CRWR Online Report 97- 5

USE OF VEGETATIVE CONTROLS FOR TREATMENT OF HIGHWAY RUNOFF

by

Patrick M. Walsh

and

Michael E. Barrett, P.E.
Joseph F. Malina, Jr., P.E.
Randall J. Charbeneau, P.E.

Principal Investigators

October 1997

CENTER FOR RESEARCH IN WATER RESOURCES

Bureau of Engineering Research • The University of Texas at Austin

J.J. Pickle Research Campus • Austin, TX 78712-4497

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT ENTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

Joseph F. Malina, Jr., P.E. (Texas No. 30998)
Research Supervisor

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the TxDOT project director, Kristie Denton, for her many helpful suggestions. We would also like to those that preceded her in that role, Peter Smith and Jay Vose.

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Pollutants found in runoff from highways may cause toxic responses in receiving waters for some conditions and are obstacles to obtaining water quality goals in the United States. This study investigated the capability of two vegetative controls, grassed swales and vegetated buffer strips, to treat highway runoff.

A grassed swale was constructed in an outdoor channel to investigate the impacts of swale length, water depth, and season of the year on removal efficiency. Results indicate that swale length and water depth affect the removal of runoff constituents by swales, and the removal efficiency can vary with the season of the year. Two vegetated strips treating highway runoff in the Austin, Texas, area also were monitored to determine removal capabilities. The filter strips removed most constituents effectively and consistently, and the inclusion of filter strips is recommended in future highway design if conditions are appropriate and right-of-way is available.

Chapter 1 Introduction

Stormwater runoff from highways can contain pollutants, including suspended solids, nitrogen and phosphorus, organic material, and metals. Concern regarding the harmful effects of these constituents on receiving waters has grown since the 1970s. The results of bioassay tests of organisms from streams and lakes receiving highway runoff have shown that highway runoff, though it may not demonstrate acute toxicity, may cause toxic responses for some conditions (Barrett et al, 1995b). In addition, highway runoff can add to existing runoff problems in urban areas. Today, sources of urban runoff, including highways, are considered “formidable obstacles to achieving water resource goals” in the United States (U.S. EPA, 1993).

Regulatory requirements reflect the need to protect the environment from urban and highway runoff effects. Approval by regulatory agencies is required before development is begun in urban areas, including the construction highways. On a national level, for example, a stormwater discharge permit is required for highways in urban areas, as part of the National Pollutant Discharge Elimination System (NPDES) enforced by the U.S. Environmental Protection Agency (EPA). In addition, state or municipal rules may apply. For example, the Texas Natural Resource Conservation Commission (TNRCC) requires a stormwater management plan before development is allowed over the environmentally sensitive recharge zone of the Edwards Aquifer in Austin, Texas.

Hence, both environmental response and regulatory reasons indicate the need for a stormwater management plan for highways. The Texas Department of Transportation (TxDOT) manages highways in Texas and funded this study for these reasons.

The BMPs investigated in this study are permanent vegetative controls: grassed swales and vegetated buffer strips. Grassed swales are shallow, grass-lined, typically flat-bottomed channels that convey stormwater at moderate slopes. In grassed swales, treatment occurs as the water flows in deep flow down the swale. Vegetated buffer strips, also known as filter strips, are not channels, but are relatively smooth vegetated areas at moderate slopes that accept highway runoff as overland sheet (shallow) flow. The mechanisms of removing constituents in runoff for the two practices are the same: filtration by grass blades or other vegetation, sedimentation, infiltration into the soil, and biological activity in the grass/soil media.

The objectives of this study are:

1. determination of the effectiveness of grassed swales and vegetated buffer strips for treating highway runoff;
2. determination of the factors that affect the removal efficiency of grassed swales and vegetated buffer strips; and
3. evaluation of the potential risk to human health and the environment caused by the deposition of metals on grassed swales and vegetated buffer strips.

The work involved in this study consisted of two parts. First, a study of grassed swales was completed in an outdoor channel. This swale provided a controlled environment that allowed for an evaluation of the effects of swale length, water depth, and season of the year on the capability of a swale to remove constituents from simulated highway runoff. The second portion of the study involved monitoring of two vegetated buffer strips that receive highway runoff. Monitoring demonstrated the effectiveness of filter strips at removing constituents from highway runoff. It also provided constituent concentrations necessary to accomplish the third objective of this project: an evaluation the environmental effects of metals deposition on vegetated BMPs.

Chapter 2 Literature Review

2.1 Factors That Affect Vegetated BMP Efficiency

Factors that affect the removal efficiency of vegetated BMPs treating urban runoff include vegetation type, slope, flow velocity, flow depth, season, and length. Only one previous study was designed specifically to understand the extent of the impacts and the relative importance of the various factors. Other insight into factors was gained incidentally while researching the effectiveness of BMPs.

Glick et al (1993) investigated the effect of vegetative cover and several other factors on filter strip effectiveness in an urban area. Four different vegetated covers were compared: wooded areas, wooded areas cleared, native grasses unmowed, and native grasses mowed. The forested areas produced the highest concentrations of pollutants, and the mowed and unmowed areas generally had the lowest concentrations. Thus, grassed areas were found to be more effective at removing pollutants than forested areas. Vegetative composition was found to have a significant impact on filter strip effectiveness.

Schueler (1987) reports that vegetation type is an important factor in filter strip performance. He reports that forested filter strips have greater pollutant removal capability than grassed filter strips, due to faster nutrient uptake and longer nutrient retention in forest biomass. The report suggests that a forested filter strip should be twice as long as a grassed one, however, because less vegetative cover is available in the forest strip.

Yousef et al (1985) also commented on vegetative cover in a grassed swale. In their study, a thick grass cover (80% grass, 20% bare soil) was found to have reduced nutrient removal efficiencies when compared to a thin grass cover (20% grass, 80% bare soil). This was attributed to increased decay of organic matter where thick grass cover was available.

Some studies commented on the effects of season on vegetated BMP effectiveness. Barrett et al (1995b) cites one study that expresses concern over reduced grassed swale effectiveness during times of summer drought, when vegetation can die or become dormant. The Seattle Engineering Department (1993) attempted to investigate the effects of season on a grassed swale, but insufficient data was collected to determine seasonal variations in removal. Yousef et al (1985) attributed a decline in removal effectiveness of organic nitrogen in a swale to increased organic debris that exists during periods of grass growth.

Glick (1993) investigated the effect of vegetated buffer strip width, or length of the strip in the direction of flow, on pollutant removal. Increased width was found to increase pollutant concentrations, rather than decrease them, as other researchers have reported. The increased concentrations were attributed to detachment of pollutants contained in the strip.

The Municipality of Metropolitan Seattle (1992) consolidated the effects of factors such as swale slope, width, length, flow velocity, and contributing watershed area by recommending a swale hydraulic residence time. Two swale configurations were investigated, one with a 4.6 minute residence time, and one with a 9 minute residence time. The study suggests that a swale with 4.6 minute hydraulic residence time is not adequate to assure adequate removal of constituents, but that the 9 minute configuration resulted in more consistent removal efficiencies, on the order of 83% for TSS. The study recommends further investigation before residence times shorter than 9 minutes can be used with confidence. No laboratory studies have been performed to carefully identify the effects of various factors, such as season, length, and water depth, on vegetative BMP efficiency. This study uses a controlled environment for measuring these effects.

2.2 Vegetated Buffer Strip Treatment Effectiveness

Most research on vegetated buffer strips has focused on the removal efficiency for filter strips in agricultural situations. Only in a few recent studies has their ability to treat urban runoff been documented, and the results vary.

Schueler et al (1992) cites only two monitoring studies of filter strips in urban areas. The studies indicates that filter strips do not trap pollutants efficiently in urban areas due to high runoff velocities; one of these studies indicated a removal rate of 28% for TSS. The Schueler report does say that filter strips can effectively remove sediments, organic material, and trace metals in areas where runoff velocity is low to moderate. It recommends a maximum flow velocity of 0.76 m/s. The ability of filter strips to remove soluble constituents, such as nutrients, is reported as variable. Design guidelines include minimum filter strip width of 15 meters, use of a level spreader device to distribute flow evenly, regular removal of accumulated sediment, and slopes less than five percent.

Yu et al (1995) report removal efficiencies for a vegetated buffer strip treating highway runoff as 64% for TSS, 59% for chemical oxygen demand (COD), -21% for TP, and 88% for zinc.

Young et al (1996) cites a 1994 study which reports 70% TSS, 40% particulate phosphorus and zinc, 25% lead, and 10% nitrate/nitrite removal efficiencies for a filter strip. It recommends that slopes of filter strips be less than 15 percent to prevent the formation of gullies in the strip, use of a level spreading device for even distribution of runoff, and dense vegetation. Furthermore, the report cites a 1995 study which recommended filter strips only for roadways with a maximum of 2 lanes and roadway average daily traffic (ADT) of less than 30,000 vehicles/day.

Table 2.1. Summary of previous filter strip studies.

Study	Notes	Removal Efficiencies
Schueler et al (1992)	recommended velocity <0.76 m/s, length>15 m	28% TSS
Yu et al (1995)	specifically hwy runoff	64% TSS; 59% COD; -21% TP; 88% zinc
Young et al (1996)	efficiencies from cited study	70% TSS, 40% P, Zn; 25% Pb; 10% NO_3/NO_2

Previous research on vegetated buffer strips used to improve highway runoff quality is sparse. Important conditions such as climate, vegetation, size and geometry of the filter strip, size of the highway, and soil type vary from study to study, making results from one investigation difficult to extrapolate to other conditions. Additional research is necessary to determine identify the expected removal efficiencies for vegetated filter strips treating highway runoff under a variety of conditions. The conditions of this research that might make it notable from other urban filter strip research include the following:

- Climate. Austin, Texas, has hot summers and mild winters, with moderate average rainfall (83 cm/yr);
- Land use. The source of runoff for the filter strips in this study is restricted to highways only. A highway provides a small watershed area in comparison to the watersheds for urban-area filter strips in other studies;
- Vegetation. The vegetation of the filter strips used in this study are common to Texas, and in particular, are commonly used by TxDOT for seeding of roadside areas. In addition, the two monitored filter strips have different vegetation types (one mixed, one mostly Buffalo grass);
- Geometry. The two monitored filter strips are the sides of V-shaped highway medians that were not originally designed for water quality enhancement. These filter strips are relatively short, with average length from pavement to median center of 7 to 9 meters.
- Extent of monitoring. Often, studies of BMPs present removal efficiencies from individual storms or average removal efficiencies from perhaps three to five storms. The high variance in constituent concentrations and other conditions from storm to storm can unfairly bias results for shorter studies. This study finds average removal efficiencies over a period of at least 14 months, with multiple storms (34 total events over all collection sites and a minimum of 19 storms monitored at any one sampling location). Monitoring of many storm events ensures the reliability of results by minimizing effects of data outliers that can strongly influence removal efficiency calculations in stormwater studies.

2.3 Effect of Metals Deposition on Vegetated BMPs

Several previous studies have shown that most metals in urban runoff are primarily found in a particulate, insoluble form. Barrett et al (1995b) refers to one study where the particulate fractions of lead, copper, and cadmium in urban runoff were respectively 90%, 75%, and 57%. Wiginton et al (1996) found that less than 2% of cadmium, lead, copper, and zinc in urban runoff were leachable and that much of the total mass of metals in urban runoff is sorbed onto soil components such as clays, organic matter, and hydrous oxides. Hence, only the small soluble portion of metal mass deposited onto vegetated buffer strips is likely to pose a risk to plants, animals that eat the plants, and groundwater resources. A large fraction of metal mass deposited on a vegetated buffer strip is bound to solids in the runoff and deposited in nearby soils in an insoluble form.

Previous research on metals accumulation in roadside vegetative areas has focused on identifying increases in metals concentrations in soil and in plant and animal life near highways. It is clear from numerous studies that atmospheric deposition results in elevated concentrations of metals including lead, zinc, cadmium, and chromium in roadside soils (Lagerwerff and Specht, 1970; Gish and Christensen, 1973). Only a few studies, however, have examined an increase in metal concentrations near roadways as a result of runoff, rather than by atmospheric deposition. In general, the studies indicate significant accumulation of metals in soils near the surface. Howie and Waller (1986) found elevated levels of iron, lead, and zinc in the first foot of soil in a swale accepting runoff from a highway. Gish and Christensen (1973) found levels of Cd, Ni, Pb, and Zn in earthworms and soils at one of their sites that were elevated beyond that which could be attributed to atmospheric deposition. They attributed the elevated concentrations to metals-rich runoff from several roadways which drained over and deposited metals at the site. Wigington et al (1986), however, concluded that there was no statistical evidence of metal accumulation due to urban runoff above that deposited by air pollutants at the highway site studied.

Barrett et al (1995b) summarized the results of numerous studies that looked at the impact of highways on metals accumulation in groundwater. The Barrett study concluded that highway runoff can have a significant impact on groundwater in some situations, but natural processes occurring in soils will attenuate metals in highway runoff prior to reaching the groundwater. One cited study found zinc concentrations in groundwater wells near a highway as high as 220 ug/L but concentrations in wells further from the highway were almost always below 50 ug/L. Another study cited in the Barrett report, however, found high concentrations of metals, including 1000-6600 ug/kg lead and 490-2400 ug/kg iron, in the top 15 cm of soil underneath a highway swale, but nearby groundwater was unaffected. Lagerwerff and Specht (1970) and Waller et al (1984) found decreasing metal concentrations with increased soil depth near highways and expected limited downward movement of metals in soils.

Some studies have documented metals accumulation in roadside areas due to deposition from highway runoff. None, however, have assessed the risks to human health and the environment associated with such deposition. More investigation is required to assess these risks and to understand whether metals deposition in vegetated BMPs can cause environmental or health problems.

2.4 Grassed Swale Treatment Efficiency

The benefits of roadside grassed swales for improvement of runoff water quality and prevention of erosion were recognized in the early 1980s. Yousef et al (1985) studied two grassed swales, 53 and 90 m long, for the removal of nitrogen, phosphorus, and heavy metals in highway runoff. Results showed the swale had moderate to high removal efficiencies (29-91%) for metals, but nitrogen and phosphorus concentrations were often higher after runoff had passed through the swale. When infiltration of pollutants into the soil was considered, however, less mass of both metals and nutrients reached receiving waters because of the swale.

Schueler et al (1992) reported varying removals of sediments and metals in urban runoff by grassed swales. However, the study states that a well-designed and maintained swale could be expected to remove 70% or total suspended solids (TSS), 30% of total phosphorus (TP), 25% of total nitrogen, and 50-90% of trace metals. Swales were recommended as a BMP to be used in conjunction with other BMPs. Cost and maintenance requirements were stated as low.

The Municipality of Metropolitan Seattle (1992) conducted an extensive study on a 60 meter grassed swale which treated runoff from a residential area. The swale showed 83% reduction for total suspended solids (TSS), 63-72% for metals, 65% for turbidity, and 74% for oil and grease. Moderate (up to 40%) to negative removals were seen for nitrogen and phosphorus, and a high variation was seen for removal of fecal coliform bacteria.

The Seattle Engineering Department (1993) studied a 173 meter long swale which also treated runoff from a residential area. The study showed that concentrations of TSS and most metals at the swale effluent were 60-70% less than influent levels, but nutrient concentration reductions were less than 40% and fecal coliform reductions were negative.

Table 2.2. Summary of grassed swale removal efficiencies.

Study	Notes	Removal Efficiencies
Yousef et al (1985)	53 to 90 m swale; hwy runoff	29-91% metals; N, P conc. increased in swale
Schueler et al (1992)		Expect 70% TSS; 30% TP; 25% TN; 50-90% metals
Mun. Met. Seattle (1992)	60 m swale; residential area	83% TSS; 63-72% metals; 65% turbidity; 74% O&G
Seattle Egr. Dept. (1993)	173 m swale; residential area	60-70% TSS, metals; 40% nutrients; neg. bacteria

Yousef et al (1985) recommended swales of minimal slope to increase contact time; soils with high infiltration rates, for maximum reduction of pollutant loadings to receiving waters; earthen cross barriers to increase retention and infiltration; and, removal of grass clippings and debris from the swale. Dorman et al (1988) prepared extensive design guidelines for grassed swales and filter strips for the Federal Highway Administration (FHWA), based on vegetation development and expected flow rates. Scheuler et al (1992) warned that swales cannot control runoff effectively if flow velocity exceeds 0.46 m/s. The report also recommended long contact times, minimum grass height of 6 inches, and regular mowing of the swale. The Municipality of Metropolitan Seattle (1992) suggested that pollutant removal in a swale is fundamentally dependent on the residence time in the swale, thus combining the effects of factors such as swale width and length, flow depth, volumetric flow rate, slope, and vegetation characteristics. The study recommended a 9 minute minimum residence time in a swale to achieve 80% removal of suspended solids. The study also recommends a maximum velocity less than 0.27 m/s, slope between 2 and 4 percent, water depth less than one half the height of the grass, and regular mowing.

Chapter 3 Channel Swale Experiments

3.1 Introduction

Construction of a grassy swale in the laboratory was deemed an ideal method for investigating the influence of individual parameters on swale efficiency. The swale allowed for repeated experiments with one varying parameter, thus demonstrating the effect of that factor on swale efficiency. The effect of water depth, season, and length of swale were investigated in this manner in these experiments. Overall efficiency of the laboratory swale was also investigated.

3.2 Methods and Materials

A grassed-lined channel was constructed at the Center for Research in Water Resources (CRWR) located on the J.J. Pickle Research Campus of the University of Texas in Austin, Texas. The soil and grass were installed during May and June of 1996 in a steel flume that was constructed in the 1960s. Eleven experiments were performed in the swale from October 1996 to May 1997.

3.2.1 Setup

The steel flume has a U-shaped cross-section with square corners (Figure 3.1). The flume bottom is 0.76 m wide and its walls are 0.61 m tall. The flume contains 7.6 cm of soil and gravel, a layer of plastic sheeting, an underdrain pipe, 5.1 to 7.6 cm of clean gravel, a fiberglass screen, and 15 to 17.8 cm of topsoil that was sodded with Buffalo grass. Buffalo grass is common in the Austin area and has been used by TxDOT along highway medians in Austin. This grass is a short, hardy, turf grass that is drought tolerant and requires little mowing. The grass sod was approximately 1.3 cm thick and the height of the grass was approximately 8 cm high at the time of planting. A perforated PVC pipe was laid as an underdrain along the length of the flume, lying along the swale centerline and on top of the plastic sheeting. The plastic sheeting was placed with a V-shaped cross-section that forced water to the underdrain. The fiberglass screen supports the topsoil and prevented soil from entering the underdrain.

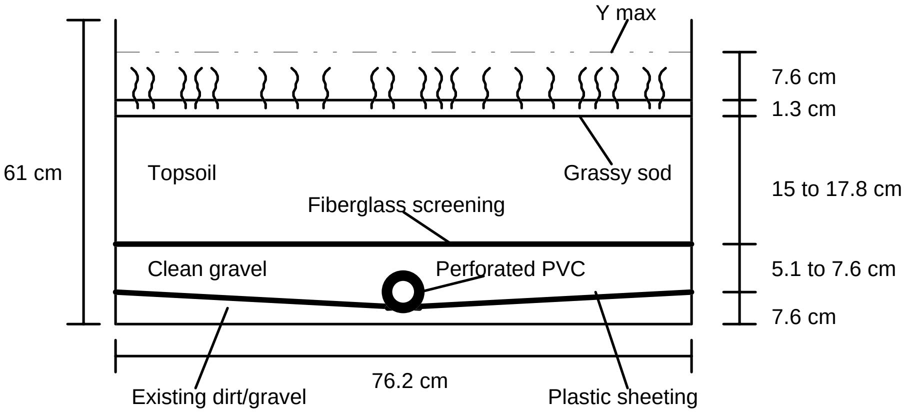

Figure 3.1. Cross-section of channel swale.

The swale was 40 m long and the average slope was 0.44%. Holes were drilled in the swale bottom at the swale influent (0 m) and at 10, 20, and 30 m along the length. ½" PVC pipes were installed vertically through these holes to the sod surface. Ball valves were installed at the end of the pipes (Figure 3.2). These pipes allowed for easy sampling of water passing over the grassy swale at any time at 10, 20, and 30 m from the inlet. At 40 m, a steel barrier was anchored to the flume to keep the gravel, topsoil, and sod in place. A weir is cut into the center of the barrier to allow discharge for the swale effluent. Water collected at the weir represented water quality at 40 m. The underdrain extends through the barrier through a 90 degree elbow for easy sampling for water quality analyses. Rulers were fastened to the side of the flume at 0, 10, 20, and 40m for monitoring of water depth.

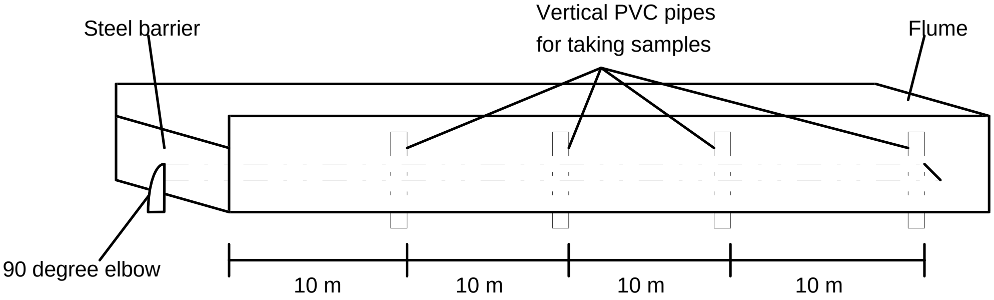

Figure 3.2. Overview of PVC Pipe Locations.

Simulated highway runoff flowed down the length of the swale during experiments. Water for the runoff originated in an open brick-lined common reservoir at CRWR (Figure 3.3). The water was continually pumped during experiments to a constant head reservoir. Overflow from this reservoir returned to the common reservoir. The discharge from the constant head reservoir then entered the first of two steel basins. A valve regulated flow to this basin. Water flowed from the first basin over a V-notch weir into a mixing basin. Flow was monitored by reading the depth of water behind the weir.

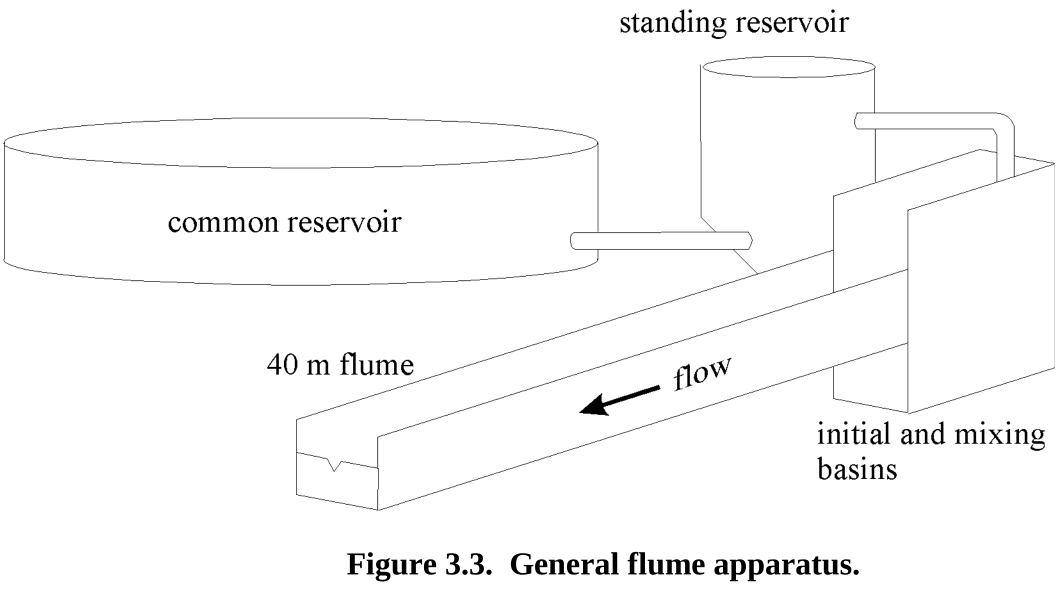

Figure 3.3. General flume apparatus.

The 61 cm x 51 cm (plan view) mixing basin was continually mixed using an approximately 30 cm blade. A mixture of synthetic, concentrated highway runoff (“cocktail” described below), was continually pumped to the water that discharged over the weir and into the mixing basin. In the basin, the water was completely mixed with the cocktail, and the water exiting the mixing basin effectively simulated highway runoff. Water exited the basin through a perforated baffle into the channel.

The influent water flowed over 1.22 m of plastic sheeting covered with 8-10 cm rocks to create an evenly distributed flow. The grass area begins immediately after the plastic sheeting, where the first vertical sample pipe is located. Occasional weeds were allowed to grow among the Buffalo grass. The grass was not mowed or weeded throughout the experiments. During a cold spell, 12 lightbulbs were suspended along a PVC frame just above the grass. This frame and the channel were wrapped in several layers of clear plastic in an effort to prevent freezing of the suspended flume during the winter. The wrapping was kept on only a few weeks; the frame and lightbulbs were left in place for the duration of the experiments.

3.2.2 The Cocktail

The highway runoff “cocktail” is synthetic highway runoff prepared onsite. The cocktail was made in a concentrated form that, when diluted with the appropriate amount of water, was representative of the average water quality of runoff from highways in Austin. Dulay (1996) developed this cocktail.

The post-dilution desired concentrations of the added constituents, as well as the mass of constituents used in these experiments for dilution in 5000 gallons of well water, are listed below in Table 3.1.

Table 3.1. Ingredients in the cocktail.

Constituent Added	Necessary Post-Dilution Concentration mg/L	Mass Required for dilution in 5000 gallons g	Mass Used After Experiment 3 g
detention pond sediment	500	20 lb	10 lb
Gleason clay	40	800	400
Velvacast kaolin	60	1200	600
coarse clay	20	400	200
$Pb(NO_3)_2$	0.16	3.03	3.03
$Cu(NO_3)_2\ 3H_20$	0.113	2.16	2.16
$Zn(NO_3)_2\ 6H_20$	0.91	17.22	17.22
Na_2CO_3	0.9	17.04	17.04

The constituent masses listed in Table 3.1, when diluted, approximate the suspended solids, nutrients, and metals in highway runoff in the Austin, Texas area. The following items should also be noted about the cocktail:

- The sediment was collected from the bottom of a local detention pond used solely for treating highway runoff and only that portion which passed through the 250 micrometer (mesh #60) sieve was used.
- Constituents such as chemical oxygen demand (COD), total organic carbon (TOC), and total phosphorus (TP) were not added separately but were associated with the detention pond sediment or were present in the reservoir water.
- Na_2CO_3 was added to provide the appropriate distribution of small, medium, and large particles, that are contained in highway runoff.
- Iron nitrate ($Fe(NO_3)_2\ 9H_20$), though prescribed in the original cocktail recipe, was not added in any of these experiments since sufficient iron was provided from rust in the basins and tanks prior to the swale.
- After experiment 3, the dose of detention pond sediment and all three clays was halved in

order to lower the TSS concentration to levels seen in the field. This reduction is noted in Table 3.1.

3.2.3 Experiment Procedure

The concentrated highway runoff cocktail was prepared by mixing continuously several gallons of untreated well water while the detention pond sediments, Na_2CO_3, and metal nitrates were added (Figure 3.4). The stirring was continued for at least ½ hour.

Figure 3.4. Addition of sediment and clays for creation of highway runoff cocktail.

The cocktail was kept continuously stirred during the experiment, and the cocktail bucket was turned regularly during the experiment to prevent sediment buildup in bucket corners opposite the stirrer. Weather conditions and a description of the grass appearance were reported prior to each experiment.

A pump was used to deliver the concentrated cocktail to the mixing basin. Reservoir water was pumped into the constant head reservoir and flowed into the first basin. The cocktail pump was started when the reservoir water flowed over the weir between the first basin and the mixing basin. The pump was calibrated and was set at a rate such that the cocktail would be used up when 5000 gallons of water had passed over the weir. The depth of water behind the weir had been decided upon prior to the experiment, depending on the desired water depth in the swale. This depth was constant throughout the experiment. The flow rate is

$$Q = 365\ h^{2.43}$$

where

Q = flow rate (L/s);
h = head on the weir (m).

One to three sets of samples were taken simultaneously along the length of the swale to determine changes in concentration along its length (Figure 3.5). Sample sets were collected at 5 minute intervals during an experiment. Water was flushed through the vertical sample pipes prior to sampling. To avoid variations during the initial flow, no sample was collected until the flow reached a quasi steady-state. Steady-state was determined by monitoring the water depth at 30 or 40 m, or by monitoring the distance the water flowed. Steady state had been reached when either remained constant. Water depth was recorded using the fixed rulers at 0, 10, 30, and 40 m after steady state had been reached.

Figure 3.5. Appearance of the swale during an experiment.

Time was also recorded during each experiment. The moment that water exited the mixing basin and entered the swale was considered time = 0. The time of each water depth measurement, weir height measurement, and sample set was recorded.

Underdrain flow also was monitored for some experiments after steady-state conditions were reached. Underdrain flowrate was measured using a volume-calibrated bucket and a stopwatch.

Each sample was collected in 4 separate bottles, and preserved for the analyses to be performed. A total of 109 samples were collected during the 11 experiments. The samples were logged and preserved in the laboratory at CRWR. All laboratory analyses were performed at CRWR. The constituents that were analyzed for all experiments were total suspended solids (TSS), turbidity, fecal coliform, fecal streptococcus, chemical oxygen demand (COD), total organic carbon (TOC), nitrate (NO_3), total Kjeldahl nitrogen (TKN), total phosphorus (TP), zinc (Zn), lead (Pb), iron (Fe), and copper (Cu). The analytical methods used for determining sample concentrations are listed in Table 3.2. Note that a bacterial analysis was not done for the channel experiments, but was included in the field experiments.

Table 3.2. Analytical methods for sample analysis.

Constituent	Method Identification	Holding Times	Preservative
TSS	Std. Methods 18th ed. 2540 B	7 days	None
Turbidity	Std. Methods 18th ed. 2130 B	24 hours	None
Fecal coliform	Std Methods 18th ed. 9222 D	24 hours	None
Fecal strep	Std Methods 18th ed. 9230 C	24 hours	None
COD	Std Methods 18th ed. 5220 D	3 months	H_2SO_4
TOC	Std Methods 18th ed. 5310 B	28 days	H_2SO_4
Nitrate	Std Methods 18th ed. 4500-NO_3-D	24 hours	None
TKN	EPA 351.4	28 days	H_2SO_4
Phosphorus	EPA 365.3	28 days	H_2SO_4
Metals	ICP Method 6010	6 months	HNO_3

3.3 Experiment Philosophy

The channel allowed for investigating five aspects of grassy swales: the effect of water depth, season of the year, and swale length on removal efficiency, the effect of highway runoff on groundwater, and the capability of the swale to reduce constituent concentrations in highway runoff. These five aspects were chosen for investigation because water depth, season, and length could be varied easily in the channel, and underdrain water quality should reflect the ability of soil to treat highway runoff after travel through approximately 24 cm of soil and gravel. Effects of the length of swale were evaluated concurrently during water depth and seasonal experiments.

3.3.1 Water Depth

Water depth can hinder the mechanisms of removal of constituents from runoff that flows over grassed swales. Filtration by the grass, impedance and increased sedimentation, and biological activity on grass blades were expected to be less effective at removing constituents in deeper water.

Four water depths were used: 3 cm, 4 cm, 7.5 cm, and 10 cm to cover the range of depths observed in swales in the field. Infiltration at water depths less than 3 cm prevented water in the swale from reaching the 20 m sampling tube. The four water depths were associated with four different flowrates as measured by the depth of the water behind the weir in the pre-mixing basin.

The data analysis for determining the effect of water depth utilized at least two sample sets at each depth, and with the exception of the 10 cm depth, each water depth was investigated in at least two separate experiments. Seasonal effects were assumed to have a negligible effect on the water depth analysis. For example, experiments 6 and 11 were performed at the same water depth at different seasons, and results for that water depth are averaged over both experiments.

3.3.2 Season

The effect of season on the grassed swale's removal efficiency was investigated. Examples of potential seasonal changes in the swale's characteristics include increased grass blade density during growth seasons, increased nutrient uptake rate during growth seasons, decreased nutrient and organic removal during plant decay, and increased infiltration during dry seasons due to an increase in permeability and decrease in soil saturation.

The seasonal analysis was performed by comparing the constituent removal capability of the swale during the dormant and growing seasons of the Buffalo grass. Experiments during the dormant season were begun with experiment 4 on December 13, 1996, during which time the grass appeared greenish brown to brown and dry. Experiments were given the "growing" season designation once green, healthy grass from the new growing season had sprouted in significant number and density. This occurred in mid to late March 1997, and experiments 8-11 thereafter were considered growing season experiments. Experiment 7 occurred during the transition period between dormancy and growth and is not included in the seasonal analysis. The effect of season was investigated at two water depths, 4 cm and 7.5 cm, by repeating experiments at those water depths in the dormant and growing seasons and comparing the effectiveness of the swale during those seasons.

3.3.3 Length of Swale and Groundwater Quality

Investigating the efficiency of the swale for various lengths, as well as sampling underdrain water quality, was performed for every experiment. Sampling from the underdrain was useful because underdrain water quality simulates water quality of recharge to groundwater from swales treating highway runoff in the field. Also, patterns in underdrain water quality through multiple experiments after construction of the swale may reflect changes in the capability of soils at field projects to filter infiltrated runoff after construction phases are completed.

3.3.4 Schedule and Experimental Conditions

A summary of the schedule, water depths, season, and furthest sampling distance for which samples could be taken (a function of how far the runoff traveled in the flume before infiltrating completely) are provided in Table 3.3 below.

Table 3.3. Summary of lab experiments.

Exp. No.	Date	Water Depth cm	Season	No. of Sample Sets Taken Along Swale Length	Furthest Sample Distance m
1	10/16/96	10	*	1	40
2	10/23/96	10	*	1	40
3	11/20/96	10	*	1	40
4	12/13/96	7.5	dormant	2	40
5	1/22/97	7.5	dormant	1	40
6	1/31/97	4	dormant	2	40
7	3/13/97	3	*	3	20
8	4/30/97	7.5	growth	2	40
9	5/13/97	3	*	3	10
10	5/19/97	10	*	2	40
11	5/22/97	4	growth	2	20

* indicates the experiment was not included in determination of dormant or growing season removal efficiencies.

3.4 Efficiency Calculations

Removal efficiencies for a constituent were calculated with respect to the concentration of that constituent sampled at 0 m. The following equation was used to calculate removal efficiency:

$$\mathbf{E} = \frac{C_0 - C_x}{C_0} \times 100\%$$

where

E = removal efficiency (%),

C_x = concentration of constituent sampled at distance x down the swale (mg/L or NTU),

C_0 = concentration of constituent sampled at the 0 m sampling tube (mg/L or NTU).

Analyses of multiple sample sets and multiple experiments were required to calculate average removal efficiencies. An average removal efficiency at a specific water depth was calculated using the following steps:

1. For each experiment at a water depth, the average C_0 was calculated by averaging all sample concentrations taken at the 0 m location, if more than one was taken.
2. Removal efficiencies for each sample were calculated using the average C_0 for that experiment from step 1 and the equation above.
3. The average removal efficiency at each sampling distance was calculated by an average of all removal efficiencies for samples at that distance from step 2. The average removal efficiency for a water depth at a particular distance along the swale is from all experiments at that water depth.

For seasonal analysis, the average removal efficiency during dormant and growth seasons were calculated for two water depths. A season's average removal efficiencies were calculated using the following steps:

1. For each experiment during a season at a particular depth, the average C_0 was calculated by averaging all sample concentrations taken at the 0 m location.
2. Removal efficiencies for each experiment at each sampling location were calculated using the average C_0 from step 1 for that experiment and the equation above.
3. The removal efficiency at each sampling distance for a season and water depth was calculated by an average of all removal efficiencies found at that distance from step 2 over all experiments at that water depth and during that season.

The removal efficiencies reported for the swale in this report represent the reduction in pollutant concentrations that occurred in runoff along the swale. To calculate a reduction in pollutant mass, rather than concentration, infiltration of contaminants into the soil must be taken into consideration.

The concentrations of constituents at the swale influent must remain constant throughout the experiment in order to insure meaningful results. For example, if the cocktail pump was clogged temporarily during an experiment, this would prevent some influent water from receiving the appropriate amount of constituents. Hence, water sampled at some locations might be cleaner than expected and falsely indicate that removal had occurred. In order to verify that the influent concentration was constant, multiple samples were taken at 5 minute intervals at the influent sample pipe during experiment 3 and experiment 5. Experiment 3 results were inconclusive; TSS levels in the 4 samples taken at 0.0 m were 440, 624, 474, and 678 mg/L. A more extensive, 6-sample test was done during experiment 5 after adding a small filter on the end of the cocktail influent tube to prevent grass from entering the cocktail pump. These results showed that the influent concentrations to the swale are relatively constant, as shown in Figure 3.6.

The constituent concentration was assumed to be equal to the detection limit when detection limits were encountered in the data. This policy was chosen because it tended to give the most conservative removal efficiencies; higher concentrations in the sampled runoff result in the lower, or more conservative removal efficiencies.

Data from experiments 1-3 were not used because the mass of cocktail ingredients changed. The use of less solids in experiments 4 through 11 could bias the calculated removal efficiencies, especially by increasing removal efficiencies for experiments 1-3 in which more sediment and clays were used. This would render a comparison between experiments 1-3 and subsequent experiments impossible. A preliminary analysis of the data observed in experiment 1 through 3 was performed and the removal efficiencies in these experiments were higher than in subsequent experiments with comparable water depths. An exception to this rule was made for analyzing underdrain water quality, for which results from all experiments were used; changes in sediment used likely has a small impact on percolate water quality.

A table with data for all constituents for all experiments is provided in Appendix A.

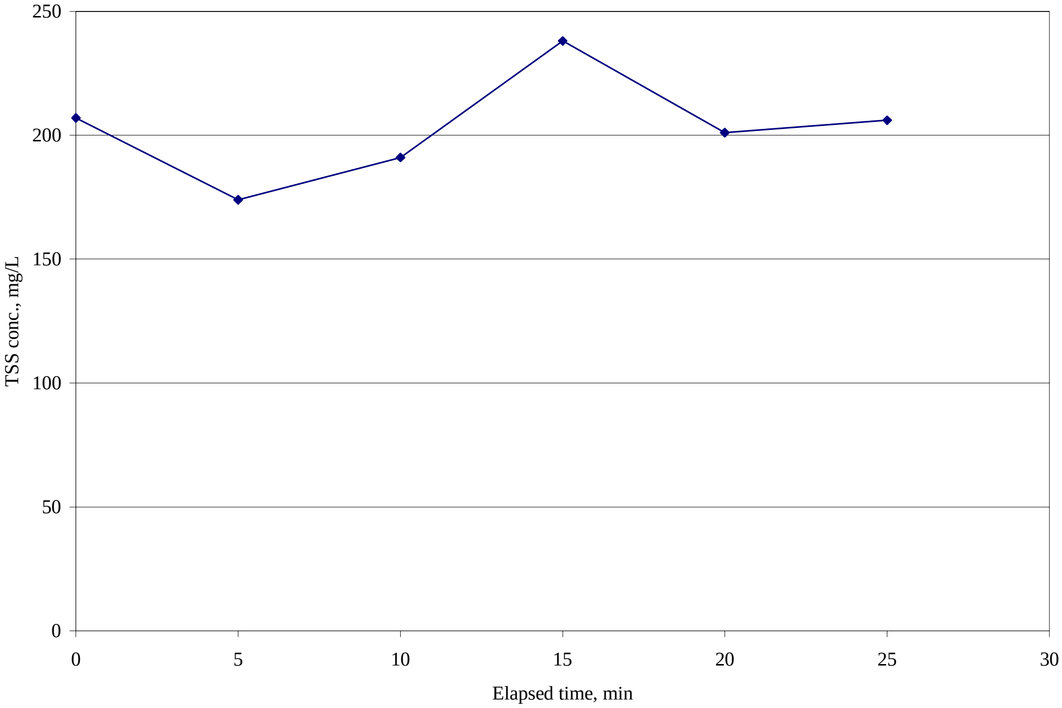

Figure 3.6. Confirmation of relatively constant influent concentrations in the swale.

3.5 Channel Experiments Results

3.5.1 General Results

Suspended solids and metals demonstrated the highest removal efficiencies in the swale, with reduction in constituent concentrations varying from 51 to 86 percent after 40 m of treatment. Removal of COD was ranged from 25 to 79 percent, and removal of nitrate, TKN, and TP ranged from –26 to 45 percent, after 40 m of treatment. The ranges of pollutant removal efficiencies for all constituents are listed below in Table 3.4. Ranges represent efficiencies observed during experiments at different water depths. The calculated removal efficiencies agree well with grassed swale field results reported by other researchers (Barrett et al, 1995b; Municipality of Metropolitan Seattle, 1992).

Table 3.4. Removal efficiencies calculated for the channel swale at different water depths.

	Distance along swale, m				
Constituent	10	20	30	40	Underdrain
TSS	35-59	54-77	50-76	51-75	73-87
COD	13-61	26-70	26-61	25-79	39-76
Nitrate	(-5)-7	(-5)-17	(-28)-(-10)	(-26)-(-4)	(-8)-(-10)
TKN	4-30	20-21	(-14)-42	23-41	24-41
Total phosphorus	25-49	33-46	24-67	34-45	55-65
Zinc	41-55	59-77	22-76	66-86	47-86
Iron	46-49	54-64	72	76	75

3.5.2 Effect of Water Depth on Swale Removal Efficiency

Average removal efficiencies at different water depths for the monitored constituents are presented in Figure 3.7 through Figure 3.13. The data in the graphs indicates that constituent removal efficiencies were reduced as water depth was increased, with the exception of nitrate and TKN. No trend is obvious for the relationship of water depth and removal efficiency for nitrate and for TKN. The data presented in Figure 3.7 indicates that removal of total suspended solids increased with decreased depth of water. However, the difference in average removal efficiencies for TSS at 20 m for different water depths was not statistically significant among all adjacent (3 and 4 cm, 4 and 7.5 cm, etc.) water depths at the 90% confidence level. This statistical analysis was performed for the data at 20 meters because the runoff at a water depth of 3 cm did not reach the 30 meter sample tube.

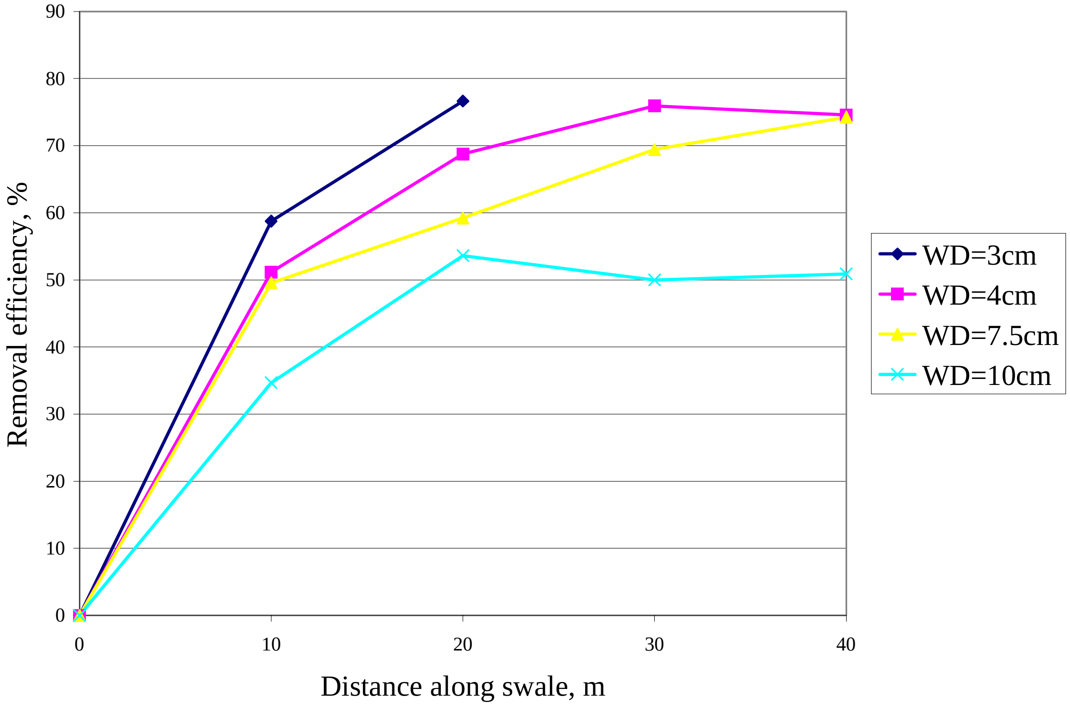

Figure 3.7. Effect of water depth and swale length on TSS removal efficiency.

The increase in removal efficiency of TSS with decreased water depth confirms expectations, since the filtration action of the grass blades is expected to be more significant for smaller water depths. However, the flow velocity in the swale was higher during experiments at deeper water depths. It is likely that the increased removal efficiency in shallower water is influenced both by the water depth and its velocity. Thus, recommendation of a maximum water depth for a swale based upon desired removal efficiency requires a simultaneous limitation on runoff velocity within the swale. These results do indicate that a grassed swale which treated slow moving, shallow (3-4 cm) runoff will achieve higher removal efficiencies for most constituents of concern than swales with deeper (7.5-10 cm) runoff at higher velocities. The trend between water depth and removal efficiency for COD, nitrate, TKN, total phosphorus, zinc, and iron are presented in Figure 3.8

through Figure 3.13. For COD, total phosphorus, and iron, the trend of increased removal efficiency with decreased depth is apparent; for nitrate, TKN, and zinc, the trend is not certain. The solubility of nitrate and TKN decreases the swale's capability for increased filtering action at lower water depths. The lack of a trend for zinc, however, is difficult to explain. Zinc is associated with sediments in the runoff, and its removal efficiency often simulates trends in sediment removal. Thus, the inverse relationship between removal efficiency and water depth would be expected for zinc; however, this trend is not apparent. More experiments could explain this result.

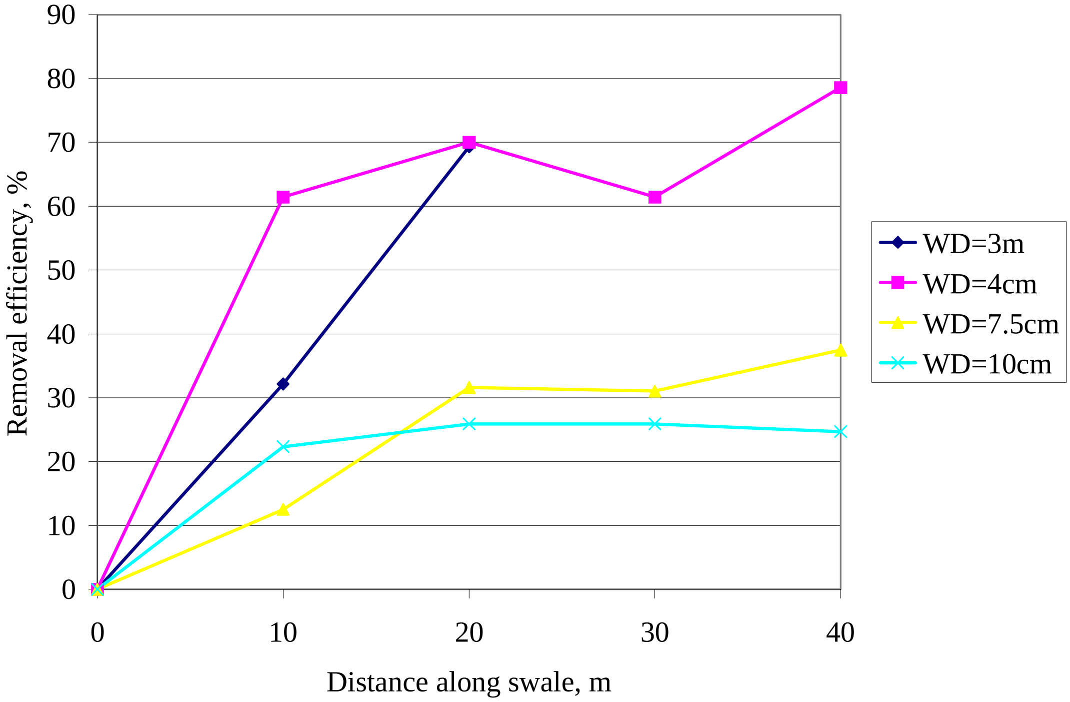

Figure 3.8. Effect of water depth and swale length on COD removal efficiency.

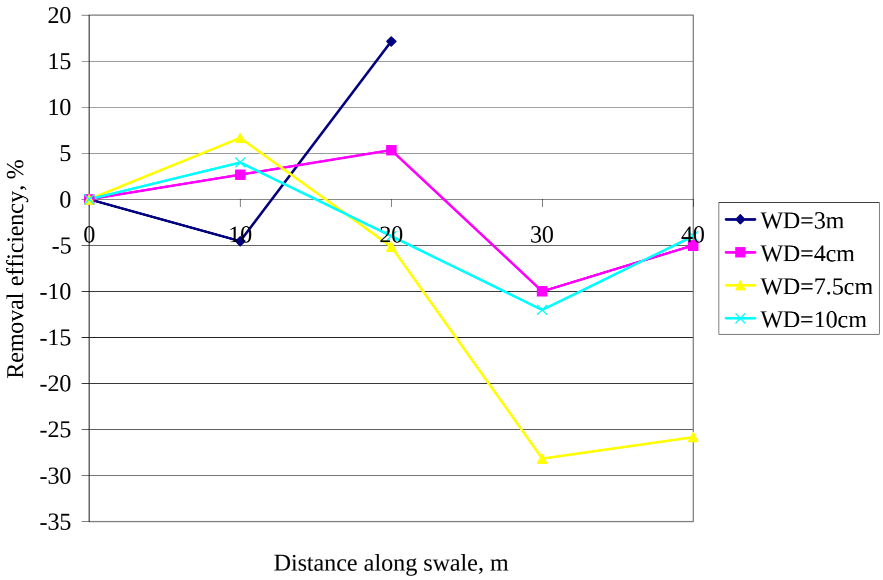

Figure 3.9. Effect of water depth and swale length on nitrate removal efficiency.

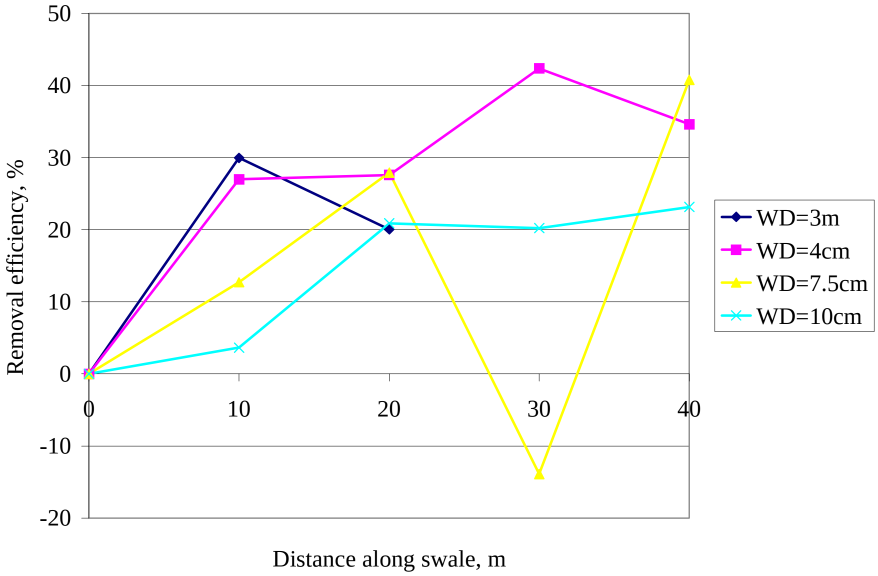

Figure 3.10. Effect of water depth and swale length on TKN removal.

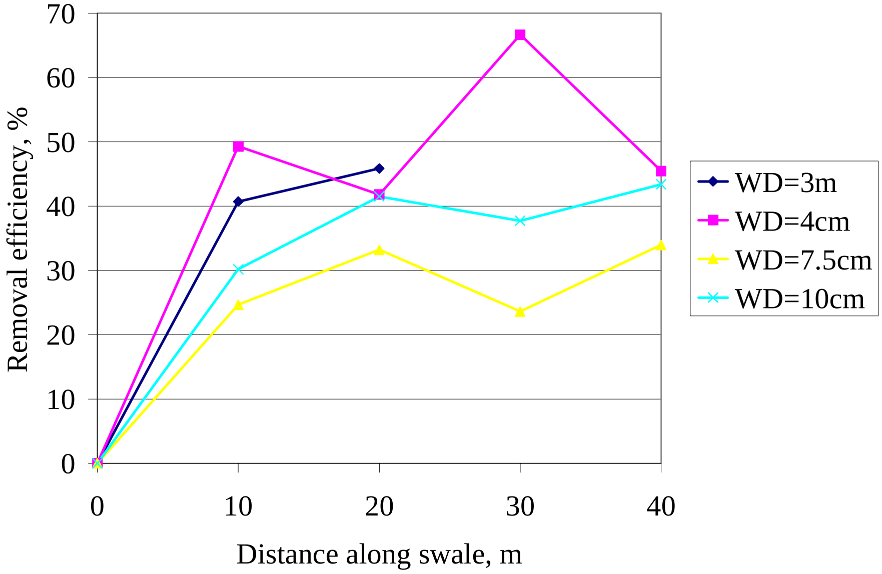

Figure 3.11. Effect of water depth and swale length on total phosphorus removal.

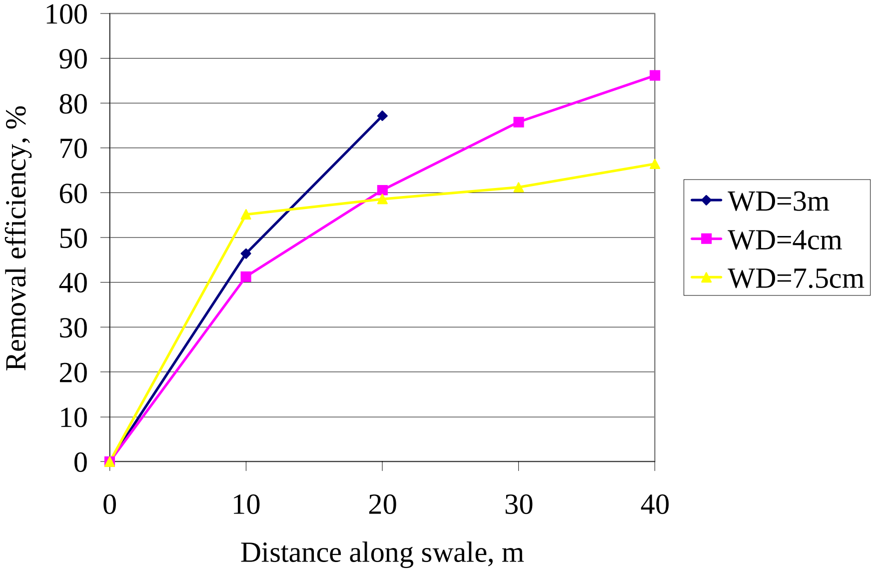

Figure 3.12. Effect of water depth and swale length on zinc removal efficiency.

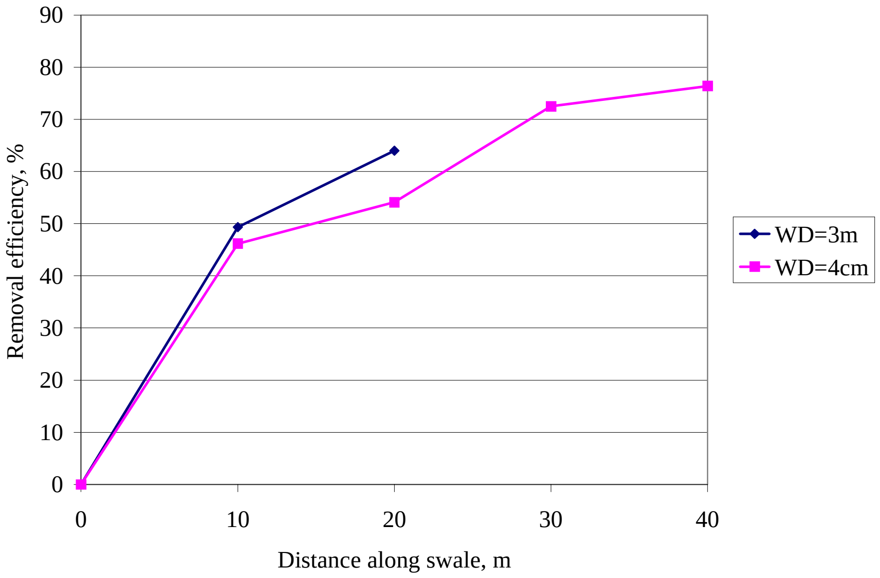

Figure 3.13. Effect of water depth and swale length on iron removal efficiency.

3.5.3 Effect of Swale Length on Removal Efficiency

Figure 3.7 through Figure 3.13 above can also be used to evaluate the effect of swale length on removal efficiency. The data in the graphs shows that removal efficiency increases with length, but the increment of increased efficiency diminishes as runoff proceeds further down the swale. This trend is especially evident for total suspended solids, chemical oxygen demand, total phosphorus, and metals. The majority of total removal occurs in the first 20 meters of flow over the swale for these constituents. The removal of total suspended solids after 20 meters accounts for 92%, 80%, and 105% of the total removal observed at 40 meters at water depths of 4, 7.5, and 10 cm, respectively. The 105% at the 10 cm water depth indicates that removal at 20 meters was actually higher than the removal observed after 40 meters of flow.

The diminishing increases in removal efficiency observed after 20 m indicates that swales longer than 20 m may not be cost-effective. This is particularly true in situations where construction or maintenance of a swale longer than is costly, such as in areas where land is expensive or where considerable excavation or landscaping is required for swale construction. If expected water depths in the swale are 7.5 cm or greater, however, 30 to 40 meter-long swales are necessary for TSS removals of greater than 60%, assuming a thick vegetated cover exists on the swale.

The diminishing increases in removal efficiency observed as swale length increased confirms intuition. Many constituents in highway runoff are attached to sediments and clays that settle out or are filtered out quickly once the runoff enters the swale. More soluble constituents and constituents attached to smaller particles which do not settle quickly are not removed effectively in the swale’s initial 20 meters, as demonstrated by the removal data for nitrate and TKN. Three visual observations from the channel study are testament to this phenomenon. First, sediments accumulated on the blades in the first 10 meters of the swale. The coating was obvious in the first 3 meters of grass, and could still be observed after 10 meters, but no sign of the coating was found at 20, 30, or 40 meters. Second, layers of sediment formed on the plastic sheet that covers the first meter of swale after runoff exits the mixing basin. The heaviest sediments fell out of suspension after less than one meter in the swale, before any grass was reached, and formed these layers. Finally, the height of the soil surface with respect to the walls of the flume rose substantially after several experiments at the 0 meter distance. Deposited sediments raised the soil surface level at the swale influent by approximately 2 centimeters after eight experiments. No noticeable increase in soil surface height occurred at distances of 10 to 40 meters. The State of Maryland (1985) recommends the periodic manual removal of sediment deposits to preserve the infiltration capacity of the soil and to prevent ponding. Removal of sediments also may prevent burying of grass blades which can cause the grass to die and encourage channelization (Municipality of Metropolitan Seattle, 1992).

The TSS removal efficiencies observed in these experiments may be used for design purposes. The data in Table 3.5 presents the length of swale necessary for a desired TSS concentration removal efficiency at an expected water depth in the swale, assuming the swale has a slope of 0.44% and thick, even vegetated cover with height of at least 10 cm. Longer swale lengths are necessary for swales of slopes greater than 0.44% or swales without thick, even vegetated cover with vegetation height of at least 10 cm.

Table 3.5. Required swale length for total suspended solids removal.

Expected Water Depth cm	Desired TSS Concentration Reduction								
	30%	40%	50%	55%	60%	65%	70%	75%	80%
3	10	10	10	10	20	20	20	20	>20
4	10	10	10	20	20	20	30	30	>40
7.5	10	10	10	20	20	30	40	>40	>40
10	10	20	20	>40	>40	>40	>40	>40	>40

3.5.4 Effect of Seasons on Swale Removal Efficiency

Removal efficiencies for total suspended solids were greater in the growth season than in the dormant winter season. The growth season removal efficiencies for total suspended solids are greater than dormant removal efficiencies at every sampling length, for both water depths (Figure 3.14 and Figure 3.15).

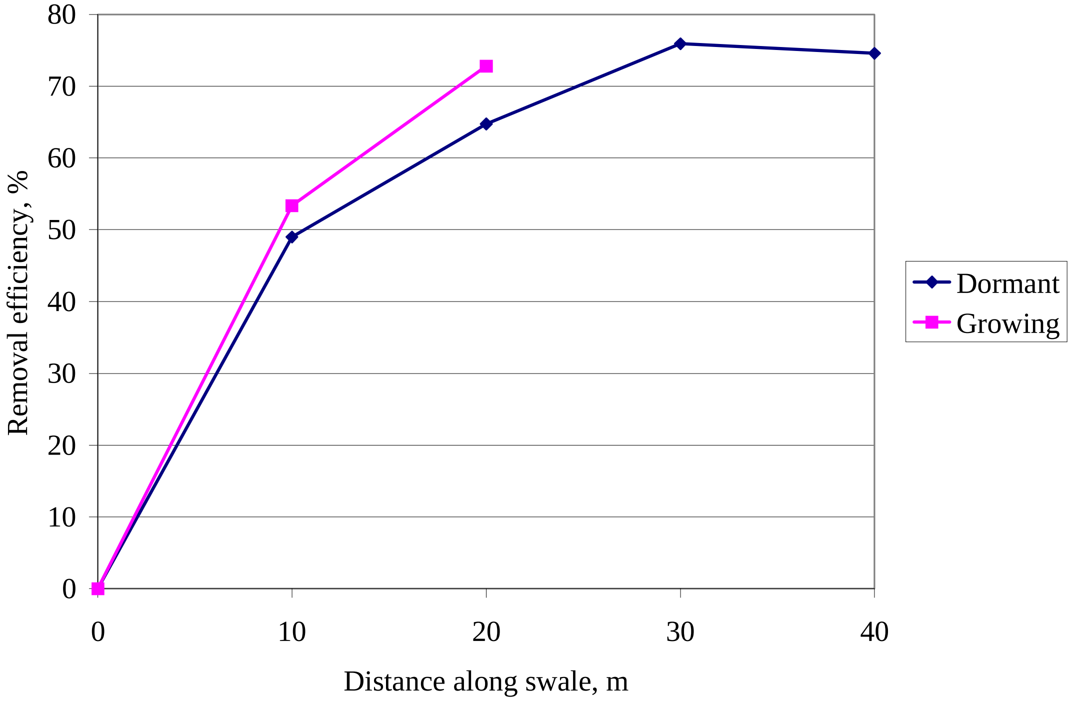

Figure 3.14. Seasonal comparison of TSS removal (water depth = 4 cm).

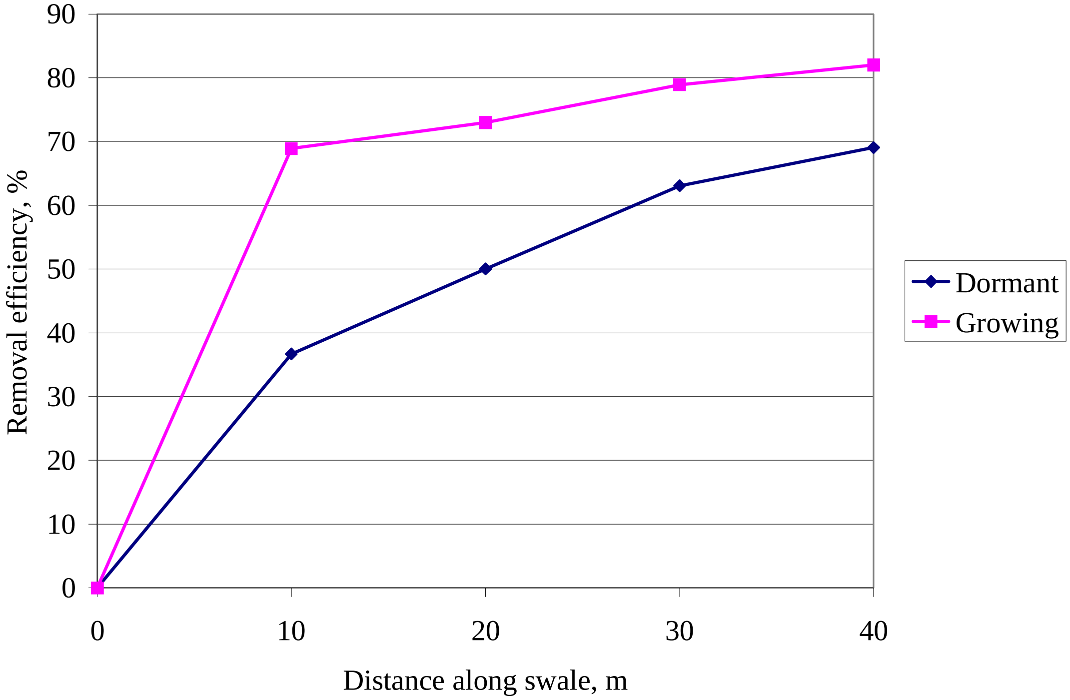

Figure 3.15. Seasonal comparison of TSS removal (water depth = 7.5 cm).

The TSS concentrations observed for the two seasons were compared statistically. The comparison shows that TSS removal efficiencies for the two seasons are significantly different from each other at 40 meters for the 7.5 cm water depth and at 20 meters for the 4 cm water depth at the 90% confidence level. This suggests that suspended solids is better removed during the growing season. On the other hand, zinc, which is often attached to sediments in runoff, was demonstrated higher removal efficiencies during the winter season for the 7.5 cm water depth (Figure 3.16). There are no definitive seasonal differences for zinc at the 4 cm water depth (Figure 3.17).

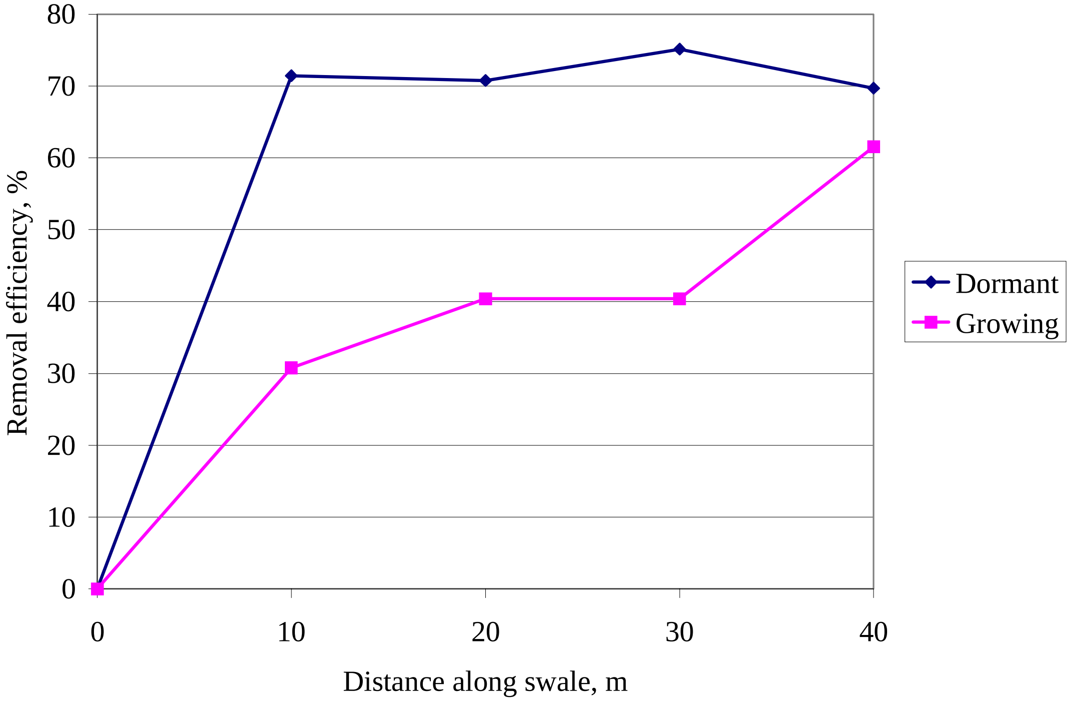

Figure 3.16. Seasonal comparison of zinc removal (water depth = 7.5 cm).

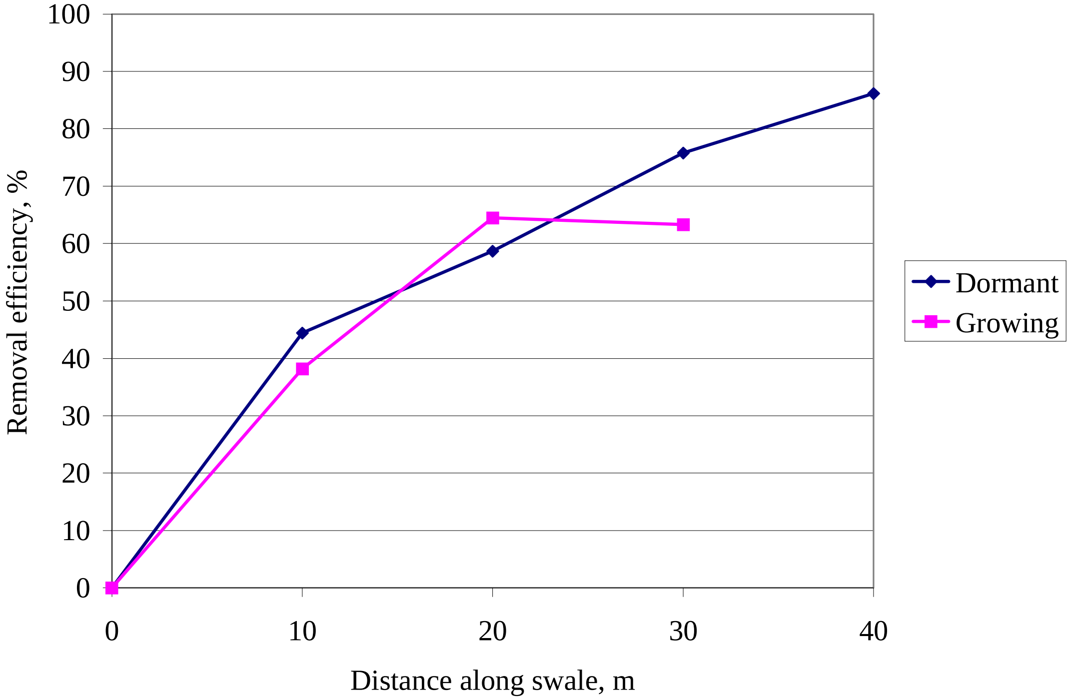

Figure 3.17. Seasonal comparison of zinc removal (water depth = 4 cm).

The higher removal efficiency for sediments in the growth season may be attributed to the increased density of grass blades in the growth season. During the growing season, new green Buffalo grass grew alongside the dead, brown grass from the previous season. The dormant Buffalo grass was shorter than the new growth of grass, and this dead grass continued to shrink and decay throughout April and May of 1997. The dead grass nonetheless contributed to the overall grass blade density, thereby increasing the filtration capability of the grass. Some of the dormant undergrowth was no longer attached to the soil. Much of the dead grass, however, was still anchored to the soil presumably by a remaining root structure. The previous generation of grass was still approximately 7.5 cm tall by the end of April, at the beginning of the growing season experiments. The new grass was 10-12.5 cm tall at that time. The shrinking dormant grass was still approximately 2.5 cm high by the last experiment on May 22.

The decaying grass also may contribute nitrogen and phosphorus and organic compounds to runoff passing through the swale. Previous recommendations to remove grass clippings from mowed swales are directed at reduction in nitrogen and phosphorus loads (Municipality of Metropolitan Seattle, 1992). Removal of the clippings prevents them from decomposing in the swale. Indeed, lower removal efficiencies for organic material, as indicated by COD data, were observed in the growing season than the dormant season at the 7.5 cm water depth (Figure 3.18). Analysis of COD was impossible at the 4 cm water depth due to loss of a runoff sample. However, neither nitrogen (Figure 3.19 and Figure 3.20) nor phosphorus (Figure 3.21 and Figure 3.22) demonstrated lower removal efficiencies in the growing season. In fact, total phosphorus removal increased during the growing season.

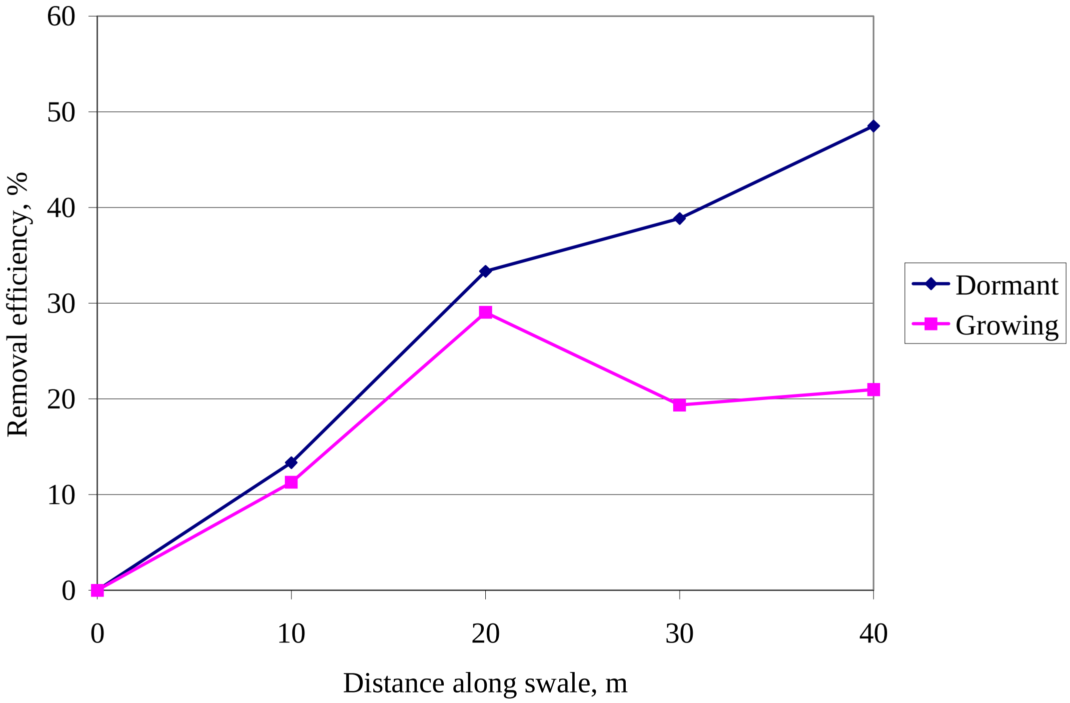

Figure 3.18. Seasonal comparison of COD removal (water depth = 7.5 cm)

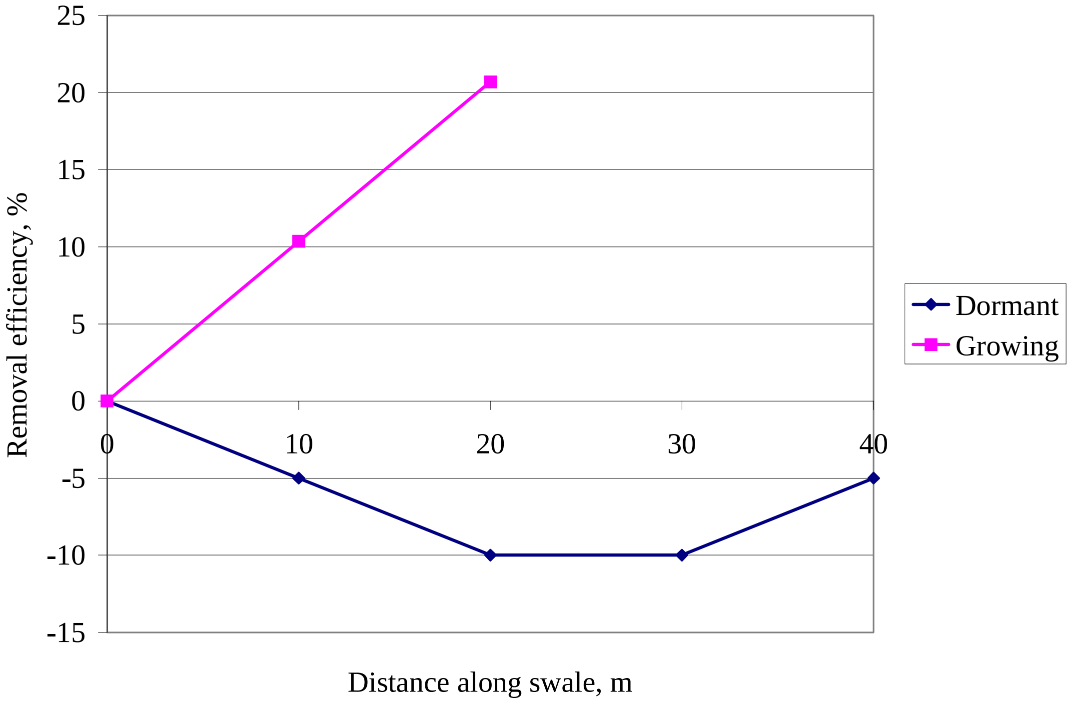

Figure 3.19. Seasonal comparison of nitrate removal (water depth = 4 cm).

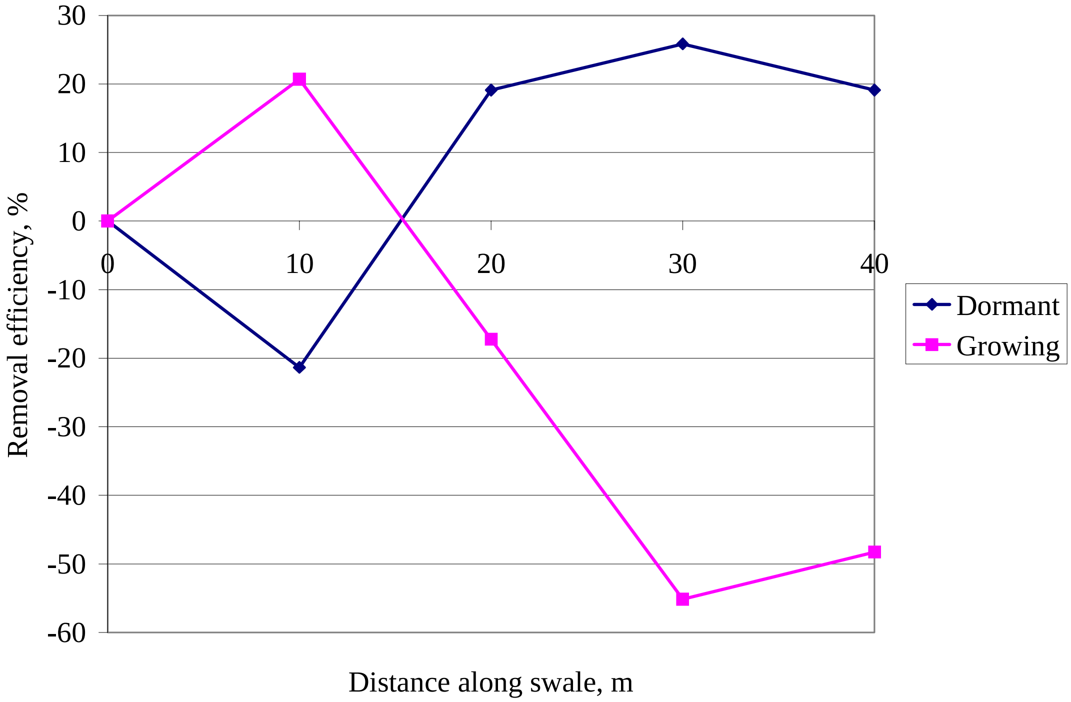

Figure 3.20. Seasonal comparison of nitrate removal (water depth = 7.5 cm).

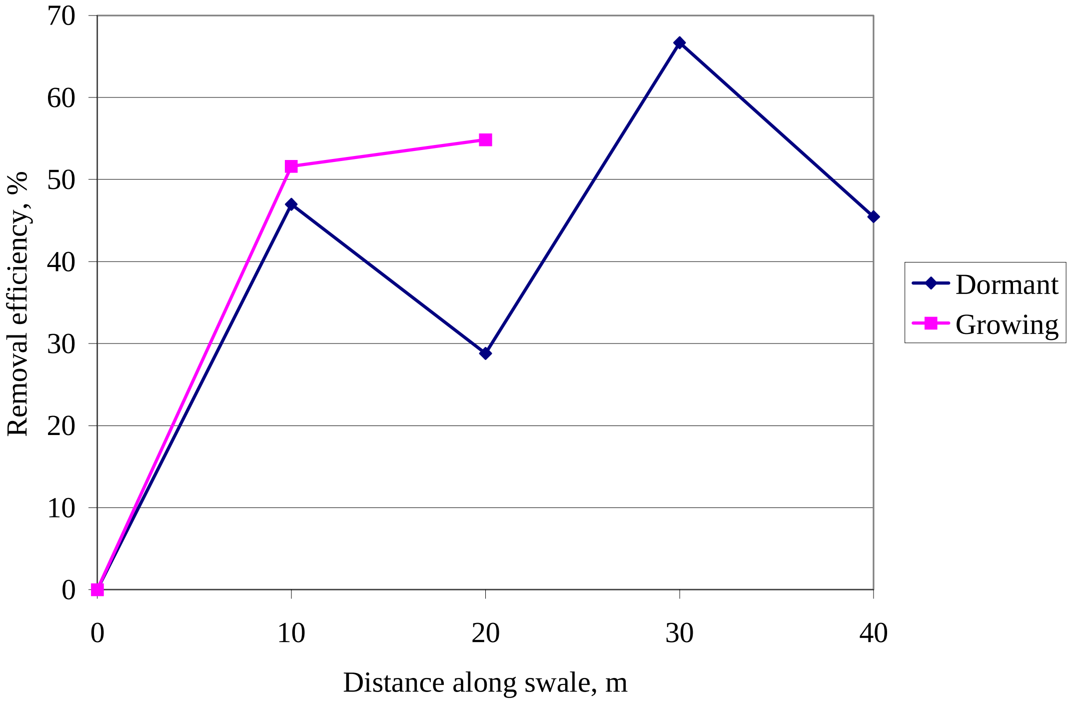

Figure 3.21. Seasonal comparison of total phosphorus removal (water depth = 4 cm).

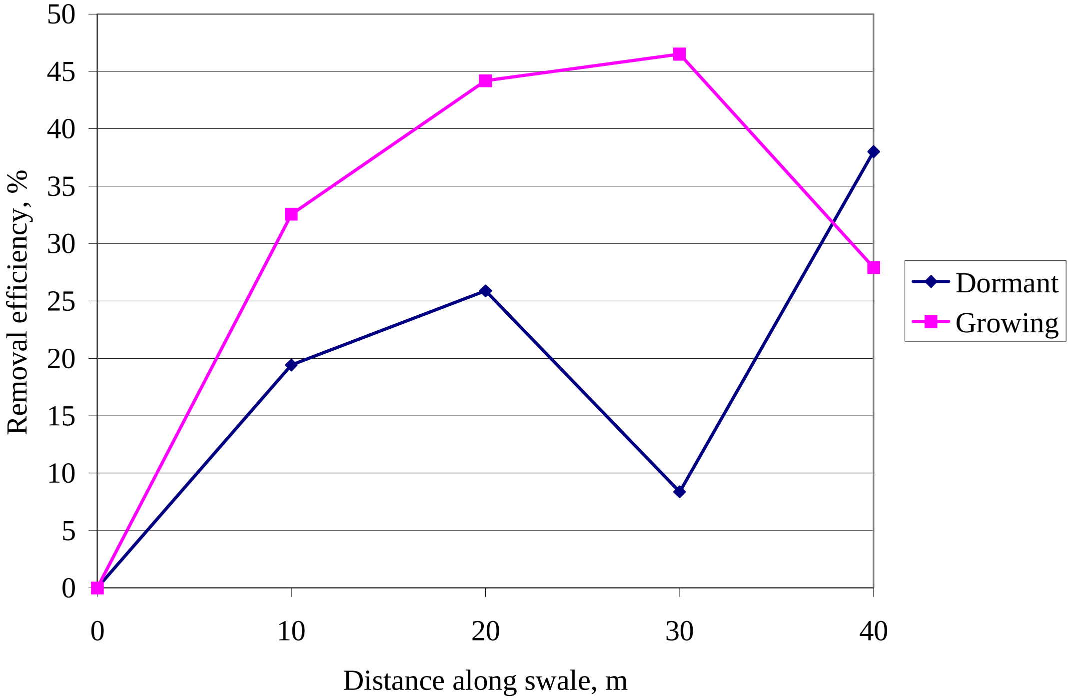

Figure 3.22. Seasonal comparison of total phosphorus removal (water depth = 7.5 cm).

Runoff flowed further down the swale for some dormant season experiments than for growth season experiments at the same water depth (Figure 3.21, etc.). Increased grass blade density may have the slowed the runoff down, which allowed the runoff to infiltrate at a greater rate during growth season experiments than in dormant season experiments. However, warmer, dryer weather may have dried out the soil in the spring, also encouraging infiltration. It is possible that the increased blade density in the spring enhanced detention of the runoff, encouraging infiltration and removal of constituents from the surface runoff.

These results indicate that swales with sodded with Buffalo grass are effective at removing runoff constituents during the dormant and growth seasons. The shift to dormant season did not have any obvious effect on the stiffness of the Buffalo grass blades. The grass blades continue to maintain height and some stiffness in the dormant season, even though the grass was brown and dry. Buffalo grass blade density does increase during the growing season because of dormant grass remaining from the previous season. This answers concerns by a researcher cited in Barrett et al (1995b) regarding reduced efficiencies during vegetation dormancy. In fact, it may be during the growing season, when the previous season’s vegetation is decaying, that removal efficiencies for organic compounds and nitrogen and phosphorus are at their lowest. Other grasses may lose their density and stiffness to greater extents than Buffalo grass during dormant seasons. If this is the case, seasonal impacts on removal efficiency can be expected to be greater for these vegetation types. A more extensive study would be required to discover the seasonal impacts for various kinds of grasses.

3.5.5 Underdrain Water Quality

The simulated highway runoff reached the underdrain by percolating through a top layer of grass sod, 16 cm of topsoil, and 6 cm of gravel before entering the underdrain pipe. Underdrain water quality was sampled for all 11 experiments except for experiments 7 and 9. The underdrain analyses focused on two aspects of the underdrain water quality.

First, changes in underdrain water quality with time were investigated. During construction of the swale, the layers of soil were compacted by wetting the grass thoroughly and walking over the sod several times. However, a slow, additional compaction and settling of topsoil likely occurred in the channel as a result of the percolation of water during the experiments. In addition, grass roots may have grown into the soil, filling cracks and pores in the soil and taking up nitrogen and phosphorus and other constituents from the runoff as the roots establish. These changes may simulate similar changes that occur after construction at sites in the field. The compaction and root development can have an impact on the quality of the underdrain water over time.

Secondly, average removal efficiency for water that entered the underdrain was measured. The underdrain water quality demonstrates the filtering capability of the soil, and reflects water quality of recharge for groundwater in situations with shallow soils.

A steady decrease in the concentration of TSS in the water sampled from the underdrain was observed through the first five experiments (Figure 3.23). This reduction in

TSS concentrations may have been caused by an increase in the filtering capability of the soil, and suggests that soil compaction may have occurred during the first five experiments. This trend of increasing percolate water quality ends, however, after the first five experiments, indicating that further compaction by the infiltrating water was minimal.

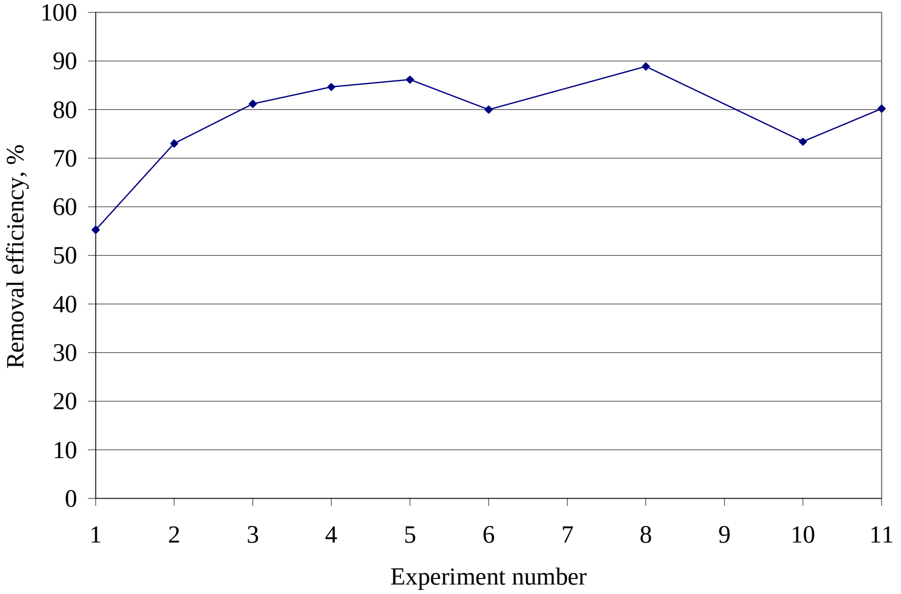

Figure 3.23. Removal of TSS during infiltration in channel experiments.

There are two implications of this trend in suspended solids removal by the topsoil. The first is that construction, which disrupts soil matrix by replacing a settled, stable soil with loose, disjoint soil, can decrease groundwater quality by reducing the filtering capability of the soil. These effects have been documented by other researchers (Barrett et al, 1995b). The second implication is that groundwater quality may increase significantly in the first 5 storm events after construction activities cease. Constituents other than TSS, however, did not demonstrate a decrease in concentration in underdrain water during the first five experiments. Turbidity (Figure 3.24) and total phosphorus (Figure 3.25), for example, showed no recognizable trend in filtering capacity of the soil. Zinc, whose removal is often linked to removal of sediment, showed relatively constant removal via soil filtration over the first 5 experiments (Figure 3.26). This may indicate that construction has little effect on the filtration capacity of soils for pollutants that are heavily associated with smaller particles, such as many metals (Barrett et al, 1995b), or pollutants that are soluble.

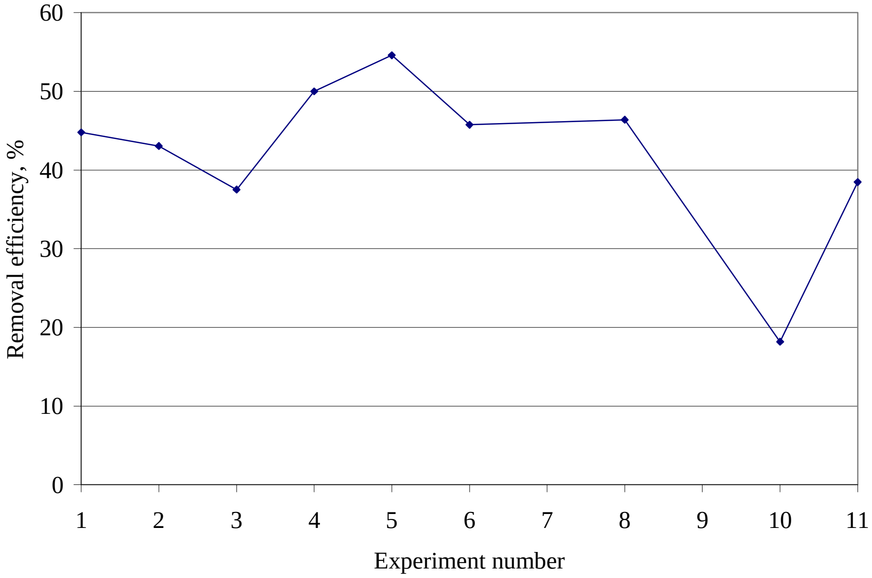

Figure 3.24. Removal of turbidity during infiltration in channel experiments.

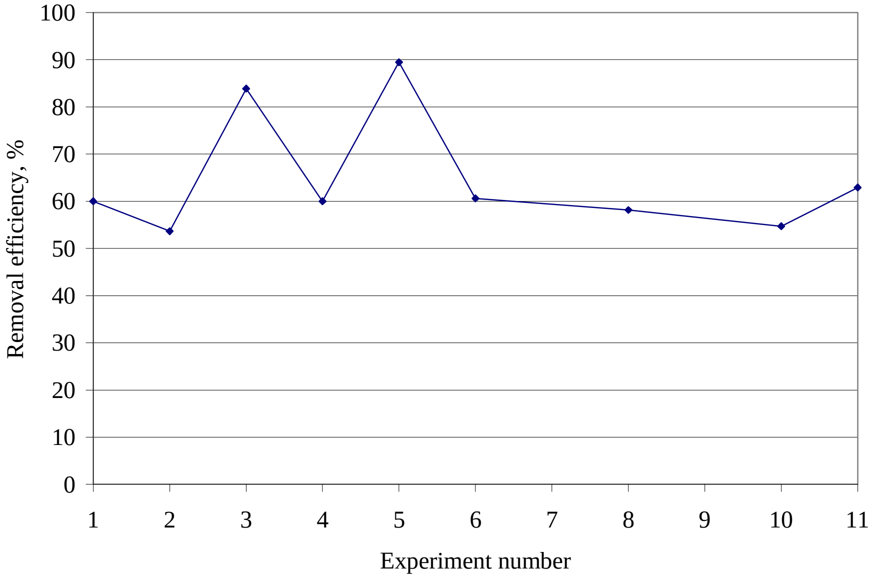

Figure 3.25. Removal of total phosphorus during infiltration in channel experiments.

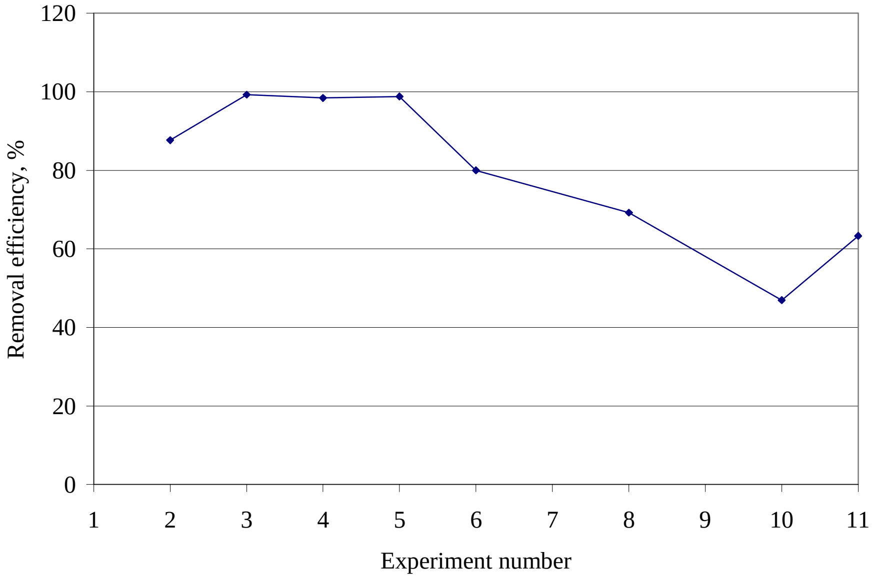

Figure 3.26. Removal of zinc during infiltration in channel experiments.

The underdrain water was used to calculate average removal efficiencies for the soil during infiltration. These removal efficiencies are listed in Table 3.6 below. The average removal efficiency of the soil was calculated using an average of removal efficiencies for each constituent over all experiments, with the following exceptions. Only experiments 5-11 were used to calculate a representative removal efficiency for TSS. Also, data for metals other than zinc is restricted to experiments 2 through 7 because of difficulties with analytical equipment.

With the exception of nitrate, the removal of constituents during infiltration was at least 37%. The underdrain water quality was higher than the surface runoff after 40 meters of treatment by the grassed swale. The primary mechanism of removal for the percolated runoff is filtration by the soil. It is likely that a thicker layer of topsoil than the 16 cm of soil used in these experiments would result in greater attenuation of pollutants.

Table 3.6. Average removal efficiency for constituents based on underdrain water quality.

Constituent	Average Removal Efficiency %
TSS	78
Turbidity	42
COD	49
NO_3	-45
TKN	37
Total phosphorus	65
Zn	80
Pb	41
Fe	74

3.5.6 Summary of Channel Swale Results

A grassed swale constructed in a steel channel removed over 50% of suspended solids, zinc, and lead after 40 meters of treatment by the swale. COD concentrations decreased 25 to 79 percent after 40 meters of treatment, and reduction of nutrient concentrations varied from negative to 45%. In general, the majority of pollutant removal occurred in the first 20 meters of swale. Increasing the water depth and velocity of surface flow of runoff in the swale reduced the removal efficiency of the swale.

More suspended solids were removed in the channel swale in the growing season than in the dormant season. During the growing season, new grass stood alongside dormant grass which increased the grass blade density in the swale. This increase in removal is attributed to the combined filtering capacity of the dead material and live grasses. The removal of nutrients and organic material may decline in the growing season, when decay of vegetation from the previous season contributes to the constituents in the runoff.

The concentrations of constituents in runoff that had percolated through the soil in the swale were generally lower than the concentrations in surface runoff after 40 meters of treatment by the swale. However, the impact of swales on groundwater quality in the field will vary with thickness of soil to groundwater, permeability of the soil, and the constituents in the highway runoff.

Chapter 4 Field Experiments

4.1 Introduction

A primary objective of this study is measurement of the efficiency of vegetated buffer strips for removing constituents in highway runoff in the Austin, Texas area. The efficiency of a vegetated buffer strip was determined by measuring concentrations of pollutants in samples of the runoff directly off the road and after highway runoff passes through the filter strip. Efficiency was calculated based on the changes in the average concentrations in the runoff samples at these locations.

Two filter strip sites were monitored in this study. Four hundred twenty-three (423) samples were collected over approximately thirty-four (34) storm events at the two sites. Two sites were selected to investigate the potential for variation in performance between vegetated buffer strips. Also, monitoring of two sites under different conditions offers a comparison that might provide insight into the factors that affect the removal efficiency of filter strips.

4.2 Methods and Materials

4.2.1 Site Selection

Field sites were selected from existing highway medians or other grassy areas near highways in the Austin area. The primary criteria that were used in the selection of field sites include:

- configuration of the drainage system at the site allowed for sampling of runoff from the highway and from the vegetated buffer strip, i.e., the road and filter runoff were not contaminated with water from other areas;
- the drainage to the vegetated buffer strip originated from a highway and did not include

runoff from other areas.

Secondary criteria included choosing two sites with different characteristics (e.g., vegetation and slope), proximity to the research facility, safety of the personnel, and security of the equipment.

Two sites were selected for monitoring. The first vegetated buffer strip is located in the median of MoPac (Loop 1) where the highway crosses Walnut Creek in northwest Austin. The Walnut Creek site was monitored during a previous study (Irish et al, 1995), and some data from the prior research was utilized in this study. This site was monitored over the period of April 1994 to May 1997. However, only data collected from the period from February 1996 to May 1997 was used to describe runoff from the road because the sampling system was modified.

The second of the two filters is located in the median of U.S. 183 immediately north of MoPac. The U.S. 183 site is also in northwest Austin. This site was monitored from March 1996 to May 1997.

4.2.2 Site Descriptions

Walnut Creek

The vegetated buffer strip at Walnut Creek is a 1055 m section of highway median which collects runoff from the northbound and southbound lanes of MoPac just south of Walnut Creek (Figure 4.1 below). The median was designed originally as a hydraulic conveyance and not as a vegetated buffer strip. The median cross-section is V-shaped with a rounded bottom. Runoff from the highway flows as sheet flow down the sides of the grassy slope. The runoff then flows along the center of the median into 4 drop inlets situated along the centerline of the median. The drop inlets discharge to a 1.22 m concrete storm drain that conveys the runoff to Walnut Creek. This storm drain collects runoff from the road and median, as well as from several grassy shoulder areas. The total drainage area of the storm drain is approximately 10.46 ha (104,600 m^2). Approximately 38% of the drainage area is paved with asphalt.

Figure 4.1. Mopac at Walnut Creek filter strip.

Runoff from either the southbound or the northbound lanes of MoPac flows to the median at any location along its length, since the cross-sectional slope of the highway changes in this section. The southern half (approximately 500 m) of the median receives runoff from the 3 southbound lanes only, and the northern 500 m of the median receives runoff from the 3 northbound lanes. Lanes not feeding to the median drain to grassy shoulder areas, which eventually drain to the 1.22 m storm drain.

The side slopes of the median vary from approximately 6.3 to 12.4%, with an average grade of approximately 9.4%. The total width of the median varies from 15.5 m to 16.2 m. The distance from the pavement edge to the lowest point in the median, or the treatment length of the filter strip, varies from 6.7 m to 8.2 m. The median drains northward with the exception of the northernmost 150 m, which drain southward to the northernmost drop inlet. Slope of the median along the centerline varies from approximately 0.75% to 2.9%, with an average grade of 1.7% along the northward-draining section.

The vegetation cover in the median is a mix of bunch grass and sod grass. A summary of the vegetation transect of the site performed in October of 1996 is shown in

Table 4.1.

Table 4.1. Vegetative composition of Walnut Creek median (October 1996).

Species Name	Percent Composition
Bermudagrass	30
Illinois Bundleflower	30
Medow Dropseed	19
Little Bluestem	10
Florida Palpalum	7
Indiangrass	2
Bare ground	2
Prairie Buffalo grass	<1

The median was planted originally in Sideoats Grama, Green Sprangletop, Switchgrass, Little Bluestem and Buffalo grass about 1989.

Water from the Mopac bridge over Walnut Creek drains to pipes which open to the creek below. The drainage area is paved with asphalt, thus providing an ideal source for water quality sampling of the road at this site.

Approximately 47,000 vehicles per day traveled on the 3 northbound and 3 southbound lanes along this section of MoPac in April 1995. The hourly traffic ranged from 100 to 3600 vehicles.

<u>183 at MoPac</u>

The vegetated buffer strip monitored at U.S. 183 at MoPac is the 356 m of grassy median of U.S. 183 just north of MoPac. This median was designed originally for hydraulic conveyance. Only the 3 southbound lanes of 183 drain into the median; the northbound lanes drain to a curb-and-gutter storm drain. The cross section of the median is V-shaped with a rounded bottom.

Figure 4.2. Vegetated buffer strip at U.S. 183 site.

The side slope of the median varies from 10.3% to 15.3%, and has an average slope of approximately 12.1%. The distance from the edge of the pavement to the lowest point in the median, or the treatment length of the filter strip, varies from 9.1 m to 7.3 m. The median drains southward with an average slope of 0.73%, varying from approximately 0.60% to 0.83% along its length. The northern edge of the drainage area of the median begins at a drop inlet that collects runoff from areas further north. The median ends at a drop inlet 356 m down gradient. This drop inlet connects to a 0.61 m concrete storm drain. The drainage area of the drop inlet consists only of the southbound lanes of 183 and the median itself. This area is 13,000 m^2, approximately 52% of which is paved.

The vegetative cover of the filter strip is primarily Prairie Buffalo grass, which was installed as plugs of sod in 1991. The vegetative composition of the median is summarized in Table 4.2. The high percentage of bare ground was caused by a brush fire that occurred sometime around July 1996 in the median. All signs of the fire disappeared within several months.

Table 4.2. U.S. 183 at MoPac Vegetation Composition (October 1996).

Species Name	Percent Composition
Prairie Buffalo grass	76
Cedar Sedge	6
Texas Frogfruit	2
Illinois Bundleflower	1
Bermudagrass	1
Bare ground	14

A curb and gutter system drains the northbound lanes of U.S. 183 at this site. All of the runoff collected in these gutters originated from the highway. The gutters drain to an 0.46 m concrete storm drain, providing an appropriate location for sampling road water quality at this site. The 1995 annual average daily traffic along U.S. 183 at this site was 111,000 vehicles.

Site Description Summary

A summary of the characteristics of the two vegetated buffer strips is given in Table 4.3.

4.2.3 Sampling/Monitoring Setup

The monitoring of both sites included the following tasks:

1) sampling of runoff from both the road and the grassy median;
2) measuring amount of flow from both the road and the median; and
3) measuring rainfall.

Table 4.3. Vegetated buffer strip description summary.

Characteristic	Walnut Creek	U.S. 183
Centerline length (m)	1055	356
Width of entire median (m)	15.5 to 16.2	14.9 to 19.5
Filter strip treatment length (m)	7.8 to 8.1	7.5 to 8.8
Average median side slope	9.4%	12.1%
Average centerline slope	1.70%	0.73%
Cross-sectional shape	V, rounded bottom	V, rounded bottom
Drainage area (m^2)	104,600	13,000
Vegetation	mixed	mostly Buffalo grass
Average Daily Traffic	47,000	111,000
Filter drainage area % paved	38%	52%
Road drainage area % paved	100%	100%

4.2.3.1 Equipment

Two Isco 3700 samplers, one Isco 674 rain gauge, and two Isco 3230 bubbler flow meters were installed at each site to sample runoff, measure rainfall, and measure flow, respectively. Two samplers and flow meters were needed in order to monitor both the road and the vegetated buffer strip. A 12 volt battery recharged by a solar panel powered the equipment. The samplers, flow meters and battery at both sites were kept in a closed steel housing. Other equipment, such as pipes, tubing, and weirs also were used and are described in sections below.

The bubbler flow meter measures flow by measuring the pressure required to force air out of a tube. This pressure indicates the height of water above the tube. The height of the water is converted to flow using equations reflecting the characteristics of either the pipe (i.e., smoothness and slope of the pipe), the weir (i.e., type and angle of the weir), or other characteristics depending upon the type of flow measuring device.

The sampler, when triggered by the flowmeter, pumps water from the area being sampled through a plastic tube and into sample bottles (see Sampling/Monitoring Procedures, page 59). The Isco 3700 samplers contained 24 bottles each holding 350 mL of sample. The rain gauges are tipping gauges with increments of 1/100 inch.

Flow and rainfall data was relayed to the flow meter, where it was stored. This information was periodically downloaded onto a laptop computer for analysis.

4.2.3.2 Walnut Creek Setup

Vegetated buffer strip

Samples from the vegetated buffer strip discharge at Walnut Creek were collected from the outfall of the 1.22 m storm drain. The runoff sample tube was fastened to the inside of the pipe several feet from the outfall to Walnut Creek. The flow meter bubbler tube was fastened to the pipe several feet further inside along a joint between two pieces of the pipe.

Flow in the storm drain was calculated using Manning’s equation for pipe flow. The following is Manning’s equation:

$$Q = \frac{1000AR^{2/3}S^{1/2}}{n}$$

where:

Q = flow rate (L/s),

A = cross-sectional area of flow (m^2),

R = hydraulic radius (m),

S = slope of the pipe (m/m), and

n = roughness coefficient of the pipe (n = 0.013).

Flowlink software was used to analyze flow data. Inputs were pipe slope, roughness and diameter, and the measured water height. The flow was calculated automatically. The flowmeter was calibrated by capturing discharge in a bucket over a measured time. The slope was adjusted so that flowrate calculated by Flowlink matched the measured flow.

Road

Runoff from the MoPac bridge over Walnut Creek drains to vertical openings in the road surface which drop water to the ground below. A 10.2 cm PVC pipe was installed to connect one of these openings to a wooden collection box at ground level. The box was 1.85 m long by 1.22 m wide by 0.61 m tall. Runoff from the road entered the box via the pipe, and discharged over a weir. The end of the sample tube from which runoff was collected initially was placed in the bottom of the box; however, the tube was moved to inside the PVC pipe to prevent sampling of resuspended sediment that had settled in the box. The flow meter bubbler tube was fastened to the bottom of the box and flow was measured from the road by gauging the height of water behind the weir.

The weir in the collection box was a compound V-notch weir. The weir has 3 sections; the bottom portion is 20.1 cm tall and has an angle of 30 degrees; the middle portion is 4.8 cm tall at a 90 degree angle, and the upper portion is rectangular with height 5.3 cm. In these experiments, the height of water in the weir rarely exceeded 20.1 cm; therefore flow was calculated with the assumption that a 30 degree weir was used. Flowlink software calculates the flow over the weir using built-in formulas for flow over a 30 degree V-notch weir. The rain gauge for the Walnut Creek site was located several feet from the 1.22 m outfall to the creek.

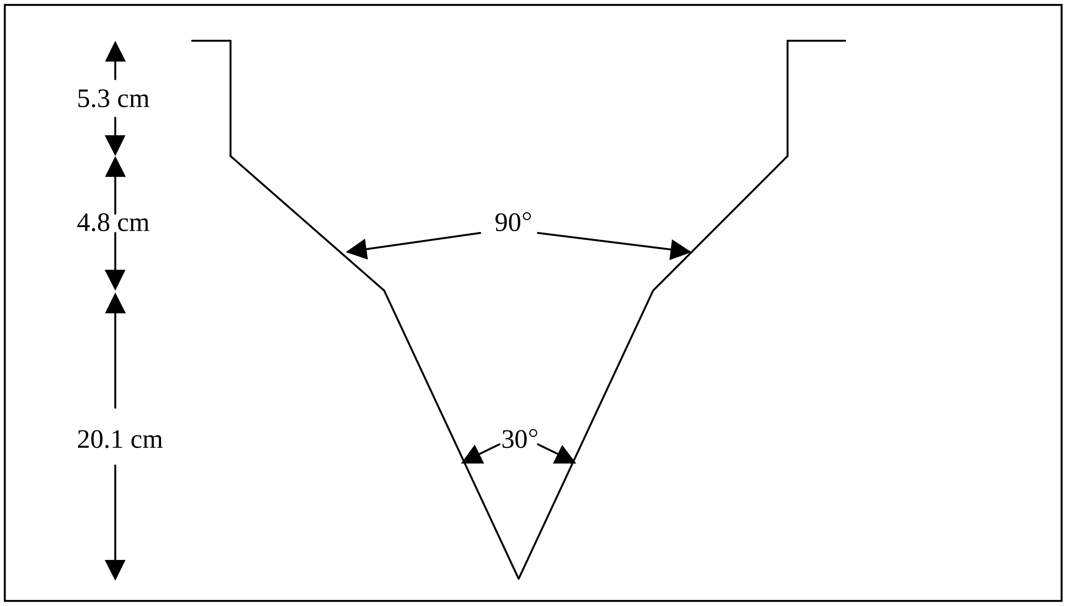

Figure 4.3. Compound V-notch weir for flow measurement.

4.2.3.3 183 at MoPac Site

Vegetated buffer strip

Discharge from the vegetated buffer strip at the U.S. 183 site was sampled from the storm drain which collects runoff from the filter. The end of the sampler tube was fastened to the pipe approximately 60 feet from the drop inlet. No storm drain connections conveyed additional water to the drain prior to this spot, i.e., 100% of the sampled water had passed across the filter. The flow meter bubbler tube was located several feet upstream of the sampler tube end.

Road

Runoff from the road at U.S. 183 was sampled from a storm drain which collects water from a curb and gutter draining the northbound lanes of U.S. 183. The sampler tube end was fastened to the bottom of this drain and the flow meter tube was fastened several feet upstream of the sampler tube.

Flow from the filter strip and road were calculated using Flowlink software. The flowmeter for the 183 filter strip was also calibrated using a bucket and stopwatch. The slope adjusted so that the flowmeter was accurate, similar to the calibration at the Walnut Creek filter strip flowmeter. The road was not calibrated; however, the road flow measurements were accurate relative to other road flow measurements. This relative accuracy was needed to weight the sample concentrations against each other so that weighted mean concentrations for the road runoff could be calculated. The rain gauge at the U.S. 183 site was located at the downstream end of the median, approximately 32 m from the downstream drop inlet.

4.2.4 Sampling/Monitoring Procedures

The flowmeters triggered the samplers during a storm event when the water level at the monitoring location reached a designated height. Once this water height was reached, samples were collected on a programmed timed schedule that varied for each location. These schedules are listed in Table 4.4. The schedules were dependent upon the duration and size of the storm peak and tail typical for each location. The samplers filled 4 bottles per sample; thus, 6 samples were possible from the 24-bottle samplers before the sample bottles required replacement. No more than 6 samples were taken for most storms. During the storm, flow and rainfall were recorded every 5 minutes.

Table 4.4. Schedule for taking samples during storm events.

Location	Elapsed time between samples (minutes)
Walnut Creek road	30, 30, 60, 60, 60
Walnut Creek filter	15, 30, 30, 60, 60
183 road	15, 15, 30, 30, 60
183 filter	30, 30, 30, 60, 60

Sample bottles were collected immediately after daytime storms; however, samples from evening, night and weekend storms were collected the following day. The samples were redistributed into laboratory bottles, labeled, logged, preserved, and refrigerated until the analyses were performed at CRWR.

4.2.5 Numerical Analysis

Concentration Reduction

A concentration reduction was calculated for each constituent by finding the average concentration of the constituent observed for the highway runoff and the median discharge and applying the following formula:

$$R = \frac{(C_r - C_s)}{C_r} \times 100\%$$

where

R = concentration removal efficiency, %

C_r = average concentration observed in runoff from highway (mg/L, CFU, or NTU)

C_s = average concentration observed in discharge from vegetated buffer strip (mg/L, CFU, or NTU)

The average concentrations were calculated in a process involving several steps. An event mean concentration (EMC) for the constituent was calculated for each storm. The EMC is an average concentration for a storm calculated using concentrations from several discrete samples which are weighted according to the amount of flow that was passing the collection point around the time each sample was taken. Appendix B includes sample concentrations and associated flow volumes used for weighting the samples.

The flow associated with each sample was determined using Flowlink software and was dependent on the sampling schedule for the site. Normally, the flow associated with each sample was the volume of runoff that passed the sampling tube from the time halfway between the previous sample and the current sample to the time halfway between the current sample and the subsequent sample. If samples 3, 4, and 5 of a storm were taken at 6 A.M., 7 A.M., and 8 A.M., then sample 4 would be associated with the volume of flow passing the flow meter bubbler tube between 6:30 and 7:30 A.M. The time interval before and after the first and last samples was normally equal to standardize these calculations.

An average of all flow-weighted averages for each storm was used to calculate the final concentrations (listed in Table 4.5). The average is the preferred estimator for the mean of a lognormally distributed data with coefficient of variation less than 1.2 (Gilbert, 1987). The storm concentration data for the sites are lognormally distributed, and the coefficient of variation for the majority of the flow-weighted averages of constituents was less than 1.2. The average was used all constituents for simplicity. Summaries of flow-weighted averages for all storms and the average concentration calculations for each site are presented in Appendix C.

Any concentration that was below the detection limit of the analytical procedure was assumed to be equal to the detection limit for the purpose of this evaluation. This approach resulted in conservative (lower) removal efficiencies. The majority of concentrations below the detection limit were observed for samples from the filter strips. Hence, assuming the detection limit was likely to increase the average concentrations in the discharge of the filter strip to a greater extent than in the highway runoff, and as a result, the calculated removal efficiencies will be smaller and more conservative.

Load Reduction

The observed reductions in concentrations demonstrate the ability of a vegetated buffer strip to remove constituents via sedimentation, filtration, dilution, biological activity, and other physical and chemical mechanisms. However, additional removal of constituents occurs as the runoff infiltrates through the soil. The reduction in total load includes the effects of infiltration and represents the total reduction in the mass of constituents that occurs in the filter strip.

An annual pollutant load is the mass of a particular constituent that is discharged through an outfall over a one-year period. Calculating a reduction in the constituent load requires some interpretation. In this study, the calculation of load reduction is directed at establishing the difference between the constituent load assuming the highway runoff were conveyed directly to a storm sewer without treatment and the load from the highway runoff after treatment by the filter strip.

Reduction in pollutant load was calculated as a percent of total load for each site using the following formula:

$$R = \frac{(L_H - L_F)}{L_H} \times 100\%$$

where

R = reduction in pollutant load from the highway as a result of treatment by the vegetated buffer strip, %

L_H = annual pollutant load to receiving waters if the runoff from the highway was not treated by the filter, kg/yr

L_F = annual pollutant load to receiving waters from the vegetated buffer strip drainage area with runoff from the highway being treated by the filter, kg/yr

Annual pollutant loads (L_H and L_F) were calculated using an adaptation of the "simple method" (EPA, 1992). The simple method was converted for metric units. The simple method used in this study is defined by the following equation:

$$L = [(P)(CF)(Rv)](C)(A)(0.00001)$$

where

L = annual pollutant load at the outfall of the drainage area (kg/yr)

P = average annual precipitation in Austin, Texas (82.6 cm/yr)

CF = correction factor that adjusts for small storms where no runoff occurs (0.9)

Rv = runoff coefficient of the drainage area concerned (m^3 runoff/m^3 rainfall)

C = average concentration of the pollutant (mg/L)

A = drainage area (m^2)

The number 0.00001 is a conversion factor used to obtain correct units. Additional notes concerning the origin of drainage area and runoff coefficient values are given below.

Drainage Area

The load after treatment by the vegetated buffer strip (L_F) was calculated based on a drainage area, A, that was assumed to be the entire drainage area of the outfall for the vegetated buffer strip. The load assuming the vegetated buffer strip was not treating the highway runoff (L_H) was calculated assuming the drainage area A was the area of the highway pavement.

Runoff Coefficient

A runoff coefficient is the fraction of volume of rainfall that produces runoff in a drainage area. In other words, the runoff coefficient is the fraction of rainfall from an area that does not infiltrate into the soil. The coefficients used to calculate L_F, the constituent loads after treatment by the filter strip, were calculated using flow data measured at the two filter strip collection drains and rainfall data collected at each site. The volume of rainfall was calculated by multiplying rainfall depth for each storm by the catchment area. Runoff volume was calculated using Flowlink software with the collected flow data. Plotting rainfall and runoff volumes for all storms results in a linear trendline. The slope of this graph is the runoff coefficient. The runoff coefficients used to calculate the loads without treatment by the filter strip (L_H) was 0.95.

4.2.6 Grab Samples

In addition to the continuous monitoring at the two filter sites, grab samples were taken along the length of the vegetated buffer strip at U.S. 183 during 5 rain events. The objective of these grab samples was to determine where the treatment was occurring, i.e. down the length of the median or along the side slopes of the median.

Grab samples were collected at points 240, 180, 120, 60, and 0 meters upstream of the drop inlet along the center of the median at the U.S. 183 site. The samples were collected while standing on the northbound side of the centerline of the median since only the southbound lanes of 183 drain into the filter. Samples were collected starting at the upstream end of the median in order to find changes in concentration for the runoff as it traveled down the median.

4.3 Field Results

4.3.1 Runoff Coefficients

The runoff coefficient for each site was calculated using the data plotted in Figure 4.4 and Figure 4.5. The calculated runoff coefficient for the Walnut Creek site is 0.30. This value agrees well with runoff coefficients for other sites in Austin with comparable percentages of impervious cover (Barrett, 1997). The runoff coefficient for the filter strip at U.S. 183 was initially calculated to be 0.66 (Figure 4.5); however, a value of approximately 0.40 is normal for a drainage area that is 52% paved, such as the U.S. 183 filter strip drainage area. The higher-than-expected runoff coefficient was suspected to be caused by runoff entering the drainage area from unanticipated sources.

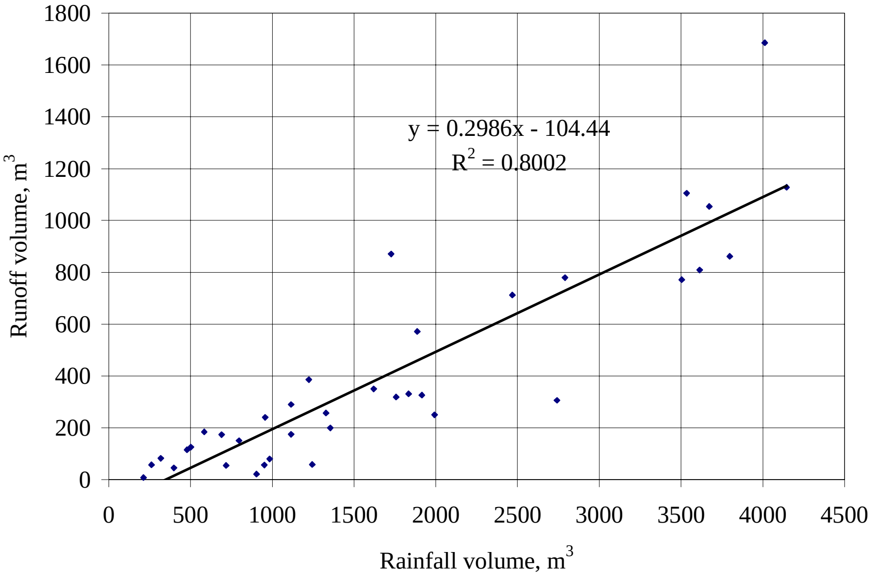

Figure 4.4. Runoff coefficient of the filter strip drainage area at Walnut Creek.

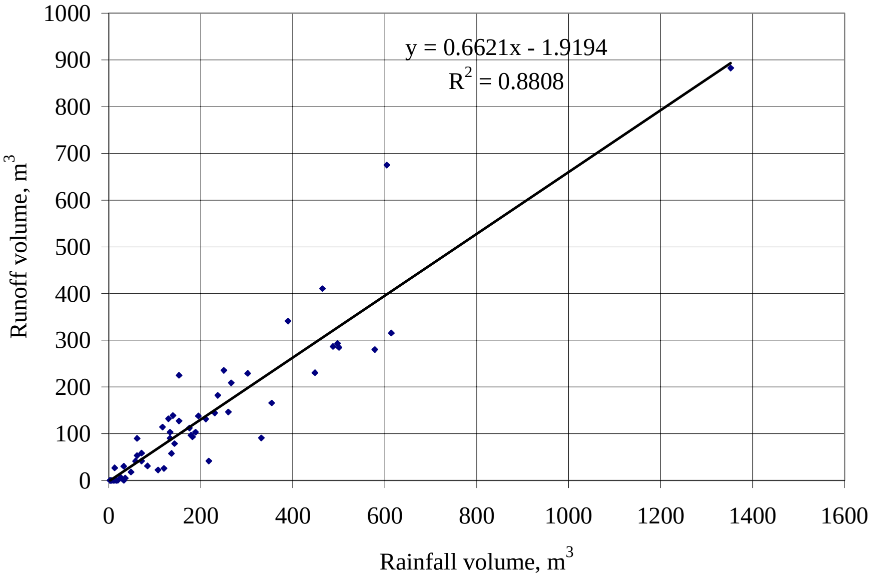

Figure 4.5. Initial calculation of runoff coefficient of filter strip drainage area at U.S. 183.

An inspection of the site proved this to be the case; erosion at the upstream drain at the U.S. 183 site caused a large amount of flow to bypass the drain and flow into the catchment area of the U.S. 183 filter strip. It was thus impossible to define the area that should be used for rainfall volume calculations at the U.S. 183 site. Therefore, a runoff coefficient and area for the filter strip drainage area at the U.S. 183 site were assumed. The area used was 13,000 m^2. This is the area of highway and median that would have drained to the filter strip drop inlet if the upstream drain erosion had not occurred.

The runoff coefficient was calculated using results from a recent study which developed a relationship between runoff coefficient and impervious cover based upon monitoring of multiple storm events at each of 18 sites in the Austin area (Barrett, 1997). The study used the following second-order equation to describe the relationship:

$$Rv = 0.3428(IC)^2 + 0.5677(IC) + 0.0125$$

where

Rv = runoff coefficient, m^3 runoff/m^3 rainfall
IC = fraction of impervious cover for the site.

According to this equation, the runoff coefficient for a site with 52% impervious cover is expected to be 0.40. This value was used for calculation of L_F. In summary, the pollutant load calculations for the U.S. 183 filter are the best possible estimate of what the loads would be if the filter were not receiving unintended runoff from other drainage areas.

4.3.2 Concentration and Loading Reductions

The average concentrations and percent concentration reduction observed at both field sites are given in Table 4.5. Table 4.6 includes the pollutant loads and loading reductions observed at both sites.

Table 4.5. Reductions in concentrations observed at two vegetated buffer strips.

	U.S. 183			Walnut Creek		
Constituent	Road Mean mg/L	Swale Mean mg/L	Reduction %	Road Mean mg/L	Swale Mean mg/L	Reduction %
TSS	157	21	87	190	29	85
Turbidity**	55	17	69	70	16	78
Fecal Col*	96000	280000	-192	NA	240000	NA
Fecal Strep*	23000	40000	-74	7100	41000	-477
COD	94	37	61	109	41	63
TOC	33.9	16.7	51	41.3	19.5	53
Nitrate	0.91	0.46	50	1.27	0.97	23
TKN	2.17	1.46	33	2.61	1.45	44
Total P	0.55	0.31	44	0.24	0.16	34
Zinc	0.347	0.032	91	0.129	0.032	75
Lead	0.138	0.082	41	0.093	0.077	17
Iron	3.33	0.69	79	2.04	0.51	75

* units are CFU/100mL, ** units are NTU

Table 4.6. Constituent loadings with and without treatment by the vegetated buffer strip.

	U.S. 183			Walnut Creek		
Constituent	Untreated Load, L_H kg/yr	Treated Load, L_F kg/yr	Load Reduction %	Untreated Load, L_H kg/yr	Treated Load, L_F kg/yr	Load Reduction %
TSS	748	79	89	5320	671	87
Turbidity**	265	66	75	1980	367	81
Fecal Col*	4600	11000	-136	NA	56000	NA
Fecal Strep*	1100	1500	-41	2000	9600	-380
COD	450	144	68	3060	952	69
TOC	162	65	60	1160	455	61
Nitrate	4.3	1.8	59	36	23	36
TKN	10.3	5.63	46	73	34	54
Total P	2.65	1.20	55	6.73	3.70	45
Zinc	1.66	0.124	93	3.62	0.75	79
Lead	0.661	0.317	52	2.61	1.79	31
Iron	15.9	2.66	83	57	11.8	79

* 10^9 CFU/yr, ** NTU*L/yr

Discussion of Concentration and Loading Reductions

In general, the monitoring results demonstrate good to excellent (often greater than 75%) removal rates for suspended solids and metals, good removal of organic compounds (60-70%), moderate removal rates for nutrients (25-60%), and negative removal of bacteria. In addition, though the highway runoff and the filter strip discharge concentrations often differ between the two sites, the removal rates for all constituents between sites are remarkably similar.

The constituent loading removal rates observed at the two filter strips are considerably higher than those found in previous studies (Young et al, 1996; Yu and Benelmouffok, 1988). This observation is not true for all constituents and all studies. The Young et al (1996) report refers to a filter strip study with comparable TSS, phosphorus, and lead removals (70, 40, and 25 percent, respectively) to this study, but removal efficiencies reported for zinc and nitrate/nitrite (40 and 10 percent, respectively) were lower than those found for the Austin, Texas filter strips. Yu and Benelmouffok (1988) report lower removal efficiencies for sediments, nutrients, and metals than the removals seen in this study. The reason for the higher removal efficiencies observed in the Austin, Texas study is difficult to identify with certainty. One possible reason is that the filter strips in other studies treated runoff from a larger drainage area than the filter strips in this study, which treated runoff only from a 3-lane highway. The Yu and Benelmouffok filter drained an 18-acre area near a highway and shopping center complex. The larger drainage area could have resulted in higher runoff velocities and water depths, thereby reducing the effectiveness of the filter strip. The difference in drainage areas might explain why filter strips may be “unreliable in urban settings” (Schueler et al, 1992), but more appropriate for treating runoff from areas with relatively small drainage areas, such as highways, as demonstrated by the results of this study. Highways provide a relatively small catchment area for a filter strips that lie along their entire length. Water depths and velocities are normally low and filter strips can act effectively in such a configuration.

The results of this study indicate that filter strips of relatively short lengths, 7 to 9 m, can be effective for removing a variety of constituents in highway runoff. The consistency seen in removal efficiencies between the two sites further confirms the removal efficiencies, and indicates that similar removal efficiencies could be expected for filter strips with similar characteristics to those studied here. This observation is particularly promising since medians that already are present along highways in Austin and in other areas may be of comparable size, geometry and other aspects to those monitored in this study. Thus, the inclusion of an effective BMP in the design of a highway is straightforward. The highway runoff can be allowed to drain as sheet flow down the sides of a grassy median or shoulder area. This design could be implemented for highways already built by the removal of curbs so that runoff flows into the median to the storm drains along the median for runoff collection.

The pollutant removal capabilities of filter strips treating highway runoff are comparable to those of structural controls, such as sand filters. A comparison of removal efficiencies for the monitored filter strips and several sand filters is given below in Table 4.7. In the Highwood and BCSM sand filters, sedimentation and filtration occur in one basin; the Seton Pond facility has separate detention and sand filtration basins. The removal efficiencies for the sand filters reflects pollutant removal only for the runoff that was captured by the facility and does not reflect reduction in removal efficiency caused by bypass of runoff during large storms. All three sand filters are located in the Austin, Texas area; the Seton Pond results are from a monitoring study performed in conjunction with this study. The filter strip removal efficiencies are comparable to sand filter removal efficiencies for all constituents.

Table 4.7 Comparison of filter strip performance with three sand filtration systems.

	Sand Filters (% mass reduction)			Vegetated Buffer Strips (% mass reduction)	
Constituent	Highwood	BCSM	Seton Pond	U.S. 183	Walnut Creek
TSS	86	75	98	89	87
COD	29	40	88	68	69
TOC	43	38	62	60	61
Nitrate	-18	-42	64	59	36
TKN	40	60	65	46	54
Zinc	40	74	94	93	79
Iron	57	65	95	83	79

The Federal Highway Administration (FHWA) makes two recommendations that are refuted to some extent by the results of this research. First, the FHWA recommends that the slopes of filter strips used to treat runoff be less than 5 percent to prevent gullies which can disrupt sheet flow. The average slopes of the filters monitored in this study, however, are 9 and 12 percent at the Walnut Creek and U.S. 183 sites, respectively. No gullies were witnessed along the median sides at either site. It may be that the short filter length and relatively small catchment area (3 highway lanes plus shoulders) for the filter strips prevented the formation of gullies. Differences in rainfall intensity or antecedent dry periods between the FHWA study and the Austin study may also explain why no gullies were witnessed at the Austin filter strips. Second, the FHWA cites the results of a study which suggest use of filter strips only for roadways with a maximum of 2 lanes and average daily traffic of 30,000 (Young et al, 1996). Both filters strips studied in Austin, Texas were 3-lane (each direction) highways and had daily traffic of 47,000 (Walnut Creek) and 111,000 (U.S. 183); nevertheless, the filter strips were effective at removing contaminants in runoff. Results indicate that filter strips are effective for 3-lane (each direction) highways at average daily traffic counts greater than 50,000.

Removal efficiencies for copper were not calculated because copper concentrations in a large majority of the samples were less than the detection limit, 0.006 mg/L. These data indicate that copper in the runoff coming from highways in Austin, Texas is minimal.

The calculated removal efficiencies for lead are considerably lower than removal efficiencies for iron or zinc, or for suspended solids. It is difficult to explain these data. Lead is one of the least soluble metals in urban runoff (Wiginton et al, 1986; Barrett et al, 1995b), and as a result one would expect lead would have a strong association with particulate matter in runoff. This would make lead easily removed by such processes as sedimentation and filtration in the vegetated buffer strips. The lower removal efficiencies observed for lead are thus contrary to expectations. The data reported by other research shows lead to be removed equally or better by vegetated BMPs over other metals (Municipality of Metropolitan Seattle, 1992). Other results are similar to the data observed in this study (Young et al, 1996). Occasional problems with the analytical equipment used for lead analyses compromised the reliability of the lead concentrations detected for some samples.

4.3.3 Grab Sample Results

The grassy medians monitored for this project were initially thought to be acting as grassy swales, that is, treatment was thought to occur as the runoff traveled in deep flow along the center of the median. However, the medians responded more like vegetated buffer strips, which treat runoff as the sheet flow travels over a broad vegetated slope. The treatment occurred along the sides of the median and in not the center.

The results of the grab samples are summarized in Figure 4.6. These data show the change in concentration of TSS along the length of the median. Total suspended solids was used as an indicator constituent for determining the removal pattern. The data reveal that a small reduction in concentration occurs down the length of median; however, this removal accounts for only a small part of the over 80% reduction in total TSS concentration. The average TSS concentration observed from the road at this site is 128 mg/L, therefore the majority of removal of TSS must be occurring along the side of the median. Therefore, the median acts as a vegetated buffer strip, not a grassy swale.

This observation indicates that the length of the median has only a small effect on pollutant removal. A longitudinally long (i.e., long in the direction perpendicular to flow) filter strip is not required to achieve removal of constituents. Thus, a median that filters sheet flow from a very short length of road, but is similar in other respects to those monitored in this study would be expected to have comparable removal capabilities. Other factors, such as the length and slope of the sides of the median and density and type of vegetative cover, may have a greater effect than the median’s longitudinal length on the efficiency of filter strips along highways.

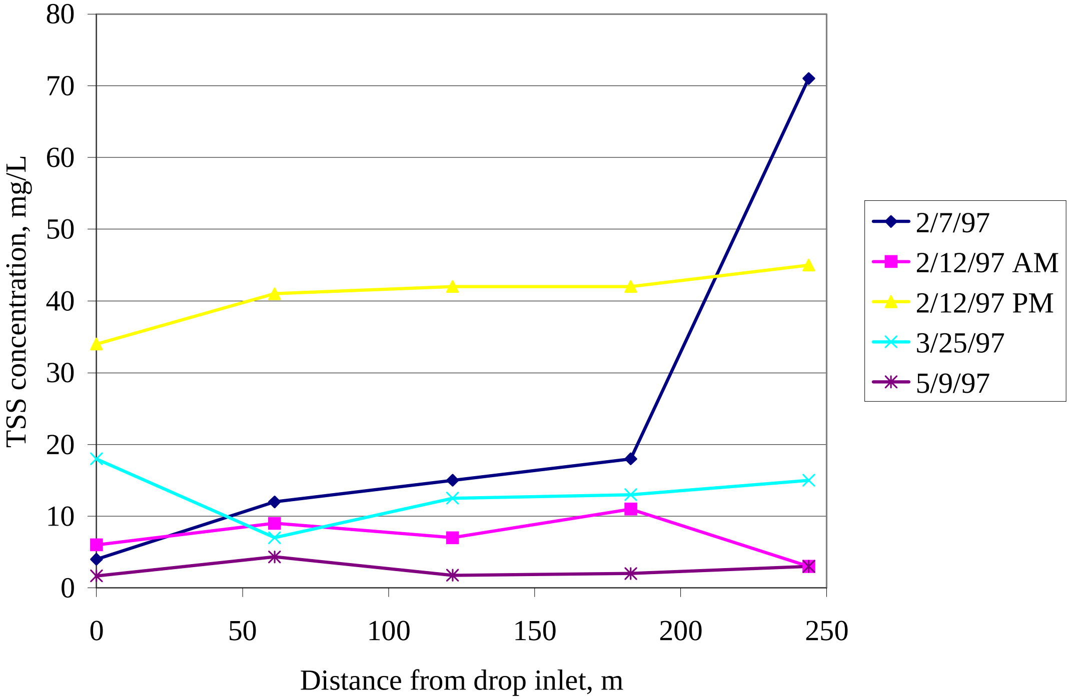

Figure 4.6. TSS concentrations along the center of the median for 5 storm events.

4.3.4 Other Monitoring Results

During the monitoring phase of this study, two important observations were noted regarding filter strips; both observations demonstrate the need for filter strip maintenance. Significant channel erosion occurred at the bottom of the Walnut Creek median. In February 1997, seven washouts were noted along the 1055 m of median. All were in the center of the median and ranged from 0.15 to 0.91 m in width, 0.15 to 0.45 m in depth, and 4.5 m to 28 m in length. The washout areas were primarily bedrock with some sediment, and devoid of vegetation (Figure 4.7). Such washouts diminish the effectiveness of filter strips by contributing sediments to receiving waters and reducing any treatment that may occur along the length of the median. In addition, the washouts can present aesthetic problems and maintenance problems, such as during the mowing of gullies. No erosion was noted at the

U.S. 183 site. The longitudinal slope of the Walnut Creek median (along the median centerline) averages 1.7%, while the average longitudinal slope at U.S. 183 is only 0.7%. Higher velocities are associated with steeper slopes; this may explain why erosion occurred at the Walnut Creek median. Future design of filter strips should consider measures to prevent erosion. The use of additional drop inlets along the median may alleviate the erosion along the Walnut Creek median.

Figure 4.7. Erosion at the Walnut Creek vegetated buffer strip.

The second observation regarding the filter strips in the field is the presence of a sediment "lip" that formed along parts of the edge where the pavement meets the grassy median at the U.S. 183 site. This lip, which formed from the settling of sediment at the pavement/median interface, grew until highway runoff was prevented from entering the median and was instead diverted to a curb and gutter system. The runoff thus traveled toward receiving waters untreated. This problem has been noted for grassed swales by other researchers as well (Schueler et al, 1992). This type of lip can likely be avoided during construction by ensuring that the level of the soil near the pavement edge is lower than the pavement. Periodic maintenance can remove sediments from along the highway/median interface.

4.4 Effects of Metals on Vegetated Areas

4.4.1 Concerns Regarding Metals Deposition on Vegetated Areas

Metals in highway runoff are removed by sedimentation, filtration, infiltration into soil, and possibly other mechanisms in vegetated buffer strips, thereby protecting receiving waters from the toxic effects of metals. These metals, however, accumulate in various forms in the filter strip itself. The fate and effect of these accumulated toxic metals on the environment is a natural concern. The objective of this portion of the study is to make a broad assessment of the risk to human health and the environment posed by metal deposition from highway runoff in vegetated buffer strips.

A simple mass balance of metals entering and leaving the vegetated buffer strip indicates that metals are accumulating in the strip. The metal loads presented in Section 4.3 can be used for such a mass balance. For example, at the U.S. 183 site, approximately 1.44 kg of zinc per year enters the filter strip from highway runoff. However, only 0.07 kg/yr of zinc exits the filter strip. The difference, or 1.37 kg per year, is deposited over the area of the filter strip. The removal of metals from the filter strip by wind and infiltration is assumed to be negligible.

The fate of metals after deposition, and the metals concerns with regard to protecting human health and the environment, should be understood before addressing any assessment of risk. Once removed from highway runoff, possible fate of trace metals within vegetated buffer strips include the following:

1. Residence in an insoluble form, i.e., attached to particulate matter, in the soil matrix;
2. Uptake of soluble metals by plants;
3. Uptake by animals who consume plants with accumulated metals;
4. Leaching of soluble metals from the soil into groundwater;
5. Removal from the filter strip to receiving waters by runoff from subsequent storm events;
6. Some evaporation of the metals is possible, as documented in recent studies (Carpi and Lindberg, 1997); and
7. Removal from the filter strip by wind action on particulates containing metals.

The primary concerns for trace metals applied to vegetated areas are the following:

1. Phytotoxicity, or toxicity to plants that uptake metals;
2. Toxicity to animals that eat plants with high metal concentrations;
3. Contamination of groundwater resources that are sources of drinking water or provide habitats for plant and animal species.

4.4.2 Use of Part 503 Regulations to Assess Environmental Risk

Assessment of the risk to human health and the environment from the accumulation of metals in the roadside environment has not been reported in any detail. A recent regulation developed by the U.S. Environmental Protection Agency may be used to assist in such an assessment. This regulation, The Standards for the Use or Disposal of Sewage Sludge, or Title 40 of the Code of Federal Regulations (CFR), Part 503, provides comprehensive requirements for the management of biosolids generated during the process of treating municipal wastewater. This regulation was passed in 1993 in compliance with requirements of the Clean Water Act of 1987. Of particular interest to this study is that the regulations provide annual and cumulative limits for the application of metals on cropland.

4.4.3 Justification of Use of 503 Regulations for Stormwater

The 503 Regulations for biosolids disposal were based upon an estimate of the environmental risk of biosolids application on cropland. Nonetheless, a meaningful comparison is possible between rates of deposition allowed by the regulations and rates of deposition found on the filter strips in this study. The notable differences in the situation for which the 503 Regulations were developed and their use for this study include the following:

- Land use. The biosolids regulations were intended for regulating land used to grow crops for human and animal consumption. Metals that are absorbed by crops are harvested and removed from the area. Vegetated BMPs, normally do not have this mechanism for removal of metals from the site unless mowing clippings are collected and removed from the area.
- Nature of applied material. The biosolids regulations pertain to application of biosolids effluents from municipal wastewater treatment plants. This analysis investigates the risk associated with highway runoff.

The similarities between the situation for which the 503 Regulations were developed and treatment of highway runoff by a vegetated buffer strip include the following:

- The environmental risks involved in metals deposition from highway runoff on filter strips are the same as those present when applying biosolids to cropland: phytotoxicity, toxicity to animals eating plants, and groundwater contamination.
- Both the application of biosolids on cropland and the treatment of highway runoff over a filter strip involve the spreading of a substance that is primarily water with some solids, including metals, over land.
- The land uses in question both contain significant vegetation.

The 503 regulations provide a starting point for an assessment of risk. A more accurate risk assessment requires an extensive study specifically regarding environmental concerns of pollutant deposition on grassy areas from highway runoff.

4.4.4 Metals Limitations Placed by the 503 Regulations

The metals limitations that are part of the 503 Regulations include annual and cumulative limits for 10 metals. The annual loading limits are the maximum amount of metal, in kilograms of metal per hectare per year, that may safely be applied to cropland; the cumulative loading limits are the cumulative amount of metal, in kilograms per hectare, that may be safely applied to cropland over time. The 503 Regulations require that biosolids application must cease if either of these limits are exceeded.

An annual metals loading rate at each site was calculated, and the calculated rate was compared to the limits provided by the 503 Regulations. This comparison provided information regarding the current presence of risk. Second, the time in years until the cumulative loading rate limitations were exceeded was calculated. This time is the site life for each site based upon metals limitations.

Annual metals loading rates for each metal were calculated by the following formula:

$$R = \frac{L_H - L_F}{A_F}$$

where

R = annual metal loading rate for one metal over the vegetated buffer strip, kg/ha/yr

L_H = annual metal load generated by the portion of the highway that drains onto the vegetated buffer strip, kg/yr

L_F = annual metal load that exits the vegetated buffer strip, kg/yr

A_F = area of the vegetated buffer strip

The annual metal loads from the highway and buffer strip, L_H and L_F, were previously presented in Table 4.6 (page 68). The site life calculation used the following formula:

$$SL = \frac{Limit_{cum}}{R}$$

where

SL = site life of the vegetated buffer strip based on metals limitations, yr

$\text{Limit}_{\text{cum}}$ = cumulative metal loading limitation from the 503 regulations, kg/ha

R = annual metal loading rate for one metal over the vegetated buffer strip, kg/ha/yr

4.4.5 Metals Risk Analysis Results and Discussion

The calculated annual metals deposition rate for each site for two metals is presented in Table 4.8, along with the 503 Regulations limits for comparison. Calculated site lives based upon metals limitations for the two metals are presented in Table 4.9.

Table 4.8. Annual metals loading rates, in comparison to the 503 Regulations.

Metal	503 Regulations Limit* kg/ha/yr	U.S. 183 Filter Strip kg/ha/yr	Walnut Creek Filter Strip kg/ha/yr
Zinc	140	4.9	9.2
Lead	15	1.2	0.25

* For metals in biosolids applied to cropland

Table 4.9. Site lives based upon metal deposition limitations.

Metal	U.S. 183 Filter Strip years	Walnut Creek Filter Strip years
Zinc	570	304
Lead	244	1202

The metals loading rates at the two sites for lead and zinc are lower than the annual metals loading limits prescribed by the 503 Regulations. Indeed, the metal loading rate on the filter strips was less than one tenth of the rate limits for application of metals in biosolids to cropland. Therefore, metal deposition from highway runoff on roadside grassy areas may not pose any risk to human health and the environment. This conclusion is reinforced by other considerations. The conservative nature of the 503 Regulations when applied to BMPs and the minimal effects of highway runoff on groundwater shown by previous research further support this claim.

The site lives for each site based upon both metals accumulation in the filter strip was over 200 years. Therefore, no adverse effects are likely to occur as a result of metals accumulation in the strips for at least 200 years.

This analysis was performed for only two metals in highway runoff. Copper was found at concentrations below detection limits in highway runoff in this study, and iron is not regulated by the 503 Regulations. Other metals, however, could be investigated. Cadmium, in particular, has a low annual loading limit (1.90 kg/ha/yr) in the 503 Regulations, and is found in highway runoff, though in low concentrations (Barrett et al, 1995b). Nickel and chromium also are detected in low concentrations in highway runoff and are regulated by the 503 Regulations.

4.5 Summary of Field Study Results

Vegetated buffer strips can effectively remove many constituents in highway runoff. The percent removal of mass of constituents in runoff within the filter strips was above 85% for total suspended solids; 68%-93% for turbidity, chemical oxygen demand, zinc, and iron; 36%-61% for total organic carbon, nitrate, total Kjeldahl nitrogen, total phosphorus, and lead; and negative removal of bacteria. These data indicate that relatively short (7-9 m) filter strips with moderate slopes (9-12%) can treat highway runoff efficiently. Filter strips that traverse highways treat a relatively small drainage area. This set of conditions may be the reason that the evaluated filter strips were effective, while in the past filter strips have been reported to be unreliable for treating runoff in developed areas.

The removal efficiencies observed at both sites, despite differences in vegetation, traffic density, median side slope and longitudinal (centerline) slope, are similar. Therefore, other filter strips, even with some varying characteristics, are likely to treat highway runoff with similar effectiveness. The observed data indicate that treatment of highway runoff occurred along the sides of the median, and not along the center of the median. Hence, an effective best management practice for treating highway runoff is accomplished by allowing runoff from the highway pavement to pass as sheet flow down a smooth, vegetated area of at least 8 meters in length and slope less than 9 to 12%.

The rate of zinc and lead deposition from highway runoff on the filter strips is less than one tenth the maximum deposition rate allowed by the 503 Regulations, which limit application rates of metals in biosolids to cropland. Any threats to human health and the environment from metals deposition from highway runoff on vegetated areas are small. Accumulation of metals in the monitored filter strips could continue for over 200 years without risk.

Chapter 5 Conclusions and Recommendations

5.1 Channel Swale Conclusions

The conclusions from experiments on the channel swale are the following:

- Removal of TSS, COD, total phosphorus, TKN, zinc, and iron was highly correlated with swale length. No trend was observed for nitrate.
- Most of the reduction in the concentration of constituents in runoff occurred in the first 20 meters of the swale. Little improvement in water quality was observed during the last 20 meters. Swales longer than 20 m may not be cost effective.
- The removal efficiency for constituents of particulate nature, such as suspended solids, organic material, and metals with the exception of zinc, decreased with increased water depth. No relationship between water depth and removal efficiency was observed for nitrate and TKN. It is uncertain whether decreasing water depth, decreased velocity, or both were responsible for increases in removal efficiency for particulate constituents. Increasing water depth and velocity of runoff in a swale will impede the swale's performance for most constituents.
- The removal efficiency of the grassed swale changed between dormant and growing season for only one constituent. Total suspended solids were removed best in the growing season, during which there is a combination of new grass and remaining dormant grass resulting in high grass blade densities.
- Dormant Buffalo grass did not decay until the subsequent growing season. Grassed swales can still be effective at removing contaminants during the dormant season.
- Percolation of runoff through layers of soil and gravel into the underdrain reduced concentrations of all constituents except nitrate.
- The removal efficiencies for the grassed swale in the channel were similar to grassed swales of other studies (Municipality of Metropolitan Seattle, 1992; Schueler et al, 1992) and similar swales can be expected to have comparable removal efficiencies.

5.2 Field Study Conclusions

The conclusions of the field study are the following:

- Vegetated channels designed solely for stormwater conveyance can be as effective as sand filters for reducing the concentrations and loads of constituents in highway runoff. The percent reduction in pollutant mass transported to receiving waters was above 85% for total suspended solids; 68%-93% for turbidity, chemical oxygen demand, zinc, and iron; and 36%-61% for total organic carbon, nitrate, total Kjeldahl nitrogen, total phosphorus, and lead.
- Simple, V-shaped highway medians or shoulder areas with length of at least 8 meters, full vegetative cover, and slopes less than 9 to 12 percent provide protection to receiving waters against constituents in highway runoff. Consequently, many highways in the state which have vegetated channels are already employing an effective best management practice.
- The removal efficiencies for the two filter strips were similar, despite significant differences in vegetation, traffic density, median side slope, and longitudinal (median centerline) slope. Other comparable filters may have similar removal efficiencies.
- The removal efficiencies for the two filter strips are comparable to removal efficiencies for sedimentation and filtration controls.
- Grab samples confirmed that the removal of constituents occurred down the sides of the median, and not down its longitudinal length. A longitudinally long median is not required for effective removal of constituents from highway runoff.
- The slopes and lengths recommended in this report are appropriate for highways, but may not be sufficient for other situations. The small drainage areas provided by highways may explain why the filter strips were effective.
- The deposition rates of lead and zinc on the filter strips were less than one tenth the allowable rate for metals application on cropland. Threats to human health and the environment from metals deposition from highway runoff on vegetated areas are

minimal.

- Vegetated buffer strips and grassed swales can be used as a pretreatment alternative for structural runoff controls, such as sand filters, which can clog from sediment loads.

5.3 Recommendations

The recommendations of this study are the following:

1. Include vegetated buffer strips or grassed swales in the design of new highways or renovation of old highways. Vegetated BMPs are especially beneficial in environmentally sensitive watersheds or recharge zones; in addition, they could be used when regulations require enhancement of highway runoff water quality. However, use vegetated BMPs only when sufficient space is available and geometry and climate allow for appropriate slopes and sufficient vegetative cover. Effective vegetated buffer strips can be included in highway design at low cost and with little obstruction to other highway design objectives.
2. Avoid curb-and-gutter systems for removal of runoff from new highways and roadways. Instead, allow the runoff to exit the pavement as sheet flow into grassy medians or shoulder areas. It is recommended that sheet flow be maintained.
3. Filter strips should have a maximum slope of 9 to 12 percent and a minimum length of 8 meters.
4. Include effective erosion control techniques in highway median design. A storm drain system with drop inlets can be used in conjunction with vegetated channels to minimize erosion and maintain shallow water depths in the swales.
5. Swale length, water depth, and velocity have a significant impact on the removal efficiency of grassed swales. Consider these factors in the design of grassed swales. One study combined the effects of these factors by recommending a 9 minute minimum hydraulic detention time for runoff in a grassed swale (Municipality of Metropolitan Seattle, 1992). Ignore the effect of season on swale efficiency for design considerations.

BIBLIOGRAPHY

Barrett, M.E., 1997, Water Quality and Quantity Inputs for the Urban Creeks Future Needs Assessment, Draft Report to the Drainage Utility Department, City of Austin, Texas, Center for Research in Water Resources, University of Texas, Austin, TX.

Barrett, M.E., Malina, J.F. Jr., Charbeneau, R.J., and Ward, G.H., 1995a, Characterization of Highway Runoff in the Austin, Texas Area, CRWR 263, Center for Research in Water Resources, Bureau of Engineering Research, Austin, TX.

Barrett, M.E., Zuber, R.D., Collins, E.R. III, Malina, J.F Jr., Charbeneau, R.J., and Ward, G.H., 1995b, A Review and Evaluation of Literature Pertaining to the Quantity and Control of Pollution from Highway Runoff and Construction, Second Edition, CRWR 239, Center for Research in Water Resources, Bureau of Engineering Research, Austin, TX.

Carpi, A., and Lindberg, S.E., 1997, “Sunlight-Mediated Emission of Elemental Mercury from Soil Amended with Municipal Sewage Sludge”, Environmental Science & Technology, Volume 31, No. 7, pp. 2085-2091.

Dorman, M.E., Hartigan, J., Johnson, F., and Maestri, B., 1988, Retention, Detention and Overland Flow for Pollutant Removal from Highway Stormwater Runoff: Interim Guidelines for Management Measures, FHWA/RD-87/056, Versar Inc., Springfield, VA.

Gilbert, R.O., 1987, Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold Company Inc., New York, NY.

Gish, C.D., and Christensen, R.E., 1973, “Cadmium, Nickel, Lead and Zinc in Earthworms from Roadside Soil,”, Environmental Science and Technology, Vol. 7, No. 11, pp. 1060-1062.

Glick, R.H., Wolfe, M.S., and Thurow, T.S., 1993, Effectiveness of Native Species Buffer Zones for Nonstructural Treatment of Urban Runoff, Technical Report No. 156, Texas Water Resources Institute, Texas A&M University.

Howie, B., and Waller, B.G., 1986, Chemical Effects of Highway Runoff on the Surficial Aquifer, Boward County, Florida, USGS Water Resources Investigations Report 86-4200.

Lagerwerff, J.V., and Specht, A.W., 1970, “Contamination of Roadside Soil and Vegetation with Cadmium, Nickel, Lead, and Zinc,” Environmental Science and Technology, Vol. 4, No. 7, pp. 583-586.

Maryland Department of the Environment, Sediment and Stormwater Administration, 1985, Inspector’s Guidelines Manual for Stormwater Management Infiltration Practices, Baltimore, MD.

Municipality of Metropolitan Seattle, 1992, Biofiltration Swale Performance, Recommendations, and Design Considerations, Publication 657, Water Pollution Control Department, Seattle, WA.

Schueler, T.R., 1987, Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs, Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, DC.

Schueler, T.R., Kumble, P.A., Heraty, M.A., 1992, A Current Assessment of Urban Best Management Practices, Techniques for Reducing Non-Point Source Pollution in the Coastal Zone, Anacostia Restoration Team, Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, D.C.

Seattle Engineering Department, 1993, Dayton Avenue Swale Biofiltration Study, Drainage and Wastewater Utility, Seattle, WA.

U.S. Environmental Protection Agency, 1992, Guidance Manual for the Preparation of Part 2 of the NPDES Permit Applications for Discharges From Municipal Separate Storm Sewer Systems, EPA 833-B-92-002.

U.S. Environmental Protection Agency, 1993, Urban Runoff Pollution Prevention and Control Planning, EPA/625/R-93/004, Office of Research and Development, Cincinnati, OH.

Waller , B.G., Klein, H., and Lefkoff, L.J., 1984, Attenuation of Stormwater Contaminants from Highway Runoff Within Unsaturated Limestone, Dade County, Florida, USGS Water Resources Investigations Report 84-4083.

Wiginton, P.J., Jr., Randall, C.W., and Grizzard, T.J., 1986, “Accumulation of Selected Trace Metals in Soils of Urban Runoff Swale Drains,” Water Resources Bulletin, Vol. 22, No. 1, pp. 73-79.

Young, G.K., Stein, S., Cole, P., Kammer, T., Graziano, F., and Bank, F., 1996, Evaluation and Management of Highway Runoff Water Quality, FHWA-PD-96-032, Federal Highway Administration, Washington, D.C.

Yousef, Y.A., Wanielista, M.P., and Harper, H.H., 1985a, “Removal of Highway Contaminants by Roadside Swales,” Transportation Research Record, 1017, pp. 62-68.

Yu, S.L., and Benelmouffok, D.E., 1988, “Field Testing of Selected Urban BMP’s,” Critical Water Issues and Computer Applications, Proceedings of the 15th Annual Water Resources Conference, ASCE, New York, NY, pp. 309-312.

Yu, S.L., Kaighn, R.J. Jr., Liao, S.L., and O'Flaherty, C.E., 1995, The Control of Pollution in Highway Runoff through Biofiltration Volume I: Executive Summary, VTRC 95-R28, Virginia Transportation Research Council, Charlottesville, VA.

APPENDIX A

Individual Sampling Results from Channel Experiments

40-meter Lab Swale Raw Data											
	TSS	Turbidity	COD	TOC	Nitrate	TKN	TP	Zinc	Lead	Iron	Copper
Sample	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
F1-0	340	268	48	16.9	0.04	1.107	0.4	0	0.1	0	0
F1-1	240	204	25	6.3	0.06	0.866	0.23	0.1	0.3	6	0
F1-2	200	228	37	6.3	0.09	1.278	0.26	0.1	0.3	6.3	0
F1-3	258	272	31	8.7	0.11	1.422	0.29	0.1	0.4	6.1	0
F1-4	258	252	51	13.4	0.17	1.757	0.43	0.1	0.4	6.6	0
F1-41	312	276	34	6.3	0.12	1.4	0.31	0.1	0.3	5.6	0
F1-42	218	220	29	9.9	0.11	0.866	0.24	0.1	0.3	4.9	0
F1-43	186	236	30	6.3	0.15	1.217	0.26	0.1	0.4	5.9	0
F1-5	152	148	37	6.3	0.15	1.051	0.16	0	0.3	3.3	0
F2-0	594	316	47	32.5	0.13	1.734	0.41	0.251	0.326	11.611	0.021
F2-1	320	292	35	22.1	0.14	1.597	0.34	0.164	0.197	7.819	<.006
F2-21	300	296	41	24.7	0.2	1.649	0.44	0.325	0.181	6.504	<.006
F2-22	226	296	37	22.1	0.17	1.55	0.33	0.184	0.235	7.528	<.006
F2-23	242	292	32	19.5	0.17	1.22	0.31	0.142	0.181	6.624	<.006
F2-24	128	204	28	16.1	0.13	1.224	0.25	0.059	0.125	3.57	<.006
F2-3		292	26	18.5	0.2	1.372	0.3	0.118	0.152	5.905	<.006
F2-4	262	284	31	18.3	0.16	1.194	0.29	0.112	0.19	5.844	<.006
F2-5	160	180	26	14.1	0.19	0.937	0.19	0.031	0.086	3.057	<.006
F3-01	440	240	69	15	0.19	6.344	2.38	0.2	0.4	5.3	<.05
F3-02	624	260	39	18.9	0.19	1.427	0.28	0.2	0.3	6.1	<.05
F3-03	474	230	37	20.7	0.21	1.45	0.31	0.4	0.5	9.9	<.05
F3-04	678	230	31	24.7	0.19	1.15	0.26	0.205	0.138	4.906	0.012
F3-1	300	210	24	15.1	0.21	1.32	0.23	0.14	0.17	2.99	<0.006
F3-2	230	210	23	13.3	0.19	0.967	0.21	0.121	0.125	2.62	<0.006
F3-3	208	210	24	13.2	0.22	0.778	0.18	0.109	0.09	2.434	<0.006
F3-4	194	200	26	13.4	0.21	1.205	0.2	0.096	0.184	2.148	<0.006
F3-5	104	150	21	13.3	0.21	0.923	0.13	0.011	0.046	1.218	<0.006
F4-0A	423	65	35	26.3	<DL	1.349	0.22	0.108	0.176	2.833	<0.006
F4-1A	250	66	27	25.1	<DL	1.123	0.22	0.015	0.165	1.75	<0.006
F4-2A	201	63	21	30.9	<DL	1.233	0.15	0.032	0.06	1.274	<0.006
F4-3A	129	56	18	22.6	<DL	0.896	0.14	0.041	0.073	1.107	<0.006
F4-4A	80	55	13	21.3	<DL	0.891	0.15	0.046	0.065	0.93	<0.006
F4-5A	47	34	12	18.9	<DL	0.797	0.08	<0.002	0.063	1.817	<0.006
F4-0B	184	67	34	33	<DL	1.269	0.23	0.15	0.136	3.168	<0.006
F4-1B	111	66	24	26.3	<DL	1.039	0.17	0.024	<0.042	1.681	<0.006
F4-2B	94	60	21	20.9	<DL	0.551	0.22	0.039	0.086	4.582	<0.006
F4-3B	80	54	21	24.2	<DL	3.723	0.36	0.029	0.088	0.979	<0.006
F4-4B	73	40	16	19.7	<DL	0.303	0.15	0.041	0.042	0.802	<0.006
F4-5B	46	32	14	19.3	<DL	0.929	0.1	0.006	0.066	0.478	<0.006
F5-01	207	83	46	5.7	0.14	1.778	0.18	0.162	0.228	4.642	<0.006
F5-02	174	88	39	5.7	0.15	1.877	0.2	0.155	0.137	3.446	<0.006
F5-03	191	88	39	9	0.15	2.025	0.2	0.145	0.15	3.835	<0.006
F5-04	238	86	42	9	0.15	1.646	0.18	0.111	0.181	2.525	<0.006
F5-05	201	85	39	5.7	0.15	1.795	0.19	0.153	0.295	3.644	<0.006
F5-06	206	85	25	16.3	0.15	1.717	0.19	0.247	0.205	4.175	<0.006
F5-1	144	83	43	9.6	0.18	1.203	0.13	0.09	0.089	2.366	<0.006
F5-2	107	79	30	9.6	0.12	1.075	0.11	0.053	0.103	1.597	<0.006
F5-3	85	73	27	6.2	0.11	1.052	0.1	0.033	0.067	1.4	<0.006
F5-4	86	71	27	6.2	0.12	1.013	0.1	0.038	0.048	0.886	<0.006
F5-5	28	39	20	2.9	0.12	0.784	0.02	<0.002	0.127	0.758	<0.006

	TSS	Turbidity	COD	TOC	Nitrate	TKN	TP	Zinc	Lead	Iron	Copper
Sample	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
F6-0A	300	200	47	40.2	0.17	2.025	0.28	0.26	NA	3.491	0.034
F6-1A	159	164	38	14.3	0.19	1.525	0.2	0.15	NA	1.758	0.018
F6-2A	108	128	22	16.1	0.19	1.468	0.13	0.107	NA	1.395	0.007
F6-3A	66	120	27	11.5	0.21	1.058	0.11	0.069	NA	0.886	0.008
F6-4A	90	104	16	11.5	0.19	1.398	0.23	0.034	NA	0.893	0.009
F6-5A	58	104	7	11.7	0.19	1.447	0.1	0.059	NA	0.866	0.01
F6-0B	290	176	93	40.4	0.23	2.153	0.38	0.26	NA	3.447	0.03
F6-1B	142	152	16	21.2	0.23	1.519	0.15	0.139	NA	1.976	0.014
F6-2B	100	136	20	16.5	0.25	1.116	0.34	0.108	NA	1.789	0.012
F6-3B	76	120	27	14.1	0.23	1.35	0.11	0.057	NA	1.022	0.008
F6-4B	60	100	14	13.9	0.23	1.334	0.13	0.038	NA	0.745	<0.006
F6-5B	60	100	26	13.9	0.25	1.032	0.16	0.045	NA	0.856	0.01
F7-0A	320	160	63	50.2	0.12	2.267	0.46	0.178	NA	2.949	0.026
F7-1A	104	100	64	22.3	0.1	1.375	0.25	0.06	NA	1.204	0.012
F7-2A	75	80	18	22.1	0.07	1.755	0.38	0.016	NA	0.951	0.007
F7-0B	286	168	90	48.1	0.11	2.006	0.62	0.221	NA	3.501	0.041
F7-1B	124	98	29	47.3	0.11	1.482	0.23	0.163	NA	2.567	0.016
F7-2B	72	82	25	22.4	0.1	1.504	0.25	0.089	NA	1.785	0.014
F7-0C	323	168	75	30.7	0.12	2.287	0.49	0.372	NA	5.626	0.053
F7-1C	134	100	33	22.7	0.14	1.881	0.23	0.139	NA	2.347	0.017
F7-2C	70	79	27	25.3	0.12	1.987	0.22	0.071	NA	1.612	0.012
F8-0A	384	80	30	NA	0.16	1.494	0.22	0.26	NA	NA	NA
F8-1A	76	77	23	NA	<0.1	1.466	0.14	0.21	NA	NA	NA
F8-2A	92	65	19	NA	<0.1	1.266	0.12	0.19	NA	NA	NA
F8-3A	68	62	22	NA	<0.1	1.168	0.11	0.21	NA	NA	NA
F8-4A	58.5	41	24	NA	<0.1	1.284	0.12	0.11	NA	NA	NA
F8-5A	36	44	15	NA	0.12	1.235	0.09	0.1	NA	NA	NA
F8-0B	275	86	32	NA	0.13	1.41	0.21	0.26	NA	NA	NA
F8-1B	129	79	32	NA	0.13	1.506	0.15	0.15	NA	NA	NA
F8-2A	86	69	25	NA	0.24	1.125	0.12	0.12	NA	NA	NA
F8-3B	71	49	28	NA	0.35	1.13	0.12	0.1	NA	NA	NA
F8-4B	60	59	25	NA	0.33	0.879	0.19	0.09	NA	NA	NA
F8-5B	37	45	16	NA	0.24	1.107	0.09	0.06	NA	NA	NA
F9-0A	420	160	36	NA	0.16	1.976	0.23	0.34	NA	NA	NA
F9-0B	344	180	33	NA	0.14	1.567	0.26	0.33	NA	NA	NA
F9-0C	302	180	28	NA	0.14	1.992	0.26	0.31	NA	NA	NA
F9-1A	218	150	24	NA	0.14	1.358	0.2	0.22	NA	NA	NA
F9-1B	118	150	28	NA	0.17	1.168	0.18	0.18	NA	NA	NA
F9-1C	128	150	26	NA	0.17	1.23	0.17	0.19	NA	NA	NA
F10-0A	226	160	44	NA	0.11	1.513	0.29	0.23	NA	NA	NA
F10-0B	218	170	41	NA	0.14	1.433	0.24	0.26	NA	NA	NA
F10-1A	140	150	30	NA	<0.1	1.452	0.15		NA	NA	NA
F10-1B	150	160	36	NA	0.14	1.387	0.22	0.16	NA	NA	NA
F10-2A	110	150	34	NA	0.12	1.21	0.13		NA	NA	NA
F10-2B	96	140	29	NA	0.14	1.121	0.18	0.4	NA	NA	NA
F10-3A	110	150	31	NA	0.14	1.225	0.16	0.243	NA	NA	NA
F10-3B	112	150	32	NA	0.14	1.125	0.17	0.14	NA	NA	NA
F10-4A	116	120	33	NA	0.11	1.039	0.14		NA	NA	NA
F10-4B	102	160	31	NA	0.15	1.225	0.16		NA	NA	NA
F10-5A	58	150	23	NA	0.12	1.135	0.12	0.09	NA	NA	NA
F10-5B	60	120	29	NA	0.15	1.098	0.12	0.17	NA	NA	NA
F11-0B	271	200	NA	NA	0.15	1.591	0.27	0.38	NA	NA	NA
F11-1B	130	170	27	NA	0.13	1.22	0.15	0.19	NA	NA	NA
F11-2B	79	150	25	NA	<0.1	1.326	0.11	0.135	NA	NA	NA
F11-5B	54	120	24	NA	0.18	1.215	0.1	0.169	NA	NA	NA
F11-0A	280	190	NA	NA	0.14	1.925	0.35		NA	NA	NA
F11-1A	127	170	30	NA	0.13	1.353	0.15	0.28	NA	NA	NA
F11-2A	71	150	26	NA	0.13	1.593	0.17		NA	NA	NA
F11-5A	55	120	24	NA	0.14	0.851	0.13	0.11	NA	NA	NA

APPENDIX B

Flow Data and Sample Concentrations

For Four Field Monitoring Locations

Highway runoff at U.S. 183 site

Sample No.	Date/Time Collected	Flow Vol L	Cum Flow L	**TSS** Conc mg/L	**Turbidity** Conc NTU	**Fecal Col** Conc CFU/100ml	**Fecal Str** Conc CFU/100ml	**E. coli** Conc CFU/100ml	**COD** Conc mg/L	**TOC** Conc mg/L	**Nitrate** Conc mg/L	**TKN** Conc mg/L	**Total P** Conc mg/L	**Zinc** Conc mg/L	**Lead** Conc mg/L	**Iron** Conc mg/L	**Copper** Conc mg/L
Storm 12																	
1	5/27/96 7:53	8090	8090	882	228	CG	670000	77000	431	212.0	4.40	NA	1.77	1.447	0.394	14.516	<0.006
2	5/27/96 8:07	86980	95070	86	37	6000	13400	290	28	24.4	0.84	NA	0.38	0.250	0.165	2.76	<0.006
3	5/27/96 8:22	22240	117310	14	50	7300	3700	1500	11	12.9	1.50	NA	0.22	0.049	0.099	0.890	<0.006
Storm 13																	
1	5/30/96 1:54	2140	2140	30	12	CG	21000	CG	93	39.7	1.70	NA	0.62	0.013	0.111	0.655	<0.006
2	5/30/96 2:09	3070	5210	52	35	435000	10000	CG	13	12.8	0.85	NA	0.38	0.002	0.117	2.160	<0.006
3	5/30/96 2:24	3450	8660	14	17	CG	25000	CG	0	12.8	0.85	NA	0.33	0.002	0.094	0.572	<0.006
4	5/30/96 2:54	126320	134980	8	11	129000	12000	16000	24	13.3	6.60	NA	0.35	0.002	0.068	0.398	<0.006
5	5/30/96 3:24	40680	175660	0	6	226000	29000	14000	35	16.3	1.75	NA	0.38	0.002	0.106	0.108	<0.006
6	5/30/96 4:24	590	176250	8	5	CG	30000	50000	43	16.8	5.80	NA	0.40	0.002	0.104	0.176	<0.006
Storm 15																	
1	6/22/96 11:38	4800	4800	328	47	NA	NA	NA	612	82.7	3.95	7.224	0.74	0.595	0.198	6.710	0.015
2	6/22/96 11:52	1890	6690	52	35	NA	NA	NA	66	34.3	1.60	2.617	0.26	0.114	0.195	1.889	<0.002
3	6/22/96 12:07	100	6790	46	47	NA	NA	NA	NA	14.4	NA	NA	NA	NA	NA	NA	NA
4	6/22/96 12:37	10	6800	NA	NA	NA	NA	NA	NA	11.8	NA	NA	NA	NA	NA	NA	NA
Storm 16																	
1	6/25/96 10:35	5450	5450	0	50	CG	14700	3000	179	50.4	7.30	3.465	0.70	0.851	0.264	8.296	0.007
2	6/25/96 10:50	7650	13100	64	15	138000	4000	700	16	15.9	7.00	1.109	0.22	0.058	0.165	1.440	<0.006
3	6/25/96 11:05	700	13800	52	27	12000	400	0	30	15.9	1.80	1.198	0.20	0.022	0.127	1.129	<0.006
4	6/25/96 11:35	3590	17390	252	13	4000	200	0	30	14	1.28	1.477	0.18	0.006	0.191	0.612	<0.006
5	6/25/96 12:05	1090	18480	84	40	5200	6400	90	45	21	4.95	0.936	0.22	0.143	0.201	1.388	<0.006
Storm 19																	
1	8/22/96 10:03	5710	5710	32	46	NA	NA	NA	209	37.6	2.7	3.089	0.52	0.289	0.169	4.457	0.006

2	8/22/96 10:17	230	5940	9	26	NA	NA	NA	38	9	1.55	0.61	0.2	0.038	0.092	0.840	<0.006
Storm 20																	
1	8/23/96 17:07	3590	3590	42	39	NA	NA	NA	124	41.9	1.6	1.786	0.31	0.122	0.085	1.609	<0.006
2	8/23/96 17:21	1710	5300	19	15	NA	NA	NA	36	9.1	0.54	0.846	0.2	0.002	0.042	0.422	<0.006
3	8/23/96 17:36	1400	6700	7	14	NA	NA	NA	35	6.9	0.47	0.416	0.2	0.002	0.042	0.402	<0.006
4	8/23/96 18:06	2470	9170	7	13	NA	NA	NA	37	11.2	0.77	1.259	0.18	0.002	0.042	0.787	<0.006
5	8/23/96 18:36	3240	12410	4	15	NA	NA	NA	28	2.6	0.54	1.38	0.15	0.002	0.042	0.227	<0.006
6	8/23/96 19:36	2850	15260	10	17	NA	NA	NA	20	NA	0.44	0.796	0.15	0.002	0.042	0.451	<0.006
Storm 21																	
1	8/29/96 12:09	3480	3480	22	42	510000	4000	2100	128	43.8	1.15	0.325	0.39	0.154	0.077	2.680	<0.006
2	8/29/96 12:23	200	3680	14	19	130000	5700	2800	34	7.5	0.67	1.299	0.15	0.002	0.042	0.560	<0.006
Storm 22																	
1	9/18/96 15:31	9250	9250	360	120	CG	12700	NA	163	61.1	2.50	3.329	0.52	0.321	0.153	5.555	<0.006
2	9/18/96 15:45	790	10040	36	34	CG	2300	NA	30	15	1.80	1.462	0.23	0.019	0.073	2.245	<0.006
3	9/18/96 16:00	20880	30920	47	64	CG	7000	NA	99	33.5	2.20	1.827	0.35	0.046	0.074	1.638	<0.006
4	9/18/96 16:30	1380	32300	23	24	CG	3400	NA	19	3.7	1.60	0.853	0.17	0.019	0.042	1.318	<0.006
5	9/18/96 17:00	20	32320	10	23	500000	4300	NA	24	8.1	1.75	0.745	0.2	0.016	0.042	0.603	<0.006
Storm 23																	
1	10/17/96 16:42	17300	17300	65	40	<200000	26000	NA	125	47.9	1.15	3.147	1.12	1.100	0.3	10.3	0.1
2	10/17/96 16:56	1100	18400	44	25	230000	<20000	NA	32	7.2	1.10	1.180	0.26	0.100	0.050	1.1	<0.05
Storm 24																	
5	10/27/96 14:00	5410	5410	334	116	20000	59000	NA	NA	60.1	0.46	6.192	2.24	1.200	0.3	8.5	0.1
6	10/27/96 14:02	910	6320	184	40	4800	20100	NA	88	55.6	0.55	1.862	0.65	0.500	0.1	5.0	<0.05

Filter strip discharge at U.S. 183 site

Sample No.	Date/Time Collected	Flow Vol L	Cum Flow L	**TSS** Conc mg/L	**Turbidity** Conc NTU	**Fecal Col** Conc CFU/100ml	**Fecal Str** Conc CFU/100ml	**E. coli** Conc CFU/100ml	**COD** Conc mg/L	**TOC** Conc mg/L	**Nitrate** Conc mg/L	**TKN** Conc mg/L	**Total P** Conc mg/L	**Zinc** Conc mg/L	**Lead** Conc mg/L	**Iron** Conc mg/L	**Copper** Conc mg/L
Storm 9																	
1	3/27/96 14:36	5130	5130	5	12	NA	28500	NA	51	22.3	0.49	0.28	0.07	0.024	0.042	0.212	<0.006
2	3/27/96 15:05	9720	14850	5	19	NA	NA	NA	57	22.3	0.81	0.26	0.18	0.019	0.042	0.347	<0.006
3	3/27/96 15:35	9920	24770	5	26	6136	NA	NA	55	21.0	0.86	0.26	0.24	0.014	0.042	0.365	<0.006
4	3/27/96 16:05	8770	33540	4	21	NA	NA	NA	40	17.9	0.78	0.26	0.23	0.002	0.042	0.262	<0.006
5	3/27/96 17:05	16830	50370	2	23	NA	NA	NA	32	32.4	0.55	0.26	0.21	0.006	0.042	0.262	<0.006
6	3/27/96 18:05	10020	60390	3	21	NA	NA	NA	30	16.8	0.41	0.26	0.2	0.012	0.042	0.295	<0.006
Storm 10																	
1	4/5/96 17:19	1360	1360	40	NA	NA	NA	NA	61	28.9	NA	NA	0.38	0.016	0.042	0.320	<0.006
2	4/5/96 17:48	13540	14900	24	NA	NA	NA	NA	26	18.3	NA	NA	0.26	0.007	0.042	0.331	<0.006
3	4/5/96 18:18	14670	29570	16	NA	NA	NA	NA	18	16.6	NA	NA	0.23	0.002	0.042	0.238	<0.006
4	4/5/96 18:48	15760	45330	16	NA	NA	NA	NA	5	13.1	NA	NA	0.15	0.002	0.042	0.232	<0.006
5	4/5/96 19:48	29020	74350	16	NA	NA	NA	NA	0	11.3	NA	NA	0.16	0.002	0.042	0.430	<0.006
Storm 11																	
1	4/22/96 12:43	1520	1520	17	10	NA	NA	NA	82	25.5	0.98	NA	0.46	0.002	0.089	0.253	<0.006
2	4/22/96 13:12	13760	15280	6	7	NA	NA	NA	67	21.2	0.80	NA	0.36	0.002	0.122	0.223	<0.006
3	4/22/96 13:42	10700	25980	3	9	NA	NA	NA	64	24.9	0.82	NA	0.33	0.002	0.095	0.992	<0.006
4	4/22/96 14:12	11900	37880	5	5	NA	NA	NA	58	25.5	0.80	NA	0.30	0.002	0.067	0.211	<0.006
5	4/22/96 15:12	4240	42120	5	9	NA	NA	NA	60	20.4	0.73	NA	0.30	0.002	0.097	0.101	<0.006
Storm 12																	
1	5/27/96 8:01	33120	33120	188	40	310000	4400	36000	60	66.4	1.10	NA	1.40	0.090	0.208	3.672	<0.006
2	5/27/96 8:30	68510	101630	24	23	440000	4700	610000	79	26.2	0.37	NA	0.78	0.002	0.086	0.990	<0.006
3	5/27/96 9:00	24790	126420	6	25	510000	4900	630000	85	24.4	0.40	NA	0.85	0.002	0.117	0.332	<0.006
4	5/27/96 9:30	12450	138870	14	20	158000	590	63000	83	26.1	0.37	NA	0.89	0.003	0.086	0.214	<0.006
5	5/27/96 10:30	10010	148880	12	14	159000	560	24000	83	31.2	0.40	NA	0.88	0.002	0.094	0.192	<0.006

Storm 13																	
1	5/30/96 2:37	29610	29610	200	64	36000	34000	21000	131	39.6	2.70	NA	0.52	0.364	0.168	3.461	<0.006
2	5/30/96 3:07	169080	198690	36	38	<20000	4800	13000	45	16.6	6.20	NA	0.23	0.070	0.079	1.147	<0.006
3	5/30/96 3:37	37940	236630	0	25	4500	2900	3500	22	8.1	1.00	NA	0.16	0.027	0.076	0.562	<0.006
4	5/30/96 4:07	18200	254830	130	34	1800	3600	6000	7	11.7	0.46	NA	0.55	0.313	0.206	3.104	<0.006
Storm 15																	
1	6/22/96 16:38	2110	2110	32	15	NA	NA	NA	45	19.0	0.76	2.55	0.54	0.002	0.042	0.356	<0.006
2	6/22/96 17:08	33270	35380	52	30	NA	NA	NA	46	22.9	3.85	2.22	0.49	0.002	0.117	1.548	<0.002
3	6/22/96 17:37	17850	53230	24	20	NA	NA	NA	45	20.7	0.83	2.04	0.42	0.002	0.161	0.557	<0.006
4	6/22/96 18:07	9100	62330	16	10	NA	NA	NA	43	17.8	NA	0.74	0.41	0.002	0.060	0.258	<0.006
Storm 16																	
1	6/25/96 11:00	13430	13430	0	6.4	990000	55000	140000	60	27.4	NA	2.62	0.39	0.013	0.180	0.580	<0.006
2	6/25/96 11:28	33340	46770	52	14	560000	24000	21000	15	18.9	5.40	1.76	0.27	0.002	0.148	0.626	<0.006
3	6/25/96 11:59	35520	82290	52	10	8900	25000	500	24	15.9	4.40	1.48	0.21	0.002	0.145	0.481	<0.006
4	6/25/96 12:28	22190	104480	48	7	360000	12400	11000	29	17.8	1.00	1.32	0.19	0.002	0.123	0.436	<0.006
5	6/25/96 13:28	11470	115950	40	9	260000	8800	1400	26	16.3	1.90	2.15	0.18	0.002	0.149	0.404	<0.006
Storm 18																	
1	8/11/96 14:45	67360	67360	116	31	CG	32000	560000	77	16.4	0.78	15.1	0.51	0.002	0.164	1.001	<0.006
2	8/11/96 15:15	46490	113850	20	17	1590000	7300	300000	42	13.1	0.36	1.76	0.35	0.002	0.141	0.856	<0.006
3	8/11/96 15:45	23960	137810	8	6.6	1890000	7000	460000	66	14.1	1	1.65	0.37	0.002	0.165	0.311	<0.006
4	8/11/96 16:15	19540	157350	48	4.7	1410000	5000	510000	60	17.4	0.5	1.81	0.37	0.002	0.131	0.174	<0.006
5	8/11/96 17:15	10060	167410	4	3.2	770000	5100	420000	70	20.7	0.44	1.83	0.38	0.002	0.145	0.110	<0.006
6	8/11/96 18:15	2990	170400	8	2.5	420000	8800	50000	79	23	0.26	3.11	0.48	0.002	0.144	0.148	<0.006
Storm 19																	
1	8/22/96 19:14	9810	9810	8	5	NA	NA	NA	86	25.9	0.27	2.42	0.53	0.002	0.124	0.152	<0.006
2	8/22/96 19:43	12150	21960	1	10	NA	NA	NA	67	19.9	0.4	1.6	0.31	0.002	0.090	0.273	<0.006
3	8/22/96 20:13	7100	29060	2	9	NA	NA	NA	58	15.9	0.3	1.79	0.26	0.002	0.093	0.201	<0.006
4	8/22/96 20:43	6350	35410	1	7	NA	NA	NA	55	15.9	0.21	1.42	0.25	0.002	0.101	0.198	<0.006
Storm 20																	
1	8/23/96 17:51	8490	8490	5	4	NA	NA	NA	76	29	0.32	2.9	0.4	0.002	0.043	0.120	<0.006
2	8/23/96 18:20	31780	40270	7	14	NA	NA	NA	61	20.2	0.33	1.21	0.27	0.002	0.042	0.285	<0.006

3	8/23/96 18:50	27500	67770	3	11	NA	NA	NA	54	13.9	0.23	1.04	0.2	0.002	0.042	0.351	<0.006
4	8/23/96 19:20	34580	102350	8	7	NA	NA	NA	44	13.7	0.16	1.15	0.19	0.002	0.064	0.276	<0.006
5	8/23/96 20:20	31650	134000	4	4	NA	NA	NA	33	11.7	0.1	0.89	0.16	0.002	0.093	0.176	<0.006
6	8/23/96 21:20	15470	149470	2	3	NA	NA	NA	36	11.7	0.1	1.05	0.15	0.002	0.042	0.068	<0.006
Storm 21																	
1	8/29/96 15:16	68130	68130	90	33	240000	91000	26000	43	14	1	1	0.44	0.003	0.068	2.064	<0.006
2	8/29/96 15:45	39410	107540	62	57	98000	74000	10000	26	9.5	2.1	1	0.27	0.002	0.069	3.725	<0.006
3	8/29/96 16:15	20380	127920	16	19	55000	44000	8000	22	7.5	0.79	1	0.22	0.002	0.042	0.904	<0.006
4	8/29/96 16:45	15570	143490	0	11	43000	34000	12000	19	7.5	1.15	NA	0.15	0.002	0.042	0.425	<0.006
5	8/29/96 17:45	8200	151690	5	6.5	2300	30000	10000	23	9.6	3.35	1.58	0.15	0.002	0.042	0.513	<0.006
Storm 22																	
1	9/18/96 16:11	22870	22870	5	5	NA	NA	NA	27	5.6	1.5	NA	NA	0.002	0.042	0.411	<0.006
2	9/18/96 16:40	35580	58450	10	9	NA	NA	NA	23	7.8	1.3	0.89	0.38	0.002	0.090	0.598	<0.006
3	9/18/96 17:10	20810	79260	7	12	NA	NA	NA	24	10	1.2	1.14	0.28	0.002	0.042	0.439	<0.006
4	9/18/96 17:40	16140	95400	3	7	NA	NA	NA	21	10	1.25	0.77	0.26	0.002	0.042	0.222	<0.006
5	9/18/96 18:40	7690	103090	1	5	NA	NA	NA	21	8.4	1.3	0.57	0.26	0.002	0.042	0.675	<0.006
Storm 25																	
1	11/7/96 2:02	33830	33830	19	14	NA	NA	NA	57	35.0	0.30	1.996	0.99	0.002	0.1	0.3	<0.0
2	11/7/96 2:31	48830	82660	34	16	NA	NA	NA	27	17.9	0.20	1.179	0.39	0.050	0.042	0.5	<0.0
3	11/7/96 3:01	28150	110810	18	13	NA	NA	NA	23	14.1	0.22	0.320	0.35	0.1	0.042	0.4	<0.0
4	11/7/96 3:31	32430	143240	3	13	NA	NA	NA	21	14.1	0.17	0.804	0.33	0.002	0.042	0.218	<0.006
5	11/7/96 4:31	45110	188350	3	6.4	NA	NA	NA	24	16.6	0.15	0.122	0.31	0.002	0.042	0.2	<0.0
6	11/7/96 5:31	34040	222390	3	6.5	NA	NA	NA	21	18.7	0.21	0.194	0.26	0.002	0.042	0.222	<0.006
Storm 28																	
1	12/15/96 5:06	30430	30430	23.00	13	NA	NA	NA	38	20.0	0.74	1.702	NA	0.002	0.067	0.330	<0.006
2	12/15/96 5:35	73040	103470	13.00	14	NA	NA	NA	18	13.8	0.45	1.015	NA	0.132	0.042	0.510	<0.006
3	12/15/96 6:05	66530	170000	9.00	11	NA	NA	NA	5	13.5	0.21	0.508	NA	0.002	0.049	0.278	<0.006
4	12/15/96 6:35	85060	255060	4.00	10	NA	NA	NA	0.0	13.5	0.26	0.522	NA	0.002	0.042	0.320	<0.006
5	12/15/96 7:35	114750	369810	3.00	10	NA	NA	NA	13	15.4	0.15	0.457	NA	0.002	0.042	0.213	<0.006
6	12/15/96 8:35	105530	475340	4.00	12	NA	NA	NA	3	13.5	0.11	0.406	NA	0.002	0.042	0.337	<0.006

Storm 26																	
1	11/24/96 5:22	11870	11870	8.00	22	NA	NA	NA	58	19.3	0.81	2.130	0.54	0.002	0.080	0.398	<0.006
2	11/24/96 5:51	25510	37380	7.00	14	NA	NA	NA	40	8.8	0.42	1.475	0.31	0.075	0.042	0.334	<0.006
3	11/24/96 6:21	37160	74540	0	17	NA	NA	NA	30	10.0	0.19	1.165	0.22	0.002	0.042	0.490	<0.006
4	11/24/96 6:51	46660	121200	12.00	24	NA	NA	NA	25	6.3	0.19	0.985	0.22	0.111	0.042	0.292	<0.006
5	11/24/96 7:51	97870	219070	5.00	19	NA	NA	NA	21	4.4	0.13	0.664	0.17	0.002	0.042	0.751	<0.006
6	11/24/96 8:51	75910	294980	7.00	18	NA	NA	NA	14	5.0	0.11	0.537	0.15	0.002	0.046	0.532	<0.006
Storm 29																	
1	2/7/97 6:56	14120	14120	16	26	9000	220000	NA	77	24.7	1.9	2.88	0.79	0.025	0.096	0.78	0.012
2	2/7/97 7:25	25750	39870	5	25	2400	300000	NA	44	18.1	1.6	1.56	0.31	0.012	0.049	0.523	0.012
3	2/7/97 7:55	21300	61170	6	25	2000	37800	NA	43	17.3	1.4	0.92	0.22	0.022	0.116	0.619	0.011
4	2/7/97 8:25	22210	83380	10	25	2000	38000	NA	33	15.5	1.15	0.88	0.21	0.118	0.093	0.794	0.02
5	2/7/97 9:25	39370	122750	4	21	2500	2500	NA	37	16.8	0.76	0.97	0.19	0.032	0.042	0.639	0.011
6	2/7/97 10:25	38670	161420	5	25	2000	24000	NA	34	16.2	0.69	1.33	0.21	0.053	0.093	0.799	0.011
Storm 30																	
1	2/12/97 6:08	20180	20180	17	23	NA	NA	NA	44	20.8	1.05	1.43	0.38	0.025		0.455	0.008
2	2/12/97 6:37	40080	60260	7	25	NA	NA	NA	25	22.5	1.4	0.85	0.16	0.042		1.054	0.011
3	2/12/97 7:07	41290	101550	1	18	NA	NA	NA	12	14.2	0.96	0.72	0.14	0.025		0.529	0.01
4	2/12/97 7:37	64780	166330	3	20	NA	NA	NA	8	12.6	0.65	1.48	0.13	0.02		0.621	0.008
5	2/12/97 8:37	60960	227290	6	23	NA	NA	NA	13	10.9	0.49	0.79	0.11	0.028		0.857	0.015
6	2/12/97 9:37	30650	257940	6	21	NA	NA	NA	12	10.9	0.4	0.7	0.09	0.025		0.706	0.008
Storm 31																	
1	3/11/97 11:54	11660	11660	34	21	NA	NA	NA	64	17.9	0.35	1.72	0.46	0.06			
2	3/11/97 12:24	21520	33180	30	39	NA	NA	NA	47	25.5	0.22	1.56	0.26	0.12			
3	3/11/97 12:54	21520	54700	16	33	NA	NA	NA	35	15.6	0.24	1.02	0.23	0.06			
4	3/11/97 13:24	30360	85060	14	27	NA	NA	NA	27	15.2	0.11	1.2	0.23	0.04			
5	3/11/97 14:24	25470	110530	9	22	NA	NA	NA	24	12.9	0.1	1.04	0.2	0.26			
6	3/11/97 15:24	11560	122090	6	19	NA	NA	NA	25	12.9	0.1	0.77	0.18	0.05			
Storm 32																	
1	3/25/97 11:41	25280	25280	14	19	5800	40000	NA	44	21.3	0.61	2.12	NA*	0.09			
2	3/25/97 12:10	37170	62450	NA	19	3200	25000	NA	34	17.3	0.47	1.25	NA	0.07			

3	3/25/97 12:40	24250	86700	NA	17	930	26600	NA	26	15.5	0.47	0.89	NA	0.05
4	3/25/97 13:10	22580	109280	1.5	16	500	43000	NA	30	15.5	0.32	1.48	NA	0.06
5	3/25/97 14:10	21720	131000	3	15	480	13500	NA	26	16	0.27	1.01	NA	0.06
6	3/25/97 15:10	44860	175860	4.5	16	240	23200	NA	22	14.8	0.31	1.26	NA	0.07
Storm 33														
1	4/2/97 18:31	9940	9940	14	16	116000	114000	NA	48	16.8	1.06	1.46	0.46	0.05
2	4/2/97 19:01	11710	21650	7	20	65000	110000	NA	46	20.3	0.94	1.33	0.28	0.04
3	4/2/97 19:31	9660	31310	8.5	20	22000	105000	NA	41	18	1.06	0.97	0.27	0.04
4	4/2/97 20:01	10030	41340	6	17	20000	126000	NA	38	16.8	0.85	0.97	0.21	0.08
5	4/2/97 21:01	13230	54570	2	15	10000	98000	NA	35	18	0.21	0.85	0.17	0.08
6	4/2/97 22:01	10810	65380	1	12	5900	60000	NA	32	14.5	0.1	0.86	0.3	0.03
Storm 34														
1	4/25/97 10:51	27260	27260	14.5	3.5	NA	NA	NA	41	23.8	0.91	2.21	0.5	0.09
2	4/25/97 11:20	44640	71900	5.5	4.9	NA	NA	NA	15	13.2	0.38	0.99	0.23	0.07
3	4/25/97 11:50	48150	120050	3	2.9	NA	NA	NA	14	11.5	0.34	1.1	0.17	0.04
4	4/25/97 12:20	92120	212170	2	4	NA	NA	NA	16	8.6	0.32	1.1	0.19	0.1
5	4/25/97 13:20	151340	363510	4	3.9	NA	NA	NA	11	7	0.25	0.86	0.12	0.07
6	4/25/97 14:20	63060	426570	2.5	2.4	NA	NA	NA	17	7.3	0.15	0.85	0.15	0.05
Storm 35														
1	5/9/97 6:54	68120	68120	47	7.4	NA	77000	NA	72	NA	0.77	2.4	NA	0.06
2	5/9/97 7:24	117780	185900	40	7.5	NA	21900	NA	34	NA	0.35	1.49	NA	0.05
3	5/9/97 7:54	69090	254990	12.5	6.4	NA	17700	NA	36	NA	0.3	1.13	NA	0.05
4	5/9/97 8:24	70960	325950	5.5	5.7	NA	17100	NA	41	NA	0.36	1.22	NA	0.03
5	5/9/97 9:24	71230	397180	1	5	NA	15500	NA	44	NA	0.39	1.22	NA	0.07
6	5/9/97 10:24	64870	462050	4.5	4.6	NA	13400	NA	35	NA	0.41	0.86	NA	0.06
Storm 36														
1	5/27/97 16:03	115150	115150	28	13	31000	55000	NA	32	13.8	0.67	1.34	0.27	0.06
2	5/27/97 16:33	74090	189240	NA*	10	8900	39000	NA	18	6.2	0.42	1.25	0.12	0.08
3	5/27/97 17:03	42570	231810	NA*	10	12100	28000	NA	18	9.6	0.36	1.27	0.15	0.04
4	5/27/97 17:33	37460	269270	4	11	13000	21000	NA	18	11.9	0.3	0.58	0.16	0.1
5	5/27/97 18:33	23520	292790	1	11	20000	36000	NA	29	16.6	0.3	0.5	0.17	0.1

6	5/27/97 19:34	8540	301330	NA*	10	5500	14700	NA	24	15.6	0.26	0.5	0.12	0.14	

Highway runoff at Walnut Creek site

Sample No.	Date/Time Collected	Flow Vol L	Cum Flow L	TSS Conc mg/L	Turbidity Conc NTU	Fecal Col Conc CFU/100ml	Fecal Str Conc CFU/100ml	E. coli Conc CFU/100ml	COD Conc mg/L	TOC Conc mg/L	Nitrate Conc mg/L	TKN Conc mg/L	Total P Conc mg/L	Zinc Conc mg/L	Lead Conc mg/L	Iron Conc mg/L	Copper Conc mg/L
Storm 6																	
1	2/29/96 10:23	40	40	522	192	NA	NA	NA	232	NA	4.400	3.15	0.58	0.388	0.116	7.489	0.023
2	2/29/96 10:53	1080	1120	430	164	NA	NA	NA	153	NA	1.330	2.06	0.54	0.272	0.097	6.301	<0.006
3	2/29/96 11:23	260	1380	328	140	NA	NA	NA	116	NA	1.320	1.80	0.46	0.244	0.057	4.989	0.007
4	2/29/96 12:23	1550	2930	228	108	NA	NA	NA	118	NA	0.520	1.10	0.33	0.209	0.042	3.196	<0.006
5	2/29/96 13:23	2050	4980	199	62	NA	NA	NA	80	NA	0.350	0.84	0.24	0.110	0.042	3.473	<0.006
6	2/29/96 14:23	400	5380	125	58	NA	NA	NA	65	NA	0.300	0.85	0.17	0.088	0.042	2.077	<0.006
Storm 8																	
1	3/26/96 1:41	20	20	560	54	NA	NA	NA	324	102.9	3.400	4.36	0.43	0.187	0.042	2.281	<0.006
2	3/26/96 2:10	70	90	456	26	NA	NA	NA	291	123.1	5.900	NA	0.38	0.180	0.042	1.611	<0.006
Storm 10																	
1	4/5/96 11:29	0	0	340	NA	NA	NA	NA	226	89.9	NA	NA	0.31	0.160	0.042	2.331	<0.006
2	4/5/96 11:59	270	270	460	NA	NA	NA	NA	217	81.7	NA	NA	0.33	0.184	0.042	2.781	0.007
3	4/5/96 12:29	40	310	688	NA	NA	NA	NA	209	75.1	NA	NA	0.010	0.149	0.042	2.282	0.007
4	4/5/96 13:29	0	310	392	NA	NA	NA	NA	219	68.5	NA	NA	0.010	0.129	0.042	2.002	<0.006
5	4/5/96 14:29	410	720	296	NA	NA	NA	NA	122	45.2	NA	NA	0.010	0.137	0.042	2.335	0.007
6	4/5/96 15:29	540	1260	660	NA	NA	NA	NA	133	50.6	NA	NA	0.010	0.193	0.042	3.233	<0.006
7	4/5/96 17:03	1240	2500	664	NA	NA	NA	NA	99	45.4	NA	NA	0.010	0.149	0.042	2.505	<0.006
8	4/5/96 18:03	2110	4610	308	NA	NA	NA	NA	52	23.3	NA	NA	0.010	0.113	0.042	1.613	<0.006
9	4/5/96 19:03	260	4870	152	NA	NA	NA	NA	53	19.8	NA	NA	0.010	NA	NA	NA	NA
12	4/5/96 22:03	1220	6090	400	NA	NA	NA	NA	49	21.7	NA	NA	0.010	NA	NA	NA	NA
Storm 11																	
1	4/28/96 23:06	320	320	706.00	124	NA	NA	NA	353	90	5.890	NA	0.12	0.394	0.277	4.916	<0.006
2	4/28/96 23:36	1070	1390	344.00	45	NA	NA	NA	71	24.1	4.600	NA	0.29	0.056	0.072	1.100	<0.006
3	4/29/96 0:06	270	1660	180.00	55	NA	NA	NA	87	31.6	1.430	NA	0.28	0.082	0.097	2.362	<0.006

4	4/29/96 1:06	30	1690	175.00	55	NA	NA	NA	100	43.6	0.820	NA	0.26	0.097	0.085	1.600	<0.006
Storm 12																	
1	5/27/96 7:15	180	180	554	192	NA	NA	NA	515	178.4	2.200	NA	0.91	0.666	0.37	12.17	0.063
2	5/27/96 7:45	1560	1740	376	168	NA	NA	NA	169	52.5	1.100	NA	0.35	0.132	0.129	3.353	<0.006
3	5/27/96 8:15	5620	7360	32	26	NA	NA	NA	16	19.5	0.650	NA	0.08	0.013	0.119	1.243	<0.006
4	5/27/96 9:15	410	7770	0	40	NA	NA	NA	30	12.9	0.650	NA	0.07	0.021	0.056	0.443	<0.006
Storm 14																	
1	6/4/96 3:22	900	900	82	31	CG	8000	CG	116	53.6	2.31	NA	0.58	0.335	0.394	6.816	0.031
2	6/4/96 3:52	5200	6100	16	7	12000	2600	11000	28	3.8	0.49	NA	0.05	0.002	0.042	0.509	<0.006
3	6/4/96 4:22	1160	7260	8	5	1000	2800	45000	21	4.4	0.49	NA	0.04	0.002	0.048	0.238	<0.006
4	6/4/96 5:22	80	7340	0	4	1600	2700	18000	20	6.2	0.85	NA	0.04	0.002	0.014	0.194	<0.006
5	6/4/96 6:22	0	7340	0	4	145000	9300	27000	30	9.9	0.98	NA	0.05	0.002	0.042	0.22	<0.006
6	6/4/96 7:22	0	7340	0	4	163000	8400	53000	34	9.6	1.26	NA	0.05	0.002	0.063	0.212	<0.006
Storm 15																	
1	6/22/96 11:37	330	330	216	42	NA	NA	NA	191	58.1	5.00	2.419	0.17	0.215	0.085	2.654	<0.006
2	6/22/96 12:06	600	930	42	33	NA	NA	NA	164	51.7	4.60	3.629	0.26	0.053	0.135	0.908	<0.006
3	6/22/96 12:36	0	930	50	45	NA	NA	NA	141	55.6	1.70	6.149	0.26	0.047	0.149	0.754	<0.006
Storm 16																	
1	6/25/96 10:59	320	320	168	30	NA	NA	NA	120	33.2	5.000	3.049	0.35	0.186	0.27	5.062	<0.006
2	6/25/96 11:28	740	1060	76	24	NA	NA	NA	76	24.4	3.400	1.953	0.32	0.036	0.173	1.256	<0.006
3	6/25/96 11:58	370	1430	64	25	NA	NA	NA	71	24.6	4.800	1.738	0.15	0.06	0.118	1.405	<0.006
4	6/25/96 12:58	10	1440	60	30	NA	NA	NA	95	38.3	4.650	NA	0.14	0.04	0.216	1.426	<0.006
Storm 19																	
1	8/22/96 9:58	1000	1000	NA	47.000	NA	NA	NA	80	26.3	1.550	1.864	0.410	0.053	0.135	0.908	<0.006
2	8/22/96 10:27	10	1010	11.000	29.000	NA	NA	NA	310	53.9	2.350	3.139	0.280	0.047	0.149	0.754	<0.006
3	8/22/96 10:57	0	1010	11.000	31.000	NA	NA	NA	297	54.6	6.600	2.648	0.300	0.174	0.147	3.837	0.012
5	8/22/96 12:57	70	1080	29.000	38.000	NA	NA	NA	332	46.3	5.000	3.383	0.310	0.03	0.055	1.09	<0.006
7	8/22/96 18:08	1020	2100	28.000	52.000	12000	1600	900	327	36.1	0.440	1.233	0.590	0.011	0.073	0.784	<0.006
8	8/22/96 18:37	60	2160	11.000	19.000	7000	6800	4800	58	17.0	1.900	1.003	0.170	0.031	0.069	1.245	<0.006
9	8/22/96 19:07	40	2200	12.000	33.000	200000	5300	20000	70	19.0	1.450	1.375	0.170	0.254	0.216	5.787	<0.006
10	8/22/96 20:07	10	2210	14.000	26.000	250000	9500	5000	88	22.6	1.400	1.583	0.210	0.063	0.084	0.95	<0.006

11	8/22/96 21:07	0	2210	15.000	26.000	240000	9700	12000	107	30.3	1.500	1.868	0.240	0.002	0.043	0.58	<0.006
12	8/22/96 22:07	0	2210	14.000	24.000	180000	7800	4500	73	23.0	3.800	1.469	0.200	0.014	0.123	0.66	<0.006
Storm 20																	
1	8/23/96 17:02	880	880	80.000	24.000	NA	NA	NA	74	41.9	1.000	1.227	0.340	0.104	0.053	2.792	<0.006
2	8/23/96 17:30	1710	2590	11.000	14.000	NA	NA	NA	22	20.2	0.300	6.496	0.230	0.005	0.042	1.146	<0.006
3	8/23/96 18:00	960	3550	8.000	7.000	NA	NA	NA	12	7.1	0.320	0.276	0.120	0.002	0.042	0.276	<0.006
4	8/23/96 19:00	560	4110	2.000	10.000	NA	NA	NA	30	9.3	0.370	0.878	0.120	0.002	0.042	0.359	<0.006
5	8/23/96 20:00	250	4360	8.000	9.000	NA	NA	NA	20	7.1	0.200	1.146	0.110	0.002	0.042	0.175	<0.006
6	8/23/96 21:00	0	4360	5.000	9.000	NA	NA	NA	35	11.4	0.710	0.923	0.140	0.002	0.042	0.025	<0.006
Storm 21																	
1	8/29/96 12:17	780	780	16.000	24.000	NA	NA	NA	54	33.0	3.500	2.043	0.140	0.012	0.053	0.895	<0.006
2	8/29/96 12:46	0	780	15.000	27.000	NA	NA	NA	78	22.3	2.300	1.897	0.100	0.028	0.104	0.85	<0.006
3	8/29/96 13:16	0	780	15.000	3.600	NA	NA	NA	74	24.2	3.350	2.673	0.110	0.002	0.068	0.767	<0.006
4	8/29/96 14:16	0	780	15.000	19.000	NA	NA	NA	59	15.9	1.300	1.770	0.090	0.002	0.06	0.65	<0.006
5	8/29/96 15:16	2670	3450	12.000	19.000	NA	NA	NA	52	13.7	4.900	1.390	0.090	0.029	0.092	0.634	<0.006
6	8/29/96 16:16	220	3670	14.000	19.000	NA	NA	NA	48	13.8	1.400	1.150	0.080	0.018	0.072	1.974	<0.006
Storm 23																	
1	10/17/96 16:32	4890	4890	297	200	<2000000	<20000	NA	155	55.3	1.30	5.482	0.19	0.4	0.2	5.8	<0.05
2	10/17/96 17:01	510	5400	78	52	2200000	<20000	NA	53	10.0	1.09	1.635	0.17	0.050	0.1	1.3	<0.0
3	10/17/96 17:31	0	5400	27	27	<200000	20000	NA	65	14.3	1.20	1.809	0.14	0.050	0.1	1.0	<0.0
4	10/17/96 18:31	0	5400	32	31	<2000000	<20000	NA	36	11.0	0.88	1.336	0.11	0.050	0.050	1.0	<0.0
Storm 24																	
1	10/27/96 5:31	740	740	24	25	<20000	3400	NA	57	29.7	0.73	NA	0.14	0.050	0.042	0.8	<0.0
2	10/27/96 6:00	290	1030	16	25	<2000	2600	NA	99	40.5	0.93	1.531	0.13	0.050	0.042	0.3	<0.0
3	10/27/96 6:30	590	1620	21	43	<2000	5300	NA	104	36.2	0.75	2.993	0.14	0.050	0.042	0.6	<0.0
4	10/27/96 7:30	170	1790	16	22	<2000	2800	NA	94	49.2	0.93	1.960	0.14	0.050	0.042	0.042	<0.0
5	10/27/96 8:30	0	1790	17	26	<2000	2400	NA	122	49.2	1.05	1.845	0.15	0.050	0.042	0.3	<0.0

6	10/27/96 9:30	0	1790	14	25	<2000	2000	NA	127	38.3	0.95	NA	0.14	0.050	0.042	0.3	<0.0
Storm 25																	
1	11/7/96 1:22	3150	3150	120	54	0	4400	NA	115	61.7	1.90	2.370	0.34	0.036	0.079	1.061	<0.006
2	11/7/96 1:51	3570	6720	20	27	<2000	2000	NA	30	12.5	0.45	0.776	0.17	0.002	0.074	0.481	<0.006
3	11/7/96 2:21	2090	8810	3	19	0	2000	NA	8	10.0	0.22	0.952	0.09	0.002	0.088	0.165	<0.006
4	11/7/96 3:21	1800	10610	4	16	<2000	6100	NA	38	21.2	1.40	0.159	0.12	0.002	0.076	0.204	<0.006
5	11/7/96 4:21	3640	14250	13	19	0	2200	NA	33	18.3	0.59	0.217	0.15	0.009	0.042	0.628	<0.006
6	11/7/96 5:21	210	14460	16	17	0	2100	NA	14	15.4	1.00	0.460	0.12	0.002	0.045	0.340	<0.006
Storm 27																	
1	12/4/96 11:40	190	190	27.00	77	<2000	5100	NA	117	35.4	2.10	4.519	0.17	0.232	0.042	4.841	<0.006
2	12/4/96 12:09	1380	1570	166.00	63	<2000	5100	NA	127	37.4	2.40	3.339	0.27	0.645	0.198	12.09	0.038
3	12/4/96 12:39	2590	4160	132.00	59	<20000	2700	NA	53	33.1	0.70	2.075	0.15	0.373	0.080	6.802	0.015
4	12/4/96 13:39	2080	6240	52.00	55	<2000	3100	NA	52	27.1	0.40	1.248	0.10	0.091	0.114	3.704	<0.006
5	12/4/96 14:39	980	7220	44.00	52	<2000	3700	NA	60	27.1	0.96	1.597	0.12	0.033	0.072	1.789	<0.006
6	12/4/96 15:39	580	7800	69.00	72	<2000	12100	NA	56	33.1	1.05	1.709	0.18	0.108	0.067	4.312	<0.006
Storm 28																	
1	12/15/96 1:24	510	510	43.00	27	NA	NA	NA	117	58.5	4.10	3.418	NA	0.043	0.057	1.180	<0.006
2	12/15/96 1:53	510	1020	23.00	25	NA	NA	NA	121	45.9	4.10	3.094	NA	0.110	0.087	0.787	<0.006
3	12/15/96 2:23	230	1250	21.00	20	NA	NA	NA	140	51.4	>10	3.544	NA	0.047	0.042	0.873	<0.006
4	12/15/96 3:23	230	1480	15.00	24	NA	NA	NA	135	53.2	>10	2.854	NA	0.027	0.042	0.583	<0.006
5	12/15/96 4:23	4840	6320	343.00	45	NA	NA	NA	139	67.4	2.10	2.413	NA	0.268	0.080	4.692	<0.006
6	12/15/96 5:23	10600	16920	202.00	47	NA	NA	NA	19	28.0	0.53	1.309	NA	0.005	0.057	1.643	<0.006
Storm 26																	
1	11/24/96 3:53	1240	1240	184.00	44	0	11900	NA	86	23.4	1.52	1.464	0.21	0.100	0.124	2.214	<0.006
2	11/24/96 4:21	200	1440	12.00	34	0	5900	NA	49	15.7	1.85	1.484	0.13	0.010	0.165	0.669	<0.006
3	11/24/96 4:51	8110	9550	41.00	37	<2000	8000	NA	52	17.7	1.95	0.840	0.10	0.002	0.042	0.652	<0.006
4	11/24/96 5:51	5760	15310	33.00	23	0	2000	NA	13	6.4	0.37	1.182	0.06	0.004	0.042	0.991	<0.006
5	11/24/96 6:51	3670	18980	11.00	20	<2000	1800	NA	12	6.4	0.50	0.460	0.04	0.002	0.139	0.193	<0.006
6	11/24/96 7:51	6720	25700	90.00	23	0	2000	NA	17	8.3	0.34	0.501	0.05	0.002	0.042	0.371	<0.006
Storm 29																	
1	2/6/97 11:44	480	480	336	290	NA	NA	NA	326	91.1	8.4	7.4	0.53	0.043	0.116	0.559	0.012

2	2/6/97 12:13	380	860	124	150	NA	NA	NA	268	73.6	8	6.78	0.32	0.106	0.183	2.213	0.039
3	2/6/97 12:43	100	960	81	150	NA	NA	NA	287	73.6	8.4	7.15	0.32	0.14	0.157	2.429	0.05
4	2/6/97 13:43	0	960	121	160	NA	NA	NA	260	88.9	10	7.4	0.31	0.138	0.142	2.558	0.05
5	2/6/97 14:43	0	960	152	180	NA	NA	NA	235	90.3	10	7.01	0.35	0.121	0.183	2.481	0.043
6	2/6/97 15:43	0	960	117	190	NA	NA	NA	324	83.8	10	6.72	0.34	0.165	0.229	3.387	0.059
Storm 30																	
1	2/12/97 4:14	640	640	440	86	<2000	80000	NA	94	44.0	4.1	3.86	0.14	0.086		1.939	0.015
2	2/12/97 4:43	1160	1800	74	74	<2000	2000	NA	41	30.4	2.8	2.44	0.14	0.078		2.943	0.021
3	2/12/97 5:13	3760	5560	118	61	<2000	2000	NA	44	22.5	1.1	2.26	0.16	0.089		1.773	0.014
4	2/12/97 6:13	3780	9340	65	63	<2000	2000	NA	44	12.6	0.88	1.11	0.09	0.076		2.219	0.011
5	2/12/97 7:13	3720	13060	216	59	<2000	1600	NA	35	19.2	0.6	1.38	0.22	0.125		2.169	0.029
6	2/12/97 8:13	1910	14970	182	55	<2000	1400	NA	37	17.6	0.8	1.45	0.12	0.086		2.223	0.038
Storm 31																	
1	3/10/97 1:51	5930	5930	1124	272	NA	NA	NA	213	111.0	NA	2.93	0.66	0.584			
2	3/10/97 2:20	4770	10700	46	29	NA	NA	NA	35	6.2	NA	1.1	0.22	0.002			
3	3/10/97 2:50	1310	12010	8	21	NA	NA	NA	17	6.2	NA	0.75	0.06	0.09			
4	3/10/97 3:50	700	12710	12	25	NA	NA	NA	33	13.4	NA	0.61	0.12	0.172			
5	3/10/97 4:50	410	13120	8	17	NA	NA	NA	24	8.0	NA	0.88	0.05	0.072			
6	3/10/97 5:50	220	13340	NA	20	NA	NA	NA	22	8.0	NA	1.28	0.06	0.002			
Storm 32																	
1	3/25/97 9:40	1240	1240	680	136	NA	NA	NA	139	144.5	1.99	2.25	0.97	0.36			
2	3/25/97 10:09	1390	2630	158	260	NA	NA	NA	46	70.9	1.23	3.04	0.33	0.1			
3	3/25/97 10:39	470	3100	62	53	NA	NA	NA	91	30.8	1.37	2.75	0.25	0.13			
4	3/26/97 11:39	5850	8950	318	66	NA	NA	NA	54	54.3	0.7	1.71	0.33	0.08			
5	3/26/97 12:39	1290	10240	38	36	NA	NA	NA	66	20.6	0.82	1.49	0.13	0.24			
6	3/26/97 13:39	1600	11840	22	34	NA	NA	NA	73	30.8	1.19	1.77	0.18	0.08			
Storm 33																	
1	4/2/97 17:15	8990	8990	480	290	NA	NA	NA	304	122.5	2.3	5.51	0.84	0.51			
2	4/2/97 17:44	1900	10890	184	170	NA	NA	NA	149	44.6	0.77	2.77	0.61	0.21			
3	4/2/97 18:14	930	11820	40	100	NA	NA	NA	87	20.3	1.02	2.2	0.29	0.12			
4	4/2/97 19:14	2300	14120	135	56	NA	NA	NA	125	31.9	0.73	2.19	0.46	0.2			

5	4/2/97 20:14	1600	15720	26	29	NA	NA	NA	70	21.6	0.74	2.06	0.24	0.12
6	4/2/97 21:14	1570	17290	34	28	NA	NA	NA	71	18.1	0.71	1.7	0.25	0.1
Storm 34														
1	4/25/97 2:48	1080	1080	77	37	15000	20500	NA	187	69.5	5	4.3	0.34	0.29
2	4/25/97 3:17	1290	2370	15	20	35000	16500	NA	73	32.9	4.35	2.76	0.16	0.17
3	4/25/97 3:47	1240	3610	13	18	26000	6600	NA	37	19.0	2.61	1.9	0.08	0.09
4	4/25/97 4:47	1240	4850	12	28	28000	25000	NA	80	31.0	2.7	2.46	0.13	0.27
5	4/25/97 5:47	1400	6250	198	150	50000	62000	NA	130	45.2	3.96	3.21	0.18	0.12
6	4/25/97 6:47	1510	7760	307	150	19000	45000	NA	162	NA	2.01	3.43	0.59	0.4
Storm 36														
1	5/27/97 15:49	3690	3690	556	114	NA	NA	NA	150	80.2	1.17	4.11	80.2	0.23
2	5/27/97 16:19	3880	7570	114	30	NA	NA	NA	20	11.9	0.29	0.84	0.01	0.09
3	5/27/97 16:49	0	7570	60	30	NA	NA	NA	48	27.1	0.76	1.46	0.08	0.09

Filter strip discharge at Walnut Creek site

Sample No.	Date/Time Collected	Flow Vol L	Cum Flow L	**TSS** Conc mg/L	**Turbidity** Conc NTU	**Fecal Col** Conc CFU/100ml	**Fecal Str** Conc CFU/100ml	**E. coli** Conc CFU/100ml	**COD** Conc mg/L	**TOC** Conc mg/L	**Nitrate** Conc mg/L	**TKN** Conc mg/L	**Total P** Conc mg/L	**Zinc** Conc mg/L	**Lead** Conc mg/L	**Iron** Conc mg/L	**Copper** Conc mg/L
Storm 5																	
1	12/17/95 7:25	2500	2500	147	32	40000	26500	NA	71	NA	1.110	0.650	0.35	0.080	0.085	2.353	<0.006
2	12/17/95 7:40	71100	73600	120	28	40500	22500	NA	56	NA	0.650	0.58	0.23	0.056	0.042	1.756	0.007
3	12/18/95 7:55	31800	105400	9	5.8	12500	22000	NA	35	NA	0.390	0.45	0.23	0.002	0.042	1.197	<0.006
4	12/19/95 8:25	28560	133960	2	4.5	18500	30000	NA	35	NA	0.240	0.43	0.27	0.002	0.042	0.180	<0.006
5	12/20/95 9:25	23900	157860	4	4	NA	NA	NA	41	NA	0.420	0.40	0.11	0.002	0.042	0.177	<0.006
Storm 6																	
3	2/29/96 11:57	3760	3760	28	48	180000	20000	100000	98	NA	1.780	1.10	0.03	0.083	0.042	1.107	<0.006
4	2/29/96 12:27	10900	14660	115	45	TNTC	31000	20000	69	NA	1.460	1.19	0.03	0.062	0.042	1.607	<0.006
5	2/29/96 13:27	35940	50600	53	35	TNTC	29000	210000	53	NA	1.000	0.80	0.03	0.014	0.042	0.632	<0.006
6	2/29/96 14:27	29420	80020	28	21	NA	NA	NA	47	NA	0.930	0.90	0.06	0.011	0.042	0.604	<0.006
Storm 15																	
1	6/22/96 16:56	3100	3100	42	3	NA	NA	NA	58	17.7	1.89	1.299	0.17	0.002	0.093	0.335	<0.006
2	6/22/96 17:10	5780	8880	22	19	NA	NA	NA	84	32.2	1.89	3.977	0.24	NA	NA	NA	NA
3	6/22/96 17:40	3470	12350	24	10	NA	NA	NA	90	37.7	4.6	4.048	0.16	0.004	0.075	0.145	<0.006
4	6/22/96 18:10	3450	15800	14	16.000	NA	NA	NA	77	27.1	7.4	0.904	0.150	0.002	0.135	0.181	<0.006
5	6/22/96 19:10	1710	17510	14	20	NA	NA	NA	72	31.8	NA	1.934	0.13	NA	NA	NA	NA
6	6/22/96 20:10	480	17990	NA	NA	NA	NA	NA	72	38.6	NA	3.584	0.20	NA	NA	NA	NA
Storm 16																	
1	6/25/96 11:38	5320	5320	NA	5	NA	NA	NA	58	24.9	3.7	2.371	0.26	0.002	0.142	0.183	<0.006
2	6/25/96 11:52	6690	12010	48	4.7	NA	NA	NA	74	28.1	1.8	3.24	0.29	0.002	0.165	0.206	<0.006
3	6/25/96 12:22	6060	18070	36	4.7	NA	NA	NA	70	26.6	2.8	1.104	0.17	0.002	0.159	0.191	<0.006
4	6/25/96 12:52	4830	22900	36	5	NA	NA	NA	58	24.7	1.9	1.526	0.12	0.002	0.152	0.191	<0.006
Storm 18																	
1	8/11/96 14:52	79590	79590	80	4.7	CG	2600	430000	35	20.400	0.980	3.696	0.160	0.002	0.121	0.138	<0.006

2	8/11/96 15:07	52110	131700	108	9.8	CG	10400	1000000	110	34.800	1.150	3.647	0.450	0.015	0.135	0.671	<0.006
3	8/11/96 15:37	50350	182050	192	3.5	CG	5700	480000	63	16.800	0.700	1.898	0.270	0.002	0.128	0.343	<0.006
4	8/11/96 16:07	25790	207840	8	2.7	1450000	5200	280000	77	27.800	0.590	2.181	0.390	0.002	0.173	0.338	<0.006
5	8/11/96 17:07	12850	220690	12	3	1160000	6000	400000	93	29.600	0.700	2.673	0.420	0.002	0.098	0.099	<0.006
6	8/11/96 18:07	10580	231270	4	1.9	620000	2500	63000	67	39.200	0.700	1.930	0.390	0.002	0.127	0.344	<0.006
Storm 19																	
2	8/22/96 18:20	10500	10500	7	8.000	380000	7000	9000	97	20.800	4.600	3.039	0.250	0.002	0.126	0.38	<0.006
3	8/22/96 18:34	9720	20220	8	10.000	120000	25000	190000	60	20.600	4.600	1.577	0.170	0.002	0.098	0.188	<0.006
4	8/22/96 19:04	7700	27920	0	5.000	20000	15000	20000	52	16.600	4.200	1.393	0.190	0.002	0.11	0.544	0.068
5	8/22/96 19:34	12820	40740	6	5.000	180000	15000	24000	52	15.000	1.300	2.175	0.210	0.002	0.076	0.405	<0.006
Storm 20																	
2	8/23/96 17:16	5360	5360	7	3.500	NA	NA	NA	24	12.100	1.100	0.609	0.090	0.041	0.069	0.143	<0.006
3	8/23/96 17:30	42390	47750	6	4.700	NA	NA	NA	48	18.400	0.680	0.591	0.200	0.002	0.042	0.717	<0.006
4	8/23/96 18:00	48920	96670	3	5.700	NA	NA	NA	33	13.600	0.330	1.218	0.190	0.002	0.042	0.007	<0.006
5	8/23/96 18:30	41780	138450	3	4.500	NA	NA	NA	18	13.700	0.200	1.107	0.180	0.002	0.042	0.018	<0.006
6	8/23/96 19:30	47610	186060	3	3.500	NA	NA	NA	38	14.100	0.150	0.781	0.190	0.002	0.061	0.007	<0.006
Storm 21																	
1	8/29/96 12:26	6870	6870	21	13.000	NA	NA	NA	24	17.200	2.000	3.696	0.11	0.002	0.134	0.067	<0.006
2	8/29/96 12:40	9170	16040	14	4.500	NA	NA	NA	45	17.200	2.500	3.647	0.12	0.002	0.124	0.103	<0.006
3	8/29/96 13:10	5950	21990	1	21.000	NA	NA	NA	47	18.400	4.400	1.898	0.12	0.002	0.07	0.109	<0.006
4	8/29/96 13:40	7510	29500	6	6.300	NA	NA	NA	48	18.400	1.400	2.181	0.13	0.002	0.073	0.9	<0.006
5	8/29/96 14:40	8810	38310	8	7.200	NA	NA	NA	39	12.700	4.200	2.673	0.14	0.002	0.141	0.148	<0.006
6	8/29/96 15:40	229040	267350	2	4.000	NA	NA	NA	40	14.600	0.510	1.930	0.13	0.002	0.044	0.049	<0.006
Storm 27																	
1	12/4/96 12:59	7610	7610	5.00	3.3	2000	2000	NA	9	9.4	0.15	0.482	0.15	0.060	0.042	0.214	<0.006
2	12/4/96 13:14	9110	16720	19.00	31	22000	22700	NA	40	22.4	1.40	1.244	0.17	0.021	0.061	1.514	<0.006
3	12/4/96 13:44	9680	26400	25.00	40	48000	28000	NA	37	23.7	1.30	1.113	0.15	0.021	0.114	1.593	<0.006
4	12/4/96 14:14	9740	36140	13.00	35	2000	16000	NA	30	27.4	1.40	1.149	0.12	0.002	0.120	0.887	<0.006
5	12/4/96 15:14	9030	45170	13.00	31	4400	12400	NA	19	21.4	0.81	0.893	0.11	0.005	0.247	1.071	<0.006
6	12/4/96 16:14	9500	54670	21.00	25	2000	11700	NA	27	18.4	0.93	0.843	0.11	0.009	0.072	0.838	<0.006
Storm 28																	

1	12/15/96 4:55	10410	10410	11.00	15	NA	NA	NA	11	20.1	0.80	0.677	NA	0.002	0.042	0.156	<0.006
2	12/15/96 5:10	32570	42980	17.00	20	NA	NA	NA	64	39.0	2.20	1.595	NA	0.002	0.087	0.470	<0.006
3	12/15/96 5:40	227380	270360	6.00	12	NA	NA	NA	41	21.5	1.00	1.353	NA	0.002	0.042	0.294	<0.006
4	12/15/96 6:10	251380	521740	11.00	12	NA	NA	NA	9	13.8	0.24	0.763	NA	0.002	0.042	0.426	<0.006
5	12/15/96 7:10	154060	675800	7.00	13	NA	NA	NA	16	15.4	0.21	0.582	NA	0.002	0.042	0.382	<0.006
6	12/15/96 8:10	159220	835020	6.00	9	NA	NA	NA	4	17.5	0.17	0.650	NA	0.005	0.137	0.473	<0.006
Storm 26																	
2	11/24/96 5:52	18430	18430	10.00	23	570000	460000	NA	50	23.2	2.10	0.500	0.29	0.002	0.042	0.202	<0.006
3	11/24/96 6:22	33560	51990	11.00	16	2000	300000	NA	40	11.9	1.10	0.970	0.25	0.002	0.099	0.169	<0.006
4	11/24/96 6:52	37270	89260	5.00	14	250000	65000	NA	29	10.1	0.39	0.744	0.18	0.012	0.061	0.235	<0.006
5	11/24/96 7:52	101270	190530	36.00	12	2000	50000	NA	18	10.1	0.29	0.720	0.16	0.002	0.061	0.552	<0.006
6	11/24/96 8:52	95450	285980	6.00	14	210000	76000	NA	18	10.1	0.24	0.574	0.19	0.002	0.051	0.269	<0.006
Storm 29																	
1	2/7/97 6:21	12250	12250	30	12	NA	NA	NA	17	4	0.78	0.889	0.1	0.273	0.247	5.982	0.054
2	2/7/97 6:36	27410	39660	24	26	NA	NA	NA	73	12.8	1.9	1.927	0.16	0.053	0.11	1.197	0.014
3	2/7/97 7:06	23260	62920	139	59	NA	NA	NA	79	25.6	1.6	1.591	0.25	0.067	0.087	1.286	0.015
4	2/7/97 7:36	16040	78960	37	38	NA	NA	NA	42	16.5	1.16	1.278	0.16	0.04	0.113	1.012	0.009
5	2/7/97 8:36	30080	109040	14	28	NA	NA	NA	39	12.3	1.1	1.908	0.16	0.007	0.042	0.011	0.002
6	2/7/97 9:36	45570	154610	12	24	NA	NA	NA	41	12.5	1	1.599	0.14	0.046	0.042	0.572	0.015
Storm 30																	
1	2/12/97 5:36	6890	6890	16	25	<2000	13200	NA	25	19	3.5	0.411	0.08				
2	2/12/97 5:50	23260	30150	18	26	<2000	13400	NA	38	17.3	3.3	1.464	0.08	0.036		0.357	0.008
3	2/12/97 6:20	26330	56480	30	26	<2000	15500	NA	36	15.8	1.85	1.139	0.11	0.107		0.488	0.024
4	2/12/97 6:50	41820	98300	11	20	<2000	190000	NA	19	12.5	1.2	1.225	0.09	0.029		0.458	0.007
5	2/12/97 7:50	85090	183390	9	16	<2000	15700	NA	16	14.2	1.15	0.678	0.14	0.032	<0.042	0.48	0.009
6	2/12/97 8:50	43660	227050	13	22	2600	14300	NA	19	14.2	0.73	1.081	0.08	0.055	0.168	0.6	0.019
Storm 31																	
1	3/10/97 2:02	29730	29730	19	27	NA	NA	NA	14	13.4	NA	0.879	0.08	0.05			
2	3/10/97 2:17	139310	169040	80	32	NA	NA	NA	38	43.1	NA	1.883	0.21	0.07			
3	3/10/97 2:47	60010	229050	78	30	NA	NA	NA	21	14.7	NA	1.121	0.09	0.08			

4	3/10/97 3:17	35060	264110	16	15	NA	NA	NA	17	10.2	NA	0.741	0.09	0.03
5	3/10/97 4:17	14450	278560	6	11	NA	NA	NA	24	12.5	NA	0.988	0.09	0.09
6	3/10/97 5:17	7950	286510	4	10	NA	NA	NA	19	16.1	NA	1.23	0.11	0.09
Storm 32														
1	3/25/97 11:42	5900	5900	9.5	5.3	NA	NA	NA	17	18	1.26	1.199	0.09	0.12
2	3/25/97 11:56	29440	35340	6	21	NA	NA	NA	46	24.2	1.59	1.907	0.1	0.15
3	3/25/97 12:26	28110	63450	12.5	22	NA	NA	NA	40	20	0.78	0.663	0.22	0.09
4	3/25/97 12:56	21420	84870	4	17	NA	NA	NA	31	14	0.47	0.786	0.16	0.24
5	3/25/97 13:56	11420	96290	2.5	16	NA	NA	NA	29	15.8	0.39	0.901	0.19	0.05
6	3/25/97 14:56	50970	147260	1	15	NA	NA	NA	33	17.5	0.61	0.786	0.16	0.09
Storm 34														
1	4/25/97 8:41	4050	4050	34	6.5	10900	25000	NA	49	36.9	2.14	1.24	0.2	0.13
2	4/25/97 8:55	8050	12100	11	7	9300	40000	NA	42	24.5	2.07	1.482	0.14	0.28
3	4/25/97 9:25	6680	18780	20	19	19200	45000	NA	51	19.7	1.59	1.5	0.18	0.2
4	4/25/97 9:55	16660	35440	6	16	10500	52000	NA	47	19.9	1.45	1.659	0.2	0.08
5	4/25/97 10:55	88360	123800	7	13	8200	40000	NA	48	19.7	1.34	1.255	0.12	0.1
6	4/25/97 11:55	117430	241230	16.5	14	6800	26000	NA	35	17.4	0.99	1.25	0.18	0.18

APPENDIX C

EMCs and Final Concentration Averages

for Four Field Sites

Storm EMC summary for road, 183 @ Mopac site (C) 19 storms

Storm	Date	Flow L	TSS EMC mg/L	Turbidity EMC NTU	Fecal Col EMC CFU/100ml	Fecal Str EMC CFU/100ml	E. coli EMC CFU/100ml	COD EMC mg/L	TOC EMC mg/L	Nitrate EMC mg/L	TKN EMC mg/L	Total P EMC mg/L	Zinc EMC mg/L	Lead EMC mg/L	Iron EMC mg/L
Storm 12	5/27/96	117310	127	53	6265	56842	5810	53	35.2	1.21	NA	0.45	0.294	0.168	3.216
Storm 13	5/30/96	176250	7	10	157726	16313	15634	27	14.3	5.21	NA	0.36	0.002	0.079	0.368
Storm 15	6/22/96	6800	247	44	NA	NA	NA	458	68.1	3.29	5.922	0.60	0.459	0.197	5.348
Storm 16	6/25/96	18480	117	27	83202	6423	NA	69	26.0	5.66	1.868	0.35	0.285	0.200	3.286
Storm 19	8/22/96	5940	31	45	NA	NA	NA	202	36.5	2.66	2.993	0.51	0.279	0.166	4.317
Storm 20	8/23/96	15260	17	21	NA	NA	NA	52	17.1	0.80	1.199	0.20	0.030	0.052	0.723
Storm 21	8/29/96	3680	22	41	489348	4092	2138	123	41.8	1.12	0.378	0.38	0.146	0.075	2.565
Storm 22	9/18/96	32320	135	78	NA	8361	NA	112	39.7	2.25	2.206	0.39	0.123	0.095	2.760
Storm 23	10/17/96	18400	64	39	NA	NA	NA	119	45.5	1.15	3.029	1.07	1.040	0.285	9.750
Storm 24	10/27/96	6320	312	105	17811	53399	NA	NA	59.5	0.47	5.569	2.01	1.099	0.271	7.996
Storm 25	11/7/96	30600	81	22	2355	4244	NA	11	15.4	0.53	0.616	0.16	0.126	0.042	1.516
Storm 26	11/24/96	25660	40	24	2000	5137	NA	38	5.5	0.41	0.590	0.43	0.022	0.082	0.370
Storm 28	12/15/96	55180	98	26	NA	NA	NA	20	18.7	0.55	0.885	NA	0.093	0.088	1.830
Storm 30	2/12/97	10110	133	66	NA	NA	NA	67	25.0	0.46	1.346	0.27	0.23	NA	2.558
Storm 32	3/25/97	20490	328	105	NA	NA	NA	81	35.5	0.43	2.055	0.58	0.44	NA	NA
Storm 33	4/2/97	12360	522	206	18363	37035	NA	122	51.9	1.63	0.308	0.69	0.69	NA	NA
Storm 34	4/25/97	3830	146	60	NA	NA	NA	38	40.3	2.47	2.455	0.56	0.35	NA	NA
Storm 35	5/9/97	152400	389	36	NA	8306	NA	19	NA	0.91	3.249	0.68	0.48	NA	NA
Storm 36	5/27/97	87389	159	48	86604	57007	NA	86	34.3	0.94	2.176	0.30	0.41	NA	NA
Straight Average			157	55	95964	23378	7861	94	33.9	0.91	2.167	0.55	0.347	0.138	3.329
Coeff of Variance			0.90	0.81	1.63	0.98	0.89	1.09	0.49	0.93	0.76	0.76	0.90	0.59	0.83

Storm EMC summary for swale, 183 @ Mopac site (D) 23 storms

Storm	Date	Flow L	TSS EMC mg/L	Turbidity EMC NTU	Fecal Col EMC CFU/100ml	Fecal Str EMC CFU/100ml	E. coli EMC CFU/100ml	COD EMC mg/L	TOC EMC mg/L	Nitrate EMC mg/L	TKN EMC mg/L	Total P EMC mg/L	Zinc EMC mg/L	Lead EMC mg/L	Iron EMC mg/L
Storm 9	3/27/96	60390	4	21	NA	NA	NA	42	23.3	0.65	0.262	0.20	0.011	0.042	0.294
Storm 10	4/5/96	74350	18	NA	NA	NA	NA	10	14.3	NA	NA	0.19	0.003	0.042	0.330
Storm 11	4/22/96	42120	5	7	NA	NA	NA	64	23.4	0.80	NA	0.33	0.002	0.096	0.404
Storm 12	5/27/96	148880	56	26	380261	4045	400495	76	35.2	0.54	NA	0.95	0.022	0.119	1.359
Storm 13	5/30/96	254830	56	39	14804	7824	12015	49	17.7	4.61	NA	0.28	0.115	0.098	1.469
Storm 15	6/22/96	62330	38	24	NA	NA	NA	45	21.4	2.71	1.966	0.46	0.002	0.119	1.036
Storm 16	6/25/96	115950	50	10	373030	24173	24651	27	18.5	3.71	1.728	0.24	0.003	0.146	0.518
Storm 18	8/11/96	170400	58	19	1511616	16655	452056	64	15.7	0.64	7.066	0.42	0.002	0.153	0.702
Storm 19	8/22/96	35410	3	8	NA	NA	NA	68	20.0	0.31	1.832	0.35	0.002	0.102	0.212
Storm 20	8/23/96	149470	5	8	NA	NA	NA	48	15.4	0.20	1.176	0.21	0.002	0.058	0.240
Storm 21	8/29/96	151690	59	34	145182	71121	17123	32	11.1	1.40	1.003	0.32	0.002	0.061	2.088
Storm 22	9/18/96	103090	7	8	NA	NA	NA	24	8.1	1.32	0.901	0.32	0.002	0.059	0.471
Storm 25	11/7/96	222390	14	11	NA	NA	NA	29	19.3	0.20	0.775	0.43	0.025	0.051	0.312
Storm 28	12/15/96	475340	7	11	NA	NA	NA	10	14.4	0.25	0.630	NA	0.022	0.045	0.322
Storm 26	11/24/96	294980	6	19	NA	NA	NA	24	6.5	0.19	0.874	0.21	0.026	0.045	0.539
Storm 29	2/7/97	161420	7	24	2798	83676	NA	41	17.4	1.12	1.299	0.27	0.044	0.077	0.690
Storm 30	2/12/97	257940	5	22	NA	NA	NA	16	14.4	0.78	1.001	0.15	0.027	NA	0.726
Storm 31	3/11/97	122090	17	28	NA	NA	NA	35	16.6	0.17	1.206	0.25	0.11	NA	NA
Storm 32	3/25/97	175860	6	17	1823	27809	NA	30	16.6	0.41	1.326	NA	0.07	NA	NA
Storm 33	4/2/97	65380	6	17	38596	101629	NA	40	17.5	0.68	1.066	0.28	0.05	NA	NA
Storm 34	4/25/97	426570	4	4	NA	NA	NA	16	9.6	0.32	1.039	0.18	0.07	NA	NA
Storm 35	5/9/97	462050	21	6	NA	26478	NA	43	NA	0.42	1.397	NA	0.05	NA	NA
Storm 36	5/27/97	301330	19	11	19077	40400	NA	24	11.4	0.48	1.122	0.19	0.07	NA	NA
Straight Average			21	17	276354	40381	181268	37	16.7	0.46	1.456	0.31	0.032	0.082	0.689
Coeff of Variance			1.009	0.555	1.766	0.831	1.238	0.495	0.365	1.187	0.974	0.558	1.086	0.459	0.753

Storm EMC summary for road, Walnut Creek site (site WCR) 24 storms

Storm	Date	Flow L	TSS EMC mg/L	Turbidity EMC NTU	Fecal Col EMC CFU/100ml	Fecal Str EMC CFU/100ml	E. coli EMC CFU/100ml	COD EMC mg/L	TOC EMC mg/L	Nitrate EMC mg/L	TKN EMC mg/L	Total P EMC mg/L	Zinc EMC mg/L	Lead EMC mg/L	Iron EMC mg/L
Storm 6	2/29/96	5380	257	100	NA	NA	NA	107	NA	0.67	1.224	0.33	0.178	0.054	3.960
Storm 8	3/26/96	90	479	32	NA	NA	NA	298	118.6	5.34	4.360	0.39	0.182	0.042	1.760
Storm 10	4/5/96	6090	432	NA	NA	NA	NA	81	34.2	NA	NA	0.02	0.139	0.042	2.181
Storm 11	4/28/96	1690	383	62	NA	NA	NA	127	38.1	4.27	NA	0.26	0.125	0.115	2.033
Storm 12	5/27/96	7770	111	59	NA	NA	NA	59	29.5	0.78	NA	0.15	0.052	0.123	1.878
Storm 14	6/4/96	7340	23	10	9889	3295	17211	38	10.0	0.72	NA	0.11	0.043	0.086	1.236
Storm 15	6/22/96	930	104	36	NA	NA	NA	174	54.0	4.74	3.200	0.23	0.110	0.117	1.528
Storm 16	6/25/96	1440	93	26	NA	NA	NA	85	26.5	4.12	2.143	0.28	0.076	0.181	2.141
Storm 19	8/22/96	2210	26	48	20496	2077	1819	202	31.2	1.16	1.593	0.48	0.036	0.103	0.953
Storm 20	8/23/96	4360	23	14	NA	NA	NA	31	19.5	0.45	3.035	0.21	0.024	0.044	1.130
Storm 21	8/29/96	3670	13	20	NA	NA	NA	52	17.8	4.39	1.514	0.10	0.025	0.083	0.770
Storm 23	10/17/96	5400	276	186	NA	NA	NA	145	51.0	1.28	5.119	0.19	0.367	0.191	5.375
Storm 24	10/27/96	1790	21	31	NA	3840	NA	83	35.4	0.79	2.422	0.14	0.050	0.042	0.581
Storm 25	11/7/96	14460	36	28	NA	3085	NA	47	25.4	0.89	0.927	0.18	0.011	0.069	0.562
Storm 27	12/4/96	7800	98	59	NA	4114	NA	68	31.6	1.01	2.050	0.16	0.280	0.107	6.050
Storm 28	12/15/96	16920	227	44	NA	NA	NA	63	41.4	1.21	1.794	NA	0.085	0.064	2.451
Storm 26	11/24/96	25700	54	28	NA	4373	NA	30	11.4	0.95	0.809	0.07	0.007	0.061	0.664
Storm 29	2/6/97	960	226	220	NA	NA	NA	299	82.4	NA	7.129	0.43	0.078	0.147	1.409
Storm 30	2/12/97	14970	147	62	NA	5159	NA	43	20.1	1.14	1.729	0.15	0.093	0.093	2.139
Storm 31	3/10/97	13340	526	136	NA	NA	NA	112	53.2	NA	1.849	0.39	0.280	NA	NA
Storm 32	3/25/97	11840	256	88	NA	NA	NA	67	57.9	1.00	1.948	0.35	0.131	NA	NA
Storm 33	4/2/97	17290	295	188	NA	NA	NA	209	77.6	1.57	3.925	0.63	0.341	NA	NA
Storm 34	4/25/97	7760	113	72	29253	30588	NA	112	38.8	3.37	3.002	0.25	0.226	NA	NA
Storm 36	5/27/97	7570	329	71	NA	NA	NA	83	45.2	0.72	2.434	0.01	0.158	NA	NA
Straight Average			190	70	19879	7066	9515	109	41.3	1.27	2.610	0.24	0.129	0.093	2.042
Coeff of Variance			0.83	0.83	0.49	1.35	1.14	0.71	0.61	0.85	0.59	0.64	0.81	0.49	0.75

Storm EMC summary for swale, Walnut Creek site (site WCS)   22 storms

Storm	Date	Flow L	TSS EMC mg/L	Turbidity EMC NTU	Fecal Col EMC CFU/100ml	Fecal Str EMC CFU/100ml	E. coli EMC CFU/100ml	COD EMC mg/L	TOC EMC mg/L	Nitrate EMC mg/L	TKN EMC mg/L	Total P EMC mg/L	Zinc EMC mg/L	Lead EMC mg/L	Iron EMC mg/L
WC-3	4/29/94	66284	62	NA	NA	NA	NA	35	NA	0.49	NA	0.22	0.041	NA	0.249
WC-5	4/30/94	37536	15	NA	NA	NA	NA	40	NA	0.45	NA	0.12	0.024	NA	0.138
WC-6	5/2/94	41068	19	NA	NA	NA	NA	47	NA	0.28	NA	0.10	0.020	NA	0.474
WC-9	5/28/94	31004	10	NA	NA	NA	NA	30	NA	0.87	NA	0.10	NA	NA	NA
WC-20	10/18/94	154861	55	NA	116000	80000	NA	38	NA	0.20	NA	0.09	0.031	0.007	1.087
WC-33	5/8/95	197330	20	NA	NA	NA	NA	21	NA	NA	NA	NA	NA	NA	NA
Storm 5	12/20/95	157860	59	16	29154	24055	NA	46	NA	0.50	0.501	0.22	0.028	0.043	1.129
Storm 6	2/29/96	80020	51	32	NA	28762	NA	55	NA	1.07	0.904	0.04	0.023	0.042	0.777
Storm 15	6/4/96	17990	24	14	NA	NA	NA	63	29.9	3.69	2.735	0.18	0.003	0.101	0.216
Storm 16	6/7/96	22900	41	5	NA	NA	NA	66	26.2	2.53	2.111	0.22	0.002	0.155	0.194
Storm 18	8/11/96	231270	95	5	1195878	5507	534135	67	25.1	0.89	2.987	0.30	0.005	0.130	0.332
Storm 19	8/22/96	40740	6	7	186991	15324	58983	66	18.1	3.49	2.107	0.21	0.002	0.101	0.373
Storm 20	8/23/96	186060	4	5	NA	NA	NA	34	14.8	0.36	0.921	0.19	0.003	0.048	0.175
Storm 21	8/29/96	267350	3	5	NA	NA	NA	40	14.9	0.85	2.065	0.13	0.002	0.054	0.080
Storm 27	12/4/96	54670	16	28	13874	15951	NA	28	20.9	1.03	0.970	0.13	0.018	0.111	1.045
Storm 28	12/15/96	835020	8	12	NA	NA	NA	20	18.0	0.51	0.900	NA	0.003	0.062	0.389
Storm 26	11/24/96	285980	17	14	140348	116393	NA	24	11.2	0.50	0.690	0.19	0.003	0.061	0.349
Storm 29	2/7/97	154610	38	31	NA	NA	NA	50	14.2	1.27	1.627	0.16	0.060	0.084	1.155
Storm 30	2/12/97	227050	14	20	NA	47200	NA	22	14.5	1.45	0.982	0.11	0.044	NA	0.473
Storm 31	3/10/97	286510	60	27	NA	NA	NA	28	27.8	NA	1.416	0.15	0.067	NA	NA
Storm 32	3/25/97	147260	5	18	NA	NA	NA	36	18.7	0.83	1.012	0.16	0.122	NA	NA
Storm 34	4/25/97	241230	13	14	8064	33900	NA	42	19.0	1.22	1.295	0.16	0.147	NA	NA
Straight Average			29	16	241473	40788	296559	41	19.5	0.97	1.451	0.16	0.032	0.077	0.508
Coeff of Variance			0.87	0.61	1.77	0.88	1.13	0.37	0.29	0.88	0.51	0.38	1.25	0.54	0.74