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16. Abstract <p>This report summarizes a four-year study on the impacts of highway construction and operation on water quality and quantity of stormwater runoff. Monitoring of water quality in one of the creeks below a highway construction site indicates that even an extensive system of temporary controls is not sufficient to prevent large amounts of suspended sediment from entering receiving waters. Parameters commonly used to characterize geotextile fabrics were found to have little relevance for estimating their sediment removal abilities or hydraulic characteristics under field conditions.</p> <p>The quality of highway runoff was determined by monitoring the quality of storm water runoff from three sites along the MoPac Expressway in Austin, Texas. The quality of the runoff was similar to that reported in other highway studies across the United States. The concentrations of pollutants appeared to be affected by changes in traffic volume, rainfall intensity, and other factors.</p> <p>A computer model was developed that will predict the quality of runoff from operating highways in the Austin, Texas, area. The majority of the variation observed in highway stormwater loading could be explained by causal variables measured during the storm event, the antecedent dry period, and the previous storm event.</p> <p>Structural controls built on the new highway segments to protect the Edwards Aquifer from stormwater runoff have not performed effectively. The hydraulic performance of the vertical sand filters has been uneven, resulting in little apparent improvement in runoff quality. A grassy swale was found to be effective for reducing runoff volumes and pollutant concentrations.</p>					
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**WATER QUALITY AND QUANTITY IMPACTS OF HIGHWAY CONSTRUCTION
AND OPERATION: SUMMARY AND CONCLUSIONS**

by

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Research Report Number 1943-7F

Research Project 7-1943

Water Quantity and Quality Impacts Assessment of Highway Construction
in the Austin, Texas, Area

conducted for the

Texas Department of Transportation

by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research

THE UNIVERSITY OF TEXAS AT AUSTIN

March 1996

IMPLEMENTATION STATEMENT

The data collected during this study can be used to estimate the impacts of highway construction and operation on the quality of receiving waters. The evaluation of techniques for the control of sediment during construction will allow the Texas Department of Transportation to select the most cost-effective procedures and to estimate the sediment removal efficiency of several of the most commonly used controls. The information on the quality of highway stormwater runoff can be used to predict the impacts of existing and proposed highways on water quality in environmentally sensitive areas, and to select the appropriate mitigation technology where necessary.

Prepared in cooperation with the Texas Department of Transportation.

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DISCLAIMERS

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SUMMARY

This report summarizes a four-year study on the impacts of highway construction and operation on water quality and quantity of stormwater runoff. Monitoring of water quality in one of the creeks below a highway construction site indicates that even an extensive system of temporary controls is not sufficient to prevent large amounts of suspended sediment from entering receiving waters. Parameters commonly used to characterize geotextile fabrics were found to have little relevance for estimating their sediment removal abilities or hydraulic characteristics under field conditions.

The quality of highway runoff was determined by monitoring the quality of storm water runoff from three sites along the MoPac Expressway in Austin, Texas. The quality of the runoff was similar to that reported in other highway studies across the United States. The concentrations of pollutants appeared to be affected by changes in traffic volume, rainfall intensity, and other factors.

A computer model was developed that will predict the quality of runoff from operating highways in the Austin, Texas, area. The majority of the variation observed in highway stormwater loading could be explained by causal variables measured during the storm event, the antecedent dry period, and the previous storm event.

Structural controls built on the new highway segments to protect the Edwards Aquifer from stormwater runoff have not performed effectively. The hydraulic performance of the vertical sand filters has been uneven, resulting in little apparent improvement in runoff quality. A grassy swale was found to be effective for reducing runoff volumes and pollutant concentrations.

1. INTRODUCTION

Environmental regulatory agencies recently have focused attention on nonpoint sources of pollution such as urban and highway runoff. Enforcement of the National Pollutant Discharge Elimination System (NPDES) regulations regarding stormwater runoff by the U.S. Environmental Protection Agency (EPA) is evidence of this effort. In Texas, the Barton Springs/Edwards Aquifer Conservation District (District) and several environmentally oriented organizations became concerned about the potential for contamination of the Edwards aquifer as a result of proposed highway construction activities over the recharge zone of the aquifer. The proposed highway construction corridor crosses and parallels three creeks and overlies a portion of the recharge zone of the Edwards aquifer which feeds Barton Springs. This concern resulted in litigation involving the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHA), which temporarily halted construction activities on the project site.

Prior to this halt in construction, the District and TxDOT negotiated a settlement, the Consent Decree, which was approved by the U. S. District Court. The District removed itself from the litigation and TxDOT began implementing certain actions and practices to answer the concerns of the District. The cooperative efforts of the two agencies have been effective in preventing and reducing pollution from both point and nonpoint sources during roadway construction activities. Many improvements and innovations have been developed for structural and non-structural Best Management Practices (BMPs) which have gained local, state, and national recognition as leaders in the field of pollution prevention and mitigation for both agencies.

The Consent Decree also ordered a study of the water quality and quantity of highway runoff and the effects of highway construction and operation on the quality of receiving waters. TxDOT and the District agreed to have the study conducted by the Center for Research in Water Resources (CRWR) at The University of Texas at Austin. CRWR, TxDOT and the District developed the objectives and scope of the study and identified specific project tasks. A technical review committee consisting of three representatives of the District, two from TxDOT, and two from the CRWR met quarterly to review activities and progress reports. The committee provided input and guidance to the CRWR project personnel dealing with the overall study, its procedures, equipment, and future work efforts.

The construction of the new highway allowed the evaluation of the hydrologic changes to creeks in the recharge zone. Effectiveness of temporary runoff control

measures were evaluated in the field during the construction process. In addition, field-scale laboratory experiments were conducted to determine the hydraulic properties and sediment removal effectiveness of silt fences under realistic operating conditions.

The quality of highway stormwater runoff was measured at three sites along an existing segment of highway to determine runoff characteristics, the probable impact of the new highway segments, and to identify treatment systems to mitigate adverse water quality impacts. A rainfall simulator was operated along a section of active highway to determine the factors which affect the quality of highway runoff. The effectiveness of sand and other media for filtration of runoff was evaluated in laboratory experiments and the performance of permanent runoff treatment systems was monitored after completion of the highway. A comprehensive review of literature pertaining to highway runoff was also performed and reported in CRWR Technical Report # 239 (Barrett et al., 1995a) and Center for Transportation Technical Report #1943-1.

2. TEMPORARY EROSION CONTROLS: USE AND EFFECTIVENESS

Most of the more important environmental impacts of highway construction results from erosion of topsoil during storms. Two strategies for minimizing these impacts of stormwater runoff from construction sites are erosion control and sediment control. Erosion control is a source management method and is usually accomplished with slope coverings. Techniques for slope stabilization include temporary and permanent vegetation, plastic sheeting, straw and wood fiber mulches, matting, netting, chemical stabilizers, or some combination of the above. Sediment control may be considered as the second line of defense. Sedimentation ponds, silt fences, and rock berms commonly are used for sediment control once erosion has occurred. These devices are designed to diminish solids loading through short term retention and/or velocity reduction and filtration.

An inventory of temporary runoff controls installed on TxDOT construction sites indicated that rock berms and silt fences were the most commonly used erosion and sediment controls on construction sites. Rock berms were used to treat the drainage from 53% of the area of the six construction sites in the study area. Silt fences and sedimentation ponds were the next most common runoff controls, treating the runoff from 23% and 22% of the total area, respectively. Sediment ponds were the most inexpensive control on a cost per area basis and were used more frequently in the earlier stages of construction. Erosion control blankets were the most expensive controls and tended to be used in the later phases of construction.

Field evaluation of the efficiency of silt fences in removing sediment carried in runoff from highway construction sites, showed that the median removal resulting from filtration was 0%. Additional removal occurred as a result of particle settling, but was not quantified in the field portion of the study. The median concentration of solids discharged from the silt fence controls was approximately 500 mg/L. Geotextile silt fences also proved to be ineffective in reducing turbidity. The median turbidity reductions for the sites monitored was about 2%. The average pore size of geotextile fabrics may exceed 600 μm , which is considerably larger than the maximum size of silt and clay particles (75 μm) which cause turbidity. Monitoring of a single rock berm also showed negligible Total Suspended Solids (TSS) removal.

The poor filtration performance of the geotextile fabrics alone indicates the disparity between test efficiency and actual field performance. The bulk of the difference could be attributed to an unrealistic particle size distribution in the slurry mixtures of previous laboratory studies. Silt and clay size particles were the primary constituents of

construction site generated sediment in this study. The observed data indicated that silt and clay size particles comprised 92% of the total suspended solids.

The field efficiency of silt fences appears to be dependent mainly on the detention time of the runoff behind the control. The detention time is controlled by the geometry of the upstream pond, hydraulic properties of the fabric, and maintenance of the control. Despite comments by project supervisors that little maintenance of controls was required, numerous installation and maintenance deficiencies were noted during the study. Holes in the fabric and inadequate "toe-ins" that result in under-runs, reduced the detention time available for particle settling. In addition, the openings released the discharge in a concentrated flow, which promoted erosion below the structure and resulted in short circuiting in the ponded area.

In contrast to the field monitoring, high removal efficiencies were achieved with silt fences in the flume studies (Figure 2.1). Four types of silt fences and a rock berm were subjected to cycles of simulated runoff events. The silt fences tested were constructed of geotextile fabrics. Properties of the fabrics, as reported by the manufacturers, are summarized in Table 2.1. The geometry of the flume resulted in the creation a large ponded area behind the control section, resulting in long detention times and settling of particles even with the fine-grained sediment used in the tests. Mean sediment removal efficiency in the flume ranged from 68 to 90% and was highly correlated with the detention time of the runoff (Figure 2.2). This observation indicates that silt fences should be sited in the field, so as to maximize the ponded volume behind the fence.

The flow rates of sediment-laden runoff through the control sections were two orders of magnitude less than those typically specified by transportation agencies. The flow rate of a sediment slurry through geotextile fences is a function of apparent opening size as well as permittivity (or other measures of clean water flow rates). The fabric with the longest detention times in this series of flume tests had the highest reported permittivity, but it also had the smallest apparent opening size, suggesting that clogging of the fabric with sediment affected the hydraulic performance. A comparison of the reported and measured permittivities is shown in Table 2.1.

In addition, tests of silt fence fabrics in a modified permeameter showed that flow rates through the fabric were not linearly related to head as is assumed in the ASTM definition (Figure 2.3). The discrepancy was due to the fact that flow is turbulent at the heads on the fabrics in silt fence applications resulting in much lower flow rates.

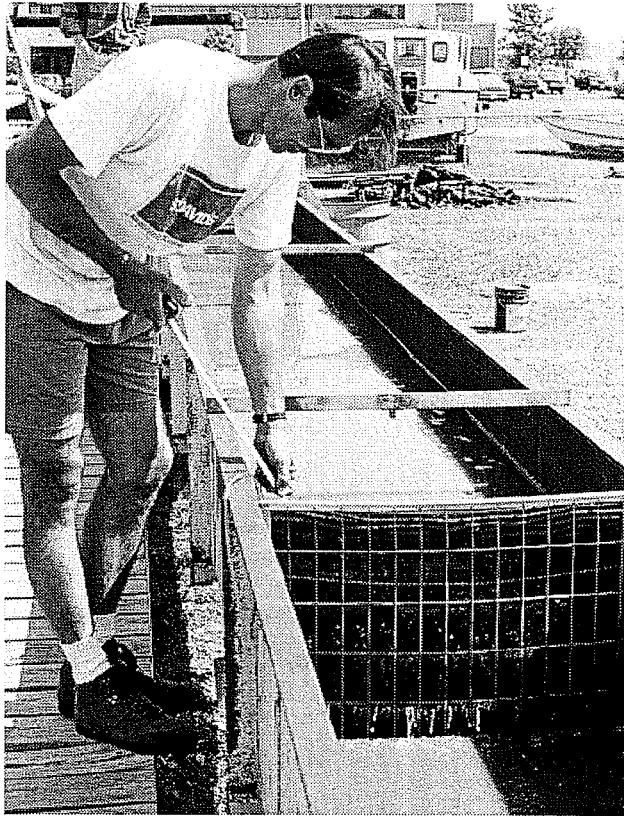


Figure 2.1 Testing Silt Fence Performance in a Flume

Table 2.1 Properties of Tested Silt Fence Fabrics

Type of Fabric	AOS, # sieve size(μm)	Permittivity, sec^{-1} reported/observed	No. of Tests
Belton woven	#30 (600)	0.4/0.015	9
Exxon woven	#30 (600)	0.1/0.002	5
Mirafi non-woven	#100 (150)	1.5/0.0004	5
Amoco woven	#20 (850)	0.2/0.012	5

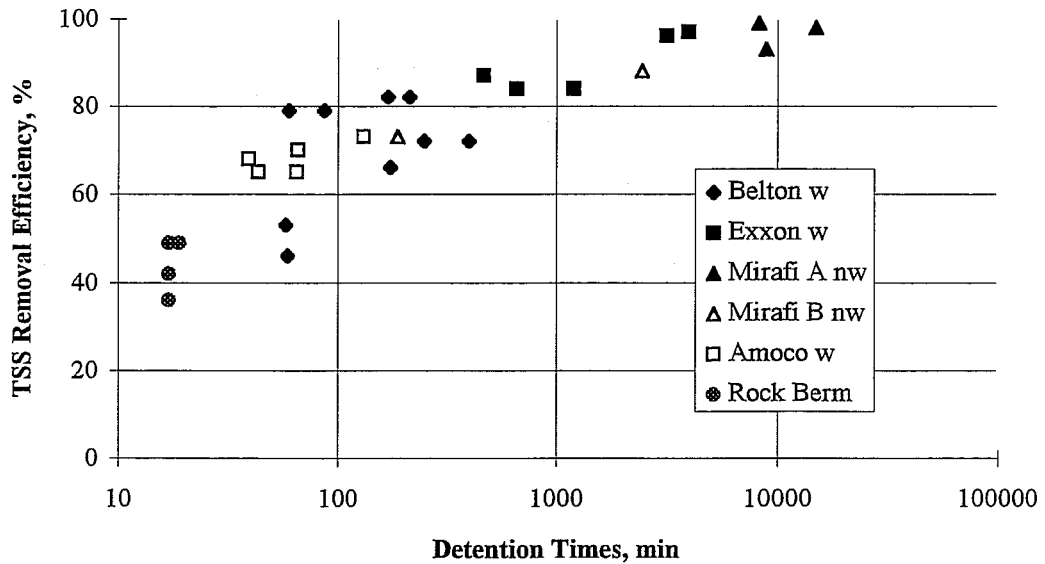


Figure 2.2 TSS Removal Efficiency as a Function of Detention Time (Flume Studies)

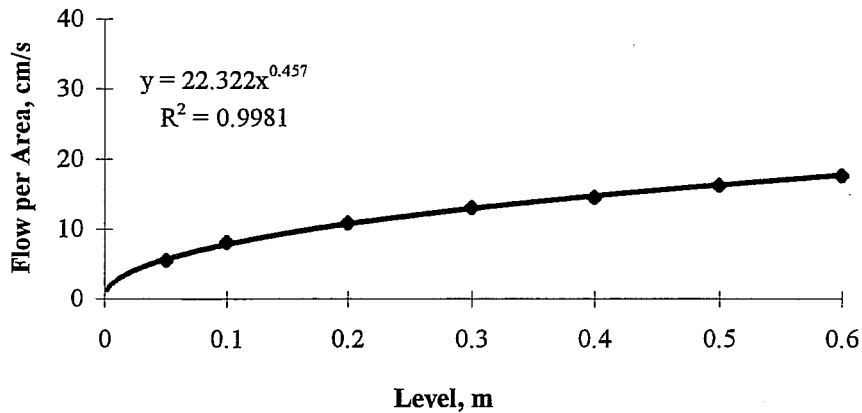


Figure 2.3 Typical Relationship Between Head and Flow Rate

Flow rates through rock berms greatly exceeded the rates typically recommended in guidelines promulgated by regulatory agencies. The short detention times and large pore size of the berms resulted in only a slight reduction in the suspended solids load in the flume test.

Despite the high sediment removal efficiency of silt fences under optimum conditions, water quality in lakes and streams below construction sites which rely on silt fences for sediment control will continue to be adversely impacted under most conditions.

The suspended sediment concentration in untreated construction runoff may exceed 3000 mg/L. A correctly installed and maintained system of silt fences might reasonably achieve a sediment removal efficiency of 85%, which would result in runoff discharged from the construction site with a sediment concentration of 450 mg/L. This concentration is higher than occurs naturally in most lakes and many small streams and would result in water quality impacts which would be apparent to even the most casual observer. Occasional large storm events which would overwhelm the storage capacity of the temporary controls could be expected to produce even more severe water quality impacts.

Use of slope coverings to minimize erosion could improve the quality of construction runoff; however their use would not be practical in an area of active construction. Complete elimination of water quality impacts would require the retention of all runoff from the construction site. In environmentally sensitive areas, large sedimentation ponds could be constructed to retain all the runoff from most storm events. In most areas, the impacts to receiving waters are usually transitory and extreme measures (i.e., 100% runoff detention) are generally not necessary.

Development of a new test or series of tests to characterize the expected performance of geotextile fabrics, when used as silt fences, is urgently needed. Field performance can not be determined from current parameters used to characterize the hydraulic properties of these fabrics. The use of these parameters results in an over-estimate of the area that can be treated without over-topping. Knowledge of the performance under field conditions would allow the development of rational guidelines governing the installation of these controls. Testing of fabrics using sediment with particle size distributions more characteristic of construction site sediment should serve as the foundation for future studies. A detailed presentation of the results of the temporary control evaluation is contained in CRWR Technical Report #261 (Barrett et al., 1995b).

3. EFFECTS OF HIGHWAY CONSTRUCTION AND OPERATION

3.1 Construction Effects

Grab samples from 10 storms were collected at monitoring sites on Danz Creek in southwestern Travis County, Texas. Nine of the storms were sampled at both locations and one storm at each site was not sampled at the other location. These samples were collected during the period from June 11, 1992 through October 10, 1993, coincident with the construction of the new highway. The data indicate that suspended solids are the most important constituent of storm water runoff from the construction corridor. The concentration of suspended solids in Danz Creek increased at least 5-fold during and immediately after storm events despite the presence of an extensive system of temporary controls (primarily silt fences). Other solid related parameters such as turbidity and iron also increased. A summary of concentrations above and below the highway crossing is shown in Table 3.1. The concentrations shown are the means and medians of the event mean concentrations (EMC's). The EMC is the average concentration of a constituent for a single storm event.

The increase in suspended solids concentration is consistent with the results of the temporary control monitoring performed as part of this overall study and described by Barrett et al. (1995b). Dilution of the construction runoff with water from upstream, easily could account for the median observed concentration downstream of the highway right-of-way of approximately 180 mg/L. This site was subject to weekly inspections, which insured adequate maintenance and installation of the temporary controls. The contractor also was required to keep all heavy equipment out of the creek crossings. Trees in the stream channels were removed by hand, where necessary, to minimize disruption to the creeks. Consequently, the reduction in sediment load to the creek was the best obtainable with the selected controls. The amount of sediment discharged to the creek would probably have been three to four times as large without the use of temporary controls and restrictions on the use of heavy equipment at the creek crossings.

Despite the high concentrations of suspended solids, no permanent change in the channel resulting from runoff during construction was obvious. The effects of construction on Danz Creek were temporary, and similar to those reported in the literature for other rivers and streams. Of particular concern in this area are the effects of construction on the water quality in the Edwards Aquifer. Approximately 85% of the recharge flow into the Barton Springs portion of the Edwards Aquifer occurs in the beds of the creeks that cross the recharge zone. The portion of Danz Creek affected by this

construction project lies on the recharge zone; therefore, higher concentrations of suspended solids could be expected to enter the aquifer during the period when runoff from the construction site occurred. Estimating the effect of higher sediment loads on water quality and storage in the aquifer was beyond the scope of this study project.

Table 3.1 EMC's in Danz Creek During Highway Construction

Parameter	Upstream Conc. (mg/L)		Downstream Conc. (mg/L)		Increase (%)
	Mean	Median	Mean	Median	
Total Coliform (CFU) ^a	2853	1875	2385	2050	9
Fecal Coliform (CFU)	2533	1825	10225	1750	-4
Fecal Strep (CFU)	6078	3900	4234	4200	8
TSS	34.8	13.9	179	79	470
VSS	4.8	2.1	20	4	88
Turbidity (NTU) ^b	28	6	112	72	1100
BOD ₅	2.8	2.7	3.2	2.2	-19
COD	16.3	11.2	14.8	13.3	18
Tot. Organic Carbon	22.9	19.1	22.1	18.4	-4
NO ₃ -N	0.78	0.48	0.67	0.65	35
Oil and Grease	ND	ND	ND	ND	NA
Cadmium	<0.009	0.004	<0.007	0.004	0
Chromium	<0.012	0.007	<0.019	0.007	0
Copper	<0.043	0.041	<0.048	0.046	11
Iron	0.699	0.358	2.697	2.489	595
Lead	<0.154	0.042	<0.126	0.042	0
Nickel	ND	ND	ND	ND	NA
Zinc	<0.029	0.023	<0.048	0.043	85

a) Colony forming units

b) Nephelometric turbidity units

3.2 Highway Operation Effects

The volume of water which runs off a given highway crossing will be relatively small and changes in water quality will probably not be measurable for bodies of water with large catchments. Monitoring of a small ephemeral stream near Austin, Texas, allowed documentation of changes in water quality and quantity resulting from highway runoff. Water quality samples were collected during 34 runoff events after the opening of a new highway. Fourteen of these events were sampled both above and below the

highway right-of-way. In this case, storm water runoff from the highway caused significant changes in both the quantity and quality of water in Danz Creek.

The paved surfaces and storm sewer system combined to increase the total volume and the maximum flow rate of the creek. Small storm events were sufficient to generate runoff below the highway right-of-way.

Storm water runoff from the highway caused increases in suspended solids, oil and grease, and zinc in Danz Creek (Table 3.2). These constituents commonly are found in highway runoff. The increases were substantial; however, the resulting water quality was well within levels appropriate for aquatic life or at concentrations commonly reported for streams during the elevated flows following storm events in undeveloped watersheds. Ambient concentrations of many constituents in the creek were higher than those in the runoff from the new highway, because of the nature of the surrounding land use. High concentrations of fecal bacteria in the creek probably were derived from livestock and wildlife in the watershed upstream of the highway right-of-way. Nutrients (nitrate and phosphorus) in the creek may have been the result of fertilization of the golf course, through which the highway passes. Dilution of the creek with highway runoff reduced the concentrations of these constituents. A detailed discussion of the surface water monitoring at Danz Creek is contained in CRWR Technical Report #262 (Barrett et al., 1995c).

Table 3.2 EMC's in Danz Creek During Highway Operation

Parameter	Upstream Concentration (mg/L)		Downstream Concentration (mg/L)		Increase
	Mean	Median	Mean	Median	%
Total Coliform (CFU)	25727	27805	16343	12000	-57
Fecal Coliform (CFU)	12380	12380	8650	2000	-84
Fecal Streptococcus (CFU)	35192	36000	23779	20500	-43
TSS	64	36	109	70	93
VSS	12	5	14	8	47
Turbidity (NTU)	25	20	34	29	43
BOD ₅	5.6	6.0	4.3	4.0	-33
COD	45	41	30	26	-37
Total Carbon	45	46	34	26	-44
Dissolved Total Carbon	43	43	27	21	-52
NO ₃ -N	0.30	0.28	0.17	0.11	-60
Total Phosphorus	0.36	0.26	0.12	0.13	-50
Oil and Grease	0.8	0.8	1.2	1.3	62
Cadmium	<0.001	0.001	<0.002	0.001	0
Chromium	<0.005	0.003	<0.009	0.002	-13
Copper	<0.005	0.002	<0.003	0.002	-14
Iron	1.756	1.184	2.634	1.365	15
Lead	<0.024	0.014	<0.049	0.014	0
Nickel	<0.007	0.005	<0.006	0.005	0
Zinc	<0.009	0.006	<0.024	0.020	235

4. QUALITY OF HIGHWAY RUNOFF IN AUSTIN, TEXAS

Water quality of highway runoff in the Austin, Texas, area was determined by monitoring runoff at three locations on Loop 1 (MoPac), which represented different daily traffic volumes, surrounding land uses, and types of highway drainage systems. MoPac at West 35th Street is a high traffic site (60,000 vehicles per day) located in central Austin. The land use of the area is mixed residential and commercial. MoPac at Convict Hill is a low traffic site (8700 vehicles per day) located on the southwestern edge of Austin. The land use around Convict Hill is mostly residential and rural undeveloped. The area draining to the catchment basin at these two sites were 100 % impervious. The Walnut Creek site is located in north Austin and consists of a combination of paved highway and grassy shoulder and median. The land use classification of the area is mostly commercial and high density residential, and approximately 47,000 vehicles per day pass this location. At Walnut Creek, the highway runoff crosses a large grassy median before entering the storm sewer system where the samples were collected.

During rainfall events the runoff flow rates were measured, and samples were collected automatically. Water quality parameters analyzed in the laboratory for all runoff samples included: turbidity, total and volatile suspended solids (TSS and VSS), 5-Day Biochemical Oxygen Demand (BOD₅), Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), oil and grease (O&G), nutrients (nitrate and total phosphorus), heavy metals (iron, lead, cadmium, nickel, lead, zinc, and copper), and bacteria (total coliform, fecal coliform, and fecal streptococcus).

Table 4.1 contains the means and medians of the EMC's from individual storms at the three sites. The highest concentrations of all constituents were measured at the high traffic site at 35th Street. The lowest concentrations were found at the Walnut Creek monitoring site. The concentrations at all sites were similar, with the exception of metals, to median values compiled in a nationwide study of highway runoff quality (Driscoll et al., 1990). Concentrations of metals measured during this study are lower than those which were measured several years ago. The elimination of leaded gasoline has resulted in an especially large reduction in the concentration of lead in highway runoff. A comparison of selected median EMC's for 35th Street and nationwide is shown in Table 4.2.

The concentrations of pollutants measured in highway runoff are also similar to those commonly reported in urban runoff. The City of Austin (COA) has conducted an extensive monitoring program to characterize the water quality of urban runoff from specific land uses (City of Austin, 1995). A comparison between the storm water quality

from an area of single family homes and the low traffic site on MoPac is shown in Table 4.3. A comparison between water quality from areas with commercial/industrial land use and the high traffic site on MoPac is shown in Table 4.4.

Table 4.1 EMC's of Constituents in Highway Runoff

Parameter	35 th Street		Convict Hill		Walnut Creek		Rainfall
	Median	Mean	Median	Mean	Median	Mean	Median
Total Coliform (CFU/100ml)	13000	48000	4200	7900	189000	145000	0
Fecal Coliform (CFU/100ml)	5800	13000	1000	22000	102000	116000	0
Fecal Streptococcus (CFU/100ml)	12000	16000	3800	17000	78000	89000	0
pH	7.15	6.94	5.61	6.14	6.51	7.16	
TSS (mg/L)	131	202	118	142	19	27	0
VSS (mg/L)	36	41	20	22	7	7	0
BOD ₅ (mg/L)	12.2	16.5	5.0	6.3	3.5	4.1	ND ^a
COD (mg/L)	126	149	40	48	35	33	6
Total Carbon (mg/L)	47	58	21	24	16	18	ND
Dissolved Tot. Carbon (mg/L)	25	31	11	14	13	15	ND
NO ₃ -N (mg/L)	1.03	1.25	0.73	0.96	0.28	0.36	0.52
Total Phosphorus (mg/L)	0.33	0.42	0.11	0.13	0.10	0.10	0.05
Oil & Grease(mg/L)	4.1	6.5	1.7	2.2	0.5	0.5	ND
Cu (mg/L)	0.034	0.038	0.007	0.010	0.008	0.007	0.003
Fe (mg/L)	2.606	3.537	1.401	2.437	0.361	0.442	0.079
Pb (mg/L)	0.050	0.099	0.016	0.041	0.007	0.009	ND
Zn (mg/L)	0.208	0.237	0.050	0.077	0.022	0.019	0.019

a) ND = not detected

Table 4.2 Comparison of Median EMC's from High Traffic Sites

Parameter	MoPac at 35 th Street (mg/L)	Driscoll et al. (1990) (mg/L)
TSS	131	142
VSS	36	39
COD	126	114
NO ₂ +NO ₃	1.03 ^a	0.76
Copper	0.034	0.054
Lead	0.050	0.400
Zinc	0.208	0.329

a) NO₃ only

Table 4.3 Comparison Low Traffic Site to Residential Land Use (Mean EMC)

Parameter	Single Family Residential (COA, 1995)	Convict Hill
Fecal Coliform (CFU/100ml)	34970	22000
Fecal Streptococcus (CFU/100ml)	44000	17000
TSS (mg/L)	171	142
BOD ₅ (mg/L)	9	6.3
COD (mg/L)	46	48
NO ₃ -N (mg/L)	1.14	0.96
Total Phosphorus (mg/L)	.29	0.13
Cu (mg/L)	.010	0.010
Pb (mg/L)	.016	0.041
Zn (mg/L)	.046	0.077

Table 4.4 Comparison of High Traffic Site to Commercial Land Use (Mean EMC)

Parameter	Industrial/Commercial (COA, 1995)	West 35th
Fecal Coliform (CFU/100ml)	79850	13000
Fecal Streptococcus (CFU/100ml)	79130	16000
TSS (mg/L)	221	202
BOD ₅ (mg/L)	12	16.5
COD (mg/L)	93	149
NO ₃ -N (mg/L)	1.82	1.25
Total Phosphorus (mg/L)	0.45	0.42
Cu (mg/L)	0.022	0.038
Pb (mg/L)	0.034	0.099
Zn (mg/L)	0.149	0.237

These comparisons show the general similarity between storm water runoff from highway surfaces and from urban areas. Much of the runoff generated in urban areas is from streets, parking lots and other paved surfaces and may therefore, contain the same pollutants as runoff from highways. Because of the similarity in water quality, the storm water control systems appropriate for improving the water quality of urban runoff would be equally effective for treating highway runoff. The water quality impacts of highway storm water runoff would be similar to those produced by runoff from an urban area of comparable size.

The concentrations of pollutants measured in highway runoff in the Austin area are below levels which would be toxic to aquatic life. Numerous bioassays and toxicity tests have been performed with highway runoff in other studies and acute toxicity

generally has not been demonstrated (Barrett et al., 1995a). The impacts of highway runoff alone, like many other nonpoint sources of pollution generally are not significant when considered singly, but may result in degradation of water quality when combined with other sources such as urban runoff. The potential chronic effects of highway runoff on aquatic species has not been adequately documented. Constituents such as polycyclic aromatic hydrocarbons (PAH) which were not monitored during this study, may also pose a threat.

The total load of pollutant discharged into many receiving waters is more important for estimating water quality impacts than is concentration. Pollutant load is the product of concentration and volume of runoff. Table 4.5 shows the estimated annual loads based on the mean EMC at each site. Normalized for surface area, the greatest loads were generated at 35th Street, while the lowest amounts were found at the Walnut Creek monitoring site. The monitored watershed at Walnut Creek had a runoff coefficient of only about 10% while the other two sites had runoff coefficients of approximately 90%. The lower concentrations at Walnut Creek, combined with the much lower flows at this site, were responsible for the low loads at this site. Annual constituent loads in untreated runoff from the new highways constructed in the recharge zone can be estimated by multiplying the area of the new highways by the storm water loads at the Convict Hill monitoring site. As development continues and traffic density increases the loads in untreated runoff will approach those measured at 35th Street.

Table 4.5 Estimated Annual Pollutant Loadings (kg/ha)

Pollutant	35th Street	Convict Hill	Walnut Creek
TSS	229	145	3.3
VSS	46	23	0.8
BOD ₅	18.7	6.5	0.5
COD	169	49	4.0
Total Carbon	66	25	2.2
Dissolved Tot. Carbon	35	14	1.8
NO ₃ -N	1.42	0.98	0.04
Total Phosphorus	0.48	0.13	0.01
Oil & Grease	7.36	2.25	0.06
Cu	0.043	0.010	0.001
Fe	4.008	2.497	0.053
Pb	0.112	0.042	0.001
Zn	0.269	0.079	0.002

A first flush effect (i.e., higher pollutant concentrations at the beginning of an event) was very evident during selected events, but was generally limited to a small volume. The overall effect of first flush was small or negligible when all monitored events were considered. The concentrations appeared to be affected by changes in traffic volume, rainfall intensity, and other factors. In addition, vehicles provided a continuous input of pollutants to the road surface and runoff for the duration of runoff events. In considering the potential effectiveness of storm water treatment systems, constant concentrations for individual storm events should be assumed. A detailed discussion of this portion of the research project is contained in CRWR Technical Report 263 (Barrett et al., 1995d)

5. FACTORS AFFECTING THE QUALITY OF HIGHWAY RUNOFF

One goal of this research project was identification of the variables which affect the build-up and wash-off of constituents from highways in the Austin, TX area and develop a water quality model which incorporates these variables. The isolation of the variables which 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 (Figure 5.1). 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 the collection of water which 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.

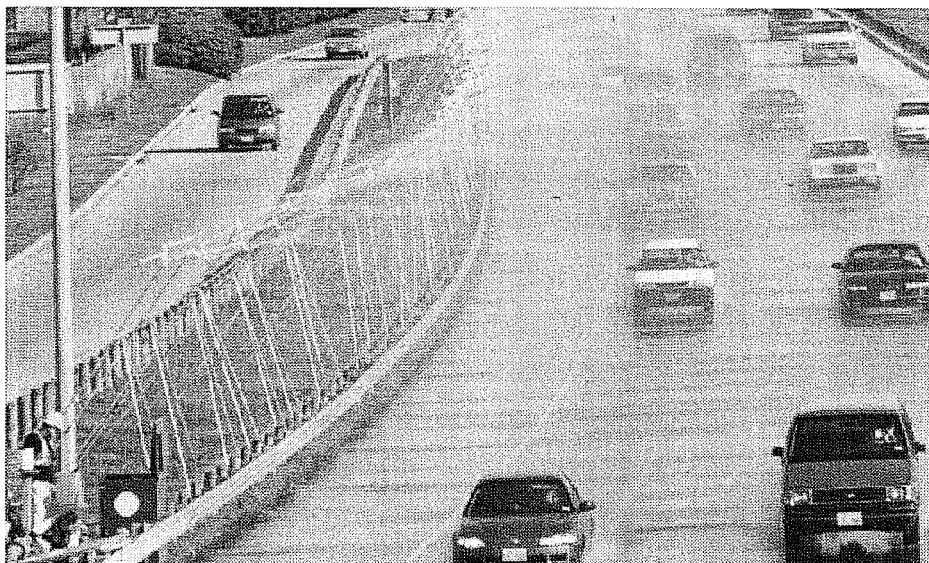


Figure 5.1 Rainfall Simulator in Operation

Thirty-five rainfall simulations were conducted between July 6, 1993 and July 14, 1994. Additionally, twenty-three natural storm events were sampled at the same location during the same period of time. 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, twenty-one 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. A comprehensive discussion of the methodology and results of this portion of the research is contained in CRWR Technical Report 264 (Irish et al., 1995).

5.1 Model of Highway Runoff Quality

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.

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 (hr) 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 dependent variable in the regression analysis is expressed as load (g/m^2); therefore, 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 which "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. Variables related to season, such as day of the year, and air and water temperature, were also tested for significance, but do not appear to affect pollutant loads. A summary of

selected water quality constituents and their relevant causal variables is presented in Table 5.1.

Table 5.1 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 & Grease		*		*					

As an example, 93% of the variation observed in the storm water loadings of total suspended solids (TSS) are explained by the total volume of storm water runoff (L/m^2), intensity of the runoff ($L/m^2\text{-min}$), total duration of the antecedent dry period (hr), and the intensity of the runoff during the previous storm event ($L/m^2\text{-min}$). This model formulation suggests that the conditions during the antecedent dry period (e.g., dust fall, 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. Therefore, efforts to mitigate the storm water loading of TSS should be directed at activities during the antecedent dry period which 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, that 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 which 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 ($L/m^2\text{-min}$), 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 ($L/m^2\text{-min}$), total volume of traffic during the storm, and the total volume of traffic during the antecedent dry period combine to explain 86% of the BOD_5 load, 95% of the 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 ($L/m^2\text{-min}$), total volume of vehicles during the storm, and the intensity of the previous storm runoff ($L/m^2\text{-min}$) 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 ($L/m^2\text{-min}$) and the total duration of the antecedent dry period (hr) 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.

Traffic volume during the storm does not appear as a statistically significant variable in every model formulation; however, traffic nevertheless, is 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 using 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 which 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.

5.2 Distribution of Highway Runoff EMCs

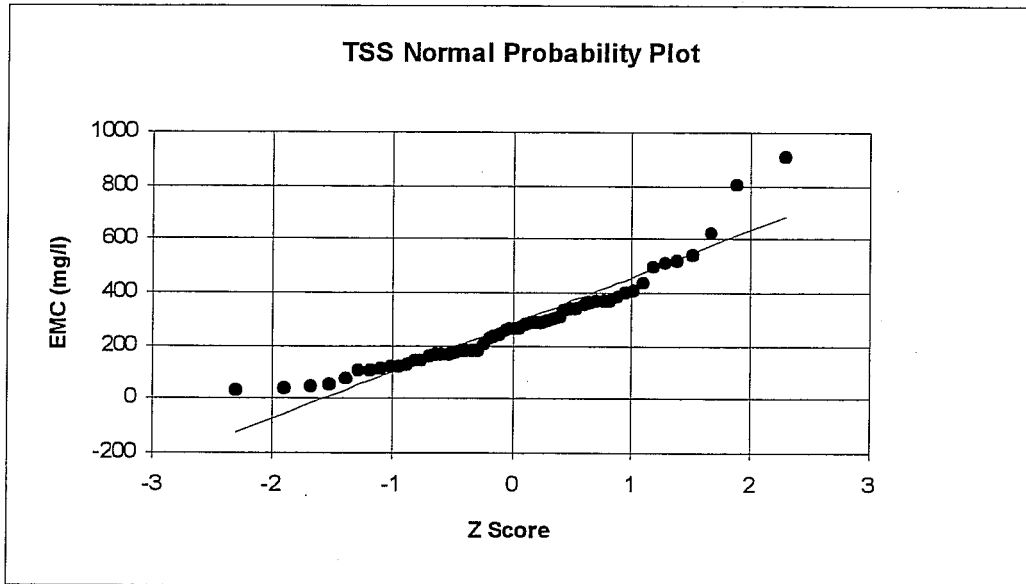
The quality of highway runoff varies from storm to storm and is highly variable. The impact of highway runoff on receiving waters can be estimated using probability distributions of runoff quality, which are normally developed from limited measurements so that the effects of extreme events can be predicted. The log-normal distribution is the most commonly used probability density model for environmental contaminant data. The

event mean concentrations (EMCs) of constituents in urban runoff, and highway runoff in particular, have been described by the log-normal distribution. The shape of the underlying distribution must be known in order to select the statistics which 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.

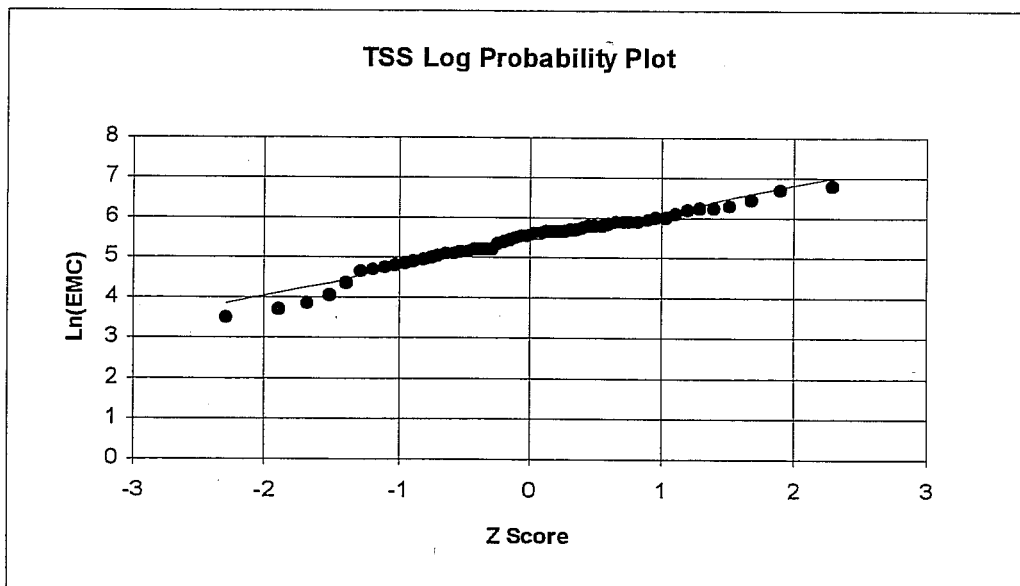
Probability plotting commonly is used to determine the shape of an underlying distribution. Probability plotting can provide a quick determination of whether the data are likely to have come from a specific type of distribution, however, the principal application of the method is the determination of the mean and variance of the distribution once the shape is known.

Normal and log-normal 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. However, reliance only on the "straightness" of the plotted points to determine the normality or non-normality of the distribution is risky at best. A probability plot can detect a skewed distribution; however, the plot cannot evaluate the amount of skewness, which 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 Figure 5.2.

The Jarque-Bera statistic tests whether a series is normally distributed. 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 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.



(a)



(b)

Figure 5.2 Probability Plots of TSS Data

6. PERFORMANCE OF PERMANENT RUNOFF CONTROLS

The effectiveness of storm water controls for improving the quality of runoff from operating highways was investigated in the field and laboratory. A detailed discussion of the methodology and results of the field and laboratory filtration studies is contained in CRWR Technical Report 265 (Tenney et al., 1995), and the monitoring of the grassy swale is described in Technical Report 263 (Barrett et al., 1995d).

6.1 Pollutant Removal Effectiveness of a Grassy Swale

The effectiveness of grassy swales for treating highway runoff was evaluated by comparing the runoff at Walnut Creek, before and after passing across a swale. The drainage system for this portion of MoPac consists of a grassy median which is underlain by a storm sewer system. Water enters the storm sewer through drop inlets after traveling along the grassy swale for as much as 100 meters. Runoff was collected from the storm sewer system at the discharge to Walnut Creek. The grassy swale is shown in Figure 6.1.



Figure 6.1 Grassy Swale, MoPac at Walnut Creek

A second sampler at this site collected runoff directly from the paved surface of the highway. The combined system of a grassy swale and storm sewer provided unexpected

benefits even though the system was not designed specifically for water quality improvement. The removal of water via the drop inlets helped maintain a shallow water depth in the swale. The piping system also acted as an underdrain for the swale; infiltration into the pipe supplied base flow to Walnut Creek event during the longest dry periods.

The grassy swale proved effective for reducing the concentrations of most constituents in runoff (Table 6.1). The low runoff coefficient due to infiltration of runoff into the swale produced an even larger reduction (90%) in pollutant load discharged (Table 4.5). This reduction of runoff volume effectively reduces the impact of constituents whose concentrations are not reduced by the swale. Large increases in bacteria counts occurred in either the swale or the storm sewer system; however, the bacteria probably do not indicate the presence of a significant human health threat. A constant seep of water is carried by the drain pipe. This condition is conducive for the growth of bacteria in the pipe. This phenomenon may be associated with an increase in the number of indicator organisms.

Table 6.1 Pollutant Removal Efficiency of a Grassy Swale

Parameter	Roadway	Grassy Swale	Removal (%)
Total Coliform (CFU/100mL)	3678	188197	-
Fecal Coliform (CFU/100mL)	1934	101545	-
Fecal Streptococcus (CFU/100mL)	6909	89482	-
TSS (mg/L)	104	27	74
VSS (mg/L)	23	7	72
BOD ₅ (mg/L)	7.5	4.1	46
COD (mg/L)	51	33	35
Total Carbon (mg/L)	34	18	48
Dissolved Tot. Carbon (mg/L)	17	15	9
NO ₃ -N (mg/L)	0.88	0.36	59
Total Phosphorus (mg/L)	0.15	0.10	31
Oil & Grease (mg/L)	3.9	0.5	88
Cu (mg/L)	0.014	0.007	49
Fe (mg/L)	2.066	0.442	79
Pb (mg/L)	0.014	0.009	35
Zn (mg/L)	0.074	0.019	74

6.2 Field Performance of Vertical Sand Filter Systems

A number of permanent runoff controls were constructed along the new highways in the Edwards aquifer recharge zone and their performance has been monitored since the highways opened. The control systems consist of a hazardous material trap, a sedimentation basin, and a vertical sand filter. The filter is constructed as part of the wall of the basin and held in place with filter fabric and rock gabions. A typical system is shown in Figure 6.2.

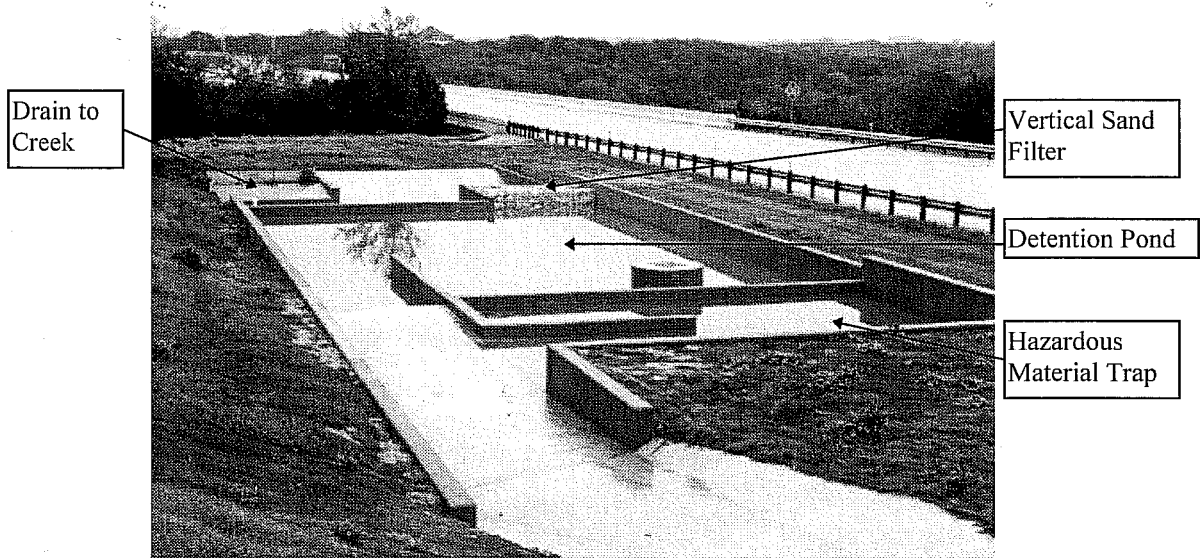


Figure 6.2 Typical Vertical Sand Filter System

Numerous problems were documented with these systems, mostly in conjunction with the performance of the vertical sand filter. Drainage rates observed for the control systems varied from 30 to 50 hours for the faster draining systems, to several days for the systems that drained slowly (Figure 6.3). Channeling of the runoff through the filter section may wash out the sand, resulting in inadequate detention times and no filtration. In other systems, the filters clogged almost immediately creating permanent storage in the sedimentation basin so that all subsequent runoff bypasses the control. Accurate determination of the pollutant removal effectiveness of these systems was not possible because of these hydraulic problems.

The use of sand and geotextile fabrics in the vertical sand filters makes it difficult to predict the drainage rate of these runoff control systems. Drainage of the runoff from the control system through the vertical filters is not controlled solely by the sand but also is affected by the geotextile fabric that is used to support the sand between the rock

gabions. Therefore, control systems designed based only on the hydraulic behavior of the sand may not drain in 24 hours as called for in the design.

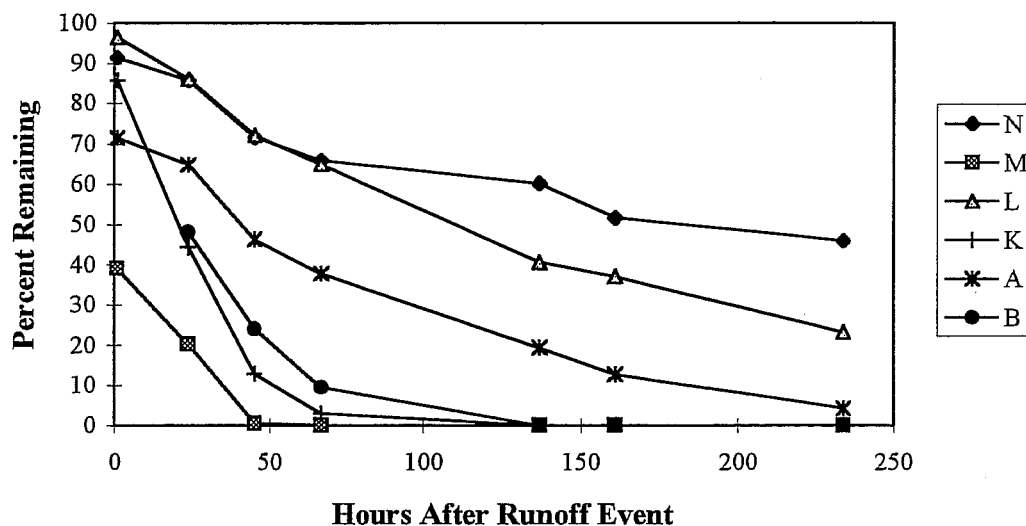


Figure 6.3 Drainage of Six Runoff Controls after Storm on 5/16/94

The hazardous material trap (HMT) retains the first flush of runoff during a rainfall event. Therefore, the HMT cannot function as a hazardous materials collection basin during runoff events when the control system is full of water, the roads are wet and the chance for an accident is higher.

Sedimentation is the most important mechanism for pollutant removal in the runoff control systems. Removal of solids as a result of sedimentation was high in control “N” which provided minimal detention time. Modifications of runoff control systems which focus on extending the detention time of the basins may be more effective in controlling suspended solids in runoff than enhancing the filter performance. Scour and resuspension of sediments was observed in the detention basins. This phenomenon causes increased suspended solids loadings on the filters resulting in discharge of higher concentrations of suspended solids in the filter effluent and in clogging of the sand filter. Sediment and suspended solids removal efficiencies can be increased and maintenance requirements reduced by the installation of rock gabions, baffles or another device which reduces resuspension of solids.

The estimate of the pollutant load contributed by the new highways “pre” and “post” control was an original goal of the study. Because of the variability in the

performance and the numerous modifications of the controls installed on the new highways no estimate of overall water quality improvement was possible.

6.3 Laboratory Filtration Experiments

Laboratory, bench-scale filtration columns using various media were investigated at the Center for Research in Water Resources. The performance of filtration media and adsorptive media was evaluated. The bench-scale horizontally-bedded vertical-flow filtration systems were dosed with stormwater runoff collected from an area highway.

Media selected for these experiments include a well-sorted medium grain size sand, a fine aggregate, grade 5 gravel, compost, and zeolites. The well sorted sand is typical of that used in sand filtration systems in the Austin area. The compost was obtained from a company in Oregon which has used it successfully in runoff controls. The zeolites were obtained locally and were tested because of their adsorption capability. The zeolites were tested in combination with the fine sand. In the latter case the column was constructed with four inches of sand on top of four inches of zeolites.

The results of laboratory studies indicate that high removal efficiencies for constituents in highway runoff can be achieved in horizontal (vertical flow) sand filter columns (Table 6.2). The data indicate that the compost is a very effective medium. It out performed the other media for the removal of TSS, oil and grease, and metals. However, the compost decomposes and subsequent breakthrough occurs. The medium-sized sand performed well for the removal of TSS and most of the metals. Clogging of the 20-cm column of sand occurred prior to breakthrough; therefore, clogging is expected to precede breakthrough in the field, where the filters are 90 cm across. The column with the medium-sized sand outperformed the column with the fine sand plus zeolites, showing that the zeolites are not a promising medium for enhancing removal via adsorption. Negative removals were obtained for nitrate in all of the columns, and indicate possible nitrification of ammonia which may occur in the columns.

Similar removal efficiencies were measured using concrete aggregate sand and the Brady sand. Pea gravel and grade 5 gravel are not effective filtration media. The gravel medium contained a significant fine portion which continued to wash out of the column for the duration of the experiment, resulting in negative removal for TSS and associated metals. Grade 5 gravel installed in runoff controls serves only as a hydraulic control device and not as a filtration media.

Table 6.2 Pollutant Removal Efficiencies of Alternative Media

Constituent	Medium Sand	Fine Aggregate	Grade 5 Gravel	Compost	Sand plus Zeolites
TSS	75	55	-91	97	46
COD	38	23	7	36	35
Nitrate	-66	-1	-17	-314	-269
Total Carbon	30	-4	0	-27	27
Oil & Grease	26	44	NA	59	20
Zinc	59	37	-6	86	60
Iron	48	53	-27	78	34
Copper	39	59	-17	61	13

The most effective runoff control system monitored during this study was a grassy swale. The swale reduced the concentrations of all pollutants monitored. In addition, the loss of runoff through infiltration to the subsurface resulted in an even greater reduction of pollutant loads. The vertical sand filters monitored on the new highway were not effective because of problems associated with the sand filter. Horizontal sand filters which have been used for many years in this area have been shown to be relatively effective for improving the quality of storm water runoff. Sand filter systems may be the best choice in urban areas where there is insufficient right-of-way for grassy swales. The use of alternative media in the filter systems appears to be promising. In laboratory tests, compost demonstrated greater removal of pollutants, except for nutrients, than all other media tested.

7. CONCLUSIONS

The negative impact of highway construction on the quality of surface waters is often significant despite improvements in the technologies used for erosion and sediment control. Monitoring of water quality in one of the creeks below a highway construction site indicates that even an extensive system of temporary controls is not adequate to prevent large amounts of suspended sediment from entering receiving waters. Deterioration in water quality has certainly been less than would have occurred in the past; however, the performance of even the best controls is often compromised by inadequate installation and maintenance.

The development of adequate guidelines for the placement of temporary sediment controls has been hampered by the lack of knowledge about the performance of silt fences and other controls in a field setting. In addition, parameters commonly used to characterize geotextile fabrics were found to have little relevance for estimating their sediment removal abilities or hydraulic characteristics under field conditions. Accurate prediction of the hydraulic properties would allow the estimation of appropriate drainage areas to minimize over-topping of these temporary controls.

The quality of highway runoff was determined by monitoring the quality of storm water runoff from three sites along the MoPac Expressway. The quality of the runoff was similar to that reported in other highway studies across the United States. Little adverse impact would be expected for all but the most sensitive receiving waters based on the quantity and quality of highway runoff generated during storms. Concentrations of many of the constituents in runoff were higher at the beginning of storm events (first flush effect); however, the continued input of pollutants from vehicles and other sources minimized the overall effect. The concentrations of pollutants appeared to be affected by changes in traffic volume, rainfall intensity, and other factors.

The use of the rainfall simulator allowed collection of sufficient data to formulate a computer model that will predict the quality of runoff from operating highways in the Austin, Texas area. The majority of the variation observed in highway stormwater loading could be explained by causal variables measured during the storm event, the antecedent dry period, and the previous storm event. This model allows prediction of potential impacts of new highways as well as provides a screening tool to identify existing highway segments that may threaten nearby receiving waters.

Permanent water quality controls may be required if stormwater runoff from a highway is identified as a threat to environmental quality. Unfortunately, structural controls built on the new highway segments to protect the Edwards Aquifer have not

performed effectively. The hydraulic performance of the vertical sand filters has been uneven, resulting in little apparent improvement in runoff quality. Testing of new filter configurations is continuing with the goal of improving the performance of these systems.

A grassy swale was found to be effective for reducing runoff volumes and pollutant concentrations. These grassy areas provide a low maintenance alternative to structural controls where sufficient land is available and the topography is appropriate.

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