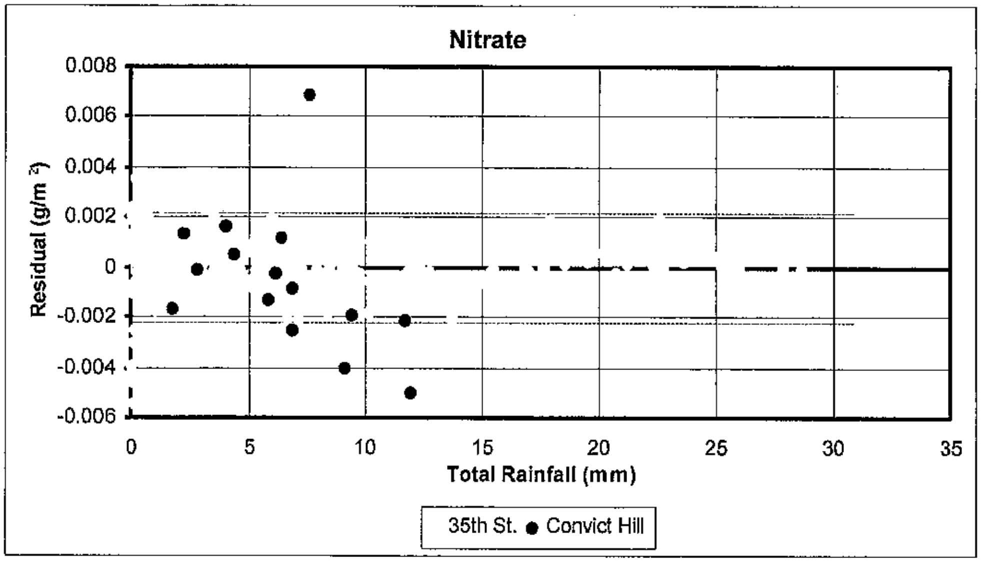


(b) Prediction Error vs. Total Rainfall

Figure 6.3.2 COD Model Predictions

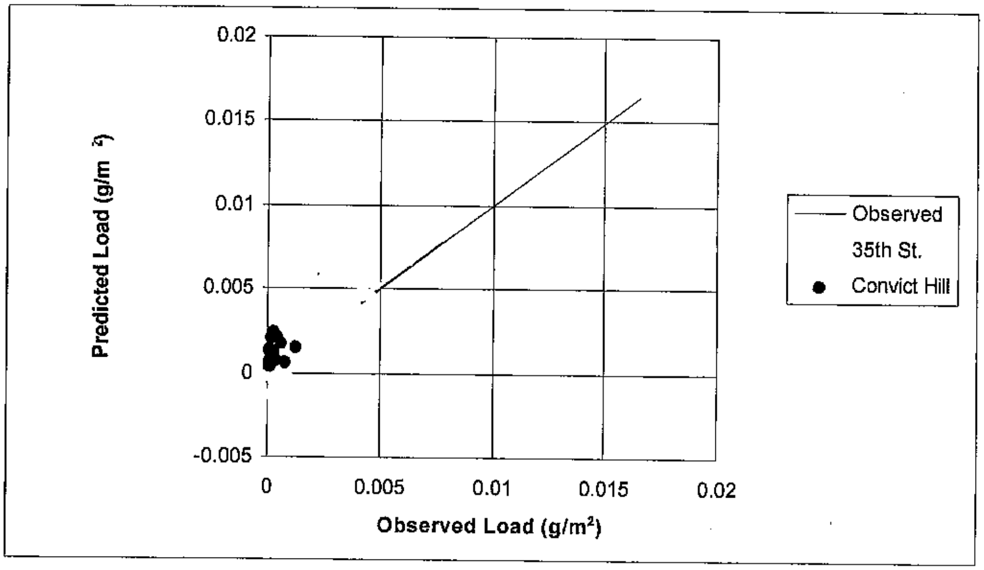


(a) Model Predictions at the Convict Hill Site

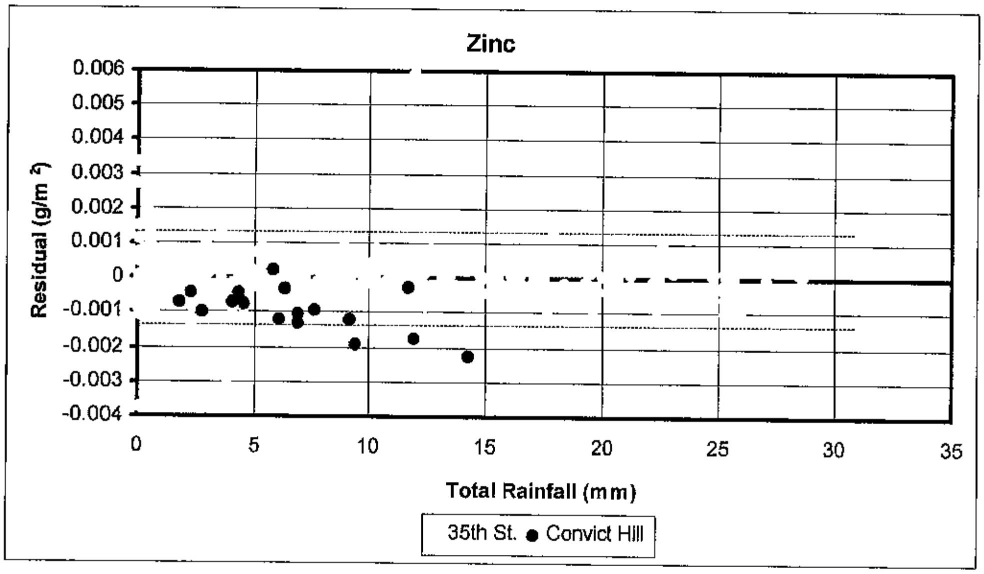


(b) Prediction Error vs. Total Rainfall

Figure 6.3.3 Nitrate Model Predictions



(a) Model Predictions at the Convict Hill Site



(b) Prediction Error vs. Total Rainfall

Figure 6.3.4 Zinc Model Predictions

and the mitigation of constituent loading. The following sub-sections examine the role of the controlling variables for each constituent group.

6.4.1 Solids

The regression results for TSS and VSS indicate that conditions during the antecedent dry period, such as dustfall and street maintenance activities (e.g., grass cutting, guardrail repair, bridge sanding, street sweeping, etc.), and the intensity of flow during the preceding storm event are the most significant variables that influence the storm loading of TSS and VSS. The absence of traffic as an influential variable does not suggest that there is no traffic contribution of solids during the storm, but simply that dustfall, street maintenance activities, and other dry period conditions overwhelm the contribution from vehicles (Figures 4.5.1 and F-2 illustrate that traffic does have some positive influence on the storm loads of TSS and VSS).

An examination of the signs of the coefficients in the solids models indicates that the storm water loading of TSS and VSS will increase with an increase in the duration of the antecedent dry period and will decrease with an increase in the intensity of the previous storm event. The (+) sign on the coefficient of the variable PFLOW in the VSS model is most likely a result of multicollinearity with PINT. This formulation is consistent with the theory that longer ADPs will result in a greater build-up of materials on the highway and that a more intense storm event will more completely cleanse the highway surface. More importantly, however, is that these formulations suggest the applicability of the solids models. For example, the duration of the antecedent dry period is a strong controlling variable (i.e., ADP is "strong" because there is only one other competing controlling variable in the model formulation); therefore, the solids model is applicable only to highways located in regions where the antecedent dry period conditions are similar to that at the West 35th Street site. For example, ADP conditions throughout the Barton Springs segment of the Edwards Aquifer recharge zone are generally similar to that at the 35th Street sampling site. For this reason, the model would be expected to give reasonable results throughout the region. However, the model would be expected to under-predict if applied in an area where the ADP is dominated by heavier dustfalls than those experienced at the West 35th Street site (e.g., summertime conditions in west Texas). Furthermore, the model will prove inaccurate if extreme ADP conditions (e.g., such as the tracking of mud onto the highway by construction vehicles, wintertime bridge sanding, etc.) are suddenly experienced in an area where the solids models are known (or at least thought) to provide reasonable results.

The formulation of the solids models also suggests constituent-specific mitigation procedures. For example, the formulation suggests that efforts to clean the highway during the dry period will reduce the storm water loading of TSS and VSS during subsequent rainfalls. The reduction in solids was confirmed by comparing the average loading of TSS and VSS in the no-sweeping data to that of the sweeping data. A *t*-test confirms a 99% probability that the TSS loads are reduced during street sweeping and a 95% probability that the VSS loads are reduced (Section 4.8).

Street sweeping should be conducted following any activity that deposits a large amount of dirt and debris onto the highway surface (this is currently a normal procedure for TxDOT). However, it also might be beneficial to sweep following a large storm event (e.g., rainfall intensities > 25.4 mm/hr). A prominent silt line was observed following both simulated and heavy natural rainfall events. The silt line was formed along the high-water mark approximately 2 to 2.5 m from the curb. The silt line is a concentration of dirt and debris that is readily accessible to street sweeping equipment.

In summary, the evaluation of the dry-period conditions are important in determining the applicability of the solids models. Reasonable results cannot be expected in regions where the dustfall is considerably different than in the Austin area or where other extreme ADP conditions exist, such as bridge sanding, the tracking of mud by construction vehicles, etc. Differences in rainfall patterns that might cause an unusual difference in the preceding storm event intensity should also be considered; however, these effects are much more subtle and not expected to have a major impact on the applicability of the model. Efforts to reduce the loading of solids in storm water runoff should be focused on (1) the removal of solids from the highway during the dry period or (2) the elimination of dry period conditions that cause dirt and debris to be deposited on the highway surface.

6.4.2 Oxygen Demand / Organics

The storm water loading patterns of the group of constituents consisting of BOD_5, COD, total carbon, dissolved total carbon, and oil and grease, are dominated by traffic. Traffic volume during both wet and dry periods influences the loading of BOD_5, total carbon, and dissolved total carbon. Traffic during the dry period alone is important in the COD model, whereas traffic during the wet period alone in important to the oil and grease model. The signs of all traffic variable coefficients in this group are positive, which is consistent with the theory that traffic is a contributor of constituents to runoff.

Traffic variations will control model applicability for this group. The model will yield the best results when used on a highway with traffic patterns similar to those at the West 35th Street site (i.e., three-lane traffic counts near 50,000 vehicles per day). The model is expected to over-predict in situations where the traffic count is significantly less, and under-predict in situations where the traffic count is significantly more. Furthermore, the models for this group are not expected to provide reasonable results for highways with extremely low vehicle counts (i.e., less than 2,500 vehicle per day).

The model formulation suggests that the storm water loading of these constituents will increase as the average daily traffic use of the highway increases, which is an expected result of local population growth. Since traffic is the principal source of these constituents, source reduction (i.e., a reduction of the traffic) is not considered a viable alternative. Mitigation procedures should therefore focus on the collection and treatment of the highway runoff.

6.4.3 Nutrients

The storm water loadings of nitrate and total phosphorus are dependent on the average traffic count during the dry period. However, the antecedent traffic count, which is a measure of the duration of the antecedent dry period, is only a marginally better predictor for this group than the duration of the antecedent dry period measured in hours. Therefore, the overall conditions during the dry period may actually be the controlling variable for this group.

Rainfall, however, is the most distinguishable source of nutrients in the storm water runoff. The analysis of rainfall samples determined that there are high concentrations (relative to the storm water runoff concentrations) of nitrate and total phosphorus in the Austin area rainfall. The median rainfall concentration for nitrate was as high as the contribution from the highway (i.e., rainfall samples contained a median concentration of nitrate of 0.47 mg/L, whereas the median EMC of nitrate in the storm water runoff was 1.00 mg/L). The median rainfall concentration of total phosphorus was approximately 25% of the total median concentration observed in the highway runoff. Nutrient levels in the rainfall will depend on atmospheric conditions both before and during the rainfall event.

Mitigation procedures should be similar to those of the organics group since source control is not a viable alternative. Similarly, the model is expected to give reasonable results only in regions where the nutrient content of the rainfall is similar to the Austin area.

6.4.4 Metals

The models for copper and lead are similar to the models formulated for the organics group in that they are highly influenced by the volume of traffic during the storm. Efforts to manage copper and lead loadings should therefore be directed toward storm water controls that collect and treat the storm water. Model applicability will be similar to that of the organics group.

The iron model is similar to TSS in that the controlling variables are conditions during the dry period. Iron loading is not influenced significantly by either wet-weather or dry-weather traffic volume. The model formulation suggests that iron should be managed similar to the solids group of constituents. Unfortunately, no significant difference was detected between the average load of iron observed during the street sweeping period compared to the average load during the no-sweeping period. Model applicability, however, should follow criteria similar to those for the solids group.

The model for zinc is influenced by the traffic count during the dry period and the runoff characteristics of the preceding storm. The model suggests that dry-period traffic is a source since traffic volume during the antecedent dry period was found to be a better predictor than the duration of the antecedent dry period measured in hours. This finding is consistent with past observations that tire wear is a significant contributor of zinc in highway runoff (Gupta, et al., 1981). Mitigation of the storm water loading of zinc is therefore limited to the control options available to copper, lead, and the organics group.

6.5 Summary

The model is applicable only to high-speed highway pavements. In general, the model will be most accurate for highway segments that are similar to the West 35th Street sampling site. The principal similarities include (1) a curbed highway segment that drains to a single outlet, (2) three active lanes of traffic, (3) average daily traffic counts greater than 50,000 vehicles/day, (4) paved shoulder widths less than 10 feet wide, (5) a relatively long watershed (i.e., greater than 700 feet) and (6) surrounding land use that is light commercial or residential. Model inaccuracies can be expected if there are extreme deviations in pavement use, average daily traffic counts, or dry period conditions. Specifically, model results can be expected to vary under the following conditions:

- The model will over-predict for watersheds where the paved shoulders (or other non-traffic-baring pavement areas) account for more than approximately 35% of the watershed.
- The model is applicable to highway segments with any number of active traffic lanes; the model will not be accurate where average daily traffic counts are extremely low (i.e., less than approximately 2500 vehicles/day)
- The model will under-predict where dry-period conditions are extreme, such as heavy mud tracking by construction vehicles, unusually heavy dustfalls (either natural or the result of local industry), or extreme highway maintenance activities such as bridge sanding.

GLOSSARY

$\bar{y}$	Arithemetic mean of the transformed data set
$\bar{x}$	Arithmetic mean of the sample data
η	Coefficient of variation
s_y	Standard deviation of the log transformed data
μ_y	True mean of the transformed random variable y=ln(x)
μ	True population mean
σ	True population standard deviation
σ^2	True population variance
σ_y^2	True variance of the transformed random variable y=ln(x)
$\hat{M}$	Unbiased estimator of the true lognormal population median
S_y^2	Variance of the log transformed data
S^2	Variance of the sample data
$\hat{\mu}$	Minimum variance unbiased (MVU) estimator of a lognormal population mean
σ_y	True standard deviation of the transformed random variable y=ln(x)
ADP	Antecedent Dry Period
ADT	Average Daily Traffic
C	Concentration (mg/L)
COV	Coefficient of Variation
CRWR	Center for Research in Water Resources
EMC	Event Mean Concentration (mg/L)
HMT	Hazardous Material Trap
K	Kurtosis
L	Length (meters, kilometers, etc.)
L^2	Area (square meters, etc.)

L^3	Volume (cubic meters, liters, etc.)
LOD	Limit of Detection
M	Mass (grams, milligrams, etc.)
m	Rank of an ordered set of data
MIT	minimum inter-event time
n	Sample size
ND	Non-Detectable
NURP	USEPA Nationwide Urban Runoff Program
Q	Flow (liters/sec, etc.)
S	Standard deviation of the sample data or Skewness
T	Time (seconds, minutes, hours, etc.)
TWC	Texas Water Commission (now integrated into the Texas Natural Resource Conservation Commission)
TxDOT	Texas Department of Transportation
USEPA	U. S. Environmental Protection Agency
VDS	Vehicles During the Storm
VIDS	Vehicle Intensity During the Storm (vehicles/hr)
W	Load (kg/d, kg/hr/m^2, kg/mm rainfall/km, etc.)
x	Sample measurement
y	Sample measurement, or ln(x)
Z	Standard Normal Deviate

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APPENDICES

Appendix A
Laboratory Analysis

Water quality samples were analyzed at the laboratory operated by The Center for Research in Water Resources at The University of Texas at Austin. The methods used to determine pollutant concentrations are summarized in Table A-1 for each constituent.

Table A-1 Laboratory Methods

Constituent	Method Description	Method Number
Total Coliforms	Membrane Filter Technique: Delayed-Incubation Total Coliform Procedure	SM 9222(C)
Fecal Coliforms	Fecal Coliform Membrane Filter Procedure	SM 9222(D)
Fecal Streptococcus	Membrane Filter Technique	SM 9230(C)
Total Suspended Solids	TSS Dried at 103 - 105°C	SM 2540(D)
Volatile Suspended Solids	Fixed and Volatile Solids Ignited at 500°C	SM 2540(E)
Turbidity	Nephelometric Method	SM 2130(B)
5-Day Biochemical Oxygen Demand	5-Day BOD Test	SM 5210(B)
Chemical Oxygen Demand	Closed Reflux, Colorimetric Method	SM 5220(D)

Table A-1 (Continued) Laboratory Methods

Constituent	Method Description	Method Number
Total Organic Carbon	Combustion-Infrared Method	SM 5310(B)
Nitrogen (Nitrate)	Nitrate Electrode Method	SM 4500-NO_3^- (D)
Phosphate	Colorimetric, Ascorbic Acid, Two Reagents	EPA 365.3
Cadmium	Inductively Coupled Plasma Method	SM 3500-Cd (D)
Chromium	Inductively Coupled Plasma Method	SM 3500-Cr (D)
Copper	Inductively Coupled Plasma Method	SM 3500-Cu (D)
Iron	Inductively Coupled Plasma Method	SM 3500-Fe (D)
Mercury	Inductively Coupled Plasma Method	SM 3500-Hg (D)
Lead	Inductively Coupled Plasma Method	SM 3500-Pb (D)
Nickel	Inductively Coupled Plasma Method	SM 3500-Ni (D)
Zinc	Inductively Coupled Plasma Method	SM 3500-Zn (D)
Oil and Grease	Spectrophotometric, Infrared	EPA 413.2

Procedure numbers with "SM" prefix are from *Standard Methods for the Examination of Water and Wastewater*, (American Public Health Association, 1992).
Procedure numbers with "EPA" prefix are from *Methods for Chemical Analysis of Water and Wastes*, (USGS, 1979).

Appendix B
Precipitation Characteristics for Austin, Texas

Table B-1
Average Precipitation in the Austin, Texas Area Compared to Natural and Simulated Rainfall Observed During the Study Period

Month	Average Precipitation (1951-1980)[a] mm	Precipitation (1993-1994)[b] mm	Simulated Rainfall (1993-1994) mm
July	44	Trace	122
August	57	19	61
September	102	9	61
October	83	61	30
November	57	25	61
December	51	29	91
January	44	36	91
February	64	54	122
March	44	43	91
April	89	43	91
May	108	93	91
June	76	19	61
Total	819	431	973

a) Larkin and Bomar, 1983
b) National Weather Service, Austin Texas

Table B-2

Rainfall Frequency for Austin, Texas (rainfall given in mm)

Duration (hrs) / Freq. (yrs)	1/12	1/4	1/2	1	2	3	6	12	24
1			33	41	48	53	61	71	81
2	13	28	41	51	58	66	79	89	104
5			51	64	79	86	104	122	140
10			58	74	91	102	122	145	170
25			69	86	109	119	147	173	201
50			79	99	122	135	163	196	226
100	22	48	86	107	135	152	183	221	254

Appendix C
Water Droplet Trajectory

The amount of energy required to throw a water droplet a given distance is illustrated by comparing the throw distance of a droplet to that of a stream with the same nozzle exit velocity. It is a common simplification to model water streams as a continuous, frictionless stream traveling through the air. The trajectory of the water stream is that of a parabola if air drag is neglected. Figure C.1 depicts the trajectory of a water stream leaving a 4.8-mm-diameter straight nozzle under 276 millipascal pressure. The flow rate is 0.4 L/sec and the exit velocity (V_e) is 23 m/sec. The nozzle is mounted at an elevation of 4.3 m and has a 30^0 departure angle. The height (z) of travel of the stream can be calculated as:

$$z = \frac{V_z^2}{2g} = \frac{[(\sin 30^o)(23m/\sec)]^2}{2(9.8m/\sec^2)} = 6.7m \qquad \text{(Eq. C.1)}$$

The time (T) to reach this height is found using the equation:

$$z = 6.7m = V_z T + 0.5gT^2 = \sin 30^0(23m/\sec)T + 0.5(9.8m/\sec^2)T^2 \qquad \text{(Eq. C.2)}$$

When solving Equation C.2 using the quadratic equation, T is found to be 0.48 seconds. Using this value of T, the horizontal distance traveled is determined as:

$$x = V_x T = \cos 30^0(23m/\sec)(0.48\sec) = 9.6m \qquad \text{(Eq. C.3)}$$

The ultimate distance of travel of the water stream can now be found using an approach similar to the above or by defining the equation for the parabola as shown in Figure C.1.

The flight of water droplets is extremely difficult to model. Evaporation, drag forces, and lift forces all affect the trajectory of the droplet. The following analysis makes use of Newton's second law to illustrate the effect of air drag on the travel of a water droplet from an elevated spray stand. The same initial velocity (23 m/sec) is used as in the water stream example. However, to simplify the calculation, the assumption is made that the trajectory is relatively flat and the water droplet leaves the spray head at a zero degree angle (i.e., flat) with respect to the x-axis. The coefficient of drag (C_d) is considered to be 0.03, and if there is little spin of the drop, the coefficient of lift can be considered zero. Assuming no loss of mass (i.e., evaporation) from the droplet during flight, the following equation can be developed for time of flight (sec) to a particular distance:

$$t = \frac{1}{\beta}[\exp(\frac{\rho C_D Sx}{2m} - 1)] \qquad \text{(Eq. C.5)}$$

where:

β	=	$\frac{\rho C_D S V_x}{2m}$ (sec)
V_x	=	Velocity (m/sec)
□	=	density of air (mg/l)
m	=	mass of droplet (g)
S	=	effective area of droplet (m^2)
x	=	distance along x axis of flight (m)

The *y*-coordinate, which represents the drop in flight of the droplet, is determined by:

$$y = \frac{-gt^2}{2} = \frac{-(23m/\sec^2)t^2}{2} = -11.5t^2 \text{ (m)} \qquad \text{(Eq. C.7)}$$

Figure C.2 shows the flight paths of 4 different droplet sizes from a 4.3-meter elevated spray head as calculated from the above equations. Comparing Figures C.1 and C.2 illustrates the additional energy required to produce rainfall versus a water stream. The throw distances shown in Figure C.2 are very close to those observed during experiments with the rainfall simulator.

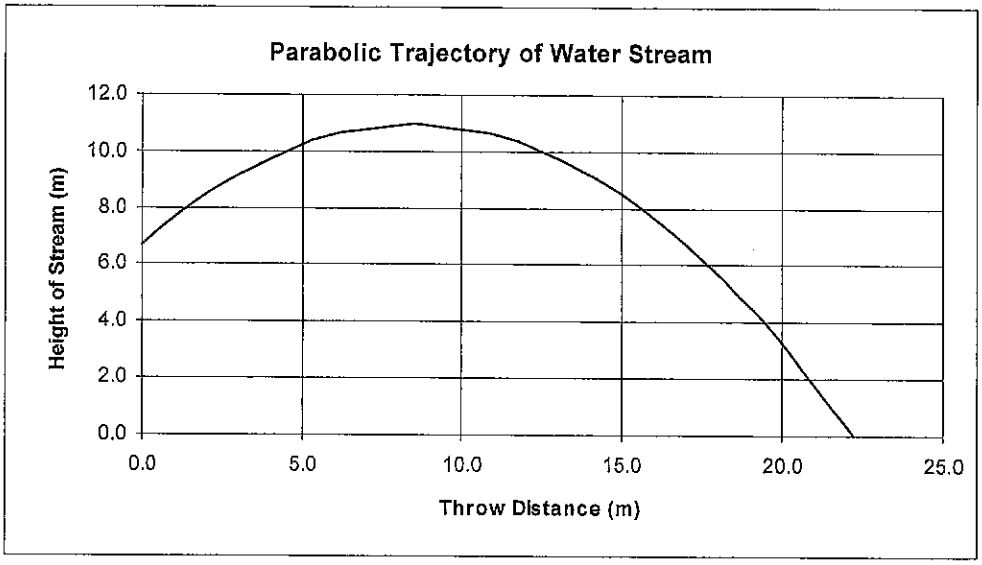


Figure C.1 Trajectory of Water Stream from a nozzle elevation of 4.3m (nozzle angle = 30^0)

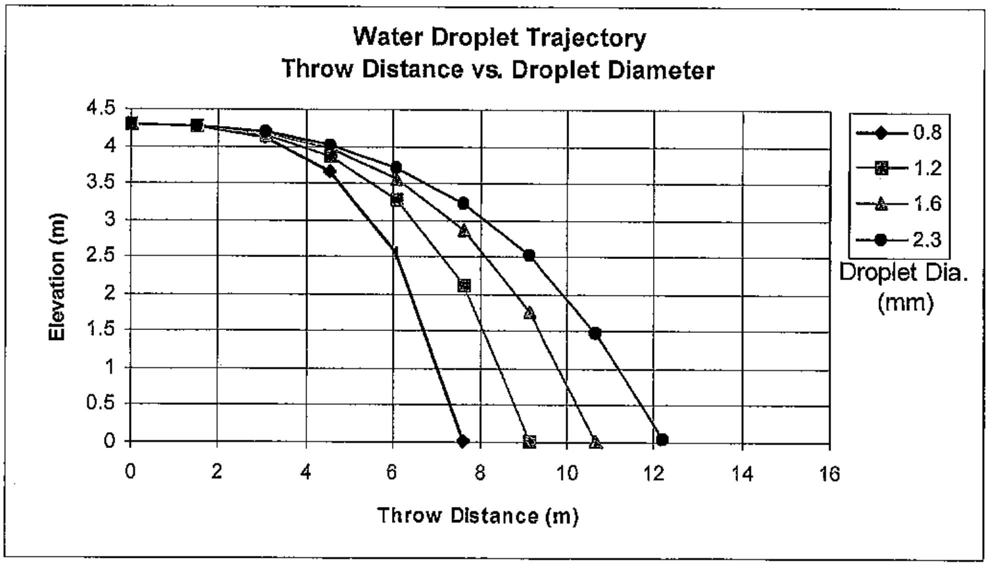
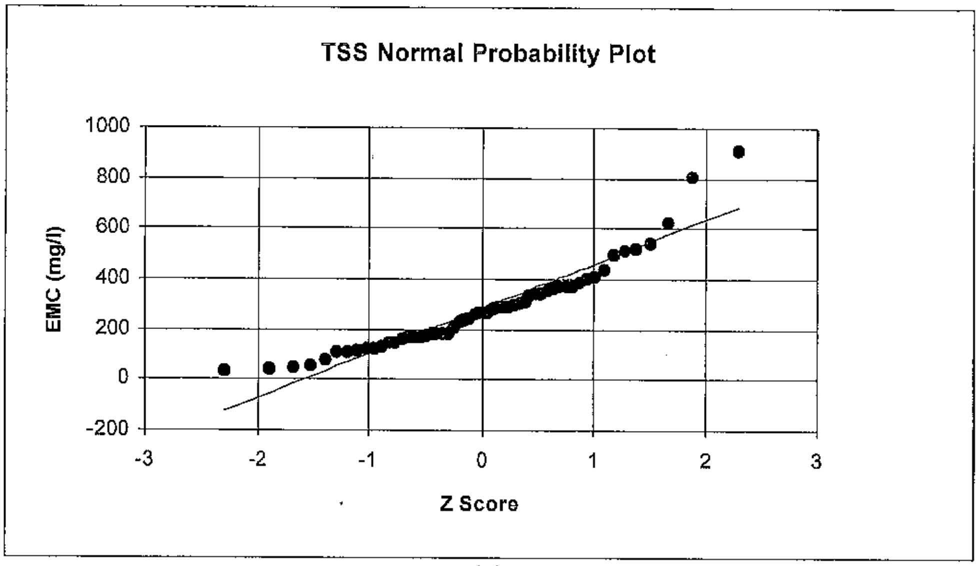
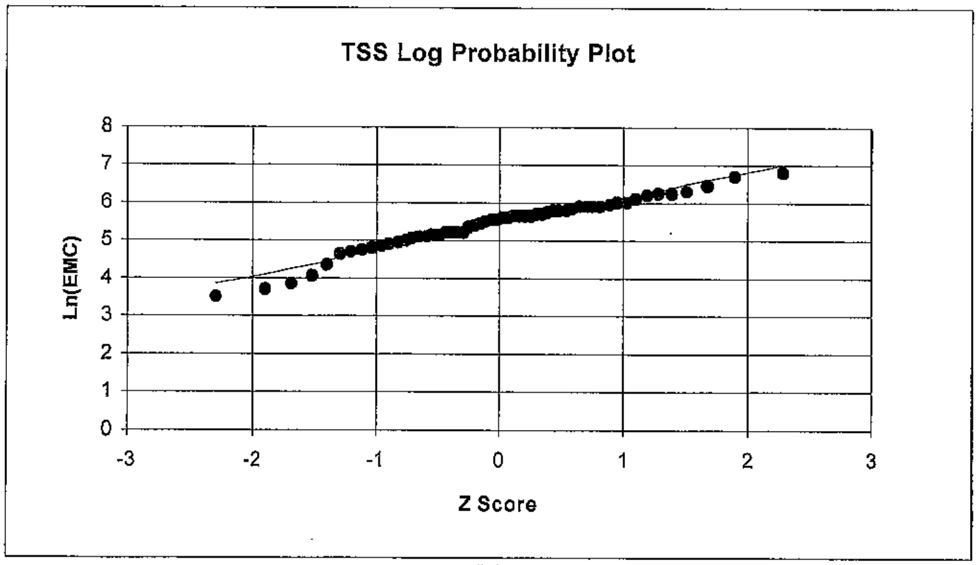


Figure C.2 Water Droplet Trajectory (nozzle angle = 0^0)

Appendix D
Probability Plots

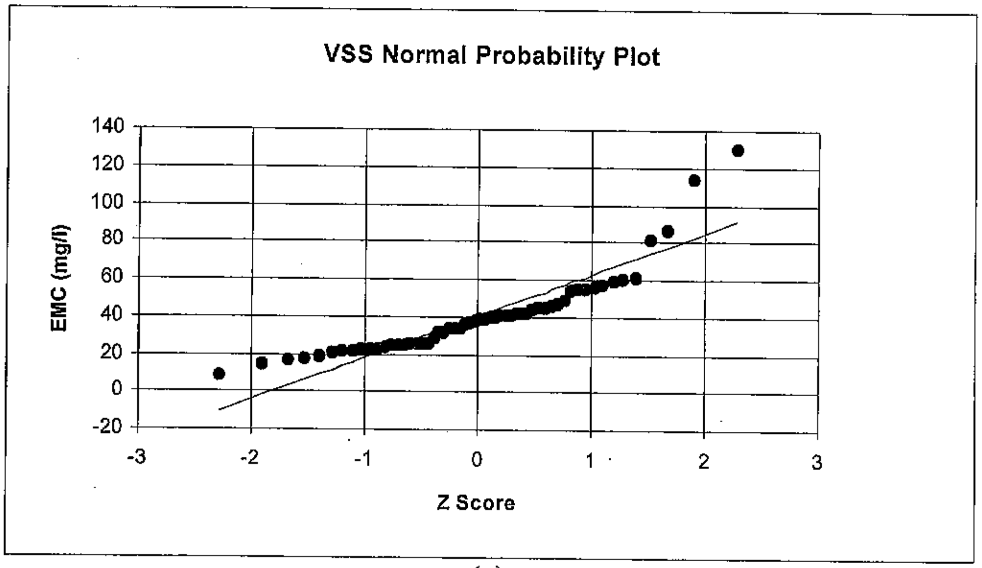


(a)

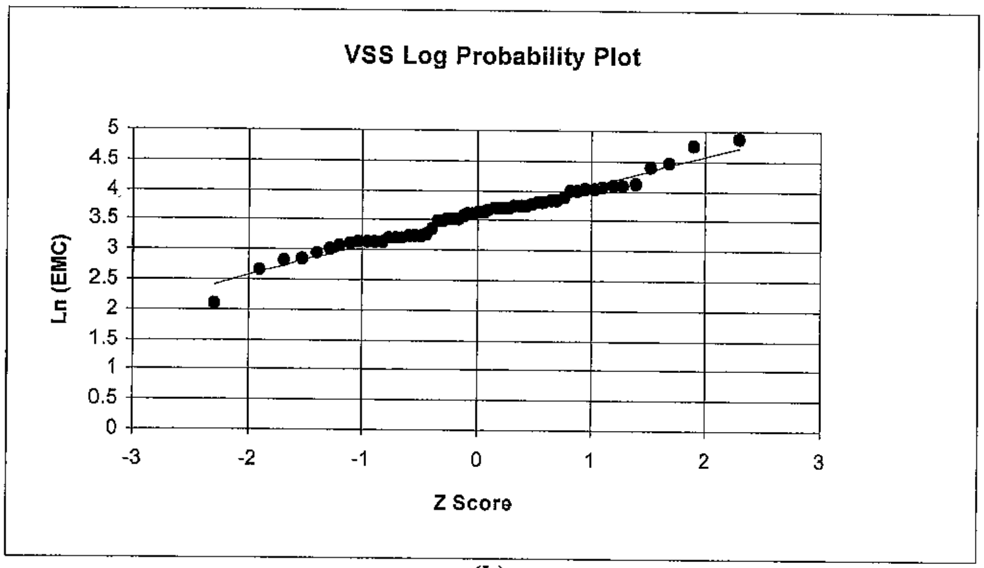


(b)

Figure D-1

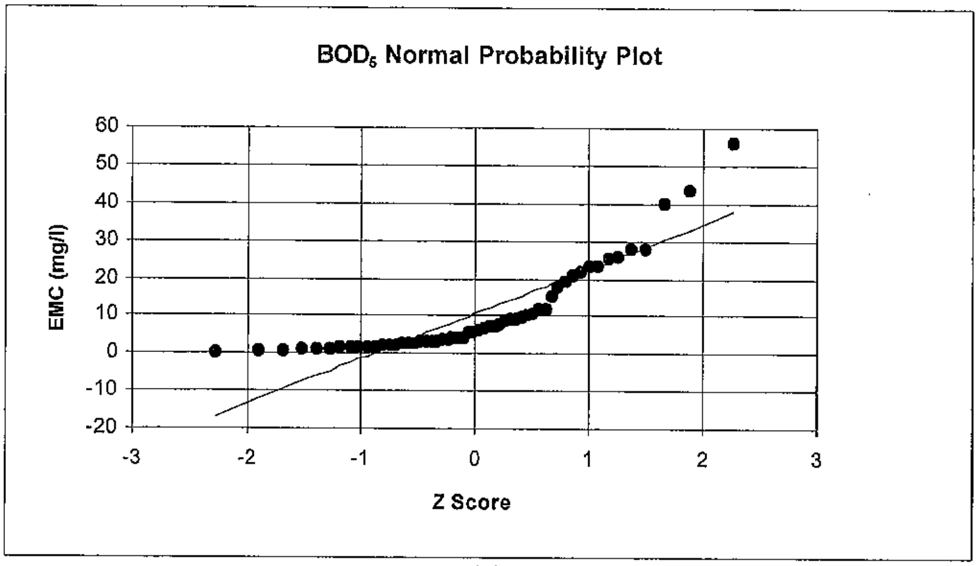

VSS Normal Probability Plot
EMC (mg/l)
140
120
100
80
60
40
20
0
-20
-3
-2
-1
0
1
2
3
Z Score

(a)


VSS Log Probability Plot
Ln (EMC)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-3
-2
-1
0
1
2
3
Z Score

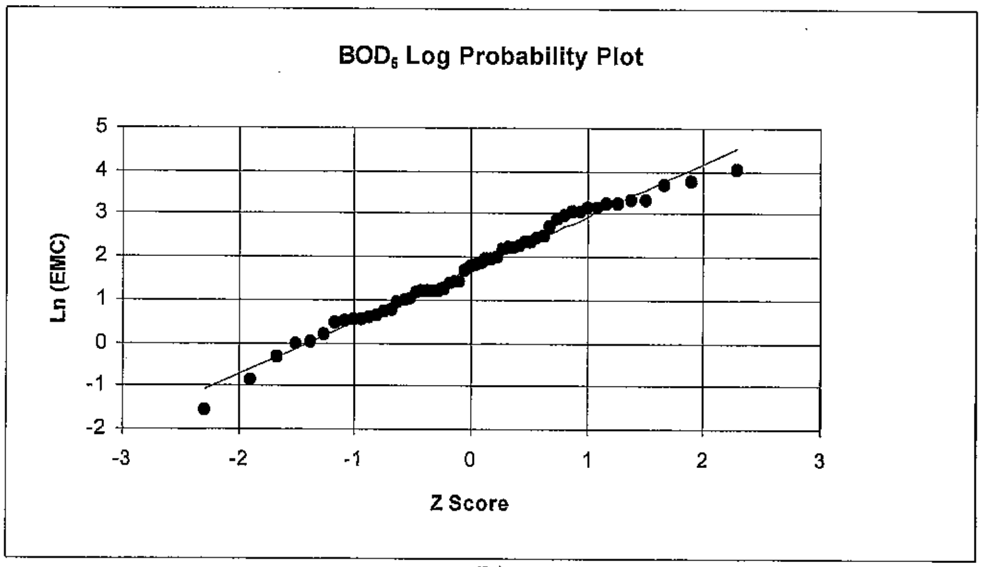
(b)

Figure D-2



BOD_5 Normal Probability Plot
60
50
40
30
20
10
0
-10
-20
EMC (mg/l)
-3
-2
-1
0
1
2
3
Z Score

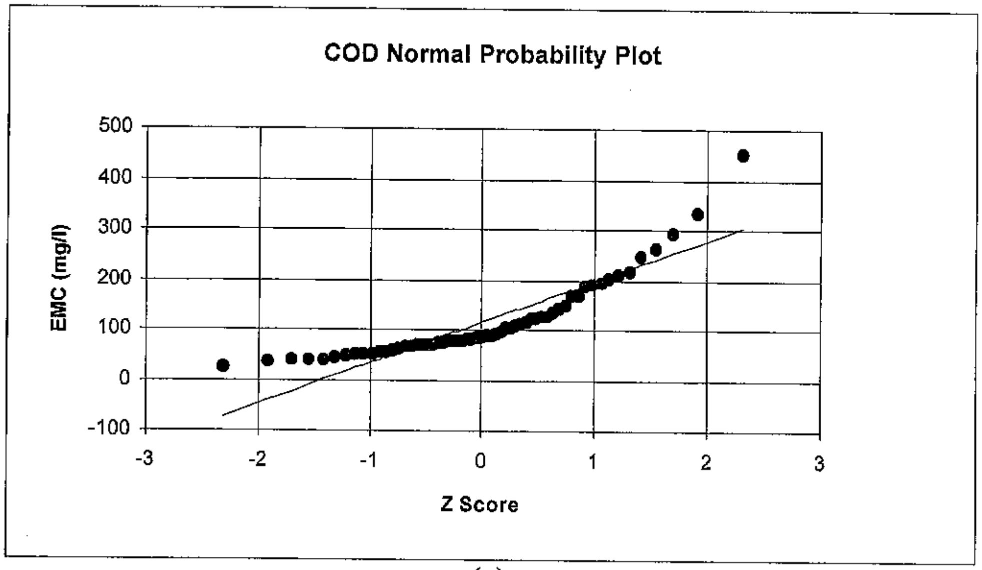
(a)



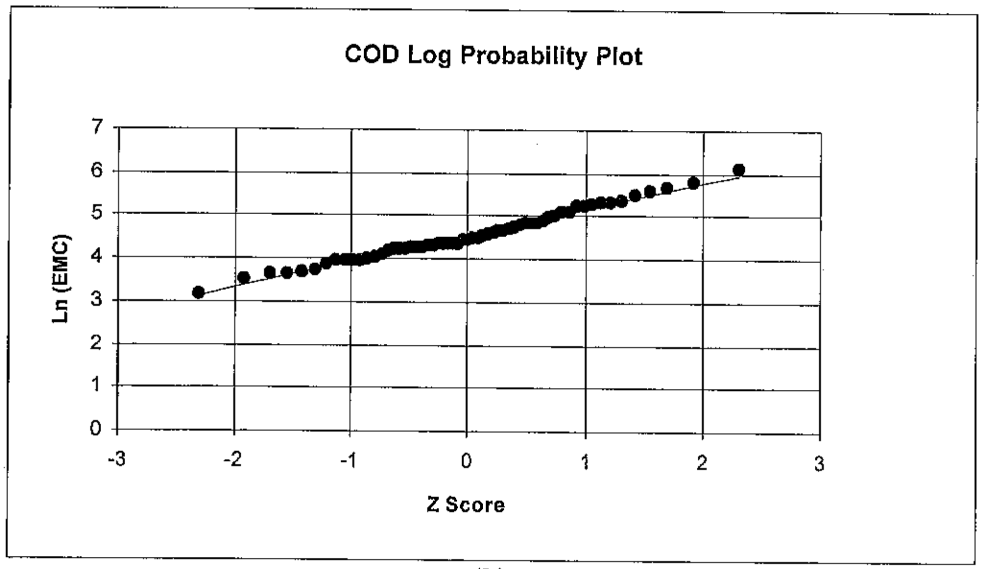
BOD_5 Log Probability Plot
5
4
3
2
1
0
-1
-2
Ln (EMC)
-3
-2
-1
0
1
2
3
Z Score

(b)

Figure D-3

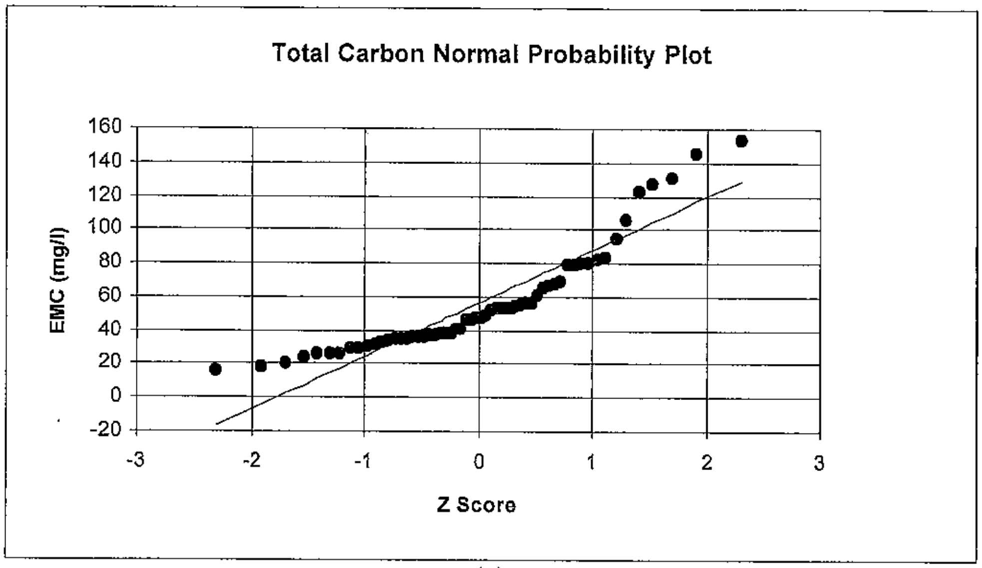

COD Normal Probability Plot
500
400
300
200
100
0
-100
EMC (mg/l)
-3
-2
-1
0
1
2
3
Z Score

(a)

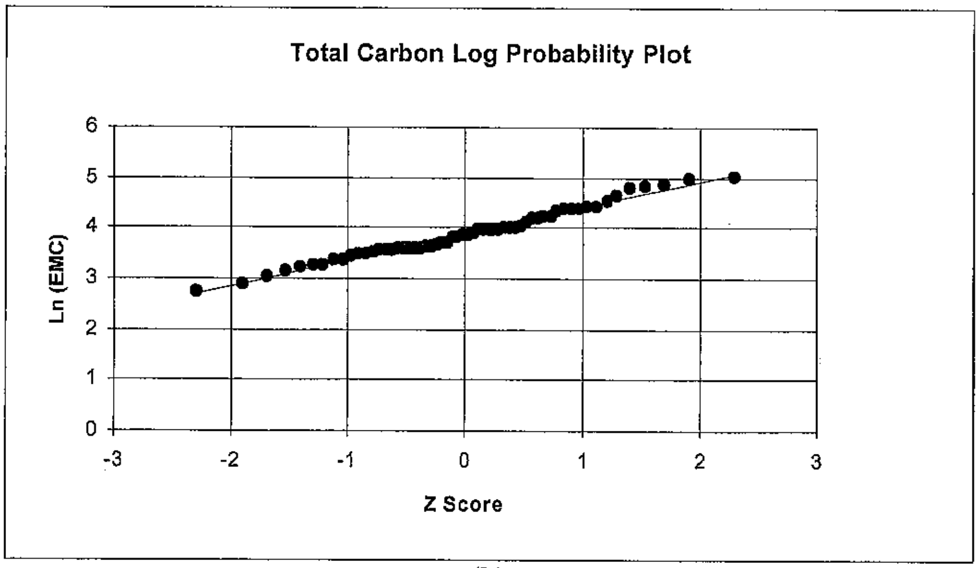

COD Log Probability Plot
7
6
5
4
3
2
1
0
Ln (EMC)
-3
-2
-1
0
1
2
3
Z Score

(b)

Figure D-4

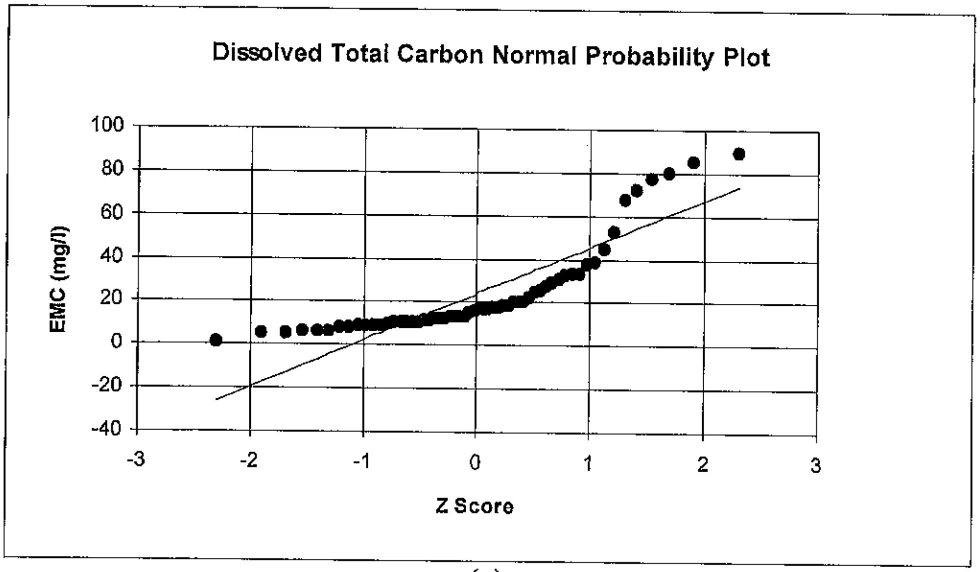

Total Carbon Normal Probability Plot
160
140
120
100
80
60
40
20
0
-20
EMC (mg/l)
-3
-2
-1
0
1
2
3
Z Score

(a)

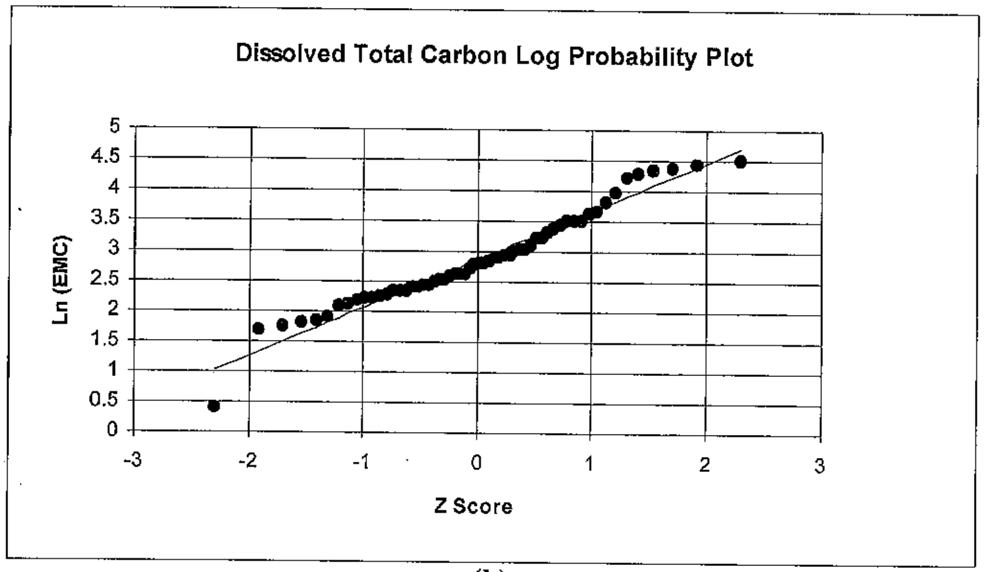

Total Carbon Log Probability Plot
6
5
4
3
2
1
0
Ln (EMC)
-3
-2
-1
0
1
2
3
Z Score

(b)

Figure D-5

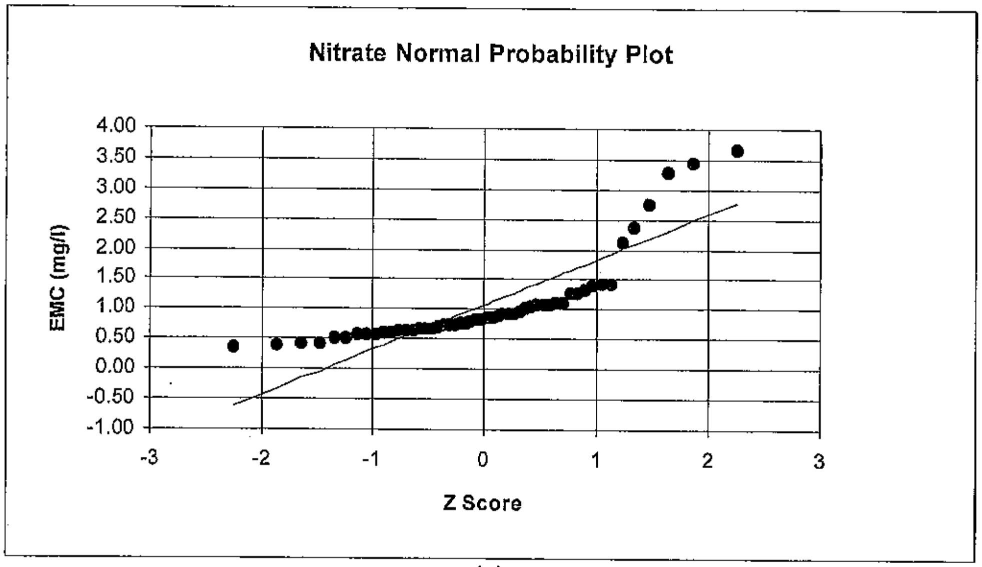

Dissolved Total Carbon Normal Probability Plot
100
80
60
40
20
0
-20
-40
EMC (mg/l)
-3
-2
-1
0
1
2
3
Z Score

(a)


Dissolved Total Carbon Log Probability Plot
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Ln (EMC)
-3
-2
-1
0
1
2
3
Z Score

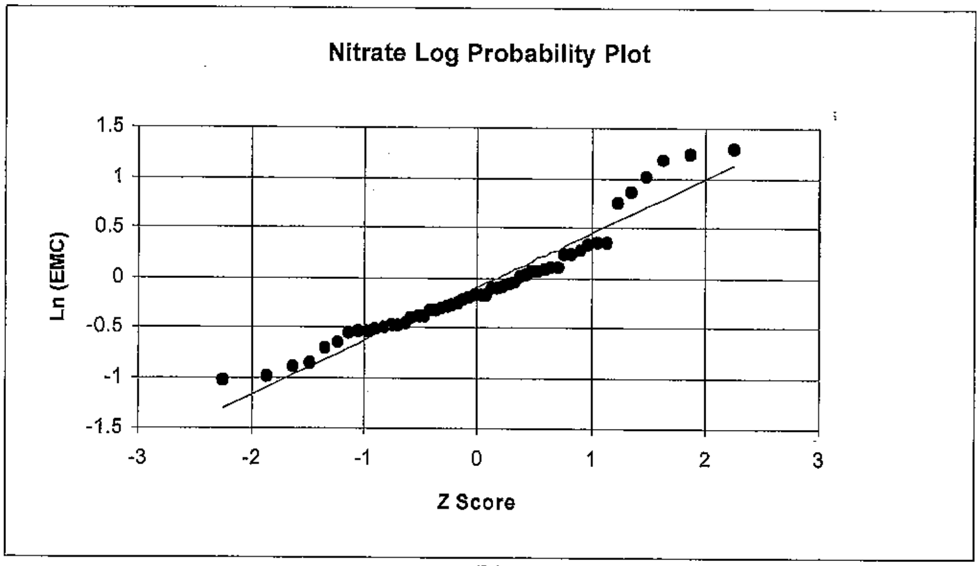
(b)

Figure D-6



Nitrate Normal Probability Plot
EMC (mg/l)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-3
-2
-1
0
1
2
3
Z Score

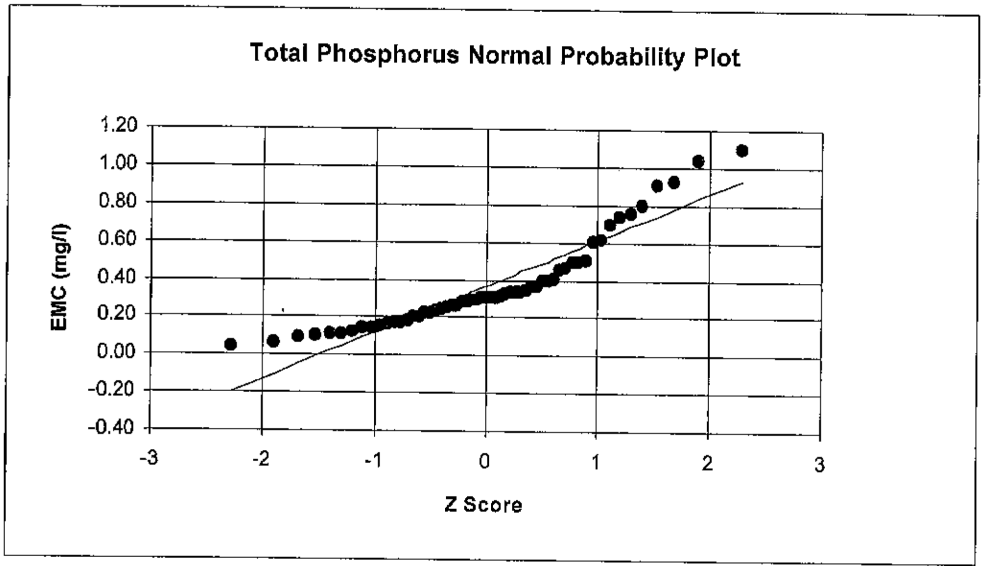
(a)



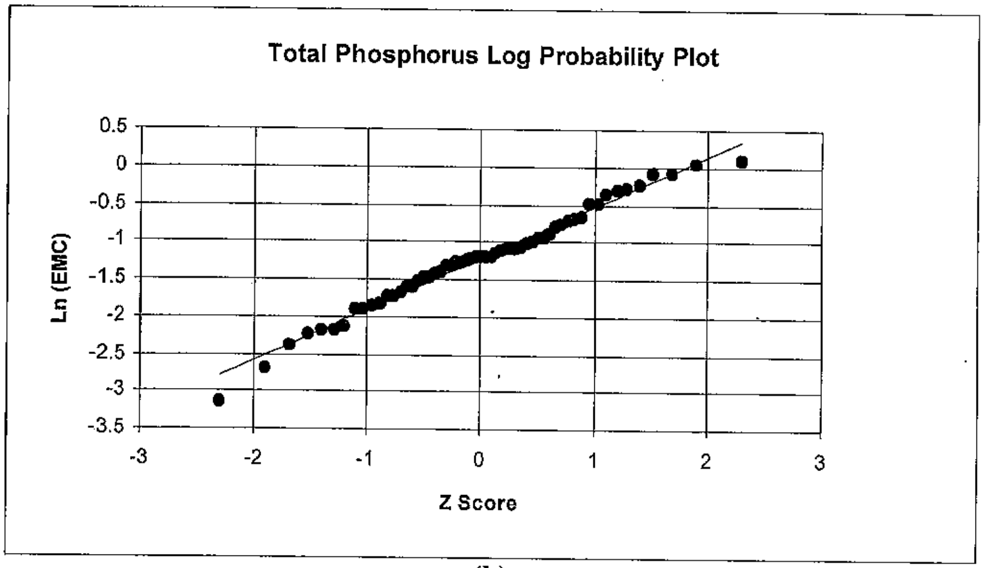
Nitrate Log Probability Plot
Ln (EMC)
1.5
1
0.5
0
-0.5
-1
-1.5
-3
-2
-1
0
1
2
3
Z Score

(b)

Figure D-7

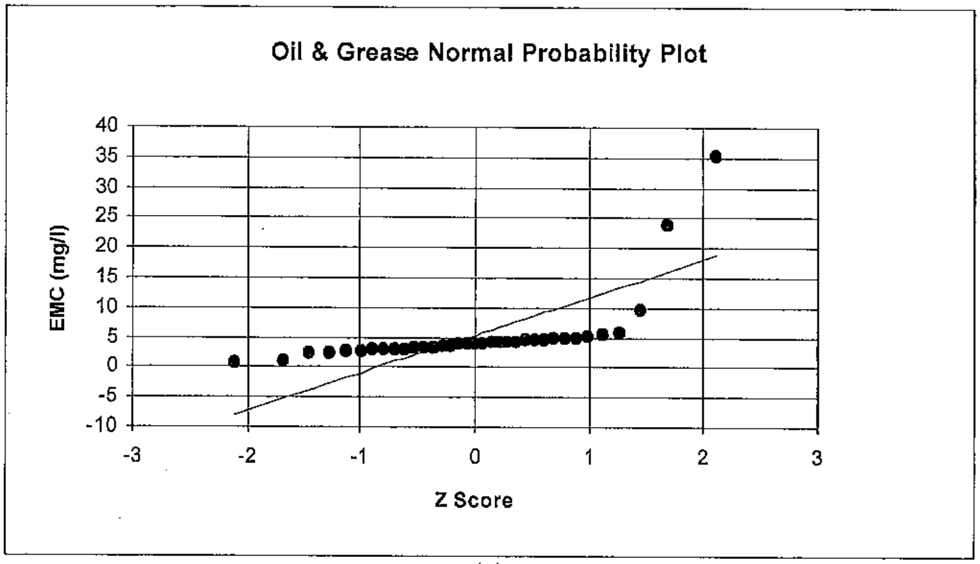

Total Phosphorus Normal Probability Plot
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
EMC (mg/l)
-3
-2
-1
0
1
2
3
Z Score

(a)


Total Phosphorus Log Probability Plot
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
Ln (EMC)
-3
-2
-1
0
1
2
3
Z Score

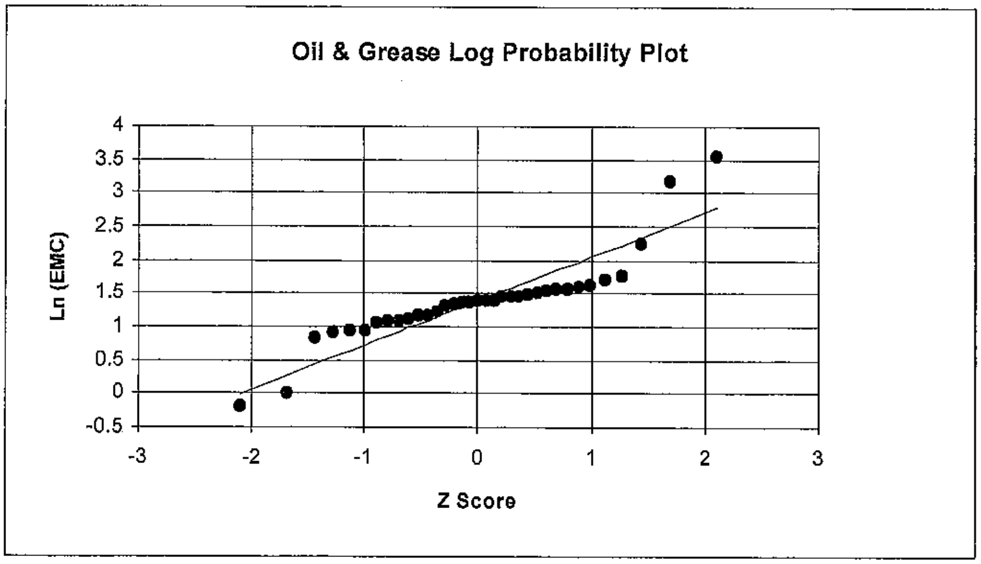
(b)

Figure D-8



Oil & Grease Normal Probability Plot
40
35
30
25
20
15
10
5
0
-5
-10
EMC (mg/l)
-3
-2
-1
0
1
2
3
Z Score

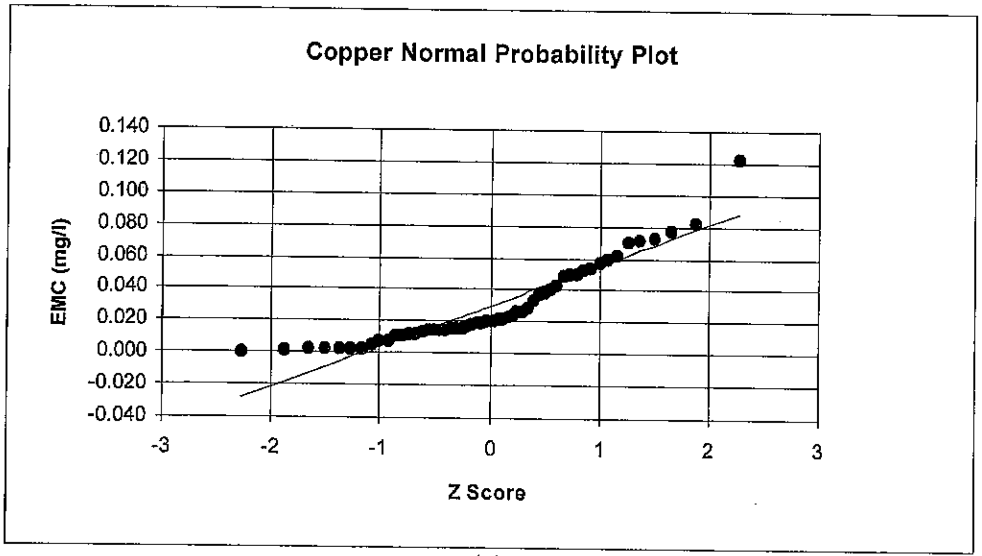
(a)



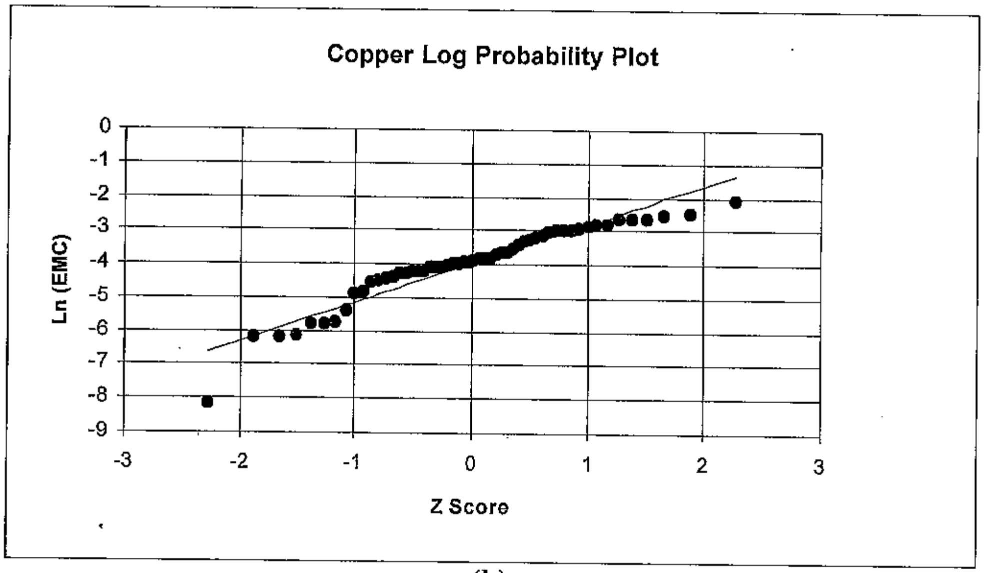
Oil & Grease Log Probability Plot
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
Ln (EMC)
-3
-2
-1
0
1
2
3
Z Score

(b)

Figure D-9

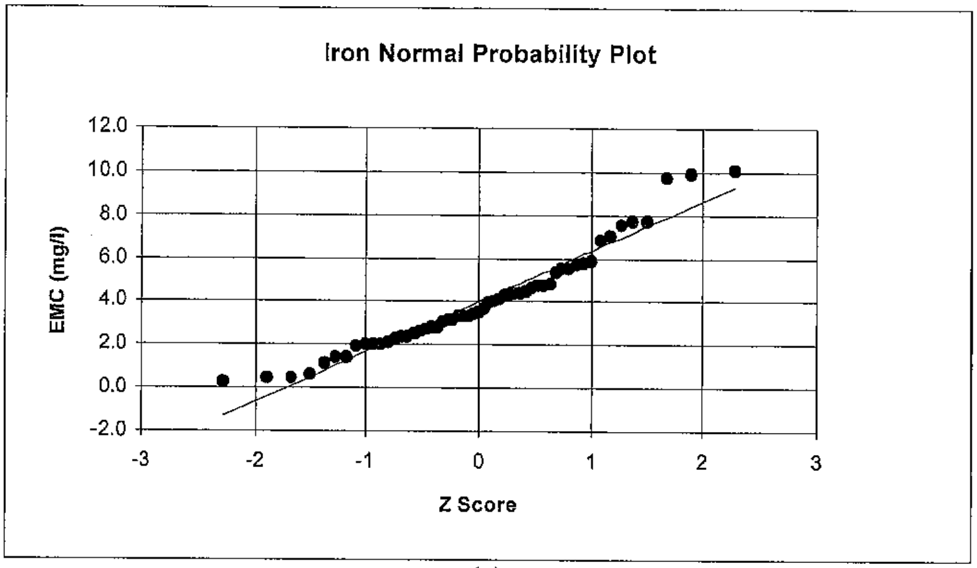


(a)

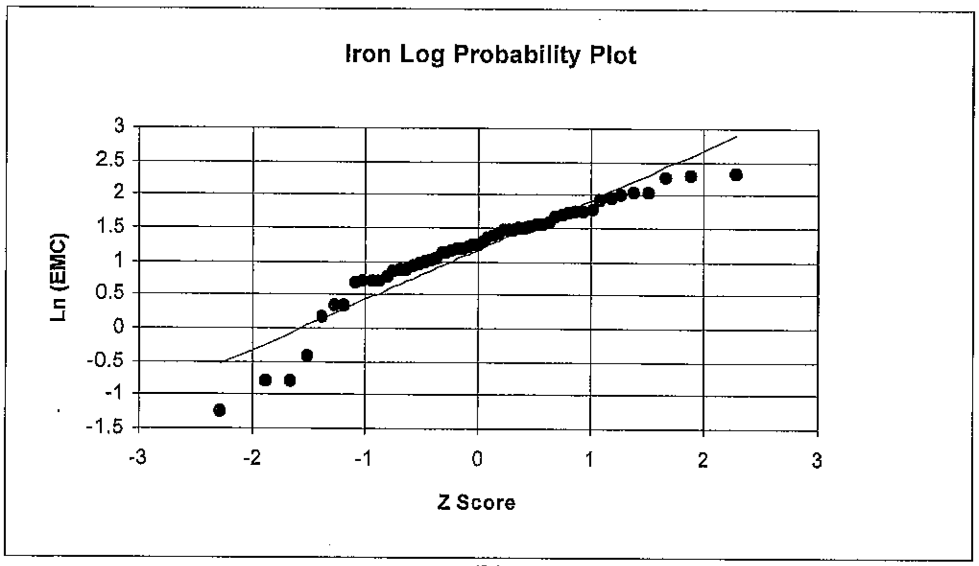


(b)

Figure D-10

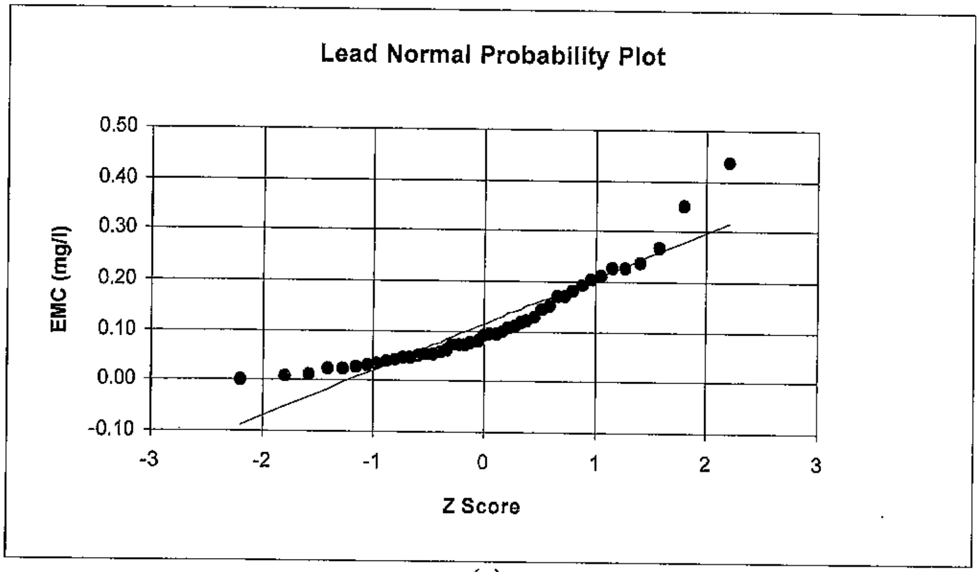


(a)

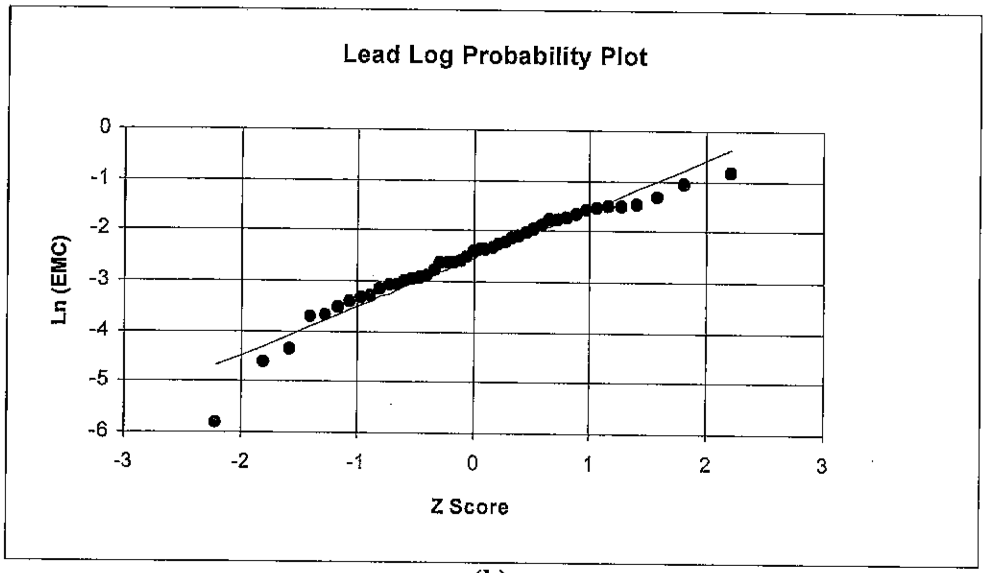


(b)

Figure D-11

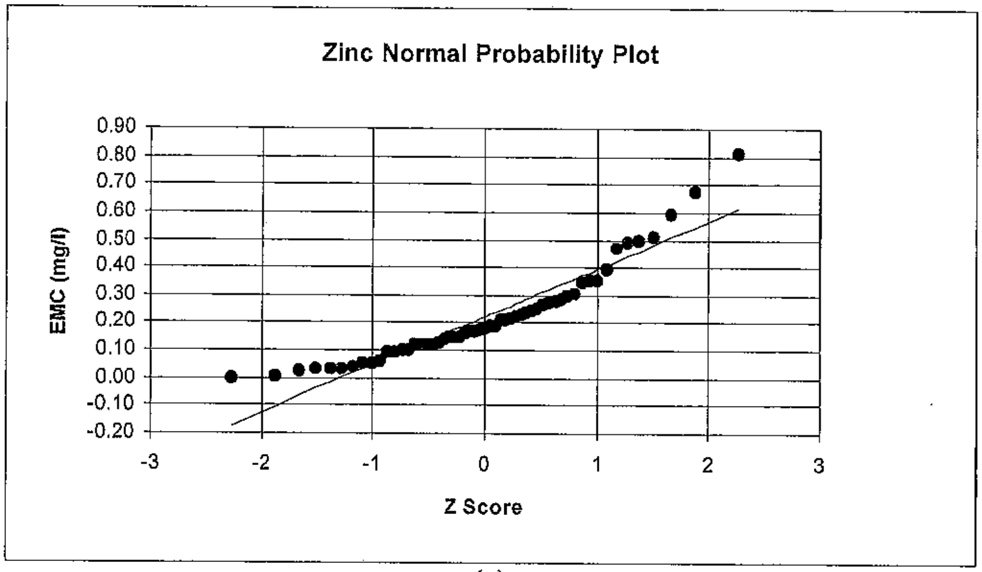


(a)

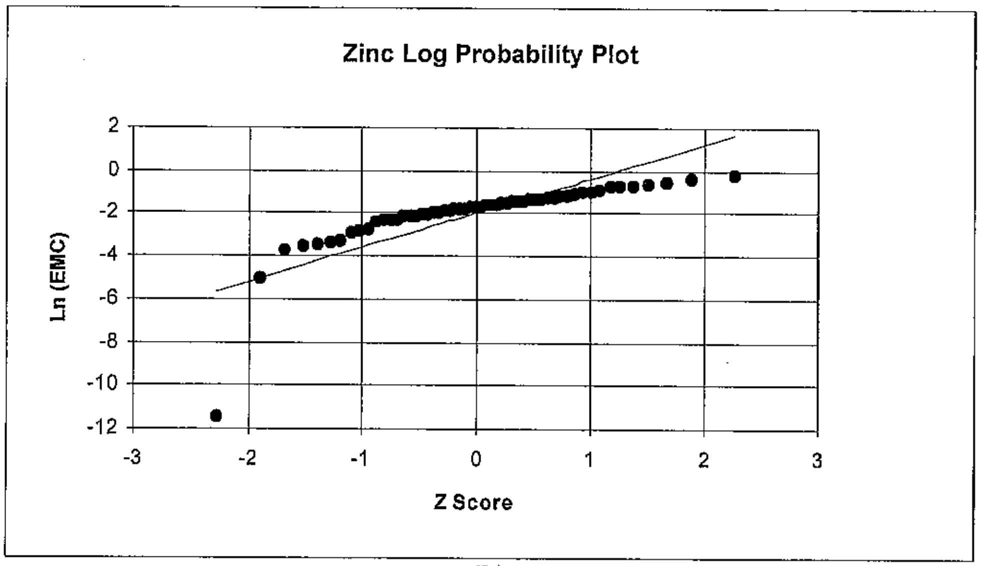


(b)

Figure D-12



(a)



(b)

Figure D-13

Appendix E
Histograms of Constituent Event Mean Concentrations

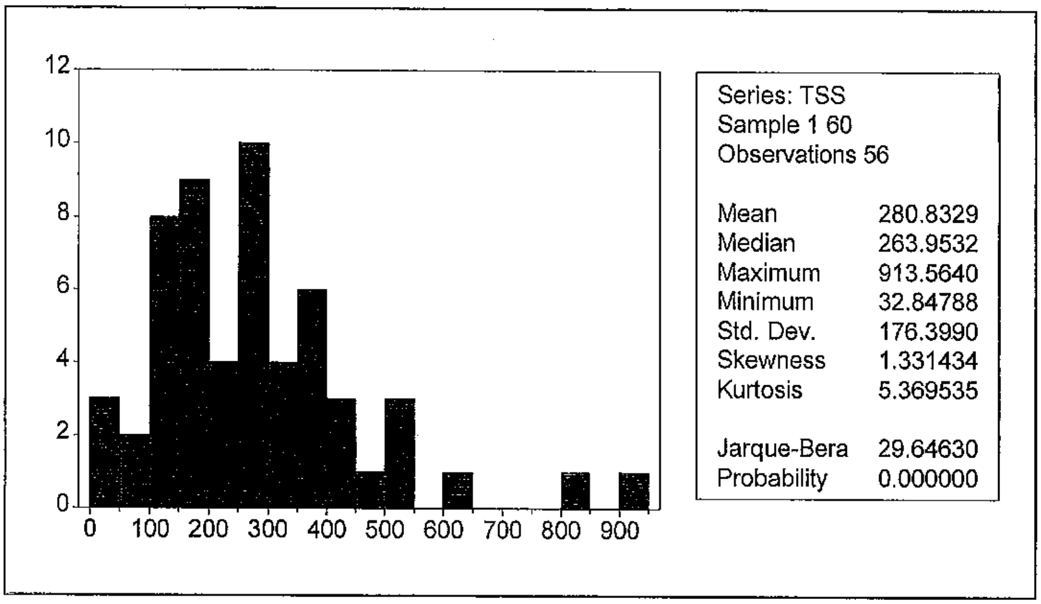


Figure E-1 Histogram of TSS Observations

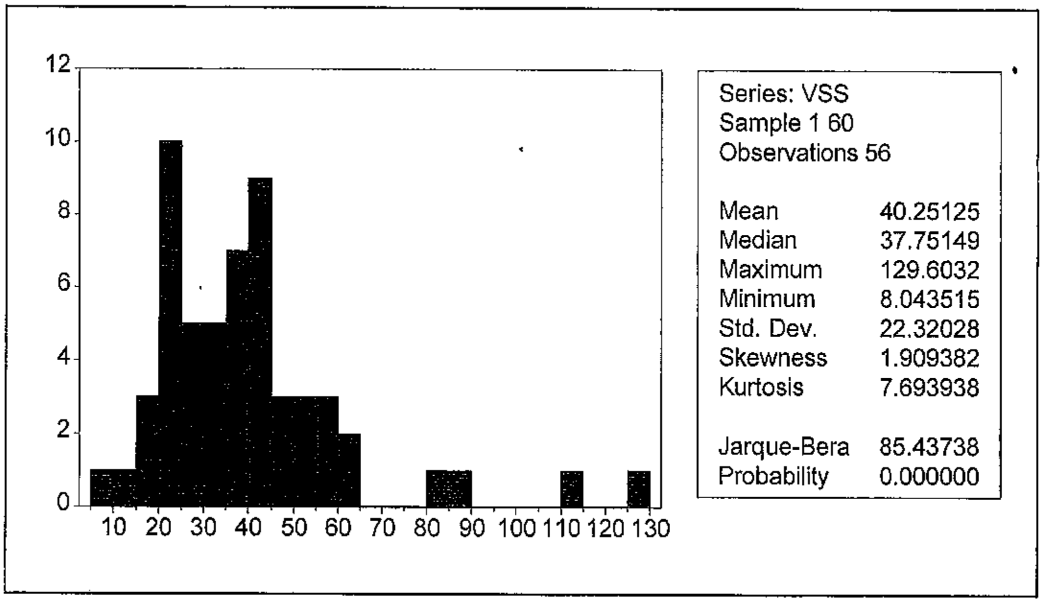


Figure E-2 Histogram of VSS Observations

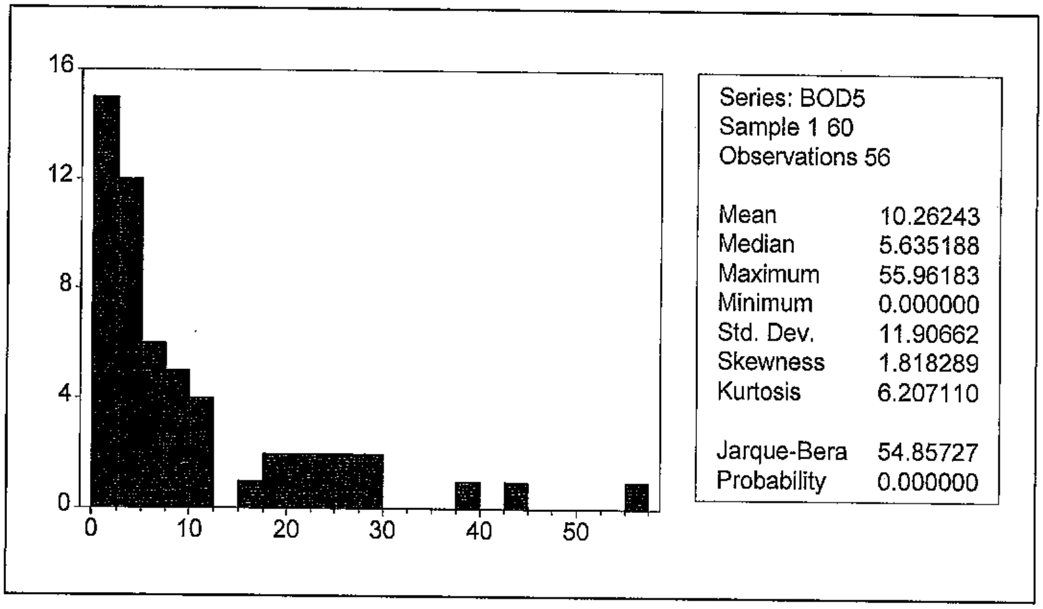


Figure E-3 Histogram of BOD_5 Observations

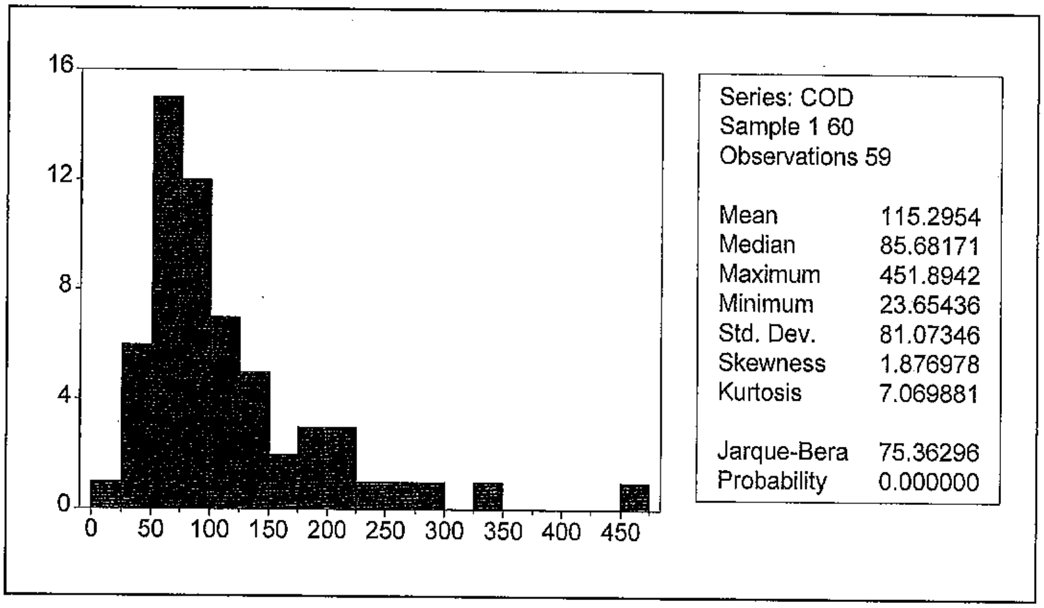


Figure E-4 Histogram of COD Observations

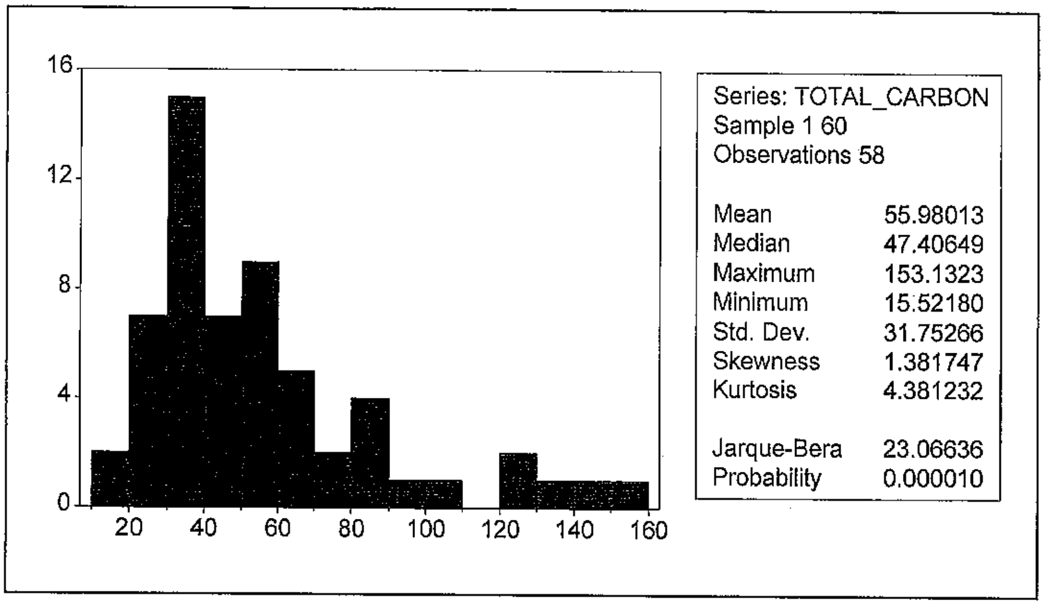


Figure E-5 Histogram of Total Carbon Observations

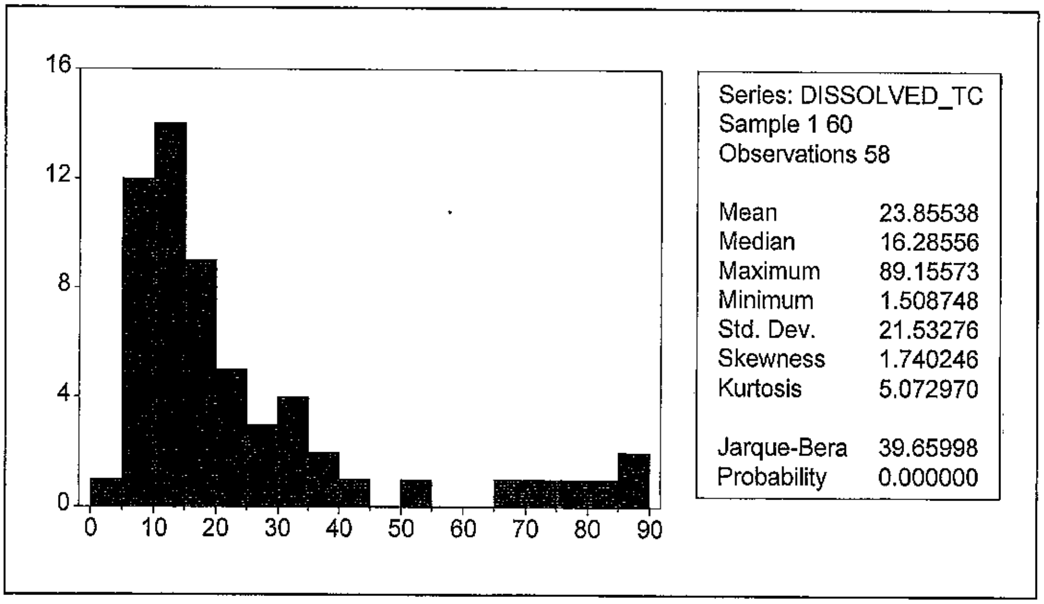


Figure E-6 Histogram of Dissolved Total Carbon Observations

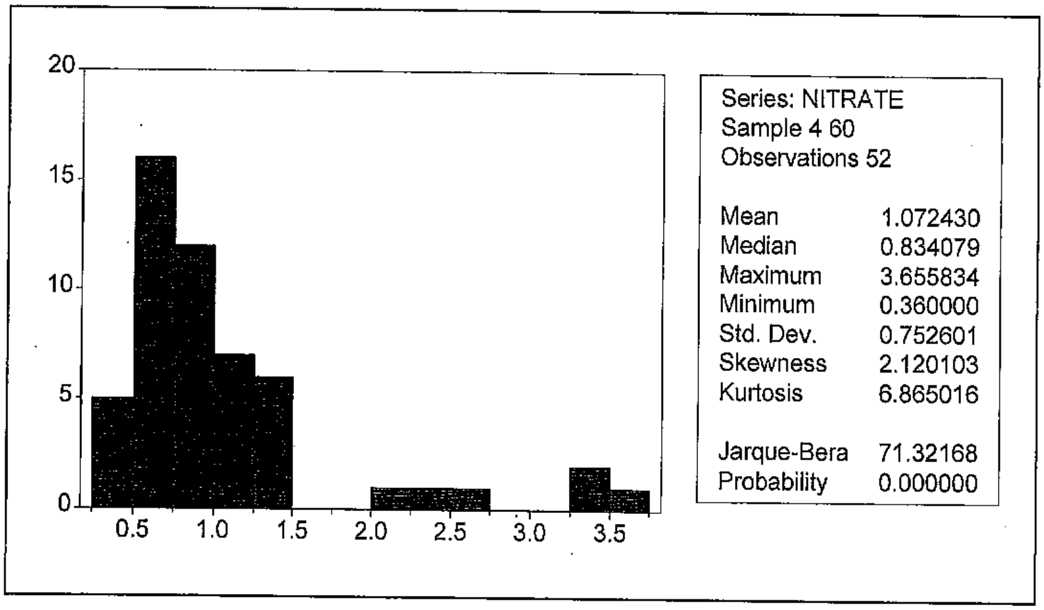


Figure E-7 Histogram of Nitrate Observations

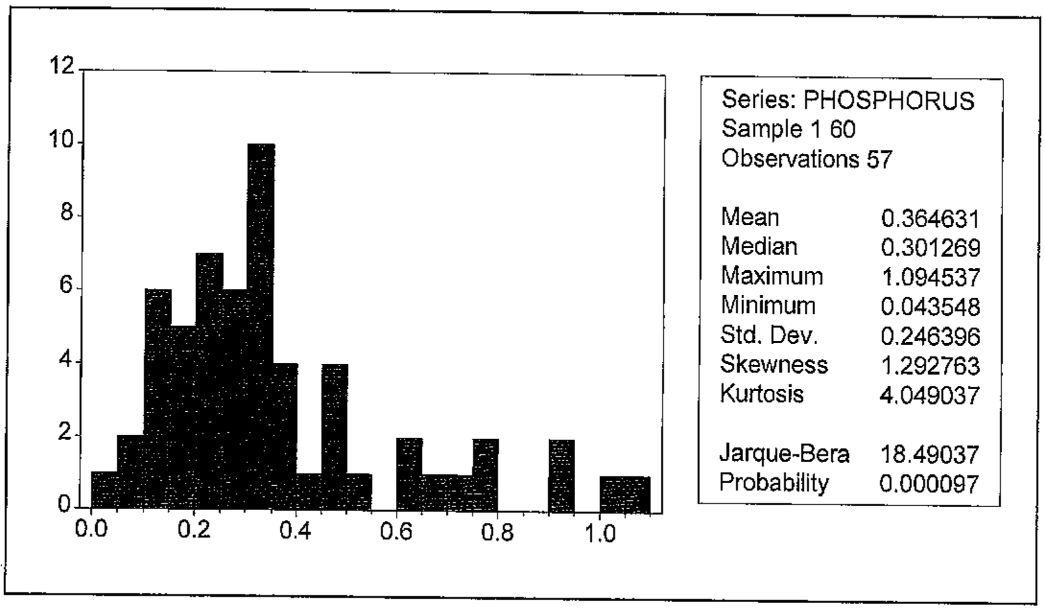


Figure E-8 Histogram of Total Phosphorus Observations

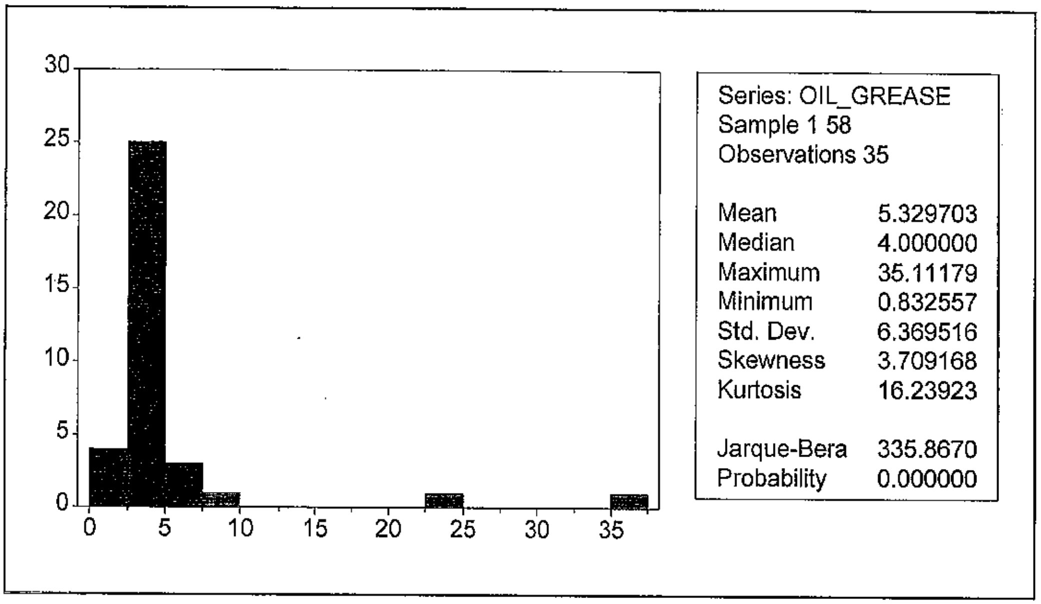


Figure E-9 Histogram of Oil and Grease Observations

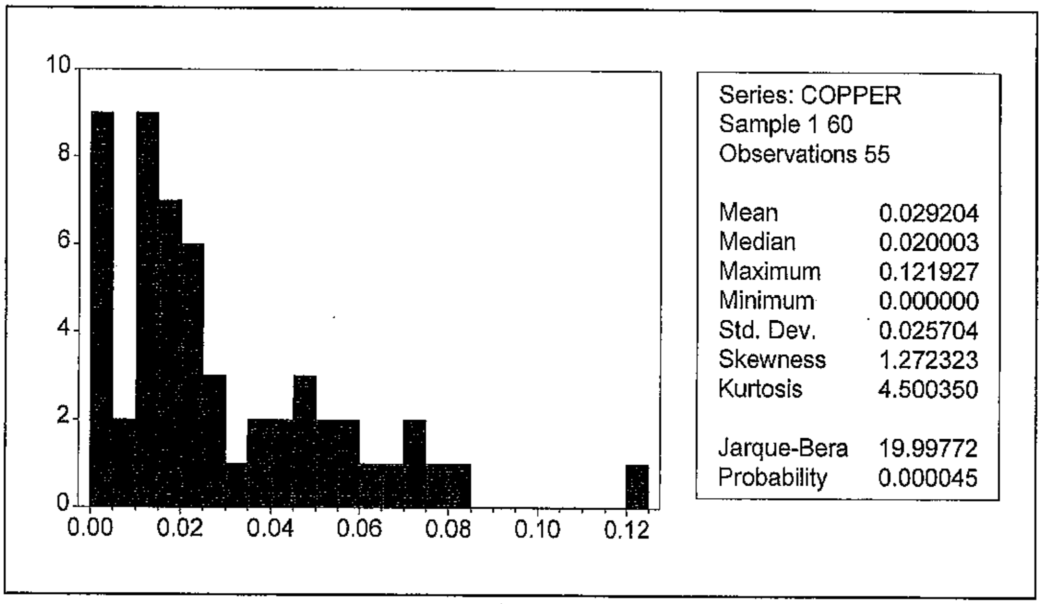


Figure E-10 Histogram of Copper Observations

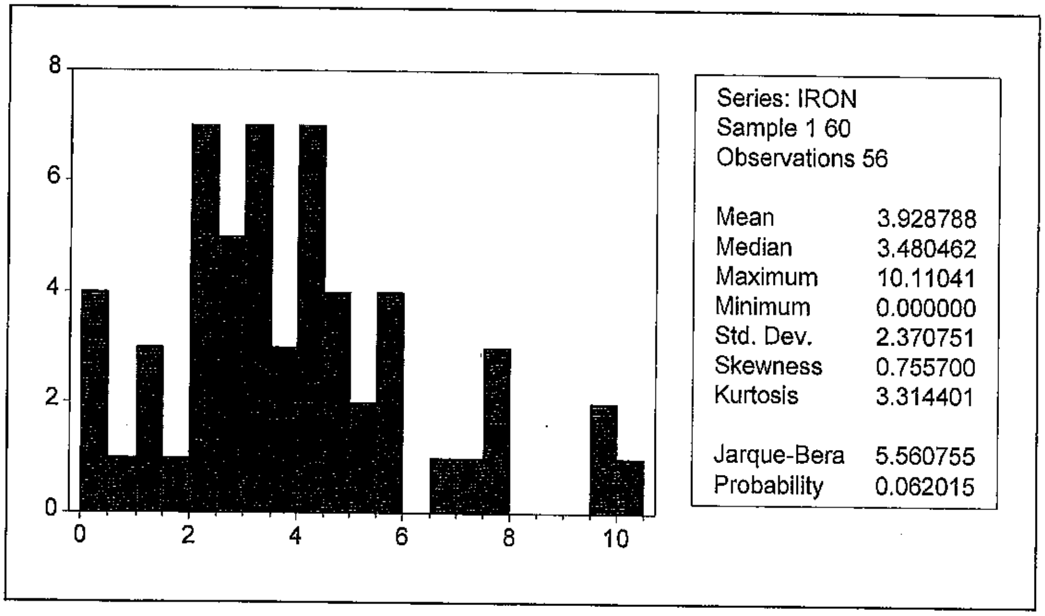


Figure E-11 Histogram of Iron Observation

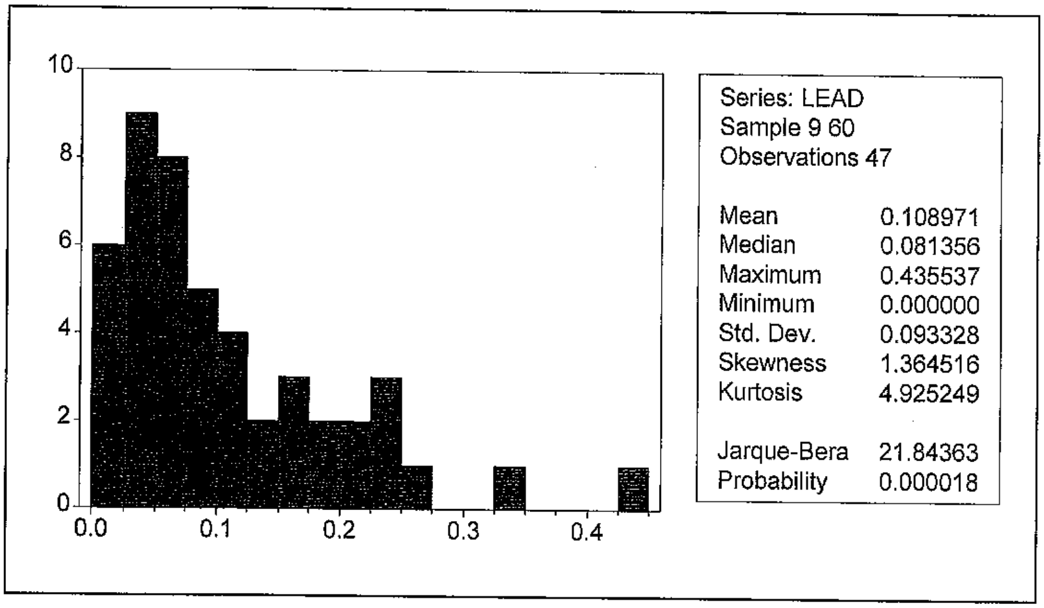


Figure E-12 Histogram of Lead Observations

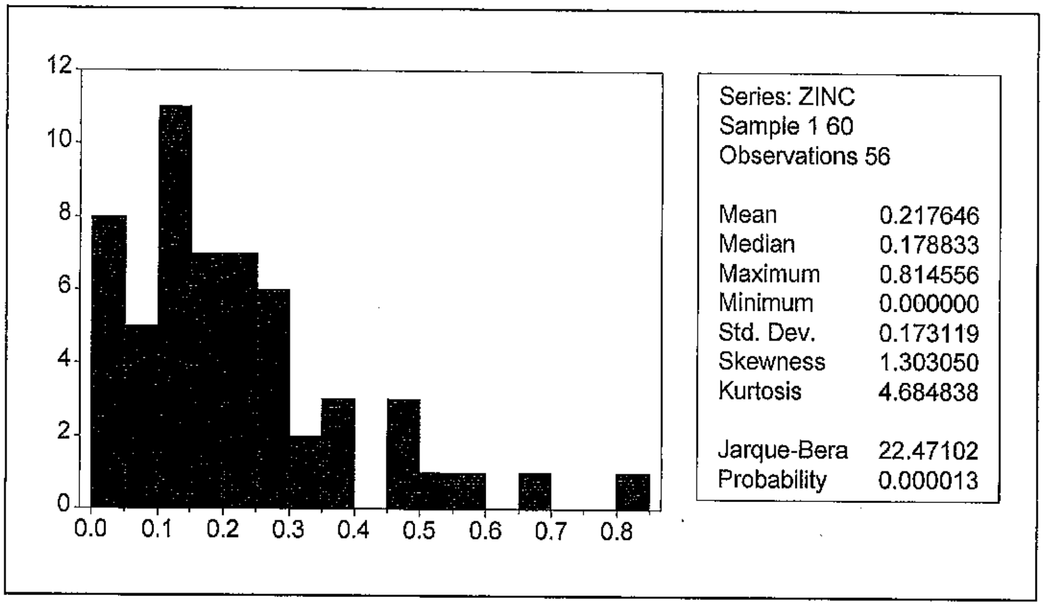
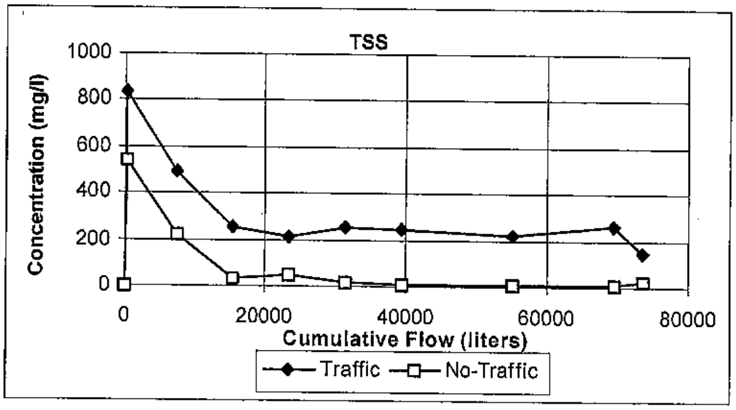
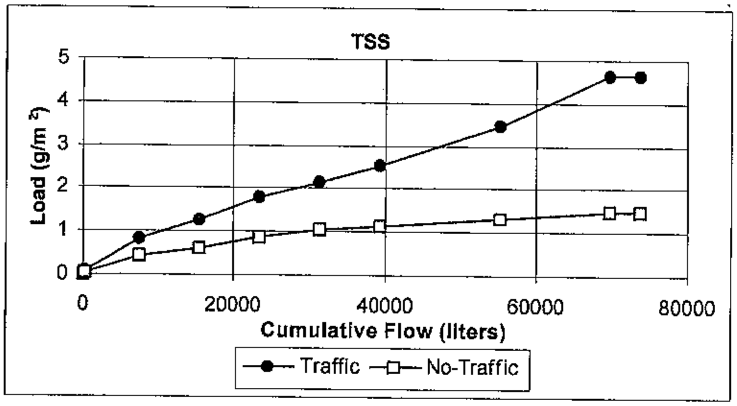


Figure E-13 Histogram of Zinc Observations

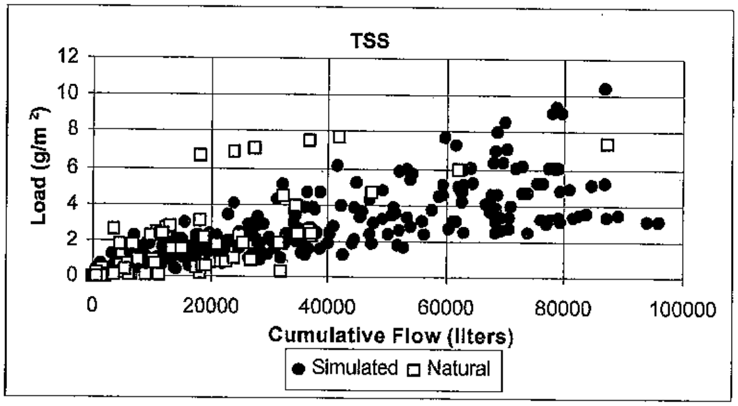
Appendix F
Constituent Wash-Off Patterns



(a) Median TSS Concentration During a Simulated Storm Event

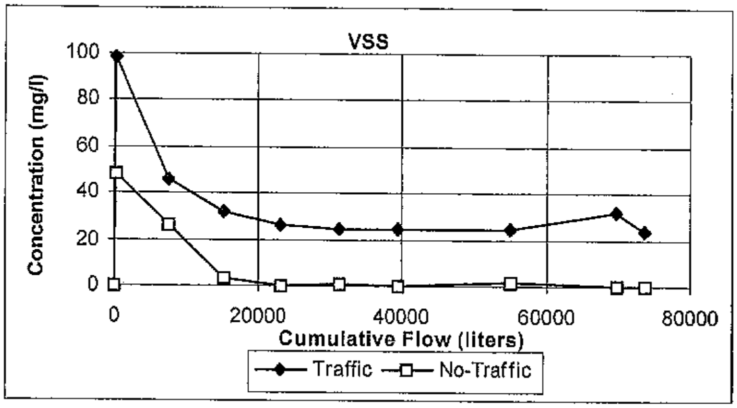


(b) Median TSS Load During a Simulated Storm Event

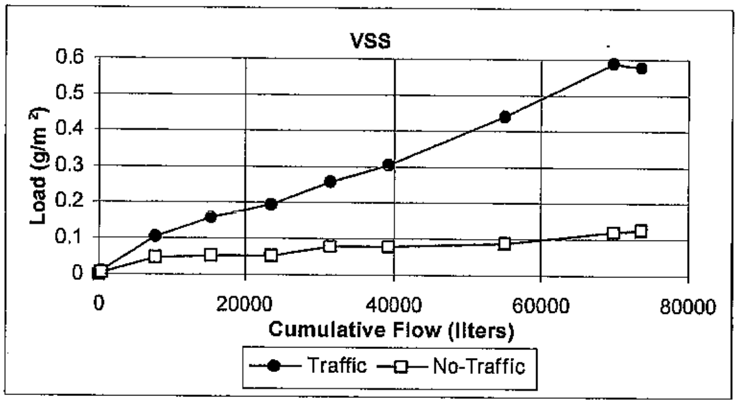


(c) TSS Load During Natural and Simulated Storm Events

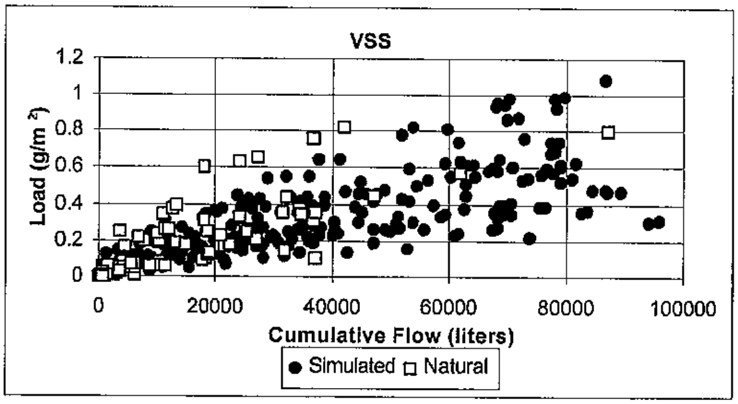
Figure F-1



(a) Median VSS Concentration During a Simulated Storm Event

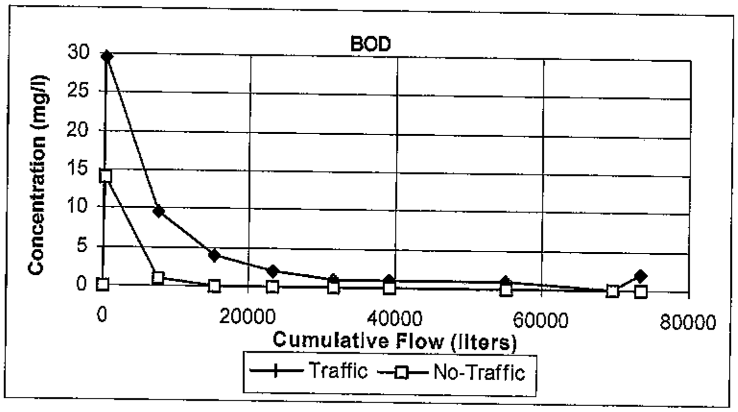


(b) Median VSS Load During a Simulated Storm Event

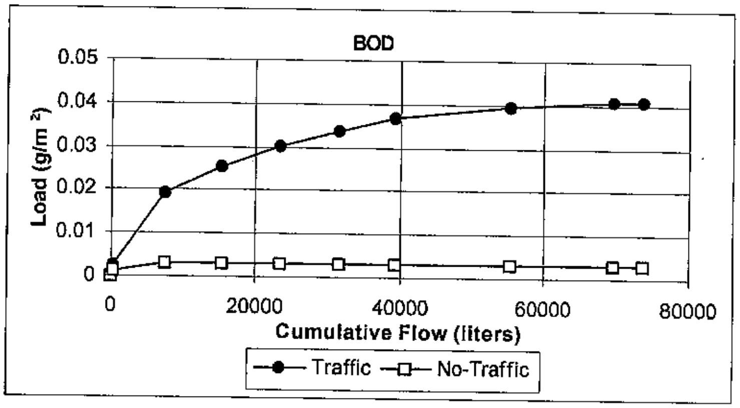


(c) VSS Load During Natural and Simulated Storm Events

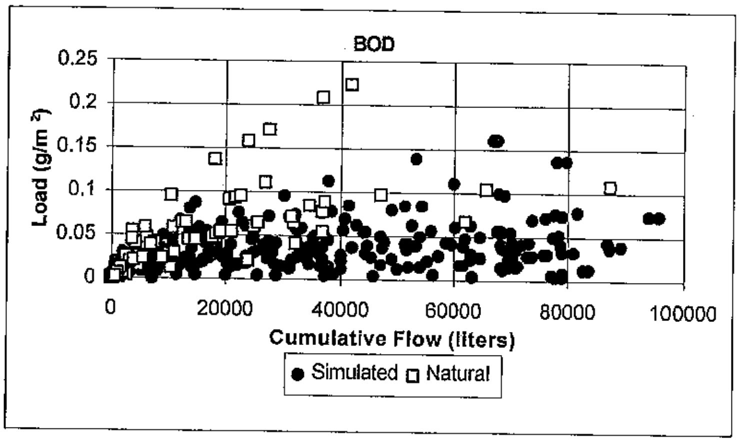
Figure F-2



(a) Median BOD_5 Concentration During a Simulated Storm Event

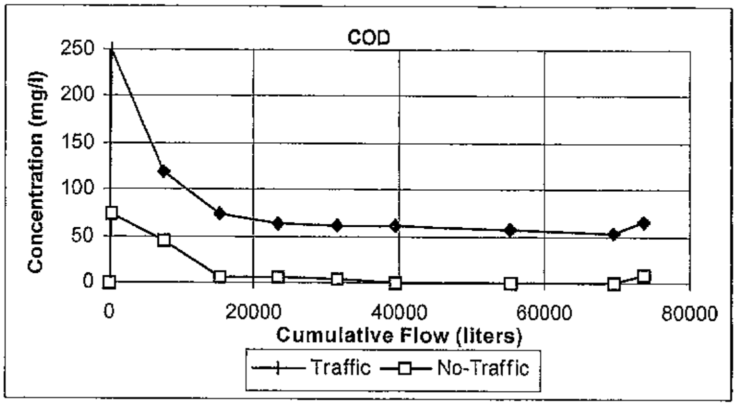


(b) Median BOD_5 Load During a Simulated Storm Event

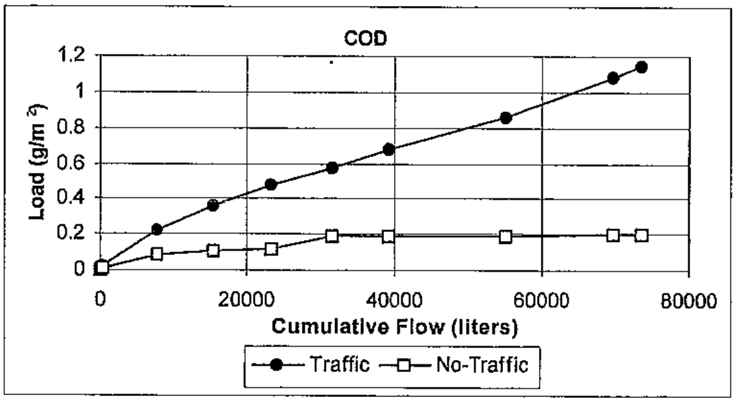


(c) BOD_5 Load During Natural and Simulated Storm Events

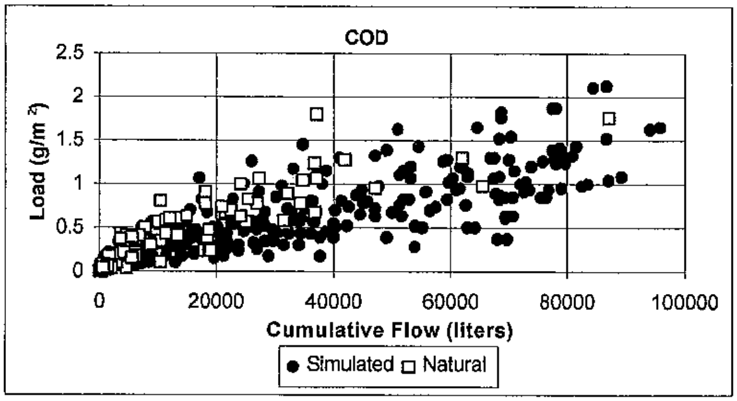
Figure F-3



(a) Median COD Concentration During a Simulated Storm Event

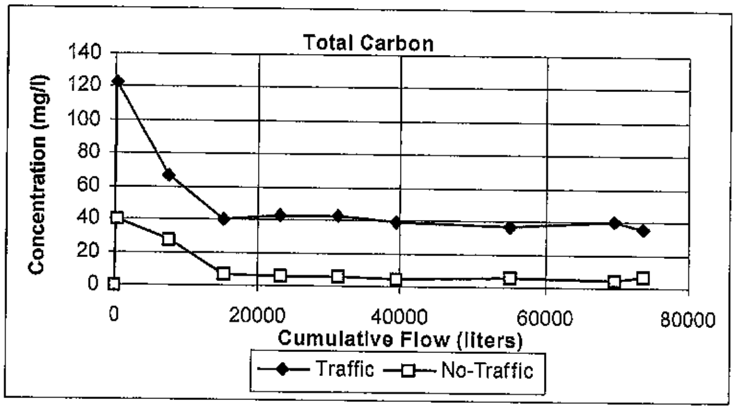


(b) Median COD Load During a Simulated Storm Event

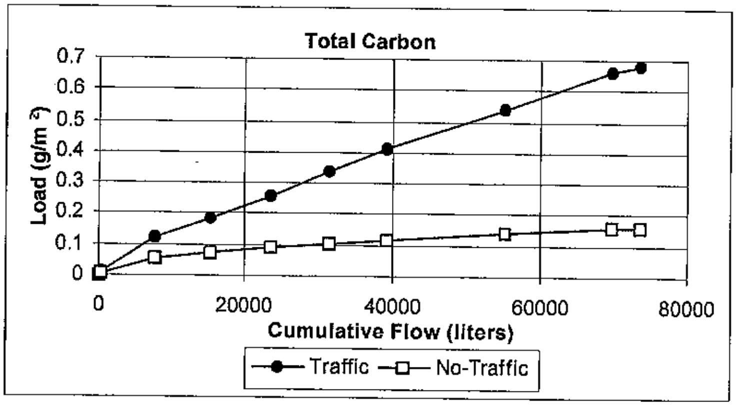


(c) COD Load During Natural and Simulated Storm Events

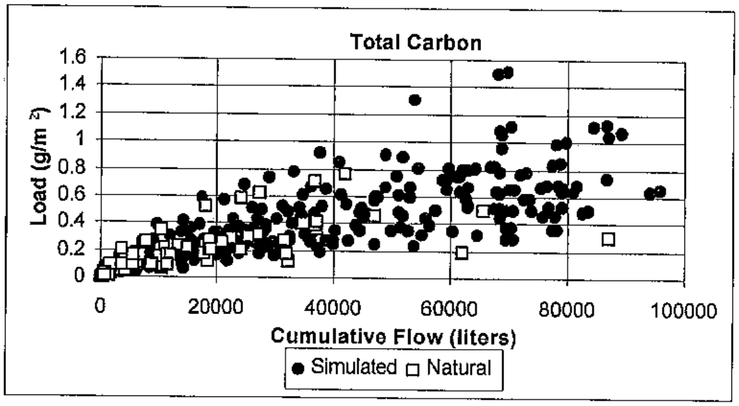
Figure F-4



(a) Median Total Carbon Concentration During a Simulated Storm Event

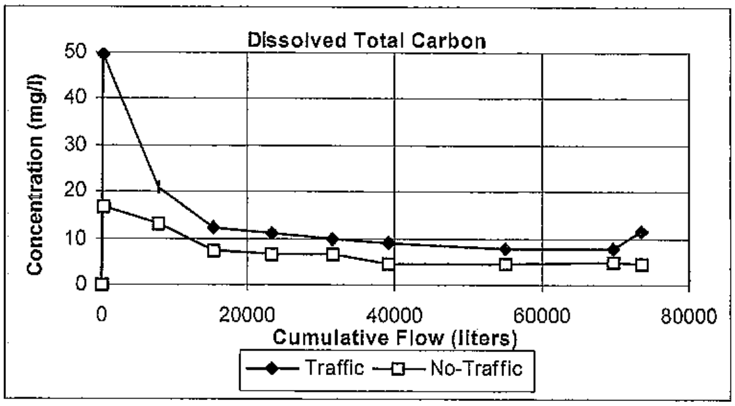


(b) Median Total Carbon Load During a Simulated Storm Event

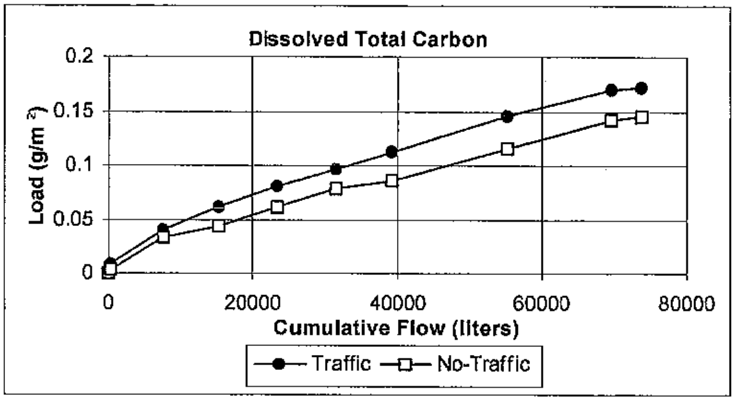


(c) Total Carbon Load During Natural and Simulated Storm Events

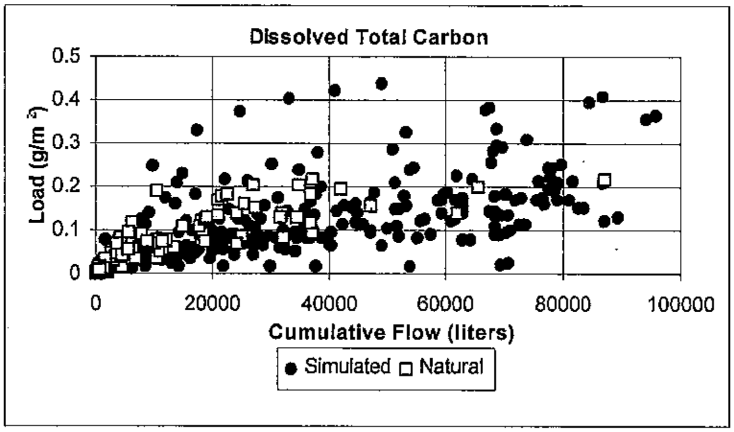
Figure F-5



(a) Median Dissolved TC Concentration During a Simulated Storm Event

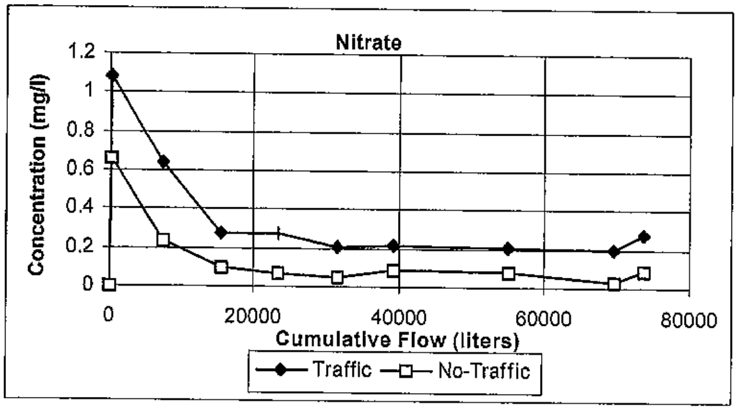


(b) Median Dissolved TC Load During a Simulated Storm Event

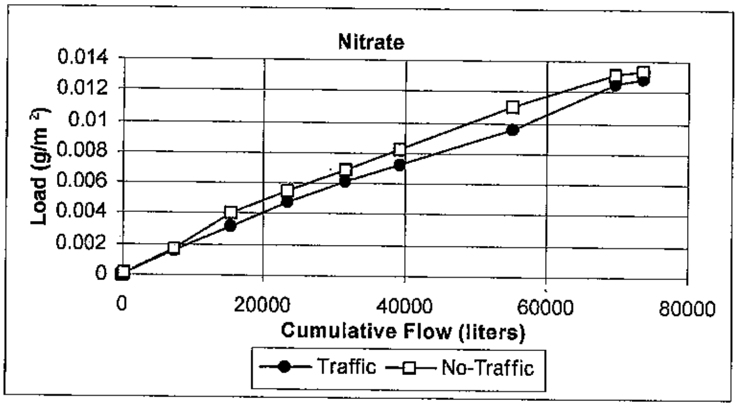


(c) Dissolved TC Load During Natural and Simulated Storm Events

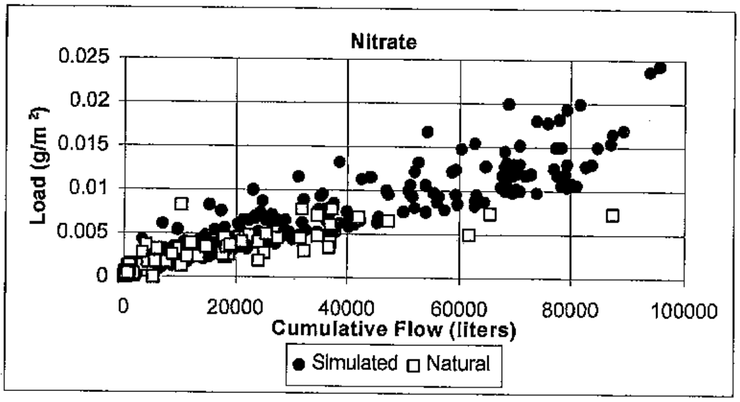
Figure F-6



(a) Median Nitrate Concentration During a Simulated Storm Event

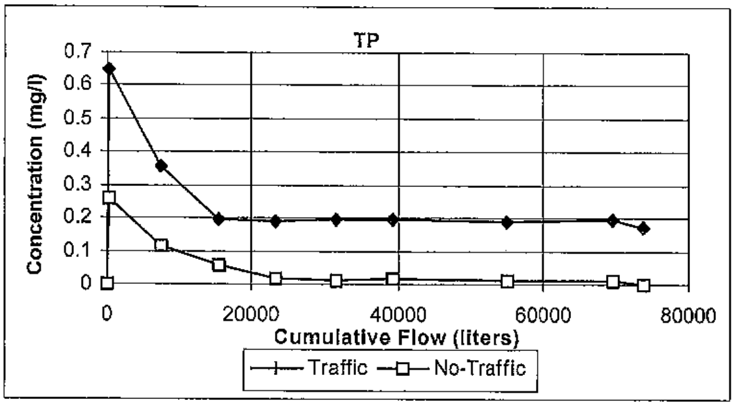


(b) Median Nitrate Load During a Simulated Storm Event

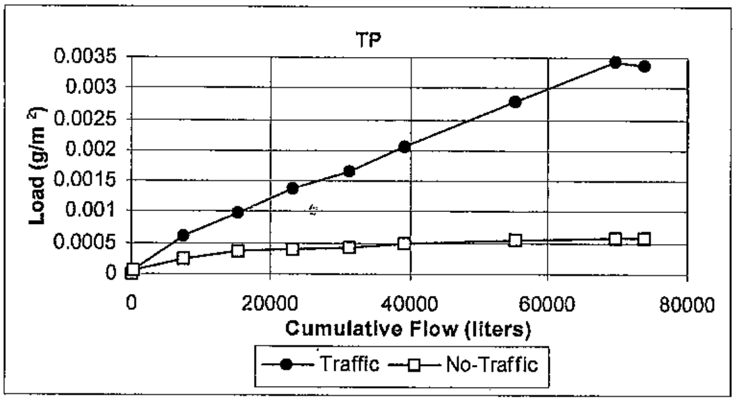


(c) Nitrate Load During Natural and Simulated Storm Events

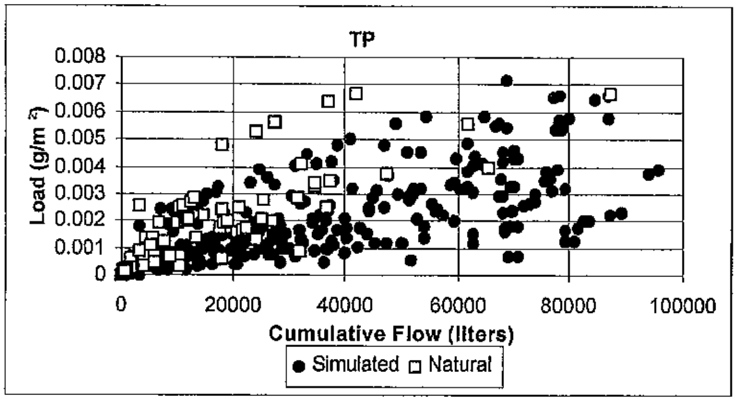
Figure F-7



(a) Median Phosphorus Concentration During a Simulated Storm Event

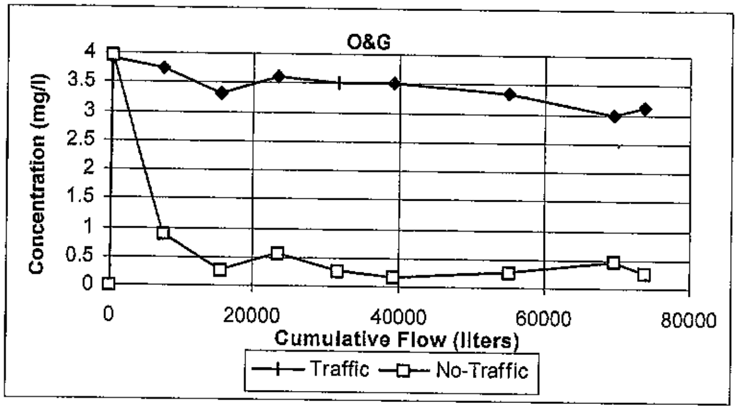


(b) Median Phosphorus Load During a Simulated Storm Event

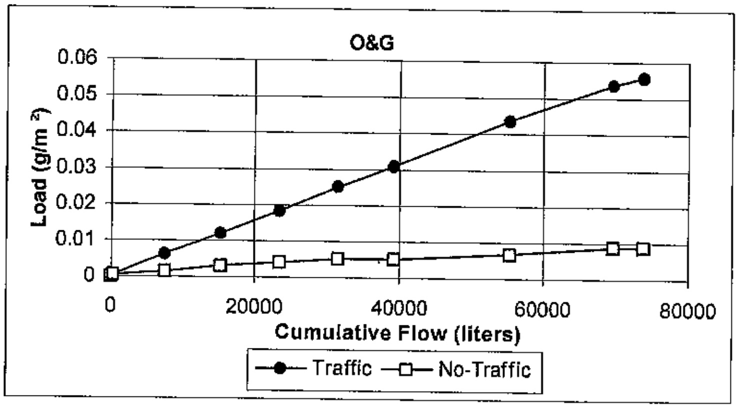


(c) Phosphorus Load During Natural and Simulated Storm Events

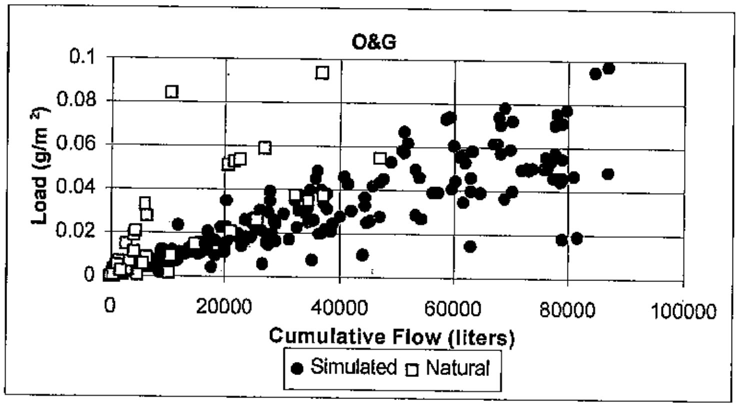
Figure F-8



(a) Median Oil and Grease Concentration During a Simulated Storm Event

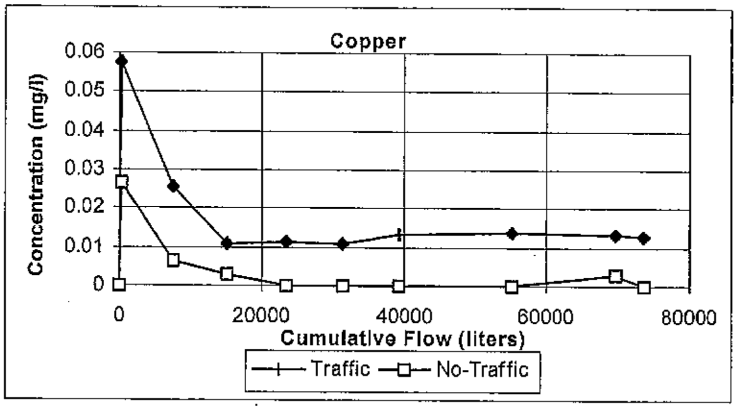


(b) Median Oil and Grease Load During a Simulated Storm Event

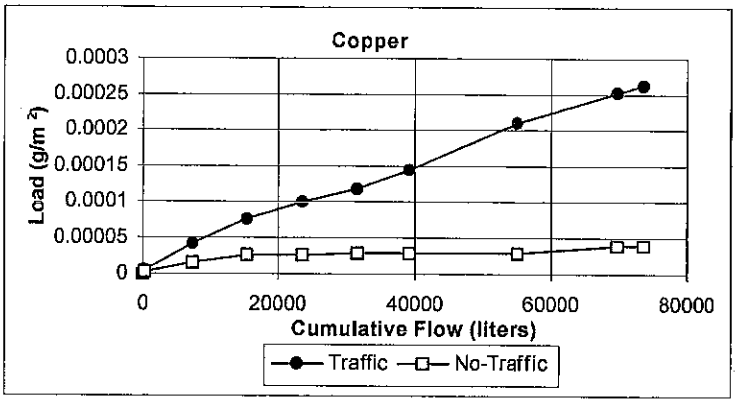


(c) Oil and Grease Load During Natural and Simulated Storm Events

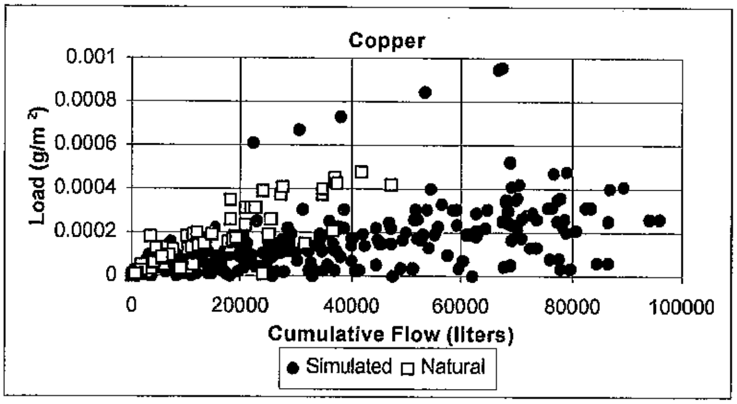
Figure F-9



(a) Median Copper Concentration During a Simulated Storm Event

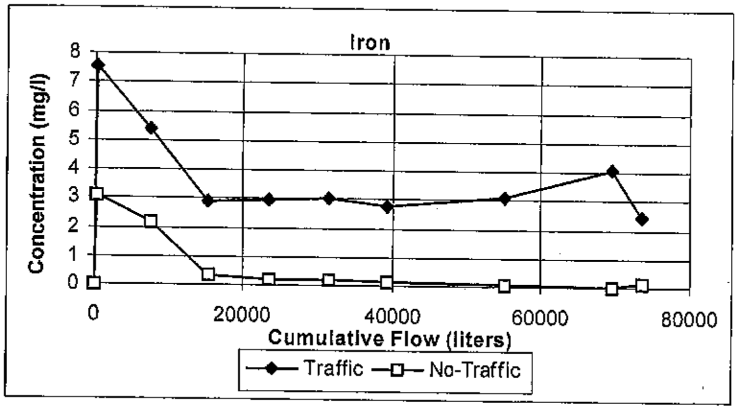


(b) Median Copper Load During a Simulated Storm Event

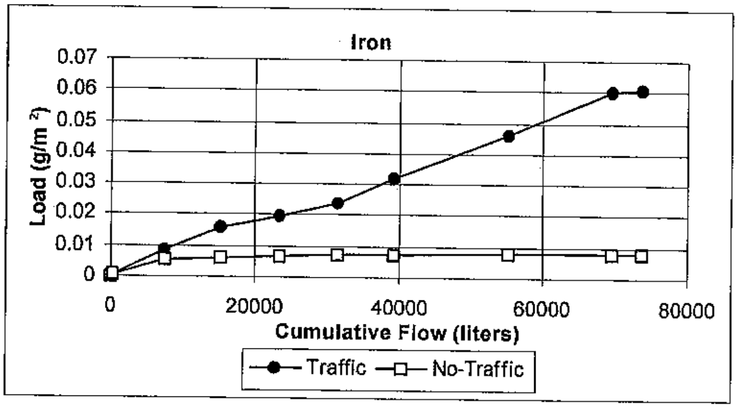


(c) Copper Load During Natural and Simulated Storm Events

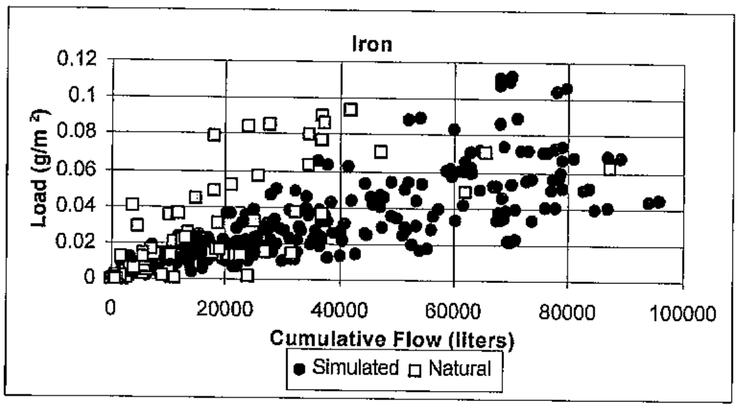
Figure F-10



(a) Median Iron Concentration During a Simulated Storm Event

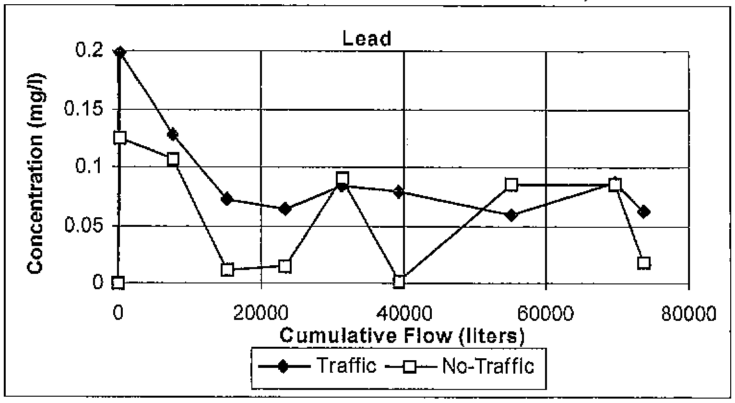


(b) Median Iron Load During a Simulated Storm Event

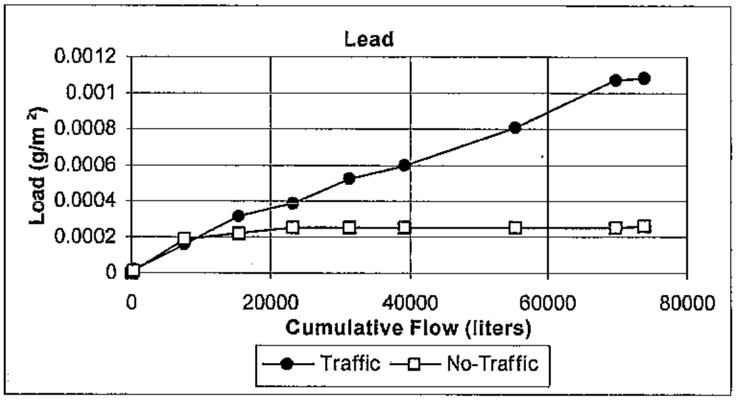


(c) Iron Load During Natural and Simulated Storm Events

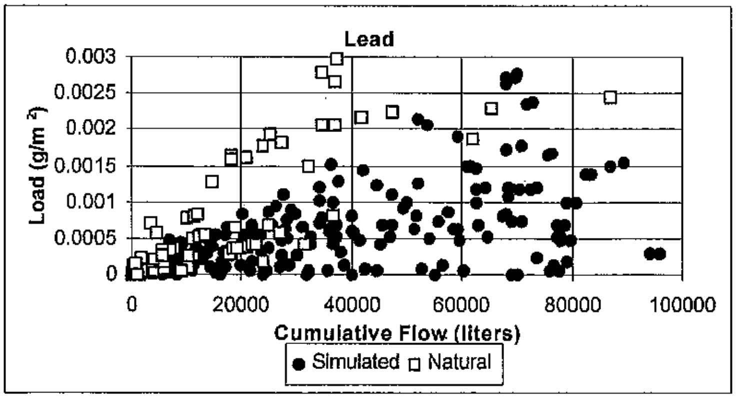
Figure F-11



(a) Median Lead Concentration During a Simulated Storm Event

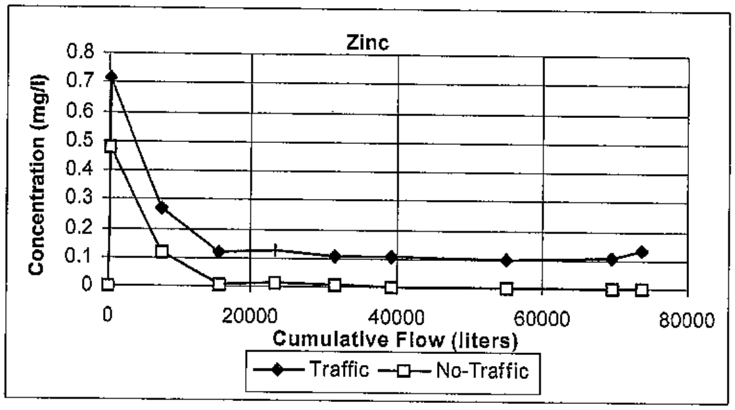


(b) Median Lead Load During a Simulated Storm Event

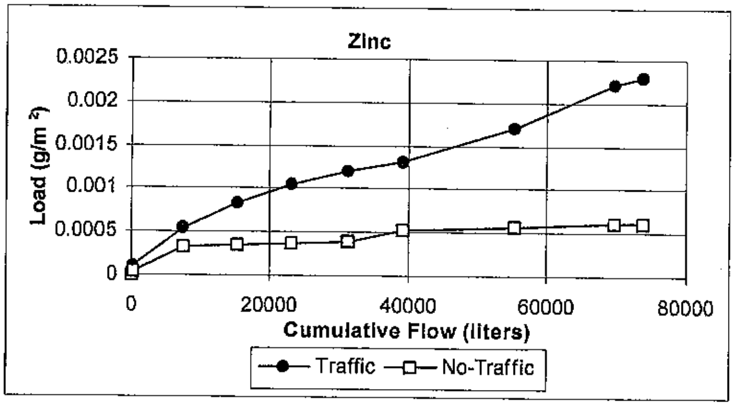


(c) Lead Load During Natural and Simulated Storm Events

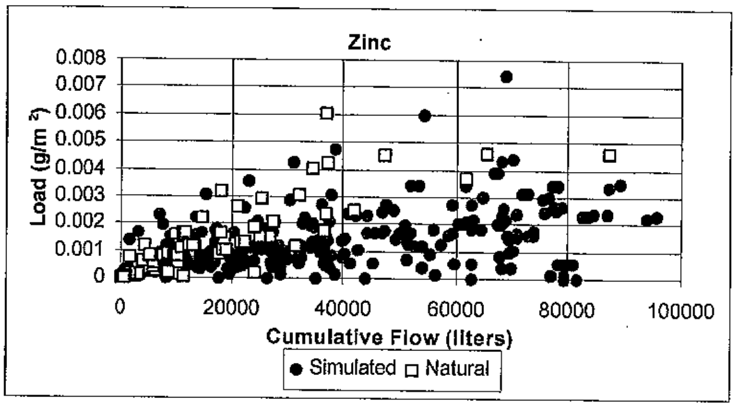
Figure F-12



(a) Median Zinc Concentration During a Simulated Storm Event



(b) Median Zinc Load During a Simulated Storm Event



(c) Zinc Load During Natural and Simulated Storm Events

Figure F-13

Appendix G

The Method of Generalized Least Squares: Corrections for Heteroscedasticity and Autocorrelation

Introduction

Least squares regression is a method used to determine the line of average relationship between a single dependent variable and one or more explanatory, or independent, variables. Consider the simple relationship between COD load, the dependent variable, and total volume of storm flow, the independent variable, illustrated in Figure G-1. Although COD load increases in direct proportion to an increase in total storm flow, there is substantial variation in the value of COD load for individual values of storm flow. The best the regression model can do is estimate the expected, or average, COD load for a given storm size. The regression model assumes that the "disturbances," or the variations from the expected value, are "well behaved," meaning that their expected value is zero, their variance is constant, and they are not correlated with each other. The problems that arise when the disturbances are not well behaved are the subject of this appendix.

Rationale for the Disturbance Term

The regression line illustrated in Figure G-1 is described by the linear function:

$$COD = 0.548 + 0.0002(Flow) \qquad \text{(G-1)}$$

Equation G-1 is not mathematically correct because not all (probably not any) of the values of COD are truly equal to the right-hand side of the equation. To achieve the identity, G-1 must be reformulated to include a disturbance term e defined as the difference between the observed value of COD and the equation value of COD for a specific value of flow.

$$COD_i = 0.548 + 0.0002(Flow_i) + e_i \qquad \text{(G-2)}$$

Given a set of observations, each disturbance term e is measurable and is referred to as the "residual." The values of the residuals can be either positive, negative, or zero and are collectively described by a normal probability distribution. The variance of this distribution determines the standard error of regression, which is a measure of the "goodness of fit" of the regression equation.

Adding a disturbance term to equation G-1 may seem like an arbitrary mathematical fix, but there are several important reasons for the existence of disturbance in the data set. First, not all of the relevant variables may have been included in the regression. In the previous example, only about 69% of the variation in COD is explained by total storm flow. There also are other variables that act in conjunction with flow to influence COD loads, such as traffic volume, traffic mix, antecedent dry period, etc.

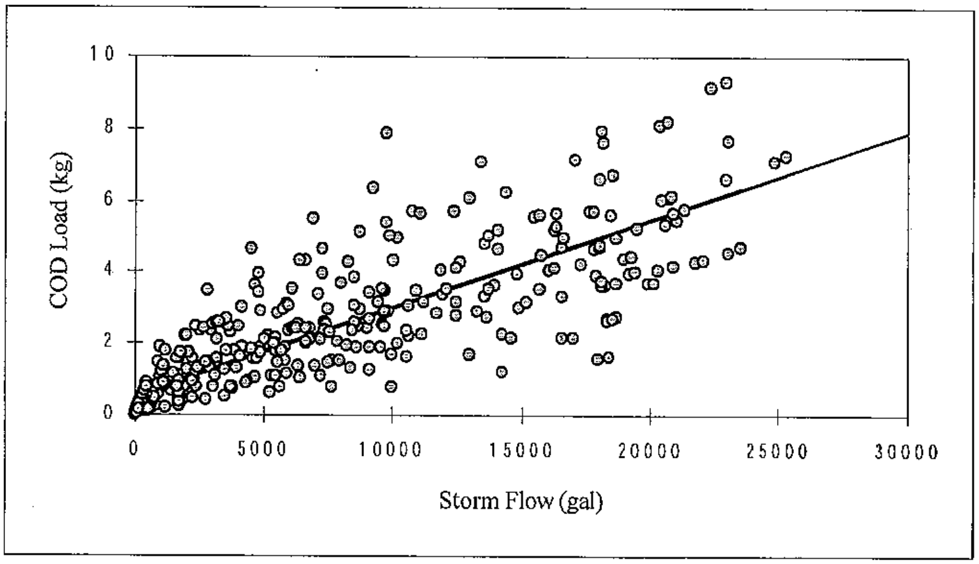


Figure G-1

Second, it is possible that the COD load measured during the storm was measured in error. This error could result from any number of reasons, including mishandling of the sample, mishap in the laboratory analysis, or a simple recording error, just to name a few.

Third, the disturbance could be the result of an inherently random component in the system under study. Natural systems are notoriously difficult to predict, and there could be any number of explanatory variables that have inherently random components.

Method of Ordinary Least Squares

The method of ordinary least squares (OLS) is the usual way to calculate the coefficients of a regression equation. OLS provides a simple procedure for calculating the coefficients of an inexact linear function by minimizing the sum of the squared differences, e^2, between the observed values of the dependent variable Y and the estimated values $\hat{Y}$. Furthermore, the OLS coefficients computed from a sample are the minimum-variance, linear, unbiased estimators of the population regression coefficients only if certain assumptions are satisfied. Mathematically, the OLS procedure is defined as

$$\text{minimize} \sum e_i^2 = \sum (Y_i - \hat{Y}_i)^2 \qquad \text{(G-3)}$$

where expression G-3 is often referred to as the error sum of squares (ESS) or the residual sum of squares.

Although OLS guarantees the "best" linear fit of the sample data, it is not necessarily the "best linear and unbiased estimator" (BLUE) for the population regression coefficients. Unlike the sample disturbance term e, the population disturbance term, denoted as U, is not observable. Consequently, the following assumptions must be made regarding the statistical properties of the population disturbance term U to complete the specification of the OLS model:

1. The disturbance term is normally distributed, and therefore the expected value, or mean, of all U's for any given value of Y is zero.
2. All values of U, associated with different values of an independent variable X, have the same variance (homoscedastic assumption).
3. Each value of U is independent of all other values of U (uncorrelated residuals).
4. The value of any independent variable X is independent of the value of U.

The complete OLS model specifies both the population regression equation and the parameters of the distribution of the population disturbance term. The population regression equation derived from the data in Figure G-1 contains two distinct statements: a scientific statement $[0.548 + 0.0002(Flow_i)]$ and a statistical statement (U and its distribution).

If any of the assumptions regarding the distributional properties of the disturbance terms are violated, the OLS coefficients will not be BLUE. Unfortunately, the highway runoff data collected during the course of this research exhibit the characteristics of both heteroscedasticity and autocorrelation, which are two of the most common violations of the disturbance term assumptions. The procedures used to identify misspecified disturbance terms, the consequences of applying OLS procedures in the presence of a misspecified disturbance term, and the remedies used to correct for such misspecifications, are discussed in the remainder of this appendix.

Heteroscedasticity

Heteroscedasticity is the formal name that describes the condition in that the variance of the residuals is not uniform across the range of an explanatory variable X. This condition is common in cross-sectional data where the observations of variables of differing magnitudes are collected at a single point in time. Re-consider the data plotted in Figure G-1. It is apparent that the variance for the COD load increases as the storm flow increases. One possible explanation for this phenomenon is that the COD loads may vary with storm intensity. For example, low-intensity storms might produce smaller COD loads than higher intensity storms, regardless of the duration, and consequently the storm volume. In any case, the values for COD load are not as variable for low storm flows as they are for the higher volume flows. This is a classic illustration of heteroscedasticity in cross-sectional data.

It can be shown that the OLS estimate of the population regression coefficients is an unbiased estimator regardless of the distributional properties (i.e., the variance or correlation) of the population disturbance term. However, the OLS coefficients are not the minimum variance estimators if the homoscedastic assumption of the disturbance term is violated. This is because the most inaccurate observations, or the observations with the largest variances, will dominate the ESS calculation. In other words, OLS will minimize an ESS that is heavily influenced by the observations that have the largest variances. Furthermore, this same calculation will lead to a biased estimate of the population variance (e.g., on average, the variance will be either underestimated or overestimated), which in turn will lead to a biased estimate of the variance of the population regression coefficients. The result is that conventionally computed confidence intervals and the conventionally employed t and F tests are no longer valid. If the population variance is underestimated (there is no theoretical basis for determining the direction of the bias), the computed confidence intervals will be narrower than they should be, providing an ill-founded belief in the precision of the model. A complete mathematical justification regarding the effects of misspecified disturbance terms is found in Johnson et. al., 1987.

Method of Generalized Least Squares

The ideal regression estimating scheme should give less importance, or "weight," to those observations coming from populations with greater variability than those that come from populations of smaller variability. Unfortunately, OLS does not follow this strategy, as it assigns equal weight to each observation. But a method known as generalized least squares (GLS) does follow this strategy and is capable of producing estimators that are BLUE. To illustrate GLS, re-consider the COD-storm flow model:

$$COD_i = 0.548 + 0.0002(Flow_i) + U_i \qquad \text{(G-4)}$$

Assume that the heteroscedastic variances σ_i^2 are known (i.e., $E(U_i^2) = \sigma_i^2$). If equation G-4 is divided through by σ_i to obtain:

$$\frac{COD_i}{\sigma_i} = 0.548\left(\frac{1}{\sigma_i}\right) + 0.0002\left(\frac{Flow_i}{\sigma_i}\right) + \left(\frac{U_i}{\sigma_i}\right) \qquad \text{(G-5)}$$

The purpose of this transformation is found in the following feature of the transformed disturbance term:

$$\text{var}\left(\frac{U_i}{\sigma_i}\right) = E\left(\frac{U_i}{\sigma_i}\right)^2$$

$$= \frac{1}{\sigma_i^2} E(U_i^2) \text{ since } \sigma_i^2 \text{ is known}$$

$$= \frac{1}{\sigma_i^2}(\sigma_i^2) \text{ since } E(U_i^2) = \sigma_i^2$$

$$= 1, \text{ which is a constant} \qquad \text{(G-6)}$$

The variance of the transformed disturbance term U is now constant, or homoscedastic. But also note that the effect of this transformation is to weight each variable by a value that is inversely proportional to its standard deviation, σ_i. If OLS is applied to the transformed variables, the COD observations from populations with large σ_i will be given proportionately less weight than the COD observations from populations with smaller σ_i during the minimizing of the ESS. Since all other OLS assumptions are retained, the OLS coefficients calculated from the transformed data will be BLUE.

To summarize, the method of GLS is merely OLS performed with a set of transformed variables that satisfy the OLS assumptions. Unfortunately, GLS is difficult in practice because the heteroscedastic variances σ_i^2, and subsequently the correct heteroscedastic transformations, are not known. Furthermore, there is no method to directly determine the best transformation. The procedure is strictly trial and error. A transformation is made, the equation is re-estimated using OLS procedures with the transformed variables, and a statistical test is used to determine if the new disturbance term is homoscedastic.

Tests for Heteroscedasticity

Heteroscedasticity can be expected in any cross-sectional analysis involving the relationship between highway runoff constituents and runoff volume, duration, antecedent dry period, traffic counts, etc., if a wide range of storm sizes are sampled. The identification of suspect variables, however, involves considerable judgment and knowledge regarding the data at hand. Although statistical tests are available for detecting the presence of heteroscedasticity, the decision as to that variables to test is strictly ad hoc.

Graphical methods, such as plotting the OLS residuals versus an independent variable, are often used to identify suspect independent variables. The heteroscedastic pattern displayed by the variable can suggest the appropriate GLS transformation (e.g., does the variance increase linearly, exponentially, etc., with the increase in the independent variable). There is no assurance, however, that two or more variables are not jointly the cause of the problem. The determination of heteroscedasticity more often depends upon the statistical evaluation of hypothesis testing. Several tests are available including the Park test, Glejser test, Spearman's rank correlation test, Goldfeld-Quandt test, and others.

A two-step procedure was used during this research to determine the degree of heteroscedasticity in the data set. The first step used the Goldfeld-Quandt test to determine heteroscedasticity among *individual* variables. If two are more variables failed the Goldfeld-Quandt test, which was the case for every runoff constituent, a second step was performed using the Breusch-Pagan test to confirm the existence of a general case of heteroscedasticity in the model. The Breusch-Pagan test was also used to confirm the presence or absence of heteroscedasticity following a GLS transformation.

The Goldfeld-Quandt Test

The Goldfeld-Quandt test is a popular method used to determine heteroscedasticity caused by a single independent variable in the model. The test is valid only if the heteroscedastic variance is positively related to an explanatory variable in the model. The degree of heteroscedasticity is calculated as the ratio of variability exhibited in the largest values of the explanatory variable, typically the upper 30 to 40% of the range of X, to the variability exhibited in the smallest values of the explanatory variable, the lowest 30 to 40% of the range of X. If the disturbance terms are assumed to be normally distributed and if the assumption of homoscedasticity is valid, it can be shown that this ratio follows the F distribution with numerator and denominator degrees of freedom equal to $(n-d-2K)/2$, where n is the sample size, d is the number of observations deleted to calculate the ratio, and K is the number of regression coefficients estimated (including the intercept). As a hypothesis test, if the computed F-ratio is greater than the critical F-ratio at the chosen level of significance, the null hypothesis of homoscedasticity is rejected.

Specifically, the Goldfeld-Quandt test was performed on each explanatory variable as follows:

1) All observations (423) are sorted by increasing value of the suspect variable.
2) The middle portion of the observations are deleted. In this study, 131 observations were deleted, leaving 146 "low" values and 146 "high" values.
3) The OLS equation is estimated for each of the two subgroups.
4) The computed test statistic is calculated by dividing the error sum of squares (ESS) of the high group by the ESS of the low group.
5) The computed test statistic is compared to the critical F-statistic. The critical F-statistic for 139 degrees of freedom (n = 423, d = 131, and K = 7) in the numerator and 139 degrees of freedom in the denominator at the 0.05 level is approximately 1.3. If the computed F-statistic is greater than the critical F-statistic, the null hypothesis of no heteroscedasticity is rejected.

In summary, if the ESS of the upper range is 1.3 times the ESS of the lower range, the variance across the range of X is considered heteroscedastic.

The structure of the Goldfeld-Quandt test limits the test to identifying heteroscedasticity caused by a single variable. If the model contains more than one independent variable, the test should be applied to as many of the variables as possible. If two or more independent variables are identified as heteroscedastic, it must be assumed that they jointly contribute heteroscedasticity to the model. In this case, a more general test should be used to confirm the presence of heteroscedasticity in the model.

Table G-1 summarizes the results of the Goldfeld-Quandt test. The results indicate that storm duration, storm flow, storm vehicle count, and antecedent traffic count are all suspected of causing heteroscedasticity in each short model. The previous storm flow is an additional suspect only in the COD short model.

Table G-1 Calculated Test Statistic in Goldfeld-Quandt Test

Constituent	Duration	Flow	Vehicle Count	Antecedent Traffic	Previous Traffic	Previous Flow
COD	3.1	9.3	3.6	3.2	0.8	1.6
Nitrate	4.5	8.0	4.5	4.0	1.0	0.7
Oil and Grease	12.5	8.3	26.0	3.3	0.4	1.0
TSS	3.0	17.0	5.1	1.9	0.8	0.5
Phosphorous	4.0	9.1	4.0	3.0	0.5	0.9
Copper	9.0	32.9	20.5	3.0	0.1	0.3
Iron	2.5	13.8	4.3	2.9	0.4	0.2
Lead	2.3	22.9	4.8	5.7	0.4	0.1
Zinc	10.0	43.5	22.0	55.0	0.04	0.5

(Critical value of $F = 1.3$)

The Breusch-Pagan Test

The Breusch-Pagan test is a more general test that examines a model for heteroscedasticity caused by one or more independent variables. Like the Goldfeld-Quandt test, a set of suspect variables must be identified prior to application of the test. In this research, each independent variable that failed the Goldfeld-Quandt test is assumed to jointly contribute to heteroscedasticity in the model.

The Breusch-Pagan test standardizes each OLS residual by dividing by the variance of the residuals. This set of standardized residuals is then regressed against the suspect explanatory variables. A test statistic is calculated as one half of the total sum of squares minus the ESS. The total sum of squares (SS) is defined as the sum of the squared deviations of the sample values of the dependent variable about the sample mean of the dependent variable. This test statistic is distributed as chi-squared with k degrees of freedom, where k is the number of suspect explanatory variables. Because the condition of homoscedasticity is assumed, the null hypothesis of homoscedasticity is rejected if the test statistic is larger than the critical value of the chi-square statistic.

Specifically, the Breusch-Pagan test was conducted during this research as follows:

1) Compute the OLS residuals ($e_i = Y_i - \hat{Y}_i$) for the model, where Y is the observed value of the dependent variable and $\hat{Y}$ is the regression value.
2) Calculate e_i^2 / S_e^2, where $S_e^2 = \sum e_i^2 / n$ and n = number of observations.
3) Regress the standardized OLS residuals, e_i^2 / S_i^2, on the suspect independent variables.
4) Calculate the test statistic as (SS - ESS) / 2 where SS is the Total Sum of Squares $\left(R^2 = 1 - \frac{ESS}{SS} \right)$
5) If the test statistic is greater than the critical value of the chi-square statistic, the null hypothesis of homoscedasticity is rejected. The critical value of chi-square distribution at the 0.05 level with 4 degrees of freedom (e.g., 4 suspect variables) is 9.49.

Heteroscedasticity Transformations

Consider the structure of the following highway runoff model estimated by OLS:

$$Y_i = \beta_0 + \beta_1 D_i + \beta_2 F_i + \beta_3 V_i + \beta_4 A_i + \beta_5 PV_i + \beta_6 PF_i + U_i \qquad \text{(G-7)}$$

where Y_i = dependent variable (kg/m2);

β_i = regression coefficients;

D_i = storm duration (min);

F_i = storm flow (L/m2);

V_i = average # of vehicles per lane during the storm;

A_i = average # of vehicles per lane during the antecedent dry period;

PV_i = average # of vehicles per lane during the previous storm;

PF_i = flow during the previous storm (L/m2)

U_i = disturbance term

As shown in Table G-1, the Goldfeld-Quandt test determined that each of the explanatory variables, with the exception of PV and PF, contributed heteroscedasticity in the base model (PF only contributed in the COD data set). Furthermore, the Breusch-Pagan test also confirmed a general case of heteroscedasticity in the base model. Therefore, a GLS transformation must be found such that the disturbance term of the transformed equation is homoscedastic. As noted above, there is no automatic method for determining the "best" transformation. The process is purely trial and error until an acceptable transformation is found. The obvious starting point is to assume that the heteroscedastic variances are directly related to each variable that failed the Goldfeld-Quandt test. Other possibilities include heteroscedastic variances that are related to the estimated values of the dependent variable, or related to the OLS residuals themselves. In all, 13 transformations were performed for the purpose of correcting for heteroscedasticity. The logic behind each transformation is described below.

Transformation I-a: Assumes that the heteroscedastic variance is a linear function of storm duration (i.e., $E(U_i^2) = D_i\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{\sqrt{D_i}} = \beta_o \frac{1}{\sqrt{D_i}} + \beta_1 \frac{D_i}{\sqrt{D_i}} + \beta_2 \frac{F_i}{\sqrt{D_i}} + \beta_3 \frac{V_i}{\sqrt{D_i}} + \beta_4 \frac{A_i}{\sqrt{D_i}} + \beta_5 \frac{PV_i}{\sqrt{D_i}} + \beta_6 \frac{PF_i}{\sqrt{D_i}} + \frac{U_i}{\sqrt{D_i}}$$

Transformation I-b: Assumes that the heteroscedastic variance is a linear function of storm flow (i.e., $E(U_i^2) = F_i\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{\sqrt{F_i}} = \beta_o \frac{1}{\sqrt{F_i}} + \beta_1 \frac{D_i}{\sqrt{F_i}} + \beta_2 \frac{F_i}{\sqrt{F_i}} + \beta_3 \frac{V_i}{\sqrt{F_i}} + \beta_4 \frac{A_i}{\sqrt{F_i}} + \beta_5 \frac{PV_i}{\sqrt{F_i}} + \beta_6 \frac{PF_i}{\sqrt{F_i}} + \frac{U_i}{\sqrt{F_i}}$$

Transformation I-c: Assumes that the heteroscedastic variance is a linear function of vehicle intensity (i.e., $E(U_i^2) = V_i\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{\sqrt{V_i}} = \beta_o \frac{1}{\sqrt{V_i}} + \beta_1 \frac{D_i}{\sqrt{V_i}} + \beta_2 \frac{F_i}{\sqrt{V_i}} + \beta_3 \frac{V_i}{\sqrt{V_i}} + \beta_4 \frac{A_i}{\sqrt{V_i}} + \beta_5 \frac{PV_i}{\sqrt{V_i}} + \beta_6 \frac{PF_i}{\sqrt{V_i}} + \frac{U_i}{\sqrt{V_i}}$$

Transformation Id: Assumes that the heteroscedastic variance is a linear function of antecedent traffic count changes (i.e., $E(U_i^2) = A_i\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{\sqrt{A_i}} = \beta_o \frac{1}{\sqrt{A_i}} + \beta_1 \frac{D_i}{\sqrt{A_i}} + \beta_2 \frac{F_i}{\sqrt{A_i}} + \beta_3 \frac{V_i}{\sqrt{A_i}} + \beta_4 \frac{A_i}{\sqrt{A_i}} + \beta_5 \frac{PV_i}{\sqrt{A_i}} + \beta_6 \frac{PF_i}{\sqrt{A_i}} + \frac{U_i}{\sqrt{A_i}}$$

Transformation I-e: Assumes that the heteroscedastic variance is a linear function of the previous storm flow (i.e., $E(U_i^2) = PF_i\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{\sqrt{PF_i}} = \beta_o \frac{1}{\sqrt{PF_i}} + \beta_1 \frac{D_i}{\sqrt{PF_i}} + \beta_2 \frac{F_i}{\sqrt{PF_i}} + \beta_3 \frac{V_i}{\sqrt{PF_i}} + \beta_4 \frac{A_i}{\sqrt{PF_i}} + \beta_5 \frac{PV_i}{\sqrt{PF_i}}$$
$$+ \beta_6 \frac{PF_i}{\sqrt{PF_i}} + \frac{U_i}{\sqrt{PF_i}}$$

Transformation II-a: Assumes that the heteroscedastic variance changes at an increasing rate as storm duration changes (i.e., $E(U_i^2) = D_i^2\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{D_i} = \beta_o \frac{1}{D_i} + \beta_1 + \beta_2 \frac{F_i}{D_i} + \beta_3 \frac{V_i}{D_i} + \beta_4 \frac{A_i}{D_i} + \beta_5 \frac{PV_i}{D_i} + \beta_6 \frac{PF_i}{D_i} + \frac{U_i}{D_i}$$

Transformation II-b: Assumes that the heteroscedastic variance changes at an increasing rate as flow changes (i.e., $E(U_i^2) = F_i^2\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{F_i} = \beta_o \frac{1}{F_i} + \beta_1 \frac{D_i}{F_i} + \beta_2 + \beta_3 \frac{V_i}{F_i} + \beta_4 \frac{A_i}{F_i} + \beta_5 \frac{PV_i}{F_i} + \beta_6 \frac{PF_i}{F_i} + \frac{U_i}{F_i}$$

Transformation II-c: Assumes that the heteroscedastic variance changes at an increasing rate as vehicle intensity changes (i.e., $E(U_i^2) = V_i^2\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{V_i} = \beta_o \frac{1}{V_i} + \beta_1 \frac{D_i}{V_i} + \beta_2 \frac{F_i}{V_i} + \beta_3 + \beta_4 \frac{A_i}{V_i} + \beta_5 \frac{PV_i}{V_i} + \beta_6 \frac{PF_i}{V_i} + \frac{U_i}{V_i}$$

Transformation II-d: Assumes that the heteroscedastic variance changes at an increasing rate as antecedent traffic count (i.e., $E(U_i^2) = A_i^2\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{A_i} = \beta_o \frac{1}{A_i} + \beta_1 \frac{D_i}{A_i} + \beta_2 \frac{F_i}{A_i} + \beta_3 \frac{V_i}{A_i} + \beta_4 + \beta_5 \frac{PV_i}{A_i} + \beta_6 \frac{PF_i}{A_i} + \frac{U_i}{A_i}$$

Transformation II-e: Assumes that the heteroscedastic variance changes at an increasing rate as the previous storm flow changes (i.e., $E(U_i^2) = PF_i^2\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{PF_i} = \beta_o \frac{1}{PF_i} + \beta_1 \frac{D_i}{PF_i} + \beta_2 \frac{F_i}{PF_i} + \beta_3 \frac{V_i}{PF_i} + \beta_4 \frac{A_i}{PF_i} + \beta_5 \frac{PV_i}{PF_i} + \beta_6 + \frac{U_i}{PF_i}$$

Transformation III: Assumes that the heteroscedastic variance is proportional to the estimated values of Y obtained from the OLS estimation of the base model (i.e., $E(U_i^2) = \hat{Y}_i^2\sigma^2$). The transformed equation to be estimated by OLS is:

$$\frac{Y_i}{\hat{Y}_i} = \beta_o \frac{1}{\hat{Y}_i} + \beta_1 \frac{D_i}{\hat{Y}_i} + \beta_2 \frac{F_i}{\hat{Y}_i} + \beta_3 \frac{V_i}{\hat{Y}_i} + \beta_4 \frac{A_i}{\hat{Y}_i} + \beta_5 \frac{PV_i}{\hat{Y}_i} + \beta_6 \frac{PF_i}{\hat{Y}_i} + \frac{U_i}{\hat{Y}_i}$$

Transformation IV-a and IV-b: Assumes the heteroscedastic variance is a linear function of the OLS residuals (i.e., $E(U_i^2) = |e_i|\sigma^2$). Model IV-a uses the residuals from regressing Y on the suspect independent variables only. Model IV-b uses the residuals from regressing Y on all independent variables in the base model. In either case, the equation to be estimated by OLS is:

$$\frac{Y_i}{\sqrt{|e_i|}} = \beta_o \frac{1}{\sqrt{|e_i|}} + \beta_1 \frac{D_i}{\sqrt{|e_i|}} + \beta_2 \frac{F_i}{\sqrt{|e_i|}} + \beta_3 \frac{V_i}{\sqrt{|e_i|}} + \beta_4 \frac{A_i}{\sqrt{|e_i|}} + \beta_5 \frac{PV_i}{\sqrt{|e_i|}} + \beta_6 \frac{PF_i}{\sqrt{|e_i|}} + \frac{U_i}{\sqrt{|e_i|}}$$

Transformation IV-b was the best transformation for the data collected during this research.

Autocorrelation

Autocorrelation (or autoregression) refers to the presence of correlation among the disturbance terms. Autocorrelation is commonly associated with time-series data where the value of a given observation may be dependent upon the value of the preceding observation. In this case, a plot of the residuals will show a pronounced pattern.

Autocorrelation is unavoidable if all of the observations recorded during each storm event are included in the highway runoff data base since each observation recorded for the same storm will be related. Although there is no correlation *between* storms, the observations *within* each storm will be correlated. A hypothetical pattern of residuals that might be expected from a data set containing four storm events is plotted in Figure G-2.

A major rationale for including the disturbance term is to measure the combined effects of all variables not included in the regression equation. Many of the variables that affect highway runoff quality are autocorrelated. For example, every observation recorded during a particular storm will be dependent upon the amount of material that resided on the highway surface at the start of the rainfall. It follows that if any of the omitted variables are autocorrelated, the disturbance term will also be autocorrelated.

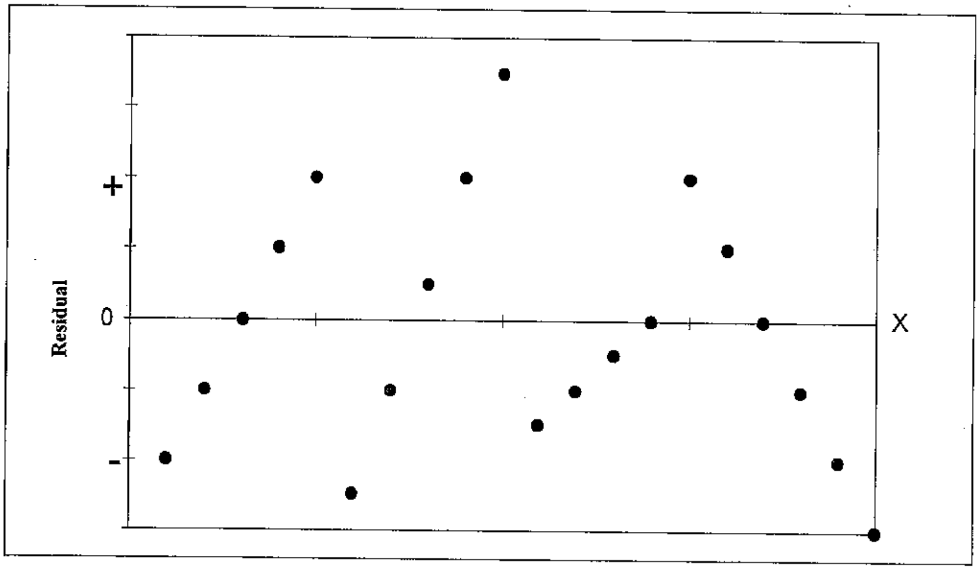


Figure G-2

The Test for Autocorrelation

Autocorrelation is defined as a disturbance term U_t whose value is dependent upon its immediately preceding value U_{t-1}, plus a random variable V_t. The subscript t is used to denote time because autocorrelation is typically a time series problem. If the relationship between U_t and U_{t-1} is linear, the autoregression is described as "first-order" and takes on the form:

$$U_t = \rho U_{t-1} + V_t \tag{G-8}$$

The term rho (ρ) is called the autoregressive coefficient and is interpreted as the change in U_t for a 1-unit change in U_{t-1}. It should also be noted that the random variable V_t (that is a disturbance term) has the classical statistical specifications and is uncorrelated with U_t.

The Durbin-Watson d statistic is commonly used to detect the presence of autocorrelation. The test is valid only for first-order autoregression and where a "lagged," or previous value of the dependent variable does not appear as an explanatory variable. The d-statistic is calculated as:

$$d = \frac{\sum_{t=2}^{T}(e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2} \qquad \text{(G-9)}$$

where the e's are the OLS residuals computed from the sample. The relationship between the d statistic and the autoregression coefficient rho can be shown by expanding G-9 to obtain:

$$d = \frac{\sum_{t=2}^{T} e_t^2 - 2\sum_{t=2}^{T} e_t e_{t-1} + \sum_{t=2}^{T} e_{t-1}^2}{\sum_{t=1}^{T} e_t^2} \qquad \text{(G-10)}$$

Because the squared terms summed over $t = 1$ and $t = 2$ will be nearly the same, G-10 can be rewritten as:

$$\begin{aligned} d &\approx \frac{\sum e_t^2 - 2\sum e_t e_{t-1} + \sum e_t^2}{\sum e_t^2} \\ &\approx \frac{2\sum e_t^2 - 2\sum e_t e_{t-1}}{\sum e_t^2} \\ &\approx 2\left(1 - \frac{\sum e_t e_{t-1}}{\sum e_t^2}\right) \end{aligned}$$

By definition, $\sum e_t e_{t-1} / \sum e_t^2 = \rho$, therefore

$$d \approx 2(1-\rho) \qquad \text{(G-11)}$$

The distribution of the d statistic is based on this approximation. If there is no first-order autocorrelation, rho is equal to zero and the d statistic is *approximately* equal to 2. But because of the approximation, there is an "inconclusive" range of values for that the d statistic can neither confirm nor deny the presence of autocorrelation. In regard to hypothesis testing, there are three critical ranges: (1) values of d for that the null hypothesis of no autocorrelation is rejected, (2) values of d for that the null hypothesis of no autocorrelation is not rejected, and (3) an inconclusive range of d values. For this reason, a Durbin-Watson table shows two critical values: the lower value (d_L) and the upper value (d_U) of the inconclusive range.

The formal hypothesis test for autocorrelation is stated as follows:

H_0: no autocorrelation.

H_a: autocorrelation

The decision rules are:

1) Reject H_0 if $d < d_L$ (positive) or if $d > 4 - d_L$ (negative).
2) Do not reject H_0 if $d_U < d < 4 - d_U$.
3) Test inconclusive if $d_L < d < d_U$, or, $4 - d_U < d < 4 - d_L$.

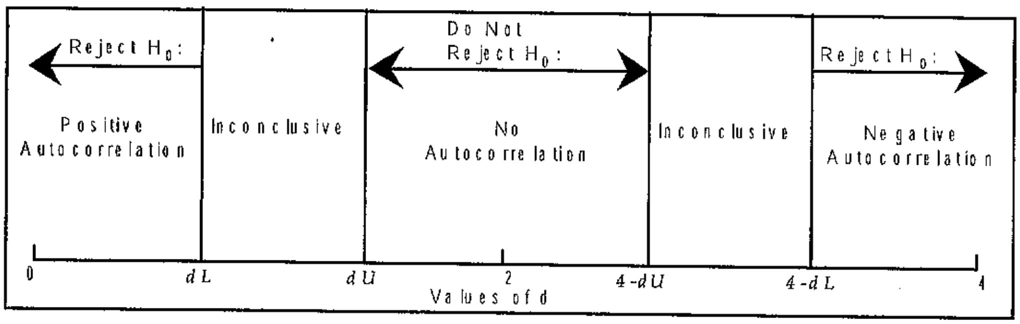


Figure G-3 Acceptance and Rejection Regions for the Durbin-Watson Statistic (after Johnson et. al., 1987)

The approximate values for d_L and d_U for 423 observations, 6 explanatory variables, and an intercept term is 1.57 and 1.78, respectively.

Autocorrelation Transformations

The solution to the autocorrelation misspecification is similar to that of heteroscedasticity. The procedure is to transform the misspecified equation into one with a uncorrelated disturbance term to permit the use of OLS procedures. The consequences of ignoring autocorrelation are the same as with heteroscedasticity, that is, OLS procedures will yield unbiased estimates of the population regression coefficients, but these estimates will not be minimum-variance estimates. As explained earlier, the OLS estimate of the population variance will be biased, that will nullify the *t* and *F* tests.

If the autoregressiveness in the sample is assumed to be first-order, equation G-8 suggests the following two-step transformation procedure:

1) Create a new set of variables Y_t^* and X_t^* (for all X) where:

$$Y_2^* = Y_2 - \rho Y_1 \qquad X_2^* = X_2 - \rho X_1$$

$$Y_3^* = Y_3 - \rho Y_2 \qquad X_3^* = X_3 - \rho X_2$$

$$\vdots \qquad\qquad \vdots$$

2) Re-estimate the OLS equation using the transformed variables.

Although the theoretical solution is straightforward, the practical solution is not simple since (1) the value of rho is not known and (2) the first observation is lost in the transformation.

The latter problem is solved by using the following transformations for the first observation:

$$Y_1^* = Y_1\sqrt{1-\rho^2} \qquad X_1^* = X_1\sqrt{1-\rho^2}$$

The appropriate value of rho is determined by using the Hildreth-Lu, or grid procedure. This is an iterative search procedure in which rho is incremented from -1 to +1 in small increments such as 0.1, 0.05, 0.01, etc. The data is transformed using each value of rho, the OLS equation is estimated, and the ESS recorded. The "best" value of rho is the one that yields the smallest ESS. Table G-2 shows the results of the grid search for rho in a COD model.

Table G-2

COD Rho Search

ρ	**ESS**
0.55	144
0.60	140
0.65	137
0.70	**135.4**
0.75	135.5
0.80	136
0.85	140
0.90	144
0.95	150

Once a value is determined for rho, the GLS method can be applied. The formal transformation is stated below:

Transformation V: Assumes that first-order autoregression is present in the base model. The transformed equation to be estimated by OLS is:

$$Y_i^* = (1-\rho)\beta_0 + \beta_1 D_i^* + \beta_2 F_i^* + \beta_3 V_i^* + \beta_4 A_i^* + \beta_5 PV_i^* + \beta_6 PF_i^* + v_i$$

Dual Transformations

All of the transformations described thus far treat the problem of heteroscedasticity and autocorrelation separately. However, both problems can occur simultaneously, and both sets of transformations can be made to the OLS equation in an attempt to remedy the problem. An OLS equation estimated using a heteroscedastic transformation, for example, can be re-estimated using a first-order autoregression transformation. Likewise, the OLS equation estimated using the first-order autoregression transformation can subsequently be re-estimated using each of the heteroscedastic transformations. Note that the result of the dual transformation is dependent upon the sequence in which the transformations are performed. Again, there is no hard and fast rule to determine the correct transformation.

During this study, two dual transformations were performed. The logic for each transformation is described below:

Transformation VI: Assumes the proper heteroscedasticity correction for Model V is the "best" transformation of Models I - IV. For example, if Model IV-b resulted in the lowest Breusch-Pagan value, the transformed equation to be estimated by OLS is:

$$\frac{Y_i^*}{\sqrt{|e_i|}} = \frac{(1-\rho)\beta_0}{\sqrt{|e_i|}} + \beta_1 \frac{D_i^*}{\sqrt{|e_i|}} + \beta_2 \frac{F_i^*}{\sqrt{|e_i|}} + \beta_3 \frac{V_i^*}{\sqrt{|e_i|}} + \beta_4 \frac{A_i^*}{\sqrt{|e_i|}} + \beta_5 \frac{PV_i}{\sqrt{|e_i|}} + \beta_6 \frac{PF_i}{\sqrt{|e_i|}} + \frac{\nu_i}{\sqrt{|e_i|}}$$

Transformation VII: Assumes that the proper correction for autoregression in the "best" transformation of Models I - IV is the first-order model. For example, if Model IV-b resulted in the lowest Breusch-Pagan value, the transformed equation to be estimated by OLS is:

$$\left(\frac{Y_i}{\sqrt{|e_i|}}\right)^* = (1-\rho)\frac{\beta_0}{\sqrt{|e_i|}} + \beta_1\left(\frac{D_i}{\sqrt{|e_i|}}\right)^* + \beta_2\left(\frac{F_i}{\sqrt{|e_i|}}\right)^* + \beta_3\left(\frac{V_i}{\sqrt{|e_i|}}\right)^* + \beta_4\left(\frac{A_i}{\sqrt{|e_i|}}\right)^*$$

$$+ \beta_5\left(\frac{PV_i}{\sqrt{|e_i|}}\right)^* + \beta_6\left(\frac{PF_i}{\sqrt{|e_i|}}\right)^* + \frac{\nu_i}{\sqrt{|e_i|}}$$

Summary

Transformation VII was determined to be the best transformation of the data collected during this research. Table G-3 lists the values of the Durbin-Watson statistic for the final model of each constituent.

Table G-3

Values of the Durbin-Watson Statistic

Constituent	Durbin-Watson Statistic
TSS	1.79
VSS	1.99
BOD_5	1.89
COD	1.74
Total Carbon	1.81
Dis. Total Carbon	1.79
Nitrate	1.94
Total Phosphorus	1.71
Oil and Grease	1.61
Copper	1.99
Iron	1.78
Lead	2.00
Zinc	1.98

$d_L = 1.57$
$d_U = 1.78$

Appendix H

Residual Histograms

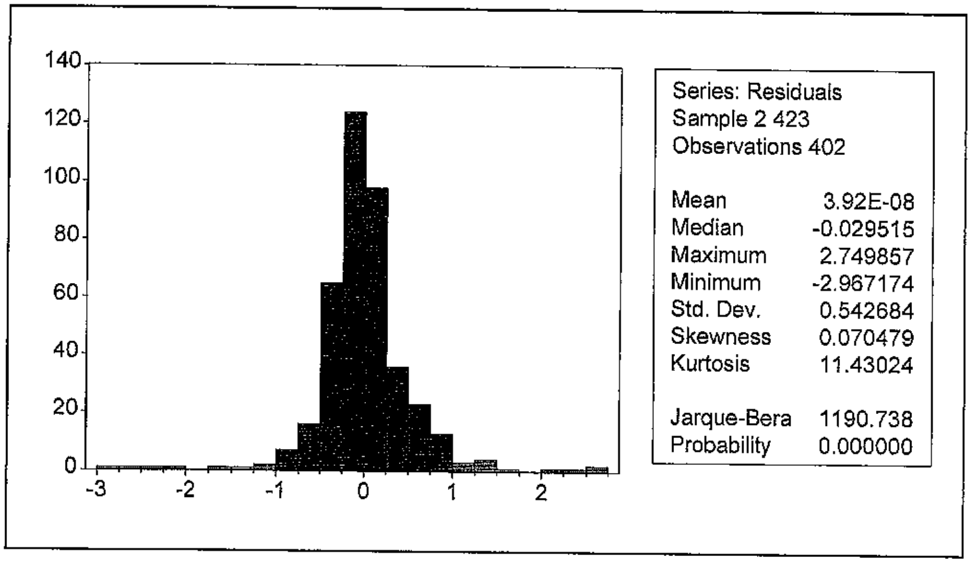


Figure H-1 TSS

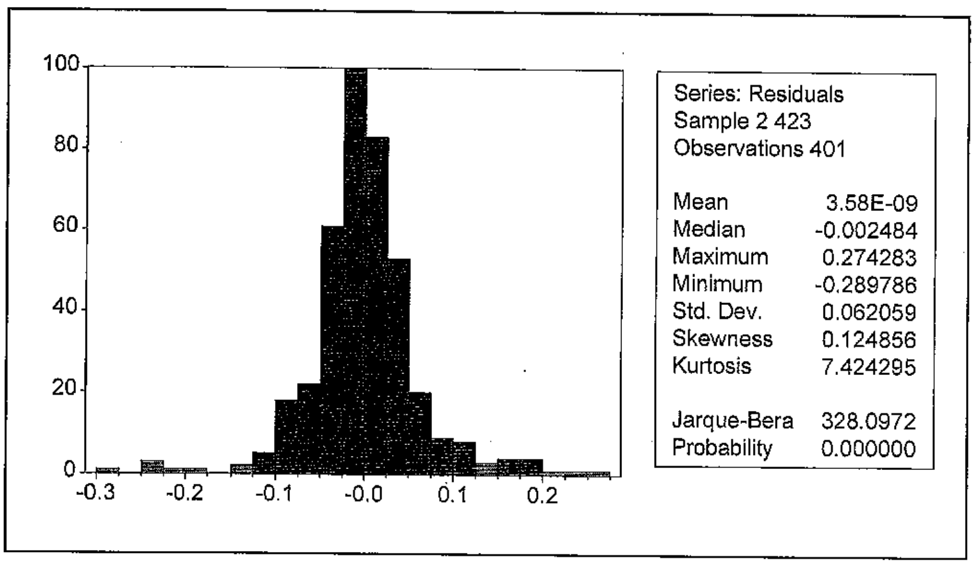


Figure H-2 VSS

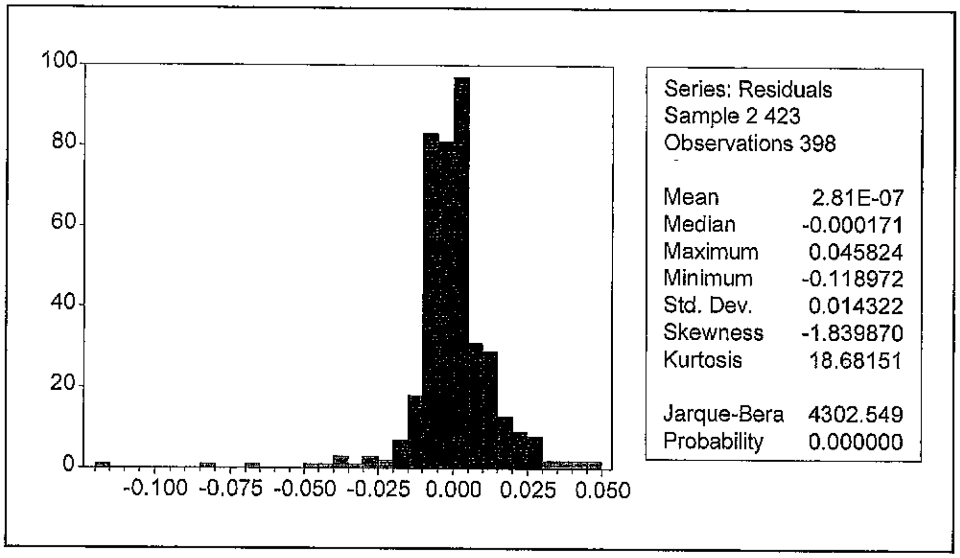


Figure H-3 BOD_5

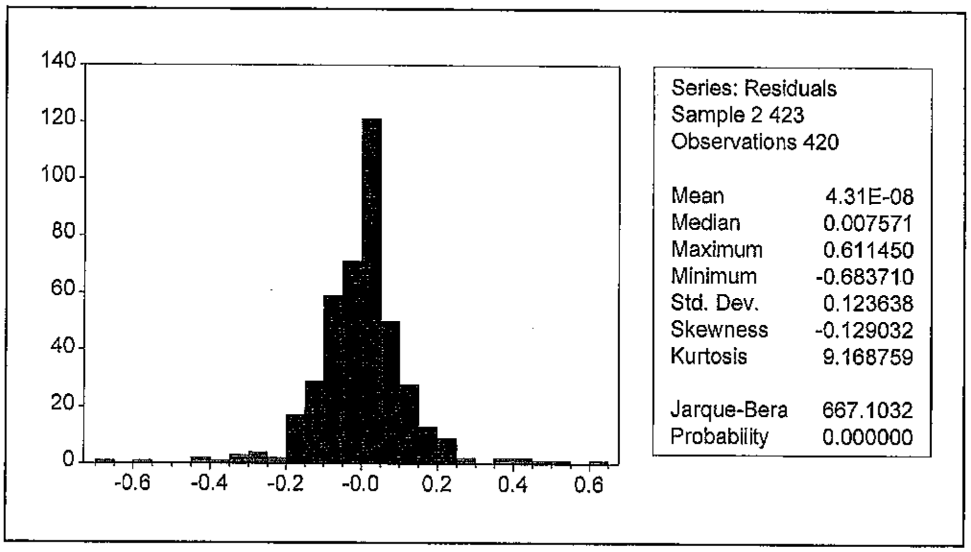


Figure H-4 COD

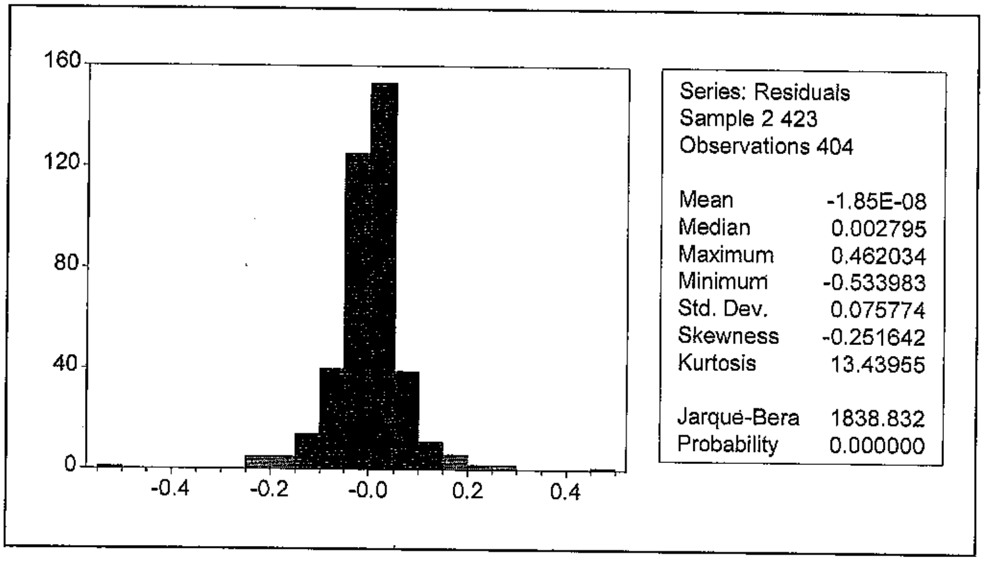


Figure H-5 Total Carbon

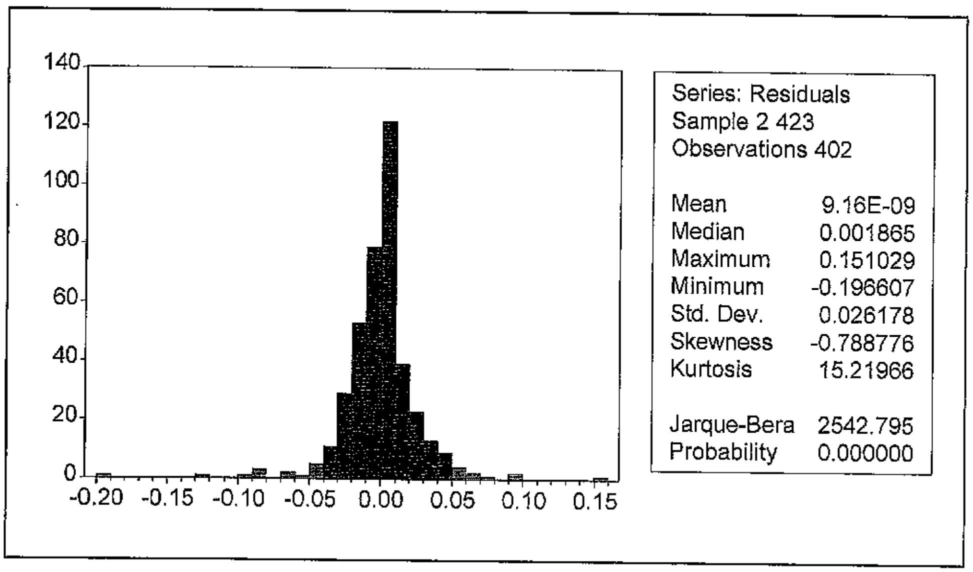


Figure H-6 Dissolved Total Carbon

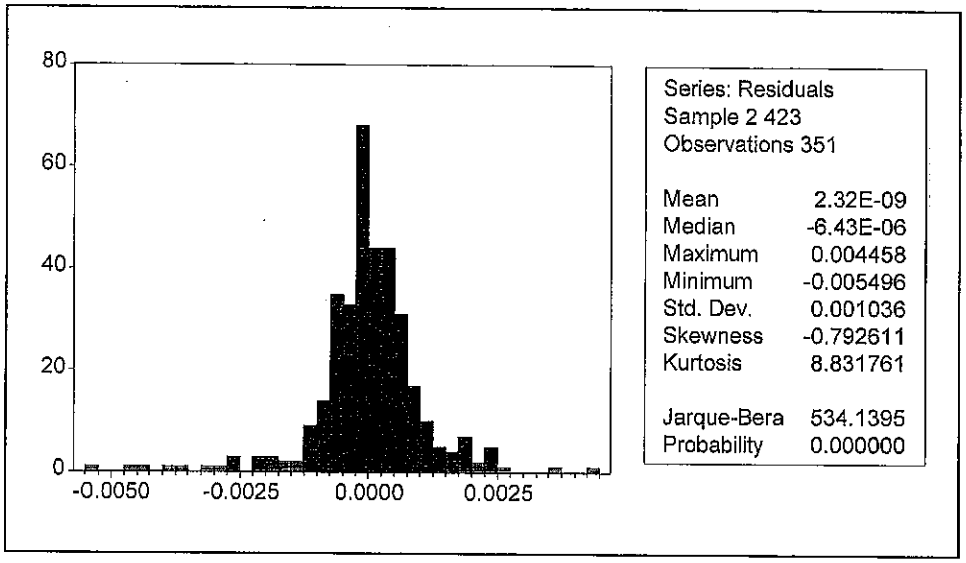


Figure H-7 Nitrate

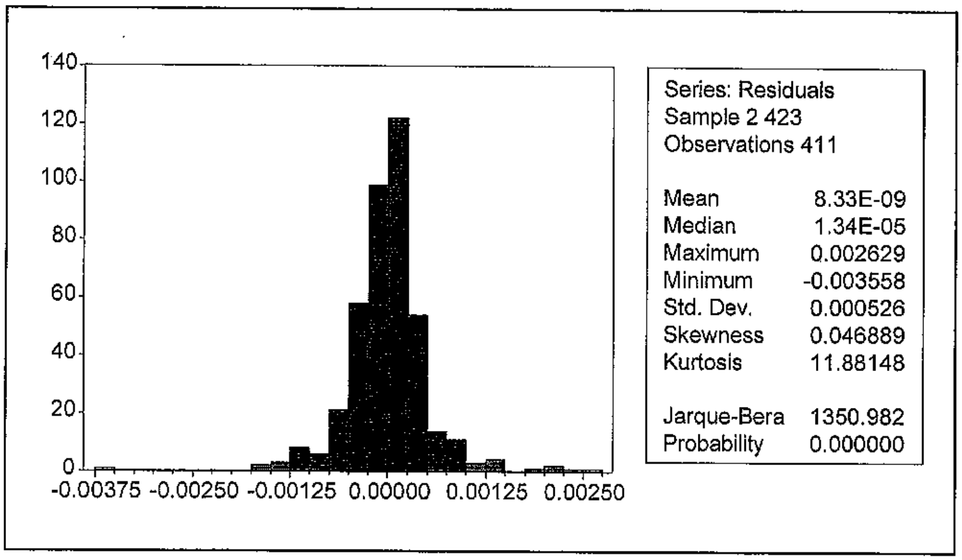


Figure H-8 Total Phosphorus

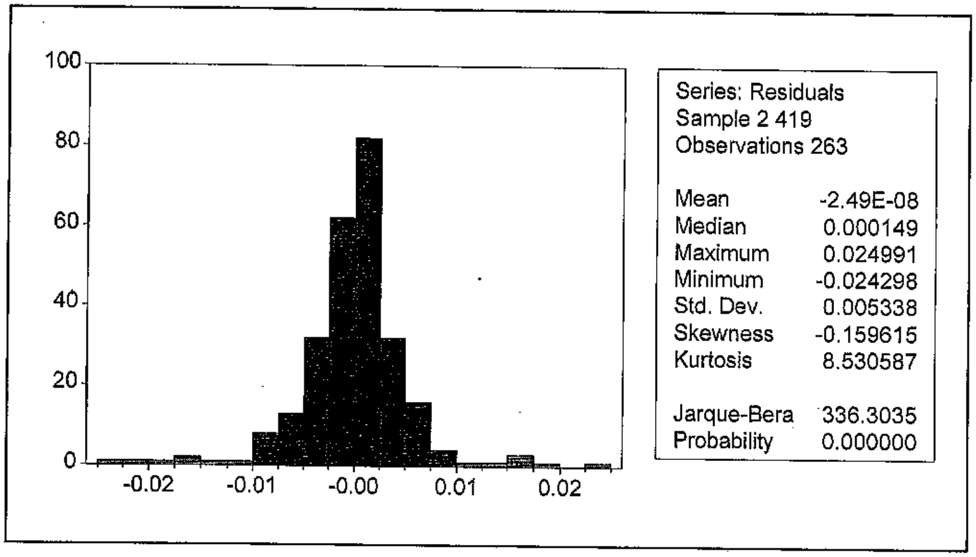


Figure H-9 Oil and Grease

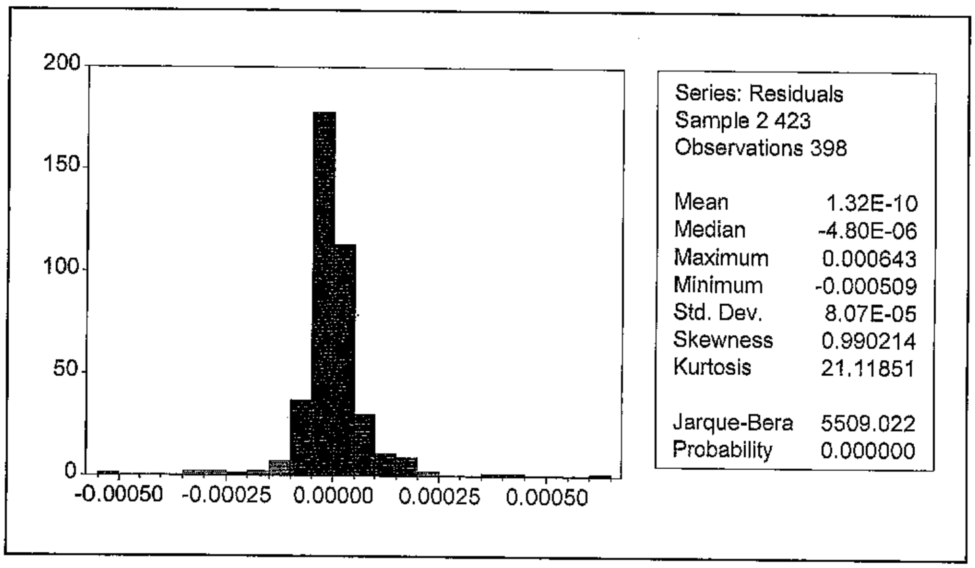


Figure H-10 Copper

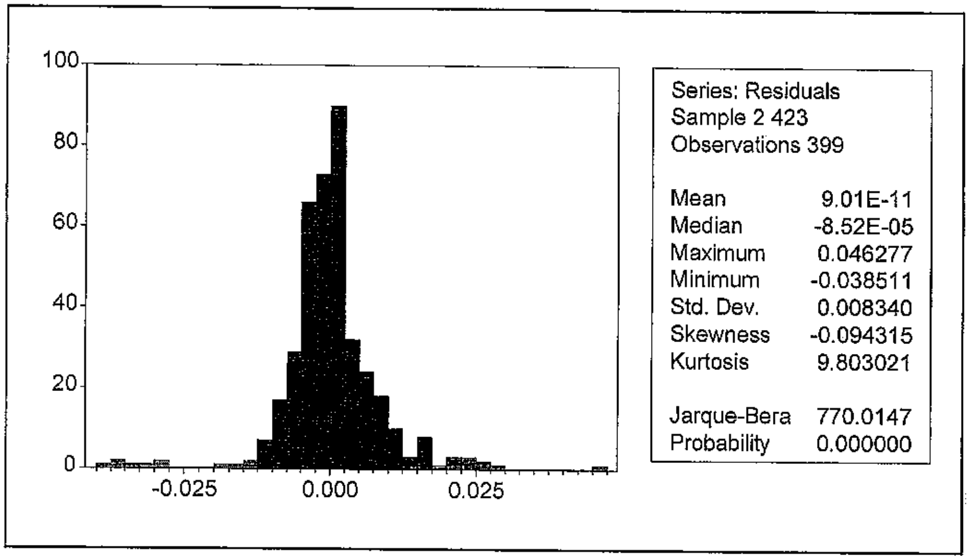


Figure H-11 Iron

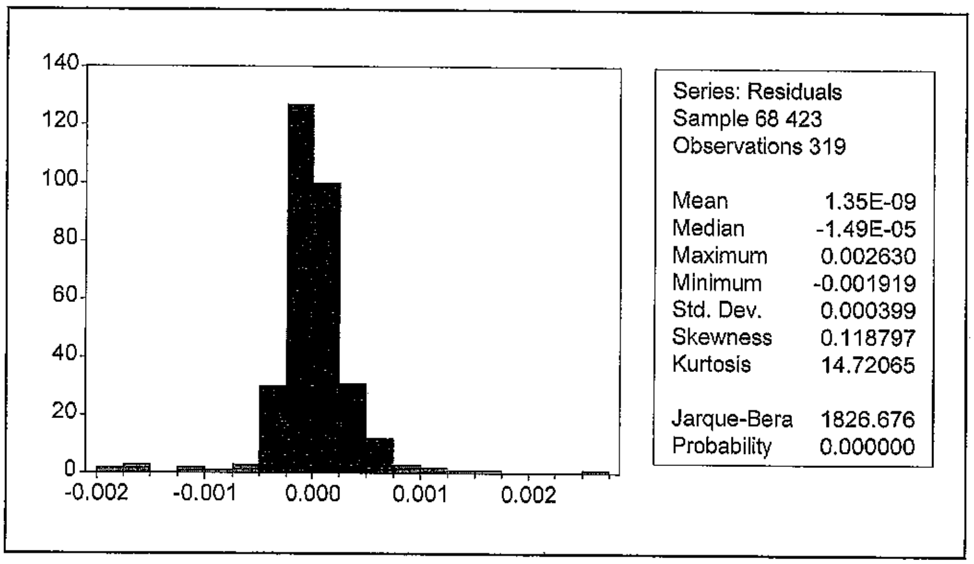


Figure H-12 Lead

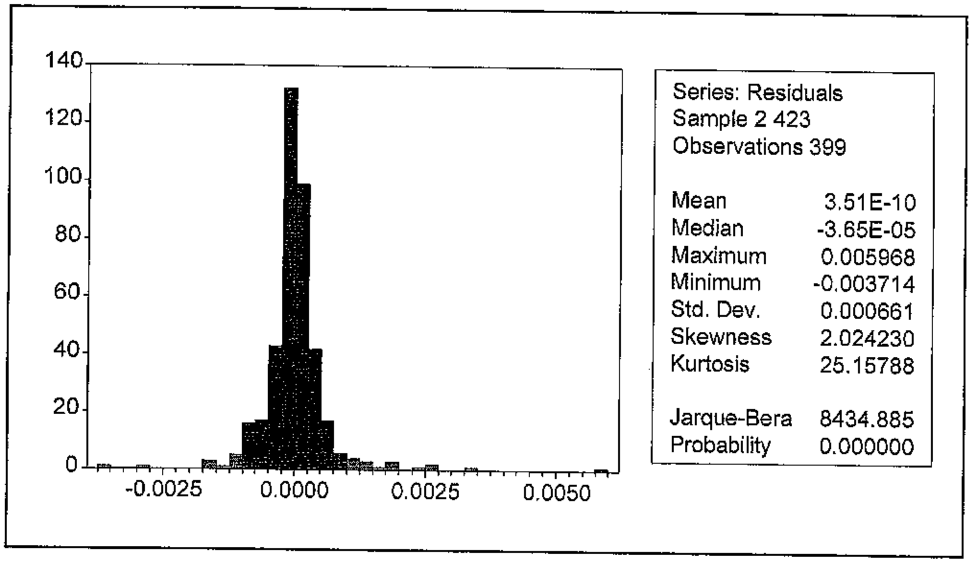
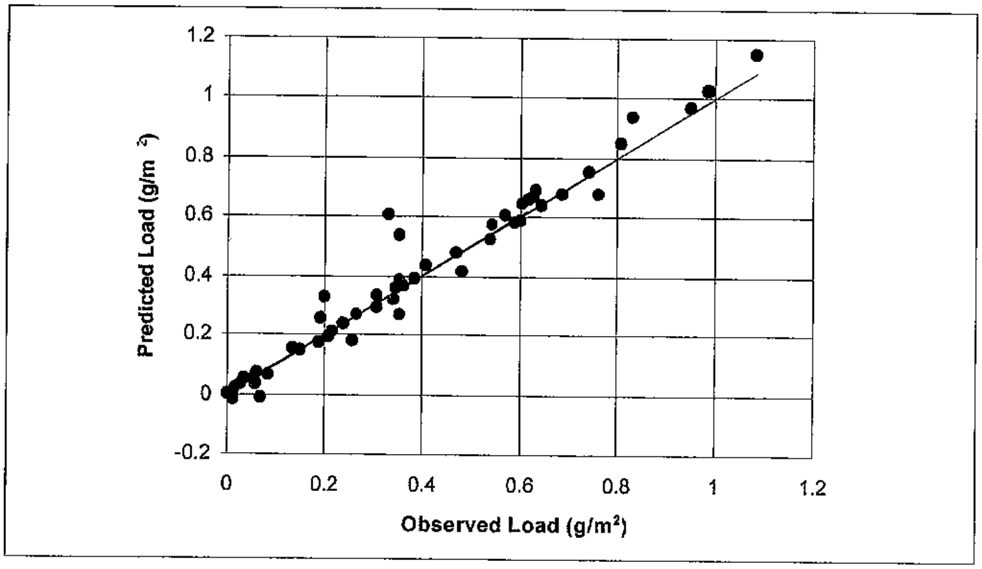
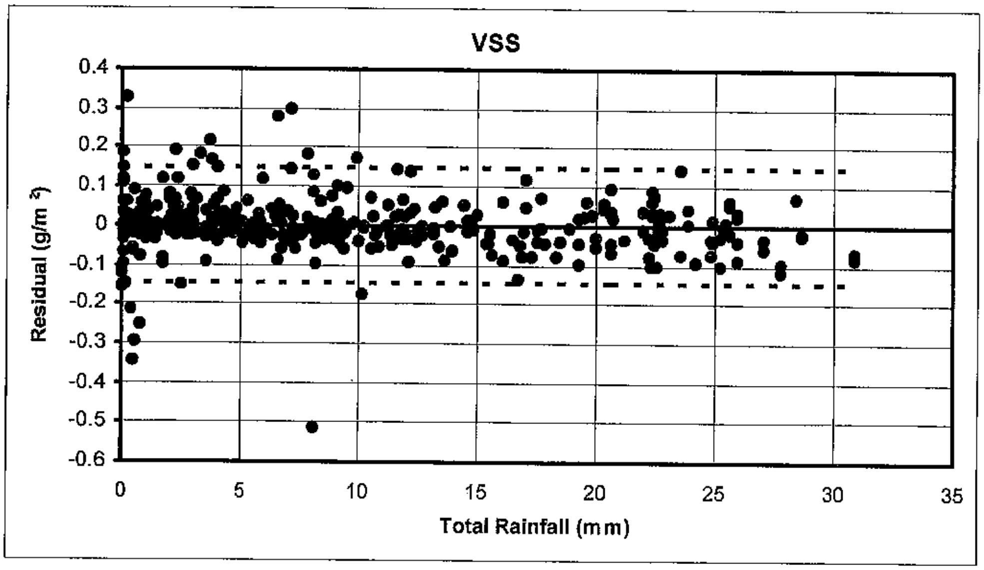


Figure H-13 Zinc

Appendix I
Regression Results

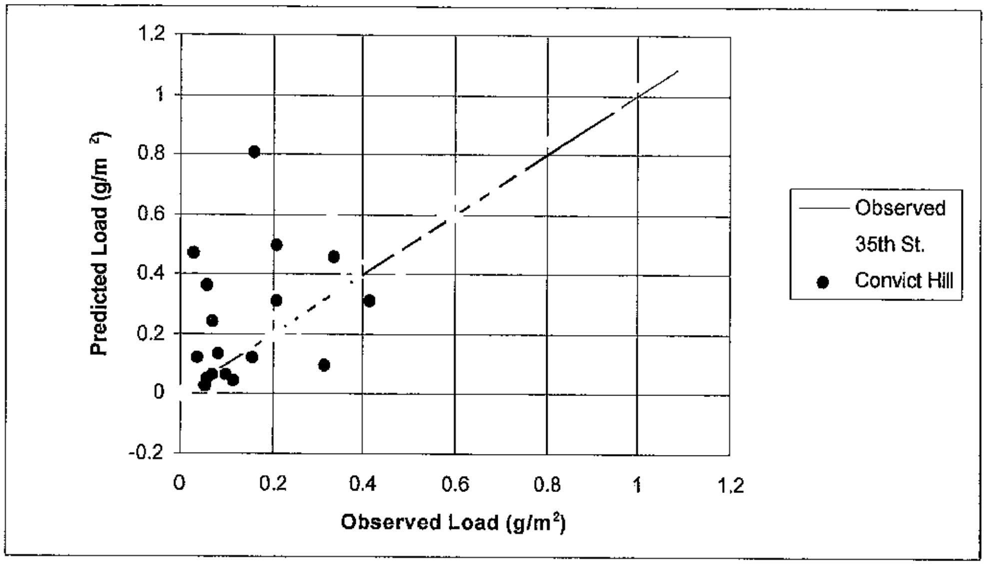


(a) Fit of Data from West 35th Street Site

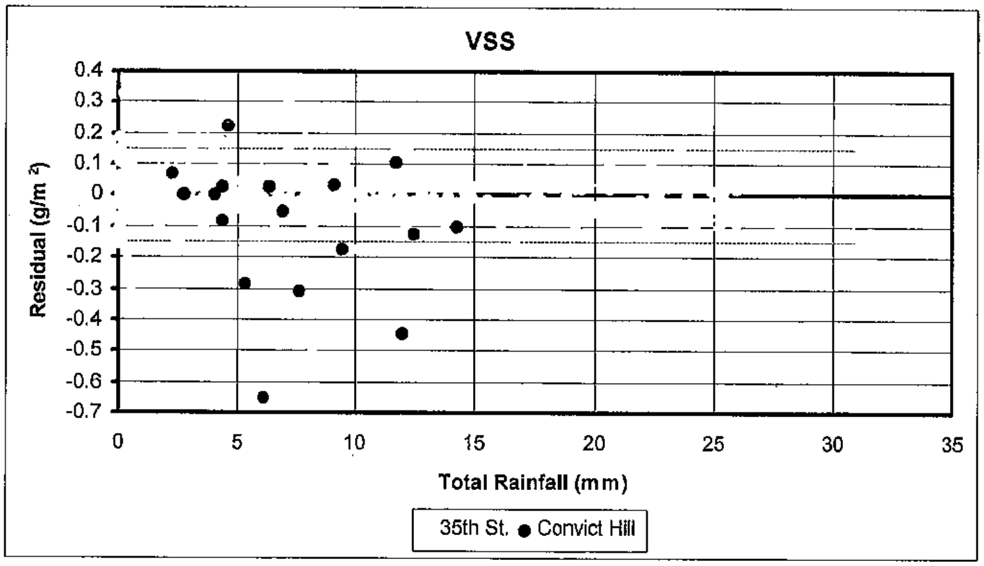


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-1 VSS Model Results

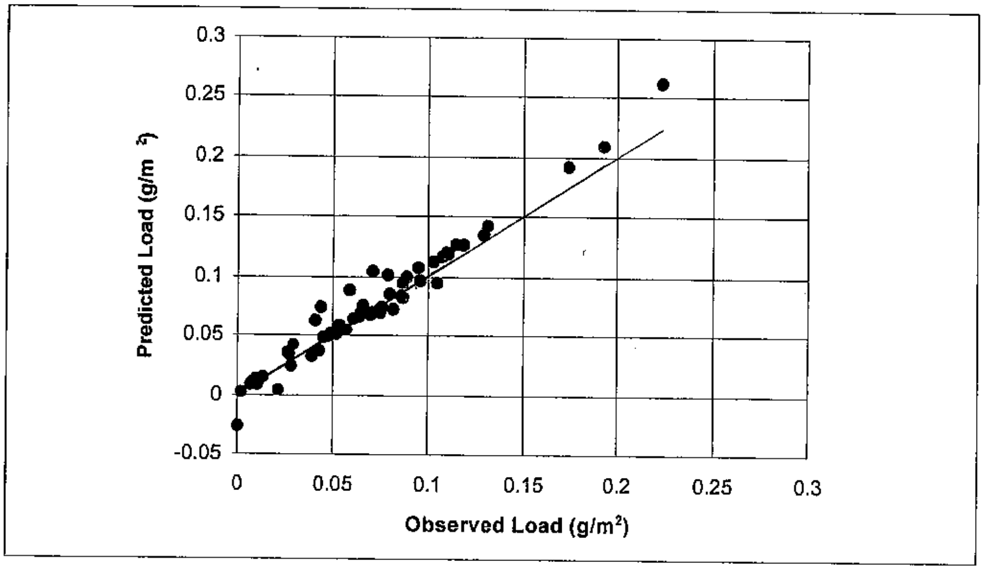


(a) Model Predictions at the Convict Hill Site

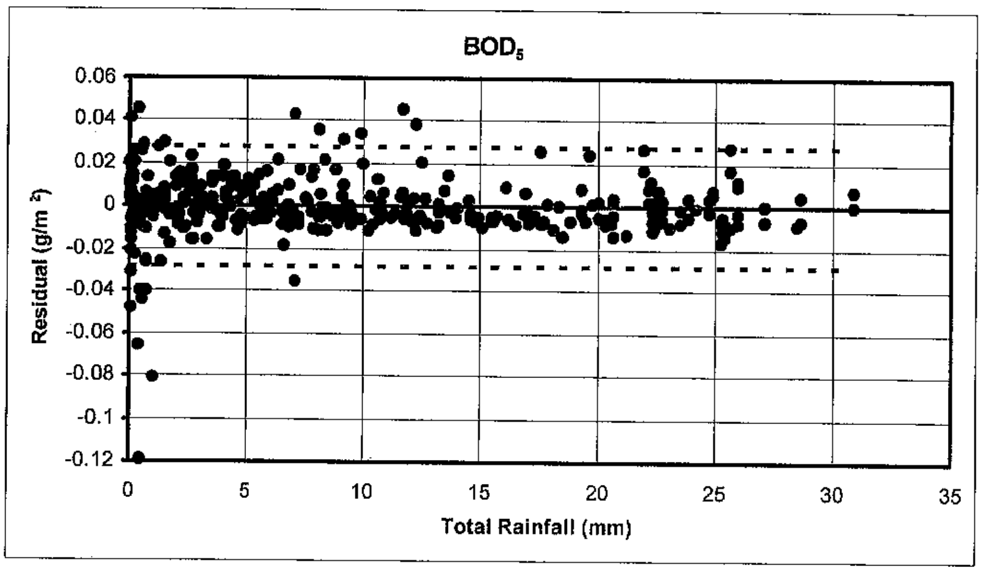


(b) Prediction Error vs. Total Rainfall

Figure I-2 VSS Model Predictions

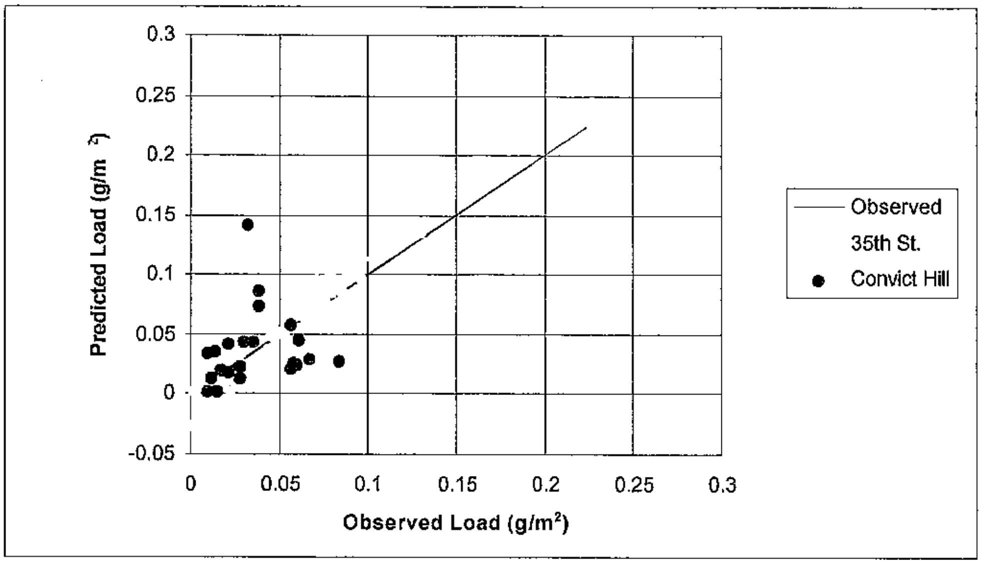


(a) **Fit of Data from West 35th Street Site**

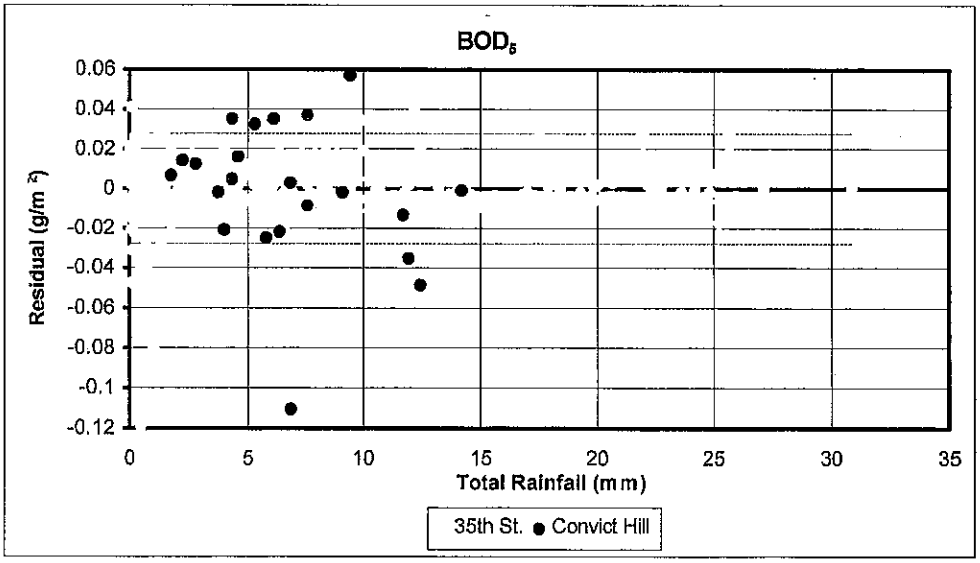


(b) **Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)**

Figure I-3 BOD_5 Model Results

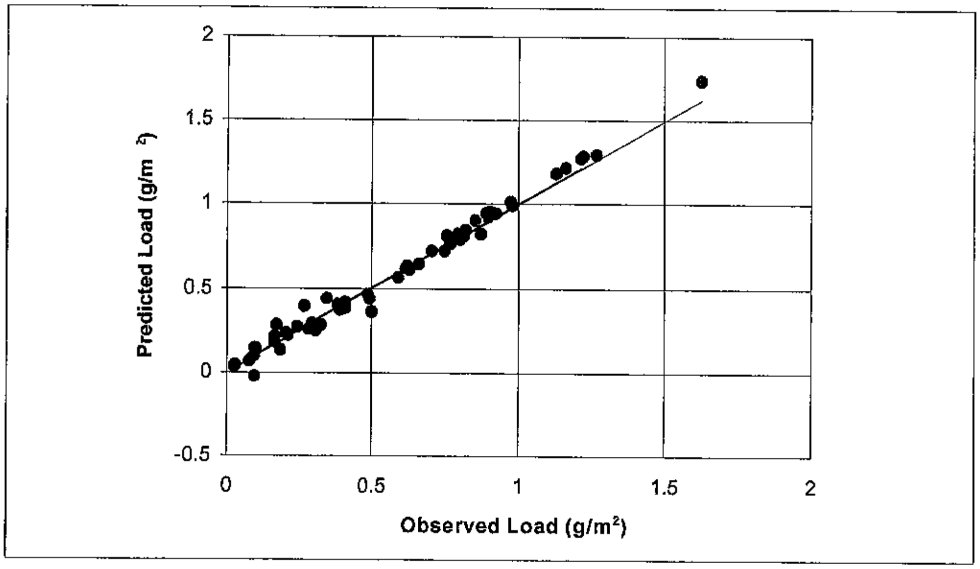


(a) Model Predictions at the Convict Hill Site

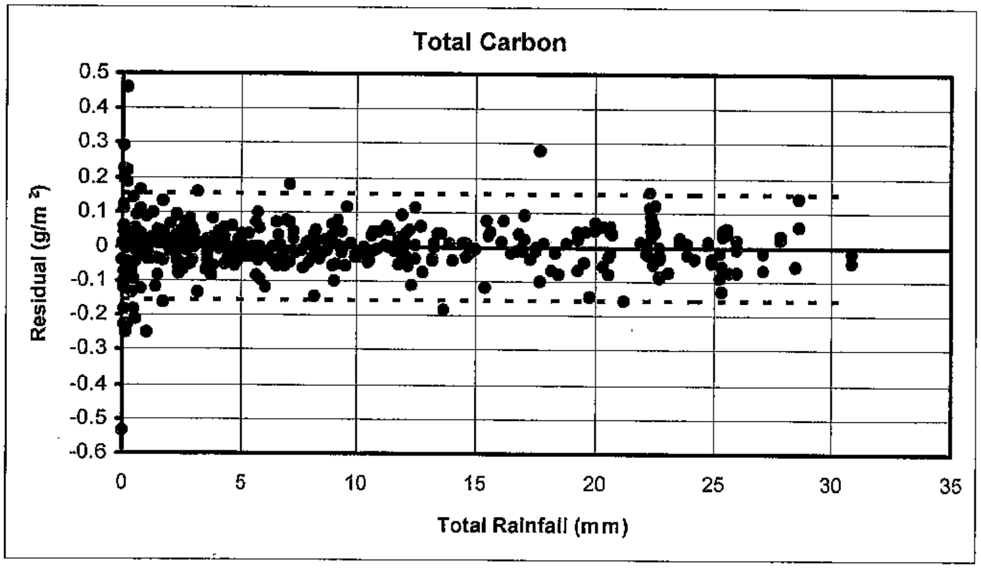


(b) Prediction Error vs. Total Rainfall

Figure I-4 BOD_5 Model Predictions

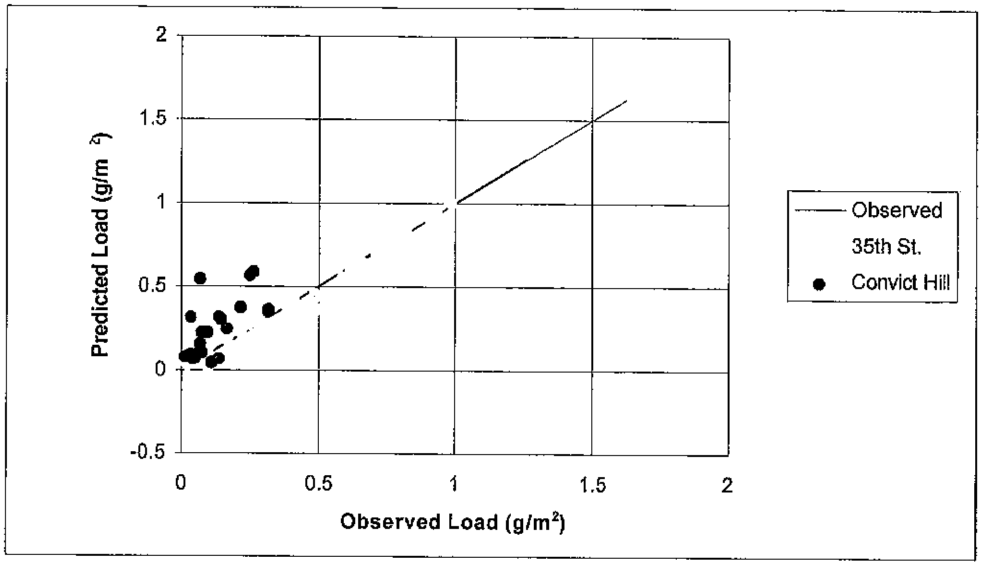


(a) Fit of Data from West 35th Street Site

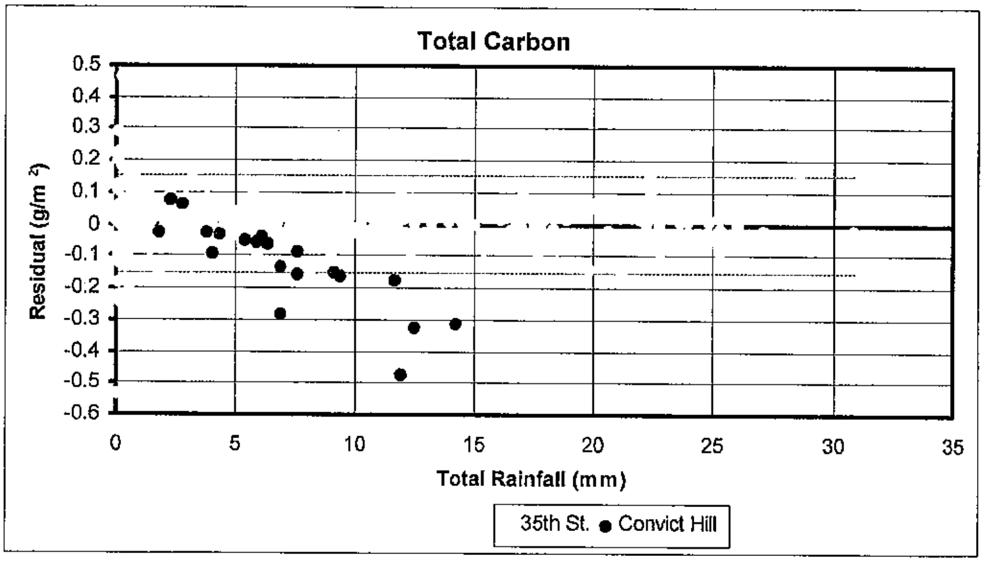


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-5 Total Carbon Model Results

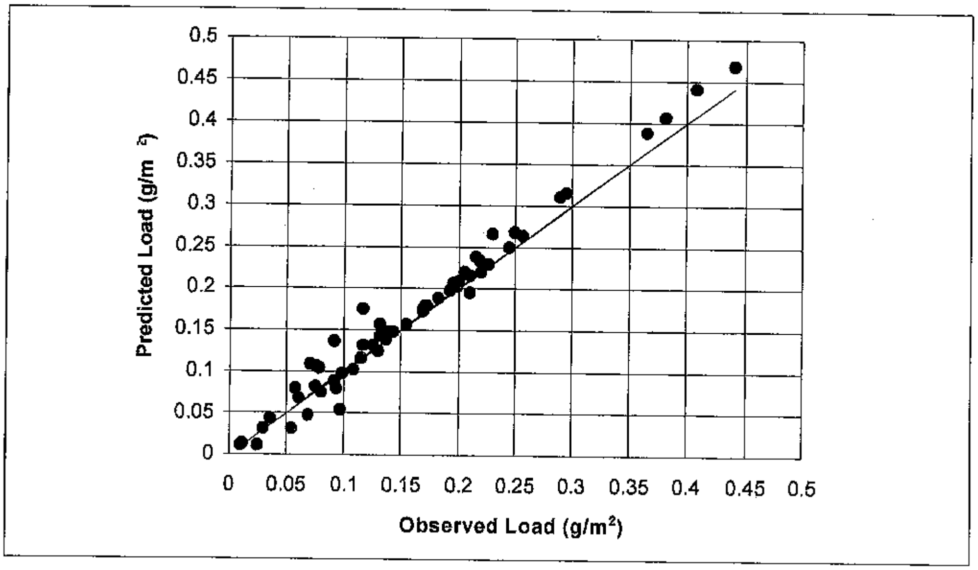


(a) Model Predictions at the Convict Hill Site

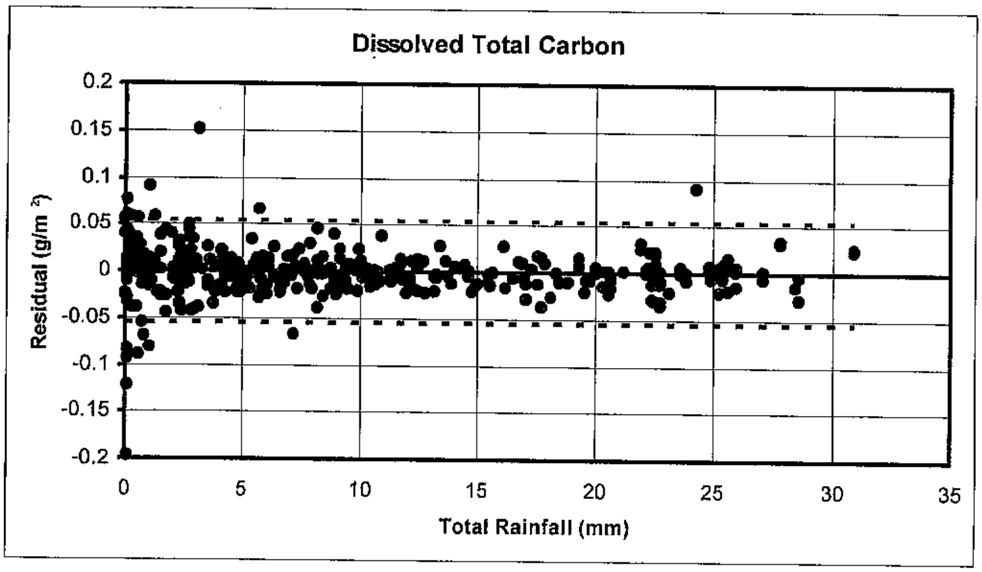


(b) Prediction Error vs. Total Rainfall

Figure I-6 Total Carbon Model Predictions

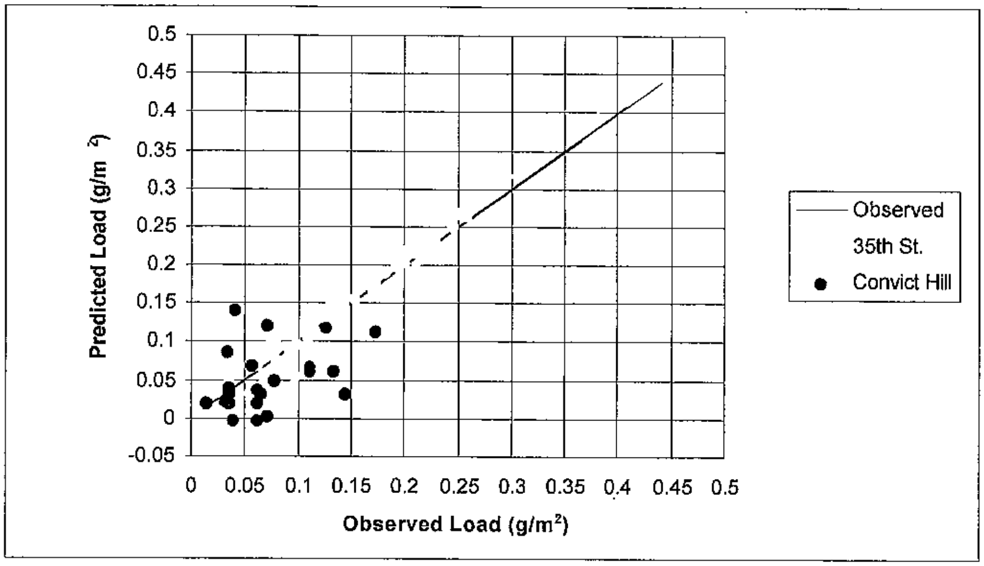


(a) Fit of Data from West 35th Street Site

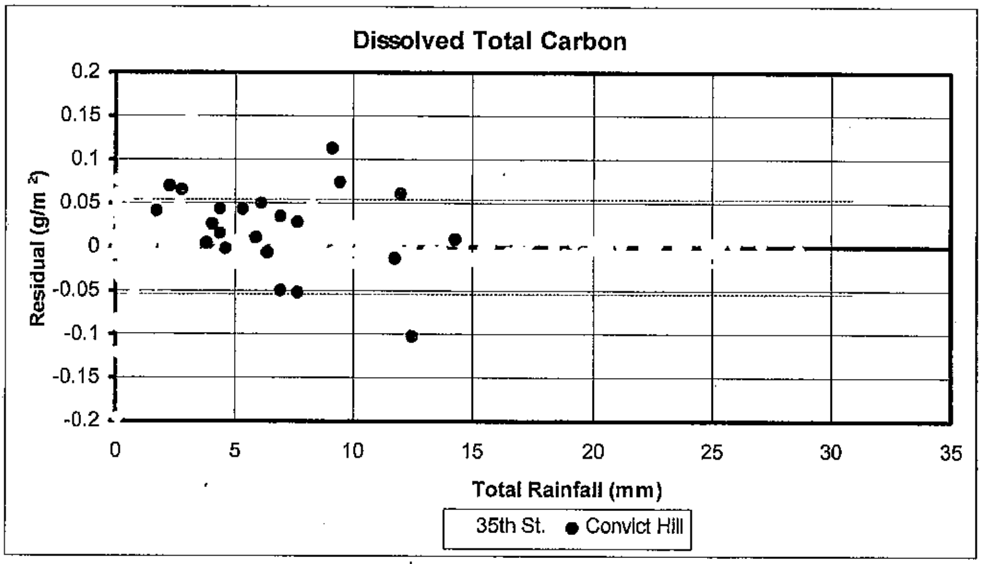


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-7 Dissolved Total Carbon Model Results

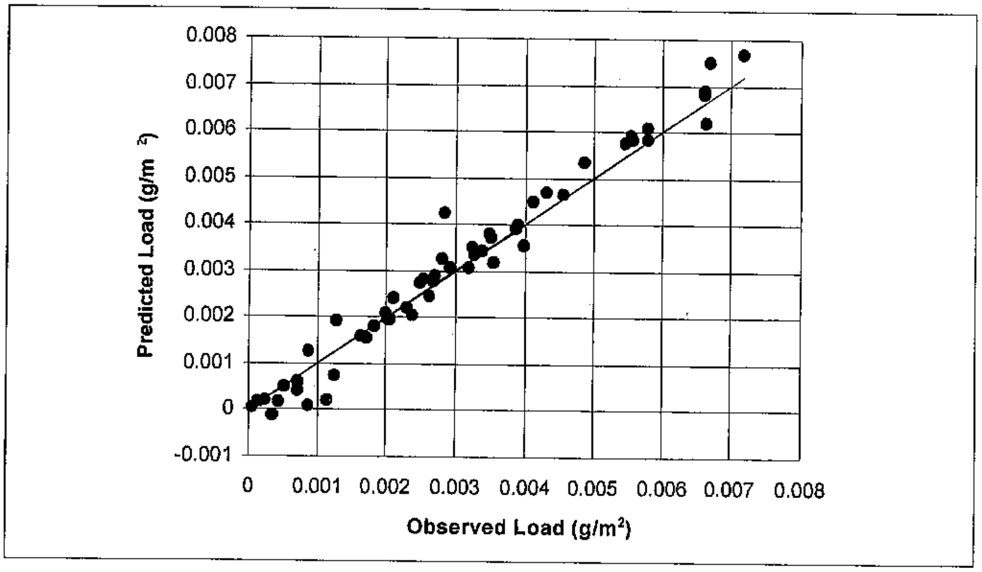


(a) Model Predictions at the Convict Hill Site

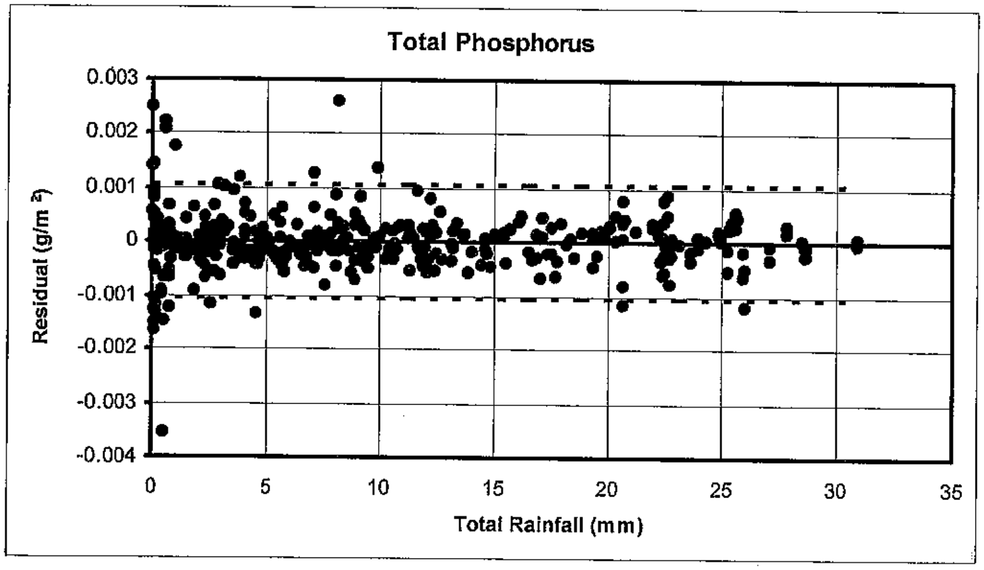


(b) Prediction Error vs. Total Rainfall

Figure I-8 Dissolved Total Carbon Model Predictions

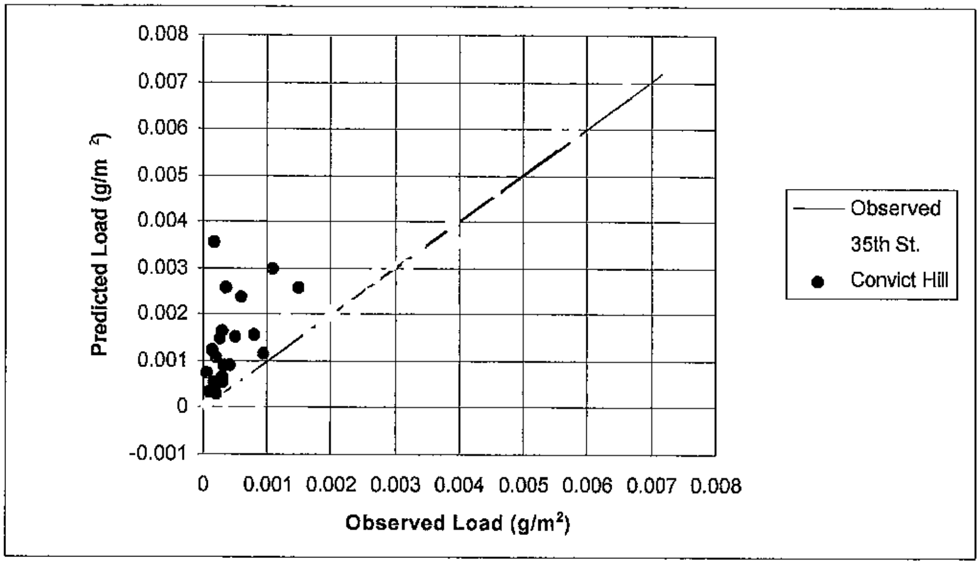


(a) Fit of Data from West 35th Street Site

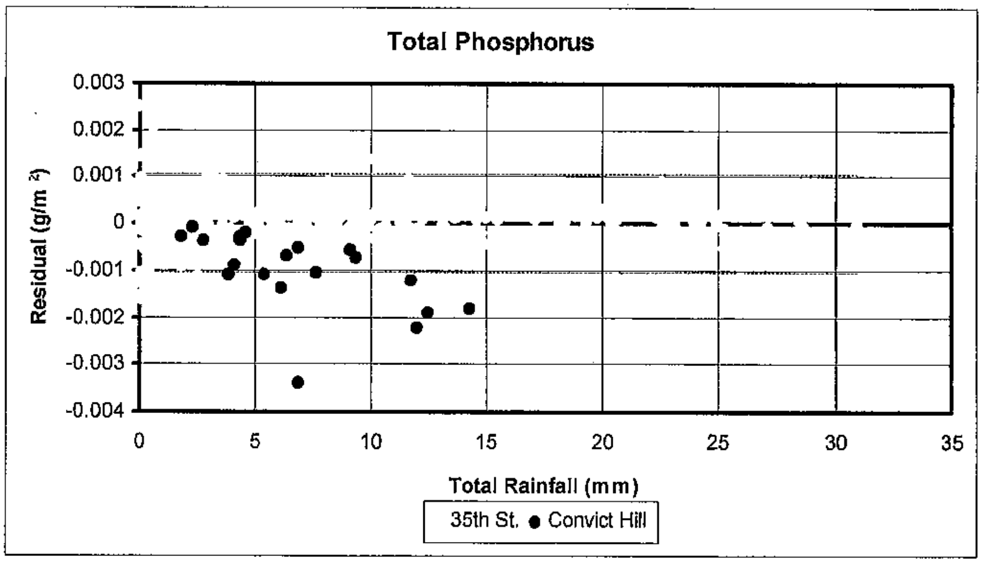


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-9 Total Phosphorus Model Results

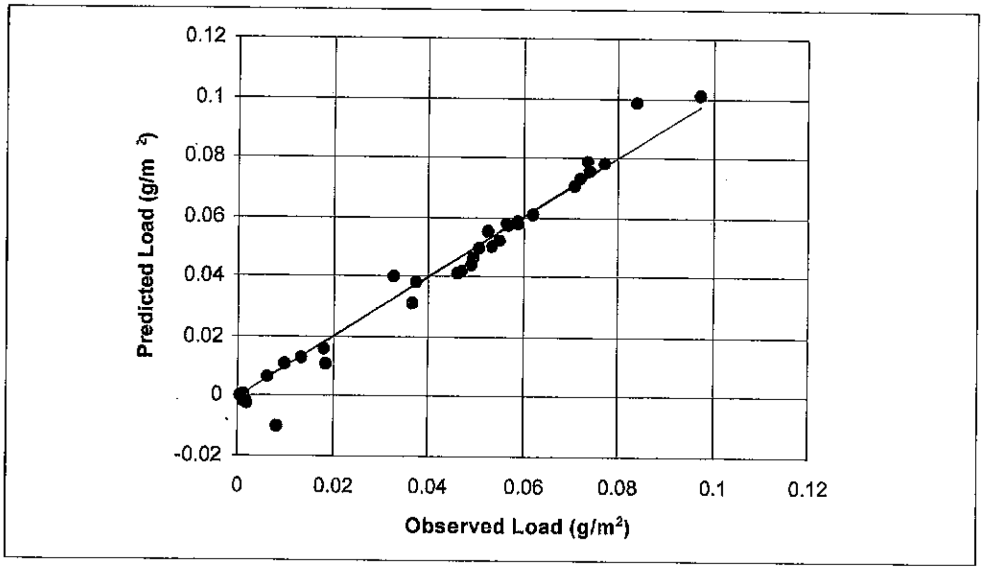


(a) Model Predictions at the Convict Hill Site

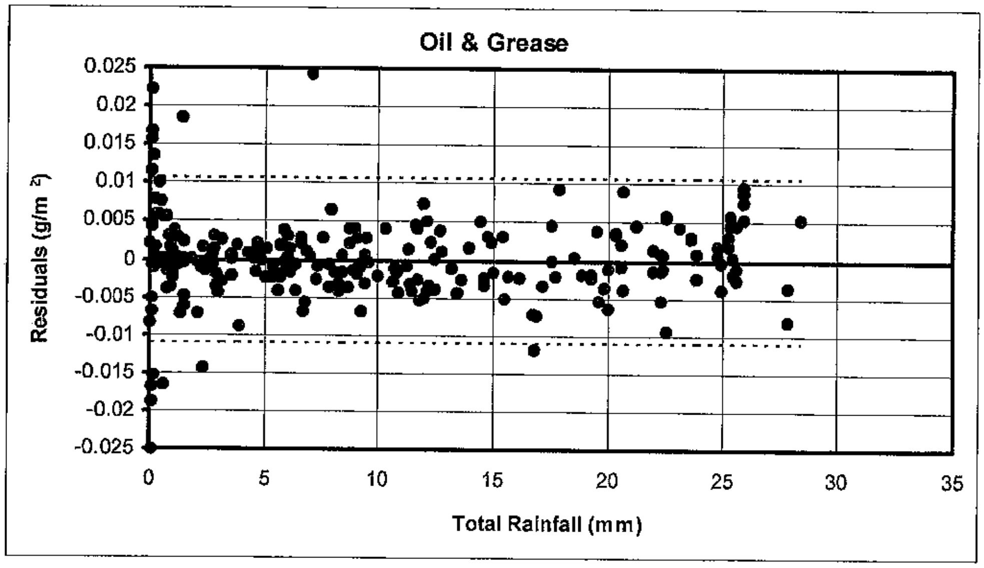


(b) Prediction Error vs. Total Rainfall

Figure I-10 Total Phosphorus Model Predictions

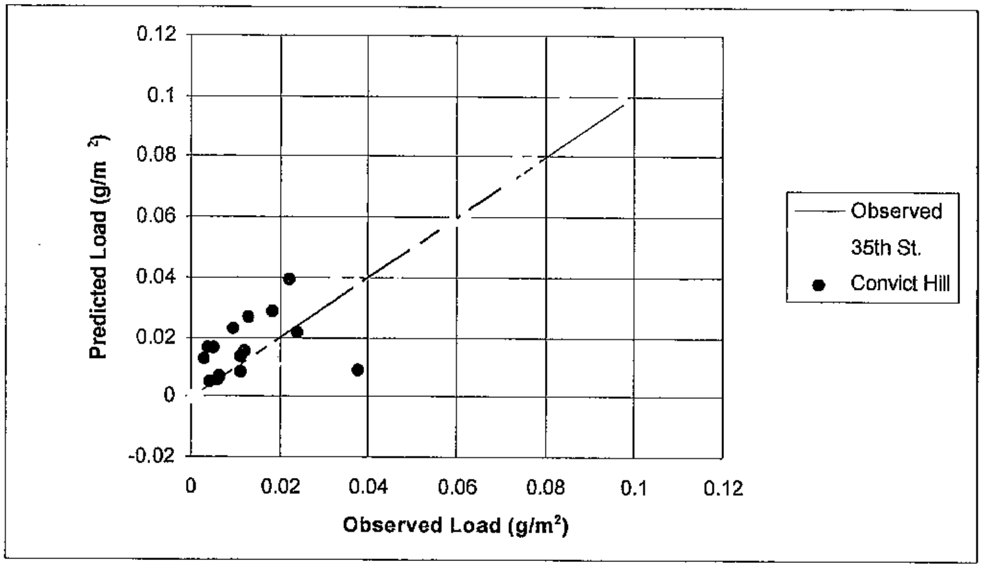


(a) Fit of Data from West 35th Street Site

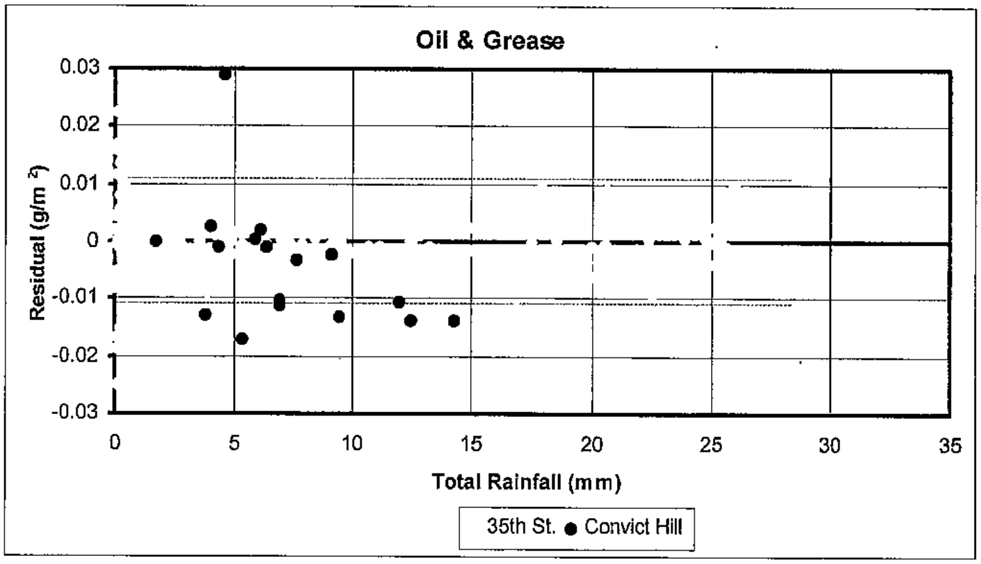


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-11 Oil and Grease Model Results

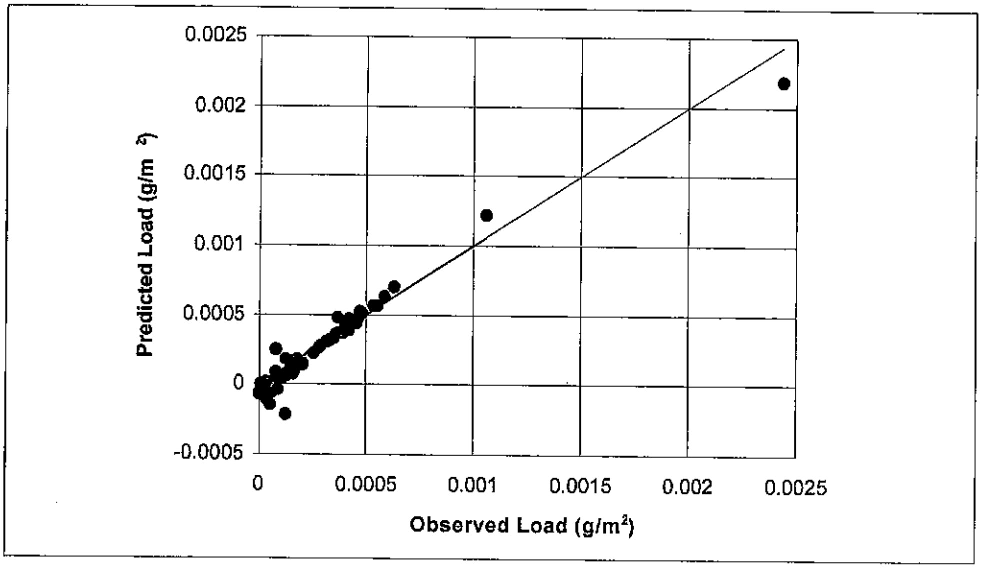


(a) Model Predictions at the Convict Hill Site

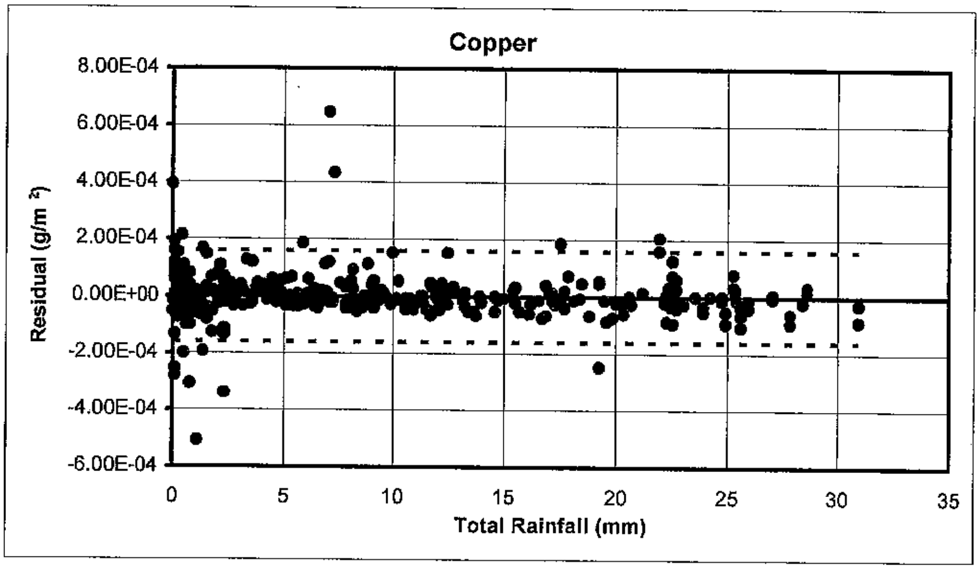


(b) Prediction Error vs. Total Rainfall

Figure I-12 Oil and Grease Model Predictions

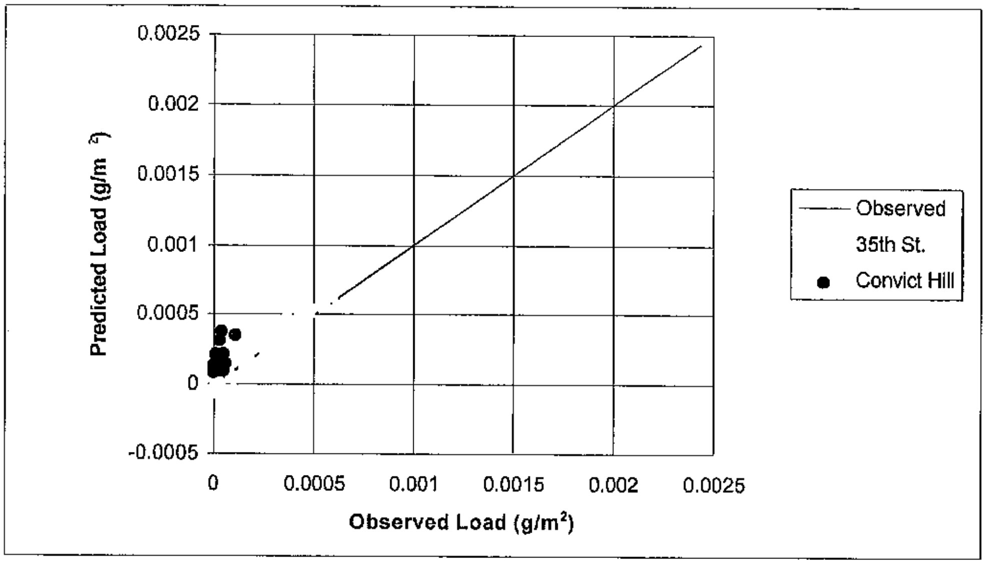


(a) Fit of Data from West 35th Street Site

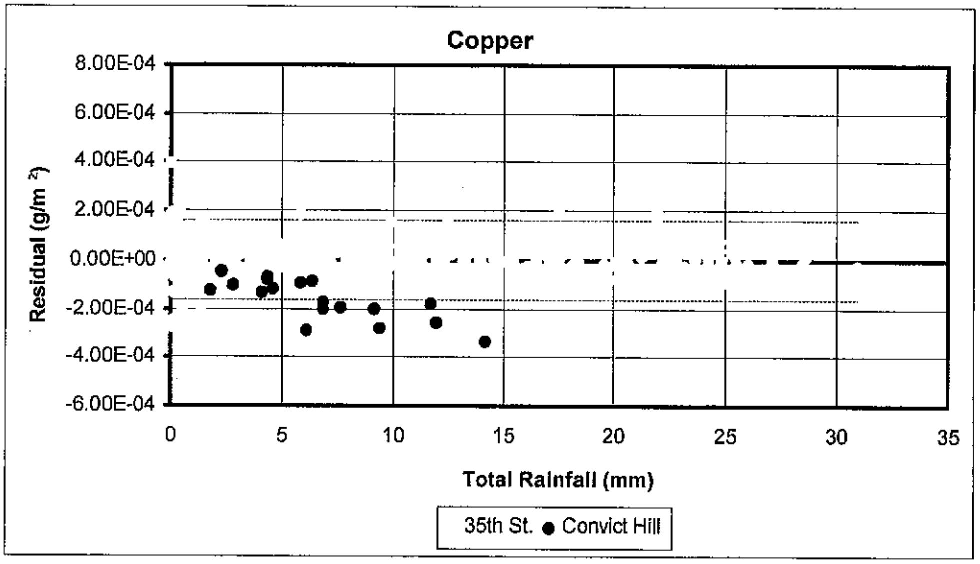


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-13 Copper Model Results

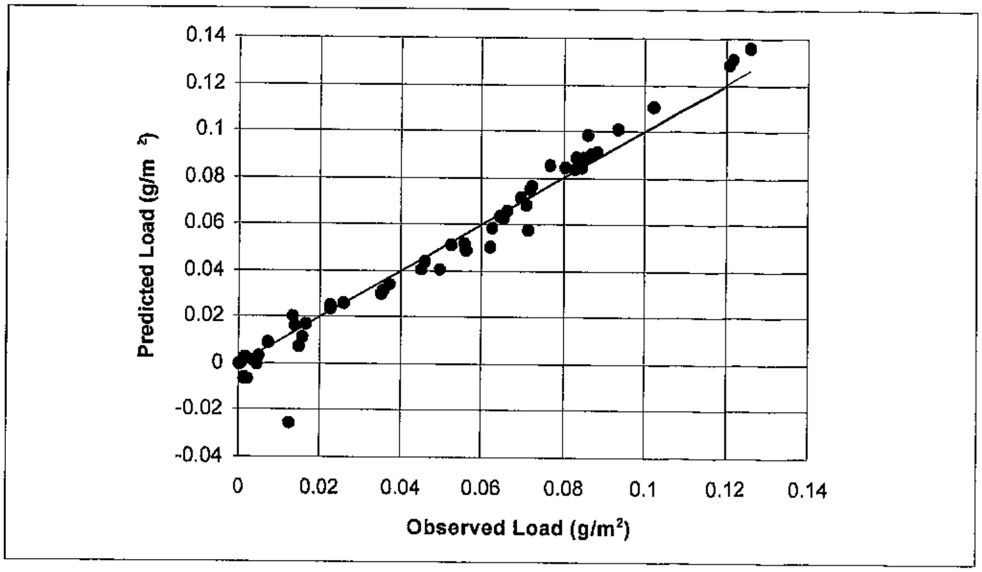


(a) Model Predictions at the Convict Hill Site

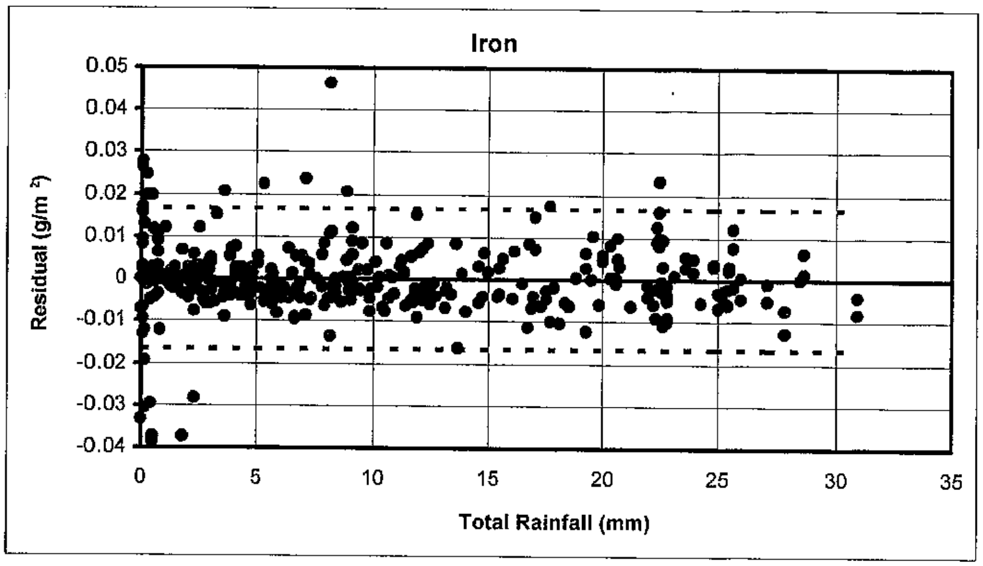


(b) Prediction Error vs. Total Rainfall

Figure I-14 Copper Model Predictions

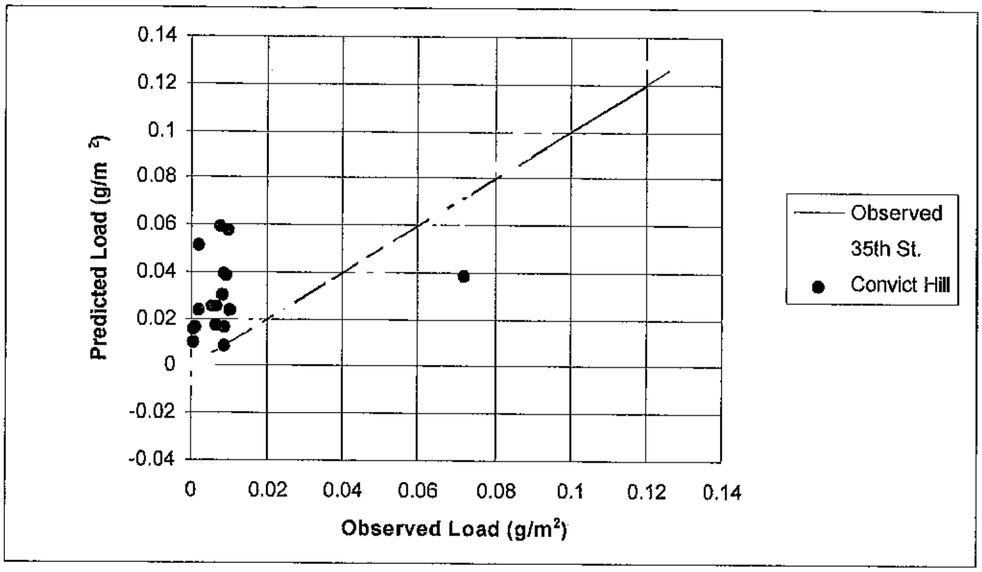


(a) Fit of Data from West 35th Street Site

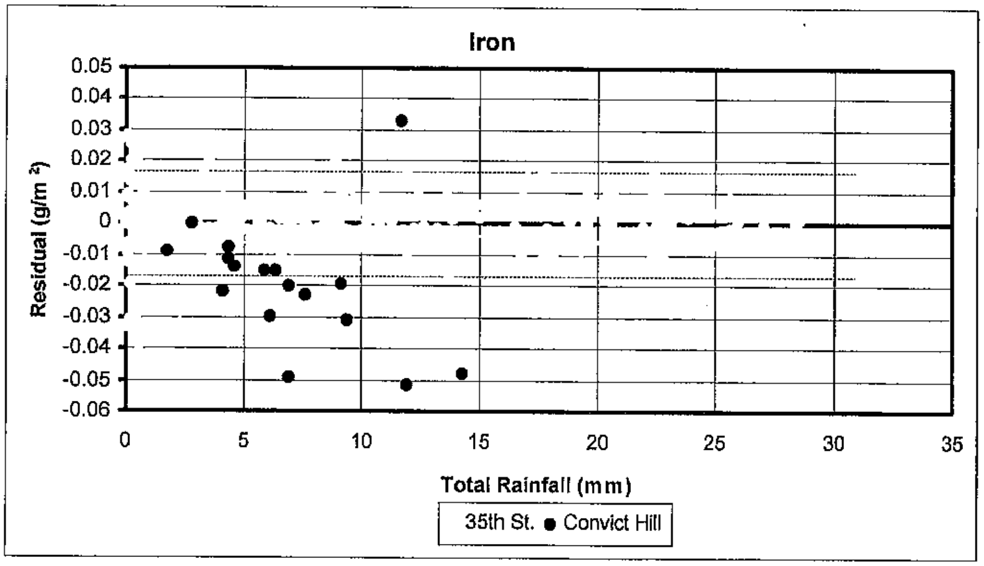


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-15 Iron Model Results

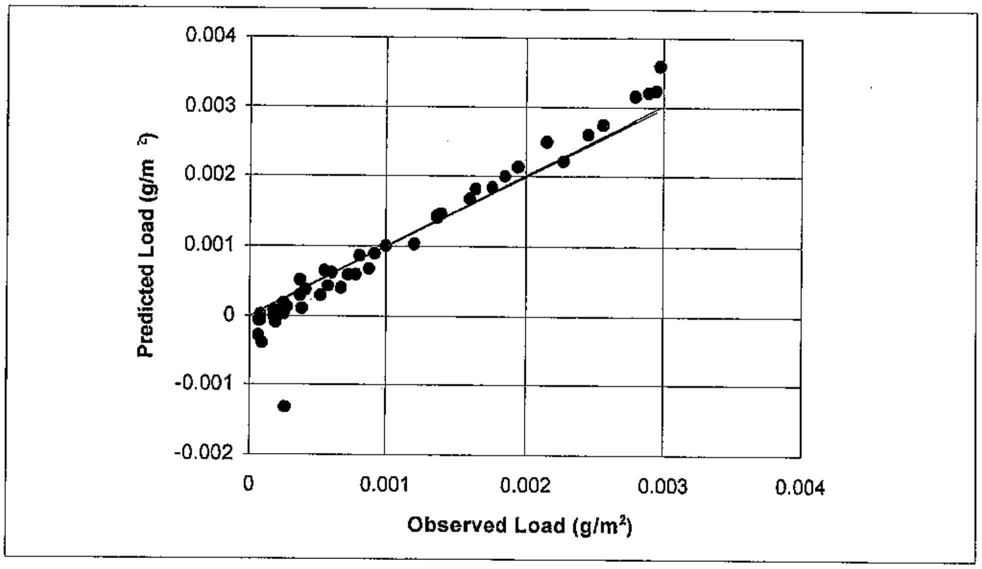


(a) Model Predictions at the Convict Hill Site

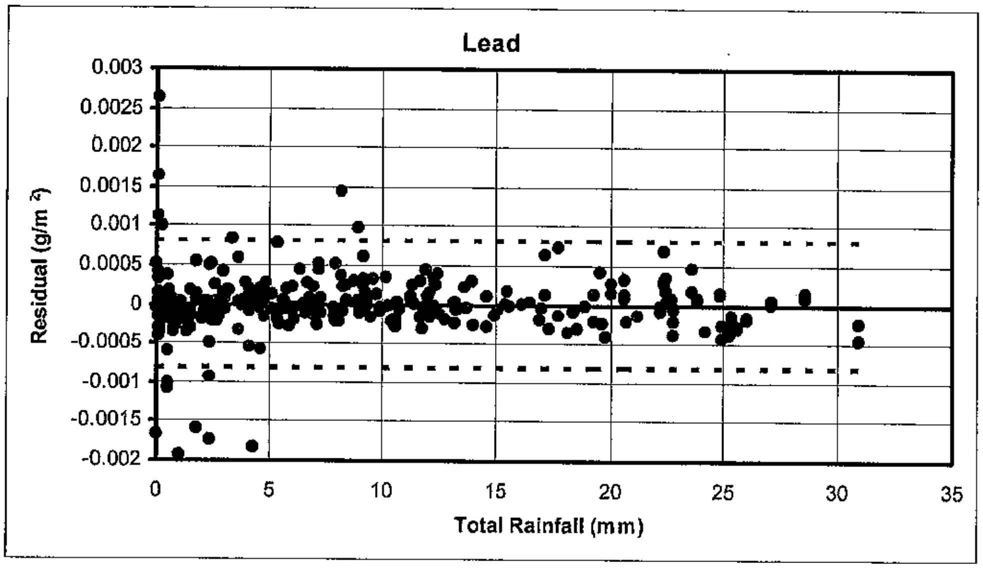


(b) Prediction Error vs. Total Rainfall

Figure I-16 Iron Model Predictions

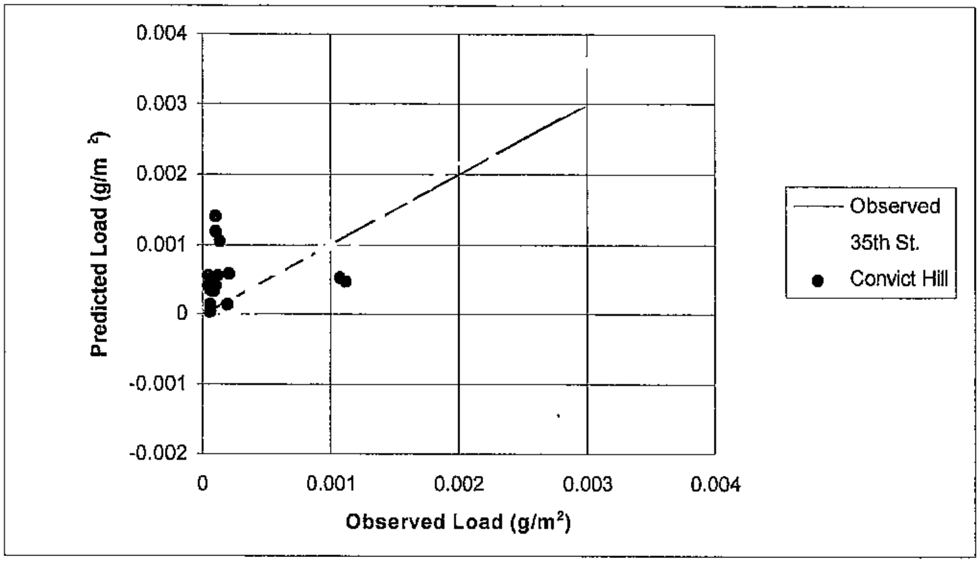


(a) Fit of Data from West 35th Street Site

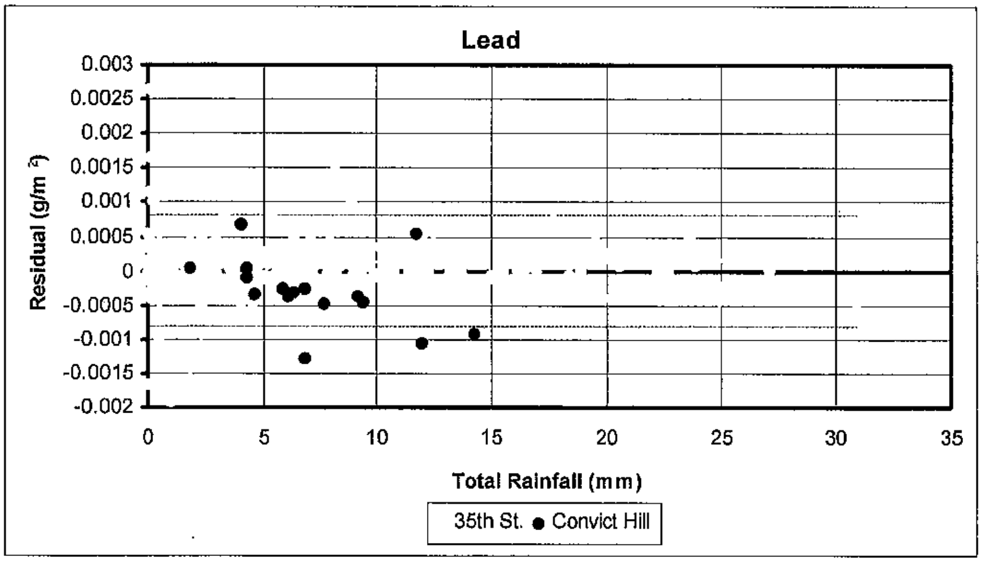


(b) Model Residuals vs. Total Rainfall (Dashed Lines Indicate ± 2 Std. Error)

Figure I-17 Lead Model Results



(a) Model Predictions at the Convict Hill Site



(b) Prediction Error vs. Total Rainfall

Figure I-18 Lead Model Predictions

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Marisa Weber

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To:	PUBCOMMENT-WQ; PUBCOMMENT-ELD; PUBCOMMENT-OCC2; PUBCOMMENT-OPIC
Subject:	FW: Public comment on Permit Number WQ0005011000
Attachments:	Final Comments to WQ0005011000_TXDOT_MS41.pdf

H

STIN
87204

From: jen.powis@thepowisfirm.com [mailto:jen.powis@thepowisfirm.com]
Sent: Friday, May 06, 2016 4:42 PM
To: DoNot Reply <donotreply@tceq.texas.gov>
Subject: Public comment on Permit Number WQ0005011000

REGULATED ENTY NAME TXDOT STATEWIDE MS4 PERMIT

RN NUMBER: RN106645369

PERMIT NUMBER: WQ0005011000

DOCKET NUMBER:

COUNTY: ARANSAS, ARCHER, BELL, BEXAR, BOWIE, BRAZORIA, BRAZOS, CALDWELL, CAMERON, CHAMBERS, CHEROKEE, COLLIN, COMAL, CORYELL, DALLAS, DENTON, ECTOR, EL PASO, ELLIS, FORT BEND, GALVESTON, GRAYSON, GREGG, GUADALUPE, HARDIN, HARRIS, HARRISON, HAYS, HIDALGO, JEFFERSON, JOHNSON, JONES, KAUFMAN, KENDALL, KLEBERG, LAMPASAS, LUBBOCK, MCLENNAN, MIDLAND, MONTGOMERY, NUECES, ORANGE, PARKER, POTTER, RANDALL, ROCKWALL, SAN PATRICIO, SMITH, TARRANT, TAYLOR, TOM GREEN, TRAVIS, UPSHUR, VICTORIA, WALLER, WEBB, WICHITA, WILLIAMSON, WISE

PRINCIPAL NAME: TEXAS DEPARTMENT OF TRANSPORTATION

CN NUMBER: CN600803456

FROM

NAME: Jen Powis

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ADDRESS: 2010 NORTH LOOP W Suite 275
HOUSTON TX 77018-8125

PHONE: 8324534404

FAX:

COMMENTS: Because Texas's Department of Transportation (TXDOT) has the most federal-aid roadways of any state in the nation, stormwater controls and pollution from those roadways are key concerns for our organizations. As such, we submit these comments regarding TXDOT's application and intent to obtain a state-wide NPDES permit from the Texas Commission on Environmental Quality (TCEQ) permit number WQ0005011000. This permit application seeks approval to discharge waters from TXDOT's Municipal Separate Storm Sewer System (MS4) region and is considered a non-traditional MS4 application. The following four (4) entities specifically request a contested case on this permit application: Galveston Baykeeper, Galveston Bay Foundation, Environment Texas and Save our Springs Alliance. The names and addresses for all four are below and all have dedicated resources and advocacy efforts for decades to improve Texas's water quality. Each member or staff listed below is directly affected through their recreational, scientific, educational, or vocational activities related to these waters across the state and are identified specifically for this purpose. These identified members should receive all future correspondence and will be adversely affected by this permit. Please see the attached comments and attachments for our full comments. Jen Powis Galveston Baykeeper 2010 North Loop West, Suite 275 Houston, Texas 77018 Kelly Davis Save our Springs Alliance 905 W. Oltorf St., Ste. A Austin, Texas 78704 Luke Metzger Environment Texas 815 Brazos St, Austin, TX 78701 Scott Jones Galveston Bay Foundation 17330 Hwy. 3, Webster, TX, 77598

May 6, 2016

Office of the Chief Clerk, MC-105
Texas Commission on Environmental Quality
P.O. Box 13087
Austin TX 78711-3087
By mail and electronically at: www.tceq.texas.gov/about/comments/html

RE: Permit No. WQ0005011000

To Whom It May Concern:

I write on behalf of the Galveston Baykeeper (GBK), a 501(c)(3) nonprofit organization working to ensure that every waterway in Texas is swimmable, fishable, and drinkable. GBK's core mission is to ensure the aquatic integrity of the Lower Galveston Bay watershed by focusing on the protection of wetlands and other critical habitats, advocating for adequate mitigation of lost wetland resources, and enforcing all aspects of compliance with the Clean Water Act. These comments are joined by multiple other non-profit organizations concerned with Texas's rivers, streams, bays and estuaries, including Galveston Bay Foundation, Environment Texas, Houston Audubon, Save Our Springs Alliance, and Turtle Island Restoration Network.

Because Texas's Department of Transportation (TXDOT) has the most federal-aid roadways of any state in the nation, stormwater controls and pollution from those roadways are key concerns for our organization. (Attachment 1, Federal Roadway Miles and Estimated Pollution). As such, we submit these comments regarding TXDOT's application and intent to obtain a state-wide NPDES permit from the Texas Commission on Environmental Quality (TCEQ) permit number WQ0005011000. This permit application seeks approval to discharge waters from TXDOT's Municipal Separate Storm Sewer System (MS4) region and is considered a non-traditional MS4 application.

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The Geographic Scope for this Permit Improperly Relieves TXDOT of Responsibility

While we applaud TXDOT for recognizing that the educational components of its MS4 must cover the entire state of Texas, we urge TCEQ to amend the geographic scope of the permit to accurately reflect TXDOT's intent, and understanding of how the MS4 permit could appropriately cover a long linear discharge area like that owned and operated by TXDOT.

In its Fact Sheet, TXDOT recognizes that it is a non-traditional MS4 and states "[t]here are no residences, businesses, or commercial and industrial facilities located within TXDOT's right of way – TXDOT regulated area . . . . Since transient users cover such a broad spectrum of society, it is important that TXDOT's educational MCM address as many people as possible with a high level of comprehension." Thus, implying accurately, that its educational program must cover the entire state of Texas. This is then reflected in its Stormwater Management Program (SWMP) when it describes TXDOT's Public Education and Outreach Goals and Objectives. (SWMP at 1.2.1). TXDOT's regulated area, however, is restricted in the definition section of the SWMP (and introductory paragraph of the permit itself) when TCEQ defines the "regulated area" to mean only "areas of the state TXDOT right of way (ROW) within the urbanized areas established by the 2000 and 2010 U.S. Census Bureau Urbanized Area Map – hereafter referred to as 'TxDOT's regulated area.'" (SWMP at 3). This is then directly referenced within the permit itself as the scope of the permit authorizes TXDOT to discharge stormwater "located within the TxDOT Right of Ways (ROW) throughout the State of Texas served by, or otherwise contributing to discharges to the MS4s owned or operated by the permittee, located within the urbanized areas (UAs) in the TxDOT districts listed in Attachment 1 via the regulated MS4 to various ditches and tributaries that eventually reach water bodies listed in Attachment 2." (Permit at 1). The Permit's Attachment 1 lists by zip code the urbanized areas within each TXDOT district, thus improperly limiting the geographic scope of this MS4 permit. This is demonstrated by the attached maps created using the zip codes from the draft permit, highlighting that by using zip codes, TXDOT has improperly avoided responsibility over its roadways within watersheds in the UA's. (Attachment 2, Maps by Zip Code from TXDOT's Permit Application, Attachment 1 including Austin, Houston, Ft. Worth, Dallas, and San Antonio, as well as the entire state). These maps demonstrate that articulating the area of responsibility by zip code fails to account for all the regulated areas within the UAs and improperly relieves TXDOT of responsibility for its roadways that likely see the most miles traveled.

More problematic for the undersigned entities, however, is that by limiting the permit area to the areas that have met the population requirements as an urbanized area, TXDOT has improperly avoided responsibility for its roadways throughout the rest of the state. TXDOT cannot have it both ways—it cannot ask the state for a state-wide permit seeking to cover it as a non-traditional linear municipal separate storm sewer system, but then at the same time, argue that the coverage should only apply to urbanized areas based on population.

This is particularly true as the regulations describing state department of transportations as "small" MS4s do not then limit the geographic scope of those permits by an analysis for urbanized areas based on population. In 40 C.F.R. §122.26(b)(16), a small municipal separate storm sewer system is defined to include "highways and other thoroughfares" as well as other non-traditional MS4s. This is important as it recognizes that certain facilities and governmental agencies, like hospitals or flood control districts would be covered under the proposed "phase II" program precisely because they may not meet urbanized area requirements based on population. Indeed, the federal Environmental Protection Agency's guidance for "small" MS4s recognizes that non-traditional MS4s are not limited by population, but are simply "non-traditional" and designated through regulation as "small" for the purposes of permitting with the National Pollutant Discharge Elimination System. (Attachment 3, EPA Fact Sheet at 1 "The Phase II Rule automatically covers on a nationwide basis all small MS4s located in 'urbanized areas' (UAs) . . . and on a case-by-case basis those small MS4s located outside of UAs that the NPDES permitting authority designates."). It is important to note that EPA's fact sheet on small MS4s also specifically states "[c]ommon pollutants include oil and grease from roadways . . . and carelessly discarded trash, such as cigarette butts, paper wrappers, and plastic bottles." All of which multiple studies have demonstrated occur in great quantities along roadways. (Attachment 4, 2013 Texas Litter Survey conducted for TXDOT).

But even if the "population" of a non-traditional MS4 should be considered, in the Houston-Galveston region alone, more than 170 million miles are traveled each day by the population and while not all of those miles are on TXDOT roadways, the number demonstrates that TXDOT's roads should be considered, in their own right, as a long linear pathway that has more than 100,000 visitors per day.[1] These transient users should be analogized to the population requirements of the permit and thus, TXDOT's permit would still have to cover all of its roadways throughout the state.

The narrowing of TXDOT's regulated area also directly contradicts with its Memorandum of Understanding between it and the predecessor agency of the TCEQ, the Texas Natural Resource Conservation Commission (TNRCC). Under 2.23(e)(ii)(I) of the Memorandum of Understanding with the Texas Natural Resource Conservation Commission entitled "Water Quality", "TXDOT project types to be coordinated with TNRCC include projects which may encroach upon threatened or impaired stream segments designated under §303(d) of the Clean Water Act and/or 5 miles upstream from the designated stream segment." This implies, that at the very least, the geographic scope for this permit would be 5 miles upstream from every stream segment designated as impaired under §303(d) of the Clean Water Act for the state of Texas. This is because TXDOT's first state-wide NPDES permit should not undermine an existing agreement requiring coordination and activity to ensure that all TXDOT programs support TCEQ's efforts on water quality. This demonstrates in part why the geographic scope must in some way be further defined to reflect TXDOT's true programmatic approach both voluntarily agreed to (in the case of state-wide education) or otherwise required by long-standing MOUs and legal authority.

The scope of its responsibility is incredibly important because TXDOT will only spend its budget dollars on areas defined in the permit. Yet, TXDOT has further attempted to limit its responsibility even within the urbanized areas by claiming that other MS4s (presumably the cities and counties) are "discharging" stormwater onto TXDOT's roadways and that TXDOT would have no responsibility to store, clean, or detain that water – instead only being required to alert the separate operator that its discharge is improper. (*See* Fact Sheet at 21 ("TXDOT can better protect the quality of its MS4 by providing increased inspection of third party outfalls. Thus, TXDOT's program to locate and eliminate illicit discharges and improper disposals to the MS4 will focus on third party outfalls."). This improperly shifts the responsibility of roadway pollution to no-man's land. Every municipality will argue that the TXDOT roadway is the ultimate entity discharging

[1] H-GAC's 2040 RTP System Overview, found at http://www.h-gac.com/taq/plan/2040/system.aspx and last visited on April 27, 2016.

(for example, a bridge)[2] and that such discharge should be covered by TXDOT's MS4. TXDOT appears to be arguing that such discharge would instead be the responsibility of the local municipality or county even though that county or city would have no ability to adopt structural controls or build green infrastructure within TXDOT's right of way in order to slow and clean the discharge. While the data TXDOT has collected may be interpreted as an adjacent MS4 operator illicitly discharging onto a Texas roadway, common sense also suggests that as it rains, water will – as water does – go towards a low point like a ditch next to a road built by TXDOT for precisely that reason. (*See e.g.*, SWMP at 2.2.2. ("Data collected during several permit terms supports the conclusion that the majority of illicit discharges to TXDOT's MS4 come from adjacent third-party MS4s.")). For TXDOT to claim that this is instead an illicit discharge from an adjacent MS4, rather than it being its responsibility to slow, clean, and detain the water as it enters its ditch or basin ignores the science behind how a watershed works.

This highlights a fundamental tension within the permit. TXDOT roads crisscross the state and roadway pollution is significant – from floatables to zinc to lead. Yet, TXDOT would rather be viewed as a mere conduit of water from other places, ignoring its role in creating the changes in the watershed and its design process to keep water off its roads. In *U.S. v. Washington State Dept. of Transportation,* a District Court in Washington found Washington's Department of Transportation liable for hazardous waste in waterways because the department had direct knowledge when designing its roadways—all of its roadways—that it seeks to direct stormwater runoff to the first available ditch, tributary or stream. 716 F. Supp. 2d 1009 (W.D. Wash. 2010). It found:

> It is undisputed that WSDOT designed the drainage systems at issue. Designing is an action directed to a specific purpose. The purpose was to discharge the highway runoff into the environment. WSDOT had knowledge that the runoff contained hazardous substances and there was an actual release of the hazardous substances into the environment. WSDOT argues that it did not have control of the hazardous substances. However, it did have control over how the collected runoff was disposed of. WSDOT did design the drainage system and, as noted by the U.S., WSDOT has the ability to redirect, contain, or treat its contaminated runoff.

Id. at 1015. TXDOT has direct knowledge that it designs roadways to collect water and shift it to man-made or natural ditches and drainages that lead to waters of the U.S. Yet, the current draft permit appears to shift the responsibility of TXDOT's design flaws to the surrounding communities. This is unfair and inappropriate. Instead, the language of the permit describing the geographic scope should be amended to say:

> TXDOT "is authorized to discharge from the Texas Department of Transportation (TxDOT) Municipal Storm Sewer System (MS4) (SIC 9621) including all regulated areas, except for any agricultural lands, located within the TxDOT Right of Ways (ROW)

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[2] Similarly, a majority of TXDOT bridges will span rivers and streams in the State of Texas that are waters of the United States. By ignoring these bridges, the permit ignores TXDOT's own design manual that requires the bridge to collect and discharge directly into a stream or river.

throughout the State of Texas served by or otherwise contributing to discharges to the MS4s owned or operated by the permittee."

If the geographic scope is not changed, the undersigned request TCEQ's analysis for why the geographic scope should be more limited than the existing MOU requiring coordination 5 miles upstream from every 303(d) listed stream segment. The undersigned also request TCEQ's analysis for why the geographic scope should be limited to UAs when TXDOT's own numbers show that every linear mile of TXDOT roadways has more than 100,000 "transient" users that should be analogous to population.

Stormwater discharges will result in exceedances of water quality standards for heavy metals

In Attachment 1 to TXDOT's application at page 10 in the paragraph entitled "Oil and Grease," TXDOT maintains that

> Oil and grease that may potentially discharge from the TXDOT MS4 does not originate from any roadway operations; the deposition of oil and grease (other than spills, which are mitigated separately as spill control/emergency response) comes from transient users of the roadway system.

Under 40 C.F.R. 123.35(b)(1)(i), TCEQ is required to develop criteria to evaluate how "storm water discharge results in *or has the potential to result in* exceedance of water quality standards, including impairment of designated uses or other significant water quality impacts, including habitat and biological impacts." [3] Based on a limited review of the following 4 stream segments which have been listed by TCEQ as impaired, it does not appear that this permit would limit the exceedances of heavy metals into impaired waters for these same heavy metals.

We reviewed the following 4 stream segments from TCEQ's 2014 Integrated Report listing impaired waters for the Clean Water Act's 303(d) list:

Segment ID	Name	Parameter
0402A_01	Black Cypress Bayou	copper in water
0402A_03	Black Cypress Bayou	copper in water
0608A_01	Beech Creek	copper in water
1407A_01	Clear Creek	Aluminum in water

[3] This provision regarding permitting small MS4, also states that any criteria discussed above must be applied to "any small MS4 located outside of an urbanized areas serving a jurisdiction with a population density of at least 1,000 people per square mile and a population of at least 10,000" implying again that limiting a "small" non-traditional MS4 only to "urbanized areas" is not appropriate.

1407A_01	Clear Creek	nickel in water
1407A_01	Clear Creek	zinc in water

Using published and well-accepted concentrations for toxic metals in roadway storm runoff and standard engineering methods to calculate average annual runoff volumes, we then estimated average annual loads for these metals from Texas highways within their watersheds. The results demonstrate that roadways are a significant contributor of these heavy metals within the watersheds of streams listed as impaired based on requirements of federal Clean Water Act.

Pollutant Loads	Inks Lake/Clear Creek	Big Cypress Bayou 0402A_01	Big Cypress Bayou 0402A_03	Beech Creek
Annual Avg. Rain (inches)[4]	28	51	49	57
Average Annual Runoff (cubic Feet/acre/year)	79,381	144,587	138,916	161,597
Copper Load (pounds/acre/year)	0.51	0.93	0.89	1.04
Nickel Load (pounds/acre/year)	49.12	89.47	85.96	100.00
Zinc Load (pounds/acre/year)	2.03	3.70	3.55	4.13
Highway Area (acres)	543	725	1,057	2,2278
Average Annual Load of Copper (pound/year)	277	674	944	2,365
Average Annual Load of Nickel (pound/year)	26,676	64,870	90,893	227,742
Average Annual Load of Zinc (pound/year)	1,103	2,681	3,757	9,413

The undersigned request TCEQ's documentation that supports the determination made by the Executive Director of the TCEQ that the permit and SWMP as implemented and detailed in the application will reduce the discharge of pollutants from the MS4, and in particular for stream segments already listed as impaired waters.

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[4] NOAA average precipitation map in GIS for 1981 through 2010.

TXDOT's assertion that oil, grease, and other heavy metals are not discharged from its MS4 but only from adjacent MS4s is inconsistent with three decades of science documenting these pollutants in roadway runoff. If TCEQ supports that assertion, please provide the documentation demonstrating that as well.

In addition, attached is a 1995 report from the Center for Research in Water Resources from The University of Texas at Austin entitled "An Evaluation of the Factors Affecting the Quality of Highway Runoff in the Austin, Texas Area" funded by the TXDOT. (Attachment 7). The Center for Research in Water Resources conducted a four (4) year investigation into the quality of the stormwater runoff from existing highways at the time in and near the recharge zone of the Barton Springs segment of the Edwards Aquifer. Even two decades ago, the engineering community and the Austin community, recognized that to mitigation of copper, lead, oil and grease, iron, zinc and nutrients required "runoff controls." Thus, again, TXDOT's new argument that pollutants of concern, like oil and grease, should be not be regulated under its stormwater permit is counter to established case law and the regulations adopted for non-traditional MS4s.

<u>Assuming Less than Primary Contact for Any Texas Stream Violates the Clean Water Act</u>

TXDOT's application improperly attempts to lower the Clean Water Act standards applied to streams not listed in its application by assuming multiple unclassified waterways in Texas have minimal aquatic life. It assumes that any

> (1) unclassified water body that is intermittent should be presumed only to support minimal aquatic life use with the associated dissolved oxygen criteria of 2.0 mg/L,
>
> (2) unclassified waterbodies that are intermittent with perennial pools should be presumed to support only minimal aquatic life use with the associated dissolved oxygen criteria of 3.0 mg/L, and
>
> (3) unclassified water bodies that are perennial shall be assigned the presumption of high aquatic life use with the associated dissolved oxygen criteria of 5.0 mg/L.

(TXDOT Fact Sheet at 69). First, any perennial water body in the state should be assumed under Texas Water Quality Standards to be primary contact I or at least an exceptional aquatic life standard. According to 30 TAC §307.7(b)(3)(A)(i), this would require as associated dissolved oxygen criteria of 6.0 mg/L. Second, any assumption that even intermittent streams do not support high aquatic life use mistakenly "declassifies" streams throughout the state that may never have been before classified under an existing NPDES. This is because with TXDOT's new "state-wide" approach, it is presumed that additional miles of roadways will now be covered by the NPDES program that were previously not covered by the multiple regional MS4 permits TXDOT had complied with before.[5] Thus, any assumption of a lower water quality standard—especially for perennial waterbodies—violates the Clean Water Act's anti-backsliding provisions.

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[5] This is true even as TXDOT attempts to forego responsibility for its entire linear system and only have this permit apply to the urbanized areas because those urbanized areas recently adopted in the 2010 Census may not have been covered by an existing phase II permit prior to 2015.

The following language in the permit should be amended because it appears the description above utilized the minimum dissolved oxygen contents required for these streams. Section 2.D.2 "Compliance with Water Quality Standards" in the permit should read:

> The requirements in this permit must provide compliance with the Texas Surface Water Quality Standards as specified in 30 TAC §§ 307.1-307.10. This includes the presumption that every unclassified water body that is perennial be assigned an exceptional aquatic life status and meet the mean and minimum dissolved oxygen criteria required by code. This also includes that any unclassified water body that is intermittent or intermittent with perennial pools be assigned an intermediate aquatic life category and meet the mean and minimum dissolved oxygen criteria required by code.

The reason the language should change is to prevent any backsliding or degradation of streams where the water quality currently is higher than presumed, and to meet the Clean Water Act's forward looking mission. This is required under the Clean Water Act. In 1987, two "anti-backsliding" provisions were added to the Clean Water Act, sections 402(o)(2) and 303 (d)(4)(B). [6,7] These provisions were added to further the purpose of the Clean Water Act and ensure that states and the federal government moved towards cleaning up the nation's waterways and that no backtracking on good stewardship would be permitted. It also codified the concept of the environmental rules and regulations being "forward" moving, in that the purpose was to continue to strive towards ensuring every waterway met drinking water standards. TCEQ and TXDOT would violate the Clean Water Act by creating a programmatic approach that implicitly allows more pollution in a variety of Texas streams. This is particularly true as TXDOT has not provided any evidence, nor supported any of these changes with a cumulative review of how the various watersheds would be impacted.

If this language is not amended, the undersigned requests TCEQ's analysis or case studies on unnamed streams that support adopting a minimum aquatic life standard instead of a more

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[6] Clean Water Act of 1972, 33 U.S.C. § 1342 402(o)(2). Section 402(o)(2) allows for less stringent water quality standards in six situations:

1) Where there have been material and substantial alterations or additions to the permitted facility which justify this relaxation;
2) Where good cause exists due to events beyond the permittee's control (e.g., Acts of God) and for which there is no reasonably available remedy;
3) Where the permittee has installed and properly operated and maintained required treatment facilities but still has been unable to meet the permit limitations (backsliding may only be allowed to the treatment levels actually achieved);
4) Where new information (other than revised regulations, guidance, or test methods) justifies backsliding from water quality-based permit limitations and other 301(b)(l)(C) limitations; and
5) & 6) technical mistakes and mistakes of law and permit modifications or variances (these exceptions do not apply to water quality based effluent limitations.)

[7] Clean Water Act of 1972, 33 U.S.C. § 1313 303 (d)(4)(B). (Section 303(d)(4)(B) provides that a permittee may backslide from a water quality-based effluent limitation where water quality meets or exceeds applicable water quality standards. Only two of these would be applicable to the TCEQ downgrade.)

robust standard and how that adoption does not violate the Clean Water Act's anti-backsliding provisions.

Additional Needs to Comply with Existing Regulations Regarding the Edwards Aquifer

As mentioned above, the current draft permit impermissibly narrows the geographic scope of TxDOT's regulated areas. In addition to leaving large swaths of land unregulated, the draft permit fails to cover areas within the recharge zone of the Barton Springs portion of the Edwards Aquifer, as the previous MS4 permit for the Austin District did. That permit, issued on October 7, 2008, specifically states that the MS4 includes areas "within rights-of-way owned and operated by the Texas Department of Transportation located within the corporate boundary and the five mile extra-territorial jurisdiction (ETJ) of the City of Austin, **within all rights-of-way located outside of the corporate boundary of the City of Austin but within the recharge zone of the Barton Springs portion of the Edwards Aquifer,** and within additional rights-of-way that are located within the Austin, Texas urbanized area, in Hays, Travis, and Williamson Counties, Texas." (emphasis added).

Thus, the 2008 MS4 covered the Barton Springs portion of the Edwards Aquifer on a watershed basis, ensuring coordinated regulation of pollutants entering the Aquifer. By contrast, the current draft permit only covers MS4s located "within the TxDOT right-of-way within the urbanized areas established by the 2000 and 2010 U.S. Census Bureau Urbanized Area Maps," and lists the cities and corresponding zip codes in the Austin District, but not including the non-urban portions of the recharge zone.

To ensure the new permit covers the same permits as the past permit, as well as compliance with the Edwards Aquifer Rules, the draft permit should at least include those areas within the recharge zone of the Barton Springs portion of the Edwards Aquifer. Should TCEQ refuse to adopt the above proposed language providing for a statewide geographic scope, TCEQ should at least revise the draft permit to include the italicized language from the 2008 Austin MS4 permit.

1. Endangered Species

The Fact Sheet and Executive Director's Preliminary Decision, at page 49, identifies stream segments and endangered species within those stream segments for urbanized areas to be covered by the permit. For the Austin District, several endangered species are listed as occurring in the Colorado River Basin (1400), thus requiring EPA review and potential consultation with the U.S. Fish and Wildlife Service (FWS). However, the list fails to include three salamander species that have recently been listed as federally endangered or threatened. These species are:

- Austin blind salamander, *Eurycea waterlooensis*
- Jollyville Plateau salamander, *Eurycea tonkawae*
- Georgetown salamander, *Eurycea naufragia*

The listing of the Austin blind and Jollyville Plateau salamanders thoroughly discusses how highway construction and operation threaten the survival of the salamander. *Determination of Endangered Species Status for the Austin Blind Salamander and Threatened Species Status for the*

Jollyville Plateau Salamander Throughout Their Ranges, U.S. Fish & Wildlife Service, 78 Fed. Reg. 51,278, 51,302-51,307 (Aug. 20, 2013).[8]

The draft permit should be amended to include the Austin blind salamander, Jollyville Plateau salamander, and Georgetown salamander as species occurring in the Colorado River Basin (1400) of the Austin District.

2. *Edwards Aquifer Protection Program*

The draft permit and Fact Sheet only briefly mention the Edwards Aquifer Rules, asserting that TxDOT must comply with these rules. The section on Edwards Aquifer Rules should be revised and expanded to include specific performance measures that are required of TxDOT under these rules. At a minimum, the permit should include the language regarding Best Management Practices and Measurable Goals under the Edwards Aquifer Rules discussion contained in TxDOT's MS4 application. Requiring these measures in the draft permit does not impose an undue burden, because TxDOT has agreed to abide by these terms, but including them in the draft permit ensures that the terms are legally binding[9] and can help inform future permit renewals.

3. *Spill Prevention and Response*

The draft permit, at page 25, includes "Additional Requirements for Previous TxDOT-Austin District Phase I Permit (WQ0004645000)" and sets out Spill Prevention and Response requirements. Among other things, TXDOT is required to, in coordination with FWS, identify potential projects to prevent spills from entering the Edwards Aquifer, and report any coordination of projects identified in an annual report. Likewise, the 2008 Austin District MS4 Permit required identification of such projects, but additionally required TXDOT to "submit an implementation schedule for those projects identified, not to exceed Year Five of the permit term." There are likely still many projects that need to be implemented, especially given ongoing road construction, and the draft permit should include specific responsibilities for TXDOT to implement spill-prevention programs. Therefore, the draft permit Part III, section B.2 (j)(1) should be revised to include the requirement that TXDOT submit an implementation schedule for projects identified with the FWS as potential projects to prevent spills from entering the aquifer.

<u>TCEQ Should Examine the Cumulative Effect in the Watershed and require more for Redevelopment</u>

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[8] See also *Determination of Threatened Species Status for the Georgetown Salamander and Salado Salamander Throughout Their Ranges*; U.S. Fish & Wild. Serv., 79 FR 10,235 (Mar. 26, 2014).

[9] While the undersigned believe the SWMP are legally enforceable, similar to the permit, the reality is that the permit will be examined more frequently when determining water quality compliance measures and thus mirroring the language in the permit places no undue burden on TXDOT.

TXDOT manages the most highway miles of any state in the nation (Attachment 1). Yet, the draft permit fails to correct past mistakes in roadway siting, or design, by not requiring redevelopment to examine the cumulative effect. This draft permit also purports to begin moving towards a watershed approach, yet does not require numeric benchmarking to ensure that a watershed approach is done cooperatively with adjacent permittees. In EPA's August 2007, Watershed Based NPDES Permitting Guidance, EPA attempted to showcase why a watershed approach would be particularly helpful, whereas here, there are multiple point sources contributing high volumes of run-off from impermeable surfaces:

> To understand the first issue, the presence or absence of far-field effects, it is important to consider the difference between localized effects and far-field effects. Localized effects, or nearfield effects, are impacts that are evident within a smaller, more immediate area close to the source of the pollutant or stressor. On the other hand, far-field effects are those impacts felt in a wider area and where there potentially are cumulative impacts from multiple sources. In most cases one could address pollutants with localized effects (e.g., acute and chronic effects of pollutants such as cyanide or chlorine) by controlling and monitoring them through individual permits or nonpoint source controls that apply effluent limitations or practices reflecting individual controls designed to ensure attainment of water quality standards in the immediate Watershed-based Permitting Technical Guidance vicinity of the discharge. Where several point source dischargers experience problems with localized effects of specific pollutants, however, a watershed permitting approach might be helpful. For instance, a monitoring consortium could be established to quantify pollutant sources, assess the impacts of pollutant discharges, and develop site-specific water quality criteria for the waterbody.[10]

Again, a cumulative approach for redevelopment should require TXDOT to re-examine pre-existing siting issues and address the issue of water quality from a watershed perspective (not just the incremental 1 acre or 5 acre redeveloped site).

<u>TCEQ Should Require Wet Weather Testing, if not Numeric Limits</u>

TXDOT's own hydraulic design manual has computed the discharge rates for stormwater and various pollutants. By TXDOT district, a computation based on roadway miles is possible to benchmark the amount of pollution directly flowing into the state's waters by the stormwater run-off from TXDOT roads. (Attachment 6). As such, the lack of wet weather testing to benchmark these discharge rates, coupled with the lack of numeric limits within the permit for discharge rates, cannot be said to "reduce the discharge of pollutants from the MS4," nor does there seem to be support for the idea that the discharges into waters already impaired by sediment, zinc, phosphorous or nitrogen would be eliminated by this permit and corresponding SWMP. Fact Sheet at 17. The SWMP has no numeric limits. It has no benchmarks for reduction in pollution. It has

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[10] The guidance document can be found here: https://www3.epa.gov/npdes/pubs/watershed_techguidance.pdf and was last viewed on April 27, 2016.

no description of impaired waters for criteria pollutants and how those waters would be further protected by TXDOT. It is not enough to maintain the status quo – this new permit application must work to address pre-existing conditions.

While the undersigned applauds TXDOT for implementing an Advanced Outfall Tracking System prior to this permit, it appears that TXDOT has already begun this work and mapped a significant portion of its regulated area. Thus, permitting it to take an additional 5 years to complete the mapping process only delays advancement towards implementing better control measures regarding those outfalls to improve water quality.

The undersigned request a copy of the hydrologic models and research performed by TCEQ in determining that the draft permit, with SWMP, would not further degrade impaired waters in the Houston District.

In addition, if only dry weather testing is required, then at the very least adequate benchmarking must be required. In both the permit and SWMP, TXDOT recites that in lieu of wet weather monitoring it will "evaluate the watershed using existing stormwater characterization data collected by" a variety of regional quasi-governmental entities. Yet, EPA's guidance document on implementing a watershed approach for a permit requires instead, benchmarking for improvement on, for example, aquatic life by examining the "percentage of river miles and lake acres identified as having a fish consumption advisory in 2002 for which water and sediment quality have improved and allow for increased consumption of safe fish." Or by examining within a watershed, the "percent of days of the beach season that beaches monitored by beach safety programs will be open and safe for swimming."[11] Thus, to allow a watershed approach in lieu of wet weather monitoring but to not require adequate benchmarking regarding the watershed approach appears to violate the Clean Water Act's requirement to monitor under 40 C.F.R. § 122.26(d)(2)(i) (Adequate Legal Authority) because the applicant does not have the ability by ordinance or contract to ensure the other entities continue collecting data. Moreover, it is unclear why TXDOT's "analysis and interpretation of this data" to be submitted to TCEQ should act to meet the primary objectives of the permitting program to monitor and benchmark, when other MS4 operators will presumably be charged with paying for and analyzing that same data. (SWMP at 2.6 (In lieu Stormwater Monitoring Program Implementation Overview)).

The following language in the permit should be added:

> Section 2(g)(1) should be amended to state:
> Minimum Investigation Requirements – The permittee shall inspect no less than 25% of the TXDOT MS4 regulated area yearly including inspection for dry weather discharges per year to ensure an adequate monitoring and IDDE program. Such program to inspect may correspond with the prior requirements under Section 2(i)(4) (Identification of Priority Areas) or, as feasible, be in addition to such other requirements.

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[11] EPA Guidance document entitled Watershed-Based National Pollutant Discharge Permitting Technical Guidance EPA 833-B-07-004 August 2007 at Exhibit 1.6 found at https://www3.epa.gov/npdes/pubs/watershed_techguidance.pdf and last viewed on 4/22/16.

Then the prior (g)(1) should be renamed: "Requirements for Known Illicit Discharges." This language is directly taken from TXDOT's proposed SWMP, attachment 3 entitled measurable goals for MCMs in the Stormwater Management Program. The reason it is more appropriately placed in the permit is because (1) the SWMP is only proposed, (2) the SWMP is easily amended without public input, and (3) the SWMP provides an alternative that eliminates a yearly requirement to detect or inspect a certain amount of regulated area, thus providing too much flexibility for TXDOT staff to lower the percentage of road miles actually inspected. This is especially important as TXDOT's SWMP also states that it will "screen all areas of the MS4 at least once during the permit term" thus implying that at the very least 20-25% of every road mile will be inspected each year under this 5 year permit. This type of minimum testing requirements are found in other MS4 permits for departments of transportations and because it does not seem to be any more burdensome to include it in the permit, the language should be amended. (For example, Arizona's Department of Transportation must inspect half of its major outfalls each year. ADOT Permit; Section 3.2.3.2.d.).

Floatables

Finally, language similar to that found in the regional permits that TXDOT is rolling off of related to floatables should be included as it requires a program to actually reduce the discharge rate of floatables in the MS4 by utilizing source controls or structural controls. These types of facilities are directly relevant to TXDOT and should be required by TXDOT as its users – the transient users traveling along the roadways throughout Texas—are direct contributors to litter, and thus, pollution in the state's waters. The language can mirror that found, for example, in Corpus Christi's permit number WQ0004200000 when it describes the storm water management program.

> III.B.6(c): Floatables The permittees shall ensure the implementation of a program to reduce the discharge of floatables (e.g. litter and other human generated solid refuse) into the MS4 which shall include source controls and where necessary structural controls and other appropriate controls

In support, attached is the most recent litter survey conducted by TXDOT and demonstrating that all parties are only too aware of the problem Texas has with floatables and litter from roadways. Should TXDOT be permitted to completely ignore this issue, it places an unmanageable burden on the counties throughout the state and improperly shifts the financial burden from the entity that created the pollution source (the roadway) to cities and counties, and ultimately, Texas's rivers and streams.

Summary

We urge TCEQ to consider adopting the changes recommended above to ensure that Texas's rivers and streams are not only protected but improved with this new state-wide permit.

Jen Powis ✓ Galveston Baykeeper	Luke Metzger ✓ Environment Texas	✓ Scott Jones Galveston Bay Foundation

2010 North Loop West, Suite 275 Houston, Texas 77018	815 Brazos St, Austin, TX 78701	17330 Hwy. 3, Webster, TX, 77598
Kelly Davis Save our Springs Alliance 905 W. Oltorf St., Ste. A Austin, Texas 78704	Helen Drummond Houston Audubon 440 Wilchester Blvd Houston, Texas 77079	Joanie Steinhaus Turtle Island Restoration Network

Marisa Weber

From: PUBCOMMENT-OCC
Sent: Friday, May 20, 2016 1:56 PM
To: PUBCOMMENT-WQ; PUBCOMMENT-ELD; PUBCOMMENT-OCC2; PUBCOMMENT-OPIC
Subject: FW: Galveston Bay Foundation comments on TXDOT MS4 permit application
Attachments: Letter to EPA and TCEQ on TXDOT MS4 permit language_GBF.pdf

For WQ0005011000

STW
87204

From: Scott Jones [mailto:sjones@galvbay.org]
Sent: Friday, August 01, 2014 10:44 AM
To: larsen.brent@epa.gov; Hanne Nielsen <hanne.nielsen@tceq.texas.gov>
Cc: Stokes, Bob <bstokes@galvbay.org>
Subject: Galveston Bay Foundation comments on TXDOT MS4 permit application

Dear Mr. Larsen and Ms. Nielsen-

Please find attached the comments of the Galveston Bay Foundation on Texas Department of Transportation's MS4 application.

We hope that you will consider them as you develop their permit. Please contact me should you have questions.

Sincerely-

Scott A. Jones
Director of Advocacy
Galveston Bay Foundation
17330 Highway 3, Webster, TX 77598
281-332-3381 x209 (direct)
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MW

July 30, 2014

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Re: The Texas Department of Transportation's Application for State-wide MS4 Stormwater permit—specific requests for inclusion

Dear Mr. Larsen and Ms. Nielsen,

The Galveston Bay Foundation (GBF), a 501(c)(3) organization founded in 1987 whose mission is to preserve, protect and enhance Galveston Bay for present users and for posterity, is writing you today to request the inclusion of stronger objective and numeric criteria for the Texas Department of Transportation's (TXDOT) application for a state-wide MS4 permit.

Non-point source runoff pollution negatively affects the vast majority of the tributaries that feed Galveston Bay. In addition, litter, including countless plastic, Styrofoam and aluminum items, blight Galveston Bay, its network tributary bayous and creeks, and our local Gulf of Mexico beaches. Not only is this litter unsightly, thus diminishing the appeal of our area to potential tourists and others who would spend money and support our local economy, it is harmful to our fish and wildlife. Litter clogs the nets of our bay's commercial fishermen. Further, rafts of litter clog our culverts, ditches, creeks, and bayous thus increasing the risk of flooding to area residents. Thus, we submit these specific recommendations regarding TXDOT's application.

To begin, in conjunction with the Houston Parks Board, we have conducted a land use study using available GIS information for Harris County and have determined that roads – all roads – account for between 22% and 42% of all impervious cover[1] for the entire county. Runoff from roads and highways is one of the biggest threats to water quality in our region. Thus, we strongly believe that more

[1] These figures were calculated by examining the National Oceanic and Atmospheric Administration's (NOAA) land classification system for the county, overlaid with publicly available GIS road data. The total land use was then calculated utilizing an average road width of between 30 feet (average two lane road) and 60 feet (average 4 lane road). Thus, roads make up a significant portion of the point source stormwater runoff for the county.

stringent stormwater management practices must be required for TXDOT in order to improve water quality in Texas's waters, including our local tributary streams and bayous and Galveston Bay.

GBF seeks the following inclusions in TXDOT's state-wide MS4 permit:

1. Objective numeric performance standards that mimic pre-development hydrology, and in particular, GBF submits that the 95th percentile storm should be managed on-site and requests that a specific date certain for relevant design manuals to be amended be included;
2. Specific green infrastructure requirements, such as additional detention beyond the minimum requirements, for all roadway development or redevelopment and a requirement that bioretention be evaluated for all repair, redevelopment or development work at an acre or more;
3. A specific numeric limit or ceiling on the amount of effective impervious area for all development or redevelopment;
4. That all funds related to the public education component of the permit be indexed by one of the following criteria:
   a. Water quality impairments for trash and other pollutants
   b. Population
   c. Regional roadway mileage
5. And finally, that an enforceable schedule for street sweeping be added to the permit language itself because all roads account for between 22% and 42% of impervious cover.

GBF strongly urges EPA to require low impact development criteria with an emphasis on green infrastructure and more on-site storage as both have been shown to have positive water quality and flood mitigation benefits.

Because there is no opportunity to comment on the proposed permit, we ask that these comments be added to the administrative record and considered during the drafting process.

Thank you for considering these comments. Please contact me at 281-332-3381 x209 or sjones@galvbay.org should you have any questions.

Sincerely,

Scott A. Jones
Director of Advocacy