ABSTRACT

Title of thesis: FIELD EVALUATION OF HYDROLOGIC AND WATER QUALITY BENEFITS OF GRASS SWALES FOR MANAGING HIGHWAY RUNOFF

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Due to growing awareness of non-point source pollution treatment, the performance of grass swales as a highway runoff treatment and the effect of including a grass filter strip pretreatment area adjacent to the swale were evaluated using a field-scale input/output study on a Maryland highway. Results of this comparison for 22 rainfall events over 1.5 years show significant peak reduction (50-53%), delay of the peak flow (33-34 min) and reduction of total volume (46-54%). The grass swales exhibited statistically significant removals by mean concentration of total suspended solids (41-52%), nitrite (56-66%) and zinc (30-40%), lead (3-11%), copper (6-28%) and cadmium. Other monitored nutrients (nitrate, TKN, and total phosphorus) exhibited variable removal capabilities (-1-60%), while the swales exported chloride (216-499 mg/l) at a significant level. Results suggest the pretreatment grass filter strip imparts no significant water quantity or quality improvement and that the swale itself is the most important treatment mechanism.

FIELD EVALUATION OF HYDROLOGIC AND WATER QUALITY BENEFITS OF GRASS SWALES FOR MANAGING HIGHWAY RUNOFF

by

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TABLE OF CONTENTS

List of Tables………...…………………………………………….….….. v

List of Figures………………………………………………………….……. vii

Chapter 1:
Introduction………………………………………………………….... 1

Chapter 2: Literature Review…………………………………...……. 6
2.1 Characterization of Stormwater Runoff……………...………. 6
2.1.1 Total Suspended Solids……………………….………. 7
2.1.2 Nutrients……………………………………………… 8
2.1.1 Chloride…………………………………….………. 8
2.1.1 Heavy Metals………………………………….………… 9
2.2 Flow Characteristics and Runoff Composition………...……… 11
2.3 First Flush of Runoff Pollutants…………………..………… 13
2.3.1 Concentrations-based first flush………….....………… 14
2.3.2 Mass-based first flush ………………………..………… 15
2.3.3 Criteria for first flush …………………………...…… 18
2.3.4 First flush Stormwater Runoff Conclusions ………..... 19
2.4 Event Mean Concentration (EMC) ………………………….… 21
2.5 Grass Swale Constituent Removal Efficiency ………………… 22
2.5.1 Reporting parameters for grass swale studies ……..… 22
2.5.2 Total suspended solids ………………………………..… 26
2.5.3 Nutrients ……………………………………...…… 29
2.5.4 Chloride ……………………………………………… 30
2.5.5 Heavy metals ……………………………………...… 31
2.5.6 Logarithmic data plotting …………………………… 32
2.5.7 Barrett regression and model storm event ……...…… 35
2.6 Grass Swale Efficiency and Hydrology ……………………..… 38
2.7 Grass Swale Efficiency and Design Parameters ……………..…… 40
2.8 Grass Swale Efficiency and Pretreatment ………………..……… 44

Chapter 3: Methods and Materials……………………...……………… 47
3.1 Site Description …………………………………….………… 47
3.2 Sampling Goals and Purpose …………………………...……… 51
3.3 Monitoring Equipment and Protocol ………..………………… 52
3.3.1 Sampling program ………………………...……… 52
3.3.2 Flow calculation …………………………………..…… 54
3.4 Analytical Methodology …………………………………….…… 56
3.4.1 TSS analysis ………………………………………… 56
3.4.2 Phosphorus analysis ……………………………….… 57
3.4.3 Nitrate, nitrite, and chloride analysis ……………….. 58
3.4.4 TKN analysis ……………………………………….... 59

3.4.5 Cadmium, copper, lead, and zinc analyses ………….. 59
3.4.6 Quality control …………………………………….……… 59
3.4.7 Data below detection limit ………………...………… 60
3.5 Hydrology Data Evaluation and Calculations ………………… 60
3.5.1 Instantaneous flow drainage area normalization ……. 62
3.5.2 Total storm volume ……………………………….. 65
3.5.3 Normalized total storm volume ……………………... 67
3.6 Pollutant Data Evaluation and Calculations …………………... 70
3.6.1 Total mass load ……………………………………… 71
3.6.2 Event mean concentration (EMC) …………………... 72
3.6.3 Normalized event mean concentration (N-EMC) …... 73
3.6.4 First flush diagrams …………………………………. 74
3.7 Statistical Analysis and Comparison ………………………….. 76
3.7.1 Overall statistical analysis procedure ……………….. 76
3.7.2 Dixon-Thompson test for outliers …………………... 79
3.7.3 Kolmogorov-Smirnov 1-sample test ………………... 80
3.7.4 Paired Student's T-test ……………………………… 81
3.7.5 Wilcoxon signed-ranks test …………………………. 83
3.7.6 F test of variances …………………………………… 83
3.8 Swale Comparison Plots ………………………………………. 84
3.8.1 Time based plots …………………………………….. 84
3.8.2 Probability plots ……………………………………... 85
3.8.3 Box and whisker plots ………………………………. 87

Chapter 4: Results and Discussion……………………………………... 88
4.1 General Observations …………………………………………. 88
4.2 Hydrology Comparison ……………………………………….. 89
4.2.1 Storm event characterization ………………………... 89
4.2.2 Flows with respect to time …………………………... 96
4.2.3 Peak flow ……………………………………………. 100
4.2.4 Time to peak flow …………………………………… 105
4.2.5 Total volume/infiltration ……………………………. 107
4.3 General Pollutant Observations ……………………………….. 115
4.4 Total Suspended Solids (TSS) ………………………………… 116
4.4.1 First flush removal comparison ……………………... 117
4.4.2 N-EMC removal comparison ……………………….. 119
4.4.3 Mass removal comparison …………………………... 123
4.5 Nutrients ………………………………………………………. 125
4.5.1 Mass removal comparison …………………………... 126
4.5.2 N-EMC removal comparison………………………... 129
4.6 Chloride ……………………………………………………….. 132
4.6.1 N-EMC removal comparison ……………………….. 133
4.6.2 Mass removal comparison …………………………... 137
4.6.3 First flush removal comparison ……………………... 138
4.7 Metals …………………………………………………………. 140
4.7.1 Zinc ………………………………………………….. 141

4.7.2 Cadmium ………………………………..………… 145
4.7.3 Copper ……………………………………………. 146
4.7.4 Lead ………………………………………………. 149

Chapter 5: Conclusions………………………………………………… 155

Appendix A: N-EMC and Mass Data for All Storm Events……………….. 163

Appendix B: Flow and Concentration Data with Respect to Time for All Storm Events ……………………..……..………………………… 166

References……………………………………………………………….. 192

LIST OF TABLES

Table 2-1 Expected concentrations and pollutant guidelines……………… 7

Table 2-2 Normalized mass and volume standards for a mass-based first flush ………………………………………………………………. 18

Table 2-3 Parameters to report with water quality data (Strecker 2001) … 24

Table 2-4 Distribution form of constituents for direct runoff (creek inflow) and flow after settling pond treatment determined by fitting probability plots (Van Buren 1997) ……………………………………...…… 35

Table 2-5 Regression results showing grass swale effluent concentrations and confidence intervals as a function of influent concentrations (Barrett 2005) ……………….………………..……………………... 36

Table 3-1 Design characteristics for three sampled channels …………… 49

Table 3-2 Sampling times for automated collection during storm events at Rt. 32 ……………………………………..…………………..… 53

Table 3-3 Analytical methods for determination of pollutant concentrations in Rt. 32 swale storm events ……………..…………… 57

Table 3-4 Site drainage areas ……………………..……………………… 64

Table 3-5 Regiment of statistical tests …………………………………….. 78

Table 4-1 Frequency of storm events for 15 stations in MD ………...…… 90

Table 4-2 Rainfall depth and storm duration for Rt. 32 storm events. Storms with complete capture shown in bold ……………………..…… 91

Table 4-3 Monitored Rt. 32 total number of storm events defined by the Kreeb (2003) matrix showing event duration vs. rainfall depth where storms with complete capture are shown in parenthesis and bold type 93

Table 4-4 Depth-duration table showing complete capture and distribution of storms in Maryland with theoretically completely captured storms in dark grey, mixed capture storms in light grey, and storms exhibiting flow in white (Kreeb 2003)……………………………………..……. 96

Table 4-5 Normalized peak flow summary statistics for all three channels and summary of peak flow reduction with complete capture storm events removed …………………………………………...…….… 101

Table 4-6 Peak flow reduction statistical test results ………………...……… 103

Table 4-7 Distribution summary statistics of delay to peak flow (min) for the SHA and MDE swales ………………………………………...……… 105

Table 4-8 Delay to peak flow statistical test results …………………..……… 107

Table 4-9 Normalized total volume summary statistics for all three channels and summary of total volume reduction with all zero volume storm events included ……………………………………………..…….. 108

Table 4-10 Normalized volume reduction statistical test results ………..… 111

Table 4-11 Total suspended solid distribution and reduction summary statistics for all three channels with complete capture storm events removed from N-EMC and first flush reduction calculations………..… 121

Table 4-12 Nutrient mass distribution and mass reduction summary statistics for all three channels ……………………………..………...… 127

Table 4-13 Chloride distribution and reduction summary statistics for all three channels …………………… …………………………………… 135

Table 4-14 Zinc distribution and reduction summary statistics for all three channels …………………………………………………..……....…. 142

Table 4-15 Copper distribution and reduction summary statistics for all three channels …………………………………………….…………..... 147

Table 4-16 Lead distribution and reduction summary statistics for all three channels ………………………………………………………...… 150

LIST OF FIGURES

Figure 2-1 Estimated contributions of various sources of metals in highway runoff (Davis 2001) ………………………………………….……….…. 10

Figure 2-2 Comparison of three methods used to calculate mass-based first flush (Sansalone and Cristina 2004) …………….……….……...…… 17

Figure 2-3 Particle trapping efficiencies for various particle sizes in a 110 m grass swale (Backstrom 2003) ……………………………...………. 27

Figure 2-4 Average particle size distributions for inlet (dark line) and outlet (grey line) of swales, where L1 and L2 are 5 m, laboratory swales, F1, F2, and F3 are 5 m, field swales, and F5, F6, and F7 are 10 m, field swales (Backstrom 2003) …………………………….……….. 28

Figure 2-5 Comparison of normal and lognormal probability plots for normally distributed concentrations (left plots) and lognormally distributed concentrations (right plots). Correct distributions are shown as straight lines (Van Buren 1997)……………………………… 34

Figure 2-6 Particle trapping efficiency of grass swales at three different particle settling velocities, where L1 and L2 are 5 m laboratory swales, F1-F4 are 5 m field swales and F5-F7 are 10 m field swales (Backstrom 2002) ……………………………………………...…….…. 41

Figure 2-7 Mean swale residence time versus particle settling velocities associated to a trapping efficiency of 50% (left) and 90% (right) in grass swales (Backstrom 2002)……..………… ....…………… 42

Figure 2-8 TSS concentrations along the center of grass swale as a function of distance from outlet, showing changes in concentration as flow passes through swale (Barrett 1998)………………..… ………… 45

Figure 3-1 Rt. 32 swale monitoring site …………………...……………… 47

Figure 3-2 Grass channel typical section (not to scale) (Maryland SHA 2004) …………………………………………………………..…….. 48

Figure 3-3 Diagram of swale study area ………………..…….………… 49

Figure 3-4 MDE swale at Rt. 32 …………………………………...…… 50

Figure 3-5 SHA swale at Rt. 32 …………………………………………… 50

Figure 3-6 Direct roadway runoff monitoring at Rt. 32 ……………….…. 51

Figure 3-7 Grass swale mass balance model ……………………………… 61

Figure 3-8 Grass swale flow balance model without rainfall dilution ….… 67

Figure 3-9 Grass swale mass balance model ……………………………… 70

Figure 4-1 Rainfall depth distribution for Maryland (Kreeb 2003) and Rt. 32 storm events ……………………………………………………… 91

Figure 4-2 Storm duration distribution for Maryland (Kreeb 2003) and Rt. 32 storm events ……………………………………………………… 92

Figure 4-3 Depth-duration plot showing completely captured storm events as empty diamonds and storms with flow as filled squares …………… 94

Figure 4-4 Normalized flow for 9/26/05 storm event, showing no runoff from swales…………………………………………………….… 97

Figure 4-5 Normalized flow for 1/11/06 storm event …………….……… 98

Figure 4-6 Normalized flow for 5/19/05 storm event …………….……… 99

Figure 4-7 Peak flow probability plot showing all storm events for influent (Direct) and swale effluent (SHA and MDE) ………………… 102

Figure 4-8 Box and whisker plot showing the distribution of delays (min) between influent peak flow and swale peak flow for SHA and MDE swales…………………………………………………...………… 106

Figure 4-9 Normalized total volume probability plot ……………..……… 109

Figure 4-10 Normalized volume reduction in both swales compared to total rainfall depth in storm event, showing decrease in removal during large storms …………………………………………..…….…….. 113

Figure 4-11 Box and whisker plot of normalized volume reduction for both swales showing positive reduction in median values and low means due to large negative reductions ……………….…..……………… 114

Figure 4-12 TSS concentrations with respect to time (5/11/06 storm event) ………………………………………………...…...… 118

Figure 4-13 Total suspended solids N-EMC probability plot …….……… 122

Figure 4-14 Nitrate N-EMC probability plot …………………………… 129

Figure 4-15 Nitrite N-EMC probability plot ……………………………… 130

Figure 4-16 TKN N-EMC probability plot ………………………… 131

Figure 4-17 Total phosphorus N-EMC probability plot ………………… 132

Figure 4-18 Chloride N-EMC probability plot …………………………… 133

Figure 4-19 Chloride concentrations with respect to time (5/19/05) …… 138

Figure 4-20 Chloride mass-based first flush diagram (5/19/05) ………… 139

Figure 4-21 Zinc N-EMC probability plot ………………………… 143

Figure 4-22 Zinc concentrations with respect to time (10/24/05) ………… 144

Figure 4-23 Zinc mass-based first flush diagram (10/24/05) …………… 145

Figure 4-24 Copper N-EMC probability plot …………………… 148

Figure 4-25 Lead N-EMC probability plot …………………………… 151

Figure 4-26 Lead concentrations with respect to time (11/16/05) ……… 152

Figure 4-27 Lead mass-based first flush diagram (11/16/05) …………… 153

Chapter 1

INTRODUCTION

The importance of the environmental threat posed by non-point source pollution resulting from stormwater runoff has received increasingly more attention by engineers, scientists, and government agencies since the 1980's as the mechanisms and severity of this problem have been analyzed. Recent research suggests that nonpoint source pollution is responsible for 30% of all identified cases of water quality impairment in the United States (US EPA 1990) and almost 50% of total water pollutant mass in the developed world (Novotny 1994). Runoff draining across agricultural land, urban areas, industrial sites, and the several million miles of highway within the United States presents a substantial environmental challenge because of the disperse nature of pollutant pathways.

Recognizing the importance of stormwater pollutant loading and prompted by the Clean Water Act Amendments, the U.S. Environmental Protection Agency established a National Pollution Discharge Elimination System to characterize storm water discharge and to develop pollution prevention plans (Wu *et al.*1998). Under this federally mandated program, most municipalities with populations larger than 10,000 must obtain a stormwater runoff discharge permit, which requires the design and implementation of best management practices (BMPs) to decrease the non-point source runoff pollutant load being discharged to local receiving water bodies. This requirement has spurred interest into structural and non-structural BMPs to quantify their effect on runoff quantity and quality, thereby allowing more accurate and appropriate stormwater treatment designs.

Detention basins, sand filters, grass swales, bioinlets, bioretention areas, hydrodynamic devices, infiltration trenches, porous pavements, wetland basins, and media filters are some of the most common stormwater BMPs used to remove runoff pollutants.

Focus on the treatment of stormwater runoff has influenced an alternative method of stormwater treatment, called Low Impact Development (LID), which relies on using natural processes and site design to treat runoff. Replacing natural vegetative areas with as little as 10% impervious surfaces within a watershed can have deleterious effects on receiving water bodies by increasing runoff volume, peak flow, and providing an area for pollutants to accumulate during dry periods (Rushton 2001). Therefore, the primary goal of the LID approach is to achieve the same site conditions pre-development and post-development with respect to hydrology, soil and vegetative cover. While conventional stormwater management methods attempt to capture and route runoff away from a site in order to treat the total volume using an end-of-pipe solution, the LID approach focuses on retaining runoff within the site and using dispersed BMPs based on processes like infiltration, evapotranspiration, and routing runoff over pervious surfaces to treat runoff immediately.

One such LID technology that has been employed for the conveyance of stormwater runoff in highway designs for many years is grass swales. Swales are shallow, grass-lined, typically flat-bottomed channels that were originally designed to convey stormwater (Barrett 1998). Swales are commonly used on highway projects because they represent an aesthetically pleasing method for conveying runoff; more recently it was discovered that water quality enhancements can be realized in these swales through sedimentation (due to the low velocity induced by the vegetation), filtering by the grass blades, infiltration, and likely, some biological processes. While recent studies have revealed grass swales as an effective LID technology, good performance data and mechanistic understanding of swale design parameters are not widely available.

Little consistent information on water quality improvements for swales is available, in large part because of the complexity of swale operation. Swales receive flow laterally through vegetated side slopes, which can greatly improve incoming water quality. Infiltration throughout the swale surface area can reduce flow volume and improve quality. However, the multiple points of water input and output can complicate simple performance analyses. This variability in performance across grass swale designs is illustrated in a summary report on swale performances from several states, which has shown sediment removals ranging from -85% (i.e., sediment increases) to 98% (Schueler 1994). These results indicate that many variables can contribute to the pollutant removal efficiency of grass swales.

As part of increased focus by the environmental community on stormwater management practices capable of treating non-point source runoff, and in recognition of the great amount of uncertainty regarding the performance and pollutant removal mechanisms of grass swales, a pilot project was constructed by the Maryland State Highway Administration (SHA). The goal for this project was to systematically quantify the effects of some operational parameters for water quality improvement using grass swales. The project focused both on measuring the overall efficiency of a grass swale on roadway runoff pollutant removal as well as the effect of the shallow sloped grass pre-treatment area adjacent to the grass swale. Many BMP design manuals recommend the inclusion of this grass filter strip pretreatment area prior to the grass swales to increase pollutant removal efficiency. With this importance attributed to the grass pretreatment area by design manuals, it is hypothesized that grass swales are effective at improving highway runoff, and that the pretreatment area is responsible for a significant amount of this improvement.

In order to tests this hypothesis by analyzing the pollutant removal capability of the swales and measuring the effect of a pretreatment area, two nearly identical swales were designed and constructed on Rt. 32, a four-lane limited access highway near Savage, Maryland. One swale was built with a pretreatment area adjacent to the swale, while the other swale received runoff directly from the roadway surface. A third sampling site, a concrete channel which received runoff directly from the roadway, was assumed to be equivalent in quantity and water quality to the inputs for the two swales. The study system was constructed to concurrently monitor representative inflow and outflow from the grass swales, allowing the determination of pollutant removal efficiency. Water quality parameters examined included those considered as being most problematic from roadway runoff – total suspended solids (TSS), nitrate (NO_3^-), nitrite (NO_2^-), Total Kjeldahl Nitrogen (TKN), total phosphorus (TP), chloride (Cl), lead (Pb), copper (Cu), zinc (Zn), and cadmium (Cd). Flow rates were also recorded to determine the effect of swales on stormwater quantity and to allow for calculation of total pollutant mass reduction. In total, 22 storm events were analyzed over a period of 1.5 years, with 18 storm events containing associated pollutant data.

This project will assist in quantifying the removal capability of grass swales for a wide variety of highway runoff pollutants, allowing for a more refined mechanistic understanding. Similarly, the research will quantify the importance of the pretreatment area prior to the grass swale, to determine if this feature, which is required in many swale design specifications, is effective or necessary. The research will also assist highway administrations and engineers in predicting removal capabilities of grass swales and thereby assist in making BMP designs more efficient and effective.

Chapter 2

LITERATURE REVIEW

2.1 CHARACTERIZATION OF STORMWATER RUNOFF

A full understanding of the composition, hydrology, and behavior of highway runoff is necessary in understanding Best Management Practice (BMP) technologies because the treatment potential of the technology is dependent on the characteristics of the influent runoff. The transport of pollutants from the roadway surface is controlled by chemical interactions between water and solids on the roadway, suspension of solids by turbulent water flow, and aquatic chemistry. These complex interactions result in pollutants that are either dissolved or particulate bound. Each phase must be treated differently in order to achieve successful runoff treatment. Particulate bound constituents can be removed by physical processes such as straining, filtration, and settling while dissolved constituents must be removed through biological means, adsorption or other physiochemical processes. Because of this, particulate bound constituents are more easily removed by roadside BMPs, yet can later cause long-term problems through accumulation of particulates. These particles can later be resuspended or the bound constituents can repartition into the runoff in the dissolved phase.

Typical ranges for the pollutants analyzed in this study are presented in Table 2-1. This shows that total suspended solids (TSS) is present at the highest concentrations in highway runoff. Nutrients and metals are at present at much lower concentrations in highway runoff, however, the regulatory guidelines show that these concentrations can be hazardous. Little information is available regarding chloride concentrations in highway runoff, however the Kaushal *et al.* (2005) study presents chloride concentrations for a wide range of freshwater streams receiving runoff from nearby impervious areas. These values therefore should be representative of expected chloride concentrations.

Table 2-1. Expected concentrations and pollutant guidelines.

Pollutant	**Expected Concentrations**		**Dangerous/Regulated Guidelines**	
		Source		**Source**
TSS	10-500 mg/l	Wu *et al.* (1998)	30 mg/l	USEPA (1999)
Nitrate	0.01-5 mg/l	Lee *et al.* (2000)		
TKN	1-50 mg/l	Lee *et al.* (2000)		
TP	0.5-20 mg/l	Lee *et al.* (2000)		
Chloride	20-400 mg/l	Kaushal *et al.* (2005)	250 mg/l	Kaushal *et al.* (2005)
Zinc	20-5,000 μg/l	Davis *et al.* (2001)	120 μg/l	MDE (2005)
Lead	5-200 μg/l	Davis *et al.* (2001)	65 μg/l	MDE (2005)
Copper	5-200 μg/l	Davis *et al.* (2001)	13 μg/l	MDE (2005)
Cadmium	<12 μg/l	Davis *et al.* (2001)	2.0 μg/l	MDE (2005)

2.1.1 *Total Suspended Solids (TSS)*

Suspended solid particulates in highway runoff are mainly from pavement wear, vehicles, atmospheric deposition, maintenance activities, and washoff from local soils. They can cause impacts that include increased water color and turbidity, decreased light penetration, clogging, and direct toxicity to aquatic organisms. Many pollutants are associated with the fine-sized particles that do not settle easily. As a result, TSS themselves cause water quality problems, as do the many pollutant constituents that adsorb to TSS. Effluent from wastewater treatment plants must contain less than 30 mg/l TSS to comply with federal Environmental Protection Agency regulations (USEPA

1999). This treatment level can be used as a reference to assess the quality of effluent leaving a BMP treatment with regards to suspended particulate matter.

2.1.2 *Nutrients*

Nutrients are another important highway runoff constituent that can cause deleterious effects for receiving water bodies. As impervious area increases, nutrients build up on surfaces, leading to high pollutant loads. Nutrients in urban runoff can accelerate eutrophication in receiving waters. Surface algal scums, water discoloration, taste and odors, depressed oxygen levels, and release of toxic compounds are all possible impacts of high nutrient levels. The most important nutrients causing accelerated algal production are nitrogen compounds and phosphorus. Nitrogen in runoff is a result of decomposing organic matter, animal and human wastes, fertilizers, and atmospheric deposition. Total Kjeldahl nitrogen (TKN) represents the sum of organic nitrogen and ammonia concentrations in water. Nitrogen is also commonly present in water in the form of nitrite and nitrate. Phosphorus is commonly found bound to fine sediments and is a result of similar sources as nitrogen, except for atmospheric deposition (Strecker *et al.*1994).

2.1.3 *Chloride*

Chloride is an anion found naturally, but is also present in deicing agents used on roadways. Concentrations of chloride of 30 mg/l have been found to damage land plants, while concentrations as low as 250 mg/l are harmful to freshwater life, not potable for human consumption, and have a distinctly salty taste (Kaushal *et al.* 2005). A study examining chloride concentrations in Maryland, New York, and New Hampshire found a noticeable trend towards higher salinity in freshwater rivers and streams over the past 15-20 years (Kaushal *et al.* 2005). While the baseline chloride concentrations for all analyzed water bodies increased during this time period, there is an increasing relationship between the amount of impervious surface coverage and the mean annual chloride concentration. This relationship is presumably due to increased deicing material applied to the impervious areas. Because chloride is a constituent of deicing agents, it would follow that concentrations in urban and suburban areas would only be elevated during the winter months. However, it appears that chloride sources persist for long after the application of road salt because concentrations of chloride in receiving water bodies remain elevated throughout the year. Spring, summer and autumn concentrations remained up to 100 times greater than streams draining watersheds without impervious surfaces (Kaushal *et al.* 2005).

2.1.4 *Heavy Metals*

Heavy metals in urban runoff have toxic effects on aquatic life and can contaminate drinking water supplies. Metal concentrations in runoff generally follow the order: Zn (20-5000 μg/l) > Cu ≈ Pb (5-200 μg/l) > Cd (<12 μg/l). Metals are present in the dissolved form and adsorbed to particulates. The bioavailability and mobility of dissolved metals are of the greater concern to aquatic life, although particulate-bound metals also pose the threat of accumulation and later partitioning into the dissolved phase.

A study by Davis *et al.* (2001) examined the source and annual loading estimates for lead, copper, cadmium, and zinc in residential urban runoff. By measuring metal concentrations in collected runoff after spraying various automotive parts with synthetic rainwater, the source and average loadings were estimated for all four metals. By combining this with atmospheric and rainfall sampling, estimates of the distribution of sources for each metal examined were quantified and shown in Figure 2-1 after adjustment for highway conditions without housing sources.

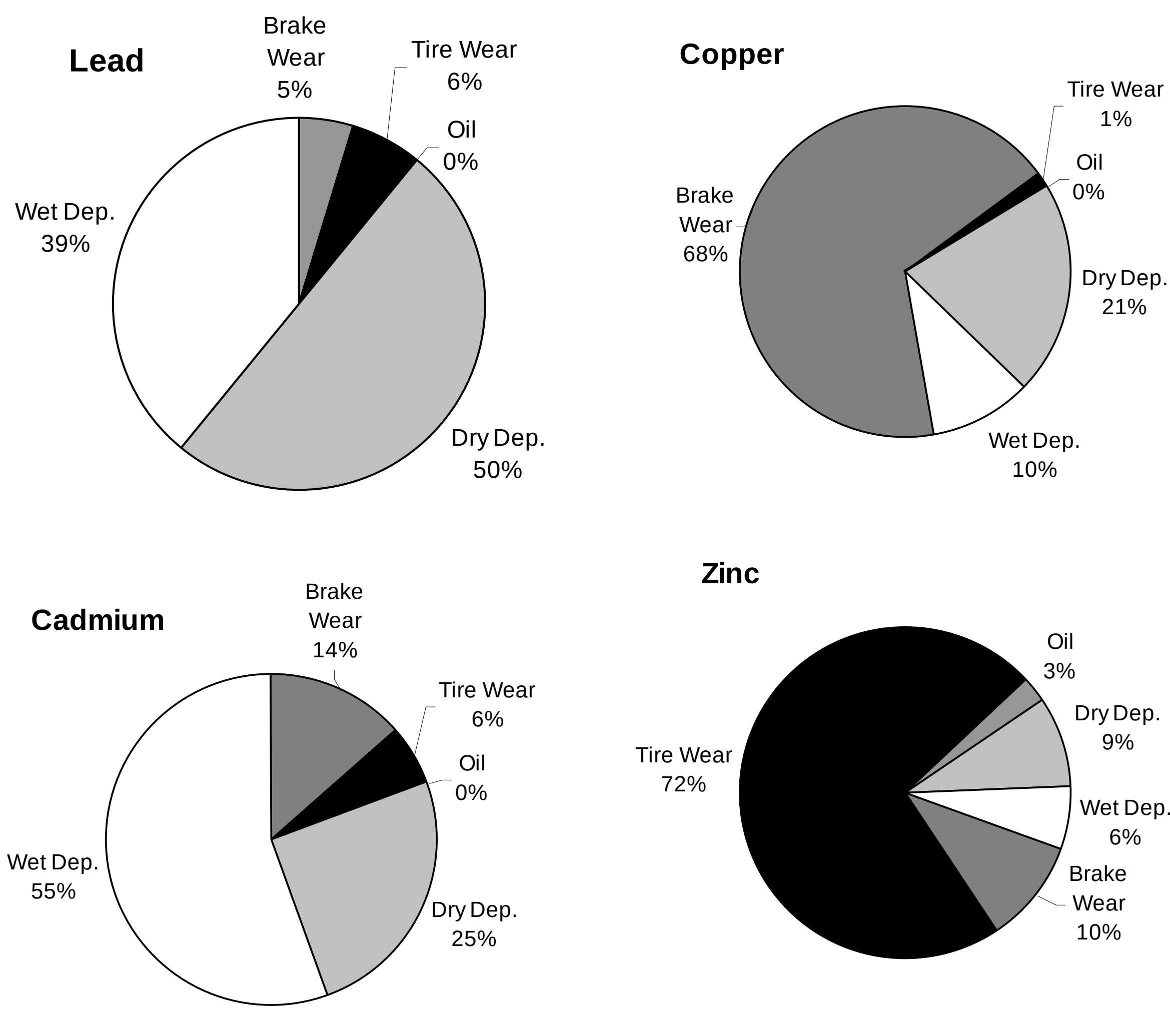

Figure 2-1. Estimated contributions of various sources of metals in highway runoff (Davis *et al.* 2001).

Lead on roadways is primarily caused by the burning of leaded fossil fuel, although since the predominance of unleaded fuels, this source has diminished (Legret and Pagotto

1999). An atmospheric source of lead remains, however, which deposits lead concentrations as wet and dry deposition. Copper in highway runoff is almost entirely due to brake wear (Davis *et al.* 2001). Brake pad material contains mostly copper with some zinc and brass, which contains several percent lead. Cadmium, though much lower in concentration than the other three metals, is mostly present in highway runoff because of atmospheric deposition (Davis *et al.* 2001). Finally, the majority of zinc is due to automobile tire wear because zinc is used as filler in automobile tires

In highway runoff, metals are present in both the dissolved phase and the particulate phase. Because of the slightly acidic properties of highway runoff (pH ranging between 6 and 7.5), zinc and cadmium are predominately in the dissolved phase while the majority of lead is associated with the particulate phase, bound to stormwater particulates and organics. This particulate-bound lead is unaffected by runoff flow rates and remains predominately particulate bound for all storm events (Dean *et al.* 2005). The percentage of bound lead can be as high as 91%, as in a multiple storm event study at a highway site in northern France (Legret and Pagotto 1999). Copper is much more dependent on rainfall conditions and is common in both the particulate and dissolved phases.

2.2 FLOW CHARACTERISTICS AND RUNOFF COMPOSITION

The composition of highway runoff is strongly affected by the physical processes and flow rates caused by rainfall on the roadway surface. These processes affect the kinetics of pollutant release and thereby divide storm events into two classifications: flow-limited or mass-limited events (Dean *et al*. 2005). Flow-limited events generally occur during low intensity rainfalls that produce low runoff volumes. Flow-limited events are classified as any storm event with mean flow rates less than 1 L min^{-1} m^{-1} of roadway length (Sansalone and Cristina 2004). Particulate-bound pollutant concentrations mirror the flow hydrograph in this case because the original source of pollutant covering the roadway surface is never exhausted and only transfers more pollutant as more flow passes the source. During flow-limited events, heavy metals in the runoff are primarily particulate bound, attached to suspended solids or organics (Dean *et al.* 2005). The speciation of these metals, which includes a single dominant species for each metal, remains constant throughout a flow-limited storm event.

Dissolved pollutant concentrations, including nutrients and chloride, act differently than particulate-bound pollutants. These dissolved contaminants are present in the highest concentrations during the initial part of the storm and then exponentially decrease in concentration as the storm event progresses (Dean *et al.* 2005). Therefore, in the case of relatively low intensity storm events, one can expect that changes in the hydrograph will have little effect on the distribution of particulate and dissolved pollutants. The concentration of particulate bound species will follow the hydrograph, while dissolved species, which are more easily transported from the road surface, will show an exponential distribution as the source is depleted.

High intensity storm events are referred to as mass-limited events because runoff concentrations are controlled by an exhaustion of the pollutants present on the roadway surface (Dean *et al.* 2005). Mass-limited events have mean flow rates greater than 1 L min^{-1} m^{-1} of pavement (Sansalone and Cristina 2004). In this type of storm, the pollutant transport profiles do not follow the hydrograph and show a first flush of pollutants during the initial part of the storm event. One reason for this first flush is that the pollutants undergo a shift in phase, from primarily the dissolved phase at the onset of rainfall to the particulate phase. As in flow-limited events, dissolved contaminants are much more easily transported in highway runoff and therefore show very high initial concentrations followed by a rapid decline. After the initial dissolved source is exhausted, the majority of contaminants are particulate bound, except for the small amount of contaminants repartitioning from the surface of solids into the dissolved phase. In Dean *et al.* (2005), highway runoff was analyzed and it was concluded that copper, zinc, and cadmium all undergo this shift from dissolved to particulate during high intensity storms, while lead, which is more tightly bound, remains associated with particulate matter throughout the storm.

2.3 FIRST FLUSH OF RUNOFF POLLUTANTS

When analyzing the transference of pollutants on the roadway surface to highway runoff, it is important to consider the concept of a first flush of pollutants. This phenomenon is defined as a disproportionately high delivery of a constituent during the initial portions of a storm event. This definition, however, is qualitative and does not provide any quantitative means for classifying a first flush or for describing the strength or severity of a first flush. This abstract definition has produced significant debate and research attempting to quantify this common runoff phenomenon.

Currently, two general methods are employed for examining the first flush in highway runoff: concentration-based and mass-based. These two methods reflect different concerns of the researcher, engineer, or regulator. Because many pollutants can be acutely toxic to aquatic plants and animals, a maximum concentration is the focus of design and discharge permits. With a focus on this concern, the concentration-based first flush is most applicable. However, when addressing concerns like Total Maximum Daily Loads (TMDLs) or chronic effects on aquatic life, the mass-based first flush is most applicable. The mass-based first flush is also important because it provides a more comprehensive representation of a storm event, combining the runoff quality concentration pollutograph with the runoff quantity flow hydrograph.

2.3.1 *Concentration-based first flush*

The concentration-based first flush is defined as a disproportionately high constituent concentration during the rising limb of the runoff hydrograph or the early portion of the runoff hydrograph. This was the first definition of a first flush proposed by researchers. By assessing the pollutant concentrations with respect to time in a pollutograph, a decision can be made about the strength of presence of a first flush. However, this definition is very difficult to quantify, as it only relies on a strong decline of concentrations. One suggested criterion defines a concentration-based first flush as any storm event where concentrations fall to 20% of the maximum concentrations during the rising limb of the hydrograph or early part of a storm (Sansalone and Cristina 2004). The difficulty with this definition is delineating where the early part of the storm event occurs. For these reasons, the term first flush in a concentration-based analysis is more useful as a general description of a pollutograph, yet cannot be used in more rigorous comparisons between storms or between pollutants.

2.3.2 *Mass-based first flush*

The mass-based first flush description compares the pollutant load with the volume of runoff. The mass-based first flush, therefore, is defined as a disproportionately high delivery of pollutant mass during the early portion of a storm event. Because pollutant mass is based on both concentration and volume, all mass-based first flush methods combine the storm pollutograph (C as a function of t) with the storm hydrograph (Q as a function of t). Since these graphs are rarely if ever available as continuous data, mass-based first flush analyses typically use discrete points. Also, because these two curves are dependent on many environmental factors, such as rainfall intensity, antecedent dry weather, and roadway characteristics, the first flush analysis cannot differentiate between any of these effects.

Unlike the concentration-based first flush definition, the mass-based first flush can be defined in a graphical or numerical fashion. There are three accepted graphical methods of analyzing a mass-based first flush. All of these methods compare M(t), the dimensionless ratio of constituent mass delivered at any time to the total mass delivered throughout an event, to V(t), the dimensionless ratio of runoff volume delivered at any time to the total volume delivered throughout an event. The discrete solutions of these two parameters are represented by the following equations:

$$V(t) = \frac{\sum_{t=0}^{k} Q(t_i)\Delta t}{\sum_{t=0}^{n} Q(t_i)\Delta t} \qquad (2\text{-}1)$$

$$M(t) = \frac{\sum_{t=0}^{k} Q(t_i)C(t_i)\Delta t}{\sum_{t=0}^{n} Q(t_i)C(t_i)\Delta t} \qquad (2\text{-}2)$$

where Q(t) = mean volumetric flow rate between successive measured flow rates C(t) = mean concentration of pollutant between successive measured concentrations, and Δt = time increment between successive measurements. A mass-based first flush is defined as:

$$M(t) > V(t) \qquad (2\text{-}3)$$

for any early time in the rainfall-runoff event. Three methods are used to determine if this condition is present. All three methods are mathematically equivalent and only function as different methods to present the same information. Figure 2-22 shows a comparison between the three methods by analyzing the same data with each method.

The first method for determining the presence of a mass-based first flush compares M(t) to V(t) as a function of the elapsed time of the storm. Time is normalized in the same manner as M(t) and V(t) by calculating the ratio between the sample time and the total time elapsed during the storm. As in the first plot of Figure 2-2, both M(t) and V(t) are plotted on the dependent axis, while normalized time is plotted on the independent axis. A mass-based first flush occurs at any period when the M(t) plot exceeds the V(t) plot, indicating that a disproportionately high percentage of mass has been delivered by a given volume of flow.

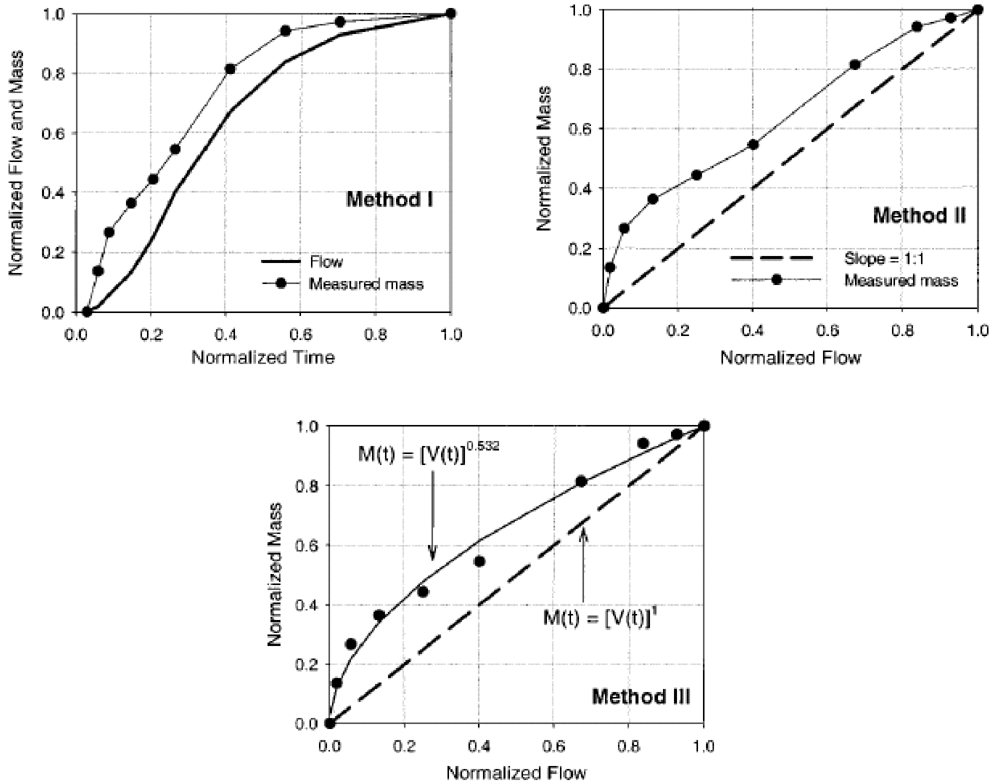

Figure 2-2. Comparison of three methods used to calculated mass-based first flush (Sansalone and Cristina 2004).

Method 2 removes time from the independent axis. Instead, this method plots normalized mass, M(t), directly against normalized volume, V(t). Because of this direct comparison, an equal delivery of normalized mass to normalized volume is represented graphically by a line with a 1:1 slope. Therefore, a mass-based first flush occurs for any period during which M(t) resides above the 45 degree bisecting line.

Finally, method 3 attempts to fit an exponential curve through the points calculated in method 2. This curve takes the form:

$$M(t) = [\ V(t)\ ]^{b} \tag{2-4}$$

Fitting the exponential parameter, b, results in a numeric representation of the first flush. Values of b less than 1 indicate the occurrence of a mass-based first flush. The lower the value of b, the more pronounced is this first flush. One of the biggest drawbacks of this method is its dependence on a good fit for the data to a power curve.

2.3.3 *Criteria for First Flush*

Using the above methods, some criteria must be developed to determine if the first flush is significant. This criterion must also have a time aspect to ensure that the highest difference between normalized mass and volume occurs in the first section of the storm. There are currently no universally accepted criteria, yet most proposed criteria have similar forms.

Research by Geiger suggests a definition of a significant first flush as any storm in which the maximum gap between the normalized mass curve and the 1:1 bisector is greater than 0.2 (Bertrand-Krajewski *et al.* 1998). Although this does establish some criteria, that normalized mass delivery must be 20% greater than the volume delivery, it does not address the time factor. The significant gap can occur at any time during the storm. This, therefore, is not an effective criterion for defining a first flush.

The prevailing criterion for defining a significant first flush uses method 2 and

Table 2-2. Normalized mass and volume standards for a mass-based first flush.

Reference	Mass (%)	Volume (%)	b
Bertrand-Krajewski *et al.*(1998)	80	30	0.185
Sansalone and Cristina (2004)	80	20	0.139
Wanielista and Yousef (1993)	50	25	0.5

defines a level of normalized mass that must be delivered during a defined initial normalized volume. Table 2-2 shows the three most common criteria for a mass-based first flush, both in terms of mass to volume ratio, and the associated exponential fitting parameter, b. Bertrand-Krajewski *et al.* (1998) uses a 30/80 criteria, which means that 80% of the total mass is delivered during the first 30% of the total storm volume. Sansalone and Cristina (2004) suggests a more restrictive 20/80 definition, while Wanielista and Yousef (1993) propose a less restrictive 25/50 first flush definition. All of these definitions represent the same concept, and as long as the same standard is used throughout a project, they are equally viable.

Extending the 30/80 standard to the curve fitting technique of method 3 creates a new criterion on the exponential parameter, b. As stated above, any first flush ratio can be represented in terms of an exponential curve with the fitting parameter, b (Equation 2-4). Lower values of b represent more pronounced first flush effects, while a b value equal to 1 represents no first flush.

2.3.4 *First Flush Stormwater Runoff Conclusions*

Using the methods and definitions of first flush, there has been an attempt to define the conditions most likely to cause a strong first flush of pollutants from roadway runoff. Sansalone and Cristina (2004) found that because flow-limited events have concentrations more proportionate to the storm hydrograph, they generally have less of a first flush than mass-limited events. This study found flow-limited concentrations typically fell from a maximum value to a value that was 20-70% of the maximum and remained in that range for the duration of the event (Sansalone and Cristina 2004). This concentration decrease does not meet the guidelines for a concentration-based first flush described by Sansalone and Cristina (2004). However, in mass-limited events, more intense rainfall occurred, which causes a disproportionate removal of constituent mass in the early part of the storm, leaving little of the pollutant on the roadway surface to be exported later. These mass-limited storms showed a much stronger first flush trend.

Differences in first flush behavior were also noted for different constituents. By comparing first flush curves for the same storm event across different measured pollutants, a noticeable trend emerges. The relative strength of the first flush from highway runoff is: COD > TSS > TP > Fe > TKN > PO_4–P (Lee *et al.* 2003). Suspended solids, therefore, are removed more efficiently and quickly from the roadway surface during the rising limb of a rainfall-runoff event, while constituents like TKN and PO_4 are more pervasive throughout a rainfall event.

Finally, hydrology plays an important role in determining the strength of a first flush during a rainfall event. Storms with many successive flow peaks generally produce first flush curves which are closer to the bisector than in the case of a simple, single peak hydrograph (Bertrand-Krajewski *et al.* 1998). It also becomes very difficult to identify a first flush in the case of a complex watershed with many subwatersheds. The addition of flow from each of these subwatersheds, each with differing travel times to the outlet, tends to cloud the first flush effect and to smear any pollutant data (Sansalone and Cristina 2004). Therefore, in the interest of studying the first flush effect, it is important to examine runoff at the upper end of a watershed, before it combines with flows from other sources. Similarly, if a treatment technology is designed to capture the high pollutant mass or concentrations during the first flush in the rising limb of the hydrograph, it is important to locate the treatment technologies as near to the upper end of the watershed as possible.

2.4 EVENT MEAN CONCENTRATION (EMC)

While the first flush analysis provides a method to examine concentrations and flows throughout a storm event, often it is more useful to have a single number that quantifies the average concentration during a storm event. For comparison purposes, discrete samples are composited into a flow weighted average, referred to as the Event Mean Concentration (EMC). The EMC is calculated by dividing the total mass of constituent exported by the total volume of runoff exported. This calculation can be written as:

$$EMC = \frac{\int_0^{T_d} CQdt}{\int_0^{T_d} Qdt} \tag{2-5}$$

where, Q is the measured stormwater flow rate and C is the pollutant concentration for each sample during the event. T_d is the event duration. The interval between samples is dt.

The EMC therefore represents the concentration that would result if the entire storm event discharge were collected in one container. Because of this, the EMC is used to describe the pollutant concentrations of a total storm event and to compare pollutant concentrations among different events.

2.5 GRASS SWALE CONSTITUENT REMOVAL EFFICIENCY

Little consistent information on water quality improvements for grass swales is available, in large part because of the complexity of swale operation. Swales receive flow laterally through vegetated side slopes, which can greatly improve incoming water quality. Infiltration throughout the swale surface area can reduce flow volume and improve quality. Thus, swales have several distributed points of water input and output, which can complicate simple performance analyses. Also, in the case of field studies, input concentrations and flow rates are variable depending on the storm event and roadway characteristics, further complicating comparisons between swale removal efficiencies.

2.5.1 *Reporting Parameters for Grass Swale Studies*

Because of the considerable number of variables affecting grass swale performance, a systematic and consistent method for reporting grass swale monitoring data is necessary. By eliminating or citing all extraneous variables in swale performance, it is possible to compare data from multiple storms and swale locations, thereby allowing trends in design and performance to be determined. To this end, the Urban Water Resources Research Council of the American Society of Civil Engineers developed a database software package called the National Stormwater BMP Database (Urbonas 1995, Clary *et al.* 2002). The stated purposes of this database are (1) to define a standard set of data reporting protocols for use with BMP monitoring efforts; and (2) to assemble and summarize historical BMP study data in a standardized format (Clary *et al.* 2002). The National Stormwater BMP Database can be accessed online through a search engine at *www.bmpdatabase.org*. The first version of the National Stormwater BMP Database contained performance data on 71 BMPs, with 7 of those being grass swales. These initial 71 BMPs underwent a quality assurance screening process to validate the monitoring methods of the studies. Currently, the database has performance data on 247 BMPs, with 24 grass swales. Table 2-3 outlines the suggested reporting parameters for grass swales accepting highway runoff according to the National Stormwater BMP Database.

By explicitly stating these variables, it is possible to draw conclusions about the effects of these design criteria and to explain differences between grass swale efficiency studies. While stating experimental design parameters presents the researcher with a better representation of grass swale conditions, in order to fully understand the effects and efficiency of a grass swale treatment technology it is important to analyze the data using multiple reporting methods. Each method provides a different measure of performance, and together they can give an effective overall test on the effects of grass swales. If possible, it is preferable to use paired inflow and outflow sampling to provide storm specific data.

The most common methods of reporting data uses paired EMCs and computes a percent removal using the formula:

$$PR = \frac{V_{in}\,EMC_{in} - V_{out}\,EMC_{out}}{V_{in}\,EMC_{in}}\,x100 \tag{2-6}$$

Where PR represents percent constituent load removed, V_{in} represents storm runoff volume inflow into the swale, EMC_{in} represents event mean concentrations of inflow volume, V_{out} represents storm runoff volume outflow from the swale, and EMC_{out} represents event mean concentrations of outflow volume. Descriptive statistics such as

Table 2-3. Parameters to report with water quality data (Strecker 2001).

Parameter Type	**Parameter**
Watershed Information	Watershed area, average slope, average runoff coefficient, length, soil types, vegetation types Total watershed impervious percentage Details about roadway Land use types (residential, commercial, industrial, open)
General Hydrology	Date and start/stop times for monitored storms Runoff volumes for monitored storms Peak 1 hour intensity Peak flow rate, depth and Manning's roughness coefficient for 2 year storm Depth to seasonal high ground-water/impermeable layer Saturated hydraulic conductivity, infiltration rate, soil group Average annual values for number of storms, precipitation, snowfall, minimum/maximum temperature
Water	Alkalinity, hardness, and pH for each monitored storm Water temperature Sediment settling velocity distribution, when available
General Facility	Type and frequency of maintenance Types and location of monitoring instruments Inlet and outlet dimensions, details, and number
Infiltration	Bottom stage/infiltrating surface area and type
Pretreatment	Area of pretreatment Relationship to other BMPs upstream
Wetland plant	Swale type, surface area, length, bottom width, and side slope Plant species and age of facility

mean, median, standard deviation, and coefficient of variation for percent removals allow a measure of average efficiency. This method has drawbacks, however, because in the case of a storm event with relatively low inflow concentrations, the percent removal would be low despite relatively clean outflow. In a similar sense, in the case of a high concentration entering the swale, there is a possibility for outflow from the swale to have constituent concentrations much higher than water quality target values, yet show high removal percentage. Because of this, it is also important to determine descriptive statistics, such as mean and standard deviation, for the EMC data without transformation. Tests such as the Student's t-test can be performed on both of these data sets to determine the significance of the swale's paired removal percentage or EMC distribution.

The Student's t-test assumes a normal distribution for EMC values. However, studies of influent and effluent EMCs from grass swales have been shown to follow a lognormal distribution (Van Buren *et al.* 1997, Harremones 1988). This means that nonparametric tests on EMCs, which do not specify a distribution, may be necessary to fully determine the distribution. Nonparametric tests, such as the Mann-Whitney and Kolmogorov-Smirnov tests, should also be performed and reported in grass swale efficiency studies.

Finally, grass swale performance data should be presented in a graphical manner. These graphical representations should include time series scatter plots of influent and effluent concentrations, graphical nonparametric analysis such as box-and-whisker plots, and normal probabililty plots of log transformed water quality data showing influent and effluent EMCs (Strecker *et al.* 2001). While the latter two graphical methods do not show the pairing between influent and effluent concentrations for specific storm events, they do allow an overall comparison between the distributions of EMC values.

2.5.2 *Total Suspended Solids*

Much of the initial research involving grass swale treatment technologies focused on treatment of suspended solids, because this is a simple parameter to test for, and because TSS is a good indicator for other water quality parameters. Grass swales tend to be very successful in removing TSS, with EMC removal values reported as: 65-98% (Schueler 1994), 85-87% (Barrett *et al.* 1998), 68% (Yu *et al.* 2001), and 79-98% (Backstrom 2003). This range of removal efficiencies is likely caused by differences in storm characteristics and swale construction. However, there have been some mechanistic studies attempting to model and describe the removal of suspended solids.

Current studies (Deletic 2001, Backstrom 2002, Backstrom 2003, Deletic 2005) have employed both real grass and artificial grass swales in order to investigate the processes involved in suspended solid removal. In Backstrom's work (2003), short runoff events (0.5 hours) were simulated by pumping water mixed with sediment into the swale at one well-defined inlet point. Inflow rates varied within the range of 0.5-1.5 l/s. Studies were performed on small scale (5-10 m) field grass swales and also on plywood channels covered with artificial grass. Results from these small scale studies were then compared to a full sized, 110 m long, roadside swale with similar design parameters and lateral flow from the roadway.

These studies concluded that grass swales are successful at removing suspended solids in runoff, however the removal efficiency is based on input concentrations. Very small reductions of suspended solids are likely to occur in a grass swale if the inflow TSS concentrations are below 30-40 mg/l (Backstrom 2003). In the case of very low influent concentrations, an export of suspended solids is possible. This conclusion is corroborated by studies performed in Barrett (2005).

Backstrom (2003) also concluded that grass swale suspended solids removal is highly related to particle size and thereby related to particle settling velocity. This conclusion was drawn from a particle size distribution analysis of the suspended solids which showed that grass swales trapped larger particles more efficiently than smaller ones. The field grassed swale (110 m) particle size distribution showed that particles larger than 25 μm were generally retained in the swale, while particles in the size interval 9 to 15 μm were exported from the swale (Backstrom 2003). The smallest diameter particles, 4-9 μm were exported to a lesser extent. Average particle trapping efficiencies for the field swale are shown in Figure 2-3.

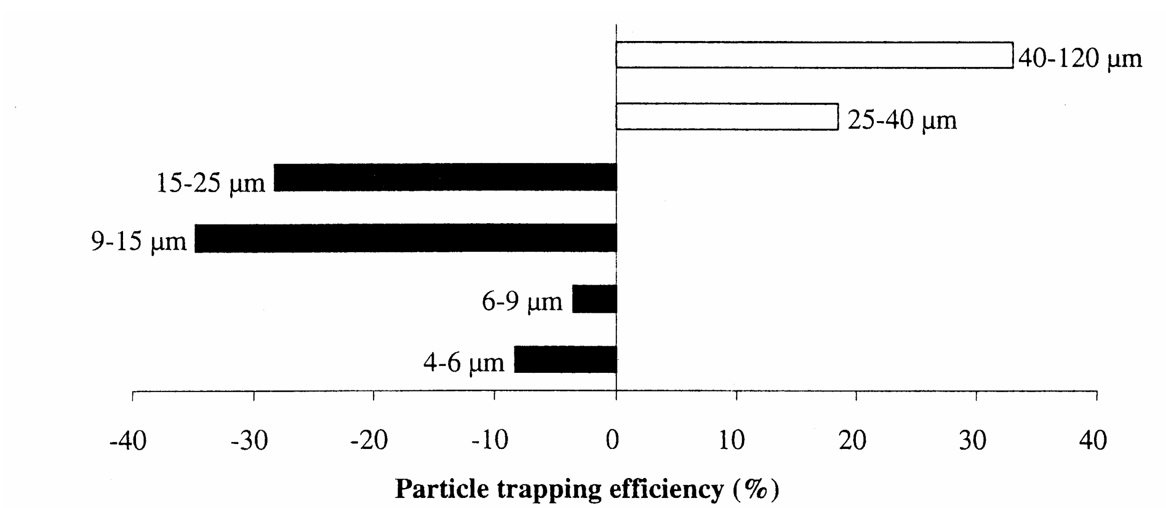

Figure 2-3. Particle trapping efficiencies for various particle sizes in a 110 m grass swale (Backstrom 2003).

Particle size distribution tests on the smaller, more controlled swales allowed a more detailed analysis of differences in particle size between influent and effluent flows. In these tests, the influent particle distributions were relatively uniform for all events with a d_{50}-value of 9.2 μm and a d_{90}-value of 26 μm. Results are shown in Figure 2-4.

Figure 2-4 shows a marked difference between the artificial grass laboratory swales and the field swales. The laboratory swales captured particles of all sizes down to

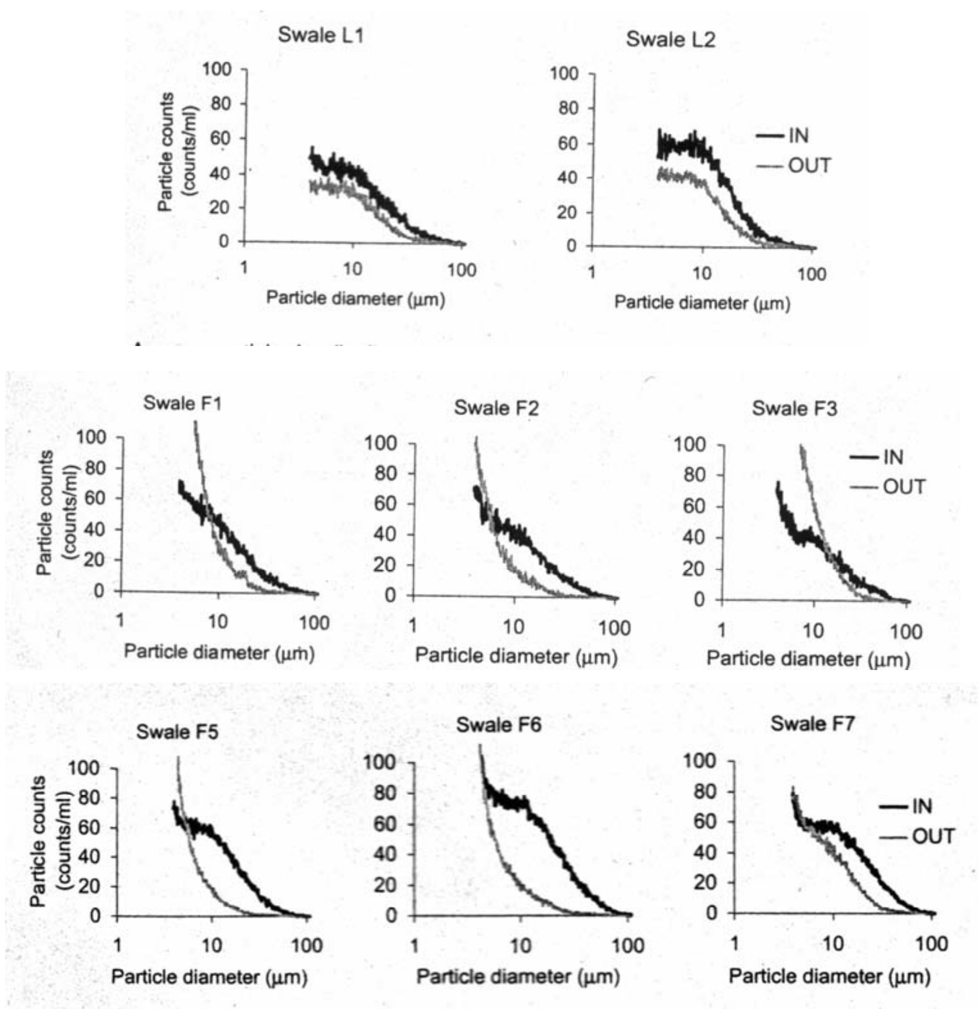

Figure 2-4. Average particle size distributions for inlet (dark line) and outlet (grey line) of swales, where L1 and L2 are 5 m, laboratory swales, F1, F2, and F3 are 5 m, field swales, and F5, F6, and F7 are 10 m, field swales. (Backstrom 2003).

the lower limit of the size interval and there did not appear to be any correlation between particle size and removal efficiency. The field swales, however, showed a visible relationship between particle size and trapping efficiency. Similar to the full scale swale, there was export of the smallest diameter particles, while the larger particles were removed. Also, there appears to be more removal of smaller diameter particles in the longer swales. The ability to remove smaller particles as travel times increase is indicative of sedimentation as the major removal method for suspended solids (Backstrom 2002). This study concludes that grass filtration plays a smaller role in removal of suspended solids in grass swale treatments.

2.5.3 *Nutrients*

Nutrient removal is much more variable than suspended solid performance and good mechanistic studies are not available, given the small number of monitoring data sets. Sampling of two grass swales in Barrett *et al.* (1998) showed significant EMC removals of nitrate (37%) and TKN (39%). A similar study by Schueler (1994) showed mass reduction of nitrate ranging from -143% (export) to 45% and mass reduction of TKN between 9 and 48% for 3 swales with very different physical properties. A study of grass swales in a parking area in Florida showed that nitrate concentrations were unaffected by grass swale treatment, however, there was a significant load reduction due to storage and infiltration (Rushton 2001). This variability in grass swale performance for nitrogen removal shows that slight differences in storm type, vegetation characteristics and swale design can have significant effects on removal efficiency.

Phosporus removal in grass swales is even more varied than nitrogen removal. Some studies have shown significant total phosphorus removal: 12-41% (Schueler 1994), 60% (Yu *et al.* 2001), and 34-44% (Barrett *et al.* 1998), while other studies have shown significant total phosphorus export (Wu *et al.* 1998, Rushton 2001, Barrett 2005). In the case of export, grass swales act as a source, rather than a treatment facility.

Researchers have hypothesized that this range of nutrient removal efficiencies is due to the fact that swales are an organic treatment method (Yu *et al.* 2001). Because the grass, decaying organic matter, and other vegetation, such as fallen leaves, contain these organic constituents, there is a significant likelihood of leaching these nutrients into flowing water. Also, variables such as mowing or fertilizing can be significant sources of nutrients in grass swales. Finally, as shown above, grass swales are much more successful in intercepting larger diameter solid particles, while nutrients like phosphorus tend to be either in dissolved form or bound to very fine sediment particles (Wu *et al.* 1998).

2.5.4 *Chloride*

No current performance data are available regarding the removal of chloride by grass swale treatments. However, studies of chloride concentrations in receiving water streams in Maryland, New York and New Hampshire have shown that while some seasonal differences in chloride concentrations occur throughout the year, this deviation is relatively small (Kaushal *et al.* 2005). This means that the common input source of chloride, roadway deicing agents used during the winter, is not sufficient to explain rising chloride concentrations. Therefore, a sink must exist between the roadway surface and the receiving waters that slowly exports chloride throughout the year. Grassy, roadside areas, like grass swales, are therefore likely repositories for chloride sources, acting as both a sink and a source.

2.5.5 *Heavy Metals*

Monitoring studies have shown that grass swales are successful at removing metals of concern in highway runoff: lead, copper, zinc, and cadmium. In most of these studies, lead and copper show moderate removal efficiencies that are slightly lower than the removal efficiencies of total suspended solids. Lead EMCs were reduced by 17-41% (Barrett *et al.* 1998), while total mass of lead was reduced by grass swales by 18-94% (Schueler 1994), and 59-87% (Rushton 2001). Similarly, total mass of copper was reduced by 14-67% (Schueler 1994), 34% (Backstrom 2003), and 23-81% (Rushton 2001). Zinc appears to be the most successfully removed metal constituent with studies showing 75-91% removal by EMCs (Barrett *et al.* 1998) and total mass removals of 47-81% (Schueler 1994), 66% (Backstrom 2003), and 46-79% (Rushton 2001). Finally, much less information is available about cadmium removal in highway runoff, as this constituent is generally present in very small amounts. However, monitoring studies have shown a wide range of removal values for cadmium, 12-98% by mass (Schueler 1994).

Positive metal removal through grass swales is corroborated by evidence showing trace metal accumulation over time in the sediment of the grass swales (Schueler 1994). All four metals, lead, copper, zinc, and cadmium, were shown to accumulate in the swale; however, their distributions are very different, highlighting differences between the metals. Copper and zinc distributions are concentrated on the surface and in the upper layers of soil of the grass swales. However, lead is much more evenly distributed throughout the deeper layers of sediment (Rushton 2001). This shows the greater likelihood of resuspension of soil particles with associated copper and zinc, to a lesser extent. This possibility was shown in research by Backstrom (2003), who found an increase in copper concentration leaving 2 grass swales. This mobilization was attributed to a buildup of colloidal bound copper prior to the monitoring period and later resuspension during the monitoring period. In the case of small storms with low influent concentrations, the swale acted as a source for all trace metals, exporting higher mass than present in the influent (Backstrom 2003).

2.5.6 *Logarithmic Data Plotting*

Another method for analyzing the pollutant removal capability of grass swales is the use of probability plots. This method is different from the above results because it does not use paired samples and instead characterizes the distribution of the data. In the case of a best management practice (BMP) efficiency study, it is important to compare the distribution of the input pollutant concentrations with the distribution of the output concentrations after treatment. This not only provides a method to compare removal, but also a method to describe any changes in the overall shape of the probability distribution.

From its inception in the 1890s, probability plots have been used by hydrologists to transform distributions of data into a more manageable and visual representation for analysis (Harter 1984). The most common of these probability plots is the normal probability plot, in which the scale of the abscissa is stretched such that the spacing represents the cumulative normal distribution. Therefore, if the data are normally distributed, they will plot as a straight line. A probability plot testing the normal distribution uses an arithmetic ordinate axis, while using a logarithmic axis allows presentation of the data as a lognormal distribution.

This method of plotting data on distribution specific probability paper has historically gained the most acceptance by hydrologists in flood frequency analysis to determine the probability of exceedance for a given design flood flow. However, by applying the same probability plot methods to water quality data for Best Management Practices (BMPs), it is possible to determine effluent concentration exceedance probabilities and to easily and visually compare different BMPs and BMP performances.

The first step in applying the probability plot approach to BMP removal is to characterize the distributions. Although probability plots can be tailored to any distribution by adjusting the x axis to match the desired cumulative distribution function, the two most common distributions are the normal and the lognormal distributions.

These distributions were shown to be sufficient to describe pollutant concentrations as shown in a study by Van Buren *et al.* (1997), which examined an on-stream stormwater management pond in an attempt to characterize the change in concentrations through the BMP facility. Influent and effluent EMCs for every monitored storm were plotted on both normal and lognormal probability plots. If the EMCs plot in a straight line, they are assumed to fit that distribution. In this study, a visual fit was used, however goodness of fit tests in the literature are available for normal and lognormal probability plots (Gan *et al.* 1991, Looney and Gelledge 1985). Examples probability plots are shown in Figure 2-5. The left figure shows plots for normally

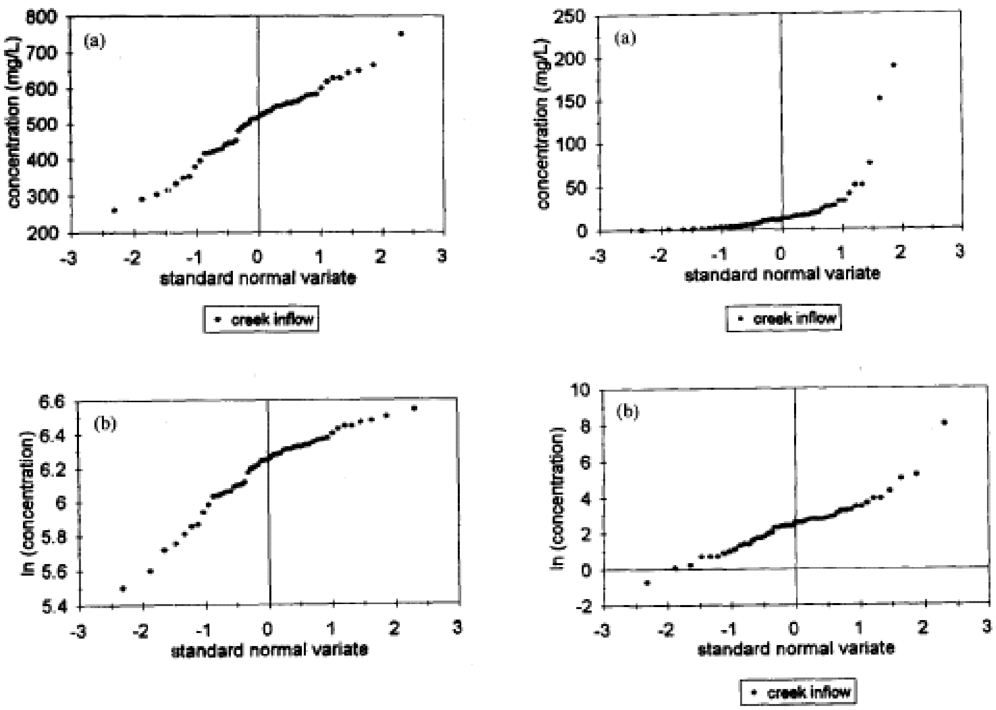

Figure 2-5. Comparison of normal and lognormal probability plots for normally distributed concentrations (left plots) and lognormally distributed concentrations (right plots). Correct distributions are shown as straight lines (Van Buren 1997).

distributed data and the right figure shows plots for lognormally distributed data. The results of the probability analysis were compared to a Cramer-von Mises statistic for goodness of fit for the assumed distributions. For almost all constituents, the tests agreed, showing that probability plots are a viable method for describing the distribution of BMP concentrations.

The results of the Van Buren *et al.* (1997) study agreed with the assumption of other studies, that the distribution of stormwater runoff concentrations are generally lognormally distributed (Harremoes 1988). Suspended solids and its associated constituents, including metals and nutrients, tend to follow a lognormal distribution. However, concentrations of dissolved constituents seem to follow the normal distribution

Table 2-4. Distribution form of constituents for direct runoff (creek inflow) and flow after settling pond treatment determined by fitting probability plots. (Van Buren 1997).

	Distribution form Source			
	Creek inflow		Pond outflow	
Constituent	PL	W^2	PL	W^2
TSS	●	●	●	●
TDS	○	○	○	◐
COD	●	●	○	○
Chloride	●	–	●	–
Tot.P	●	●	●	●
Sol.P	○	–	●	–
Sulphate	○	○	○	○
Ammonia	●	●	○	–
Sol.TKN	●	◐	○	◐
Tot.TKN	●	–	●	–
Oil & Gr	●	●	●	●
Phenol	●	●	●	●
Copper	●	●	●	●
Zinc	●	●	●	●

PL probability plots.
W^2 Cramer-von Mises statistic.
● Log-normal distribution indicated*.
○ Normal distribution indicated*.
◐ Normal or log-normal distribution.
– Both the normal and log-normal distributions rejected at 90% significance level.
*Probability plot, by visual inspection, CVM test, indicated distribution not rejected at 95%; other distribution rejected at 99%.

(Van Buren *et al.* 1997). Table 2-4 shows the results for the characterization of influent and effluent distributions.

Although this method has been suggested by Strecker *et al.* (2001) as a useful reporting method for BMP concentrations, there is no recorded use of probability plotting paper for grass swale monitoring studies in the literature.

2.5.7 *Barrett Regression and Model Storm Event*

Yet another method for comparing performance of runoff BMPs was described by Barrett (2005). His research is based on the hypothesis that effluent concentrations are linearly correlated to influent concentrations. This method has the advantage of using paired storm data. Using this hypothesis, effluent EMCs were plotted as a function of the paired influent and a regression line was calculated and tested for statistical significance at the 90% confidence level. In the case that no statistically significant regression could be determined, the mean effluent concentration was used. The linear regression took the form:

$$C_{eff} = a\, C_{inf} + b \qquad (2\text{-}7)$$

where C_{eff} = predicted effluent EMC, C_{inf} = influent EMC, and a and b are the slope and y-intercept respectively. Using this regression equation, effluent quality can be calculated for any arbitrary influent quality. If the regression line is below the bisecting line, $y = x$ $(a < 1)$, the BMP effluent concentrations are lower than influent concentrations and therefore, the BMP functions as a removal treatment. However, if the regression line is above the $y = x$ bisector $(a > 1)$, the BMP exports the specified constituent.

The regression analysis for 6 grass swales treating highway runoff in southern California over 39 storm events resulted in the equations in Table 2-5. For grass swales, a significant regression fit was found for all constituents except for orthophosphorus, which is presented as a mean value. Effluent concentrations are presented with x representing the influent concentration. The uncertainty presented in Table 2-5 is at the

Table 2-5. Regression results showing grass swale effluent concentrations and confidence intervals as a function of influent concentrations (Barrett 2005).

	TSS (mg/L)	Nitrate (mg/L as N)	OrthoP (mg/L)	Dissolved Zn (μg/L)	Dissolved Cu (μg/L)
Expected Effluent Conc.	0.42x + 11.0	1.31x – 0.03	0.40	0.40x + 7.7	0.55x + 3.3
90% Confidence Interval	$54.6\left(\frac{1}{39}+\frac{(x-84.5)^2}{139{,}000}\right)^{0.5}$	$0.69\left(\frac{1}{38}+\frac{(x-0.71)^2}{6.1}\right)^{0.5}$	0.12	$54.6\left(\frac{1}{39}+\frac{(x-99)^2}{213{,}600}\right)^{0.5}$	$54.6\left(\frac{1}{39}+\frac{(x-16)^2}{4256}\right)^{0.5}$

90% confidence level.

By fitting this regression equation for multiple constituents and multiple BMP types, Barrett compared BMP performance for a design storm with given influent concentrations. Comparisons were drawn for effluent EMCs and also, by multiplying influent and effluent EMCs by their respective flow volumes, a load reduction was calculated. The following equation was used:

$$L_r = 1 - (C_{eff}/C_{inf}\,(1 - I)) \tag{2-8}$$

where L_r = Load reduction and I = Fraction of runoff lost to infiltration and evapotranspiration in the BMP. On average, Barrett found a reduction of 47% of runoff in grass swales. This value is applied in the load equation as I for grass swales.

A design storm event with influent EMCs averaged from all monitored storm events (114 mg/l TSS, 0.97 mg/l nitrate, 0.12 mg/l orthophosphorus, 122 μg/l zinc, and 18 μg/l copper) was calculated. Using this design storm, the average runoff reduction, and the regression equations for grass swales, Barrett determined the expected effluent concentrations and load reductions for total suspended solids, nitrate, orthophosphorus, dissolved zinc, and dissolved copper. The results of this design storm are very similar to the above grass swale monitoring studies and corroborate their conclusions that grass swales are efficient in the removal of suspended solids and metals, while nutrients show variable results and potential export of constituents. Grass swales showed a significant reduction of suspended solids concentrations (from 114 mg/L to 58.9 mg/L) and loadings (75%), although this removal was not as great as other monitored BMPs (Barrett 2005). Nitrate effluent concentrations for the design storm were higher than influent (increase from 0.97 mg/l to 1.25 mg/l), yet showed load removal (40%) caused by infiltration, while orthophosphorus is exported by grass swales in both concentration and total mass loading. Finally, zinc and copper were removed successfully, with load reductions between 60 and 80%. The mass reductions for metals associated with grass swales and filter strips are among the best of the monitored BMP technologies.

2. 6 GRASS SWALE EFFICIENCY AND HYDROLOGY

Because grass swales are based on water flow, the hydrology involved in this treatment process requires investigation. The standard highway swale is designed to move runoff from the largest storm events away from the roadway. Because of this, highway swales are not designed for smaller storm events (0.2 – 1 in) that produce the majority of annual runoff through the swale (Schueler 1994). Grass swale pollutant removal effectiveness is dependent on the vegetation reducing the peak velocity, while infiltration reduces total runoff volume, and the longer travel time allows for chemical, biological, and other hydrological processes to take place.

Percent runoff volume reduction has been reported as: 30-47% (Rushton 2001) and 33% (Backstrom 2003). This reduction is due to infiltration into the swale soil. Besides reduction of total volume, grass swales tend to smooth flow peaks. The reduction of flow peaks was characterized by the normalized peak discharge factor (PDF), defined as the ratio of peak discharge of runoff to total rainfall amount (Wu *et al.* 1998). The grass swales in this study showed a reduction of PDF by 11-22% when compared to the direct highway runoff (Wu *et al.* 1998).

The hydrology of grass swales can be characterized and compared using the Rational formula and the corresponding runoff coefficient, C:

$$q_p = C\ i\ A \tag{2-9}$$

where q_p represents peak discharge (l/s), A represents drainage area (ha), i represents rainfall intensity (cm/hr) and C is a unitless coefficient. Wu *et al.* (1998) used a modified version of this equation to compare swale characteristics. Dividing by drainage area yields:

$$q_p / A = C\ I \tag{2-10}$$

and integrating over the storm duration yields the equation:

$$R = C\ (P) + b \tag{2-11}$$

where R represents the total runoff (cm), P is the total rainfall (cm), and b is the y intercept. By plotting rainfall data against runoff data, a linear regression allows the calculation of the fitting parameters. C is the Rational formula runoff coefficient and by setting R equal to zero, the amount of rainfall needed to satisfy initial abstraction and other losses prior to the occurrence of runoff can be estimated (Wu *et al.* 1998). These two parameters provide an understanding of the initial infiltration capability of the swale and the percentage of infiltration once runoff begins flowing out of the swale.

Storm characteristics appear to play an important role in swale hydraulics. Several studies found that during small storms, removal of total runoff volume was significant. However, as would be expected due to soil saturation, during large or intense storms, the total volume of runoff exiting the grass swales was equal to or larger than that entering the swale (Schueler 1994, Yu *et al.* 2001, Rushton 2001).

Pollutant removal efficiency appears to be independent of storm volume. A plot of TSS removal through grass swales versus total volume of storm runoff showed no relationship (Barrett 1998). Total runoff volume is not a good predictor variable for grass swale removal efficiency because the removal mechanism is based on both infiltration and increased particle settling due to decreased flow velocities. Long, large volume storms do not necessarily correspond to intense rainfall and therefore do not produce a greater water depth through the swale than do small, intense storm events. At high flow depths, water is not slowed by grass in the swale, allowing sedimentation, and also is too high to undergo filtration. Therefore, grass swales are most effective at removing highway pollutants during long, low intensity storms or very short storms that can be completely captured during the initial abstraction period (Yu *et al.* 2001).

2.7 GRASS SWALE EFFICIENCY AND DESIGN PARAMETERS

As shown above, grass swales function at their optimum efficiencies when the flow velocities are reduced through contact with the grass layer, allowing for increased sedimentation, filtration, infiltration, and other biological and chemical processes. It follows, therefore, that any design parameter for the construction of grass swales should focus on increasing these processes. There is a lack of research detailing the exact effect of certain design parameters on grass swale pollutant removal efficiency. However, current research supports the importance of parameters that increase hydraulic retention time and offers some efficiency trends when swales with a range of design parameters are compared.

The first, and possibly simplest, method to increase travel time within the swale is to extend the swale length. In research by Backstrom (2002), 7 field swales with a wide range of design conditions were compared during storm events artificially created with constant flows and constant TSS concentrations. Particle trapping efficiencies for three different particle settling velocities, corresponding to three different particle sizes are presented in Figure 2-6. Swales were grouped into two lengths, 5 meters (F1, F2, and F3) and 10 meters (F5, F6, and F7) with all other design parameters identical between the pairs F1 and F5, F2 and F6, and F3 and F7. By comparing the paired results in Figure 2-6, it becomes apparent that increasing swale length greatly increases particle trapping efficiencies (Backstrom 2002). This difference is most notable for the smallest particles (0.1 m/h settling velocity, diameter < 25 μm). This large increase in sediment removal for small particles supports the conclusion that sedimentation is the controlling process in these swales. Other research agrees that increasing swale length increases suspended solid removal greatly (Yu *et al.* 2001).

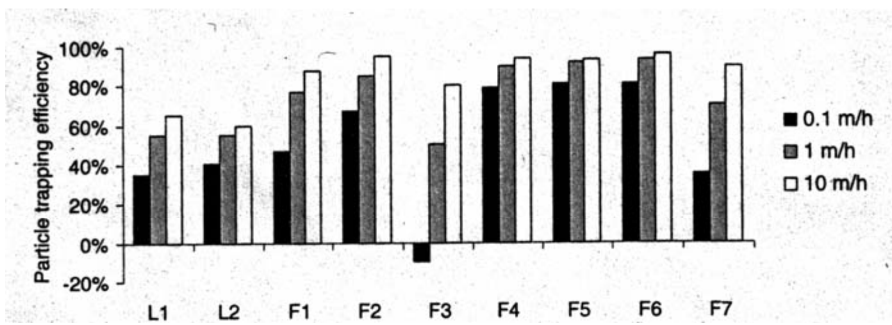

Figure 2-6. Particle trapping efficiency of grass swales at three different particle settling velocities, where L1 and L2 are 5m laboratory swales, F1-F4 are 5m field swales, and F5-F7 are 10 m field swales (Backstrom 2002).

Backstrom (2002) further examined the process of sedimentation in grass swales, with the intent to create design criteria for particle trapping with respect to particle size and settling velocity. For a given trapping efficiency, this research fit an exponential relationship between the mean swale residence time in seconds (T) and the particle settling velocity in m/h (Vs^*):

$$Vs^* = a\, e^{B\,T} \quad (2\text{-}12)$$

where a and B are constants. Using this fit, it is possible to determine the swale residence time necessary to achieve a certain trapping efficiency, given a design particle. Swales in this study showed a good fit at the 50% and 90% trapping efficiencies, however, there were two distinct groups related to the soil infiltration rates. Figure 2-7 shows this relationship between swale residence time and the ability of the swale to capture increasingly smaller suspended particles. A more comprehensive study could produce a series of curves for differing soil infiltration rates, showing the design relationship between particle size, swale residence time, and particle trapping efficiency. This study corroborates findings by Yu *et al.* (2001), that swale pollutant removal reaches a plateau when swales are longer than approximately 75 m, regardless of shape. Beyond a certain residence time, sedimentation is no longer effective and processes like filtration and resuspension begin to control concentrations.

The importance of infiltration rates in Backstrom's calculations highlights the

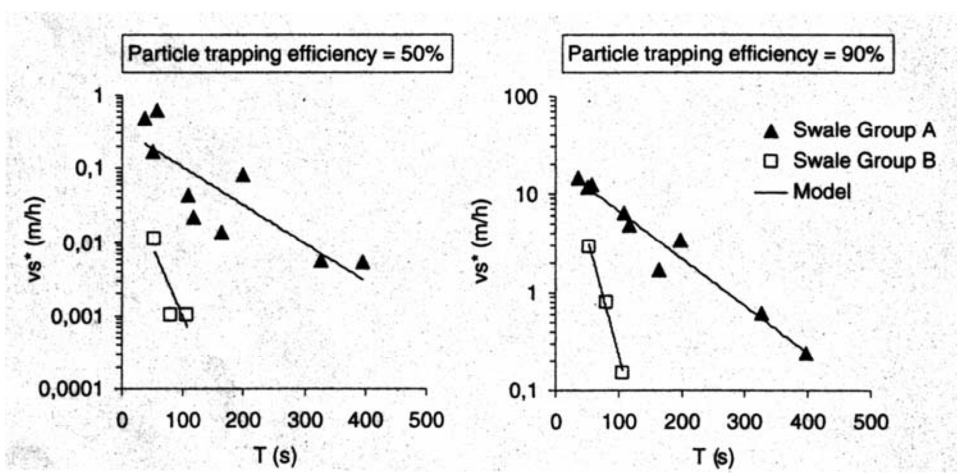

Figure 2-7. Mean swale residence time versus particle settling velocities associated to a trapping efficiency of 50% (left) and 90% (right) in grass swales (Backstrom 2002).

importance of swale design parameters other than length. Many other factors, such as channel slope, soil type, vegetative cover, and age affect the residence time and removal efficiency of grass swales. In a study by Schueler (1994), 3 swales with similar lengths (60 m) and a wide range of conditions were analyzed. The first swale, with low slope, sandy soil and dense grass cover exhibited the best removal capability by total mass reductions: TSS (98%), nitrate (45%), TKN (48%), total phosphorus (18%), and metals (50-70%). By comparison, the worst pollutant removals occurred in a swale with moderate slope and poor grass cover. This poor grass cover caused severe erosion during large storms, resulting in an export of TSS (-85% by mass) and nitrate (-143% by mass). This swale also showed little capability to remove organic nitrogen, total phosphorus or metals. The last swale showed a moderate removal efficiency due to its high slope, but good vegetative cover. The conclusions of this study agree with others that grass swales are most efficient when they have low slopes, soil with high infiltration capability and dense grass cover (Yu *et al.* 2001).

Another possible grass swale design parameter is the inclusion of check dams along the length of the swale. Check dams are small weirs placed along the length of the grass swale to increase the retention time and to temporarily block the flow of runoff, increasing sedimentation and infiltration. By creating synthetic storm events and comparing removal efficiency of a swale with a check dam and without the dam during high intensity events and low intensity events, Yu *et al.* (2001) found that the inclusion of the check dam made a significant water quality improvement. The effect of the check dam is less pronounced during high intensity storms.

Current research does not show quantifiable, empirical relationships between grass swale design and removal efficiency, however it does show significant trends related to design criteria. Guidelines based on these trends were presented by Yu *et al.* (2001), which recommended a maximum 5% longitudinal slope, 30-60 m length, 0.6 m bottom width, soil with high infiltration rate, dense deep-rooted flood tolerant vegetation, and the inclusion of check dams. These recommendations are based on trends, however, and not on a unified physical model of grass swale processes.

2.8 GRASS SWALE EFFICIENCY AND PRETREATMENT

Another important design parameter for grass swale construction is the location of the highway swale and any pretreatment that occurs prior to flow through the swale. Currently, little research is available regarding the effect of pretreatment in grass swales and that research which is available is contradictory.

In a study of two grass swales in Austin, Texas by Barrett (1998), grab samples were used to determine the distribution of TSS concentrations along the center of the swale. Analyis of these grab samples showed little change in TSS concentrations along the length of the median, as shown in Figure 2-8. It is assumed, therefore, that most suspended solid removal occurred in pretreatment or along the side slope of the swale, not along the length of the swale. This study also concluded that pretreatment areas function primarily through filtration and not sedimentation. Therefore, swale length is less important than the pretreatment area adjacent to the swale. This study added provisions for pretreatment areas to the above recommended grass swale design guidelines. Recommendations of the study state that pretreatment length should be at

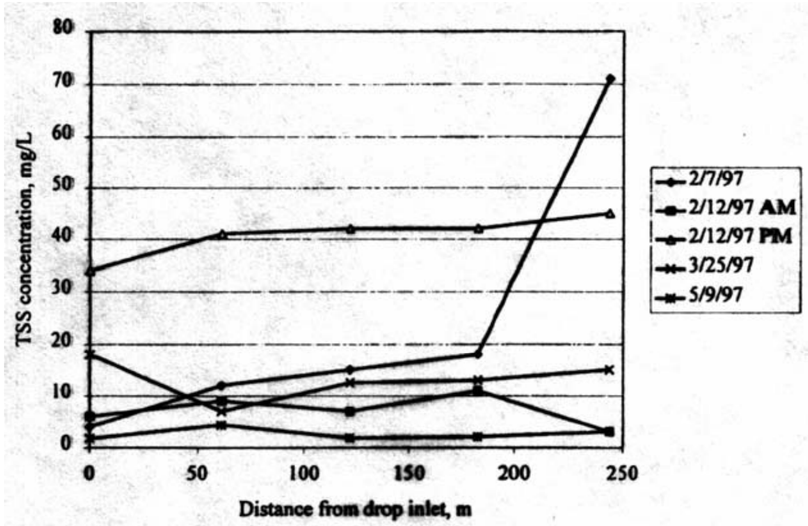

Figure 2-8. TSS concentrations along the center of grass swale as a function of distance from outlet, showing changes in concentration as flow passes through swale (Barrett 1998).

least 8 m (from pavement edge to center of swale) and that the ratio between swale area and contributing impervious area should be as close to 1 as practical (Barrett 1998).

While a similar study by Wu *et al.* (1998) agrees that including a pretreatment area can improve runoff quality, it concludes that the pretreatment area is not as important for improving water quality as Barrett (1998) had suggested. Wu *et al.* (1998) concludes that the roadside shoulder and pretreatment area is responsible for 10-20% hydrologic reduction of peak runoff discharges and a 30% reduction of TSS loadings when compared to a swale without a pretreatment area. However, these results are difficult to compare because the swales are not designed in a comparable manner. The swale without pretreatment area accepts flow from one direction at a constant slope, while the swale with pretreatment accepts flow two directions, with variable slopes and with 15% more pervious coverage (Wu *et al.* 1998).

Other studies, however, have disagreed with these conclusions. Instead, they conclude that sedimentation is the most important process in removing runoff pollutants and therefore swale length is the most important factor in swale removal efficiency (Backstrom 2003, Schueler 1994). These studies suggest that while a pretreatment area can provide pollutant removal, it is primarily due to extending the retention time for the runoff and does not supersede the importance of the grass swale in treatment.

Chapter 3

METHODS AND MATERIALS

3.1 SITE DESCRIPTION

The monitoring location for this study was MD Route 32 near Savage, Maryland. This is a four-lane (two in each direction) limited access highway. The sampling areas are just south of the Vollmerhausen Road overpass (Figure 3-1). The area adjacent to the sampling area is wooded with nearby residential development; however, the roadway is raised so that runoff is only created by the roadway (Figure 3-2).

Two swales were constructed in the highway median to receive runoff laterally from the southbound roadway lanes (Figure 3-3). The first is a swale constructed based on Maryland Department of the Environment (MDE) guidelines, with a 15.2 m wide sloped grass pretreatment area between the roadway and the swale channel (Figure 3-4). The

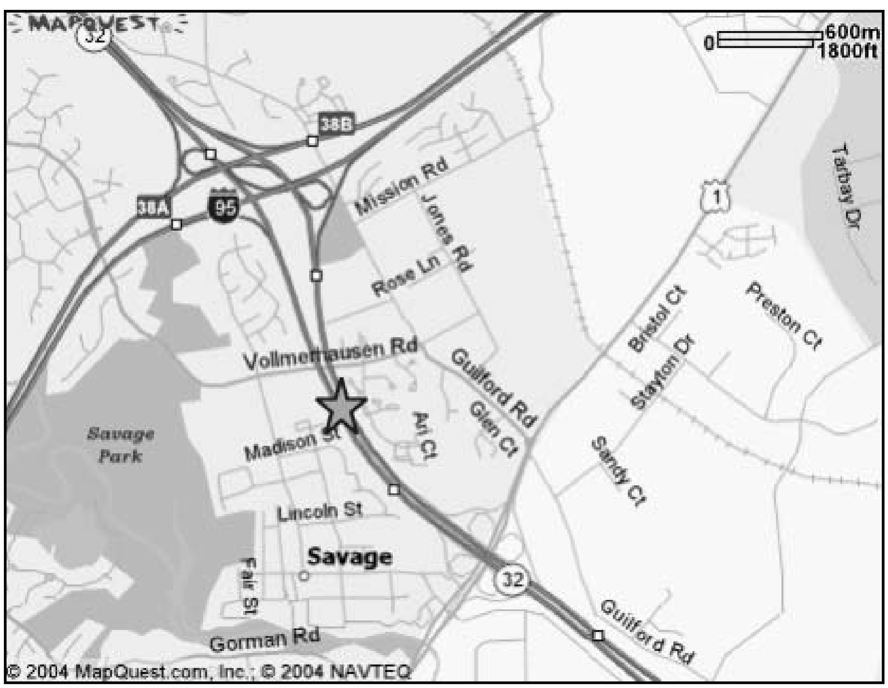

Figure 3-1. Rt. 32 swale monitoring site.

pretreatment area was constructed with a 6% slope on the southern side of the MDE swale.

The second swale, to the north, was identically constructed, but without the pretreatment area (known as SHA swale, Figure 3-5). Both swales converge at an inlet where water flow and quality measurements are made.

Both swales were constructed with identical cross-section designs (Figure 3-2), with side slopes of 3:1 (33%) and 4:1 (25%) on either side of the swale. Both swales were constructed with a 0.61 m bottom width and the channel slope for both swales is 1%.

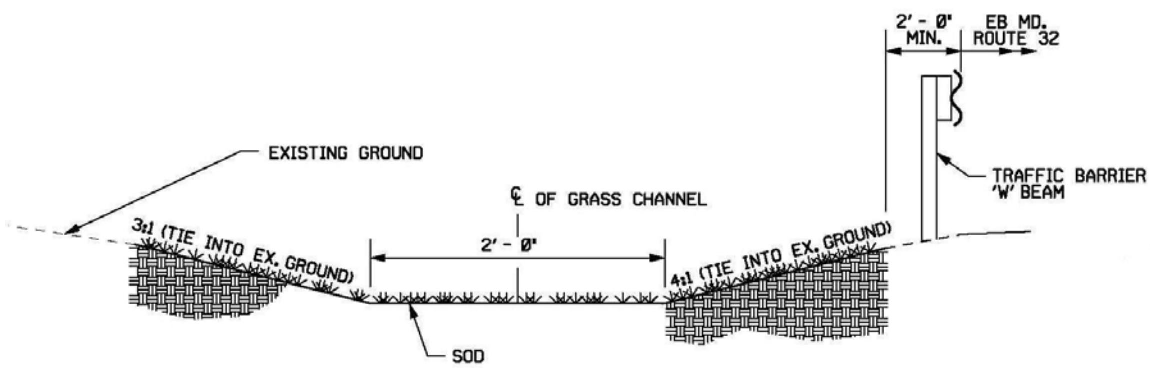

Figure 3-2. Grass channel typical section (not to scale) (Maryland SHA 2004)

Topsoil used in the swales had an organic content between 1.5 to 10 percent by weight and a pH value between 6.0 and 7.5. The soil grading distribution is 20-75% sand (2.0-0.050 mm) by weight, 10-60% silt (0.050-0.002 mm) by weight, and 5-30% clay (less than 0.002 mm) by weight. Grass seed used for the grass swale and pretreatment area is composed of 90% tall fescue, 5% Kentucky bluegrass, and 5% perennial ryegrass.

Since swale input flow is distributed along its length, a third sampling area was designed and constructed to sample runoff directly from the highway (known as Direct, Figure 3-6), south of the swales. This allows a more accurate representation of instantaneous swale input flow and water quality from the roadway surface without disrupting flow into the swales. Sampling areas were designed so that all three swales had nearly identical roadway drainage areas. Table 3-1 shows the specific design parameters for these 3 channels.

Table 3-1. Design characteristics for three sampled channels.

	Direct	**SHA Swale**	**MDE Swale**
Roadway Area (ha)	0.271	0.224	0.225
Swale Area (ha)	0	0.169	0.431
Total Area (ha)	0.271	0.393	0.656
Channel Material	Concrete	Grass	Grass
Channel Slope	0.2%	1.6%	1.2%
Channel Length (m)	168	198	137
Pretreatment Slope	-	-	6%
Pretreatment Width (m)	-	-	15.2 (from roadway to channel center)

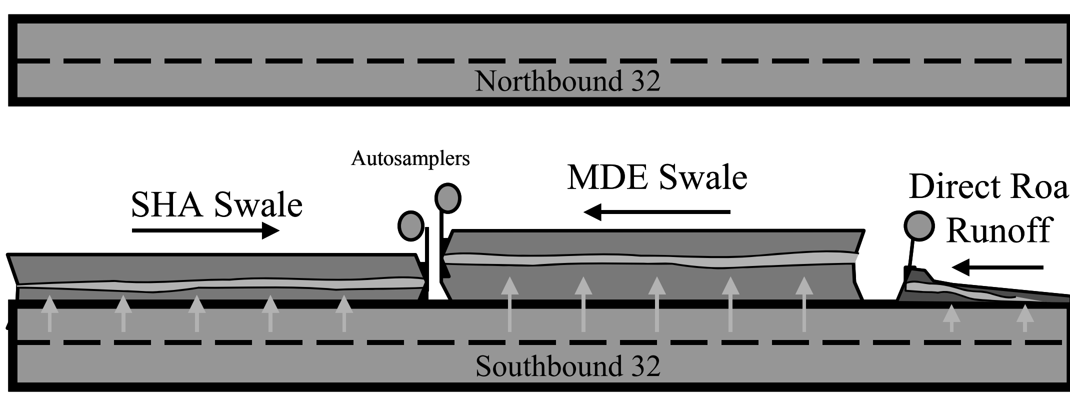

Figure 3-3. Diagram of swale study area.

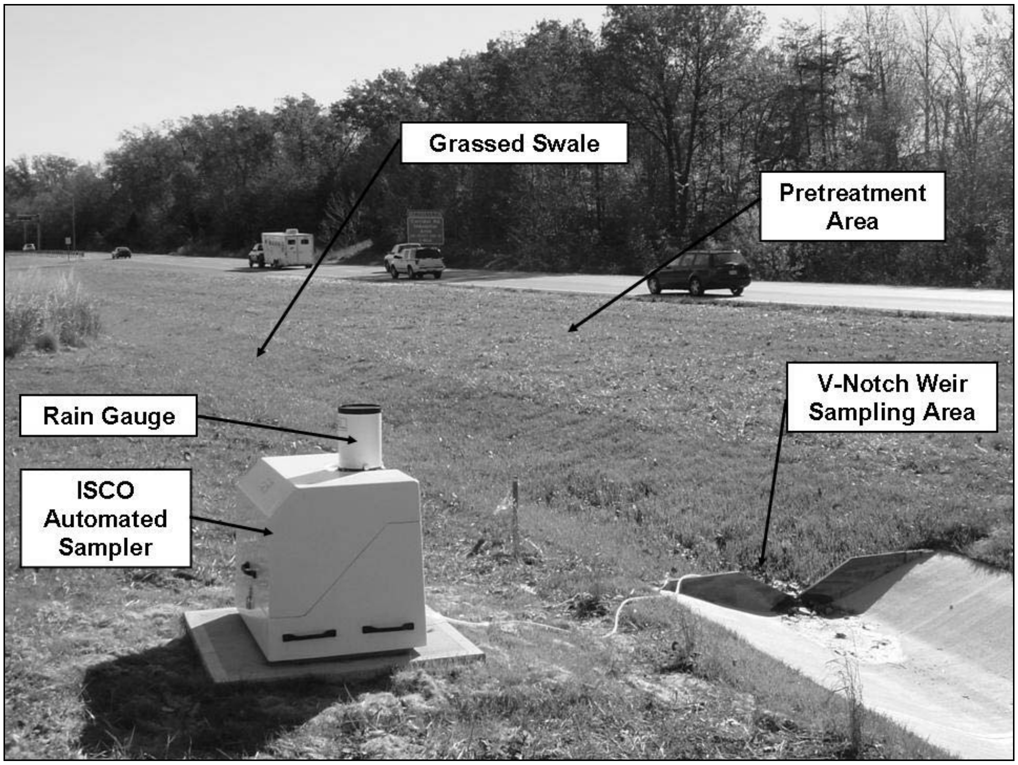

Figure 3-4. MDE swale at Rt 32.

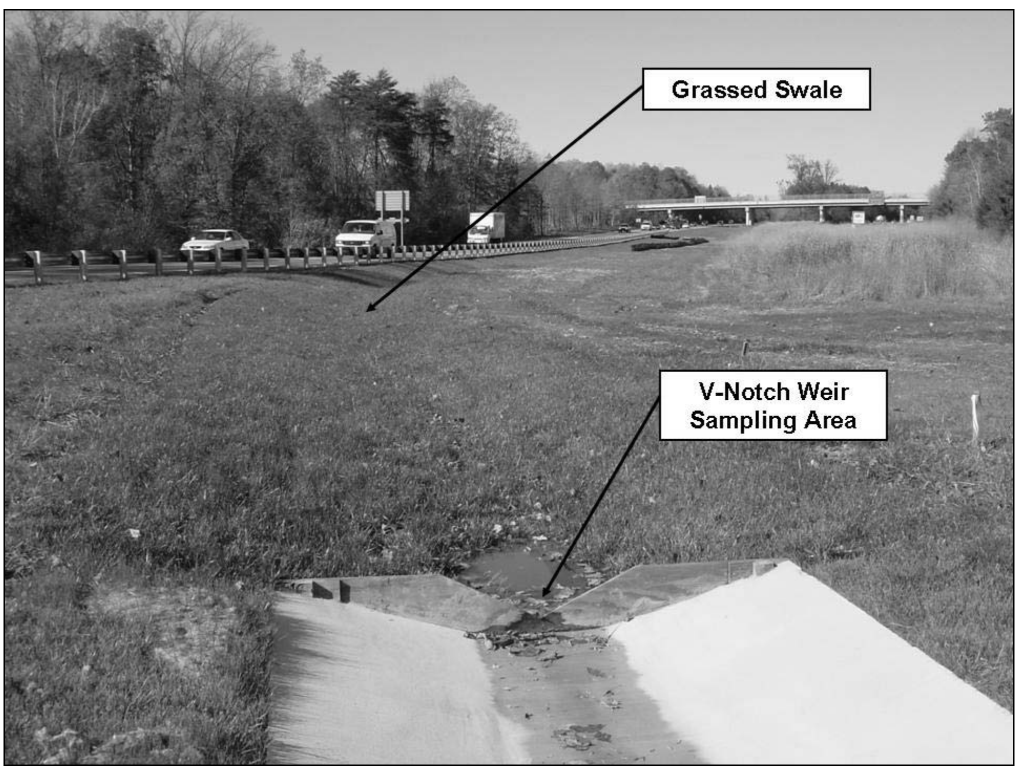

Figure 3-5. SHA swale at Rt 32.

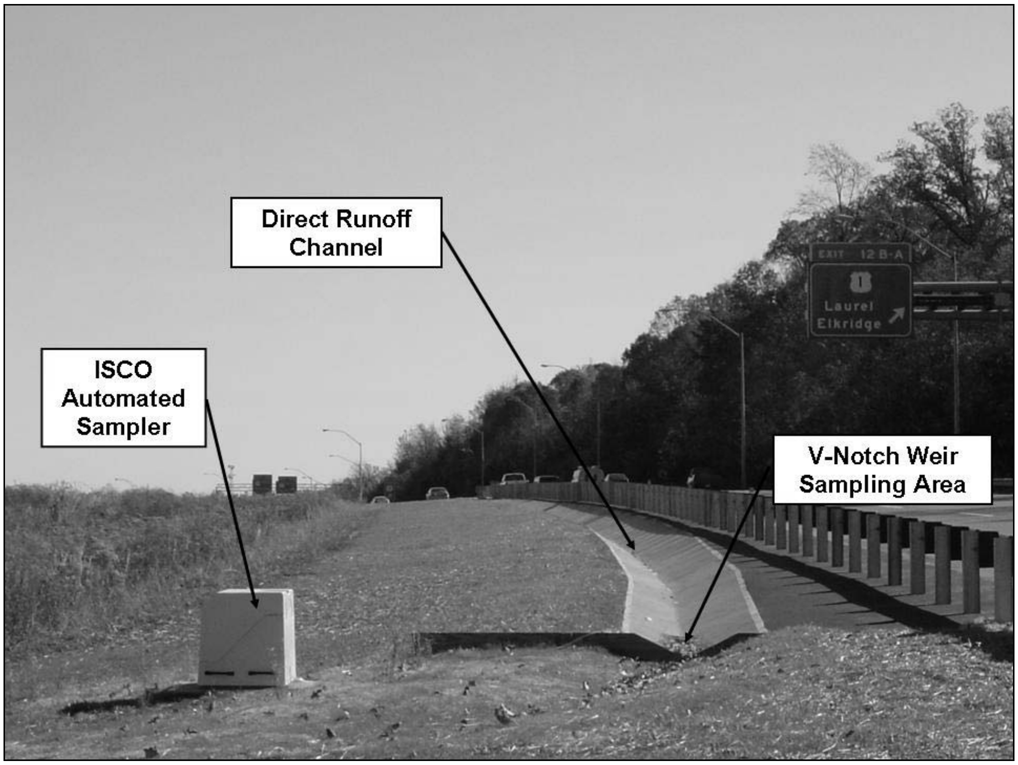

Figure 3-6. Direct roadway runoff monitoring at Rt. 32.

3.2 SAMPLING GOALS AND PURPOSE

The system is designed as an input/output study. The flow and pollutant load from the direct highway runoff are considered equal to the influent characteristics for each swale. This assumed influent is compared to flow and water quality measured at the outlet of each swale. Removal efficiencies are, thus, directly calculated for each storm event. Additionally, the removal efficiencies for each swale can be directly compared to one another. A goal of sampling one storm event per month was established.

3.3 MONITORING EQUIPMENT AND PROTOCOL

3.3.1 *Sampling Program*

Construction of the grassed swales was completed in late October 2004. The sampling program began in November 2004 and continued through May 2006.

In order to monitor flows and sample water quality, a V-notch wooden weir was constructed at the end of each swale and the direct channel. An ISCO Model 6712 Portable Sampler was installed in a secured vault adjacent to each swale. Each sampler has a bubble flow meter calibrated with the corresponding weir to monitor flow rates through the weir. The bubble tube was attached to the weir, level with the V-notch. A stainless steel strainer was placed just upstream of the weir.

One ISCO 674 Tipping Bucket Rain Gauge with 0.0254-cm sensitivity was installed on top of a sampler vault and connected to one of the portable samplers. This tipping bucket logs rainfall depth in 2-minute increments.

Each sampler contains twenty-four 300-ml glass bottles that are cleaned with wire brushes, acid washed in 10% HNO_3 for at least 20 minutes and rinsed with deionized water before placement in the sampler. The sampling program is set to collect 12 samples per event (filling 2 bottles per sample to ensure adequate volume for all the water quality testing). The sample timing is presented in Table 3-2, with an emphasis on obtaining more samples in the early part of the precipitation event. The sampler for direct stormwater runoff has an adjusted sampling schedule in order to cover the time period of the two swales. Preliminary sampling showed that the grassed swales trigger a few hours later, presumably due to initial abstraction, so the direct stormwater sampling times were lengthened accordingly.

Table 3-2. Sampling times for automated collection during storm events at Rt. 32.

	Time	
Sample Number	Direct Runoff	Two Swales
1	zero minutes	zero minutes
2	20 minutes	20 minutes
3	40 minutes	40 minutes
4	1 hour	1 hour
5	1 hour, 20 min	1 hour, 20 min
6	2 hours	1 hour, 40 min
7	2 hr, 40 min	2 hours
8	3 hr, 20 min	2 hr, 20 min
9	4 hr, 20 min	2 hr, 40 min
10	5 hr, 20 min	3 hr, 40 min
11	6 hr, 20 min	4 hr, 40 min
12	8 hr	6 hr

A sampling event is triggered when the head behind the weir reaches 0.0305 m, which corresponds to a flow of about 0.430 l/s. This flow rate corresponds to a rainfall intensity of 0.0640 cm/hr, based on the direct sampler with a drainage area of 0. 271 ha and a Rational Method coefficient of 0.9. Samples were picked up within 24 hours and transported to the Environmental Engineering Laboratory, College Park, MD. At the lab, samples were immediately analyzed for total phosphorus, nitrate, nitrite, and TSS. After these initial analyses, remaining samples were preserved and refrigerated. One bottle for each sample, containing approximately 100 ml of sample was preserved for metal analyses using six drops of concentrated trace level HNO_3. The second bottle for each sample was preserved by adding 2 ml of concentrated H_2SO_4 to 200 ml of sample for TKN analysis. TKN and metal digestion was completed within two weeks. Metal analyses were carried out within 6 months.

3.3.2 *Flow Calculation*

Swale flows were calculated at the end of each channel by monitoring flow depth behind a V-notch thin plate weir using a bubble flow meter. V-notch thin plate weirs are generally used at sites where low discharges occur, because they are highly sensitive at low flow conditions. In deriving the following equation for flow over a v-notch weir, the approach velocity head is neglected. The flow rate over a triangular weir that conforms to all ASTM standards (2001) is determined from:

$$Q = \tfrac{8}{15}(2g)^{1/2} C_e \tan\left(\theta/2\right)(H_e)^{5/2} \tag{3-1}$$

where g represents acceleration due to gravity, θ represents the angle of V-notch, and C_e and H_e are the discharge coefficient and effective head respectively. Effective head, H_e, is the measured head plus an adjustment for the combined effects of viscosity and surface tension for water. For large notch angles, like those used in this study, this adjustment becomes increasingly negligible and is therefore neglected in head calculations for this study.

Each v-notch weir was constructed from plywood, with a θ angle of 125° and a C_e value of 0.585 (ASTM 2001). Using these values, the above flow formula simplifies to:

$$Q = 2.65\ H_e^{5/2} \tag{3-2}$$

where H_e is the water head above the weir notch, in meters, and Q is the flow in cubic meters per second. The design criteria (ASTM 2001) recommend measuring the head, H_e, at a distance of 4 times the maximum head to eliminate the drawdown effect and to ensure that the velocity head is negligible. Physical limitations of the swale design limited the location of the bubbler line to immediately adjacent to the weir. Therefore, head was measured at the v-notch weir and a relationship was developed between head at the weir, H_{weir}, and the head at a distance for which velocity was negligible. The curve describing the relationship between H_e and H_{weir} was solved iteratively using equation 3-2 and the following equations which represent Bernouli's equation and the physical geometry of the weir opening

$$H_e = \frac{v^2}{2g} + H_{weir} \tag{3-3}$$

$$Q = Av = \left(H_e^{\,2} \tan\left(\frac{\theta}{2}\right)\right) v \tag{3-4}$$

where v represents the velocity at the v-notch and A represents the area of water flowing through the v-notch weir. By iterating these equations and equation 3-2, the flow velocity, v, and head at a sufficient distance, H_e, was calculated for the range of H_{weir} values encountered in this study. Each of these values was then plotted to create a rating curve, which was subsequently analyzed to determine a line of best fit. The data was best represented linearly, with a correlation coefficient, R, of 0.9999, and the following equation

$$H_e = 1.2276\, H_{weir} \tag{3-5}$$

Combining equation 3-5 with equation 3-2 results in the following equation used in this study to calculate flow through the weir.

$$Q = 2.65(1.2276\, H_{weir})^{5/2} \tag{3-6}$$

Error for flow measurement with a V-notch weir that is designed correctly can be calculated using the square root of the sum of squares of the individual error contributions. In standard weirs this becomes:

$$e = \left[(e_1)^2 + (e_2)^2 + n^2(e_3)^2\right]^{0.5} \tag{3-7}$$

where e is the total percentage error of a flow measurement, e_1 is the estimated error in the discharge coefficient, C_e (2% for V-notch), e_2 is the estimated error in tan θ/2 (2%), n is the exponent of the head in the discharge equation (2.5 for V-notch), and e_3 is the estimated error in the head measurement (1% for head in the range of this study) (ASTM 2001). This results in an estimated error in flow measurements for most flow depths of 3%. Bubbler modules were zeroed before every storm event to ensure an accurate baseline and were checked to ensure that height measurements showed minimal variation with time.

3.4 ANALYTICAL METHODOLOGY

Analytical methodologies for pollutant measurements are described in detail below and are summarized in Table 3-3.

3.4.1 *TSS Analysis*

This test followed Section 2540D of Standard Methods (APHA *et al.*1995). A well-mixed sample was filtered through a weighed standard glass-fiber filter and the residue retained on the filter was dried to a constant weight at 103 to 105°C for 1 hour. The detection limit is 1 mg/L.

3.4.2 *Phosphorus Analysis*

Total phosphorus analysis was divided into two general procedural steps: (a) conversion of the various phosphorus forms to dissolved orthophosphate by persulfate digestion, and (b) colorimetric determination of dissolved orthophosphate. As phosphorus may occur in combination with organic matter, a persulfate digestion method was used to oxidize organic matter effectively to release phosphorus as orthophosphate.

This test followed Section 4500-P of Standard Methods (APHA *et al.* 1995). Fifty-ml samples were placed into Erlenmeyer flasks; 20 drops of H_2SO_4 solution were added, along with 0.5 g $K_2S_2O_8$ (J. T. Baker). The flasks were then boiled until about 10 ml of liquid remained. Later, 20 ml of distilled water was added to each flask. The liquid in each flask was further diluted to 100 ml with deionized water. Four ml of ammonium

Table 3-3. Analytical methods for determination of pollutant concentrations in Rt. 32 swale storm events.

Pollutant	Standard Method (APHA *et al.* 1995)	Detection Limit (mg/L)
Total Suspended Solids, TSS	2540D	1
Total Phosphorus	4500-P	0.24
Total Kjeldahl Nitrogen, TKN	4500-N_{org}	0.14
Copper	3030 E	0.002
Lead	3030 E	0.002
Zinc	3030 E	0.025
Cadmium	3030 E	0.002
Nitrite	4500-NO_2^- B	0.01 as N
Nitrate	Dionex DX-100 ion chromatograph	0.1 as N
Chloride	Dionex DX-100 ion chromatograph	2

molybdate reagent and 10 drops of stannous chloride reagent were added to each flask. The samples were allowed to sit for 10 minutes. Finally, the samples were placed into a spectrophotometer (Shimadzu model UV160U) to measure the color at 690 nm. A detection limit of 0.24 mg/L as P has been established.

3.4.3 *Nitrate, Nitrite, and Chloride Analyses*

Analyses of nitrate and chloride were routinely performed using a Dionex DX-100 ion chromatograph. The eluent was 2.0 mM sodium carbonate/0.75 mM sodium bicarbonate (J. T. Baker) solution. The flow rate was adjusted to 2.0 ml/min to clearly differentiate nitrate and chloride peaks. The concentration of nitrate in the samples was determined against standards of 0.2, 0.4, 1.0, 1.4, and 2.0 mg/L as N prepared with $NaNO_3$ (Fisher Scientific) in deionized water. The concentration of chloride in the samples was determined against standards of 1, 3, 5 and 8 mg/L prepared using 1000 mg/L chloride stock solution (Fisher Scientific) in deionized water. Standard concentrations above the instrument detection limits were employed for nitrate and chloride due to the wide spread of sample concentrations found over the course of a storm event. The scale and standard concentrations were set to a range appropriate for the majority of samples in an event.

Spectrophotometric measurement of nitrite was carried out similarly, using Standard Method 4500-NO_2^- B (APHA *et al.* 1995). Standards of 0.02, 0.08, 0.12, 0.24 mg/L as N were prepared by diluting a 1000 mg/L stock solution (Fisher Scientific).

3.4.4 *TKN Analysis*

TKN was measured via Standard Method 4500-N_{org}, Macro-Kjeldahl Method (APHA et al., 1995). TKN analysis was completed in three steps: (a) digestion of a 200-ml sample by evaporation after addition of 50 ml of digestion regent prepared as detailed in the Standard Method, (b) distillation of digested sample diluted to 300 ml and treatment with 50 ml of NaOH-NaS_4O_3 reagent, and (c) titration of distillate with standard 0.02 N H_2SO_4 titrant. The detection limit is 0.14 mg/L for TKN.

3.4.5 *Cadmium, Copper, Lead, and Zinc Analyses*

Metal analyses were divided into two steps: (a) digestion of samples by evaporation of 75 to 100 ml of sample, after addition of 5 ml of concentrated trace metal-grade HNO_3 (Standard Method 3030 E), and (b) analysis of cadmium, copper and lead on the furnace module of a Perkin Elmer Model 5100ZC atomic absorption spectrophotometer, Standard Method 3110, and zinc on the flame module, Standard Method 3111 (APHA et al., 1995). Standards for cadmium, copper, lead and zinc were prepared using 1000 mg/L Fisher Chemicals stock solutions.

3.4.6 *Quality Control*

Laboratory blanks were created by pouring deionized water into a cleaned bottle every 3 monitored storm events. These laboratory blanks were then subjected to the same laboratory procedures as the runoff samples in order to verify that no contamination of the samples occurred during handling and that the baseline for measuring various constituents was sufficiently low.

For all measured constituents, the residual concentrations in the field blanks were low enough to be considered negligible, proving that contamination was not occurring and that the analysis and detection methods were accurate.

Standards were checked regularly to ensure that the standards curve still applied to the samples. Nitrate and chloride standards used in the ion chromatograph were checked every time new eluent was added to the instrument, which was roughly every 20 samples analyzed, while metal standards were checked every 10 samples analyzed.

3.4.1 *Data Below Detection Limit*

In cases where the concentration of a pollutant was below the method detection limit, the range between zero and the detection limit was listed. The detection limit corresponds to the highest possible concentration of the constituent in the sample that would still be undetectable by the analytical procedure. For all subsequent concentration, mass, and statistical calculations, the mean value between zero and this detection limit was used for that particular sample.

3.5 HYDROLOGY DATA EVALUATION AND CALCULATIONS

For both hydrology and pollutant concentration data, it is necessary to examine grass swale performance in a manner that accurately models and compares the swales. Concentrations and flow data are viewed with respect to time, but are also combined and examined such that performance can be evaluated using a single measure. These methods are based on both a mass balance and a flow balance around the grass swale. The flow balance and mass balance are shown graphically in Figure 3-7.

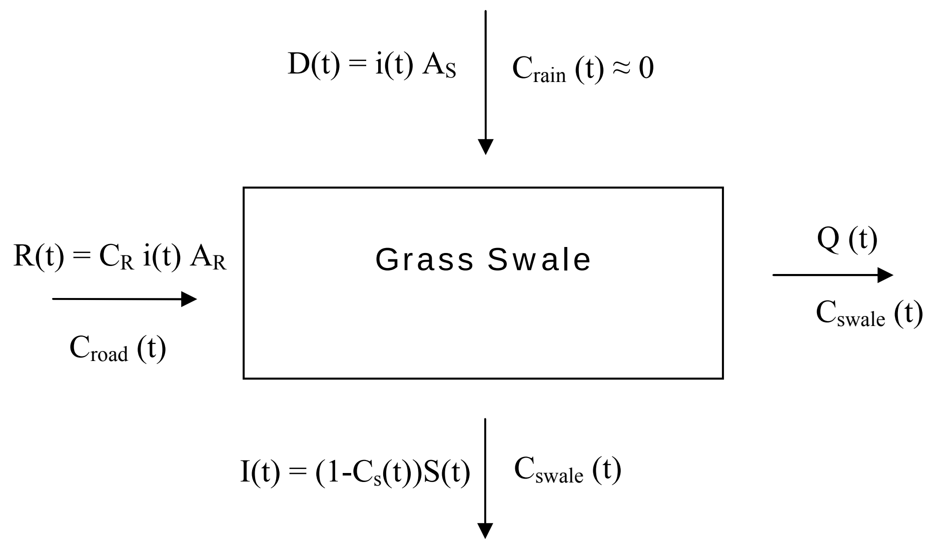

Figure 3-7. Grass swale mass balance model.

For this combined flow and concentration model, R(t) represents runoff flow into the swale from the roadway surface, D(t) represents flow from rainfall directly onto the swale, I(t) represents infiltration into the swale soil, and Q(t) represents the final flow out of the swale. This figure also includes pollutant concentrations as a function of time, with $C_{road}(t)$ representing constituent concentration from the roadway, $C_{rain}(t)$ representing concentration in rainfall, and $C_{swale}(t)$ representing the constituent concentration in the swale. A flow balance around the swale results in the following equation.

$$R(t)+D(t)-I(t)=Q(t) \tag{3-8}$$

The mass balance around the grass swale is:

$$R(t)C_{road}(t)+D(t)C_{rain}(t)-I(t)C_{swale}(t)+T(t)=Q(t)C_{swale}(t) \tag{3-9}$$

With T(t) representing a grass swale treatment term. This term represents the total sum of filtration, sedimentation, and any other processes occurring within the grass swale.

The treatment term can represent a removal, in the case of a negative T(t), or export, in the case of a positive T(t) term.

For the purposes of calculations, it is assumed that the pollutant concentration in rainfall is negligible compared to that from the roadway surface, and is therefore assumed to be zero. This results in the mass balance equation

$$R(t)C_{road}(t) - I(t)C_{swale}(t) + T(t) = Q(t)C_{swale}(t) \tag{3-10}$$

3.5.1 *Instantaneous Flow Drainage Area Normalization*

In order to obtain a useful comparison between the hydrology results of the grass swales and the direct runoff channel, the flow data must be normalized. The method described in this section refers to a direct comparison between the input and output of the swale at any given instant. This normalization is necessary because although the roadway drainage areas are nearly identical, differences in the total drainage area (including grass swale area) cause differences in the input flows for each channel. By analyzing the instantaneous flow balance around the grass swale, the inflow and outflow with respect to time can be compared by normalizing the data using the static properties of the grass swales. These flow comparisons with respect to time can then be used to compare peak flows, flow delays, and changes in the distribution of flow.

Highway runoff is modeled by the Rational Method:

$$R(t) = C_R \; i(t) \; A_R \tag{3-11}$$

where C_R is the highway runoff coefficient representing the percentage of water that runs off the roadway surface, i(t) is the rainfall intensity (m/hr) and A_R is the drainage area of the impervious roadway surface (m^2). Using these units, R(t) has units of m^3/s. In all cases, rainfall is represented as a function of time because this quantity is dynamic and continuously changing throughout the storm duration. In a similar way, the rainfall that falls directly onto the grass swale surface, D(t), is modeled with the Rational Method. However, because this rainfall does not contact anything before it enters the swale, no runoff coefficient, C, is included in the formula.

$$D(t) = i(t)\, A_s \tag{3-12}$$

The infiltration into the grass swale soil is modeled using a slightly modified Rational Method equation.

$$I(t) = (1 - C_S(t))\, S(t) \tag{3-13}$$

Since I(t) is defined as the infiltration flow out below of the swale, the Rational Method runoff coefficient must be subtracted from 1, as C_S represents the fraction of runoff that passes over a surface. The runoff coefficient, C_s, is a dynamic property represented as a function of time because the infiltration capacity of the swale media changes as pore spaces are filled with water. This percentage of runoff is multiplied by S(t), a variable representing the flow through the swale at any given time. This is a dynamic property that represents the amount of water flowing through the swale at any given time. Finally, Q(t) represents the flow leaving the swale.

Substituting these flows into Equation 3-8 yields:

$$Q(t) = C_R\, i(t) A_R + i(t) A_S - (1 - C_S(t)) S(t) \tag{3-14}$$

Because only two flows enter the swale, R(t) and D(t), S(t) is related to both of these quantities. The flow through the swale can be described by

$$S(t) = s'(t)\left[R(t) + D(t)\right] \tag{3-15}$$

where s′(t) is a function that accounts for the physical properties of the swale which both delay flow and change the proportion of the flow (e.g., grass height, channel slope, shape, roughness, hydraulic travel times and other factors). Because s′(t) is related to travel distance and because flow enters the swale along its entire length, the s′(t) variable changes along the length of the roadway. Substituting equation 3-9 into equation 3-8 yields

$$Q(t) = C_R\, i(t) A_R + i(t) A_S - s'(t)\left(1 - C_S(t)\right)\left[C_R\, i(t)\, A_R + i(t)\, A_S\right] \tag{3-16}$$

Grouping the static quantities and dynamic quantities separately yields

$$Q(t) = \left[A_S + C_R\, A_R\right]\left[i(t) - s'(t) + C_S(t)\, s'(t)\right] \tag{3-17}$$

Normalizing the swale outflow by the static component results in:

$$\frac{Q(t)}{A_S + C_R\, A_R} = i(t) - s'(t) + C_S(t) s'(t) \tag{3-18}$$

This equation is the basis for the drainage area normalization. Dividing the swale flow by this area-based normalization factor allows a standard comparison between swales and employs only those properties that are constant throughout a storm event. Although C_R likely varies between 0.9 and 1 during the storm event, this is considered negligible and a constant value of 0.95 will be used for all normalization calculations. The drainage areas used for this normalization are shown in Table 3-4.

Table 3-4. Site drainage areas.

	Direct	SHA Swale	MDE Swale
Roadway Area A_R(ha)	0.234	0.224	0.225
Impervious Channel Area (ha)	0.037	-	-
Swale Area A_S(ha)	-	0.169	0.431
Total Area (ha)	0.271	0.393	0.656
Modified Area (acre) $=A_S + C_R A_R$ (Eq. 3-18)	0.257	0.382	0.645

All swale flows used for comparison purposes will be normalized by this modified area. This method only allows for comparisons of inflow and outflow with respect to time, however, because of the variability and complicated form of s′(t), it does not allow any instantaneous analysis of infiltration.

3.4.2 *Total Storm Volume*

To calculate the total volume during a storm event and the associated reduction in volume due to the swales, the flow balance described by the swale model is used. The total storm volume leaving any of the channels is calculated by integrating the flow over the storm duration as

$$V = \int_0^{T_d} Q(t)\, dt \tag{3-19}$$

Where V represents the total volume, Q represents the flow leaving a particular point, and T_d is the duration of the storm event. Applying this principle to equation 3-8, the total storm volumes are calculated by

$$\int_0^{T_d} Q(t)dt = \int_0^{T_d} R(t)dt + \int_0^{T_d} D(t)dt - \int_0^{T_d} I(t)dt \tag{3-20}$$

$$V_{Swale} = V_{Road} + V_{Rain} - V_{Infil} \tag{3-21}$$

The total volume from direct rainfall can be calculated by

$$\int_0^{T_d} D(t)dt = A_S \int_0^{T_d} i(t)\, dt \tag{3-22}$$

In a similar manner, the total volume due to runoff from the roadway surface can be calculated by integrating equation 3-11. In the swale setup employed, the roadway flow is calculated from the direct channel. However, while the site was designed to have identical roadway areas, these areas are slightly different for the direct channel and the two swales. Therefore, for all comparisons of mass, the direct channel volume data must be scaled by roadway area to match the grass swale roadway areas. In this way, the direct channel is equivalent to the roadway flow inputs for the grass swales. The flow entering the swale is therefore be calculated as:

$$R(t) = Q_{Direct}(t)\left(\frac{A_{Road\ Swale}}{A_{Road\ Direct}}\right) \tag{3-23}$$

where Q_{Direct} is the flow measured at the Direct channel outflow, and $A_{RoadSwale}$ and $A_{RoadDirect}$ are the roadway drainage areas for the swale and direct channel, respectively.

In the interest of simplifying calculations and because the roadway drainage areas of the swales are so similar to one another (0.224 ha = SHA, 0.225 ha = MDE), this input flow normalization will occur with the average ratio for the two swales roadway drainage area. Therefore, the input flow normalization will be calculated as

$$R(t) = Q_{Direct}(t)\left(\frac{0.224\ ha}{0.234\ ha}\right) = 0.961 Q_{Direct}(t) \tag{3-24}$$

This simplification will result in an error of only 0.27% for all flow calculations and should not affect results significantly.

Using these two inputs, the flow balance becomes:

$$\int_0^{T_d} 0.961 Q_{Direct}(t)\,dt + A_S \int_0^{T_d} i(t)\,dt - \int_0^{T_d} I(t)\,dt = \int_0^{T_d} Q(t)\,dt \tag{3-25}$$

where the first term, the volume due to the roadway, the second term, the volume due to direct rainfall, and the last term, the volume leaving the grass swale, can all be calculated from storm data. This, therefore, allows a calculation of total infiltration volume and a complete understanding of the total flow volumes for all portions of the flow balance.

3.4.3 Normalized Total Storm Volume

While the total storm volume is important, it is difficult to draw useful comparisons between the two swales because there is a large difference between pervious swale areas. It is important, for an effective comparison, to determine the volume of runoff leaving the grass swale in the case that the swale receives water only from the roadway surface, which is considered identical for all three channels and not from direct rainfall landing on the swale, which is different due to differences in pervious area. To this purpose, a new hypothetical swale model is developed in which no rainfall is allowed to fall on the pervious swale area. This model therefore shows the flow resulting from only roadway runoff and infiltration. The conceptual model is shown in Figure 3-8

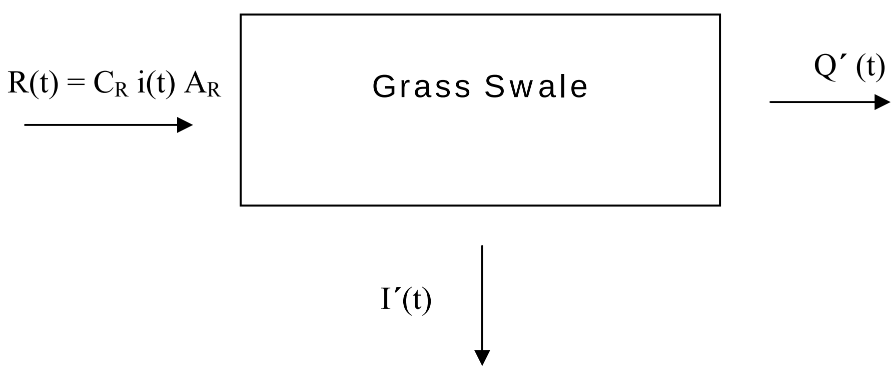

Figure 3-8. Grass swale flow balance model without rainfall dilution.

where $I'(t)$ represents infiltration rate without rainfall flow and $Q'(t)$ represents flow leaving the swale neglecting rainfall onto the swale. The flow from the roadway surface, $R(t)$ is unaffected by this normalization and is identical to the road runoff parameters calculated above. A flow balance around this model swale results in the following equation.

$$R(t) - I'(t) = Q'(t) \tag{3-26}$$

A relationship between I(t), the infiltration rate including rain on the swale, and I′(t), the infiltration rate without this extra rainfall flow, is required to solve this equation. For the purposes of this model, it is assumed that the infiltration rate is dependent primarily on soil characteristics and is not affected by the flow rate through the swale.

The Horton Equation for infiltration is one of the most commonly used infiltration models and is shown by the equation (Horton 1940):

$$f_p = f_c + \left(f_o - f_c\right) e^{-kt} \tag{3-27}$$

where f_p represents the infiltration capacity of the soil at a given time, f_c is the equilibrium infiltration capacity, f_o is the initial infiltration capacity, k is a constant representing the rate of decreased infiltration capacity and t is the time since the start of the infiltration (Horton 1940). This equation is entirely dependant on time and soil conditions, which suggests that infiltration rates would be equal given the same soil conditions. Water depth is not a variable in this equation.

Another infiltration model, the Green-Ampt method, is based on a physical approximation. The infiltration rate for this equation is determined by Darcy’s Law and results in the following equation (McCuen 1989):

$$f = K\left[\frac{h - (-\Psi - L)}{L}\right] \tag{3-28}$$

where K represents the hydraulic conductivity of the soil, h represents the depth of ponded water, Ψ represents the soil suction head, and L represents the depth of the wetting front below the ground surface. A common assumption for solving this equation is that the ponding depth is negligible. In both the Horton equation and the Green-Ampt method, the soil characteristics are the limiting factors for infiltration and the flow or ponding depth is unimportant. Therefore, the assumption that the infiltration rate for the soil with extra rainfall flow is equal to the infiltration rate for the same storm without rainfall flow is reasonable. This assumption is represented as:

$$I(t) = I'(t) = R(t) + D(t) - Q(t) \tag{3-29}$$

Substituting this equation into the flow balance yields

$$R(t) - [R(t) + D(t) - Q(t)] = Q'(t) \tag{3-30}$$

$$Q(t) - D(t) = Q'(t) \tag{3-31}$$

Conceptually, this equation means that the flow leaving the swale without rainfall is equal to the flow measured during the storm event minus the flow onto the swale by rainfall directly landing on the swale. The inflow volume for this normalized model is identical to that calculated above; however the new normalized outflow volume from the swale is calculated by integrating equation 3-31.

$$V'(t) = \int_0^{Td} Q(t)dt - \int_0^{Td} D(t)\,dt \tag{3-32}$$

which becomes:

$$V'(t) = \int_0^{Td} Q(t)dt - A_S \int_0^{Td} i(t)\,dt \tag{3-33}$$

where Q(t) is the flow measured at the output of the swale, A_S is the total pervious area of the swale, i(t) is the rainfall intensity measured at the site, and V′(t) is the volume leaving the swale if the swale receives water only from the roadway surface.

3.6 POLLUTANT DATA EVALUATION AND CALCULATIONS

For pollutant data comparisons, a mass balance around the grass swale is necessary in conjunction with the flow balance. Combining the flow and mass balance yields the following model.

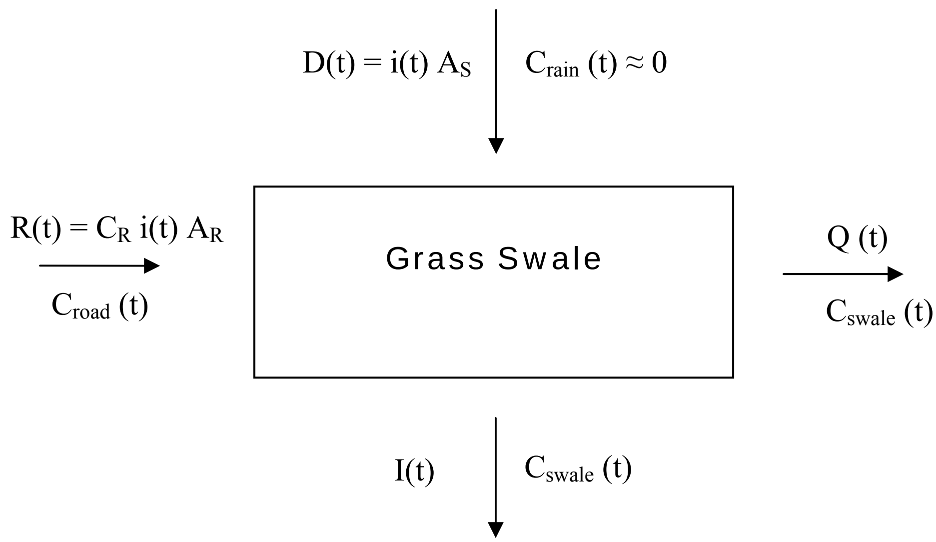

Figure 3-9. Grass swale mass balance model.

This mass balance includes pollutant concentrations as a function of time, with $C_{road}(t)$ representing constituent concentration from the roadway, $C_{rain}(t)$ representing concentration in rainfall, and $C_{swale}(t)$ representing the constituent concentration in the swale. The mass balance around the grass swale is

$$R(t)\,C_{road}(t) + D(t)C_{rain}(t) - I'(t)C'_{swale}(t) + T(t) = Q'(t)C'_{swale}(t) \qquad (3\text{-}34)$$

with T(t) representing a grass swale treatment term. This term represents the total sum of filtration, sedimentation, and any other processes occurring within the grass swale. The treatment term can represent a removal, in the case of a negative T(t), or export, in the case of a positive T(t) term.

For purposes of calculations, it is assumed that the pollutant concentration in rainfall is negligible compared to that from the roadway surface, and is therefore zero. This results in the mass balance equation

$$R(t)C_{road}(t) - I(t)C_{swale}(t) + T(t) = Q(t)C_{swale}(t) \tag{3-35}$$

3.6.1 *Total Mass Load*

For each pollutant in this study, the total mass (M) of the constituent in the flow leaving the direct channel or the grass swale is calculated as

$$M = \int_0^{T_d} QCdt \tag{3-36}$$

where Q is the measured stormwater flow rate and C is the pollutant concentration for each sample during the event. T_d is the event duration. The interval between samples is dt.

Taking the integral of each term in equation 3-35 with respect to time allows the calculation of total mass for each term throughout the storm duration.

$$\int_0^{Td} R(t)C_{road}(t)dt - \int_0^{Td} I(t)C_{swale}(t)dt + \int_0^{Td} T(t)dt = \int_0^{Td} Q(t)C_{swale}(t)dt \tag{3-37}$$

and becomes:

$$M_{road} - M_{\text{infil}} + M_{treat} = M_{swale} \tag{3-38}$$

This mass balance means that the sum of the pollutant inputs, infiltration, and treatment result in the total mass measured leaving the swale outflow.

In order for the mass removal comparison highlighted in equation 3-37 to be correct, the Direct channel flow data must be scaled by the roadway area of the swales to match the grass swale roadway areas in the same manner stated in Section 3.5.2. In this way, the direct channel is equivalent to the roadway inputs for the grass swales. The mass entering the swale should therefore be calculated as

$$M_{road} = 0.961\int_{0}^{Td} Q_{Direct}(t)C_{road}(t)\,dt \tag{3-39}$$

The total mass balance for the grass swale therefore becomes

$$M_{treat} - M_{\text{infil}} = \int_{0}^{Td} Q(t)C_{swale}(t)\,dt - 0.961\int_{0}^{Td} Q_{Direct}(t)C_{road}(t)\,dt \tag{3-40}$$

This equation compares the total mass input and the total mass output and calculates the mass removed by the sum of infiltration and treatment through the swale.

3.6.2 *Event Mean Concentration (EMC)*

Another useful parameter for analyzing concentration data is the event mean concentration (EMC). The EMC is essentially a flow weighted mean concentration found by dividing the total mass leaving the channel by the total volume leaving the channel.

$$EMC = \frac{M}{V} = \frac{\int_0^{Td} Q(t)C(t)\,dt}{\int_0^{Td} Q(t)\,dt} \tag{3-41}$$

The EMC represents the concentration that would result if the entire storm event discharge were collected in one container. Because the EMC represents a single, mean concentration, it is generally used to compare pollutant concentrations among different events.

3.6.3 *Normalized Event Mean Concentration (N-EMC)*

The EMC is a valuable tool for comparing the concentration that would result from the effluent of a grass swale during a given storm event. However, because of the difference in total drainage area caused by the inclusion of swale area, there is a significant difference in rainfall flow as shown in Section 3.4.2. With the assumption stated above that no significant pollutant mass is present in the rainfall, the EMC, unlike total mass, is affected by dilution. As shown in equation 3-40, rainfall volume does not impart any pollutant mass, yet the rainfall volume adds a portion to the total volume calculation, as shown in equation 3-41. While the EMC is important because it shows the actual field-based resulting concentration exported to receiving waters, another evaluation method is necessary to describe the true removal capability of the swale by eliminating the effects of dilution. The Normalized Event Mean Concentration (N-EMC) assumes the same conceptual model used in the calculation of normalized flow volumes (Section 3.4.3) - that rain falls only on the roadway surface and thereby calculates the concentration that would occur if the grass swale surface was shielded from the rainfall and the resulting storm event discharge was collected in one container. Because the flow balance around this model is identical to the normalized flow balance calculated in equation 3-26, the volume used in calculating the N-EMC is the same normalized volume calculated by equation 3-33.

The mass balance around the grass swale is identical to the mass leaving the swale with rainfall because there is no mass flux from the rainfall. The N-EMC for this hypothetical situation without dilution is based on the same principle as the EMC, with the total mass leaving the swale divided by the normalized total volume of flow leaving the swale without rainfall on the swale. This relationship is shown as

$$N-EMC=\frac{M_{swale}}{V'_{swale}}=\frac{Mass_{swale}}{Volume_{swale}-Volume_{\text{swale-rainfall}}}=\frac{\int_0^{Td} Q(t)C_{swale}(t)\,dt}{\int_0^{Td} Q(t)\,dt-A_S\int_0^{Td} i(t)\,dt} \tag{3-42}$$

where the $Mass_{swale}$ is the total constituent mass leaving the swale as calculated in section 3.5.1, $Volume_{swale}$ is the total volume of runoff leaving the swale, and $Volume_{\text{swale-rainfall}}$ is the total volume of rainfall landing on the swale area during the storm event.

Swale N-EMCs can then be compared to the EMC of the direct channel, because this concrete channel has no dilution effects. The direct channel EMC is therefore the influent mean concentration, the swale N-EMC is the effluent mean concentration and any difference between the two can be attributed to the sum effect of infiltration, I(t), and treatment, T(t).

3.6.4 *First Flush Diagrams*

First flush diagrams are used to compare the delivery of constituent mass to the delivery of flow volume. If pollutant mass is exported at disproportionately high levels during the initial part of the storm event when compared to volume, then it is considered a first flush of that particular pollutant.

First flush diagrams are constructed by combining the hydrograph curve, Q(t), and the pollutograph curve, C(t). In order to compare these two curves on the same graph, a dimensionless form is used. The dimensionless relationships are

$$V(t) = \frac{\int_0^k Q(t)dt}{\int_0^n Q(t)dt} \tag{3-43}$$

$$M(t) = \frac{\int_0^k Q(t)C(t)dt}{\int_0^n Q(t)C(t)dt} \tag{3-44}$$

where V(t) is the dimensionless ratio of the total volume of runoff observed at any time k to the total volume of runoff observed for the event, k is any time between the beginning of runoff and the time coinciding with the cessation of runoff (n), and Q(t) is the hydrograph of the runoff event. Similarly, M(t) is the dimensionless ratio of constituent mass delivered throughout an event and C(t) is the function for measured concentrations as a function of time. Because flow and concentrations are not continuously monitored, these two dimensionless ratios are solved discretely for a time step equal to the sampling times.

The dimensionless ratios are shown graphically by plotting V(t) on the independent axis and M(t) on the dependent axis. A line, L, with a slope of 1:1 is drawn from the origin and represents a storm event in which mass delivery is completely proportional to flow. A constituent exhibits some first flush behavior if M(t) exceeds the bisector, L, in the early portions of the storm.

A mass-based first flush is quantified in this study as any storm in which mass delivery exceeds 50% during the first 25% of storm volume (Wanielista and Yousef 1993). Comparisons are performed on the M(t) value during this 25% by volume first flush period to determine if the grass swales tend to remove the first flush and spread mass loading more evenly throughout the storm event.

3.7 STATISTICAL ANALYSIS AND COMPARISON

Analysis of the hydrology and constituent data is meant to examine two issues. The first examined hypothesis is if either grass swale is making a statistically significant improvement on the hydrology or contaminant data. The second major question is whether inclusion of a grass pretreatment area prior to the grass swale makes a statistically significant difference in hydrology and contaminant data. With the assumption that the drainage stretches of highway for each swale are identical after normalization by area, the direct concrete channel is viewed as equivalent to the input for each swale. Using these data as an input and the swale data as an output, it is possible to calculate differences in any hydrologic or contaminant based measure and to determine the statistical significance of that removal.

3.7.1 *Overall Statistical Analysis Procedure*

A battery of statistical tests will be performed on the data to check hypotheses about removal and to compare the swales to the input and to one another. These statistical tests are considered paired tests because the values for the three channels are paired according to each particular storm event. It is assumed that the sampled storm events are from a random population and that preexisting differences between these storm events can cause differences in performance. However, the concern for this study is the differences between the channel input and output. By pairing data points, the statistical methods test the effect of the swale treatment for each particular storm and eliminate all extraneous variability caused by differences in storms.

Because of this pairing of data, there are two inputs into this regiment of statistical tests. To check whether either grass swale has a significant effect on treating the highway runoff, the input ΔA is used. This variable represents the difference in any data type to be compared and can represent concentration data such as total mass, EMC, N-EMC, and first flush, or flow data such as peak flow and total volume. This input can be calculated as a direct difference or as a percent removal as shown by the following equations

$$\Delta A = A_{\text{influent}} - A_{\textit{effluent}} \tag{3-45}$$

$$\Delta A_{\%} = \frac{A_{\text{influent}} - A_{\textit{effluent}}}{A_{\textit{effluent}}} \times 100 \tag{3-46}$$

where A_{influent} represents the input parameter being compared and A_{effluent} represents that parameter's value leaving the swale.

To test the hypothesis that including a pretreatment area adjacent to the grass swale improves concentration and flow parameters significantly, a different paired parameter is used. This variable, ΔB, represents the difference in removal between the MDE swale (with pretreatment) and the SHA swale (without pretreatment). As with the paired samples above, this variable eliminates the variability caused by differences in storm events and examines the difference in performance between these two samples during identical storm events. ΔB can be calculated for either removal or removal percentage using the following equations

$$\Delta B = A_{MDE} - A_{SHA} \quad (3\text{-}47)$$

$$\Delta B_{\%} = A_{\%MDE} - A_{\%SHA} \quad (3\text{-}48)$$

A ΔB value greater than zero shows that the pretreatment swale was more effective than the no-pretreatment swale for a particular storm.

Table 3-5 describes the regiment of statistical tests performed on the paired variables above to determine if the swales have significant removals and if there is any difference between the swales. This table lists the tests, the purpose for each test and the hypothesis being examined in each statistical test.

Table 3-5. Regiment of statistical tests.

Step	Test	Purpose	Hypothesis
1	Dixon-Thompson Test (for both A and B) (McCuen 2002)	Identify and possibly remove outliers	Ho: all points are from same population Ha: the most extreme point is not from the same population
2	Kolmogorov-Smirnov 1-Sample Test (for both A and B) (McCuen 2002)	Check for normality (for both A and B)	Ho: population is normally distributed Ha: population is not normally distributed
3	Paired Student's T-Test (McCuen 2002)	Determine if removal in either swale is greater than zero Determine if removal in MDE is greater than removal in SHA	Ho: $\mu_A = 0$ Ha: $\Delta\bar{A} > 0$ Ho: $\mu_{swale} = 0$ Ha: $\Delta B > 0$
4	Wilcoxon Signed-Ranks Test (Wilcoxon 1945)	Determine if removal in either swale is greater than zero (non-parametric, non-normal distribution) Determine if removal in MDE is greater than removal in SHA (non-parametric, non-normal distribution)	Ho: $\mu_{swale} = 0$ Ha: $\Delta A > 0$ Ho: $\mu_{swale} = 0$ Ha: $\Delta A > 0$
5	F Test of Variances (McCuen 2002)	Determine if significant difference in variances between swales	Ho: $\sigma^2_{MDE} = \sigma^2_{SHA}$ Ha: $\sigma^2_{MDE} < \sigma^2_{SHA}$

Steps 1 and 2 (Table 3-5) are important to satisfy assumptions for the other tests and to better characterize the data. This extra information will allow a more educated decision on which tests are most applicable in the case of disagreeing results.

Steps 3, 4 and 5 actually compare the relative performance of the grass swales. The paired Student's T-test and the Wilcoxon Signed-Ranks test on the ΔA data compare swale effluent to influent and determine if the swales are effectively removing the pollutant being analyzed, while these two tests performed on ΔB data compare the performance of the two swales and determine if the pretreatment area is effective in increasing pollutant removal. For each hypothesis, there is a test for normally distributed data and a test using a non-parametric test that does not require a normal distribution. Generally the normally distributed tests are more strict in their results, yet suffer from the necessity of normally distributed data. By performing both tests and testing for normality, a more accurate conclusion can be drawn from the data. The final test, the F test of variances performed only on the ΔB data, compares the variability of each swale's removal and tests if the swale with a pretreatment area has more consistent, and therefore less variable, removals.

3.7.2 *Dixon-Thompson Test for Outliers*

The Dixon-Thompson Test (1953) for Outliers is useful for determining if a particular point is an outlier not from the same population as the rest of a data set. This particular test is useful because it can be used for data sets with small sample sizes. This test assumes that

1. Data are independent measurements from a normal population
2. Extreme events found to be outliers are from a population with either a shifted mean or the same mean but a larger variance.

The Dixon-Thompson Test is only valid for detecting one outlier. To use the test, the data set is sorted from largest to smallest, and the most extreme value is tested as an outlier. This point is tested using one of the test statistics that depend on the sample size. The resulting R test statistic is compared to a critical value for a 5% rejection level.

If the R value is larger than this critical value, the point is considered a candidate to be considered an outlier. However, in order to be removed from the data set as an outlier in this study, there must be some physical reason for the abnormally high or low value, such as an abnormally large storm volume or an abnormally intense rainfall. If the point is considered an outlier, it is then removed from the data set and all subsequent calculations.

3.7.3 *Kolmogorov-Smirnov 1-Sample Test*

The Kolmogorov-Smirnov 1-Sample test is used to compare a data set to any proposed probability distribution function (PDF). For this study, the proposed PDF is a normal distribution. The null hypothesis for this test is that the data are from a normal distribution with a population mean and standard deviation equal to those calculated for the data set. The alternative hypothesis is that the data set is not from this normally distributed population. The Kolmogorov-Smirnov 1-Sample test determines if the sampled data are significantly different from the proposed distribution. Otherwise, the proposed distribution is accepted.

A 5% level of significance is used for this test. The data are separated into cells such that only one value is present within each cell and the corresponding cumulative probability for that particular cell is calculated from the normal distribution. The test statistic, denoted as D, is the maximum absolute difference between the observed cumulative distribution and the specified probability distribution function. This D value can then be compared with a critical value, $D_{0.05}$, of the test statistic obtained from tables. If the computed value, D, is greater than the critical value $D_{0.05}$, the null hypothesis should be rejected and it can be assumed that the data set is not normally distributed with that particular mean and standard deviation. If the computed value, D, is less than the critical value, the null hypothesis is accepted and the data is considered to be normally distributed.

3.7.4 *Paired Student's T-Test*

A paired Student's T-test examines whether the removal for either swale is greater than zero. Therefore, the hypotheses for this test are

$$\text{Ho: } \mu_A = 0 \qquad (3\text{-}49)$$

$$\text{Ha: } \Delta\bar{A} > 0 \qquad (3\text{-}50)$$

where A represents the paired difference between input and output of any particular data set being examined or

$$\text{Ho: } \mu_B = 0 \qquad (3\text{-}51)$$

$$\text{Ha: } \Delta B > 0 \qquad (3\text{-}52)$$

where B represents the paired difference between the two swales for any particular data set being examined. The paired Student's T test assumes that

1. The scale of measurement for the data has the properties of an equal-interval scale.
2. The paired differences have been randomly drawn from the source population
3. The source population from which the paired differences have been drawn can be reasonably supposed to have a normal distribution.

The test statistic, t, can be calculated by

$$t = \frac{\overline{A} - 0}{S/\sqrt{n}} \tag{3-53}$$

where $\bar{A}$ represents the sample mean of A, S represents the standard deviation of A, and n represents the number of paired samples. The test statistic for B is calculated in an identical manner. The critical value for the t test statistic is a function of the 5% level of significance and also the degrees of freedom, $v = n - 1$. With these two values, a critical value can be found in tables for the t distribution. Finally, if the calculated t value is greater than the critical t value, the null hypothesis can be rejected. In the case of testing the variable ΔA, it is assumed that the grass swale is successfully removing the constituent or parameter being analyzed. For ΔB, a rejection of the null hypothesis means that the pretreatment area is making a significant difference for the constituent or parameter being analyzed.

3.7.5 Wilcoxon Signed-Ranks Test

The Wilcoxon Signed-Ranks test is similar in purpose to the Student's T-test. However, this test is a nonparametric alternative and therefore does not assume a normal distribution (Wilcoxon 1945). It only requires that data be paired and that the distribution of differences is continuous, independent, and is representative of the same population.

To perform this test, the paired differences, ΔA or ΔB, are ranked by absolute value. In the case where there is zero difference, the point is eliminated from this test. After the differences are ranked from smallest to largest, their signs are the applied to their rankings. The mean value of these sign dependent rankings, r, is then calculated and used to calculate the test statistic with the following formula

$$z = \frac{r - 1/2}{\sqrt{\frac{(n+1)(2n+1)}{6n}}} \tag{3-54}$$

The critical value for the standard normal distribution, z, is found in a table for a 5% level of significance. When testing ΔA, if the calculated z value is greater than z_{crit}, then the particular swale is removing the constituent at statistically significant levels. When testing ΔB, if the calculated z is greater than z_{crit}, then the MDE swale is more effective at removing the constituent or hydrologic parameter than the SHA swale.

3.7.6 F Test of Variances

In order to compare the variances of the SHA and MDE swale, the two sample F test is used. The null hypothesis for this test is that the variances of these two data sets are equal, while the alternative hypothesis being tested is that the variance of removals in the SHA swale is larger than the variance of removals in the MDE swale. This test examines the assumption that swales with pretreatment have more consistent removal than a swale without pretreatment. For this one tailed hypothesis, the computed F statistic is the ratio

$$F = \frac{\sigma^2_{SHA swale}}{\sigma^2_{MDE swale}} \tag{3-55}$$

where σ^2 is the variance of removals in each respective swale. The critical F statistic is found using a 5% level of significance and degrees of freedom $v_1 = n_{SHA} - 1$ and $v_2 = n_{MDE} - 1$. If the computed F is smaller than the critical F, the null hypothesis is accepted and there is no significance in variance between the swales removal. If the computed F is larger than the critical F, the null hypothesis is rejected and the removal in the SHA swale has a higher variance.

3.8 SWALE COMPARISON PLOTS

3.8.1 *Time Based Plots*

For individual storm events, constituent concentration, rainfall and flow rates are all plotted against time. These plots allow a more detailed view of each storm event and afford the opportunity to draw qualitative conclusions about the behavior of pollutants and flow in different storm situations. Time based plots also show the difference between the swales and the direct runoff with respect to time. This can show delays in peak flow, delays of peak concentrations, and overall removal of both concentrations and flow. Time based plots are important in understanding each storm event individually and drawing hypothetical trends.

3.8.2 *Probability Plots*

Probability plots allow an easy method for evaluating the fit of data to a particular cumulative distribution and drawing comparisons between these distributions. Probability plots are used in this study to compare the distributions of the assumed inputs for the grass swales (direct channel) to the effluent from each swale. This not only provides a method to compare removal, but also a method to describe any changes in the overall shape of the probability distribution. Runoff concentrations are generally assumed to follow a lognormal distribution, however some constituents do follow a normal distribution (Van Buren 1997). Because both of these distributions are feasible, data is plotted on both lognormally distributed and normally distributed plotting scale, with more attention given to the lognormal distribution.

Probability plots are designed with a horizontal scale that is modified such that the spacing represents the cumulative normal distribution. Therefore, if the data are normally distributed, they will plot as a straight line. A probability plot testing the normal distribution uses an arithmetic ordinate axis, while using a logarithmic scale allows presentation of the data as a logarithmic distribution.

In order to be plotted on the horizontal axis, the cumulative probability for each data point must be determined. The cumulative probability is assigned by ordering the points from smallest to largest and assigning a probability based on a plotting position function. These functions are approximations of the cumulative distribution function and therefore there are many proposed plotting position functions, all of which have positives and weaknesses. Almost all plotting position functions take the form

$$plotting\ \ position = \frac{i-\alpha}{N+1-2\alpha} \tag{3-56}$$

where i represents the ith smallest number in sample of size N, and α represents a constant that describes the plotting position function. The most commonly used plotting position function is the Weibull plotting position with $\alpha = 0$, which simplifies the general equation to

$$plotting\ \ position = \frac{i}{N+1} \tag{3-57}$$

Although this is the most commonly used plotting position function, it was used primarily because of simplicity and its theoretical application to return periods (Harter 1984). However, this study does not use the concept of yearly maximum return periods. Also, when tested against known distributions, the Weibull plotting position function introduces bias at the extremities (Cunnane 1978). When tested against various distributions, a distribution with α = 3/8 is the best compromise for describing normally distributed data on probability plotting paper with the least bias (Cunnane 1978, Looney 1985). For this study, therefore, the plotting position function below is used to plot data on probability plots.

$$plotting\ \ position = \frac{i-.375}{N+0.25} \tag{3-58}$$

If the data plot along a straight line, it is considered to fit the distribution being used, either normal or lognormal. These plots therefore show the distribution shape for the particular data. By drawing a line of best fit, and comparing the swale line to the input line, removals can be compared. In the case of the storms with complete flow capture, points are plotted along the horizontal axis, but are not considered when drawing this line of best fit. Comparisons of the probability plot along any horizontal line show the percentage of storms for input and output that will exceed a given concentration. Likewise, a comparison along a vertical line show the concentration that will be exceeded for a given percentage of storms.

3.8.3 *Box and Whisker Plots*

Box and Whisker plots are a graphical description similar to the nonparametric analysis. These plots give a general description of the distribution of data without using descriptive statistics based on normality, like the mean and standard deviation. Instead, this plot gives a visual assessment of the difference between influent and effluent median concentrations and some benchmarks to describe the distribution non-parametrically.

Box and Whisker plots are created by drawing a box around the middle 50% of the data points, with a line showing the median value. The minimum and maximum values are shown as well as lines connecting to the box. By comparing Box and Whisker plots of the input and output of the swales for a particular pollutant, it is possible to determine a general shape of the distribution for each data set and the amount of removal.

Chapter 4

RESULTS AND DISCUSSION

4.1 General Observations

In total, 22 storm events were sampled with 4 of those storm data sets containing only hydrologic data. Of the remaining 18 storm events monitored for pollutants, 9 storm events showed measurable flows through the grass swales, while the remaining 9 storm events were considered to be completely captured by the swales.

The SHA swale sampler was hit by an errant vehicle during a snow storm in Januray 2005, which caused a delay in sampling during the months of February and March. The impact of the vehicle also caused internal damage to the battery for the SHA swale sampler, which affected its ability to retain a full charge. Because of this, pollutant data are unavailable for two storm events following this accident (1/13/05 and 6/3/05) in which the battery in the SHA swale failed to retain enough power to pump water from the weir. After discovery that the battery was unable to function properly, a new battery was installed and no further sampling problems were encountered.

Another issue complicating a full comparison of pollutant data was technical problems with lab equipment used to analyze pollutant concentrations. The ion chromatograph was offline between the 9/26/05 storm event and the 1/29/06 storm event, causing the nitrate samples to be discarded, as they must be analyzed within a week of sampling. Despite other problems with laboratory equipment, no other samples were lost due to preservation methods.

Finally, other factors, such as mowing, likely produced some variation in pollutant removal efficiency. Although the initial study procedures recommended that the swales be allowed to grow throughout the study duration, the swales were mowed occasionally throughout the study, most notably in August 2005 and April 2006. This and other environmental factors such as temperature and antecedent moisture had an effect on the grass swales, yet this effect was difficult to quantify and thereby account for. Further research at the lab or pilot scale is necessary to define the importance of these factors which complicate analysis.

4.2 Hydrology Comparison

4.2.1 Storm Event Characterization

The rainfall intensity, duration, and frequency expected at this site is assumed to be typical of Maryland storm events. Storm trends in Maryland were analyzed by Kreeb (2003). This study analyzed rainfall volume and duration for 10,352 storm events at 15 stations within the state of Maryland (Kreeb 2003). Table 4-1 presents the findings and shows the average percentage of storms in Maryland that produce a given rainfall volume and duration. Hydrology results from the Rt. 32 site are compared to this study to determine if the storm events sampled are representative of the average type of storms that occur in Maryland.

Table 4-1. Frequency of storm events for 15 stations in MD (Kreeb 2003).

Event Duration	Rainfall Depth (cm)					
	0.0254-0.254	0.255-0.635	0.636-1.27	1.28-2.54	> 2.54	Sum
0-2 hr	0.2857	0.0214	0.0167	0.0043	0.0008	0.3289
2-3 hr	0.0164	0.0257	0.0221	0.0089	0.0025	0.0756
3-4 hr	0.0085	0.0223	0.0198	0.0083	0.0038	0.0627
4-7 hr	0.0099	0.0351	0.0475	0.0221	0.0087	0.1233
7-13 hr	0.0058	0.0337	0.0629	0.0528	0.0266	0.1818
13-24 hr	0.0024	0.007	0.0397	0.0611	0.0515	0.1617
>24 hr	0	0.0009	0.0043	0.0172	0.0435	0.0659
Sum	0.3287	0.1461	0.213	0.1747	0.1374	1

Table 4-1 shows that in Maryland, a significant number of storms (33%) are expected that result in less than 0.254 cm of rainfall. This table also shows that storms lasting shorter than 2 hours represent 91% of these 0.254 cm rainfall depth storms. Therefore, a significant percentage of storms (about a third) in the Maryland area have low rainfall and duration. The remaining two thirds of storms are more evenly distributed among rainfall depths and durations. The remaining storm depths are distributed around a mean value between 0.635 and 1.27 cm, while storm durations are distributed around a mean value between 7 and 13 hours.

The duration and total rainfall depth for storm events captured in this study are shown in Table 4-2 where storms with complete capture are shown in bold. Complete capture is defined as a storm event exhibiting measurable flow in the direct channel and no measurable flow in the swale outfalls. These data were used to compare storm events during this study and to determine if the storms sampled are representative of storm

Table 4-2. Rainfall depth and storm duration for Rt. 32 storm events. Storms with complete capture shown in bold.

Date	Total Rainfall (cm)	Duration (hr)
11/4/2004	3.15	11.8
11/12/2004	2.64	12.0
12/19/2004	**0.20**	**4.2**
1/13/2005	5.44	12.0
4/1/2005	5.69	27.0
5/19/2005	4.67	15.0
6/3/2005	**1.55**	**16.4**
6/27/2005	**0.43**	**2.5**
7/18/2005	**0.28**	**0.2**
8/5/2005	**0.48**	**0.2**
8/8/2005	**0.89**	**4.7**
9/26/2005	**0.25**	**2.5**
10/7/2005	17.32	13.0
10/21/2005	**0.23**	**0.3**
10/22/2005	1.32	19.0
10/24/2005	2.62	27.0
11/16/2005	1.83	6.2
1/11/2006	0.58	1.4
1/29/2006	**0.15**	**1.5**
3/1/2006	**0.25**	**4.2**
4/21/2006	**0.74**	**5.6**
4/22/2006	3.53	15.5

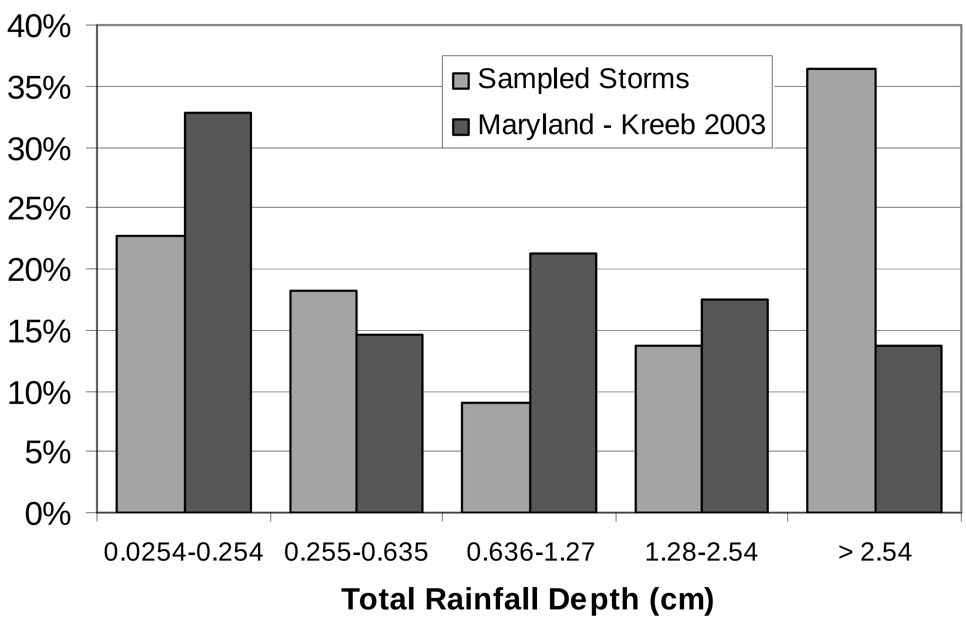

Figure 4-1. Rainfall Depth Distribution for Maryland (Kreeb 2003) and Rt. 32 Storm Events

events in the state of Maryland.

Table 4-2 shows that the sampled total rainfall depths were between 0.15 and 17.32 cm, with a mean of 2.5 cm. Storm durations varied between 0.2 hours and 29 hours with a mean of 9.19 hours. Figure 4-1 shows a comparison between the distribution of total rainfall depth for the Kreeb (2003) study and the storms monitored in this study while Figure 4-2 shows the distributions of storm durations. Figure 4-1 shows a disproportionate number of large rainfall depth storm events in this study, most likely because larger storms are more predictable and therefore easier to schedule monitoring times. This predominance of large storms has the possibility of producing outliers and should therefore be noted. However, the distribution of storm durations of monitored storms closely resembles the distribution of storm durations in the state of Maryland (Kreeb 2003). Both distributions have a large number of storms below 2 hour durations and then another peak close to the 7-13 hour range. Comparing the distributions for rainfall depth and storm duration, it appears that the monitored storms are representative of the population of storm events expected in Maryland and are a good storm data set to analyze.

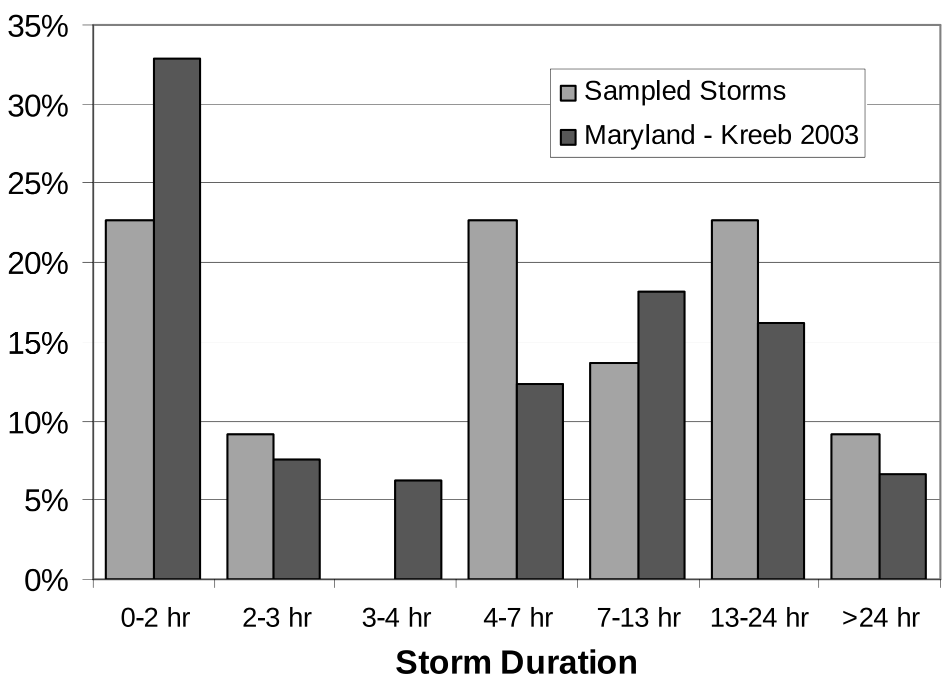

Figure 4-2. Storm Duration Distribution for Maryland (Kreeb 2003) and Rt. 32 Storm Events

Table 4-3. Monitored Rt. 32 total number of storm events defined by the Kreeb (2003) matrix showing event duration vs. rainfall depth where storms with complete capture are shown in parenthesis and bold type.

	Rainfall Depth (cm)					
Event Duration	0.0254-0.254	0.255-0.635	0.636-1.27	1.28-2.54	> 2.54	Sum
0-2 hr	0 **(2)**	1 **(2)**				1 **(4)**
2-3 hr	0 **(1)**	0 **(1)**				0 **(2)**
3-4 hr						
4-7 hr	0 **(2)**		0 **(2)**	1		1 **(4)**
7-13 hr					3	3
13-24 hr				1 **(1)**	3	4 **(1)**
>24 hr					2	2
Sum	0 **(5)**	1 **(3)**	0 **(2)**	2 **(1)**	8	11 **(11)**

Another trend is evident when the storm events are analyzed according to whether the grass swales completely captured the inflow runoff. To view this trend, the monitored storms were categorized in the same table used by Kreeb (2003) according to rainfall depth and storm duration. These data are shown in Table 4-3 with storms with total capture shown in bold.

Table 4-3 shows the distribution of storms in greater detail, while also showing a trend in runoff capture for these swales. It appears that all monitored storms below 0.254 cm of total rainfall were fully captured by both swales. The cell showing 0-2 hour storms with 0.255-0.635 cm rainfall depth demonstrates the possibility that for a small rainfall depth, there can be effluent from the swale if the duration is short, signifying an intense storm.

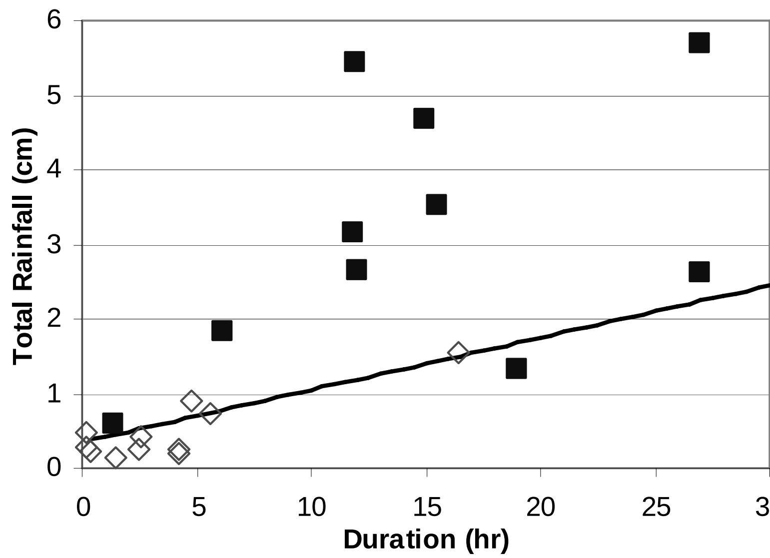

Figure 4-3. Depth-Duration plot showing completely captured storm events as empty diamonds (◊) and storms with flow as filled squares (■)

The above storm data were plotted with the storm duration on the x axis and the total rainfall depth on the y axis. Storms were split into two groups, with storms showing complete swale capture represented by open diamonds and storms with swale flow represented by closed squares. This allowed a comparison of the storm conditions that result in full capture by the swales (Figure 4-3**)**. One outlying point did not fit on this scale. This point, the 10/7/05 storm event, with 17.3 cm rainfall over a 13 hour duration, is close to the 25-year storm according to the Baltimore Intensity-Duration-Frequency curve and thereby obscures the other data.

Figure 4-3 shows a distinction between storms with complete capture and those with flow through the swales. This trend is shown by a line, above which there is flow through the swales and below which complete swale capture results. The slope of this line indicates that for any given rainfall amount, a shorter duration may cause swale discharge, while a longer storm duration will fully capture flow. This line is not a regression line, but was manually drawn to show the upper envelope of the total capture storm conditions. One storm event shows flow when the envelope line suggests that it should not. The peak of this storm occurred less than 24 hours after a storm event was completely captured by the grass swales. This suggests that the swales were saturated and therefore had diminished capability for completely assimilating the runoff. Because these figures plot total rainfall against storm duration, the slope of this line can be viewed as the maximum average rainfall intensity that can be fully captured by the swales. Likewise, the y intercept represents the rainfall depth that can be captured by the swales, regardless of storm duration. The line describing the swales transition from fully capturing flow to exhibiting measurable flow is:

$$R = \left(0.07 cm / h\right) D + 0.35 cm \tag{4-1}$$

where R represents total rainfall depth in cm and D represents storm duration in hours.

By transposing this model onto the Kreeb (2003) distribution of storm events in Maryland, Table 4-4 is created, where grey cells represent full capture and light grey cells represent capture of only a portion of storms in that cell.

Using this table and an estimate of a 50% capture rate for cells containing both captured and storm events with outflow, an estimate of the total percentage of storm events captured by grass swales of this size and design can be calculated. It is therefore estimated that on average these grass swales would fully capture 67% of all storm events within the state of Maryland. These captured storms would result in no hydrologic output and thereby no pollutant export, although there is a possibility of later export or resuspension by subsequent storms.

Table 4-4. Depth-Duration table showing complete capture and distribution of storms in Maryland with theoretically completely captured storms in dark grey, mixed capture storms in light grey, and storms exhibiting flow in white (Kreeb 2003).

	Rainfall Depth (cm)					
Event Duration	0.0254-0.254	0.255-0.635	0.636-1.27	1.28-2.54	> 2.54	Sum
0-2 hr	0.2857	0.0214	0.0167	0.0043	0.0008	0.3289
2-3 hr	0.0164	0.0257	0.0221	0.0089	0.0025	0.0756
3-4 hr	0.0085	0.0223	0.0198	0.0083	0.0038	0.0627
4-7 hr	0.0099	0.0351	0.0475	0.0221	0.0087	0.1233
7-13 hr	0.0058	0.0337	0.0629	0.0528	0.0266	0.1818
13-24 hr	0.0024	0.007	0.0397	0.0611	0.0515	0.1617
>24 hr	0	0.0009	0.0043	0.0172	0.0435	0.0659
Sum	0.3287	0.1461	0.213	0.1747	0.1374	1

4.2.2 Flows With Respect to Time

Examining flows with respect to time for the direct channel and the two swales shows the detailed, instantaneous reaction of these channels to variations in rainfall intensity. All flows are calculated and normalized by drainage areas using equation 3-18, resulting in units of l/s/ha, to allow a direct flow comparison. These time-based plots show more detail, and while they do not lend themselves to statistical comparison, they are very important to defining hydraulic trends for the 3 treatments.

The first type of flow behavior is exhibited during storms with complete capture by the grass swales. In the instance where rainfall intensity and duration are not large enough to produce flow through the swales, there is still flow through the direct channel.

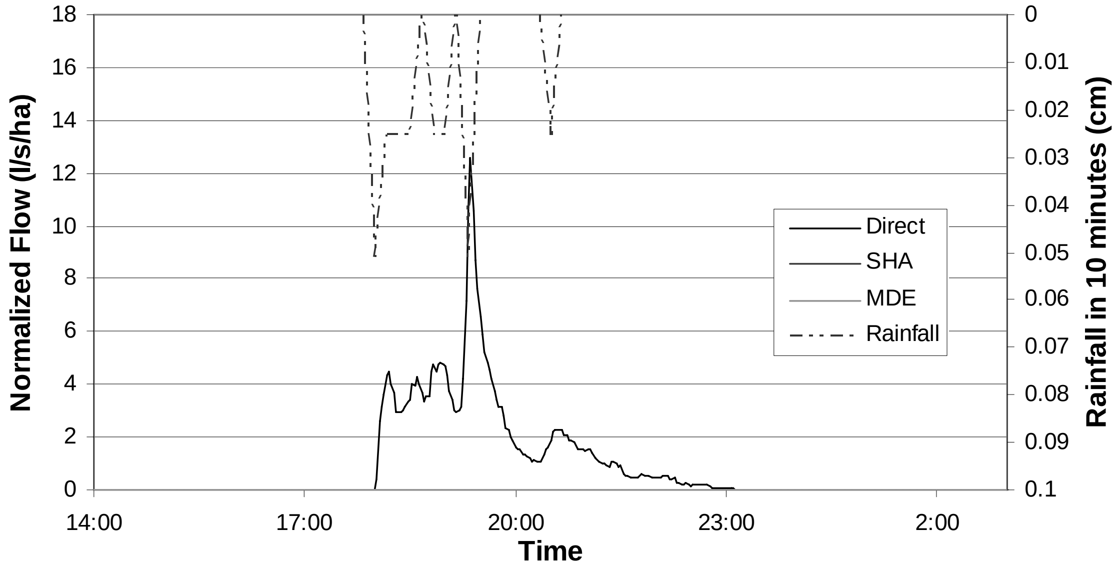

Figure 4-4. Normalized flow for 9/26/05 storm event, showing no runoff from swales as constant zero flow in SHA and MDE swales (1,000 l Direct)

As shown in Figure 4-4, during these smaller storms, the flow from the direct channel mirrors the rainfall hyetograph.

There is very little delay between the initial rainfall and the onset of flow for the direct channel. Similarly, peaks in flow for the direct channel correspond to peaks in rainfall. All similar storms exhibit similar behavior as shown in Appendix B.

Without any type of treatment, it is apparent that there is little flow mitigation and even small rainfall intensities will produce runoff. This runoff is nearly immediate and has large peaks in flow corresponding to changes in rainfall intensity. Both grass swales are equally effective in completely capturing low-intensity storm events.

For higher intensity events, flow is not completely captured by the grass swales. In this type of storm event, the hydrographs show two distinct mitigation trends. First, the hydrographs show a decrease in peak flow through the grass swales and second, the

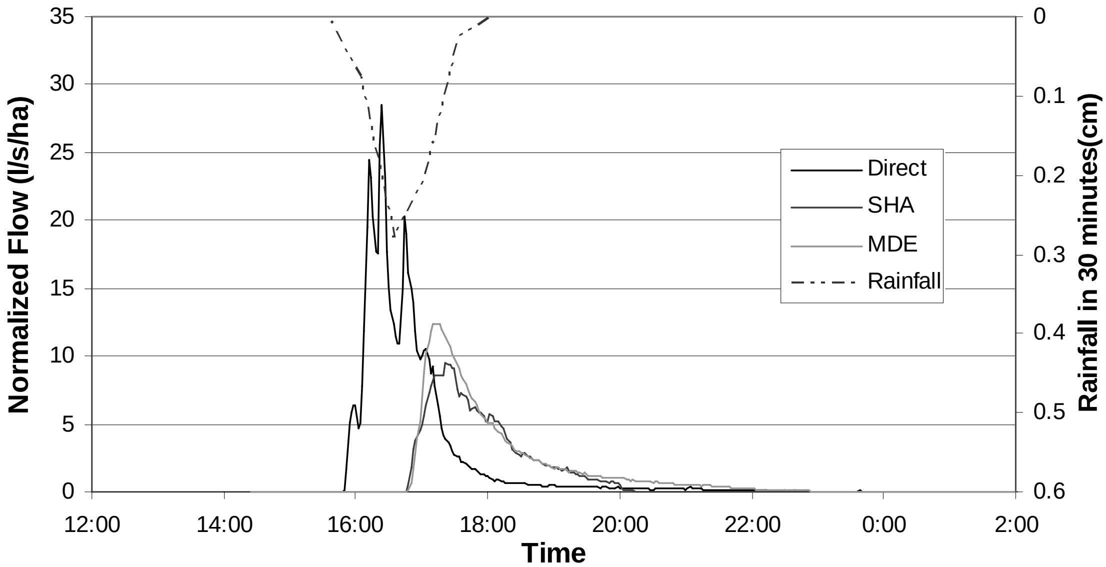

Figure 4-5. Normalized Flow for 1/11/06 Storm Event
(19,500 l Direct, 8,090 l SHA, 12,900 l MDE)

hydrographs show a time delay for both initial flow and peak flow when the grass swales are compared to the direct channel.

Figure 4-5 shows the treatment response to one slug of rainfall. This storm is important to analyze because the storm event rainfall distribution is close to a standard design storm, with a rising limb, peak intensity in the middle of the storm event, and then a decline in intensity. This rainfall hyetograph allows an analysis of swale response without influence of secondary peaks, reduced infiltration capacities and other processes that tend to complicate performance analysis. All three hydrologic trends, peak flow reduction, time delay and flow smoothing, are apparent during this storm event.

While it is not evident at the 30 minute rainfall interval, there were peaks in rainfall intensity as shown by the peaks in the direct roadway runoff. None of these peaks are evident in the swale flows. Finally, while there appears to be very minimal delay between the peak rainfall intensity and the direct runoff peak flow, there is an hour delay for both grass swales. This delay is likely caused by infiltration of the initial flows and longer travel times caused by flow through the grass matrix.

Other storm events with more variable rainfall distributions show similar patterns, yet are more complicated. Figure 4-6 shows an example of a storm event with two rainfall peaks, one very intense while the other is much more evenly distributed. Both swales show significant peak flow reduction when compared to the direct runoff. However, in this case, it appears that the MDE swale is less capable of reducing peak flows. For storms with high rainfall intensities, this is a common phenomenon, perhaps caused by the longer maximum flow path in the SHA swale (198 m as compared to 152.2 m). This extra length may provide more opportunity for spreading of the peak flow due to a greater difference in flow times. Despite this difference, both swales are still successful in reducing the peak flow rate and also capturing the initial portion of the

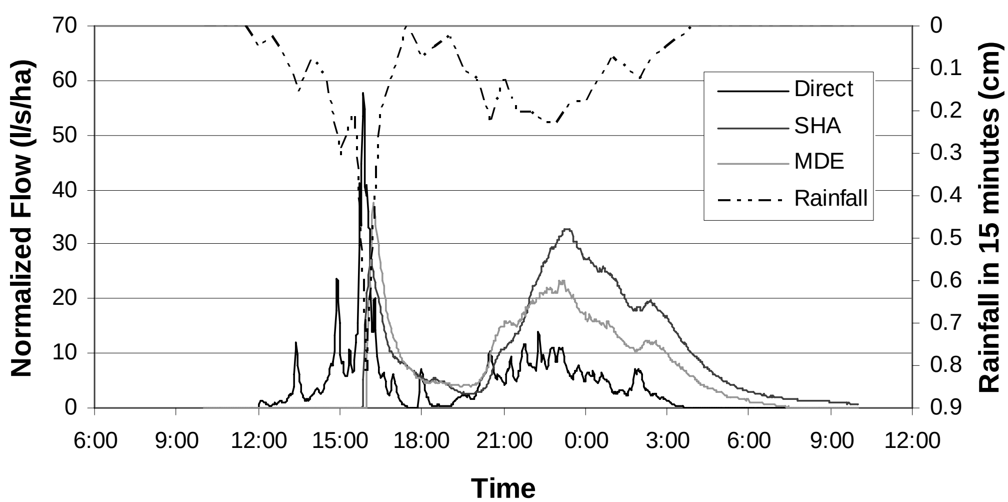

Figure 4-6. Normalized Flow for 5/19/05 Storm Event
(81,500 l Direct, 238,000 SHA, 251,000 MDE)

storm volume. While there is only a 25 minute delay between the peak flows of the influent and the swale output, both swales completely capture all direct runoff for 4 hours prior to the extreme peak in rainfall. This initial abstraction is characteristic of swale performance.

The second peak shows another common characteristic in the grass swales. After the pore spaces in the soil are filled with infiltrated storm water from preceding rainfall, the swales offer only minimal flow mitigation. The flows through the grass swales show significant smoothing when compared to the direct runoff, but do not necessarily show flow reductions. In this case, a flow increase is actually found, likely caused by increased exfiltration from groundwater storage caused by the previous rainfall peak. The 11/16/05 storm event, shown in Appendix B, has a similar storm distribution with almost identical results.

For all monitored storms, the grass swale hydrographs showed the same trends as outlined above, with complete flow capture for lower intensity storms and peak flow reduction, delay to peak, initial abstraction, and flow smoothing. In general very little difference in hydrologic performance was noted between the two swales, except in the case of some storm events where the MDE swale was less effective at reducing the peak flows.

4.2.3 Peak Flow

In order to determine the significance of peak flow reductions, the peak flows for each storm were recorded and compared both graphically and statistically. It is hypothesized that grass swales mitigate highway runoff by decreasing the peak flow and distributing this flow throughout the storm duration in a more natural manner. Peak flow is an important monitored parameter because high peak flows can result in washout of receiving channels, causing export of sediment and other associated constituents.

The peak flows for 23 storm events were compared, including five storms that did not have associated water quality data. Peak flows were normalized using the modified drainage area method described in Section 3.4.1. The peak flow data for all storms are compiled in Appendix B and are summarized in Table 4-5. It appears that the mean peak flow for both the SHA swale and the MDE swale are lower than the direct channel. However, this mean considers all storm events in one distribution, causing a high standard deviation through differences between individual storm events.

Both grass swales were successful in reducing the distributions of peak flow, as shown graphically in the probability plot (Figure 4-7). Storms with complete capture are represented by empty points along the x-axis because zero flows cannot be plotted on a

Table 4-5. Normalized peak flow summary statistics for all three channels and summary of peak flow reduction with complete capture storm events removed

	Direct Channel	**SHA Swale**	**MDE Swale**
Mean (l/s/ha)	57.5	24.3	22.5
Median (l/s/ha)	37.0	7.95	6.86
Standard Deviation (l/s/ha)	61.8	56.9	42.5
# Samples	23	23	23

	SHA Reduction		**MDE Reduction**		**MDE Reduction – SHA Reduction**	
	l/s/ha	%	l/s/ha	%	l/s/ha	%
Mean	34.7	53.0	37.9	50.2	3.19	-2.73
Median	26.3	58.8	27.5	50.0	0.12	1.0
Standard Deviation	30.2	25.5	31.7	26.4	24.7	14.7
# Samples	13	13	13	13	13	13

logarithmic scale. Regression lines in this probability plot show the estimated population distribution of peak flows for each of the three channels. The good fit for these regression lines indicates that the population distribution of peak flows for each of the three channels are lognormally distributed, with most of the peak flows in the lower ranges and few much larger storms causing high peak flows. Both grass swales show complete attenuation of flows for almost 50% of the monitored storm events, which is close to the 67% estimate made in Section 4.2.1. The difference between the theoretical capture probability and the capture percentage in this study is most likely caused by a bias towards larger storm events, which are more easily sampled. Both swales also exhibit successful reduction of peak flow, as shown by the difference between the direct regression line and the swale regression lines. This is shown, for example, by examining the 100 l/s/ha exceedance. The peak flows from roadway runoff will exceed 100 l/s/ha

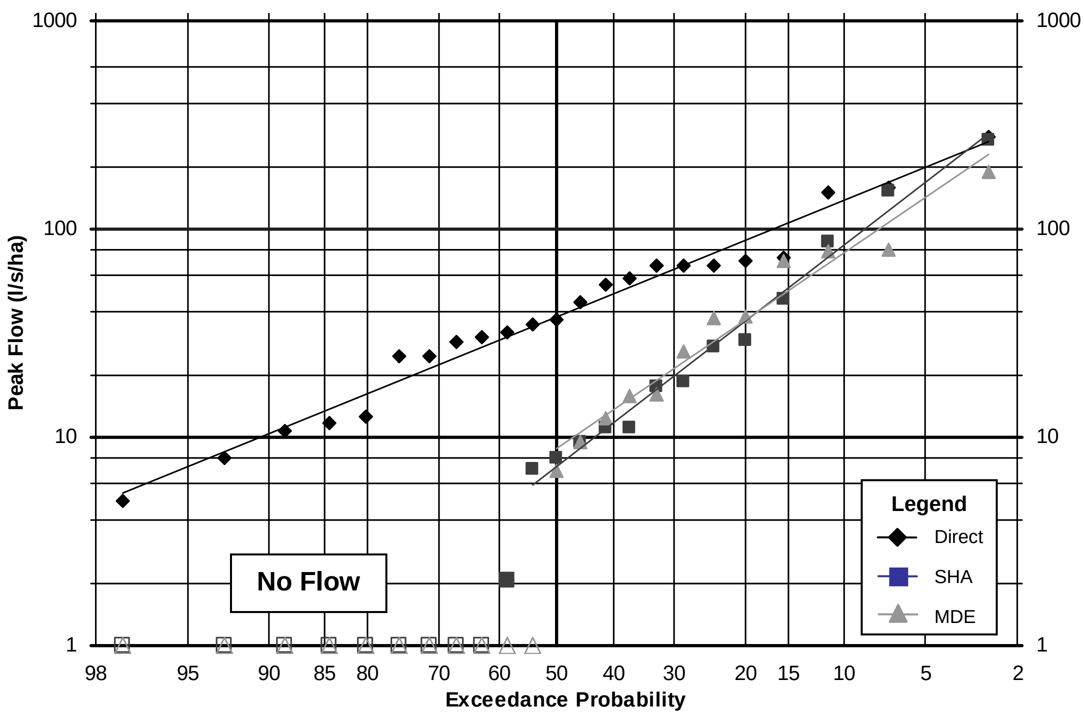

Figure 4-7. Peak flow probability plot showing all storm events for influent (Direct) and swale effluent (SHA and MDE).

for 17% of all storm events, while both grass swales will only exceed this peak flow during 8% of storm events. Little difference exists between the SHA and MDE swale performance, which suggests that the added pretreatment area does little to decrease the peak flow leaving the swale.

While the probability plot (Figure 4-7) shows that the grass swales reduce the peak flows on a population level, it is important to examine the paired peak flow reductions to ensure that the peak flows are reduced on an individual storm basis. Reduction of peak flows for both swales were strongly positive, showing successful peak flow mitigation by the grass swales (Table 4-5). A slightly negative difference between the MDE and SHA swale removals means that the SHA swale had lower peaks than the MDE swale for the analyzed storms. The significance of this difference was verified through the statistical regiment outlined in Section 3.6. Results of these statistical tests are given in Table 4-6. A check represents a statistically significant result for each particular test, while an X represents no statistical evidence to the contrary.

Table 4-6. Peak Flow Reduction Statistical Test Results

Step	**Examined Hypothesis**	**SHA Removal**		**MDE Removal**		**MDE – SHA Difference**	
		l/s/ha	%	l/s/ha	%	l/s/ha	%
1	Outliers?	✗	✗	✗	✗	✓	✗
2	Normally Distributed?	✓	✓	✓	✓	✓	✓
3	Significant Removal? (normal distribution)	✓	✓	✓	✓	✗	✗
4	Significant Removal? (nonparametric)	✓	✓	✓	✓	✗	✗
5	Unequal Variance?	-	-	-	-	✗	✗

One peak reduction point (5/11/06) was identified as a potential outlier, however, was not sequestered from the data set because there were no physical occurrences during this storm to suggest that it was from a different population altogether. All peak flow reductions were sufficiently close to the normal distribution to warrant the use of tests based on normality, however the nonparametric tests are also important because of the presence of storm events that might be considered outliers.

The Student's T test and the nonparametric Wilcoxon test agree that both swales showed significant peak flow reduction as analyzed by the absolute values and by percent. It appears, therefore, that grass swales are successful at decreasing the peak flows from highway runoff. In calculating an expected reduction, the median value was used because box and whisker plots suggested some storms with very high reductions that greatly influenced the mean. Therefore, for storm events with detectable flow through the grass swales, a reduction of 26-28 l/s/ha or 50-59% can be expected. It is important to note that those peak reduction calculations only refer to flow during storm events with detectable flow, and that roughly 67% of storm events in the state of Maryland would be completely captured, thereby resulting in 100% peak reduction.

When comparing the effect of the pretreatment area adjacent to the grass swales, however, there is not sufficient evidence to show that the pretreatment area is more effective at decreasing the peak flow. Therefore, both swales effectively decrease the peak flow during a given storm event, but the difference between this reduction is minimal. The process responsible for reducing the peak flow is therefore not the added pretreatment area and must be related to the grass swale flow mechanism.

4.2.4 *Time to Peak Flow*

The time-based flow plots tend to support the hypothesis that there is a delay in peak flow between the direct runoff and the grass swale flows. The delays, in minutes, between the peak flow of direct runoff and grass swale are summarized in Table 4-7 and the distributions of the delays are shown as a box and whisker plot in Figure 4-8.

These data showed that both swales increased the amount of time before the runoff peak reaches the weir. The difference between the MDE swale and the SHA swale showed that the SHA swale delays the peak flow slightly more than the MDE swale, however the significance of this difference is tested below.

Results from the statistical tests used to determine the significance of these delays are shown in Table 4-8. No statistically significant outliers were found in this data set. For both swales, the distribution of delays follow a normal distribution and these delays were statistically significant when compared to the null hypothesis that there is no delay. The swales, therefore, are effective in delaying the peak flow. This delay was likely caused by differences in flow path length and also retardation caused by the grass surface.

Table 4-7. Distribution summary statistics of delay to peak flow (min) for the SHA and MDE swales

	SHA Swale Delay	**MDE Swale Delay**	**MDE – SHA Delay**
Mean (min)	34.2	33.1	-1.1
Median (min)	28	28	-8
Standard Deviation (min)	28.4	25.3	22.6

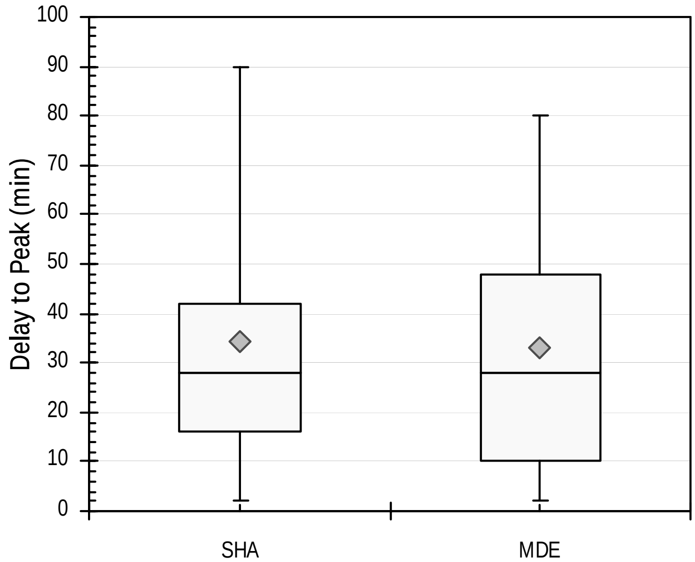

Figure 4-8. Box and whisker plot showing the distribution of delays (min) between influent peak flow and swale peak flow for SHA and MDE swales

These results are reasonable when compared with the travel times from the furthest point predicted by a simplified version of Manning's Equation (McCuen 1998)

$$V = kS^{0.5} \tag{4-2}$$

where V represents velocity in m/s, k is a function of land cover that encompasses Manning's roughness coefficient and the hydraulic radius, and S is the unitless slope. This is a very simplified version of Manning's Equation, which assumes a standard roughness and hydraulic radius, and was used to verify that these results were reasonable. Using the swale slopes, channel lengths (in m), and k values of 0.46 for dense grass and 14.1 for the concrete channel, the travel times from the furthest point were calculated for each channel. The resulting travel times are 2.0 minutes for the direct channel, 57.1 minutes for the SHA swale, and 49.1 minutes for the MDE swale. This results in a calculated maximum delay of 55.1 minutes for the SHA swale and 47.1 minutes for the MDE swale. This is the travel time from the furthest point of each swale and therefore due to the integration of flows along the length of roadway, the actual delay to peak should be less than this delay, as is shown by the results of this study.

Table 4-8. Delay to peak flow statistical test results

Step	Examined Hypothesis	SHA Delay	MDE Delay	MDE – SHA Difference
1	Outliers?	✗	✗	✗
2	Normally Distributed?	✓	✓	✓
3	Significant Removal? (normal distribution)	✓	✓	✗
4	Significant Removal? (nonparametric)	✓	✓	✗
5	Unequal Variance?	-	-	✗

No statistically significant difference is noted between the delay to peak flow for each swale, although the SHA swale has a slightly larger mean delay. Likewise, there is no statistically significant difference between the amount of variance in readings for the two swale delays. These results confirm the calculations shown above that showed only a slightly longer delay for the SHA swale when compared to the MDE swale. Grass swales are therefore an effective way to increase the amount of time to the peak flow, while the pretreatment adjacent to the grass swale is much less important in modifying the total hydraulic travel time. For grass swales built with a similar design, the median delay to the peak flow is between 28 and 34 minutes.

4.2.5 Total Volume/Infiltration

Another hypothesized hydrologic benefit of grass swales for highway runoff is the ability to infiltrate a certain percentage of the flow. Using the normalized total volume outlined in Section 3.5.3, the total volume of runoff leaving the swales was calculated by subtracting the total volume of rainfall falling directly onto the swales (Equation 3-33). This allows a more accurate, direct evaluation of the swale performance by comparing the volume of runoff leaving the roadway and that same input after it leaves the grass swales.

Data summarizing the total normalized flow volume for each channel are shown in Table 4-9. These mean, median and standard deviation values compare the total distribution of 23 storm events sampled, including those storms with zero outflow from the swales. Table 4-9 shows that total storm volumes are largely variable and that the data are scattered, as shown by the large standard deviations and the great difference between the mean and median values. The mean values suggest that the swales do not decrease the total flow volume, while the median values suggest that the swales are

Table 4-9. Normalized total volume summary statistics for all three channels and summary of total volume reduction with all zero volume storm events included

	Direct Channel	**SHA Swale**	**MDE Swale**
Mean (l)	70,900	123,000	89,400
Median (l)	34,600	8,090	11,500
Standard Deviation (l)	124,000	299,000	186,000
# Samples	23	23	23

	SHA Reduction		**MDE Reduction**		**MDE Reduction – SHA Reduction**	
	l	%	l	%	l	%
Mean	-5,700	45.7	3,410	53.7	18,200	8.1
Median	10,700	89.3	11,000	100	4,280	6.8
Standard Deviation	45,300	83.6	33,500	76.1	36,500	34.6
# Samples	20	20	20	20	10	10

successful in reducing total volume. This stresses the importance of examining the data set more closely.

The volume probability plot (Figure 4-9) shows the total runoff volumes for all monitored storm events. This plot shows once again that 40-50% of storm events for both swales were captured, and therefore have complete runoff volume removal. A threshold point exists in Figure 4-9, where the swales are no longer capable of removing a significant volume of the runoff. This threshold point, at 80,000 l, represents a distinct change in slope for the swale data and also the point at which the swale total volumes begin to exceed the direct runoff. Above this threshold point, the grass swale data follows the direct runoff volume closely. This plot suggests that the grass swales are

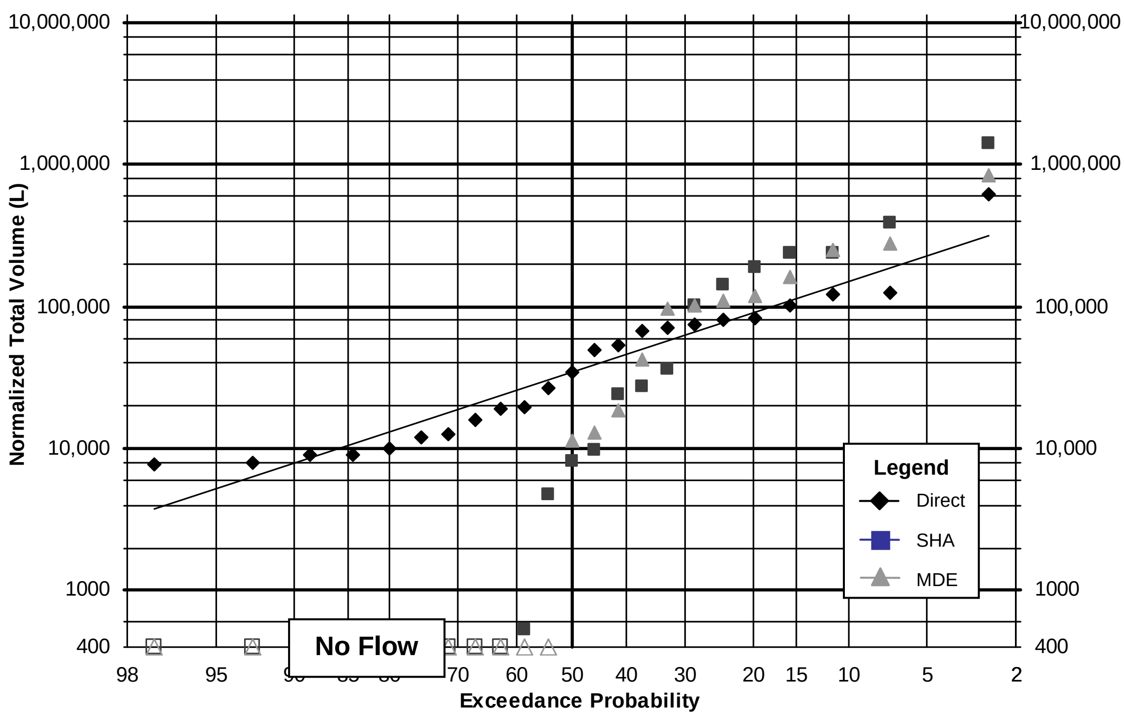

Figure 4-9. Normalized total volume probability plot.

effective at completely capturing 50% of storm events, reducing the total runoff volume for 20% storm events, but have little effect on total volume on the largest 30% of storm events.

To confirm this conclusion and to obtain a more accurate comparison, runoff volume removals were calculated on a single storm basis. When these removals were evaluated, the Dixon-Thompson test identified three storms that exhibited removal outliers, 11/4/04, 10/7/05 and 4/1/05. These outliers make conceptual sense because they are from different conditions, and therefore a different population than the rest of the monitored storms. The first outlier storm event, 11/4/04, was the first monitored storm. The outliers during this storm appeared in the difference between the swales. Likely this large difference was caused by the freshly seeded pretreatment area in the MDE swale, which had not fully grown to maturity. During this storm, the MDE swale was ineffective at removing total runoff, while the SHA was very successful at removing total runoff volume because it did not rely on seeded areas, as the swales were sodded. The second storm event, 10/7/05, was identified in Section 4.1.1 as the 25-year storm event using Baltimore area IDF curves. This storm event was therefore removed from total volume consideration, as was the 4/1/05 storm event. The 4/1/05 storm event was characterized by multiple small waves of rainfall, which possibly caused a problem with the underlying infiltration assumptions for the calculation of normalized storm volume. All three storms were removed, as they represented very different physical conditions than the other storm events. Table 4-9 shows a summary of the normalized total volume reductions with these three anomalous storm events removed, resulting in 20 total storm events. For the comparison between the SHA and MDE swale removals, only those storm events in which there was measurable flow in all three channels were used, resulting in 10 sample points.

Again, the total runoff volume removal data show a large variance and great difference between the mean and median removals. This is likely caused by the three competing processes shown in Fig. 4-9; complete removal, flow reduction, and no noticeable effect beyond a threshold of 80,000 l. Statistical tests comparing the total flow volume reductions of the two swales were performed to determine the significance of the volume removal, with a focus on the non-parametric tests because of the large variance in the data and the non-normality determined by the Kolmogorov-Smirnov 1-Sample Test. Results of statistical analysis are summarized in Table 4-10.

Table 4-10. Normalized volume reduction statistical test results

Step	**Examined Hypothesis**	**SHA Removal**		**MDE Removal**		**MDE – SHA Difference**	
		l/s/ha	%	l/s/ha	%	l/s/ha	%
1	Outliers?	✓ (10/7/05)	✓ (4/1/05)	✗	✓ (4/1/05)	✓ (11/4/04)	✓ (11/4/04)
2	Normally Distributed?	✗	✓	✗	✓	✓	✓
3	Significant Removal? (normal distribution)	✗	✓	✗	✓	✗	✗
4	Significant Removal? (nonparametric)	✗	✓	✓	✓	✗	✗
5	Unequal Variance?	-	-	-	-	✗	✗

The presence of outliers was discussed above. Because of this first step, the 11/4/04, 10/7/05 and 4/1/05 storm events were removed from all subsequent calculations. Although only two monitored categories tested significantly different from a normal distribution, all categories were very close to the critical values used to determine if a data set is significantly different from a normal distribution. All categories would be considered different from a normal distribution at the 10% rejection level. The combination of these tests and the large difference between the mean and median removals suggest that the nonparametric tests should be applied to this data set, rather than the paired Student's T-test.

Using the nonparametric Wilcoxon Signed-Ranks Test, there is a significant reduction of the runoff volume percent by both swales. Both swales successfully removed an average of 46-54% of the total volume entering from the roadway surface. The grass swales are effective when percent removals are considered, however, there is more variability, and thereby less significance when the absolute volume removals are compared. This is likely caused by the swales' inability to sufficiently control the largest 30% of storm events, as shown by Figure 4-9. This inability is highlighted by plotting the removal against the total rainfall in Figure 4-10 with the three anomalous storms removed for clarity.

Figure 4-10 shows that as total rainfall increases, the amount of volume reduction decreases until it reaches a negative value. This confirms that during large storms, little volume reduction occurs when compared to the total storm volume. During large storms, flow entered the system, either directly by overland flow from other areas or from water infiltrating from a subsurface source. This effect made less difference on the percentage data, however, as shown in Figure 4-11 the largely negative removals, in terms of absolute flow volume, caused the mean to be significantly lower than the median 50% of removals. The total volume removal data is thereby not sufficiently represented by the normal distribution. Because of this condition, the median value appears to be a more

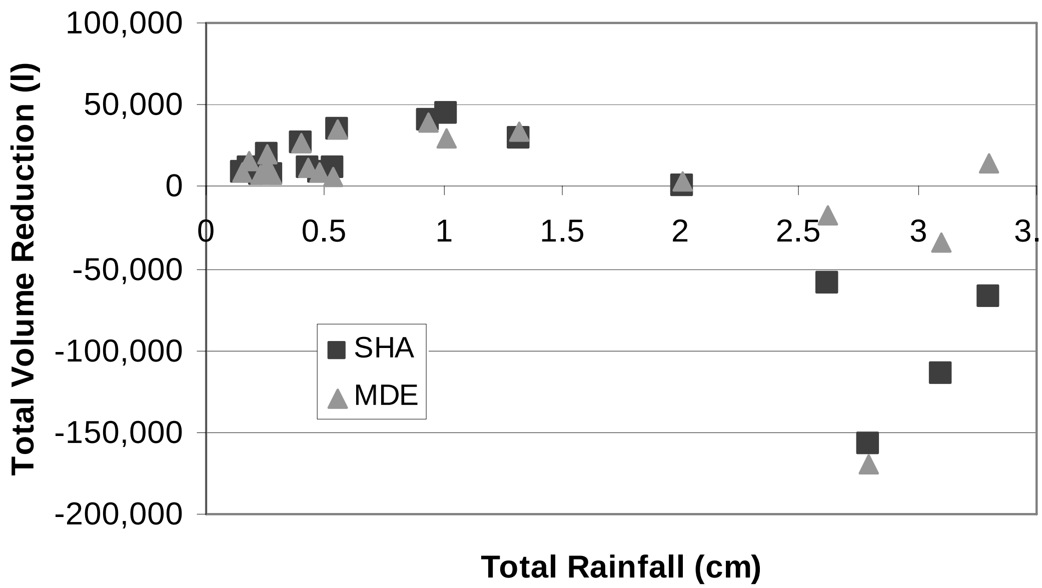

Figure 4-10. Normalized volume reduction in both swales compared to total rainfall depth in storm event, showing decrease in removal during large storms.

accurate representation of central tendency and the non-parametric tests are more important for determining significance. Also, these plots show that there is little difference between the middle quartiles for each swale, represented by the rectangle. The reduction percentage box and whisker plot shows that many storms had a 100% removal rate, as the median value is 100% for both swales.

Finally, when comparing the total runoff volume reductions for the two swales, the MDE swale appears to be slightly more effective at reducing total flow volumes than the SHA swale. This difference is, however, not statistically significant according to the non-parametric Wilcoxon test. The SHA and MDE swales showed very little difference in absolute volume removal, while the difference between the two in percent volume removal would be significant at the 10% significance level. The difference between the swales is most evident during the large storm events, as shown in Figure 4-10. However, as shown by the distribution of removals in Figure 4-11, there is very little difference

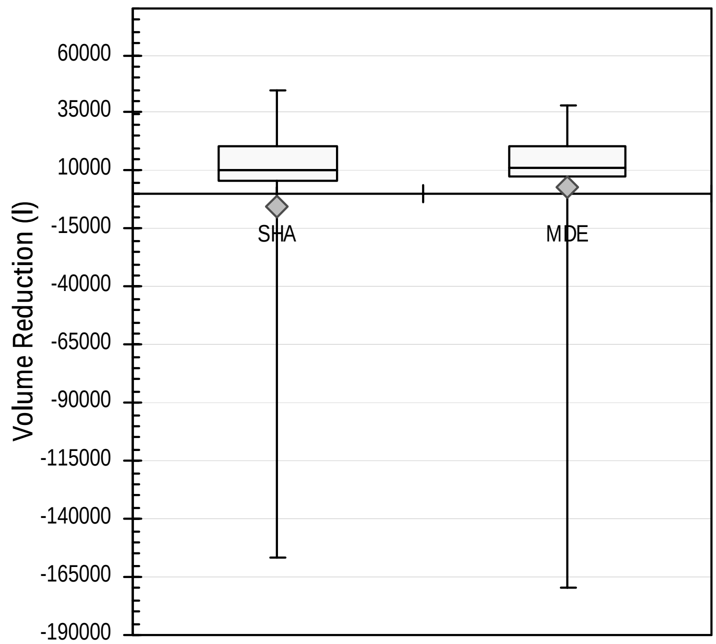

Figure 4-11. Box and whisker plot of normalized volume reduction for both swales showing positive reduction in median values and low means due to large negative reductions.

between the median volume removals. As stated above, these largely negative removal values during large storms suggest that flow from outside the swales is entering the system, either by overland flow or by groundwater flow. Because of the design location of the SHA swale at the bottom of a sloping hill, with a silt fence protecting against excess runoff, this swale is much more susceptible to excess runoff that may be able to enter the swale during only the largest storm events. Because the SHA swale and the MDE swale showed little hydraulic differences in all other aspects, and because the statistical significance is greatly influenced by a few highly negative storm events, it is much more likely that there is no true difference in hydrologic response between the swales and that this difference is only caused by extraneous flow entering the system during large storm events.

Therefore, it can be concluded that both swales are successful at reducing the total runoff volume by 46-54%, and that there is little difference between the swales removal efficiency. Both swales begin to lose effectiveness during storm events above a threshold limit of 80,000 l, which corresponds to a rainfall depth of 3.28 cm. According to Kreeb (2003), a rainfall depth greater than 2.54 cm occurs in only 14% of storm events on average in the state of Maryland. The MDE swale exhibited a slightly higher ability for reducing total volume during large events, however it is very likely that this difference is caused by excess runoff entering the test area and not by any difference in the MDE swale design and removal efficiency.

4.3 General Pollutant Observations

Two major computational methods, N-EMC (equation 3-42) and total mass (equation 3-37), are used to quantify and compare the effect of the grass swales on highway runoff entering the swales. These methods differ in both how they are treated computationally and the conclusions that can be drawn from each. The normalized event mean concentration (N-EMC) refers to the flow weighted mean concentration being discharged from the grass swales, after a drainage area normalization occurs. Because the N-EMC represents a theoretical average concentration, the difference between the influent and effluent N-EMC represents the ability of the swale to reduce the resulting concentration during a particular storm. Therefore, in the case of complete capture of runoff, when all runoff infiltrates into the grass swale soil, the N-EMC treatment term is not useful. Describing the resulting N-EMC as zero does not describe the same treatment method as in storm events with flow through the swale. Also, according to the mathematical definition of N-EMC (equation 3-42) the total mass delivery is divided by total volume. However, in a completely captured storm, the result is undefined. Therefore, when comparing N-EMC data in this study, only storm events with flow through all three channels were considered. In this way, the N-EMC reduction describes the sum treatment effect of the grass swales on concentrations as flow passes through the swale.

Alternatively, the total mass reduction is related to the total, sum effect of the swales on pollutant load. Because the total pollutant load over the sampling duration is the important parameter being considered, total mass is an additive quantity. Therefore, total mass removals during all storms can be compared, including those storm events which are completely captured by the swales. This is supported by the calculation of total mass, which involves integrating mass and concentration together (equation 3-36). Zero flow therefore results in zero mass. Because of this, all storm events, including those with zero flow, were included in calculations of total mass reduction in this study. Total mass reduction, unlike N-EMC reduction, considers the effect of the grass swales in a long-term pollutant loading manner.

4.4 Total Suspended Solids (TSS)

Total suspended solids is the most important regulatory indicator of water quality because suspended solids are the most significant aquatic pollutant by mass in waterways. Also, other pollutants, such as metals, tend to bind to solids and thereby are related to the concentration of TSS. Because of this importance, special attention in sampling was placed on quantifying suspended solids removal. All 12 samples were analyzed for every storm to give a more accurate representation of TSS concentrations with respect to time, which thereby provided an assumed trend for the other measured pollutants. Eighteen storm events were evaluated for TSS with 9 events exhibiting complete capture of runoff. For N-EMC statistical tests, only those storms with measurable flow through the swales were considered. However, for calculations of total mass, all storm events were considered, as a complete mass balance would include storms with complete capture as zero mass delivered.

4.4.1 First Flush Removal Comparison

An analysis of TSS concentrations with respect to time affords a more detailed view of how the swales reduce total TSS mass and normalized event mean concentrations. The 5/11/06 storm event (Figure 4-12) shows a typical trend for TSS concentrations. In the direct runoff, TSS concentrations react immediately to changes in rainfall and TSS concentrations are disproportionately high following the onset of rainfall. The direct channel exhibits a concentration-based first flush according to the Sansalone and Cristina (2004) definition of any storm event where concentrations fall to 20% of the maximum concentration during the rising limb of the hydrograph or early part of a storm. While this first peak in concentration is larger than the following TSS peak concentration, it is caused by a much less intense rainfall. This supports the conclusion that the direct runoff TSS concentrations show a concentration-based first flush immediately after the rainfall onset. These high TSS concentrations correspond to the suspended solids that have accumulated on the roadway surface. Following this initial first flush, peaks in concentration follow the rainfall hyetograph, but generally with lower concentrations

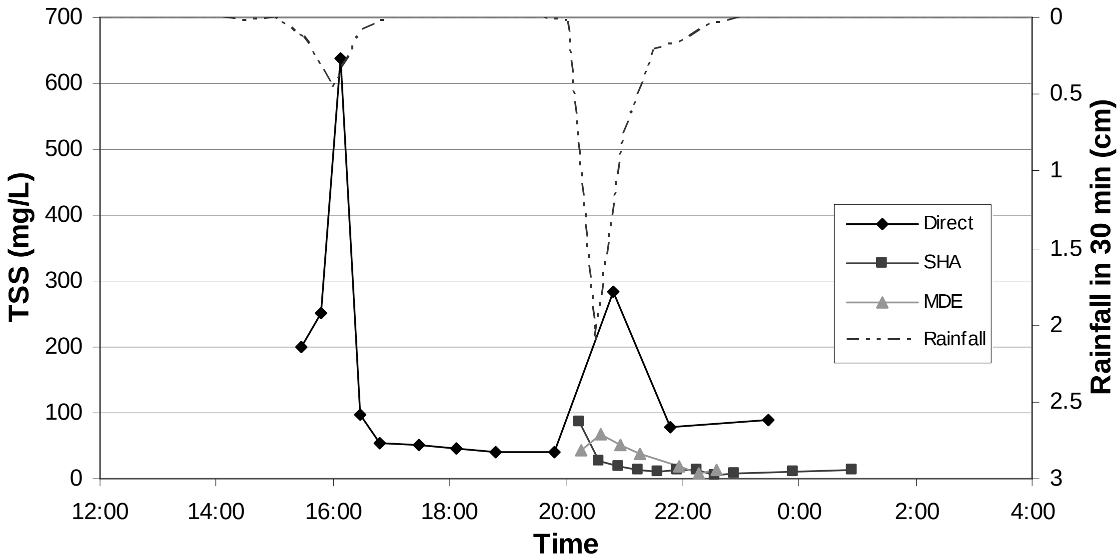

Figure 4-12. TSS concentrations with respect to time (5/11/06 storm event).

than the initial first flush. These results are typical of all TSS data collected for the direct highway runoff.

The swales successfully decrease TSS total mass and N-EMC by the processes shown in Figure 4-12. Both swales successfully intercept the high concentration first flush by completely capturing the runoff volume. Successful removal occurs because the first flush corresponds to conditions when the grass swales are most capable of reducing runoff volume (i.e., low soil moisture content). Removal of the initial storm runoff is very important to decreasing total concentration. Also, as seen in Figure 4-12, the swale TSS concentrations after the first flush remain lower than the direct runoff for the remainder of the storm event. This is attributable to sedimentation and filtration along the length of the swale.

The second, more quantifiable method for determining the presence of a first flush of pollutant is the use of First Flush diagrams, which plot the dimensionless ratio of mass to total mass against the ratio of volume to total volume, as described in Equations 43 and 44. The percent mass delivery during the first 25% of storm volume delivery was thereby calculated for each storm event. Wanielista and Yousef (1993) defined a mass-based first flush by a 50% mass delivery during this period. The distribution of percent mass delivery during the first 25% of storm volume and the difference in first flush between the swales and direct channel are summarized in Table 4-11.

Although there is a mean decrease in mass delivery during this first flush period for the swales (9.4% SHA and 4.5% MDE), this difference is not statistically significant. This lack of significance is caused by a large variance in reductions for first flush mass delivery. Although the swales do not reduce the mass deliver during the initial part of the storm event at a constant rate, when the first flush mass delivery of the swales are compared to a value of 50%, the definition of first flush (Wanielista and Yousef 2003), both swales have significantly lower mass delivery. Unlike the swales, the direct channel does not produce an average first flush mass delivery lower than 50% because of large variance between storms. This suggests that while the swales might not reduce the first flush mass delivery at a consistent rate, over the course of many storm events, the grass swales do not produce a mass-based first flush, while the influent TSS concentrations do on occasion.

4.4.2 N-EMC Removal Comparison

The normalized EMC (N-EMC) allows a direct comparison of the total suspended solid concentration that would result if swale inflow was only directly from roadway runoff and the entire resulting effluent volume was captured in a single container.

Equation 42 describes the procedure for calculation of this parameter. Summary statistics for the N-EMC are shown in Table 4-11. EMC values are not shown because the EMC is not an accurate method for comparing these swales with differing drainage areas, and thereby different dilution amounts. However, identical conclusions were drawn from the EMC data as the N-EMC data for TSS. N-EMC values are identical to EMCs for the direct channel and are approximately 30% larger than EMC values for the two grass swales. Table 4-11 shows almost an order of magnitude difference between the mean values of the influent and effluent N-EMCs, suggesting successful TSS removal. The distribution of N-EMC reduction (Table 4-11) agrees with the hypothesis that the swales reduce the TSS N-EMC.

Visually, the effect of the swales on TSS N-EMC values is shown in Figure 4-13, a probability plot showing the distribution of N-EMCs for all three channels. The difference between the Direct N-EMCs and the swale data suggests that both swales are successful in decreasing the resulting concentration from any given storm event. Using a TSS concentration of 100 mg/l for comparison purposes, the inflow exceeds this concentration for 35% of storm events. When compared with the swales, however, the resulting N-EMC for the MDE swale will only exceed 100 mg/l TSS during about 4% of storm events and the SHA swale never exceeded 100 mg/l during this study. It appears that the SHA and MDE data are similar for many of the storm events, and only differ at a few very high concentrations.

Table 4-11. Total Suspended Solid distribution and reduction summary statistics for all three channels with complete capture storm events removed from N-EMC and first flush reduction calculations.

		Direct Channel	SHA Swale	MDE Swale	SHA Reduction		MDE Reduction		MDE Reduction-SHA Reduction	
						%		%		%
Total Mass (g)	Mean	3,120	737	1,220	2,350	84.4	2,230	73.1	-1,070	-25.7
	Median	1,370	16.9	171	1,020	100	1,280	95.2	-435	-9.60
	Standard Deviation	4,100	1,930	2,770	2,710	25.6	2,470	50.3	1,430	48.9
	# Samples	18	16	17	15	15	16	16	6	6
N-EMC (mg/l)	Mean	107	10.5	16.6	61.0	41.1	51.6	51.6	-13.4	-11.1
	Median	93.1	3.71	6.62	24.1	50.9	12.3	12.3	-2.51	-2.33
	Standard Deviation	100	13.9	17.8	97.3	51.0	88.3	88.3	24.0	28.7
	# Samples	18	16	17	8	8	9	9	7	7
First Flush (%)	Mean	38.6	36.8	32.0		9.36		4.52		1.61
	Median	42.2	34.3	30.8		6.11		13.2		-3.39
	Standard Deviation	22.0	8.95	10.1		17.1		19.3		15.1
	# Samples	10	8	9		8		9		7

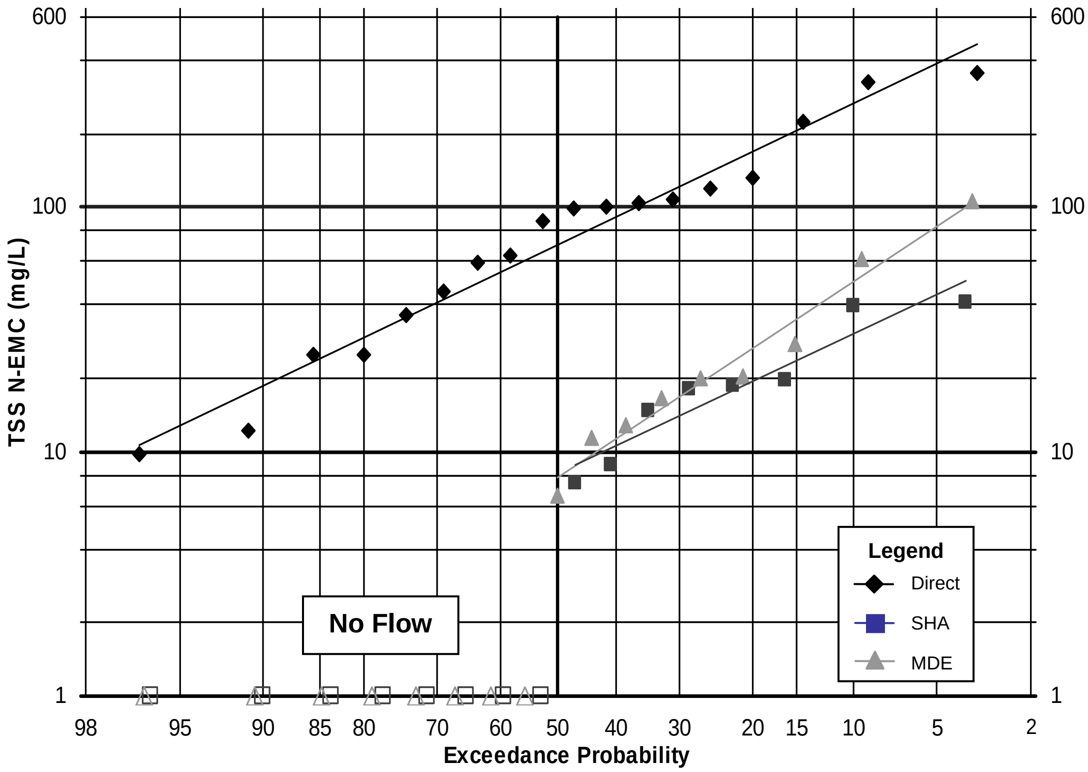

Figure 4-13. Total Suspended Solids N-EMC probability plot.

The battery of statistical tests did not identify any outliers or any distributions that were significantly different from the normal distribution. Both swales significantly decreased the N-EMC concentration (94-102 mg/l mean) and had a significant removal percentage (65-71% mean). These removals are reasonable when compared to other studies which show grass swale TSS removals of 65-98% (Schueler 1994), 85-87% (Barrett *et al.* 1998), 68% (Yu *et al.* 2001), and 79-98% (Backstrom 2003).

No statistically significant difference exists between N-EMC reduction for the two swales. Likewise, there was no significant difference between the variance of N-EMC removal values. Therefore, it can be concluded that the grass swales have nearly identical removal capabilities for suspended solids N-EMCs and that the pretreatment adjacent to the MDE swale did not significantly affect the reduction on TSS N-EMCs.

4.4.3 Mass Removal Comparison

By multiplying the concentration data and the flow data, the total suspended solid mass discharged from each channel was calculated for every storm event (Equation 3-40). The total mass data allow a calculation of the total mass removal by treatment and infiltration, as shown in Equation 3-40. Total mass discharges are summarized in Table 4-11. The central values, mean and median, suggest that a larger mass of suspended solids is discharged through the direct channel than through the swales.

Suspended solid mass removal was calculated on an individual storm basis to determine if the mass removal was statistically significant. Summary statistics for suspended solid mass removal are shown in Table 4-11. Both the SHA and MDE swales exhibit positive mass removal as shown by the mean and median removal values. Variability within the mass data is large, as shown by the high standard deviation values compared to the mean. Finally, it appears that the SHA swale is more capable of removing TSS total mass, as shown by negative (MDE-SHA) difference values.

The significance of these hypotheses was tested by comparing the distribution of mass removal, described as $M_{infil} + M_{treat}$ in Equation 3-40. One outlier was noted, and because the storm event (4/1/05) had a very different storm pattern than all other storms, it was sequestered from further analysis. All distributions of total mass removals were sufficiently close to the normal distribution to be considered normal, although due to high values, the nonparametric Wilcoxon test was also employed to determine the statistical significance of TSS mass removals.

Both swales exhibited a statistically significant ability to reduce the total TSS mass, when compared to the mass entering the swale system. This total suspended solid mass was significantly reduced in terms of absolute mass (2,350 g SHA, 2,230 g MDE) and also in terms of removal percent (84.4% SHA, 73.1% MDE).

The difference between the suspended solid mass removals for each swale highlights the difference between the designs and the importance of the shallow sloped pretreatment area. The statistically significant negative difference between the MDE and SHA removal efficiency suggests that the SHA swale, without a pretreatment area, is more effective at removing the suspended solids than the MDE swale. Therefore, the grass swale is more important for removal efficiency than lateral flow over the pretreatment area. The effectiveness of the SHA swale, which has a longer swale length and also a longer travel time (Section 4.1.4), implies that suspended solid removal is controlled by mechanisms like sedimentation and filtration. The importance of swale length in removing suspended solids found here agrees with studies by Backstrom (2002) and Yu *et al.* (2001). The importance of using a longer swale distance is even more noticeable when the total suspended solid mass export is calculated for all storm events over the duration of the study. During 18 storm events, spread over 2 years, the total influent mass for both swales is 56.1 kg, while the MDE swale released 20.7 kg and the SHA swale released 11.8 kg of suspended solids. Therefore, total suspended solid mass removal appear to be dependent on total travel time, and swales should be designed accordingly.

Because the swales are capable of both reducing the total mass and N-EMC for suspended solids, it can be concluded that the swales are more dependent on sedimentation and filtration than infiltration. If infiltration had been a significant removal mechanism, the ratio of pollutant mass to runoff volume would remain constant, as shown by the mass balance in Figure 3-9. Infiltration reduces the total volume, and thereby the total pollutant mass. Because of the successful reduction of both TSS mass and N-EMC, it can be concluded that suspended solid reduction is due primarily to sedimentation and filtration The grass swales appear to reduce total mass and mean concentrations by removing the initial high TSS concentrations first by capturing the runoff through infiltration and then by reducing the subsequent steady-state concentrations by sedimentation and filtration. Also, the inclusion of a pretreatment area makes no significant difference in removal capability because it does not significantly affect sedimentation, infiltration, or filtration ability, which are all dependent on total hydraulic travel time.

4.5 Nutrients

Literature reports mixed results for nutrient removal by grass swales, ranging from 60% removal to 150% export. This study examined nitrogen as nitrate, nitrite, and Total Kjeldahl nitrogen and total phosphorus. As in other studies, removal efficiencies for the grass swales often had a wide variance that ranged from strongly positive to strongly negative. In general, the grass swales show widely variable abilities to remove nutrients from highway runoff. The most consistent trend in nutrient data was the reduction of nitrite concentrations. The widely variable removal capabilities suggest that the nutrient removal is dependent on factors that were not constant throughout the study like seasonal changes and mowing frequency.

For the evaluation of grass swale treatment efficiency regarding nutrients, more emphasis was placed on the total mass loads than the N-EMC data because of the environmental issues surrounding nutrients in receiving waters. Nitrogen and phosphorus sources are generally of greater concern because of their accumulating effects on processes like algal growth and eutrophication rather than an acute toxicity. Also, because of technical problems with laboratory equipment, there are only a few storm events with measurable flow through the swale and available nutrient data. Therefore, nutrient mass loading and removal was the primary focus, and nutrient N-EMC data was used to corroborate conclusions drawn from mass data. In nearly all cases, these two data sets agreed.

4.5.1 Mass Removal Comparison

Nutrient mass removal was calculated using Equation 40 and represents the treatment term in the mass balance around the grass swale. Summary statistics for nutrient mass and removals are shown in Table 4-12. For both swales, nitrate, TKN and total phosphorus mass removal vary greatly. However, it appears that both swales are capable of decreasing nitrite total mass by an average of 3.2-5.2 g (69-98%).

The mass removal for nitrate, TKN, and total phosphorus do not indicate any statistically significant removal or export by the swales. This suggests that the mass flux is greatly variable. Most likely this is caused by seasonal variations and changes in the organic makeup of the swales. Because these nutrients are primarily derived from

Table 4-12. Nutrient mass distribution and mass reduction summary statistics for all three channels.

		Direct Channel	SHA Swale	MDE Swale	SHA Reduction		MDE Reduction		MDE Reduction-SHA Reduction	
						%		%		%
Nitrate (g)	Mean	91.4	107	123	-27.8	11.1	-31.4	-1.29	-31.9	-36.1
	Median	40.0	0	48.9	15.3	100	12.5	56.7	-20.4	-48.2
	Standard Deviation	97.0	159	160	81.9	142	105	146	74.1	42.7
	# Samples	10	8	10	8	8	10	10	3	3
Nitrite (g)	Mean	7.63	2.79	3.44	5.19	69.3	4.44	54.7	-0.890	-18.5
	Median	5.24	0.0577	1.39	3.86	98.3	3.16	78.0	-1.11	-11.8
	Standard Deviation	6.32	6.37	5.96	4.40	46.7	4.80	60.7	1.87	42.5
	# Samples	18	16	17	16	16	17	17	7	7
TKN (g)	Mean	82.4	52.5	90.9	26.4	42.1	-4.88	5.01	-27.9	-85.6
	Median	53.7	4.00	63.2	39.5	100	31.3	79.8	-27.6	-45.0
	Standard Deviation	79.1	79.2	121	103	99.8	133	144	13.4	90.1
	# Samples	16	14	15	13	13	14	14	5	5
TP (g)	Mean	16.5	22.1	29.1	5.99	59.7	-0.476	39.1	-1.81	10.5
	Median	9.44	1.30	5.79	5.35	100	4.45	100	-5.62	-22.8
	Standard Deviation	20.3	54.8	49.2	11.5	68.1	24.7	106	9.06	75.5
	# Samples	18	16	17	13	13	14	14	4	4

organic material, it is likely that the grass swales may at times be contributing nutrient mass (in the form of decaying organic matter) or uptaking nutrients during peak growth seasons. Many other factors, such as mowing and falling leaves, likely influence the mass flux of nutrient into or out of the swales. It appears, therefore, that grass swales are dependent on other environmental factors to ensure successful removal of most nutrients. With the limited number of data points and large variance, it is difficult to predict the sum effect of the grass swales on nitrate, TKN, and total phosphorus.

Nitrite reduction, however, is statistically significant for both swales. This significant decrease of total nitrite mass allows some insight into the processes occurring within the grass swale. Nitrite is a very common intermediate in the nitrogen cycle and is rapidly oxidized to nitrate under aerobic conditions by nitrifying bacteria, or by other chemical catalysts. Most likely because of extended travel time, aerobic mixing by filtration through grass blades, inclusion of natural bacteria in the swale, or some change in the pe-pH chemistry of the runoff along the grass swale, nitrite is being oxidized to nitrate. More research is required to confirm the exact process causing this reduction in total nitrite mass.

The two different grass swale designs show no statistically significant difference in mass removal, except for in the case of TKN. The SHA swale was more capable of decreasing the effluent TKN mass than the MDE swale by an average of 28 g. TKN, being a measure of organic nitrogen and ammonia, is highly related to the amount of decaying organic matter in a system. Because the MDE swale produced a higher TKN mass than the SHA swale, it suggests that the natural matter in the swale drainage area is responsible for a significant portion of the total TKN mass. Because the MDE swale has a larger grassed drainage area, this natural material possibly causes excess TKN.

4.5.2 N-EMC Removal Comparison

Nutrient mean concentrations tend to follow similar patterns as the nutrient total mass comparisons and provide similar conclusions. Visually, nutrient N-EMCs can be compared by probability plots (Figures 4-14 – 4-17). These plots suggest that the swales have a negligible effect on nitrate concentrations, as shown by Figure 4-14. The intersection point between the direct runoff distribution and the swale distribution suggests that some storm events with noticeable flow showed nitrate removal, while some storm events showed an export of nitrate. This confirms the previous conclusion that nitrate concentrations are affected by many environmental factors, such as season, mowing, and other organic debris.

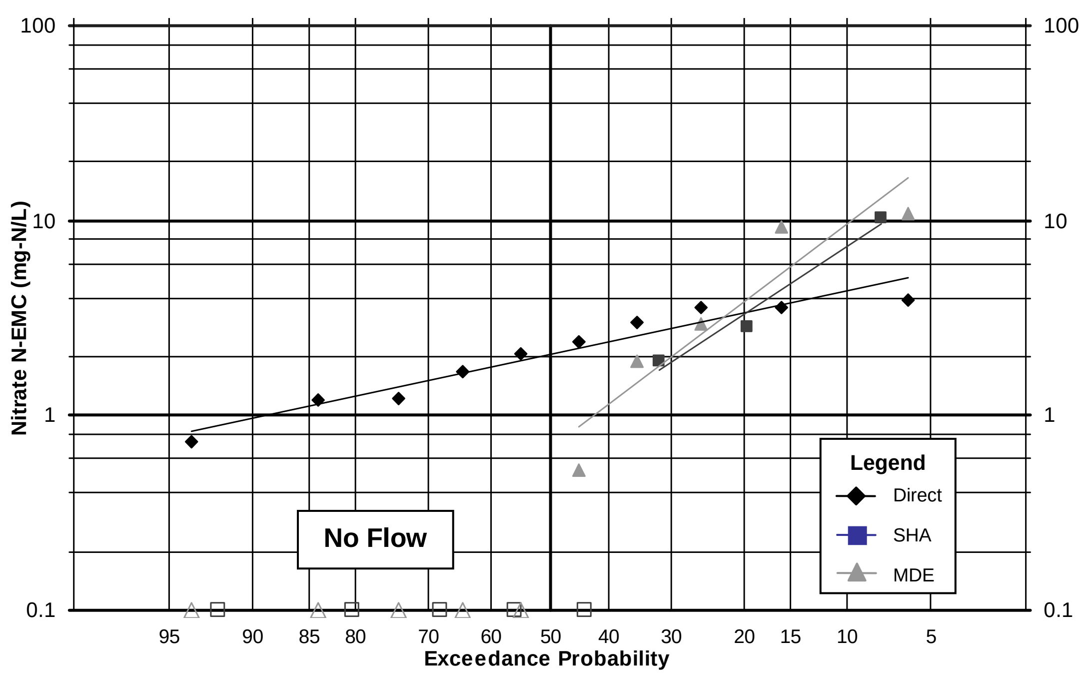

Figure 4-14. Nitrate N-EMC probability plot.

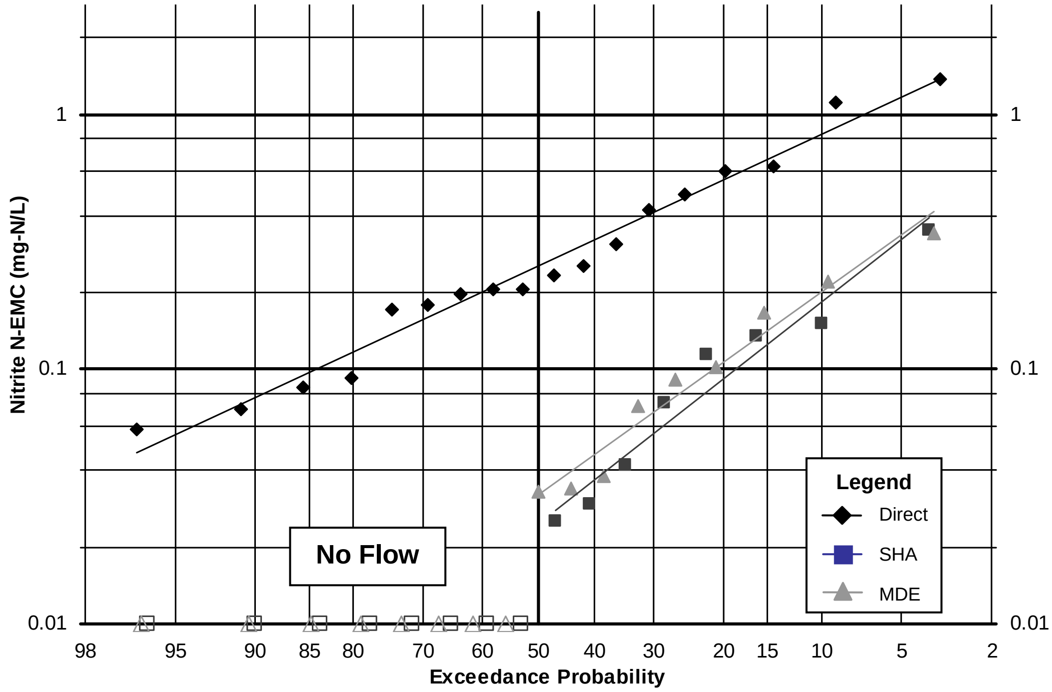

Figure 4-15. Nitrite N-EMC probability plot.

Similar to findings above for total pollutant mass, the grass swales tend to reduce the mean concentration of nitrite noticeably, although the difference between the SHA and MDE swale removal is negligible (Figure 4-15). While the probability plots suggest slight TKN removal (Figure 4-16), this reduction is small and must be confirmed through statistical tests. The probability plot for total phosphorus shows almost no noticeable difference between the swales and the direct runoff phosphorus distribution.

Testing the significance of these N-EMC reductions confirms that both grass swales have widely variable effects on the mean nitrate concentrations. However, nitrite concentrations are decreased by a statistically significant level. The SHA swale reduces nitrite concentrations an average of 0.35 mg/l (66%), while the MDE swale reduces

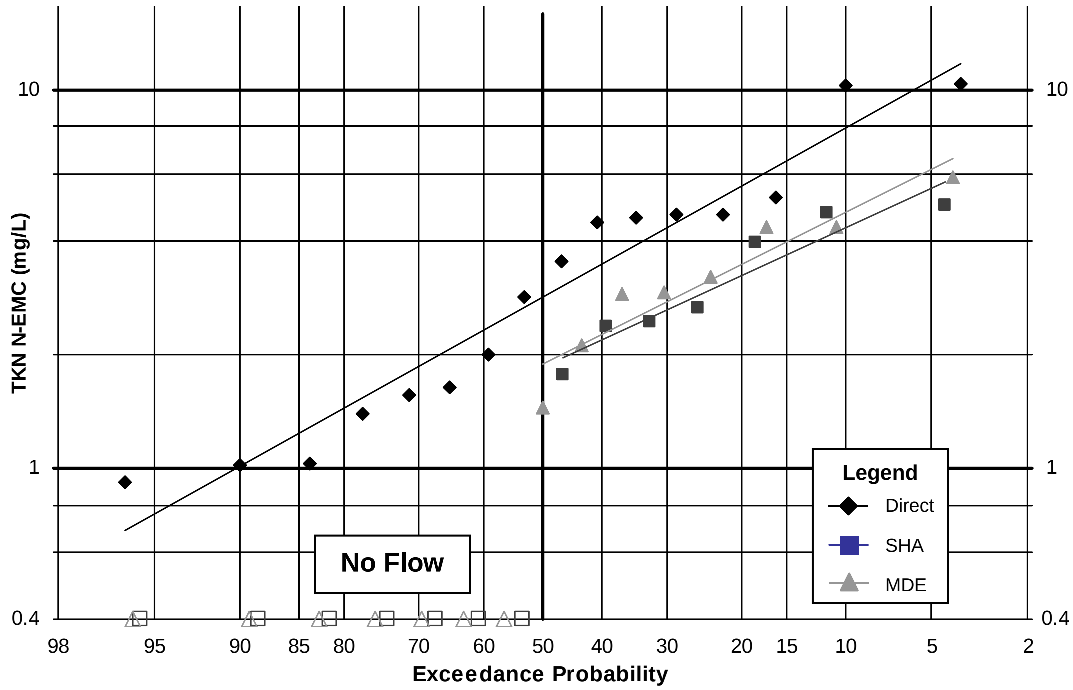

Figure 4-16. TKN N-EMC probability plot.

nitrite concentrations an average of 0.32 mg/l (56%). The difference between these swales is not statistically significant. Despite the difference in the TKN and total phosphorus probability plots, for storms with measurable swale flow both swales significantly increase the mean concentrations of TKN (by 1.1-1.3 mg/l) and total phosphorus (0.28-0.37 mg/l).

The grass swales therefore appear to have variable effects on nitrate concentrations and mass, while reducing mass and concentration of nitrite, likely by oxidation to nitrate. While mass data was too variable to obtain a statistically significant conclusion, the swales did increase the N-EMCs of TKN and total phosphorus when compared to the influent highway runoff. Unfortunately, because of technical difficulties with the ion chromatograph instrument, a full set of nitrate readings was not available.

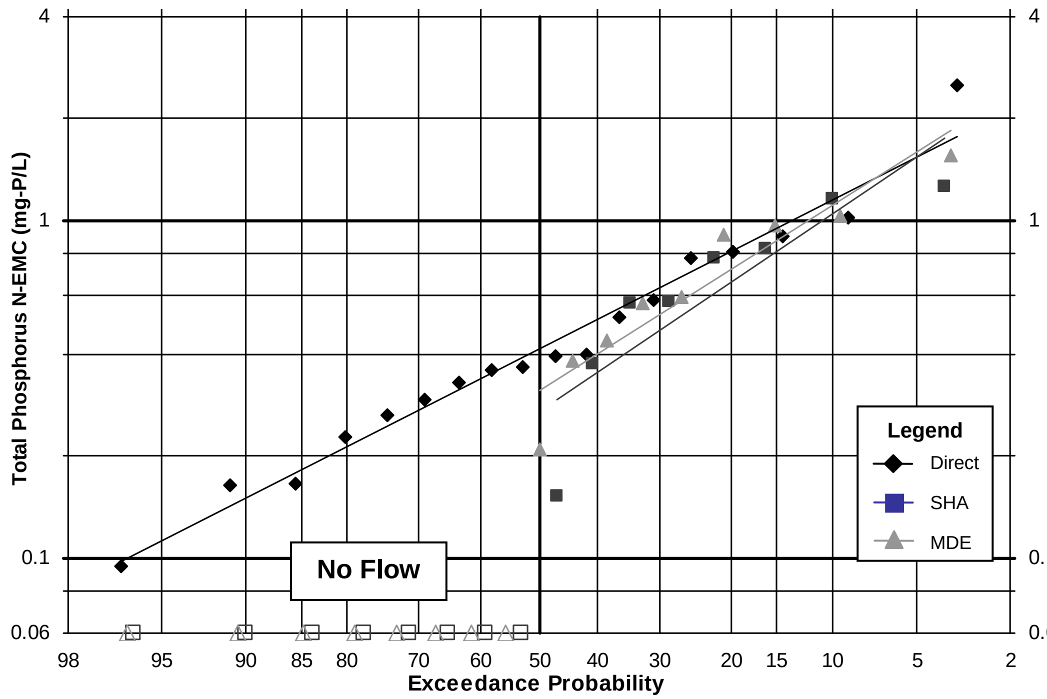

Figure 4-17. Total phosphorus N-EMC probability plot.

This made drawing any significant conclusions regarding nitrate and the combined total nitrogen (nitrate, nitrite, and TKN) impossible.

4.6 Chloride

Chloride is increasingly becoming a pollutant of concern as it appears that baseline chlorine concentrations in receiving water bodies are approaching a level that exceeds the tolerance level for freshwater aquatic life (Kaushal *et al.* 2005). The maximum chloride limit recommended for the protection of freshwater life is 250 mg/l (Kaushal *et. al.* 2005). For comparison purposes, 18 storm events were analyzed with respect to chloride concentrations to determine the removal capability of the grass swales.

4.6.1 N-EMC Removal Comparison

The N-EMC data suggest that both swales are exporting rather than removing choride from the highway runoff as it passes through the swale treatment areas. This is shown graphically in the chloride probability plot (Figure 4-18) and summarized in Table 4-12. As shown in Figure 4-18, both swales appear to be producing mean concentrations that are much larger than the influent concentrations. Only one storm event (3/2/06) produced chloride concentrations in the direct channel (137 mg/l) high enough to approximate chloride concentrations leaving the swales (114 mg/l SHA and 271 mg/l MDE means). This high concentration chloride storm event shown in the probability plot as the highest point in direct data was the first rainfall event following a February 12 snow storm which produced 7-8 inches of snow. Although a long period without

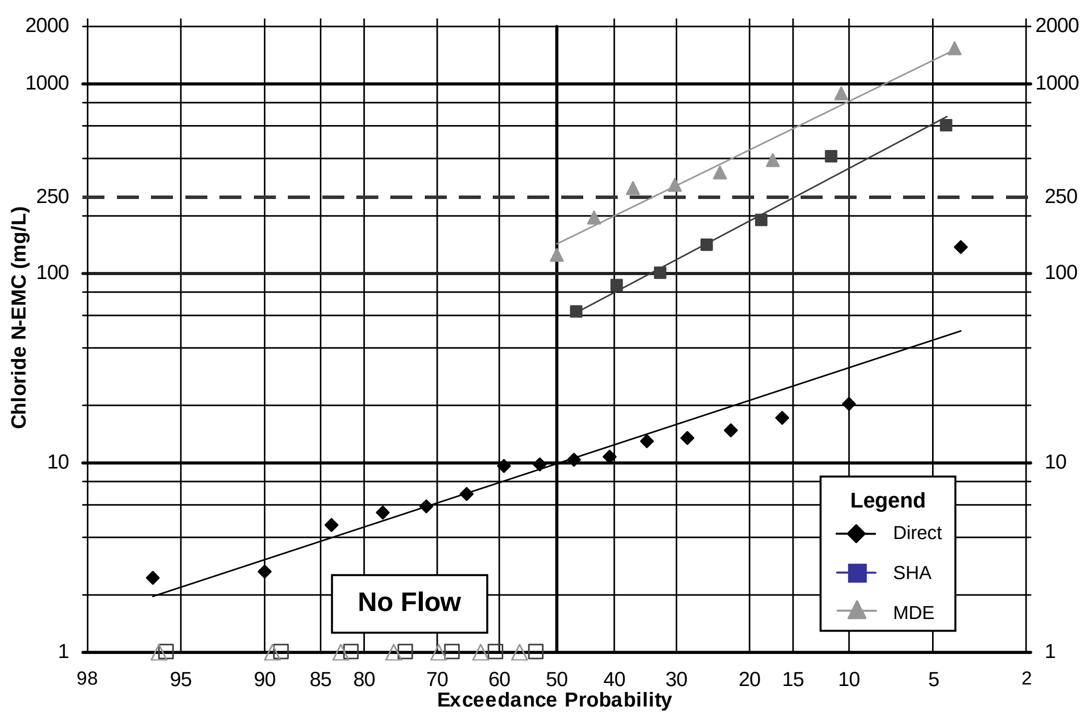

Figure 4-18. Chloride N-EMC probability plot.

precipitation followed this snowfall event, there was likely some residual chloride on the roadway surface left from salting operations.

It is also important to note that while the runoff from the roadway surface never approaches a level dangerous to aquatic life (250 mg/l), both swales export chloride concentrations similar to and exceeding this concentration. Based on the data collected, the SHA swale would produce chloride concentrations that exceed this threshold during 15% of storm events, while the MDE swale would exceed this threshold during 35% of storm events. While the grass swales are successful at removing chloride during small storm events by completely capturing runoff volume, both swales act as a source of chloride during storms with measurable flow. Also, it appears that the MDE swale exports more chloride than does the SHA swale.

Statistical tests suggest that the increase in chloride mean concentrations for both swales are statistically significant. As shown in Table 4-13, the SHA swale increased the mean chloride concentration for storms with detectable flow by an average of 216 mg/l, while the MDE swale increased mean chloride concentration by an average of 499 mg/l. These chloride increases are significant when compared to inflow chloride concentrations which are generally in the range of 2-20 mg/l.

This significant increase in mean chloride concentration suggests that the swales have a large source of chloride. As chloride presumably only enters the system in

Table 4-13. Chloride distribution and reduction summary statistics for all three channels.

		Direct Channel	SHA Swale	MDE Swale	SHA Reduction		MDE Reduction		MDE Reduction-SHA Reduction	
						%		%		%
Total Mass (g)	Mean	343	3,730	13,000	-1,500	-605	-9,070	-2,680	-9,620	-3,740
	Median	236	196	5,870	25.2	100	-2,790	-342	-7,840	-3,890
	Standard Deviation	365	7,660	20,300	3,070	1,190	15,100	3,880	4,460	2,800
	# Samples	16	14	15	13	13	14	14	5	5
N-EMC (mg/l)	Mean	17.8	114	271	-216	-2,660	-499	-6,870	-321	-4,400
	Median	10.1	31.1	125	-135	-3,130	-308	-5,400	-194	-3,260
	Standard Deviation	32.1	181	427	202	1,690	476	4,760	345	4,380
	# Samples	16	14	15	7	7	8	8	6	6
First Flush (%)	Mean	33.0	30.2	30.9		4.77		4.51		-6.31
	Median	32.0	28.6	30.0		5.83		1.16		-3.77
	Standard Deviation	11.6	5.73	9.28		13.6		14.4		9.65
	# Samples	9	7	8		6		7		5

significant quantities during the winter through salting operations, it is interesting to note that chloride concentrations leaving the swales remain elevated throughout the year. This suggests that a large reservoir of chloride accumulates in the roadside grass and soil during the winter and slowly releases chloride during subsequent storm events throughout the year.

This hypothesis is further confirmed by the statistically significant difference in mean chloride concentrations between the SHA and MDE swales. Despite equivalent influent water characteristics, the MDE swale, which has a greater grass area, exports significantly higher mean chloride concentrations. It appears, therefore, that the chloride is not entering the system by roadway runoff, but is entering from the grass receiving area, as the chloride increase is related to the amount of grass area prior to the outflow. Likely, there are a few storm events during the winter, immediately after salting operations, that produce chloride concentrations on the order of the grass swale chloride concentrations. These storms deposit the chloride in the grass swale areas that remains recalcitrant and slowly releases chloride during storm events throughout the year. Unfortunately, because of the difficulties associated with sampling during cold weather (possibility of pump damage due to freezing), only one such storm event was captured. This storm, the highest concentration in the direct channel data shown in Figure 4-18, occurred weeks after salting and likely did not contain as much chloride as expected because much of the salt on the road surface was removed by snowmelt and other environmental forces during the 2-3 weeks following salting.

4.6.2 Mass Removal Comparison

The total mass data suggests a similar conclusion as noted with N-EMC data; that both swales are exporting rather than removing choride mass from the highway runoff. As shown in Table 4-13, the mean chloride mass leaving both swales (1,840 g SHA, 9,430 g MDE) is much larger than the mean chloride mass entering the swales (351 mg/l). Similarly, when the total chloride mass exported is summed for all analyzed storm events, it suggests a total export of chloride from the grass swales (4,050 g Direct, 23,500 g SHA, 71,600 MDE).

When chloride removals are considered on a storm by storm basis, the trend of chloride mass export by the swales continues (Table 4-13). The SHA swale contributes an average of 1,500 g chloride, while the MDE swale adds an average of 9,070 g chloride. According to both tests of significance (normal and non-parametric), both grass swales export a statistically significantly larger chloride mass than the influent, in terms of absolute mass and also percent. This supports the conclusion stated above that the grass swales have accumulated deicing salt and are acting as a source during storm events throughout the year. However, the difference between the total sum of chloride mass exported from each channel suggests that this study has not sampled the events that provide the grass swale area with its supply of chloride. As this grass swale area was newly built and only experienced 2 winters with which to accumulate chloride, storms with very high chloride loads must have gone undetected or the soil used in construction must have been exposed to high chloride mass loads prior to this study.

The mass export difference between the swales is also statistically significant. The higher increase in chloride concentrations for runoff through the MDE swale suggests the same conclusion drawn by the difference in N-EMC. The excess pervious, grassy area in the MDE must be providing the excess chloride, confirming the hypothesis that the chloride originates in the grass areas and not from highway runoff.

4.6.3 First Flush Removal Comparison

By analyzing chloride concentrations with respect to time, it becomes apparent that the first flush associated with chloride concentrations is relatively small. The 5/19/05 storm event (Figure 4-19) exhibits typical behavior for chloride concentrations. The chloride concentrations almost exactly mirror the rainfall and flow distribution, which in turn suggests a nearly constant mass delivery. This is confirmed through the first flush diagram (Figure 4-20) which shows nearly a straight line along the bisector, which represents equal mass and volume delivery. Table 4-13 provides summary statistics for the percent mass delivery during the first 25% volume delivery. As shown in the table and in the example storm event, chloride mass is exported from the swale at a constant

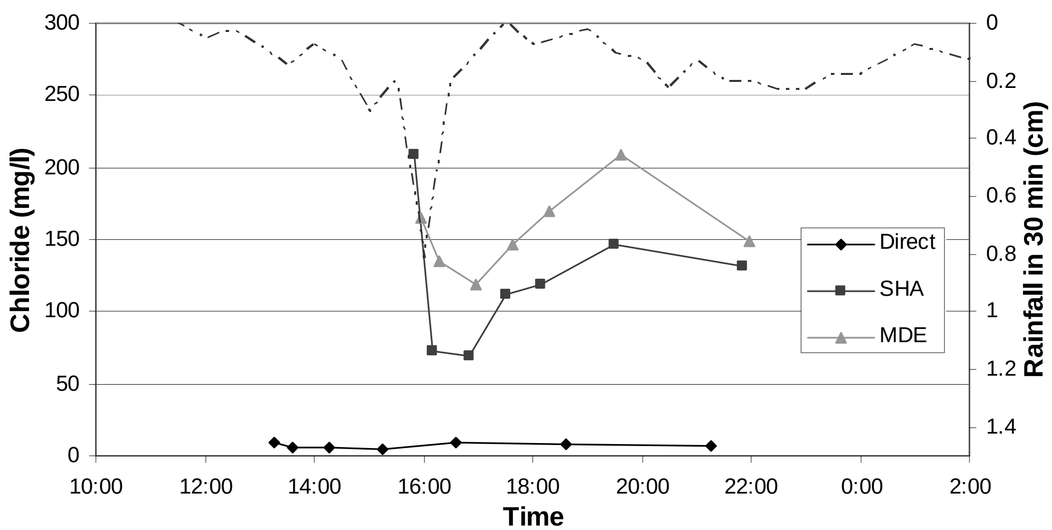

Figure 4-19. Chloride concentrations with respect to time (5/19/05).

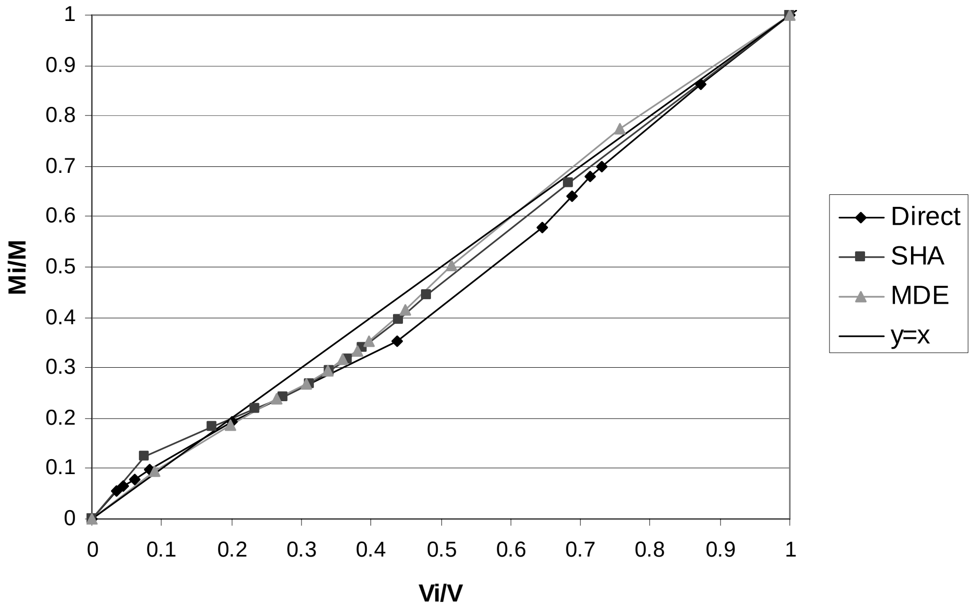

Figure 4-20. Chloride mass-based first flush diagram (5/19/05).

rate. Neither swale shows a mass delivery that is statistically significant when compared to the bisector.

This behavior is not typical of a constituent being exported from a roadway source. If chloride was derived from the roadway, it should have a higher mass delivery during the initial rising limb of the storm and decrease as the roadway source is depleted. However, the nearly constant chloride delivery suggests a large, inexhaustible source which releases chloride as flow passes by it, further supporting the conclusion that the grass area itself is the source for high chloride concentrations.

These findings are similar to research by Kaushal *et al.* (2005), which identified a significant, long-term increase in salinity for 6 streams in Maryland, New York and New Hampshire. Similar to the results shown in this research, Kaushal (2005), found that chloride concentrations in receiving bodies remained elevated throughout the year and that many urban water bodies currently exceed the 250 mg/l aquatic life threshold. It is possible that the cause for yearly highly elevated chloride concentrations is roadside areas like those in this study, which retain the deicing salt and release it throughout the year.

Finally, although it may appear that the grass swales are contributing to an increase in chloride concentrations, a much more likely scenario is that the grass swales serve to collect and slowly release chloride. Without these swales, a large slug of chloride likely enters the receiving water bodies at one time immediately following road salting operations. Swales do not remove chloride, but rather spread its release over time. Therefore, if a decrease in chloride concentrations is desired, a reduction of salting operations is necessary.

4.7 Metals

To quantify the grass swales effect on common metals in highway runoff, lead, copper, zinc and cadmium samples were analyzed for 10 to 14 storm events, depending on the particular metal. For each metal, the reduction in mean concentration, total pollutant mass, and normalized mass delivery during the first flush period was calculated and compared to the influent to determine its significance.

For the metals analyzed the grass swales were effective at reducing the mean concentrations. Overall metal reduction based on total mass and N-EMC generally follows the order from largest removal to lowest: Zn, Cu, and Pb. Cd showed negligible effect because much of the influent concentrations were below detection limits. This order of removal, with zinc most readily removed and copper and lead removed at moderate levels agrees with other grass swale removal studies (Schueler 1994, Barrett *et al.* 1998).

For the aquatic conditions found in highway runoff, zinc and cadmium are expected primarily in the dissolved phase, while lead is primarily particulate bound, and copper shows a mixture of particulate bound and dissolved species (Dean *et al.* 2005). This allows some insight into the removal mechanism for each of these metals, and therefore each of these groups will be analyzed separately and compared.

4.7.1 Zinc

Zinc is the most prevalent metal in highway runoff, and also shows the greatest removal by the grass swale system. N-EMC removal was on the order of 30-60% and total mass removal was between 75-89%. Removals are summarized in Table 4-14. These findings agree well with studies in the literature, which show zinc EMC reductions of 75-91% (Barrett *et al.* 1998) and mass removals between 46% and 81% (Schueler 1994, Backstrom 2003, Rushton 2001).

The effect of the grass swales on zinc concentrations is shown visually in Figure 4-21. In this probability plot, the Maryland Department of the Environment acute and chronic aquatic toxicity limit (MD Department of Environment 2005) for zinc, 120 μg/l, is plotted as a dashed line. This toxicity limit allows a comparison demonstrating the improvement in receiving water quality, showing that 90% of storm events will produce roadway runoff that exceeds this value. However, after swale treatment, only 35% of storm events will exceed the limit of 120 μg/l.

Figure 4-14. Zinc distribution and reduction summary statistics for all three channels.

		Direct Channel	SHA Swale	MDE Swale	SHA Reduction		MDE Reduction		MDE Reduction-SHA Reduction	
						%		%		%
Total Mass (mg)	Mean	10,600	3,770	7,560	9,150	84.8	7,130	75.0.	-4,340	-19.2
	Median	6,730	425	2,400	5,980	100	6,110	89.3	-2,320	-17.6
	Standard Deviation	9,498	6,770	12,800	8,860	26.6	6,140	33.4	4,410	12.5
	# Samples	14	12	14	11	11	12	12	5	5
N-EMC (µg/l)	Mean	473	92.7	124	174	40.2	129	30.4	-71.7	-19.9
	Median	351	10.5	86.9	131	58.9	83.0	44.3	-68.5	-20.2
	Standard Deviation	386	120	136	205	41.2	159	45.8	57.1	17.5
	# Samples	14	12	14	6	6	7	7	5	5
First Flush (%)	Mean	32.6	28.1	28.4		3.89		4.35		-0.339
	Median	28.2	26.3	28.4		0.0248		-0.893		-1.35
	Standard Deviation	12.6	7.39	3.53		20.3		12.3		11.3
	# Samples	8	6	8		5		7		5

As suggested by Figure 4-21, both grass swales successfully reduce the mean concentration and total mass for zinc at a statistically significant level. As stated above, zinc is expected to be present predominantly in the dissolved state; however, during intense storm events, the distribution of this metal changes to primarily particulate bound (Dean *et al.* 2005). This trend from dissolved to particulate phase metals combined with analysis of the zinc concentrations with respect to time suggest a zinc removal method. As shown in the 10/24/05 storm event (Figure 4-22), which is typical of zinc concentrations, the direct runoff shows high initial concentrations; however, when analyzed in a first flush diagram (Figure 4-23) mass delivery is nearly constant. This suggests that dissolved zinc is the predominant species initially because zinc does not exhibit first flush trends that follow TSS data for this storm event. The grass swales are unable to reduce the mass-based first flush of zinc at a statistically significant level, likely

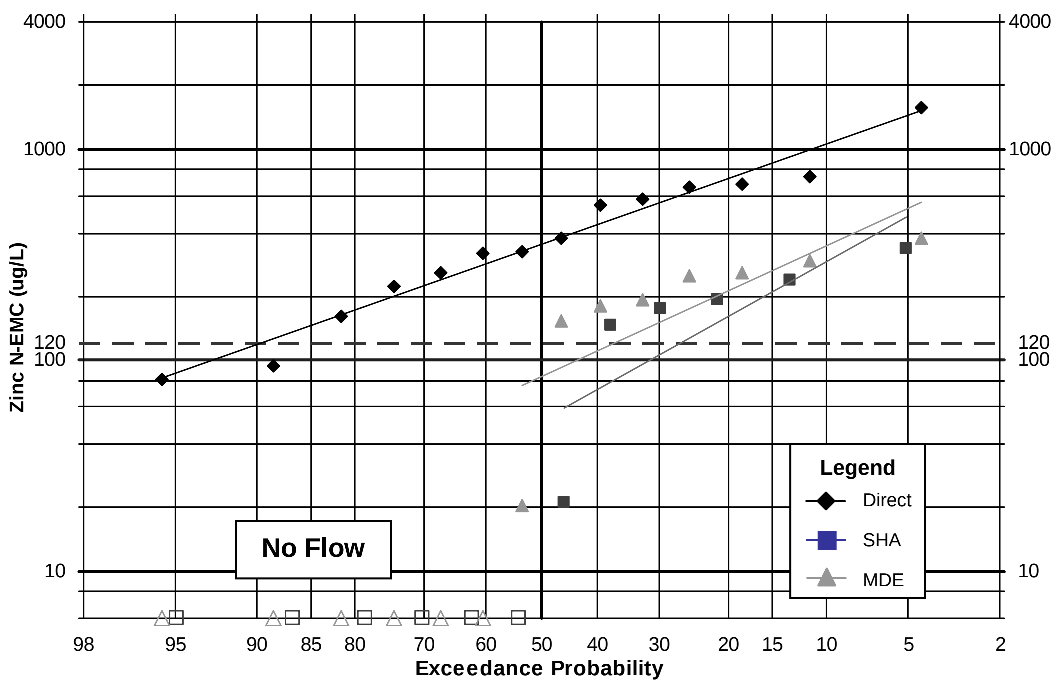

Figure 4-21. Zinc N-EMC probability plot.

because of this predominance of dissolved species. Zinc concentrations and mass are therefore reduced by completely capturing flow during the high initial dissolved zinc concentrations, removing dissolved zinc through adsorption processes, and removing particulate bound zinc through sedimentation and filtration in the latter parts of the storm event after the distribution has shifted to predominantly particulate bound zinc.

For zinc removal in terms of both mass and mean concentration, the SHA swale shows better removal capability. The difference between the SHA swale and MDE swale is statistically significant at the 5% level. Presumably, this difference is caused by the excess channel length in the SHA swale. The relationship between increased swale length and increased zinc removal agrees with research by Yu *et al.* (2001) which presents a regression curve describing zinc removal as a function of swale length. The extra swale length allows more time for adsorption and more length for sedimentation of particulate bound zinc.

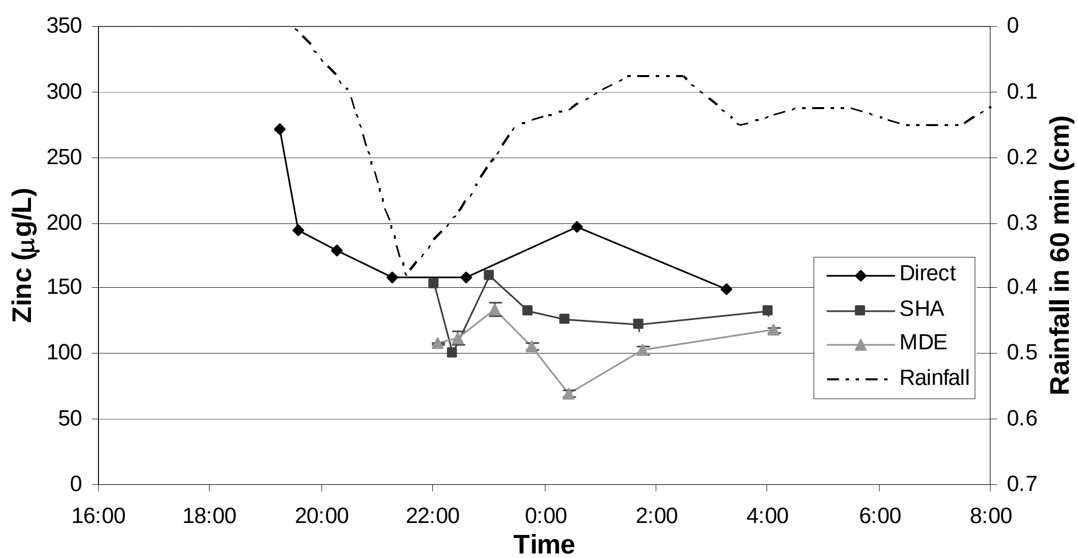

Figure 4-22. Zinc concentrations with respect to time (10/24/05).

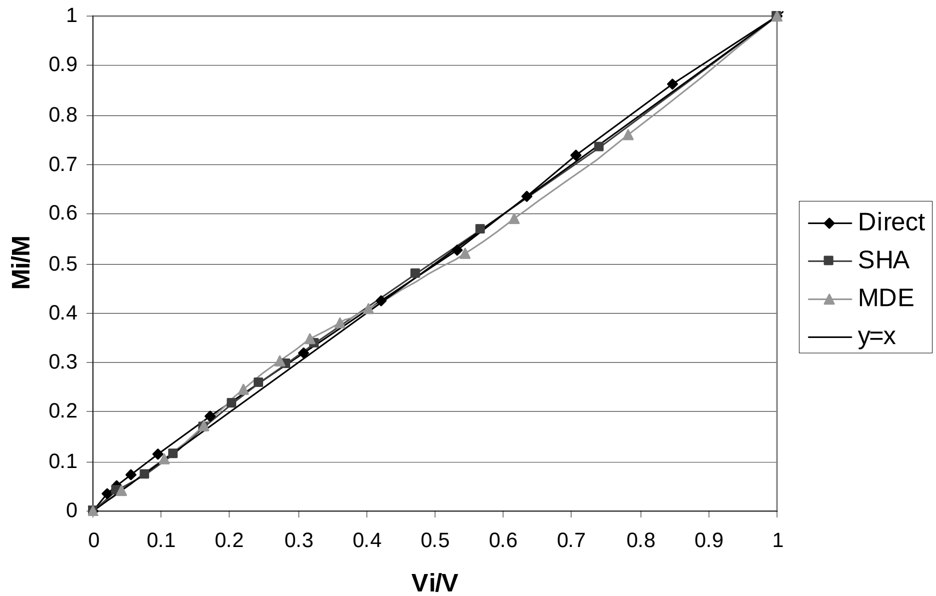

Figure 4-23. Zinc mass-based first flush diagram (10/24/05).

4.7.2 Cadmium

Quantifying cadmium removal by the grass swales is difficult because cadmium concentrations for both the influent and effluent were often below detection limits. However, it does appear that the grass swales successfully decrease cadmium concentrations because the assumed input direct channel did produce cadmium concentrations above detection limits, while only 2 swale samples (1 in the SHA and 1 in the MDE swale) during the entire study were above the detection limit of 2 μg/l. Because of this, cadmium concentrations for the swales could theoretically be between 0 and 2 μg/l causing reduction calculations to have ranges that render them ineffective as a comparison method. Using the half detection limit value (1 μg/l) for those samples below detection limit produces an average N-EMC of 1.98 μg/l in the direct runoff, which is still below the detection limit. However, peak concentrations in the direct runoff do show some concentrations during 4 storm events that are greater than the detection limit. No statistical tests were performed on the cadmium data because of this, yet it does appear that the swales are reducing cadmium concentrations given the lack of concentrations above detection limits.

4.7.3 Copper

The swales show a moderate capacity for removing copper, as shown by the removal summary in Table 4-15 and by the probability plot in Figure 4-24. The removal summary shows reduction of copper mass between 32% and 70% and reductions of mean concentrations between 5.7% and 35%.

As shown in Figure 4-24, the MDE acute copper toxicity limit for aquatic life is 13 μg/l (MD Department of Environment 2005). Runoff directly from the roadway surface exceeds this threshold limit in nearly every monitored storm event, suggesting a 94% probability of exceedance. However, with the grass swale treatment, the probability of exceedance is decreased to 40%. This represents a valuable removal for the improved health of receiving water bodies. The probability plot also highlights the overall decrease of copper concentrations and the relative lack of difference between results for the two swale designs.

Copper mass removal by the swales is statistically significant for both swale designs. Mass removals shown here for the SHA swale (770 mg, 70%) and the MDE swale (415 mg, 46.1%) are reasonable when compared to other similar studies which report 14-67% (Schueler 1994) and 23-81% (Rushton 2001) mass reduction.

Table 4-15. Copper distribution and reduction summary statistics for all three channels.

		Direct Channel	SHA Swale	MDE Swale	SHA Reduction		MDE Reduction		MDE Reduction-SHA Reduction	
						%		%		%
Total Mass (mg)	Mean	1,270	758	922	770	70.0	415	46.1	-344	-13.1
	Median	997	140	320	811	100	63.1	88.4	-328	-8.37
	Standard Deviation	933	1,210	1,202	585	44.3	790	61.3	509	40.1
	# Samples	12	10	12	9	9	11	11	4	4
N-EMC (µg/l)	Mean	54.1	14.6	16.1	3.98	5.70	11.0	28.0	7.89	20.9
	Median	42.3	4.83	8.64	5.40	13.4	14.1	35.3	4.99	22.3
	Standard Deviation	37.0	19.9	22.5	9.37	45.1	12.5	41.0	12.7	35.8
	# Samples	12	10	12	5	5	6	6	5	5
First Flush (%)	Mean	32.2	31.0	30.0		3.97		2.21		-1.25
	Median	26.4	31.8	28.9		-2.47		3.61		-2.08
	Standard Deviation	15.7	5.06	8.49		19.1		11.0		7.89
	# Samples	7	5	7		5		7		5

According to the probability plot (Figure 4-24), both swales appear to be capable of reducing the mean concentrations when compared to the direct runoff. This N-EMC reduction is statistically significant for the MDE swale, however is not for the SHA swale. Although the mean and median value for SHA copper removal is positive, the variance and low number of samples makes this difference not significant.

The statistically significant removal in the MDE swale and lack of significant removal in the SHA swale suggests that the MDE swale is slightly better at decreasing copper N-EMC; however, when the difference between these swales on an individual storm basis is tested, the difference is not significant. Similarly, there is no significant difference between swale perform in terms of copper mass reduction. The inclusion of a wide pretreatment area, therefore, does not appear to make a difference on grass swale

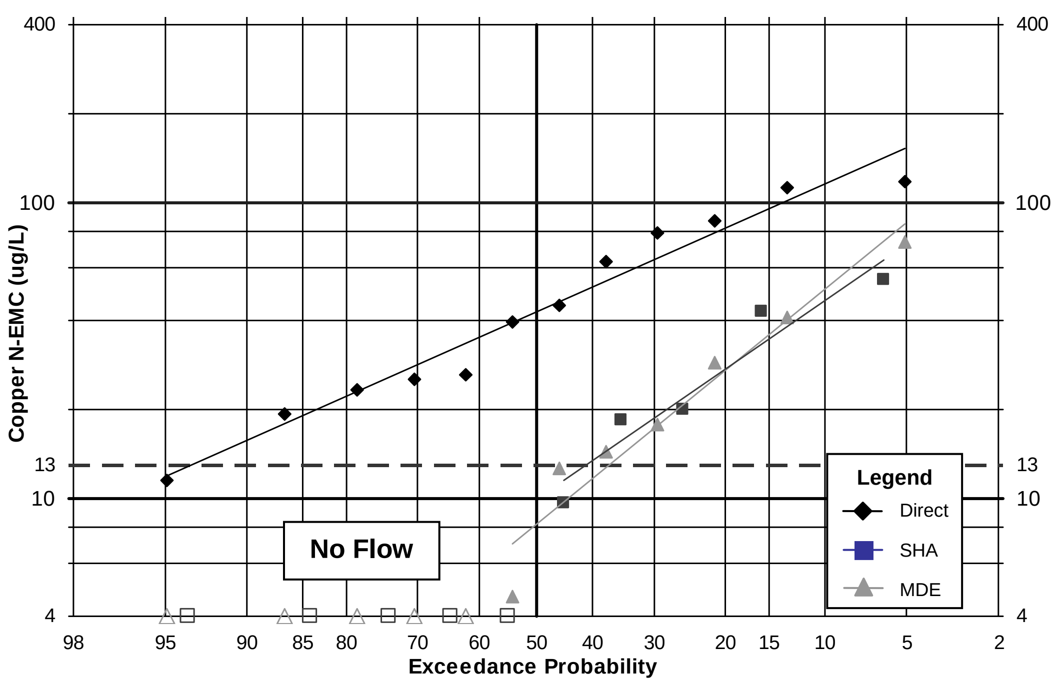

Figure 4-24. Copper N-EMC probability plot.

efficiency with respect to copper.

Finally, copper concentrations with respect to time closely mirror the trends shown in zinc removal. Like zinc, there is no statistical evidence that the grass swales reduce the mass-based first flush of copper. This suggests that like zinc, the initial first flush is primarily composed of copper in the dissolved form (Dean *et al.* 2005). Copper removal is most likely based on a similar removal mechanism to that described for zinc in Section 4.5.1.

4.7.4 Lead

Lead shows a slightly different pattern than copper and zinc because it is predominantly found bound to particulate and organic matter in highway runoff (Dean *et al.* 2005). Despite this difference in composition, and thereby removal mechanism, lead is also successfully removed by both grass swales. This is shown in the removal summary (Table 4-16) and the probability plot (Figure 4-25).

Lead mass removal for the SHA swale (73%) and the MDE swale (59%) are both statistically significant and reasonable when compared to mass reductions of 18-94% shown in the literature (Schueler 1994, Rushton 2001). Therefore, the grass swales are successfully removing lead mass

Table 4-16. Lead distribution and reduction summary statistics for all three channels.

		Direct Channel	SHA Swale	MDE Swale	SHA Reduction		MDE Reduction		MDE Reduction-SHA Reduction	
						%		%		%
Total Mass (mg)	Mean	524	366	321	350	72.6	267	59.1	-123	-16.6
	Median	398	83.6	181	371	100	255	85.3	-54.0	-5.66
	Standard Deviation	372	667	412	240	41.0	257	48.1	186	31.3
	# Samples	11	10	11	9	9	10	10	4	4
N-EMC (µg/l)	Mean	22.6	7.23	5.98	1.41	2.21	0.909	-5.07	4.72	17.3
	Median	24.0	2.88	4.75	1.28	10.5	0.424	3.47	1.01	9.84
	Standard Deviation	16.0	10.2	6.62	3.30	38.7	11.0	62.3	6.92	26.0
	# Samples	11	10	11	5	5	7	7	5	5
First Flush (%)	Mean	42.0	27.2	30.3		18.5		11.7		-4.52
	Median	32.9	21.2	31.7		15.5		1.21		-10.3
	Standard Deviation	20.7	10.9	3.94		20.8		18.0		10.9
	# Samples	6	5	6		5		6		5

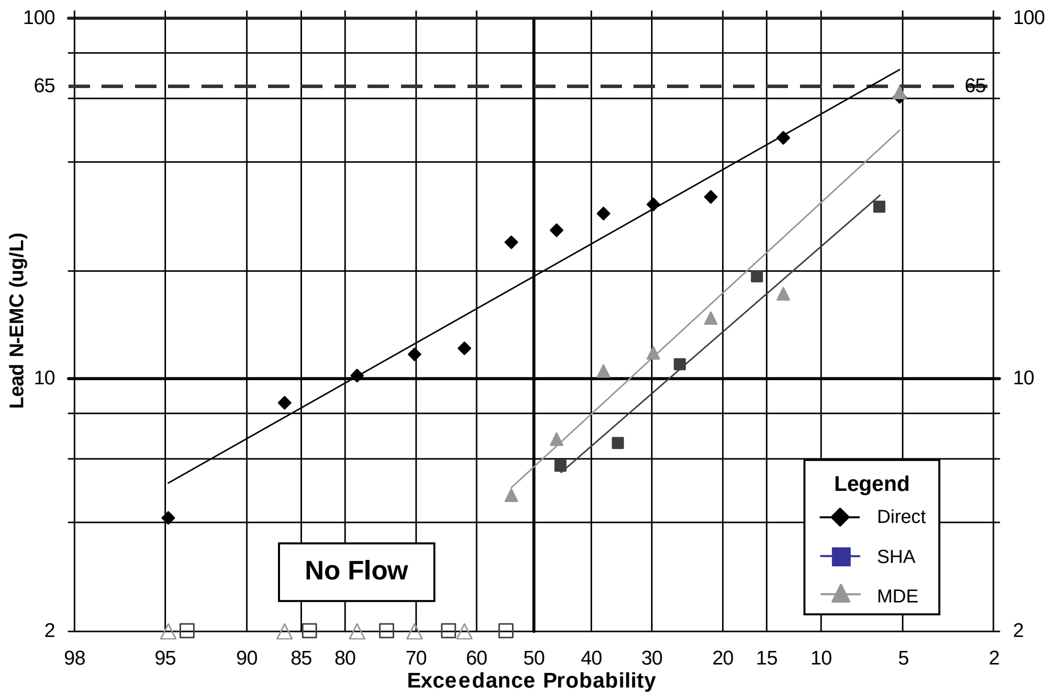

Figure 4-25. Lead N-EMC probability plot.

When concentration removal is considered, as in the probability plot, results are more variable. The lead N-EMC probability plot (Figure 4-25) shows a decrease in lead concentrations when the grass swale effluent is compared to the direct runoff. However, the trend lines drawn through the points suggest that the highway runoff will exceed the maximum allowable concentration for acute lead toxicity of 65 mg/l (MD Department of Environment 2005) very rarely (8% of total storm events), while the grass swales appear to reduce the probability of this occurrence to roughly 4%. This small difference suggests that at high influent concentrations, the grass swales are less capable of reducing lead concentrations, while at low concentrations, they appear to be very successful. This conclusion is further supported by the battery of statistical tests, which show that during

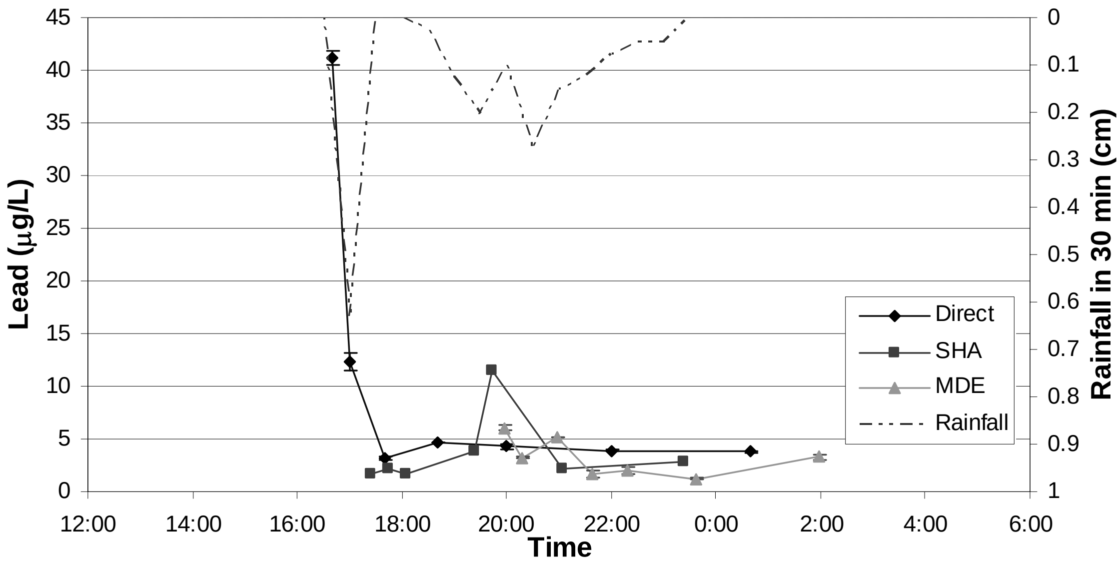

Figure 4-26. Lead Concentrations with Respect to Time (11/16/05)

storm events with measurable flows, the grass swales do not show a statistically significant reduction of normalized mean concentrations.

Because lead is primarily particulate bound, the removal mechanism is different from the other metals and can explain the discrepancy between high lead mass removal and low average lead concentration reduction. Evidence for the different behavior of lead in the grass swales is shown in plots showing lead concentrations with respect to time. The 11/16/05 storm event, shown in Figure 4-26, is typical of lead concentrations with respect to time. The direct channel exhibits a large first flush of constituent from the direct runoff, which is captured by the swale, followed by concentrations that follow the magnitude of flow. Unlike the zinc and copper data, the lead data show a significant mass-based first flush (Figure 4-27), indicative of a particulate bound metal. Both swales show a statistically significant ability to reduce the first flush of lead, unlike the dissolved metals, zinc and copper.

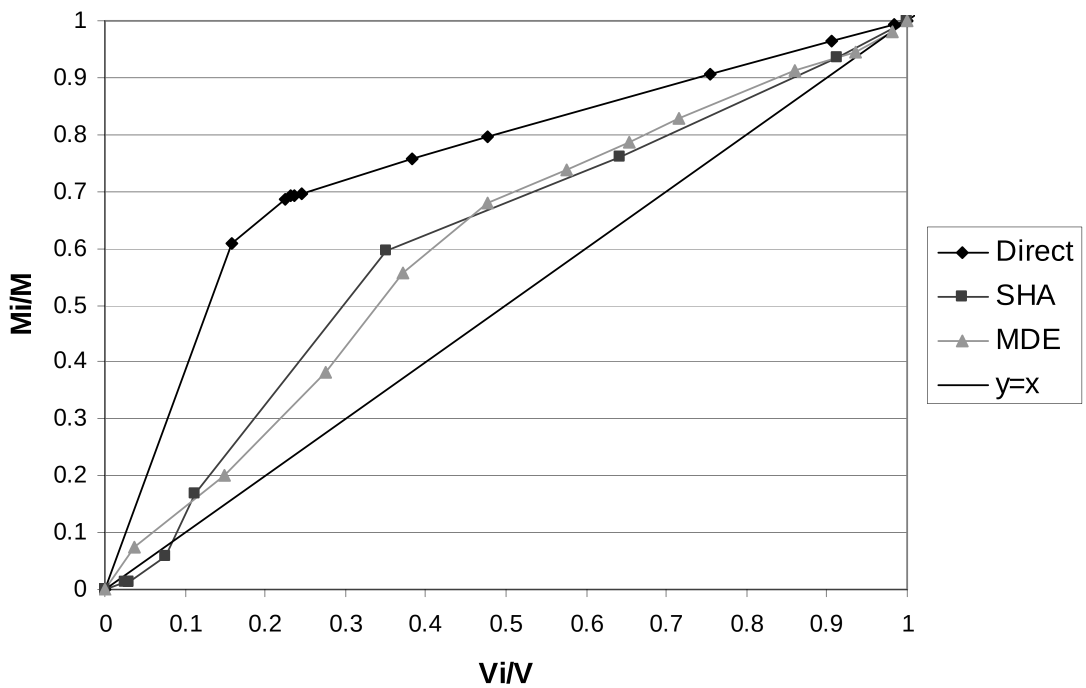

Figure 4-27. Lead mass-based first flush diagram (11/16/05).

The ability to reduce the mass-based first flush and the knowledge that lead is particulate bound suggests that removal mechanisms for lead are identical to those for suspended solids: sedimentation and filtration. This removal mechanism explains the varying ability for the grass swales to reduce N-EMCs for lead. During small storms, the grass swales are capable of removing lead by sedimentation; however, during very intense storm events these removal mechanisms must compete with the resuspension of lead-bound particulates, shorter retention times, more turbulence, and less contact with grass blades, which greatly increases the variability of N-EMC removal. It is important to note, however, that over the course of many storms, the grass swales do appear to effectively reduce the quantity of lead being exported to receiving water bodies.

Finally, the SHA swale reduces both total mass and N-EMC more effectively than the MDE swale. This statistically significant difference is reasonable because the removal mechanisms for lead are similar to the removal mechanisms for suspended solids. As shown in Section 4.2.3, the SHA swale is more effective at reducing TSS mass and concentrations because of its longer travel time, which allows for more sedimentation and filtration. Removal of lead, therefore, appears to be dependent on travel time and is not affected by the inclusion of a pretreatment area adjacent to the swale.

Chapter 5

CONCLUSIONS

The purpose of this study was to evaluate the performance of grass swales as a stormwater management practice using field-scale monitoring. The project focused on characterizing the overall performance of grass swales in treating highway runoff and evaluating the effect of the shallow slope grass pretreatment area adjacent to the swale in many highway designs.

In order to test these hypotheses, two nearly identical swales were constructed in the median of MD Rt. 32, a four-lane highway, near Savage, Maryland. One of these swales was designed to meet Maryland Department of the Environment (MDE) specifications for grass swale construction, which includes a shallow sloped, filter strip pretreatment area adjacent to the grass swale. The second swale was built such that highway runoff immediately entered the swale without any filter strip or other pretreatment area prior to the swale. A third sampling site, a concrete channel which received runoff directly from the roadway, was assumed to be equivalent in quantity and water quality to the inputs for the two swales. All three sites had identical roadway drainage areas. This method of full-scale experimental design allowed hydrology and pollutant data to be collected at consistent intervals for both influent and effluent without disturbing the operation of the grass swales.

To extract meaningful comparisons between the three channels (2 swales and direct runoff), methods of normalizing hydrologic and pollutant data were devised. The hydrologic effect of the grass swales on highway runoff was determined using peak flow, delay to peak flow, and total normalized volume. Also, because of the sampling method, flow rates with respect to time were compared, allowing a more comprehensive view of the grass swales hydrologic effects. In a similar manner, pollutant concentrations were compared by total mass and by a normalized EMC, which allowed a comparison between flow weighted mean concentrations without the dilution effect of excess rainfall on the grass swale areas.

When hydrologic parameters are considered, it appears that the grass swales are effective at creating a more natural flow delivery with less shock to the receiving water bodies. Both swales significantly reduce the peak flow when compared to the direct runoff by an average of 50-53%. This peak flow reduction is important in reducing the threat of channel scour and likely is responsible for some of the water quality improvement through mechanisms related to lower flow velocities, such as sedimentation. The swales are also capable of increasing the amount of time before the runoff peak is discharged when compared to the direct highway runoff. The mean delay to peak flow is 33 to 34 minutes for both swales. Longer travel times in the grass swales are likely caused by the added flow path length and also the flow retardation caused by the grass surface. These results are reasonable when compared to theoretical flow delays calculated using Manning’s equation. This significant delay and reduction of peak flows, combined with qualitative trends gathered from the flows with respect to time, suggest that the grass swales are effective at infiltrating initial flows and spreading the subsequent flows. This smoothing and spreading of peak flows means that receiving water bodies downstream of the swales receive a more manageable and constant flow, which reduces channel scour and other problems associated with large flow peaks.

Besides the hydrologic improvements achieved by the grass swales through changing the distribution of effluent flows, the swales also have an important effect on total runoff volume. This volume reduction, normalized to remove the extra flow caused by differences in swale drainage areas, is significant in terms of percent reduction for both swales. The effect of the grass swales on total volume reduction is not constant, however, and shows three distinct treatment modes. In the lowest intensity storm events, the grass swales completely capture runoff, such that no measurable flow occurs at the swale outfall. A regression line describing the maximum rainfall depth and duration that can be completely captured by the swales was determined as:

$$R = (0.07 cm / h) D + 0.35 cm \tag{5-1}$$

where R represents total rainfall depth (cm) and D represents storm duration (hours). Using this relationship and data on storm events in the state of Maryland (Kreeb 2003), it was determined that grass swales using these design parameters should completely capture 67% of storm events in Maryland. For storm events with slightly higher rainfall intensities, the grass swales are effective at reducing the total runoff volume through infiltration, however, begin to lose effectiveness above a threshold limit of 80,000 l which corresponds to a rainfall depth of about 3.3 cm. These very large storm events, which only occur in 14% of storm events in Maryland, are not significantly effected by the grass swales in terms of volume reduction. Therefore, the swales theoretically completely capture the smallest 67% of storm events, successfully reduce the total volume in 19% of storm events, and show no effect on the largest 14% of storm events in Maryland. The cumulative effect of these three treatment conditions is that swales successfully reduce the total runoff volume by an average of 46-54%.

The grass swales exhibit generally positive reduction of pollutant mass and mean concentrations for many of the water quality constituents considered in this study. Total suspended solids, nitrite, and the metals zinc, copper, lead and cadmium show statistically significant reductions in total mass and, in most cases, N-EMCs. Reduction of N-EMCs was more difficult to prove because this comparison only included those storms with measurable flow. Mass reduction, however, included all complete-capture storm events and compared the swale effect using a more long-range and cumulative approach. The grass swales successfully removed TSS at a mean rate of 73-84% by mass and 41-52% by N-EMC (reduction of 52-61 mg/l TSS), suggesting that the swales are very capable of reducing suspended solids. Metals were all significantly removed by the swales in terms of mass, with zinc showing the highest removal (75-85% mean), followed by copper (47-70%) and lead (59-73%) which both had similar removal. Cadmium concentrations were almost entirely below detection limits, which made calculation of a removal percentage impossible, however, the swales do appear to be successfully removing this metal. Nitrite is also successfully removed by the swale in terms of mass (55-69%) and N-EMC (56-66%, 0.33 mg/l) likely by oxidation to nitrate in the swale.

Other nutrient removals by the grass swales are much more variable and thereby less significant. The grass swales showed no significant mass removal for any of the remaining measured nutrients (nitrate, TKN and total phosphorus), while the N-EMC data showed a statistically significant increase in TKN and total phosphorus. The high variability in nutrient removal and these statistical findings suggest that the grass swales are greatly affected by factors beyond the control of this study, such as seasonal differences, mowing, or other releases of organic matter. Overall, these differences tend to cancel in terms of mass loading over a long period, however. Because the mass loading is variable and the runoff volume is reduced, the mean concentrations of these nutrients is slightly elevated.

Chloride represents the one pollutant that shows very different results than all other measured constituents. The grass swales appear to be exporting chloride mass and increasing the resulting chloride N-EMC throughout the duration of this study. This increase in chloride is large (mean increase of 216-499 mg/l) and is statistically significant. These results suggest that a large reservoir of chloride accumulates in the roadside grass and soil during winter salting operations and slowly releases chloride during storm events throughout the year. Roadway salting operations appear to the be the only reasonable source for these highly elevated chloride concentrations, and therefore, there must be storm events during the winter or snow melt-off events that cause very high chloride mass delivery to the swale inflow. These storm events were not measured in this study because of the difficulties in sampling near-freezing temperatures.

Overall, the swale data do not appear to show any significant improvement by including a grass pretreatment area adjacent to the swale in terms of both hydrologic improvement and pollutant removal. Actually, for many of the measured parameters, the SHA swale without the pretreatment filter strip shows a statistically significant improvement over the MDE swale. No consistent significant difference exists between the SHA swale and the MDE swale in terms of peak flow reduction, delay to peak flow, or total runoff volume reduction. The pollutant data suggest that the SHA swale is more effective at removing total mass than the MDE swale for suspended solids, TKN, chloride, zinc, and lead. This difference in pollutant removal suggests that the grass swale itself is the most important pollutant removal mechanism and that the grass pretreatment area is of much less importance.

The relative unimportance of the pretreatment area can be explained by defining the treatment mechanisms for different pollutants. Pollutants that are particulate-bound or particulate-related are treated through initial runoff infiltration and then by reducing subsequent concentrations by sedimentation and filtration. This treatment method appears to be very effective, as pollutants like TSS and lead are readily removed by the grass swales. The other metals are likely governed in part by these processes, as their speciation can become predominantly particulate bound during intense rainfall (Dean *et al.* 2005). Despite the inclusion of a pretreatment area in the MDE swale, the SHA swale has a longer maximum travel distance (SHA 198m, MDE 152 m), allowing for more sedimentation and filtration and thereby better particulate-bound pollutant removal.

Dissolved constituents are governed by a different set of treatment mechanisms. Initially, these pollutants are removed by infiltration in a similar manner to particulate-bound pollutants; however, once the soil pore spaces are saturated, the swales remove dissolved pollutants through adsorption and some chemical and biological methods. Nitrite reduction is likely governed by chemical or biological oxidation, while the dissolved metals are most likely removed through adsorption, until their distribution becomes more particulate-bound. As shown by highly variable results in nutrient removal, the treatment methods for dissolved pollutants in grass swales are dependent on many chemical and physical factors and differ for each pollutant.

The results of this study suggest that grass swales are an inexpensive, effective, natural method of controlling the hydrologic effects of highway runoff and reducing pollutant loads and concentrations for suspended solids and metals. The design of grass swales for pollutant removal should focus on increasing infiltration through soil characteristics and increasing sedimentation and filtration through increasing hydraulic retention times. Because of this, additional swale length, thickness of grass, and swale slope are important design factors. The inclusion of a grass pretreatment area adjacent to the grass swale does not make any significant difference in hydrologic or water quality improvement in swales of this size (200 m length).

The conclusions suggested by this research, as applied in a highway design environment, suggest that the greatest runoff hydrology and water quality benefits will occur when the grass swales are as long as possible. The importance of increased retention times suggests that swales should be designed with long swale length, shallow channel slopes, thick vegetation, and soils that promote infiltration. When possible, it is best to allow grass in the swales to grow naturally to fill the channel depth. Inclusion of a pretreatment area may add some improvements; however, if the swales are designed correctly with a long length, the improvement is negligible. Care should be taken in design to ensure that no washout occurs by ensuring that the slopes are shallow and that the soil is firm enough to prevent channel scour. Finally, this research suggests that grass swales generally improve runoff characteristics and should be employed, where physical limitations allow, instead of concrete channels even in those sites that cannot provide the necessary width for a pretreatment area.

Further research is required to fully examine grass swales and their effect on nutrients. A larger data set would allow a better test of removal significance. Also, more nutrient data is required to define the underlying causes for widely variable nutrient removals. A more thorough examination of metal speciation in grass swale effluent would also afford a better understanding of the removal mechanisms in the grass swales and how dissolved or particulate-bound metal fractions change throughout the swale. Finally, by classifying storm events according to their attributes, such as number of rainfall peaks or intensities, the relationship between constituent removal and storm characteristics can be further explored.

Appendix A

N-EMC and Mass Data for All Storm Events

	TSS (mg/L)			Nitrate (mg/L)			Nitrite (mg/L)			TKN (mg/L)			TP (mg/L)		
Storm Event	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE
11/12/2004	25.1	14.8	12.8	3.00	10.3	10.8	0.204	0.0295	0.0379	1.03	2.43	2.11	0.398	1.26	0.969
12/19/2004	45.3	7.42					0.196	0.0254		1.63	1.76		0.166	0.573	
1/13/2005	100		11.4	1.21		0.521	0.0582		0.0342	1.56		1.45	0.331		0.568
4/1/2005	12.1	19.7	19.9				0.0851	0.0419	0.0333	0.921	2.37	2.92	0.294	0.771	0.441
5/19/2005	25.1	18.5	27.6	0.728	2.83	1.91	0.0700	0.0735	0.0915	1.39	4.71	4.36	0.164	0.153	1.03
6/3/2005	36.2		16.6	3.57		9.31	0.0926		0.0714	2.01		4.35	0.265		0.592
6/27/2005	59.5	0.00	0.00	1.67	0.00	0.00	0.421	0.00	0.00	3.54	0.00	0.00	0.805	0.00	0.00
7/18/2005	357	0.00	0.00	1.22	0.00	0.00	0.253	0.00	0.00	4.58	0.00	0.00	0.0951	0.00	0.00
8/8/2005	132	0.00	0.00	2.37	0.00	0.00	0.309	0.00	0.00	2.83	0.00	0.00	0.359	0.00	0.00
9/26/2005	98.7	0.00	0.00				1.11	0.00	0.00	5.20	0.00	0.00	0.516	0.00	0.00
10/21/2005	119	0.00	0.00				0.622	0.00	0.00	10.2	0.00	0.00	2.50	0.00	0.00
10/24/2005	9.70	8.85	6.62				0.171	0.114	0.167	1.02	2.66	3.20	0.228	0.568	0.211
11/16/2005	108	18.0	20.5				0.205	0.151	0.101	4.70	3.96	2.88	0.398	0.374	0.383
1/11/2006	327	39.6	61.6				0.235	0.352	0.343	4.47	4.93	5.88	0.894	0.822	0.904
1/29/2006	87.6	0.00	0.00				0.486	0.00	0.00	4.67	0.00	0.00	0.367	0.00	0.00
3/2/2006	225	0.00	0.00	3.60	0.00	0.00	1.37	0.00	0.00	10.4	0.00	0.00	0.771	0.00	0.00
5/7/2006	63.4	0.00	0.00	3.91	0.00	0.00	0.603	0.00	0.00				1.02	0.00	0.00
5/11/2006	104	40.9	105	2.07	1.89	2.97	0.180	0.135	0.221				0.582	1.15	1.56

	Cl (mg/L)			Lead (ug/L)			Copper (ug/L)			Zinc (ug/L)			Cadmium (ug/L)		
Storm Event	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE
11/12/2004	17.3	62.1	125	12.2	10.9	11.8	25.3	19.9	28.7	80.5	21.1	20.6	1.00	1.30	1.65
12/19/2004	20.6	86.1													
1/13/2005	6.87		290	46.5		62.2	19.4		12.6	94.7		252	2.19		1.72
4/1/2005	9.73	411	891	28.7	29.8	14.7	39.4	42.9	17.8	321	336	153	4.58	1.35	1.44
5/19/2005	5.86	190	282	24.1	19.1	10.6	63.6	55.1	40.9	541	146	181	1.47	1.52	1.77
6/3/2005	5.45		337	8.62		17.2	23.3		74.0	226		194	1		1.89
6/27/2005	13.1	0.00	0.00	60.7	0.00	0.00	117	0.00	0.00	1580	0.00	0.00	2.26	0.00	0.00
7/18/2005	9.54	0.00	0.00	25.8	0.00	0.00	113	0.00	0.00	738	0.00	0.00	1.00	0.00	0.00
8/8/2005	2.68	0.00	0.00	32.0	0.00	0.00	86.4	0.00	0.00	664	0.00	0.00	1.00	0.00	0.00
9/26/2005	10.4	0.00	0.00	11.7	0.00	0.00	79.3	0.00	0.00	261	0.00	0.00	1.00	0.00	0.00
10/21/2005	10.8	0.00	0.00	30.6	0.00	0.00	45.2	0.00	0.00	575	0.00	0.00	4.24	0.00	0.00
10/24/2005	2.46	100	395	4.14	6.62	6.80	11.5	18.3	14.5	162	193	261			
11/16/2005	4.68	139	197	10.2	5.76	4.75	26.1	9.67	4.68	378	176	295			
1/11/2006	14.9	602	1540							677	240	377			
1/29/2006	13.4	0.00	0.00							324	0.00	0.00			
3/2/2006	137	0.00	0.00												
5/7/2006															
5/11/2006															

	TSS (g)			Nitrate (g)			Nitrite (g)			TKN (g)			TP (g)		
Storm Event	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE
11/12/2004	1300	480	649	155	339	450	10.6	1.09	2.34	53.5	72.1	105	20.7	36.8	44.2
12/19/2004	768	33.7					3.33	0.115		27.7	7.99		2.82	2.60	
1/13/2005	8510		2140	113		97.8	5.34		6.42	121		272	29.2		106
4/1/2005	268	1360	1420				1.94	2.89	2.38	20.7	164	209	6.39	53.2	31.5
5/19/2005	1460	1080	2860	42.3	160	181	4.06	4.12	8.48	81.0	258	402	9.54	8.07	96.0
6/3/2005	1670		357	165		177	4.28		1.39	92.7		80.2	12.3		12.1
6/27/2005	742	0.00	0.00	20.8	0.00	0.00	5.25	0.00	0.00	44.1	0.00	0.00	10.0	0.00	0.00
7/18/2005	2890	0.00	0.00	9.93	0.00	0.00	2.05	0.00	0.00	37.1	0.00	0.00	0.771	0.00	0.00
8/8/2005	1240	0.00	0.00	22.3	0.00	0.00	2.90	0.00	0.00	26.6	0.00	0.00	3.37	0.00	0.00
9/26/2005	1020	0.00	0.00				11.5	0.00	0.00	53.9	0.00	0.00	5.35	0.00	0.00
10/21/2005	1450	0.00	0.00				7.55	0.00	0.00	124	0.00	0.00	30.3	0.00	0.00
10/24/2005	397	232	171				7.01	3.66	4.77	41.6	82.9	90.8	9.34	17.3	5.79
11/16/2005	8010	521	1010				15.3	4.38	4.91	350	115	141	29.6	10.9	18.4
1/11/2006	6900	285	662				4.96	2.54	3.69	94.4	35.5	63.2	18.9	5.92	9.71
1/29/2006	785	0.00	0.00				4.36	0.00	0.00	41.9	0.00	0.00	3.29	0.00	0.00
3/2/2006	2350	0.00	0.00	37.6	0.00	0.00	14.3	0.00	0.00	108	0.00	0.00	8.05	0.00	0.00
5/7/2006	550	0.00	0.00	33.9	0.00	0.00	5.23	0.00	0.00				8.84	0.00	0.00
5/11/2006	15800	7800	11500	314	360	324	27.3	25.8	24.1				88.4	220	170

	Cl (g)			Lead (mg)			Copper (mg)			Zinc (mg)			Cadmium (mg)		
Storm Event	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE	Direct	SHA	MDE
11/12/2004	898	1480	7940	634	258	655	1310	756	1610	4180	851	893	44.1	38.4	71.5
12/19/2004	349	391													
1/13/2005	614		54400	4180		11700	1730		2360	8910		47200	228		323
4/1/2005	221	28300	63800	614	2060	1050	846	2960	1270	6820	23200	11000	107	92.9	103
5/19/2005	341	10300	26500	1400	987	1030	3690	3040	3740	31400	8390	17200	85.2	84.0	164
6/3/2005	252		5870	398		381	1080		1440	10400		3900	43.2		38.8
6/27/2005	163	0.00	0.00	756	0.00	0.00	1460	0.00	0.00	19700	0.00	0.00	28.2	0.00	0.00
7/18/2005	77.4	0.00	0.00	209	0.00	0.00	915	0.00	0.00	5980	0.00	0.00	7.76	0.00	0.00
8/8/2005	25.2	0.00	0.00	300	0.00	0.00	811	0.00	0.00	6240	0.00	0.00	9.02	0.00	0.00
9/26/2005	108	0.00	0.00	122	0.00	0.00	823	0.00	0.00	2710	0.00	0.00	9.97	0.00	0.00
10/21/2005	132	0.00	0.00	371	0.00	0.00	45.2	0.00	0.00	575	0.00	0.00	4.24	0.00	0.00
10/24/2005	100	3330	11200	170	194	181	469	544	405	6640	5940	7110			
11/16/2005	349	4050	9500	792	167	233	2020	281	234	28100	5110	14500			
1/11/2006	314	4340	16600							14300	1730	4050			
1/29/2006	120	0.00	0.00							2900	0.00	0.00			
3/2/2006	1430	0.00	0.00												
5/7/2006															
5/11/2006															

Appendix B

Flow and Concentration Data with Respect to Time for All Storm Events

11/12/2004

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	11/12/2004 3:22	0	1.49	15.0	44.6	139	1.00	0.753	5.20	2.70	0.313	67.1	80.7
3, 4	11/12/2004 3:42	20	0.92	9.84	33.8	189	1.00	0.224	4.02	1.78	0.413	18.7	15.2
5, 6	11/12/2004 4:02	40	1.85	122	25.8	134	1.00	0.169	3.57	1.37	0.405	23.5	12.3
7, 8	11/12/2004 4:22	60	0.27	234	17.8	79.0	1.00	0.115	3.12	0.961	0.397	12.3	9.40
9, 10	11/12/2004 4:42	80	0.27	119	16.7	45.8	1.00	0.219	3.35	1.32	0.374	7.69	12.3
11, 12	11/12/2004 5:02	100	0.51	3.59	15.5	12.5	1.00	0.323	3.57	1.69	0.352	10.0	15.1
13, 14	11/12/2004 5:22	120	1.38	2.29	15.2	12.5	1.00	0.261	3.20	1.24	0.371	9.94	14.7
15, 16	11/12/2004 5:42	140	1.89	1.00	14.9	12.5	1.00	0.199	2.82	0.796	0.390	27.5	14.3
17, 18	11/12/2004 6:02	160	2.41	4.39	23.3	73.3	1.00	0.183	2.85	0.856	0.406	17.3	14.0
19,20	11/12/2004 7:02	220	3.70	7.79	31.7	134	1.00	0.166	2.88	0.916	0.422	30.4	13.7
21, 22	11/12/2004 8:02	280	3.78	5.31	26.4	73.3	1.00	0.198	3.06	1.02	0.430	27.2	17.7
23,24	11/12/2004 9:02	340	1.66	2.83	21.1	12.5	1.00	0.231	3.24	1.12	0.438	24.1	21.6

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	11/12/2004 7:14	0	1.61	6.21	15.2	54.0	1.00	0.0455	6.40	3.54	1.60	15.2	57.6
3, 4	11/12/2004 7:34	20	2.84	6.21	17.1	12.5	1.00	0.0273	5.80	2.08	0.927	16.0	119
5, 6	11/12/2004 7:54	40	3.48	7.19	19.3	24.8	1.00	0.0281	6.20	1.87	0.899	10.0	71.8
7, 8	11/12/2004 8:14	60	5.29	8.18	21.4	37.0	1.00	0.0289	6.60	1.66	0.872	8.86	24.4
9, 10	11/12/2004 8:34	80	5.69	6.63	22.7	24.8	1.00	0.0289	6.30	1.73	0.927	13.8	21.1
11, 12	11/12/2004 8:54	100	5.49	5.08	24.0	12.5	1.00	0.0289	6.00	1.79	0.981	14.8	17.8
13, 14	11/12/2004 9:14	120	4.85	5.96	18.6	12.5	1.00	0.0264	11.7	1.84	0.943	12.5	39.8
15, 16	11/12/2004 9:34	140	4.24	6.84	13.2	12.5	1.00	0.0240	17.4	1.89	0.904	13.6	61.8
17, 18	11/12/2004 9:54	160	3.41	9.71	13.2	12.5	1.00	0.0215	12.0	1.86	0.928	11.3	67.8
19,20	11/12/2004 10:54	220	3.88	12.6	13.2	12.5	1.00	0.0190	6.60	1.84	0.952	10.0	73.8
21, 22	11/12/2004 11:54	280	4.27	9.90	12.2	12.5	1.00	0.0182	6.40	1.84	0.991	8.59	47.9
23,24	11/12/2004 12:54	340	5.10	7.21	11.2	12.5	1.00	0.0173	6.20	1.84	1.03	11.4	22.0

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	11/12/2004 7:26	0	5.74	3.98	16.0	12.5	1.00	0.0240	4.60	1.89	1.15	6.25	34.4
3, 4	11/12/2004 7:46	20	9.29	5.95	19.2	12.5	1.00	0.0355	7.00	1.60	0.516	11.3	184
5, 6	11/12/2004 8:06	40	9.73	10.9	27.8	12.5	1.00	0.0397	6.80	1.50	0.573	11.3	145
7, 8	11/12/2004 8:26	60	9.78	15.8	36.4	12.5	1.00	0.0438	6.60	1.39	0.631	7.50	105
9, 10	11/12/2004 8:46	80	8.66	11.8	25.5	12.5	1.00	0.0355	6.20	1.36	0.583	8.75	99.9
11, 12	11/12/2004 9:06	100	7.00	7.80	14.6	12.5	1.00	0.0273	5.80	1.33	0.535	7.32	94.4
13, 14	11/12/2004 9:26	120	5.55	6.11	13.6	12.5	1.00	0.0206	6.10	1.31	0.528	10.3	84.1
15, 16	11/12/2004 9:46	140	4.73	4.43	12.7	12.5	1.00	0.0140	6.40	1.29	0.522	8.75	73.8
17, 18	11/12/2004 10:06	160	4.25	4.78	12.4	12.5	1.00	0.0173	6.60	1.20	0.554	8.70	53.4
19,20	11/12/2004 11:06	220	5.42	5.13	12.1	12.5	1.00	0.0206	6.80	1.12	0.586	5.00	33.0
21, 22	11/12/2004 12:06	280	5.02	5.47	12.7	12.5	1.00	0.0140	6.90	1.09	0.564	5.06	40.8
23,24	11/12/2004 13:26	360	6.92	5.82	13.4	12.5	1.00	0.00742	7.00	1.07	0.541	7.50	48.6

12/19/2004

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	12/19/2004 17:20	0	2.88					0.404		3.19	0.304	111	16.2
3, 4	12/19/2004 17:40	20	1.50					0.0521		2.69	0.281	98.8	13.9
5, 6	12/19/2004 18:00	40	0.71					0.107		2.38	0.191	65.4	14.8
7, 8	12/19/2004 18:20	60	0.43					0.163		2.07	0.101	47.8	15.8
9, 10	12/19/2004 18:40	80	0.55					0.317		1.60	0.194	23.5	31.7
11, 12	12/19/2004 19:20	100	0.47					0.312		1.42	0.182	26.2	39.6
13, 14	12/19/2004 20:00	120	0.47					0.307		1.24	0.169	32.7	47.5
15, 16	12/19/2004 20:40	140	0.41					0.260		1.53	0.177	32.7	44.1
17, 18	12/19/2004 21:40	160	0.38					0.214		1.82	0.185	7.14	40.7
19,20	12/19/2004 22:40	220	0.31					0.00		0.00	0.00	0.00	0.00
21, 22	12/19/2004 23:40	280	0.30					0.00		0.00	0.00	0.00	0.00
23,24	12/20/2004 1:20	340	0.27					0.00		0.00	0.00	0.00	0.00

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	12/19/2004 19:16	0	0.35					0.0289	0.00	1.96	0.403	1.00	63.7
3, 4	12/19/2004 19:36	20	0.41					0.0256	0.00	1.72	0.474	16.3	58.7
5, 6	12/19/2004 19:56	40	0.37					0.0223	0.00	1.27	0.551	1.27	82.6
7, 8	12/19/2004 20:16	60	0.39					0.0240	0.00	1.67	0.551	11.1	102
9, 10	12/19/2004 20:36	80	0.37					0.0215	0.00	1.57	0.427	8.70	80.6
11, 12	12/19/2004 20:56	100	0.35					0.0190	0.00	1.47	0.304	7.59	59.8
13, 14	12/19/2004 21:16	120	0.36					0.0182	0.00	1.17	0.381	6.25	61.2
15, 16	12/19/2004 21:36	140	0.33					0.0173	0.00	0.866	0.458	9.76	62.6
17, 18	12/19/2004 21:56	160	0.34					0.0173	0.00	1.17	0.474	1.00	64.1
19,20	12/19/2004 22:56	220	0.27					0.0173	0.00	1.47	0.490	5.06	65.5
21, 22	12/19/2004 23:56	280	0.25					0.00	0.00	0.00	0.00	0.00	0.00
23,24	12/20/2004 1:16	340	0.18					0.00	0.00	0.00	0.00	0.00	0.00

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/0/1900 0:00	0	0.00										
3, 4	1/0/1900 0:00	20	0.00										
5, 6	1/0/1900 0:00	40	0.00										
7, 8	1/0/1900 0:00	60	0.00										
9, 10	1/0/1900 0:00	80	0.00										
11, 12	1/0/1900 0:00	100	0.00										
13, 14	1/0/1900 0:00	120	0.00										
15, 16	1/0/1900 0:00	140	0.00										
17, 18	1/0/1900 0:00	160	0.00										
19,20	1/0/1900 0:00	220	0.00										
21, 22	1/0/1900 0:00	280	0.00										
23,24	1/0/1900 0:00	360	0.00										

1/13/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (m	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/13/2005 21:46	0	1.34	72.6	38.4	479	22.1	0.239	1.34	2.10	0.734	105	9.18
3, 4	1/13/2005 22:06	20	0.63	462	24.4	167	13.5	0.0537	0.533	1.50	0.371	90.0	6.24
5, 6	1/13/2005 22:26	40	0.87	245	22.7	218	9.24	0.0736	1.39	1.21	0.262	22.8	5.97
7, 8	1/13/2005 22:46	60	1.86	29.1	21.1	269	5.01	0.0934	2.25	0.925	0.153	20.5	5.70
9, 10	1/13/2005 23:06	80	0.73	66.4	17.4	162	4.90	0.102	2.66	0.858	0.117	30.4	4.89
11, 12	1/13/2005 23:46	120	0.41	104	13.7	54.4	4.80	0.110	3.08	0.792	0.0820	19.2	4.08
13, 14	1/14/2005 0:26	160	0.30	67.1	12.4	105	2.90	0.119	4.07	0.736	0.106	16.2	6.60
15, 16	1/14/2005 1:06	200	0.26	30.4	11.1	155	1.00	0.128	5.06	0.680	0.130	20.3	9.12
17, 18	1/14/2005 2:06	260	0.28	36.2	16.3	130	1.00	0.0942	3.22	0.748	0.249	14.8	8.46
19,20	1/14/2005 3:06	320	8.00	42.1	21.6	105	2.48	0.0603	1.37	0.816	0.368	22.8	7.80
21, 22	1/14/2005 4:06	380	7.47	42.0	19.9	81.3	1.00	0.0529	1.07	1.81	0.353	164	7.14
23,24	1/14/2005 5:46	480	5.03	42.0	18.2	57.8	1.00	0.0455	0.766	2.80	0.339	124	6.48

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (m	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/0/1900 0:00	0	0.00										
3, 4	1/0/1900 0:00	0	0.00										
5, 6	1/0/1900 0:00	0	0.00										
7, 8	1/0/1900 0:00	0	0.00										
9, 10	1/0/1900 0:00	0	0.00										
11, 12	1/0/1900 0:00	0	0.00										
13, 14	1/0/1900 0:00	0	0.00										
15, 16	1/0/1900 0:00	0	0.00										
17, 18	1/0/1900 0:00	0	0.00										
19,20	1/0/1900 0:00	0	0.00										
21, 22	1/0/1900 0:00	0	0.00										
23,24	1/0/1900 0:00	0	0.00										

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (m	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/13/2005 22:58	0	2.27	24.4	10.4	137	1.00	0.0206	0.378	1.57	0.210	11.4	165
3, 4	1/13/2005 23:18	20	5.25	434	10.7	186	1.00	0.0190	0.393	1.89	0.198	3.70	135
5, 6	1/13/2005 23:38	40	5.81	242	9.19	255	1.00	0.0182	0.404	1.60	0.175	2.50	127
7, 8	1/13/2005 23:58	60	4.68	50.7	7.63	324	1.00	0.0173	0.414	1.32	0.153	6.10	118
9, 10	1/14/2005 0:18	80	3.97	33.1	8.17	234	1.00	0.0198	0.415	1.24	0.145	6.33	133
11, 12	1/14/2005 0:38	100	3.30	15.5	8.70	144	1.00	0.0223	0.415	1.17	0.137	5.13	147
13, 14	1/14/2005 0:58	120	2.62	19.1	9.91	140	1.00	0.0190	0.314	1.20	0.199	2.47	158
15, 16	1/14/2005 1:18	140	2.15	22.6	11.1	136	1.00	0.0157	0.213	1.23	0.262	2.53	169
17, 18	1/14/2005 1:38	160	1.52	19.6	9.66	134	1.00	0.0173	0.282	1.27	0.286	1.27	189
19,20	1/14/2005 2:38	220	1.65	16.5	8.21	132	1.00	0.0190	0.352	1.30	0.310	3.66	209
21, 22	1/14/2005 3:38	280	42.76	21.7	7.23	137	1.00	0.0198	0.304	0.857	0.342	2.56	179
23,24	1/14/2005 4:58	360	19.61	27.0	6.26	142	1.00	0.0206	0.256	0.416	0.374	20.0	148

4/1/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	4/1/2005 21:32	0	1.46	34.1	57.1	570	5.00	0.212		2.77	0.419	72.6	26.8
3, 4	4/1/2005 21:52	1	2.83	31.4	40.6	344	4.29	0.102		1.24	0.271	8.33	14.5
5, 6	4/1/2005 22:12	2	2.28	22.4	29.8	254	2.65	0.0802		0.746	0.255	8.22	10.2
7, 8	4/1/2005 22:32	3	1.66	13.3	19.0	164	1.00	0.0587		0.248	0.239	8.22	5.94
9, 10	4/1/2005 22:52	4	0.12	25.5	36.2	313	3.34	0.0901		0.515	0.286	5.48	6.96
11, 12	4/1/2005 23:32	5	0.04	37.7	53.4	461	5.69	0.122		0.781	0.332	11.0	7.98
13, 14	4/2/2005 0:12	6	0.79	35.5	48.6	371	7.85	0.107		0.840	0.313	8.57	8.82
15, 16	4/2/2005 0:52	7	1.06	33.3	43.9	281	10.0	0.0934		0.899	0.294	4.35	9.66
17, 18	4/2/2005 1:52	8	0.10	26.8	36.9	239	6.25	0.0860		0.899	0.310	6.94	8.40
19,20	4/2/2005 2:52	9	0.00	20.4	29.9	196	2.50	0.0785		0.899	0.326	5.71	7.14
21, 22	4/2/2005 3:52	10	0.94	30.4	42.0	341	3.96	0.0595		0.771	0.334	8.41	6.15
23,24	4/2/2005 5:32	11	0.41	40.4	54.0	486	5.43	0.0405		0.642	0.342	11.1	5.16

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	4/1/2005 22:28	0	2.24	8.55	26.9	157	1.00	0.0471		3.50	0.374	23.9	941
3, 4	4/1/2005 22:48	1	3.85	29.5	28.2	156	2.66	0.0554		3.11	0.622	17.6	365
5, 6	4/1/2005 23:08	2	3.71	43.2	62.8	238	1.83	0.0455		2.58	0.691	19.7	315
7, 8	4/1/2005 23:28	3	3.02	56.9	97.5	320	1.00	0.0355		2.04	0.760	19.5	265
9, 10	4/1/2005 23:48	4	2.53	41.9	66.1	283	1.00	0.0388		1.24	0.838	15.6	289
11, 12	4/2/2005 0:08	5	2.44	26.8	34.8	246	1.00	0.0421		0.429	0.917	21.6	314
13, 14	4/2/2005 0:28	6	2.79	25.5	34.6	274	1.00	0.0413		1.04	0.872	22.5	384
15, 16	4/2/2005 0:48	7	2.94	24.1	34.3	302	1.00	0.0405		1.64	0.827	15.1	453
17, 18	4/2/2005 1:08	8	4.35	20.3	29.6	323	1.00	0.0355		1.64	0.628	18.9	360
19,20	4/2/2005 2:08	9	4.47	16.5	24.8	345	1.00	0.0306		1.64	0.429	12.8	266
21, 22	4/2/2005 3:08	10	2.42	22.4	30.8	289	1.00	0.0289		2.25	0.631	14.5	311
23,24	4/2/2005 4:28	11	2.78	28.3	36.8	233	1.00	0.0273		2.85	0.833	14.7	355

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	4/1/2005 22:32	0	4.38	7.43	18.8	145	1.00	0.0273		3.43	0.679	30.6	494
3, 4	4/1/2005 22:52	1	7.18	14.1	16.5	129	1.00	0.0405		2.88	0.416	25.7	895
5, 6	4/1/2005 23:12	2	5.27	12.5	14.5	148	1.00	0.0364		2.70	0.366	17.1	801
7, 8	4/1/2005 23:32	3	3.73	10.8	12.5	168	1.00	0.0322		2.52	0.316	13.9	707
9, 10	4/1/2005 23:52	4	2.97	9.42	12.1	129	1.00	0.0281		2.24	0.320	14.1	634
11, 12	4/2/2005 0:12	5	2.83	8.06	11.7	89.1	1.00	0.0240		1.96	0.323	11.1	560
13, 14	4/2/2005 0:32	6	3.27	7.49	11.1	82.3	1.00	0.0198		1.91	0.302	9.46	621
15, 16	4/2/2005 0:52	7	3.49	6.92	10.4	75.4	1.00	0.0157		1.86	0.281	11.1	682
17, 18	4/2/2005 1:12	8	6.42	8.12	10.9	84.3	1.00	0.0198		1.80	0.252	13.9	620
19,20	4/2/2005 2:12	9	4.18	9.32	11.5	93.2	1.00	0.0240		1.75	0.223	12.0	557
21, 22	4/2/2005 3:12	10	2.00	11.3	11.4	100	1.00	0.0182		1.64	0.252	6.94	531
23,24	4/2/2005 4:32	11	4.39	13.3	11.2	107	1.00	0.0124		1.52	0.281	8.11	505

5/19/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/19/2005 13:16	0	1.76	46.1	160	1110	2.19	0.232	1.38	3.57	0.426	62.7	9.18
3, 4	5/19/2005 13:36	20	0.46	18.4	53.7	335	1.00	0.173	0.960	2.62	0.0531	18.7	6.24
5, 6	5/19/2005 13:56	40	0.73	30.4	46.8	303	1.00	0.144	0.870	2.40	0.0772	28.4	5.97
7, 8	5/19/2005 14:16	60	1.00	42.5	39.9	270	1.00	0.115	0.780	2.17	0.101	17.1	5.70
9, 10	5/19/2005 14:36	80	2.87	32.1	48.3	355	1.00	0.0835	0.750	1.76	0.157	26.0	4.89
11, 12	5/19/2005 15:16	120	5.72	21.7	56.8	440	1.00	0.0521	0.720	1.34	0.214	16.2	4.08
13, 14	5/19/2005 15:56	160	5.04	18.7	67.1	530	1.00	0.0521	0.660	1.37	0.135	40.0	6.60
15, 16	5/19/2005 16:36	200	0.68	15.6	77.5	620	1.00	0.0521	0.600	1.40	0.0563	24.3	9.12
17, 18	5/19/2005 17:36	260	0.46	14.1	89.0	444	1.00	0.0703	0.660	1.04	0.0563	31.2	8.46
19,20	5/19/2005 18:36	320	0.26	12.6	100	267	1.00	0.0884	0.720	0.673	0.0563	13.7	7.80
21, 22	5/19/2005 19:36	380	1.35	23.6	77.2	614	5.37	0.0777	0.780	0.986	0.143	10.8	7.14
23,24	5/19/2005 21:16	480	2.08	34.7	54.0	961	9.73	0.0669	0.840	1.30	0.230	30.7	6.48

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/19/2005 15:50	0	6.56	6.84	32.1	129	1.00	0.0306	1.77	3.79	0.0113	25.0	209
3, 4	5/19/2005 16:10	20	8.64	9.79	40.9	103	1.00	0.0653	1.95	3.10	0.00491	12.3	72.8
5, 6	5/19/2005 16:30	40	5.36	8.35	43.7	97.2	1.00	0.0570	1.80	2.49	0.00813	8.16	71.2
7, 8	5/19/2005 16:50	60	3.63	6.90	46.5	91.4	1.00	0.0488	1.65	1.88	0.0113	6.58	69.6
9, 10	5/19/2005 17:10	80	3.12	7.36	35.4	90.3	1.00	0.0488	1.82	2.55	0.0370	11.3	91.0
11, 12	5/19/2005 17:30	100	2.63	7.82	24.2	89.2	1.00	0.0488	1.98	3.22	0.0627	1.39	112
13, 14	5/19/2005 17:50	120	2.16	9.51	27.1	98.8	1.00	0.0521	2.00	3.21	0.130	12.3	116
15, 16	5/19/2005 18:10	140	1.97	11.2	30.1	109	1.00	0.0554	2.01	3.19	0.198	9.33	119
17, 18	5/19/2005 18:30	160	1.55	12.8	32.6	112	1.00	0.0512	2.16	3.19	0.198	13.5	133
19,20	5/19/2005 19:30	220	1.17	14.4	35.1	115	1.00	0.0471	2.31	3.19	0.198	10.4	147
21, 22	5/19/2005 20:30	280	4.36	15.1	35.7	97.8	1.00	0.0463	2.00	3.17	0.157	16.2	139
23,24	5/19/2005 21:50	360	9.25	15.8	36.3	80.6	1.00	0.0455	1.68	3.16	0.117	9.33	131

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/19/2005 15:58	0	14.86	4.56	17.4	110	1.00	0.0372	0.840	2.99	0.570	22.4	165
3, 4	5/19/2005 16:18	20	18.09	9.75	20.3	97.0	1.00	0.0504	1.20	1.48	0.602	30.5	135
5, 6	5/19/2005 16:38	40	10.69	8.35	18.5	134	1.00	0.0545	1.20	1.83	0.573	32.4	127
7, 8	5/19/2005 16:58	60	7.09	6.96	16.8	170	1.00	0.0587	1.20	2.17	0.544	26.7	118
9, 10	5/19/2005 17:18	80	5.01	6.49	17.9	131	1.00	0.0694	1.25	2.03	0.583	23.0	133
11, 12	5/19/2005 17:38	100	3.84	6.01	18.9	91.5	1.00	0.0802	1.29	1.89	0.622	16.0	147
13, 14	5/19/2005 17:58	120	3.16	5.60	18.9	93.4	1.00	0.0703	1.31	2.20	0.580	17.6	158
15, 16	5/19/2005 18:18	140	3.04	5.18	18.8	95.2	1.00	0.0603	1.32	2.51	0.538	13.9	169
17, 18	5/19/2005 18:38	160	2.76	5.79	24.6	97.4	1.00	0.0545	1.23	2.82	0.585	13.2	189
19,20	5/19/2005 19:38	220	3.75	6.40	30.3	99.7	1.00	0.0488	1.14	3.13	0.631	12.2	209
21, 22	5/19/2005 20:38	280	9.97	5.42	27.1	94.2	1.00	0.0496	1.05	2.79	0.594	9.21	179
23,24	5/19/2005 21:58	360	13.36	4.43	24.0	88.7	1.00	0.0504	0.960	2.45	0.557	6.67	148

6/3/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	6/3/2005 3:26	0	1.12	7.02	37.3	248	1.00	0.403	5.28	3.78	0.390	45.3	13.4
3, 4	6/3/2005 3:46	20	0.93	7.82	22.1	192	1.00	0.141	2.88	2.26	0.255	22.4	8.82
5, 6	6/3/2005 4:06	40	1.50	6.92	20.5	199	1.00	0.122	2.76	1.92	0.263	1.30	7.86
7, 8	6/3/2005 4:26	60	0.88	6.02	18.9	205	1.00	0.103	2.64	1.58	0.271	16.0	6.90
9, 10	6/3/2005 4:46	80	0.19	7.96	18.5	250	1.00	0.150	2.76	1.87	0.283	9.33	6.57
11, 12	6/3/2005 5:26	120	0.27	9.90	18.1	294	1.00	0.198	2.88	2.15	0.294	5.23	6.24
13, 14	6/3/2005 6:06	160	3.79	10.1	23.5	268	1.00	0.124	3.51	2.22	0.286	11.5	5.49
15, 16	6/3/2005 6:46	200	5.35	10.3	28.9	242	1.00	0.0504	4.14	2.29	0.278	71.1	4.74
17, 18	6/3/2005 7:46	260	0.90	8.41	21.0	226	1.00	0.0793	3.24	1.83	0.263	31.6	4.62
19,20	6/3/2005 8:46	320	0.72	6.57	13.1	209	1.00	0.108	2.34	1.37	0.249	4.05	4.50
21, 22	6/3/2005 9:46	380	0.72	6.15	16.6	194	1.00	0.106	3.66	1.37	0.252	6.49	6.30
23,24	6/3/2005 11:26	480	0.36	5.73	20.1	178	1.00	0.103	4.98	1.37	0.255	10.8	8.10

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	6/3/2005 7:38	0	3.14	10.5	62.2	135	1.00	0.0504	5.61	3.14	0.442	17.1	178
3, 4	6/3/2005 7:58	20	5.68	9.09	21.1	91.9	1.00	0.0455	5.88	2.14	0.342	12.3	122
5, 6	6/3/2005 8:18	40	4.57	11.2	27.7	112	1.00	0.0413	5.03	2.21	0.365	10.7	162
7, 8	6/3/2005 8:38	60	3.12	13.3	34.3	133	1.00	0.0372	4.17	2.29	0.387	7.74	202
9, 10	6/3/2005 8:58	80	2.13	9.88	36.7	127	1.00	0.0380	4.34	2.24	0.381	7.79	202
11, 12	6/3/2005 9:18	100	1.53	6.45	39.1	122	1.00	0.0388	4.50	2.20	0.374	8.00	201
13, 14	6/3/2005 9:38	120	1.16	19.6	81.4	136	2.04	0.0388	4.67	2.40	0.345	11.0	200
15, 16	6/3/2005 9:58	140	0.85	32.7	124	151	3.08	0.0388	4.83	2.61	0.316	9.33	199
17, 18	6/3/2005 10:18	160	0.61	19.7	85.0	132	2.04	0.0405	5.91	2.67	0.332	10.7	206
19,20	6/3/2005 11:18	220	0.97	6.68	46.2	114	1.00	0.0421	6.99	2.73	0.349	9.46	212
21, 22	6/3/2005 12:18	280	1.38	6.47	46.2	111	1.00	0.0438	6.48	3.00	0.329	6.67	256
23,24	6/3/2005 13:38	360	1.33	6.27	46.2	107	1.00	0.0455	5.97	3.28	0.310	8.11	300

6/27/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	6/27/2005 13:18	0	0.66	33.5	105	1640	2.86	0.0355	1.44	3.81	0.609	157	11.1
3, 4	6/27/2005 13:38	20	0.03	34.0	60.0	2260	1.00	1.38	0.840	3.73	0.435	52.6	16.2
5, 6	6/27/2005 13:58	40	2.45	80.3	149	2480	2.57	0.908	1.26	4.09	0.944	0.00	15.2
7, 8	6/27/2005 14:18	60	2.68	127	239	2690	4.15	0.434	1.68	4.45	1.45	154	14.3
9, 10	6/27/2005 14:38	80	0.17	72.1	136	1590	2.57	0.336	1.67	3.73	0.933	48.7	13.5
11, 12	6/27/2005 15:18	120	1.82	17.6	34.1	494	1.00	0.237	1.65	3.02	0.413	21.5	12.7
13, 14	6/27/2005 15:58	160	0.22	13.9	33.0	456	1.00	0.210	4.22	2.50	0.430	55.0	12.3
15, 16	6/27/2005 16:38	200	0.05	10.3	31.9	418	1.00	0.183	6.78	1.98	0.448	32.5	12.0
17, 18	6/27/2005 17:38	260	0.00	12.4	32.3	394	1.00	0.206	7.53	2.24	0.445	22.9	12.5
19,20	6/27/2005 18:38	320	0.00	14.4	32.8	369	1.00	0.229	8.28	2.50	0.442	16.3	13.0
21, 22	6/27/2005 19:38	380	0.00	17.1	37.3	493	1.00	0.214	1.50	2.93	0.448	9.52	13.4
23,24	6/27/2005 21:18	480	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

7/18/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	7/18/2005 18:48	0	5.88	28.6	97.5	802	1.00	0.279	1.26	5.08	0.104	399	9.90
3, 4	7/18/2005 19:08	20	0.56	16.2	330	634	1.00	0.138	1.38	3.10	0.0563	236	11.1
5, 6	7/18/2005 19:28	40	0.18	15.5	182	471	1.00	0.188	1.44	2.38	0.0724	145	9.71
7, 8	7/18/2005 19:48	60	0.10	14.8	33.6	307	1.00	0.239	1.50	1.66	0.0884	54.4	8.34
9, 10	7/18/2005 20:08	80	0.02	7.40	16.8	154	1.00	0.120	0.750	0.832	0.0443	0.00	4.17
11, 12	7/18/2005 20:48	120	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00
13, 14	7/18/2005 21:28	160	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00
15, 16	7/18/2005 22:08	200	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00
17, 18	7/18/2005 23:08	260	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00
19,20	7/19/2005 0:08	320	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00
21, 22	7/19/2005 1:08	380	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00
23,24	7/19/2005 2:48	480	0.00	0.00	0.00	0.00	0.00	0.000476	0.00	0.00	0.0000969	0.00	0.00

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

8/8/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	8/8/2005 18:16	0	3.77	49.2	116	1030	1.00	0.532	2.34	5.09	0.438	273	2.93
3, 4	8/8/2005 18:36	20	3.57	19.5	69.2	384	1.00	0.126	2.58	0.956	0.320	11.3	2.68
5, 6	8/8/2005 18:56	40	0.45	11.1	42.3	305	1.00	0.125	2.64	0.875	0.265	4.94	2.42
7, 8	8/8/2005 19:16	60	0.03	9.91	33.0	139	1.00	0.158	2.52	1.36	0.310	2.53	3.92
9, 10	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11, 12	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13, 14	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15, 16	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17, 18	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19,20	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21, 22	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23,24	1/0/1900 0:00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

9/26/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	9/26/2005 18:04	0	0.90	25.2	142	619	1.00	2.92		11.0	1.12	338	27.1
3, 4	9/26/2005 18:24	20	0.94	14.9	111	427	1.00	2.82		8.72	0.708	177	22.7
5, 6	9/26/2005 18:44	40	1.14	12.5	95.9	347	1.00	1.72		7.07	0.594	72.3	14.6
7, 8	9/26/2005 19:04	60	1.39	10.1	80.7	268	1.00	0.629		5.41	0.480	46.5	6.54
9, 10	9/26/2005 19:24	80	1.11	9.32	69.7	177	1.00	0.426		3.76	0.418	100	5.68
11, 12	9/26/2005 20:04	120	0.41	8.58	58.6	86.0	1.00	0.222		2.10	0.355	24.3	4.81
13, 14	9/26/2005 20:44	160	0.36	10.1	49.7	117	1.00	0.492		2.37	0.336	20.1	4.53
15, 16	9/26/2005 21:24	200	0.14	11.7	40.8	148	1.00	0.761		2.63	0.316	27.1	4.25
17, 18	9/26/2005 22:24	260	0.03	9.48	43.4	140	1.00	1.01		2.23	0.339	24.1	4.24
19,20	9/26/2005 23:24	320	0.00	7.27	45.9	133	1.00	1.26		1.82	0.361	28.8	4.23
21, 22	9/27/2005 0:24	380	0.00	7.49	46.8	116	1.00	1.16		2.61	0.373	26.6	4.26
23,24	9/27/2005 2:04	480	0.00	7.72	47.7	99.0	1.00	1.05		3.39	0.384	28.7	4.28

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

10/21/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	10/21/2005 8:34	0	3.68	82.5	128	1220		0.310	#VALUE!	20.3	3.68	295	17.2
3, 4	10/21/2005 8:54	20	1.23	7.44	32.5	320		0.219	#VALUE!	7.07	1.43	74.7	10.8
5, 6	10/21/2005 9:14	40	0.44	6.81	26.4	296		0.445	#VALUE!	5.36	1.50	16.2	7.65
7, 8	10/21/2005 9:34	60	0.27	6.18	20.2	272		0.670	#VALUE!	3.66	1.57	18.5	4.47
9, 10	10/21/2005 9:54	80	0.18	5.32	20.9	248		0.721	#VALUE!	3.79	1.80	31.2	5.09
11, 12	10/21/2005 10:34	120	0.14	4.46	21.5	224		0.771	#VALUE!	3.92	2.02	16.0	5.71
13, 14	10/21/2005 11:14	160	0.22	4.21	20.2	212		0.840	#VALUE!	4.69	2.55	16.3	6.16
15, 16	10/21/2005 11:54	200	0.16	3.96	19.0	200		0.909	#VALUE!	5.46	3.07	15.9	6.61
17, 18	10/21/2005 12:54	260	0.13	4.67	21.7	217		0.982	#VALUE!	5.47	3.07	12.5	7.07
19,20	10/21/2005 13:54	320	0.12	5.38	24.4	234		1.06	#VALUE!	5.49	3.08	12.5	7.52
21, 22	10/21/2005 14:54	380	0.27	3.90	17.2	219		1.19	#VALUE!	4.85	2.14	11.0	8.12
23,24	10/21/2005 16:34	480	0.29	2.43	10.1	204		1.32	#VALUE!	4.22	1.19	12.3	8.71

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

10/24/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	10/24/2005 19:16	0	0.73	6.88	24.5	272		1.16		3.74	0.483	44.3	10.8
3, 4	10/24/2005 19:36	20	0.49	19.3	20.5	194		0.250		2.80	0.374	21.3	9.51
5, 6	10/24/2005 19:56	40	0.67	12.0	18.9	187		0.476		2.67	0.360	22.8	8.65
7, 8	10/24/2005 20:16	60	1.35	4.62	17.4	179		0.702		2.55	0.345	18.7	7.79
9, 10	10/24/2005 20:36	80	1.30	4.12	14.4	168		0.413		1.90	0.297	14.6	5.12
11, 12	10/24/2005 21:16	120	2.34	3.63	11.4	158		0.123		1.26	0.249	9.76	2.45
13, 14	10/24/2005 21:56	160	1.90	3.79	12.1	158		0.117		0.910	0.220	13.6	1.93
15, 16	10/24/2005 22:36	200	1.27	3.94	12.9	158		0.110		0.560	0.191	7.50	1.40
17, 18	10/24/2005 23:36	260	1.17	4.07	11.6	178		0.102		0.492	0.199	6.33	1.33
19,20	10/25/2005 0:36	320	0.80	4.20	10.3	197		0.0934		0.424	0.207	9.88	1.25
21, 22	10/25/2005 1:36	380	0.96	3.84	9.48	174		0.0810		0.639	0.212	3.75	1.29
23,24	10/25/2005 3:16	480	1.75	3.49	8.62	150		0.0686		0.853	0.217	6.25	1.32

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	10/24/2005 22:02	0	1.64	3.09	12.6	153		0.0851		2.23	0.506	7.32	158
3, 4	10/24/2005 22:22	20	2.03	2.95	12.9	99.7		0.0884		2.00	0.271	7.50	117
5, 6	10/24/2005 22:42	40	2.02	3.98	13.3	130		0.0984		1.88	0.337	5.00	94.2
7, 8	10/24/2005 23:02	60	2.08	5.02	13.8	160		0.108		1.77	0.403	7.59	71.6
9, 10	10/24/2005 23:22	80	2.00	4.06	11.3	147		0.0967		1.76	0.474	15.0	72.9
11, 12	10/24/2005 23:42	100	1.87	3.10	8.87	133		0.0851		1.76	0.544	2.44	74.2
13, 14	10/25/2005 0:02	120	1.87	4.75	10.2	129		0.0802		1.76	0.392	3.75	81.8
15, 16	10/25/2005 0:22	140	2.00	6.40	11.5	126		0.0752		1.76	0.239	3.70	89.3
17, 18	10/25/2005 0:42	160	2.33	4.65	10.9	124		0.0760		1.76	0.308	1.25	72.2
19,20	10/25/2005 1:42	220	1.53	2.89	10.3	122		0.0769		1.76	0.377	2.50	55.1
21, 22	10/25/2005 2:42	280	2.02	4.16	12.4	127		0.0703		1.76	0.392	5.00	51.2
23,24	10/25/2005 4:02	360	4.11	5.44	14.5	132		0.0636		1.76	0.406	9.76	47.3

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	10/24/2005 22:06	0	2.86	4.36	4.70	108		0.0752		1.75	0.156	4.94	182
3, 4	10/24/2005 22:26	20	4.24	3.55	6.75	112		0.0719		1.75	0.0306	2.47	240
5, 6	10/24/2005 22:46	40	3.99	3.40	7.38	123		0.0703		1.52	0.0964	1.25	202
7, 8	10/24/2005 23:06	60	3.94	3.25	8.00	133		0.0686		1.29	0.162	3.75	164
9, 10	10/24/2005 23:26	80	3.57	3.14	7.13	120		0.0694		1.37	0.156	2.50	154
11, 12	10/24/2005 23:46	100	3.10	3.03	6.26	106		0.0703		1.45	0.149	3.70	144
13, 14	10/25/2005 0:06	120	2.89	2.28	5.00	87.8		0.0744		1.45	0.0772	1.22	152
15, 16	10/25/2005 0:26	140	2.92	1.52	3.74	69.9		0.0785		1.44	0.00491	3.80	159
17, 18	10/25/2005 0:46	160	3.20	1.74	5.04	86.3		0.0752		1.29	0.0402	1.23	156
19,20	10/25/2005 1:46	220	1.66	1.97	6.35	103		0.0719		1.13	0.0756	2.50	154
21, 22	10/25/2005 2:46	280	2.83	2.64	6.05	110		0.0661		1.16	0.0836	2.50	152
23,24	10/25/2005 4:06	360	4.96	3.32	5.76	118		0.0603		1.18	0.0916	3.66	150

11/16/2005

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	11/16/2005 16:40	0	9.77	41.1	97.9	1260		0.778		16.1	1.35	431	9.92
3, 4	11/16/2005 17:00	20	4.15	12.3	36.1	496		0.0802		19.2	0.284	272	2.84
5, 6	11/16/2005 17:20	40	0.45	7.75	23.4	327		0.138		10.6	0.251	61.2	3.22
7, 8	11/16/2005 17:40	60	0.31	3.19	10.6	159		0.196		1.96	0.217	25.3	3.60
9, 10	11/16/2005 18:00	80	0.25	3.93	12.5	183		0.196		1.73	0.228	18.7	6.11
11, 12	11/16/2005 18:40	120	4.26	4.68	14.4	208		0.196		1.51	0.239	27.8	8.62
13, 14	11/16/2005 19:20	160	2.97	4.47	13.6	219		0.140		1.37	0.243	42.0	5.46
15, 16	11/16/2005 20:00	200	5.74	4.27	12.7	231		0.0835		1.24	0.246	27.3	2.30
17, 18	11/16/2005 21:00	260	3.11	4.09	9.89	193		0.0785		1.18	0.225	49.4	2.68
19,20	11/16/2005 22:00	320	1.60	3.91	7.04	156		0.0736		1.13	0.204	26.2	3.06
21, 22	11/16/2005 23:00	380	0.20	3.86	7.79	146		0.0818		1.06	0.196	13.7	2.78
23,24	11/17/2005 0:40	480	0.00	3.82	8.55	136		0.0901		0.990	0.188	14.8	2.50

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	11/16/2005 17:24	0	0.95	1.68	5.38	83.3		0.0917		6.63	0.490	67.5	163
3, 4	11/16/2005 17:44	20	0.17	2.16	5.49	124		0.0752		2.29	0.474	14.8	136
5, 6	11/16/2005 18:04	40	0.00	1.65	5.68	78.6		0.0901		2.94	0.451	27.5	139
7, 8	11/16/2005 18:24	60	0.00	2.77	6.37	94.5		0.0926		10.7	0.392	21.2	144
9, 10	11/16/2005 18:44	80	0.00	2.77	6.37	94.5		0.0926		10.7	0.392	21.2	144
11, 12	11/16/2005 19:04	100	0.00	2.77	6.37	94.5		0.0926		10.7	0.392	21.2	144
13, 14	11/16/2005 19:24	120	1.61	3.90	7.06	110		0.0951		18.4	0.332	14.8	149
15, 16	11/16/2005 19:44	140	1.34	11.5	11.2	128		0.0884		2.60	0.300	11.3	146
17, 18	11/16/2005 20:04	160	2.91	6.82	8.35	123		0.0843		2.02	0.273	11.2	112
19,20	11/16/2005 21:04	220	3.52	2.17	5.53	118		0.0802		1.44	0.246	8.75	78.2
21, 22	11/16/2005 22:04	280	2.40	2.52	5.51	117		0.122		1.75	0.212	11.1	75.6
23,24	11/16/2005 23:24	360	1.06	2.88	5.49	117		0.165		2.06	0.178	10.0	73.0

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	11/16/2005 19:58	0	2.57	6.04	5.82	103		0.118		7.65	0.387	51.3	227
3, 4	11/16/2005 20:18	20	8.01	3.24	5.51	227		0.0669		1.98	0.339	20.7	202
5, 6	11/16/2005 20:38	40	8.93	4.23	4.34	259		0.0653		1.70	0.262	12.5	155
7, 8	11/16/2005 20:58	60	6.89	5.21	3.18	290		0.0636		1.41	0.185	15.0	108
9, 10	11/16/2005 21:18	80	7.49	3.43	2.45	204		0.0603		1.45	0.170	11.2	101
11, 12	11/16/2005 21:38	100	6.96	1.65	1.72	118		0.0570		1.49	0.156	6.25	94.0
13, 14	11/16/2005 21:58	120	5.43	1.86	1.91	143		0.0562		1.53	0.170	8.75	85.9
15, 16	11/16/2005 22:18	140	4.44	2.07	2.10	167		0.0554		1.57	0.185	6.21	77.8
17, 18	11/16/2005 22:38	160	3.43	1.66	1.80	135		0.0562		1.45	0.246	8.75	89.3
19,20	11/16/2005 23:38	220	1.79	1.24	1.49	103		0.0570		1.33	0.307	8.86	101
21, 22	11/17/2005 0:38	280	0.81	2.26	1.61	132		0.0579		1.39	0.252	8.75	117
23,24	11/17/2005 1:58	360	0.43	3.28	1.73	162		0.0587		1.44	0.198	7.50	133

1/11/2006

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/11/2006 15:52	0	1.92			925		1.01		14.9	1.53	464	19.9
3, 4	1/11/2006 16:12	20	5.53			1010		0.156		5.46	1.07	669	15.6
5, 6	1/11/2006 16:32	40	3.74			711		0.135		3.42	0.813	212	10.7
7, 8	1/11/2006 16:52	60	2.71			415		0.113		1.39	0.554	91.1	5.84
9, 10	1/11/2006 17:12	80	0.85			312		0.147		1.17	0.697	43.2	22.9
11, 12	1/11/2006 17:52	120	0.23			208		0.181		0.961	0.840	40.7	40.0
13, 14	1/11/2006 18:32	160	0.12			206		0.206		1.04	0.883	39.0	28.4
15, 16	1/11/2006 19:12	200	0.08			204		0.231		1.12	0.927	40.0	16.8
17, 18	1/11/2006 20:12	260	0.06			186		0.215		1.20	0.880	37.0	29.6
19,20	1/11/2006 21:12	320	0.04			167		0.199		1.27	0.833	34.6	42.4
21, 22	1/11/2006 22:12	380	0.01			168		0.201		1.48	0.946	32.9	41.1
23,24	1/11/2006 23:52	480	0.00			169		0.203		1.68	1.06	36.2	39.7

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/11/2006 16:50	0	1.88			109		0.153		4.80	0.358	31.7	353
3, 4	1/11/2006 17:10	20	3.39			103		0.201		1.75	0.355	23.5	208
5, 6	1/11/2006 17:30	40	2.68			102		0.159		1.66	0.347	10.1	214
7, 8	1/11/2006 17:50	60	2.12			101		0.117		1.57	0.339	8.54	221
9, 10	1/11/2006 18:10	80	1.46			97.9		0.117		1.62	0.336	12.7	261
11, 12	1/11/2006 18:30	100	0.96			94.7		0.118		1.67	0.332	13.6	300
13, 14	1/11/2006 18:50	120	0.70			92.3		0.112		1.66	0.352	12.3	309
15, 16	1/11/2006 19:10	140	0.52			89.9		0.105		1.66	0.371	12.7	318
17, 18	1/11/2006 19:30	160	0.17			106		0.104		1.64	0.307	12.5	293
19,20	1/11/2006 20:30	220	0.00			122		0.103		1.63	0.243	7.41	268
21, 22	1/11/2006 21:30	280	0.00			122		0.103		1.63	0.243	7.41	268
23,24	1/11/2006 22:50	360	0.00			122		0.103		1.63	0.243	7.41	268

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/11/2006 16:50	0	4.06			152		0.0967		5.77	0.230	24.1	1100
3, 4	1/11/2006 17:10	20	7.50			130		0.133		1.05	0.300	18.5	403
5, 6	1/11/2006 17:30	40	5.26			112		0.114		1.17	0.324	25.6	344
7, 8	1/11/2006 17:50	60	3.45			93.8		0.0951		1.30	0.349	18.3	285
9, 10	1/11/2006 18:10	80	2.34			98.3		0.0926		1.22	0.244	17.7	301
11, 12	1/11/2006 18:30	100	1.63			103		0.0901		1.14	0.140	10.0	317
13, 14	1/11/2006 18:50	120	1.19			89.4		0.0793		1.15	0.223	16.5	362
15, 16	1/11/2006 19:10	140	0.97			76.2		0.0686		1.16	0.307	10.0	408
17, 18	1/11/2006 19:30	160	0.63			83.5		0.0653		1.03	0.214	8.64	415
19,20	1/11/2006 20:30	220	0.35			90.7		0.0620		0.894	0.121	8.75	423
21, 22	1/11/2006 21:30	280	0.14			71.8		0.0694		0.963	0.180	8.54	434
23,24	1/11/2006 22:50	360	0.01			52.8		0.0769		1.03	0.239	6.25	445

1/29/2006

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	1/29/2006 11:40	0	2.02			674		1.03		14.1	0.744	275	26.8
3, 4	1/29/2006 12:00	20	1.20			311		0.161		1.82	0.262	55.0	14.5
5, 6	1/29/2006 12:20	40	0.40			255		0.196		1.47	0.241	23.8	10.2
7, 8	1/29/2006 12:40	60	0.58			200		0.231		1.13	0.220	19.0	5.94
9, 10	1/29/2006 13:00	80	0.39			179		0.300		1.19	0.217	17.1	6.96
11, 12	1/29/2006 13:40	120	0.24			158		0.370		1.25	0.214	11.1	7.98
13, 14	1/29/2006 14:20	160	0.20			175		0.394		1.33	0.231	10.0	8.82
15, 16	1/29/2006 15:00	200	0.14			192		0.419		1.40	0.249	7.41	9.66
17, 18	1/29/2006 16:00	260	0.12			180		0.435		1.41	0.262	11.1	8.40
19,20	1/29/2006 17:00	320	0.10			168		0.451		1.42	0.275	10.0	7.14
21, 22	1/29/2006 18:00	380	0.08			161		0.478		1.43	0.312	9.88	6.15
23,24	1/29/2006 19:40	480	0.05			154		0.505		1.44	0.349	9.88	5.16

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

3/2/2006

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	3/2/2006 6:06	0	0.99					1.67	8.28	53.5	1.85	1230	134
3, 4	3/2/2006 6:26	20	1.10					1.46	6.15	9.47	0.731	324	209
5, 6	3/2/2006 6:46	40	0.45					1.47	4.41	7.20	0.686	141	152
7, 8	3/2/2006 7:06	60	0.27					1.48	2.67	4.92	0.641	166	94.2
9, 10	3/2/2006 7:26	80	0.18					1.31	2.58	4.64	0.601	177	122
11, 12	3/2/2006 8:06	120	0.13					1.14	2.49	4.36	0.560	71.0	149
13, 14	3/2/2006 8:46	160	0.11					1.12	2.31	4.27	0.525	99.9	142
15, 16	3/2/2006 9:26	200	0.09					1.10	2.13	4.19	0.490	74.3	135
17, 18	3/2/2006 10:26	260	0.07					1.15	2.30	3.99	0.498	49.1	121
19,20	3/2/2006 11:26	320	0.06					1.19	2.46	3.79	0.506	38.5	107
21, 22	3/2/2006 12:26	380	0.65					1.40	2.57	4.32	0.658	39.0	128
23,24	3/2/2006 14:06	480	0.38					1.60	2.67	4.86	0.811	77.7	149

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

5/7/2006

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/7/2006 22:36	0	1.00					1.02	8.28		2.14	186	
3, 4	5/7/2006 22:56	20	0.97					0.790	6.15		1.20	143	
5, 6	5/7/2006 23:16	40	1.14					0.616	4.41		0.968	49.4	
7, 8	5/7/2006 23:36	60	0.66					0.442	2.67		0.740	45.0	
9, 10	5/7/2006 23:56	80	0.26					0.460	2.58		0.744	26.6	
11, 12	5/8/2006 0:36	120	0.16					0.479	2.49		0.747	19.5	
13, 14	5/8/2006 1:16	160	0.19					0.465	2.31		0.744	16.3	
15, 16	5/8/2006 1:56	200	0.18					0.452	2.13		0.740	18.5	
17, 18	5/8/2006 2:56	260	0.18					0.499	2.30		0.788	19.8	
19,20	5/8/2006 3:56	320	0.16					0.545	2.46		0.837	15.2	
21, 22	5/8/2006 4:56	380	0.10					0.598	2.57		0.917	18.3	
23,24	5/8/2006 6:36	480	0.06					0.651	2.67		0.997	14.6	

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2													
3, 4													
5, 6													
7, 8													
9, 10													
11, 12													
13, 14													
15, 16													
17, 18													
19,20													
21, 22													
23,24													

5/11/2006

Direct

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/11/2006 15:28	0	5.88					0.796	2.55		0.833	200	
3, 4	5/11/2006 15:48	20	10.31					0.133	1.29		0.483	250	
5, 6	5/11/2006 16:08	40	2.21					0.164	1.59		0.355	638	
7, 8	5/11/2006 16:28	60	0.88					0.194	1.89		0.227	96.3	
9, 10	5/11/2006 16:48	80	0.51					0.212	2.67		0.345	53.1	
11, 12	5/11/2006 17:28	120	0.24					0.229	3.45		0.464	52.5	
13, 14	5/11/2006 18:08	160	0.10					0.241	3.29		0.450	46.3	
15, 16	5/11/2006 18:48	200	0.02					0.252	3.12		0.435	40.7	
17, 18	5/11/2006 19:48	260	26.38					0.176	2.37		0.586	40.0	
19,20	5/11/2006 20:48	320	5.03					0.100	1.62		0.737	284	
21, 22	5/11/2006 21:48	380	2.03					0.110	1.89		0.673	78.5	
23,24	5/11/2006 23:28	480	0.42					0.120	2.16		0.609	89.0	

SHA

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/11/2006 20:14	0	35.56					0.133	1.71		1.03	85.2	
3, 4	5/11/2006 20:34	20	76.16					0.0934	1.17		0.875	27.5	
5, 6	5/11/2006 20:54	40	36.86					0.0926	1.37		0.851	19.8	
7, 8	5/11/2006 21:14	60	17.31					0.0917	1.56		0.827	13.9	
9, 10	5/11/2006 21:34	80	10.49					0.106	1.68		0.821	11.2	
11, 12	5/11/2006 21:54	100	7.66					0.120	1.80		0.814	12.5	
13, 14	5/11/2006 22:14	120	7.06					0.123	1.88		0.817	12.3	
15, 16	5/11/2006 22:34	140	5.37					0.126	1.95		0.821	6.25	
17, 18	5/11/2006 22:54	160	2.56					0.124	1.97		1.01	7.41	
19,20	5/11/2006 23:54	220	0.44					0.122	1.98		1.20	11.2	
21, 22	5/12/2006 0:54	280	0.00					0.0608	0.990		0.600	13.3	
23,24	5/12/2006 2:14	360	0.00					0.00	0.00		0.00	0.00	

MDE

				Metals				Nitrogen			Phosphoro	Solids	Chloride
			Average Fl	**Pb**	**Cu**	**Zn**	**Cd**	**Nitrite - N**	**Nitrate -N**	**TKN -N**	**TP**	**TSS**	**Cl**
Bottle #	Sampling Time	Time (min)	(L/s)	Conc. (ug/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (ug/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
1, 2	5/11/2006 20:16	0	60.36					0.105	1.14		0.721	44.6	
3, 4	5/11/2006 20:36	20	77.96					0.0901	1.23		0.731	67.9	
5, 6	5/11/2006 20:56	40	18.34					0.0942	1.44		0.734	50.0	
7, 8	5/11/2006 21:16	60	9.62					0.0984	1.65		0.737	37.5	
9, 10	5/11/2006 21:36	80	9.17					0.108	1.68		0.665	0.00	
11, 12	5/11/2006 21:56	100	8.62					0.118	1.71		0.593	19.8	
13, 14	5/11/2006 22:16	120	7.74					0.119	1.83		0.567	7.59	
15, 16	5/11/2006 22:36	140	5.68					0.120	1.95		0.541	12.2	
17, 18	5/11/2006 22:56	160	2.63					0.0599	0.975		0.271	0.00	
19,20	5/11/2006 23:56	220	0.91					0.00	0.00		0.00	0.00	
21, 22	5/12/2006 0:56	280	0.33					0.00	0.00		0.00	0.00	
23,24	5/12/2006 2:16	360	0.04					0.00	0.00		0.00	0.00	

References

ASTM. (2001). *Standard Test Method for Open-Channel Flow Measurement of Water with Thin-Plate Weirs*. D 5242-92, 637-644.

Barrett, M.E., Walsh, P.M., Malina, J.F., Charbeneau, R.J. (1998). "Performance of Vegetative Controls for Treating Highway Runoff." *J. Envir. Engrg.*, ASCE, 124 (11), 1121-1128.

Barrett, M.E. (2005). "Performance Comparison of Structural Stormwater Best Management Practices." *Water Env. Res.*, 77 (1), 78-86.

Bäckström, M. (2002). "Sediment Transport in Grassed Swales During Simulated Runoff Events." *Water Sci. Technol.*, 45 (7), 41-49.

Bäckström, M. (2003). "Grassed Swales for Stormwater Pollution Control During Rain and Snowmelt." *Water Sci. Technol.*, 48 (9), 123-134.

Bertrand-Krajewski, J., Chebbo, G., Saget, A. (1998). "Distribution of Pollutant Mass vs Volume in Stormwater Discharges and the First Flush Phenomenon." *Wat. Res.*, 32 (8), 2341-2356.

Chow, V.T. (1954). "The Log-Probability Law and its Engineering Applications." *Proceed. of ASCE*, 80 (536), 1-25.

Clary, J., Urbonas, B., Jones, J., Strecker, E., Quigley, M., O'Brien, J. (2002). "Developing, Evaluating and Maintaining a Standardized Stormwater BMP Effectiveness Database." *Water Sci. Technol.*, 45 (7), 65-73.

Cunnane, C. (1978). "Unbiased Plotting Positions – A Review." *J. Hydrol.*, 37, 205-222.

Davis, A.P., Shokouhian, M., Ni, S. (2001). "Loading Estimates of Lead, Copper, Cadmium, and Zinc in Urban Runoff from Specific Sources." *Chemosphere*, 44, 997-1009.

Dean, C.M., Sansalone, J.J., Cartledge, F.K., Pardue, J.H. (2005). "Influence of Hydrology on Rainfall-Runoff Metal Element Speciation." *J. Envir. Engrg.*, ASCE, 131 (4), 632-642.

Deletic, A. (2005). "Sediment Transport in Urban Runoff over Grassed Areas." *J. Hydrol*., 301, 108-122.

Deletic, A. (2001). "Modelling of Water and Sediment Transport over Grassed Areas" *J. Hydrol.*, 248, 168-182.

Gan, F.F., Koehler, K.J., Thompson, J.C. (1991). "Probability Plots and Distribution Curves for Assessing the Fit of Probability Models." *The Amer. Statis.,* 45 (1), 14-21.

Harremoës, P. (1988). "Stochastic Models for Estimation of Extreme Pollution from Urban Runoff." *Wat. Res.,* 22 (8), 1017-1026.

Harter, H.L. (1984). "Another Look at Plotting Positions." *Commun. Statist.-Theor. Meth.,* 13 (13), 1613-1633.

Hodges 1997

Kaushal, S.S., Groffman, P.M., Likens, G.E., Belt, K.T., Stack, W.P., Kelly, V.R., Band, L.E., Fisher, G.T. (2005). "Increased Salinization of Fresh Water in the Northeastern United States." *PNAS,* 102 (38), 13517-13520.

Kirby, J.T., Durrans, S.R., Pitt, R., Johnson, P.D. (2005). "Hydraulic Resistance in Grass Swales Designed for Small Flow Conveyance." *J. Hyd. Engrg., ASCE*, 131 (1), 65-68.

Kreeb, L.B., and McCuen, R.H. (2003). *Hydrologic Efficiency and Design Sensitivity of Bioretention Facilities.* University of Maryland, College Park, MD.

Lee, J.H., Yu, M.J., Bang, K.W., Choe, J.S. (2003). "Evaluation of the Methods for First Flush Analysis in Urban Watersheds." *Water Sci. Technol.,* 48 (10), 167-176.

Legret, M., Pagotto, C. (1999). "Evaluation of Pollutant Loadings in the Runoff Waters from a Major Rural Highway." *Sci. Total Environ.,* 235, 143-150.

Looney, S.W., Gelledge, T.R. (1985). "Probability Plotting Positions and Goodness of Fit for the Normal Distribution." *The Statistician.,* 34, 297-303.

Looney, S.W., Gelledge, T.R. (1985). "Use of the Correlation Coefficient with Normal Probability Plots." *The Amer. Statis.,* 39 (1), 75-79.

Maryland Department of the Environment. MDE. (2005). "Numerical Criteria for Toxic Substances in Surface Waters." Document #26.08.02.03-2. Baltimore, MD.

Maryland State Highway Administration. (2004). "State Highway Administration Plans of Proposed Highway – MD 32 Grass Swale Study – Phase 1." SHA Contract #AT560A21. Baltimore, MD.

McCuen, R. (2002). *Modeling Hydrologic Change: Statistical Methods*: CRC Press, Boca Raton.

Novotny, V.; Harvey, O. (1994) *Water Quality: Prevention, Identification, and Management of Diffuse Pollution*; Van Nostrand Reinhold, New York.

Rushton, B.T. (2001). "Low-Impacat Parking Lot Design Reduces Runoff and Pollutant Loads." *J. Water Resour. Plan. Manage., ASCE*, 127 (3), 172-179.

Sansalone, J.J., Buchberger, S.G. (1997). "Partitioning and First Flush of Metals in Urban Roadway Storm Water." *J. Envir. Engrg.*, ASCE, 123 (2), 134-143.

Sansalone, J.J., Cristina, C.M. (2004). "First Flush Concepts for Suspended and Dissolved Colids in Small Impervious Watersheds." *J. Envir. Engrg.*, ASCE, 130 (11), 1301-1314.

Schueler, T.R. (1994). "Performance of Grassed Swales Along East Coast Highways." *Watershed Protection Techniques.,* 1 (3), 122-123.

Strecker, E.W., Quigley, M.M., Urbonas, B.R., Jones, J.E., Clary, J.K. (2001). "Determining Urban Storm Water BMP Effectiveness." *J. Water Resour. Plan. Manage., ASCE*, 127 (3), 144-149.

Urbonas, B.R. (1995). "Determining Urban Storm Water BMP Effectiveness." *J. Water Resour. Plan. Manage., ASCE*, 121 (23), 23-34.

U.S. EPA. (1990). "National water quality inventory – 1988 report to Congress," *EPA* 440-4-90-003.

Van Buren, M.A., Watt, W.E., and Marsalek, J. (1997). "Application of the Log-Normal and Normal Distributions to Stormwater Quality Parameters." *Wat. Res.*, 31 (1), 95-104.

Wanielista, M., Yousef, Y. (1993). *Stormwater Management*., Wiley, New York.

Wilcoxon, F. (1945). "Individual Comparisons by Ranking Methods." *Biometrics*, 1, 80-83.

Wu, J.S., Allan, C.J., Saunders, W.L., and Evett, J.B. (1998). "Characterization and Pollutant Loading Estimation for Highway Runoff." *J. Envir. Engrg.*, ASCE, 124 (7), 584-592.

Yu, S.L., Kuo, J., Fassman, E.A., Pan, H. (2001). "Field Test of Grassed-Swale Performance in Removing Runoff Pollution." *J. Water Resour. Plan. Manage., ASCE*, 127 (3), 168-171.