Vegetated Biofilter for Post Construction Storm Water Management for Linear Transportation Projects – Dormant Grass Test Supplement

Gayle F. Mitchell, R. Guy Riefler, and Andrew Russ

for the
Ohio Department of Transportation
Innovation, Research,
and Implementation Section

and the
United States Department of Transportation
Federal Highway Administration

State Job Number 134349

December 2010

Ohio Research Institute for Transportation and the Environment

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
USFHWA/OH-2010/7 Supplement		

4. Title and Subtitle
Vegetated Biofilter for Post Construction Storm Water Management for Linear Transportation Projects – Dormant Grass Test Supplement

5. Report Date
December 2010

6. Performing Organization Code

7. Author(s)
Gayle F. Mitchell, R. Guy Riefler, and Andrew Russ

8. Performing Organization Report No.

9. Performing Organization Name and Address
Ohio Research Institute for Transportation and the Environment (ORITE)
141 Stocker Center
Ohio University
Athens OH 45701-2979

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
State Job No. 134349

12. Sponsoring Agency Name and Address
Ohio Department of Transportation
Innovation, Research, and Implementation Section
1980 West Broad St.
Columbus OH 43223

13. Type of Report and Period Covered
Technical Report Supplement

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the Ohio Department of Transportation (ODOT) and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract
The vegetated biofilter is a low impact development technique that can be integrated into stormwater management of linear transportation systems and capitalize on the natural environment to mitigate stormwater. In the project report (USFHWA/OH-2010/7), the behavior of a 4 ft (1.2 m) wide by 14 ft (4.3 m) long prototype vegetated biofilter slope under simulated storm events at various pollutant concentrations, slopes, and flow rates was evaluated. This supplement discusses the behavior of the same prototype during dormant or winter conditions at slopes and flow rates as follows: 8:1, medium; 4:1, medium; and 2:1, medium. Tests were conducted using methods similar to that of the original study. The influent pollutant concentration during the simulated storm events was at the "medium" level, which included medium concentration during the first part and low concentration in the trailing portion of the event. The pollutants included the same seven metals, soil, and oil used in the original study. In addition chlorides were added in the influent to simulate and measure the effects of salt used for pavement winter maintenance on the biofilter. The prototype vegetated biofilter foreslope under dormant conditions provided fair to excellent performance in removal of pollutants (seven metals, suspended material, and oil and grease) from a medium concentration simulated storm water runoff. Over 80 percent removal was achieved for all constituents except iron (75%), zinc (58%) and chlorides (negligible). TSS removal declined from a summer condition average removal of about 95% to 80% for the dormant condition. Results at slopes of 8:1, 4:1, and 2:1 did not indicate declining performance with increasing slope. Vegetation coverage was about 60 % for the dormant tests contrasted to an average 83% during the summer tests, which contributed to the reduction in removals. Within the parameters of this study, findings indicated that the foreslope portion of the vegetated biofilter even during a dormant condition significantly reduces the quantity of pollutants in the runoff.

17. Key Words
Vegetated Biofilter, Storm Water Management, Swale, Filter Strip, Low Impact Development

18. Distribution Statement
No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	60	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

Vegetated Biofilter for Post Construction Storm Water Management for Linear Transportation Projects – Dormant Grass Test Supplement

Prepared in cooperation with the
Ohio Department of Transportation
and the
U.S. Department of Transportation, Federal Highway Administration

Prepared by

Gayle F. Mitchell, R. Guy Riefler, and Andrew Russ

Ohio Research Institute for Transportation and the Environment
Russ College of Engineering and Technology
Ohio University
Athens, Ohio 45701-2979

Final Report Supplement
December 2010

Acknowledgements

Several people at Ohio University assisted with the research. The metals' analysis was directed and conducted by Dr. Glen Jackson, Associate Professor, and Bobby Deimler, Ph.D. student, Department of Chemistry. Laboratory and field assistance was provided by Lauren Armeni, Environmental Science M.S.graduate. Thanuja Mallikavachchi and Jourdan Siemer, M.S. candidates Civil Engineering, provided assistance on laboratory and graphical analysis of data. Dr. Glenn Matlack, Professor of Environmental and Plant Science, provided advice on grass species and trained personnel on measuring density and coverage. Dr. Shad Sargand, Russ Professor of Civil Engineering, designed the test frame and beds. Mike Krumlauf of ORITE assisted in the design and building of some of the equipment. From ODOT, Jennifer Gallagher, Program Manager, and staff of the Innovation, Research, and Implementation Section of the Office of Innovation, Partnerships and Energy, which sponsored this project, are acknowledged. Technical assistance provided by the Technical Liaisons, Mike Wawszkiewicz and Rob Lang of the ODOT Office of Production, is gratefully acknowledged.

Table of Contents

List of Figures

List of Tables

1 Introduction

This document is a supplement to a study on the use of vegetated biofilters as a Best Management Practice (BMP) under the project entitled “Vegetated Biofilter for Post Construction Storm Water Management for Linear Transportation Projects” [Mitchell, Riefler, and Russ, 2010b]. The project entailed studying the removal of selected pollutant constituents from simulated stormwater runoff as functions of grass slope, distance, influent concentration, and influent flow rate. The measurements in that project were all conducted on active grass in spring, summer, or early autumn (between the second half of May and the first half of October), so there remained a question of whether the relatively high level of pollutant removal seen in those tests would be maintained when the grass was dormant.

1.1 Objectives

The goal of this supplement is to examine the effectiveness and design of vegetated biofilters during conditions of dormancy that occur during winter months (December – March) in Ohio. During this time the vegetation is inactive, receives less sun, and temperatures are lower.

For reference, the goal of the original project was to examine the slope portion of vegetated biofilters to evaluate capture and treatment of the water quality volume for highway storm runoff. This goal was accomplished through the following objectives [Mitchell, Riefler, and Russ, 2010b]:

- Developing a biofilter foreslope prototype and conducting testing to determine:
    - Its ability to capture the water quality volume
    - Its performance in removing typical roadway runoff contaminants
        - Its performance efficiency computed as the percent change between influent and effluent quality
    - The impact of its slope
    - The accumulation of contaminants in the foreslope soil and vegetation
    - The suitability of foreslope designs to accommodate different concentrations of runoff and/or intensity of storms
    - Potential resuspension of particles

1.2 Literature Review and Synthesis

The reader is referred to the main project report for a discussion of the literature pertaining to this project [Mitchell, Riefler, and Russ, 2010b]. The literature did indicate the following observation specific to winter conditions:

Snowmelt runoff appears to be more polluted with metals and suspended solids than rainfall runoff [Sansalone and Buchberger, 1995; Sansalone and Glenn, 2002]. The metals are transported by oil, grease, and suspended solids to the snow banks alongside the road. Mitchell et al [2002] noted that the concentration of metals in snow for one snowfall event decreased exponentially with increasing distance away from the edge of the highway [Mitchell, Riefler, and Russ, 2010b].

In an article entitled "Perchlorate and Ion Chemistry of Road Runoff" [Munster and Hanson, 2009], the authors focus on determining the amount of perchlorate in the roadway runoff, but also present data on other ions, including chloride. They report concentrations for chloride between 156 mg/L and 306 mg/L.

Novotny, Murphy, and Stefan [2008] monitored several urban lakes in the Minneapolis-St. Paul metropolitan area over a period of time to see how they reacted after being exposed to road runoff both in the winter during the deicing process and in the spring and summer as well. The chloride concentrations reported in this paper annually ranged from 76 mg/L to 386 mg/L depending upon the specific lake that was being measured. A set of values were also reported for February, a winter month, specifically which was 132 mg/L at the top layer of the lakes and 186 mg/L in the deeper sections. These lakes had concentrations of Na and Cl that were respectively 10 and 25 times higher than comparable non-urban lakes. The authors present evidence that the increases in lake salinity with time were highly correlated with Minnesota DOT purchases of rock salt for winter maintenance, and that chloride concentrations for individual lakes were correlated with the amount of impervious (e.g. paved) area in the watershed, and conclude that the application of deicing salt has led to degradation of these lakes.

A Swedish study entitled "Mobilisation of Heavy Metals by Deicing Salts in a Roadside Environment" [Backstrom et al., 2004] was conducted to determine how the increase in sodium and chloride from the deicing agents would affect the ability of heavy metals to travel away from the road. In this study, lysimeters were used to make the measurements. Two different roadways were analyzed in this study. One roadway was newer and in a forested area, while the other was an older road and was in an open setting. At the newer roadway concentrations for chloride were reported to be between 41 mg/L and 779 mg/L. At the older roadway chloride concentrations were reported to be between 40 mg/L and 1740 mg/L. The large difference in concentration is partially due to the distance the lysimeters were from the roadway. The more concentrated samples were taken from lysimeters closer to the roadway while the less concentrated samples were farther away. Concentrations of heavy metals were observed to increase through a variety of mechanisms, including ion exchange and formation of chloride complexes, depending on the metal. Levels of pH were observed to decrease by one unit due to ion exchange on the asphalt concrete pavements studied.

2 Method and Equipment Overview and Modifications

The method used in the research discussed in this supplement follows that used on Bed 2 with medium pollutant concentration, and the reader is referred to that report for the full details [Mitchell, Riefler, and Russ, 2010b]. In the following, selected details from the original report are highlighted for ready reference, and any variations or additions to the methods used are discussed.

2.1 The Test Matrix

The experiment was originally designed around a test matrix giving a sequence of tests involving the application of artificial road runoff (water with constituents added to approximate pollutants found in highway runoff) in simulated storm events to a constructed vegetated biofilter tilted at different slopes. The vegetated biofilters ("beds" or "test beds") are 4 ft (1.23 m) by 14 ft (3.86 m) and filled with a foot or more of soil; seeding was used to establish grass. The beds were placed on a frame that enabled tilting to inclines of 8:1 (12.5% or 7.12° from horizontal), 4:1 (25% or 14°), and 2:1 (50% or 26.6°). The bed and frame apparatus is described in more detail in the project report [Mitchell, Riefler, and Russ, 2010b]. There were four beds prepared and seeded, one each for testing with high concentration (Bed1), medium concentration (Bed 2), and low concentration runoff (Bed 3), and one as a spare. Bed 2 (medium concentration) was selected to perform the testing under dormant conditions.

The method for creating the artificial runoff and the setting of pollutant concentrations is described in Section 2.3.1. The application of artificial runoff using a specially devised apparatus is described in [Mitchell, Riefler, and Russ, 2010b]. The runoff flow event included a portion that was equivalent to the water quality volume precipitation depth of 0.75 in (19 mm) of polluted runoff at the selected concentration level (medium for dormant grass) lasting for 15 min at a simulated medium flow followed by a tailing portion that was a step lower in concentration (low) at a lower flow rate for the remaining 45 min. The flow levels and details of the dormant simulated storm events are described in detail in Section 2.4.

The procedures used to analyze the collected samples are given in Section 2.9. In brief, the soil cores were collected to determine the presence of metals before testing (baseline cores) and after all events (final cores). The artificial runoff was applied in specified simulated storm events, during which specimens were collected from the influent and effluent, which was collected from surface runoff and from the underdrain (also labeled as "ground" to distinguish from "surface") after migration through the soil, following the sample collection procedures described in Section 2.5. The research aim was to compare the effluent concentrations to those in the influent samples. The pollutants included total and dissolved metals, suspended solids, and oil and grease, all of which were included in the artificial runoff. Resuspension was studied by tagging soil particles used in the first pollutant removal test at the 8:1 slope with the rare earth metal Lanthanum (La) and then analyzing for the metal in subsequent tests.

Table 1 shows the test matrix for the laboratory experiments, which summarizes the information above with the addition of the date(s) during which each experiment was conducted. The chronology runs left to right, then down. Baseline cores were taken from the active bed, and the bed was repaired with cores from Bed 4 (the spare). The biofilter was allowed about a week to recover. For the dormant case, the core data from Bed 2 at the end of testing in June 2009 was used as the baseline data since extracting the cores under dormant conditions would have compromised the bed. The medium concentration tests on dormant grass were conducted on Bed 2 March 15-19, 2010. Previous tests on summer grass had been conducted May 11,15,21,28, June 16, 24-27, 2009. The hydraulic testing, using tap water, involved some trial and error adjustment of flow mechanisms and pumping system and took up to two weeks. After hydraulic testing, the baseline and pollutant removal tests followed at the dates in Table 1. The last step with each bed was final core removal, which followed shortly after the last test.

Table 1. Test matrix for the vegetated biofilter experiment, including dates of experiments.

	Slope:	Baseline	8:1	4:1	2:1		Resuspension & Tracer
	Flow Rate:		Med	Med	Med	High	
Pollutant Concentration	High	9/4/08	9/11/08	9/16/08	9/19-08	9/30/08	10/10-16/08
	Medium	5/11/09	5/15/09	5/21/09	5/28/09	6/16/09	6/24-27/09
	Low	7/27/09	7/28/09	7/30/09	8/4/09	8/6/09	8/11-13/09
	Dormant Medium	3/15/10	3/17/10	3/17/10	3/19/10	-	-

2.2 Condition of Bed and Vegetation Coverage

Standard ODOT grass seed mix (ODOT specification 659.09, Slope Mixture 3B) was originally planted at twice the specified rate to ensure dense growth. A quantity of 119 g (4.2 oz.) of seed mix was used; the bed area was 4x14=56 ft^2 (1.22 x 4.27 = 5.20 m^2).

Development of grass was assessed by measurement of coverage by dividing the test bed into a grid of 39 approximately 1.02 ft × 1.08 ft (31.0 cm × 32.9 cm) squares. Thirteen of the squares were randomly selected for measurement and the percentage of area covered with live plant matter was estimated. Figure 1 shows grass coverage in Bed 2 as a function of time from March 2009; the rectangular windows indicate times and approximate coverage values when pollutant removal tests were conducted. The grass coverage for Bed 2 was 76%-97% during the medium concentration summer tests, and 51.5%-68.1% (average 59.8%) during the dormant grass tests discussed in this report supplement. The lower coverage figure was expected for dormant grass. Figure 2 shows the condition of the grass at the time of the testing under dormant conditions.

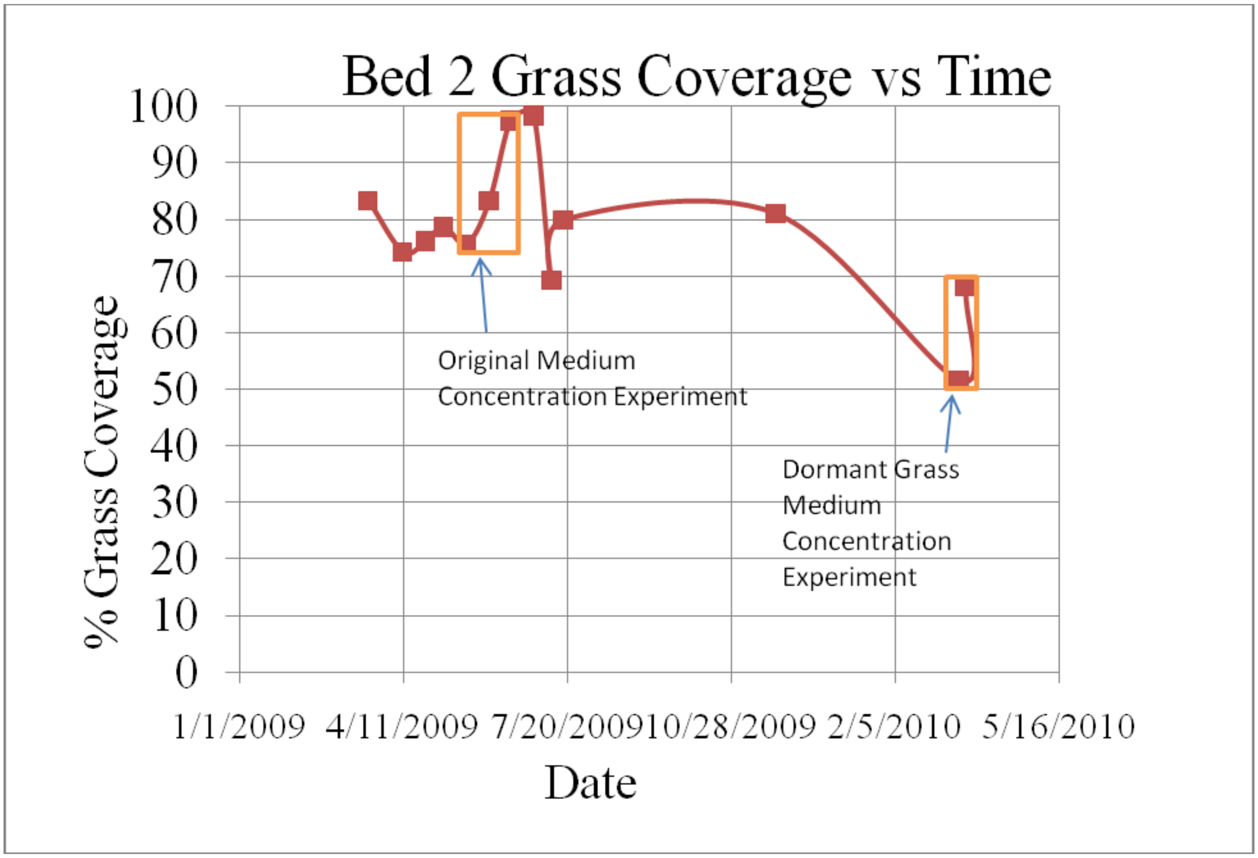


Figure 1. Grass coverage in Bed 2 as function of time. Rectangular areas indicate when pollutant removal tests were conducted on the bed.

Figure 2. View along test bed during baseline testing at 2:1 slope illustrating condition of grass under dormant conditions.

2.2.1 Maintenance of Test Beds

During the growing season, the grass was trimmed to a height of 4-5 in (10-13 cm) and watered when required by the weather. At the onset of winter, trimming and watering was halted.

Pollutant removal tests were conducted when the temperature was above freezing to ensure the simulation of a realistic rainfall runoff event. The air temperature during the period of pollutant removal testing (March 15-19) ranged from daytime maximums of 45°F (7.2°C) to 65°F (18.3°C) to nighttime minimums of 31°F (-0.6°C) to 39°F (3.9°C).

Before each pollutant removal test, the bed was leveled and tap water was applied using a sprinkler until the bed was brought to field capacity, and a steady constant flow could be observed from the ground drainpipe.

2.3 Artificial Runoff Formulation and Simulated Storm Events

2.3.1 Formulation of artificial stormwater runoff for this project

The formulation for artificial runoff used in this supplement was at medium and low concentrations as defined in the original project report [Mitchell, Riefler, and Russ, 2010b]. Initially, 5th percentile, mean, and 95th percentile concentrations were determined from studies of highway runoff [Barrett et al., 1998a; Drapper, Tomlinson, and Williams, 2000; Driscoll, Shelley, and Strecker, 1990; Flint and Davis, 2007; Gupta, et al., 1981, Kayhanian, et al., 2003; Kayhanian and Stenstrom, 2005; Mesfin, et al., 2007; Sansalone and Buchberger, 1997; Sansalone and Teng, 2005; Wu, Allan, and Saunders, 1998]. However, the number of data points available was low for many metal analytes, placing the 5th (95th) percentile outside the range of the minimum (maximum) value detected, so the minimum (maximum) value was substituted in such cases. Of the seven metals reported only three metals, Cu, Pb, and Zn, had data distinguishing dissolved forms from the total. The 5th percentile/minimum values reported are larger for dissolved species than for total, because the data set for total concentration of each of these metals is different. The concentrations of runoff constituents obtained from the literature are shown in Table 2, including metals, total suspended solids (TSS), chemical oxygen demand (COD), and oil and grease (O&G).

For the dormant grass test, winter conditions were further simulated by adding reagent grade NaCl to the influent to account for increased chloride concentrations from road salting. Literature values for total chlorides were taken from the International BMP Database [ASCE et al, 1996], after selecting for winter conditions, northern locations, and direct runoff locations. This resulted in 164 data points with an average chloride value of 262 mg/L and 5th percentile of 28 mg/L. The higher value was used for target concentrations of 262 mg/L in the water quality volume. Since tap water contained ~50 mg/L chloride, chloride above this level was added to the artificial mixture for the water quality volume to reach the 262 mg/L target. The tailing or low concentration portion was tested at the background tapwater chloride concentration because the target level was below the existing chloride level [Athens Water Treatment Plant 2009].

Table 2. Concentrations of metals and other contaminants in roadway runoff taken from literature along with concentrations adopted in this project for artificial runoff at low, medium, and high concentrations.

Constituent		unit	Literature			DL	Artificial runoff		
			5%/min	Mean	95%/max		Low	Med	High
Total metals	Cd	(μg/L)	0.05	2	6	4	20	100	500
	Cr	(μg/L)	1	6	17	5	25	125	625
	Cu	(μg/L)	3	55	179	7	35	175	875
	Fe	(μg/L)	249	7719	16500	3	250	7700	16500
	Ni	(μg/L)	2	9	30	19	95	475	2375
	Pb	(μg/L)	1	271	1133	43	215	1075	5375
	Zn	(μg/L)	7	425	1660	4	10	425	1700
Dissolved metals	Cu	(μg/L)	5	39	105	7	-	-	-
	Pb	(μg/L)	3	11	21	43	-	-	-
	Zn	(μg/L)	80	444	756	4	-	-	-
	TSS	(mg/L)	9	207	737	-	9	207	737
	COD	(mg/L)	13	111	274	-	13	111	274
Chlorides	NaCl	(mg/L)	27.9	262	353	-	50*	262	-
Alkalinity	$CaCO_3$	(mg/L)	-	-	-	-	170	170	170
	pH		-	-	-	-	7.0±0.1	7.0±0.1	7.0±0.1

DL = Typical detection limit

* Low target chloride level in artificial runoff represents tap water value from Athens Water Treatment Plant [2009]

Note: Oil and grease were added via a separate distribution system.

Because the minimum concentrations in Table 2 of metals, excepting Fe, were near the detection limits for the inductively coupled plasma-optical emission spectrometer (ICP-OES), the artificial runoff was reformulated to ensure removals would be measureable at "low" concentration, which was set to 5 times the typical analytical detection limit. Then "medium" concentration was set to 5 times the low level, and "high" concentration at 5 times the medium level. Other components included in Table 2, such as pH and alkalinity, were controlled to achieve an appropriately buffered solution.

2.3.2 Metals

ICP standards were used for Cd, Cr, Cu, Ni, and Pb (Fisher Scientific, Waltham, MA) at an initial concentration of 10,000 ppm. Due to the higher concentrations needed for Zn and Fe, zinc nitrate hexahydrate and iron(III)nitrate nonahydrate (Fisher Scientific, Waltham, MA) were used to make the different concentrations in the artificial runoff.

Concentrated stock solutions were first made up in volumes of 3 L (0.79 gal) for transportation to the experimental site. The 3 L (0.79 gal) stock solutions were prepared in 5% nitric acid solution to prevent precipitation. The concentrated 3 L (0.79 gal) stock solutions were diluted to 152 L (40. gal) in the first tank (water quality portion) and to 95 L (25 gal) in the tank for the tailing portion of flow. The contents were mixed for three hours before beginning the experiment.

2.3.3 pH

The background alkalinity of the tap water of about 170 mg $CaCO_3$/L was used for the artificial runoff, and after addition of all amendments to the water the pH was adjusted to 7.0±0.1 by addition of H_2SO_4 or NaOH and/or KOH.

2.3.4 Total Suspended Solids (TSS)

Total suspended solids reported in the literature averaged 207 mg/L with a standard deviation of 108 mg/L. The 95% confidence intervals, shown in Table 2, were used as the target concentrations. Locally obtained Class A-6 clay soil was used as the suspended solids source. The TSS source was the same as that used in the grass beds, described in [Mitchell, Riefler, and Russ, 2010b].

The soil was dried and passed through a 0.841 mm (#20) sieve and added to the water before metals to allow sorption reactions to occur. The average particle diameter was 78.9 μm with $d_{10\%}$ = 4.44 μm and $d_{90\%}$ =768 μm. The artificial runoff was mixed for 3 hours before application for adsorption of metals to the soil to reach equilibrium. Since natural rainfall events are highly variable, it would be impossible to simulate all such events in this type of study. Instead, this mixing procedure was selected to create reproducible conditions.

Soil for the first pollutant removal test in each bed, at the 8:1 slope, was mixed with lanthanum (III) oxide powder in a 10:1 ratio and wetted and dried three times. This permanently binds the La to the soil particles allowing them to be tracked [Polyakov and Nearing, 2004].

2.3.5 Oil and Grease

Oil and grease is defined as all material extracted by n-hexane using the prescribed Clean Water Act Analytical Test Method [USEPA, 2008b]. A separate parallel oil application system was used to deliver oil to the bed. The concentration of oil (Mobil Clean 5000 10W-30 motor oil) added was 100 and 20 mg/l for the “first portion” and “second portion”, respectively of the two parts of the simulated storm events.

2.4 Determination of flow rates during simulated storm events

High and medium runoff flow rates were used in the original test matrix. For the dormant study medium flow rate events at all three slopes were studied. The definition of what constitutes a medium event was based on storm hydrographs representing storms of a certain severity and duration. OEPA’s definition of water quality volume (WQv) and associated precipitation depth of 0.75 inches (19 mm), as provided by ODOT [2009], was used. This equates to the first 0.75 inches (19 mm) of precipitation delivered over the area draining into the bed, which for a linear transportation system was assumed to be a two-lane section of roadway of length equal to the width of the effective bed, with the further assumption that all of the water runs off. Thus given the water quality volume, what remains is to determine the amount of time over which to deliver this volume of water to the bed. For convenience, the 0.75 inches (19 mm) of precipitation used to determine the WQv is referred to as the water quality depth. Table 3 is adapted from Table 17 of [Mitchell, Riefler, and Russ, 2010b] to describe the simulated medium flow storm events applied under dormant conditions.

Table 3. Parameters for simulated storm events at medium concentration on Bed 2 under dormant conditions.

		English units		Metric units	
	Intensity or flow rate		Medium		Medium
	Recurrence rate	(yr)	2	(yr)	2
First Portion	Contaminant concentration level		Medium		Medium
	Rainfall rate	(in/hr)	3.00	(mm/hr)	76.2
	Flow rate	(gal/min)	2.21	(l/min)	8.38
	Duration	(min)	15	(min)	15
	Rainfall	(in)	0.75	(mm)	19.1
	Volume	(gal)	33.2	(l)	125.7
Second Portion	Contaminant concentration level		Low		Low
	Rainfall rate	(in/hr)	0.60	(mm/hr)	15.2
	Flow rate	(gal/min)	0.44	(l/min)	1.68
	Duration	(min)	45	(min)	45
	Rainfall	(in)	0.45	(mm)	11.4
	Volume	(gal)	19.9	(l)	75.4
Overall	Average rainfall rate	(in/hr)	1.20	(mm/hr)	30.5
	Average flow rate	(gal/min)	0.89	(l/min)	3.35
	Total duration	(min)	60	(min)	60
	Total rainfall	(in)	1.20	(mm)	30.5
	Total volume	(gal)	53.1	(l)	201.2
Literature	Maximum rainfall rate	(in/hr)	4.32	(mm/hr)	109.7
	Average rainfall rate	(in/hr)	1.26	(mm/hr)	32.0
	Water quality volume precipitation depth	(in)	0.75	(mm)	19.1
	Water quality volume	(gal)	33.2	(l)	125.7

2.5 Experimental Method

The sequence of tests on the dormant grass bed was as follows:

- The data collected from the Bed 2 final cores taken at the end of the previous testing in June 2009 were established as baseline data for the dormant tests.
- Hydraulic testing was conducted to ensure the pumping, delivery and drainage systems were operational; adjustments of the equipment were made as needed.
- Baseline flow tests were conducted using tap water at all three slopes to determine what contaminants, if any, would emanate from the bed. A water quality volume providing a water quality depth of precipitation (0.75 in or 19 mm) of tap water was administered as per the first part (first 15 minutes) of a medium flow event, with samples collected every five minutes from surface and ground.
- Pollutant removal tests followed with the medium concentration artificial runoff at the following flow rates and slopes:
  - 8:1 slope, medium flow
  - 4:1 slope, medium flow
  - 2:1 slope, medium flow

- Collection of a final set of 20 cores to determine metals embedded in the soil, foliage, and roots after the application of the contaminated artificial runoff. Cores were taken within a week after the final test.

The influent was applied via the drip bar at a medium flow rate and medium concentration, and two types of effluent were collected at the base of the bed: surface flow was collected across the width of the bed, which exited through a drainpipe at the corner, and ground flow was collected from the central drainpipe or underdrain. Samples were collected in a series of bottles – 15 ml for total metals, 15 ml run through a syringe with a 0.4 μm (0.016 mil) filter for dissolved metals, two 125 ml bottles for TSS tests, 250 ml for oil and grease. When particle size specimens were collected, a 250 ml bottle was used. In addition, the flow rate of effluent was measured by recording the time to fill a 1 L beaker. During pollutant removal tests, grab samples of influent and effluent were also collected with each analysis sample and tested with a Hanna Instruments HI9828 multi-parameter probe that measured pH, temperature, ORP in mV, and conductivity in μS/cm.

The timing of influent samples was at 0 min, 5 min, 10 min, 30 min, and 50 min after the start of the event. Collection of surface samples started when flow started and continued at approximately 5 min intervals, with the exact times recorded, until flow ceased.

To facilitate sample collection, bottles were prelabeled using moisture-resistant plastic labels printed with specimen number (a code with I (influent), S (surface), or G (ground) followed by a number), date of test, concentration, flow rate, and sample type (total metals, dissolved metals, TSS, O&G). Samples were collected and immediately preserved in coolers for subsequent chemical analysis.

2.6 Initial Conditions for the Test Beds

The behavior of the vegetated biofilter in the field will vary considerably based on initial soil moisture conditions. If the soil is initially very dry, a storm event may be completely absorbed by the soil and vegetation, generating no runoff from the biofilter into the receiving ditch. A completely saturated biofilter is expected to transmit the maximum amount of runoff across its surface into the ditch. Infinite situations are possible between these two extremes, with a portion of runoff being absorbed and a portion transported. For this study, before initiation of each simulated storm event, tap water was applied to the vegetated biofilter with a sprinkler until the bed was brought to field capacity and not capable of absorbing more water, a condition which for this study is referred to as "saturation", though to truly saturate the soil would require sustained immersion underwater. By watering the bed to field capacity, it was possible to obtain a relatively reproducible initial soil moisture conditions in an outdoor test plot otherwise subject to variations in sunlight intensity, wind, humidity, and natural rainfall events. Besides creating a reproducible initial condition for the bed, testing at field capacity would produce test results that were expected to represent worst-case conditions for effluent.

To achieve field capacity, the test bed on the frame was leveled horizontally. Clay material, as well as a railing, was placed along the perimeter of the test bed to prevent any seepage around the edges. Then, the test bed was irrigated with tap water at a slow rate to prevent any scouring or erosion, using a sprinkle, for a minimum of three hours. The criterion for being at field capacity was a steady constant flow of water emanating from the central (ground) drainpipe at the base of the bed. Once at field capacity, the bed was tilted to the angle for the experiment. Once water ceased flowing out through the underdrain, typically about 15 minutes, the bed was judged ready for an experiment.

2.7 Artificial Runoff Testing

Baseline tests using tap water were conducted at 8:1, 4:1, and 2:1 slopes and medium flow rate. Effluent samples were collected. Testing was then conducted using the polluted water at the 8:1 slope, followed by the slope of 4:1, and then the slope of 2:1 all at medium flow. The bed was brought to field capacity before each test. At the end of the pollutant runoff tests, final core samples were then collected and analyzed.

The artificial runoff was pumped from a completely stirred drum to the inlet pipe structure at the head of the bed and then delivered via orifices in a drip bar onto a distributor plate to provide nearly uniform flow over the width of the bed. The first 15 minutes of medium concentration influent was provided from drum 1, while the next 45 minutes of low concentration influent came from drum 2 as the storm event proceeded according to the rates given in Table 3. Influent samples were obtained periodically using a trough to intercept the influent from the distributor plate. Samples of surface runoff were obtained at the down slope end of the bed via a semicircular pipe, fitted with a pipe through the side of the bed. Groundwater samples were taken periodically from the underdrain exiting from the bottom of the bed. Samples were directly filtered (for dissolved metals) or conveyed on-site into pre-labeled bottles, preserved as prescribed, and stored in coolers filled with ice for transport to the researchers' laboratories for storage in the refrigerator and subsequent analysis. During the test, the pH was measured periodically at influent and effluent with a portable probe. Flow rates were obtained for the surface and ground water using a graduated beaker and stop watch. The times at which samples were collected during baseline and pollutant removal tests are as given in Table 4.

Table 4. Sample collection times during simulated storm events on each bed.

Bed	Conc.	Slope	First part (min)	Tailing part (min)	Influent sampling times (min)	Groundwater sampling times (min)	Surface sampling times (min or mn:sc)
2	baseline	8:1	15	-	-	5, 10, 15	9, 14, 19
		4:1, 2:1	15	-	-	5, 10, 15	5, 10, 15
2	medium	8:1	15	45	0, 5, 10, 20, 40	5, 10, 20d, 30, 40, 50, 60	8:57, 11:48, 13:37, 15:30, 16:43
		4:1	15	45	0, 5, 10, 20, 40	5, 10d, 15, 20, 30, 40, 50, 60	3:41, 5:11, 7:30, 11, 15, 20 (partial)
		2:1	15	45	0, 5, 10, 20, 40	5, 10d, 15, 20, 30, 40, 50d, 60	5:03, 7:45, 10:33, 15, 22:55 (partial)

Notes: d after a ground sampling time indicates a duplicate sample was collected.
(partial) indicates low surface flow with limited number of sample bottles filled.

The influent, surface water and ground water (underdrain) samples were each analyzed for TSS, oil and grease, dissolved metals, total metals, and particle size.TSS is not relevant for groundwater samples. Several turbid samples of influent and surface water were selected for particle size analysis. The sample analysis protocol is presented in Appendix A. Required holding times were strictly adhered to. For quality assurance and quality control (QA/QC), every 10 samples were split for duplicate analyses and wash blanks were collected daily from filtering and coring apparatuses. Analytical procedures included standard QA/QC practices such as periodic analysis of ultrapure water blanks and calibration standards.

2.8 Resuspension

Although it has been established that vegetated biofilters can capture suspended sediment, concern remains that the particles may be remobilized by subsequent storms. To investigate this possibility, the first artificial runoff test on each test bed was conducted with suspended sediment that had been tagged with lanthanum (La). This metal is rarely found in the natural environment and binds irreversibly to soil making it useful for tracking the movement of soil particles. Using established methods, soil was tagged with lanthanum and then added to the artificial runoff to reach the appropriate suspended solids concentration [Polyakov and Nearing 2004].

The method involved first drying the soil to be tagged overnight. The soil particles were thoroughly mixed at a ratio of approximately 1:10 with lanthanum(III) oxide (La_2O_3). This mixture was wetted and then air-dried three times. A few samples of the tagged soil were collected and digested using USEPA method 3050B [USEPA, 1996], then given to the chemistry laboratory for analysis. The remaining soil was ready for use in the resuspension test.

The artificial runoff mixture with tagged soil was applied in the first pollutant removal test at 8:1 slope, medium flow, and subsequent tests used only untagged suspended solids. Detection of La in the total metals analysis in second and later tests indicated the presence of TSS applied during the first test in the collected effluent. A correlation was developed between total La concentration measured by the ICP-OES and the tagged TSS concentration; thus La concentration could be used to estimate the concentration of tagged TSS in the sample, which could then be compared to the results of the TSS test that measured the total amount of tagged and untagged TSS and the percentage of TSS that was resuspended from the first test determined.

2.9 Analytical Techniques

Samples collected, including all cores, baseline samples, and pollutant samples, were analyzed using a common set of analytical techniques described in this section. Samples were preserved and analyzed according to the standard Clean Water Act Analytical Test Method (40 CFR Part 136) 1664 [USEPA, 2008a] or where needed using Standard Methods [Clescori et al., 2000]. Quality control procedures were adhered to including the proper use of blank, split, and positive control samples.

Petroleum products were determined by measuring total oil and grease using the standard Clean Water Act Analytical Test Method (40 CFR Part 136) 1664 [USEPA, 2008b]. Suspended solids were determined by filtering and gravimetric measuring. Metals samples were preserved with nitric acid and analyzed by inductively coupled plasma (ICP) (Varian ICP-AES or ICP-MS) following United States Environmental Protection Agency (USEPA) Method 6010b [USEPA, 2007]. Both filtered and unfiltered samples were analyzed to determine the fraction of total metals dissolved and the interaction of sediment and metals in transport. Particle size distributions of suspended solids samples were determined for selected samples using a particle size analyzer (Beckman-Coulter LS230).

Vegetation samples and soil cores were carefully separated into grass or stem, roots and soil; the roots were carefully washed to remove soil as best as possible. Water content of soil and vegetation was determined in order to determine concentration in mg/kg of dry matter.

Metal contaminants were extracted using heated acid extraction.

To monitor the presence of salt, chlorides were measured by ion chromatography following USEPA Method 300.0 [USEPA, 1993b] using a Dionex (Sunnyvale, CA) IC25A with a AS14A, 5 µm column and Atlas suppressor calibrated with certified standards.

3 Baseline Test Results

Preceding the performance testing, one baseline run at each slope (8:1, 4:1, and 2:1) with medium flow was performed using tap water to determine background concentrations released from the bed with clean influent (tap) water. Average values for three samples collected at 5 min intervals at the three slopes are shown in Table 5; nondetects were averaged at half the detection limit, unless all samples were below the detection limit, which is then indicated with "<". Results were fairly consistent across the different slopes, except for TSS which was substantionally higher for TSS at a slope of 2:1. Metals and TSS concentrations detected in surface runoff in the dormant test were significantly higher than concentrations from the baseline active growth tests, particularly Fe and Zn which were an order of magnitude higher.

The Athens City tap water used in this experiment is treated using an ion exchange process with sodium as the exchangeable ion to counteract hardness. The sodium averages 116 ppm at the plant tap, final hardness is 144 ppm, chloride is 70 ppm, with free chlorine at 0.86 ppm, iron at 0.04 ppm and Mn at 0.01 ppm [Athens Water Treatment Plant, 2009]. Reported metal contaminants are copper at 210 ppb (range of detection up to 600 ppb) and lead at 4.7 ppb (range of detection up to 7.2 ppb).

Table 5. Average concentrations in baseline tests. Values preceded by "<" were below detection limits.

		8:1 Surface	8:1 Underdrain	4:1 Surface	4:1 Underdrain	2:1 Surface	2:1 Underdrain
Total Metals	Cd (µg/L)	11.4	10.9	9.9	10.3	10.4	12.4
	Cr (µg/L)	5.4	6.0	5.8	5.7	5.9	6.0
	Cu (µg/L)	7.4	13.0	11.4	6.9	9.5	9.9
	Fe (µg/L)	1470.2	1244.6	1829.9	695.0	1693.5	2544.5
	Ni (µg/L)	11.9	12.5	13.9	11.8	13.3	12.7
	Pb (µg/L)	53.1	40.7	23.0	26.3	32.4	64.8
	Zn (µg/L)	209.2	122.3	224.3	54.0	406.3	211.8
Dissolved Metals	Cd (µg/L)	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
	Cr (µg/L)	0.4	2.2	1.2	2.2	1.0	2.1
	Cu (µg/L)	<0.34	<0.34	<0.34	<0.34	<0.34	<0.34
	Fe (µg/L)	211.4	273.9	210.0	275.8	210.7	281.7
	Ni (µg/L)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Pb (µg/L)	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
	Zn (µg/L)	<1.0	<1.0	11.4	<1.0	7.4	<1.0
TSS (mg/L)		13.36	38.62	17.73	15.46	63.70	20.30
O&G (mg/L)		24.54	106.42	11.89	3.23	< 4	144.31
Cl (mg/L)		46.6	42.4	45.1	42.7	45.8	42.5

Particle size analyses were performed on baseline samples, and results are shown in Figure 3. Particles in the surface runoff originated from the bed. For the 2:1 and 4:1 runs, particle sizes were similar with median sizes of 183 µm and 109 µm, respectively. The sediment from the 4:1 sample was more poorly sorted however with 70% of the particles coming from the 92 µm to 161 µm range. The sediment in the 8:1 sample was much larger, possibly because it was the first test, with a median size of 1,570 µm. These particles were also poorly sorted with 60% in the 1377 µm to 2000 µm size range.

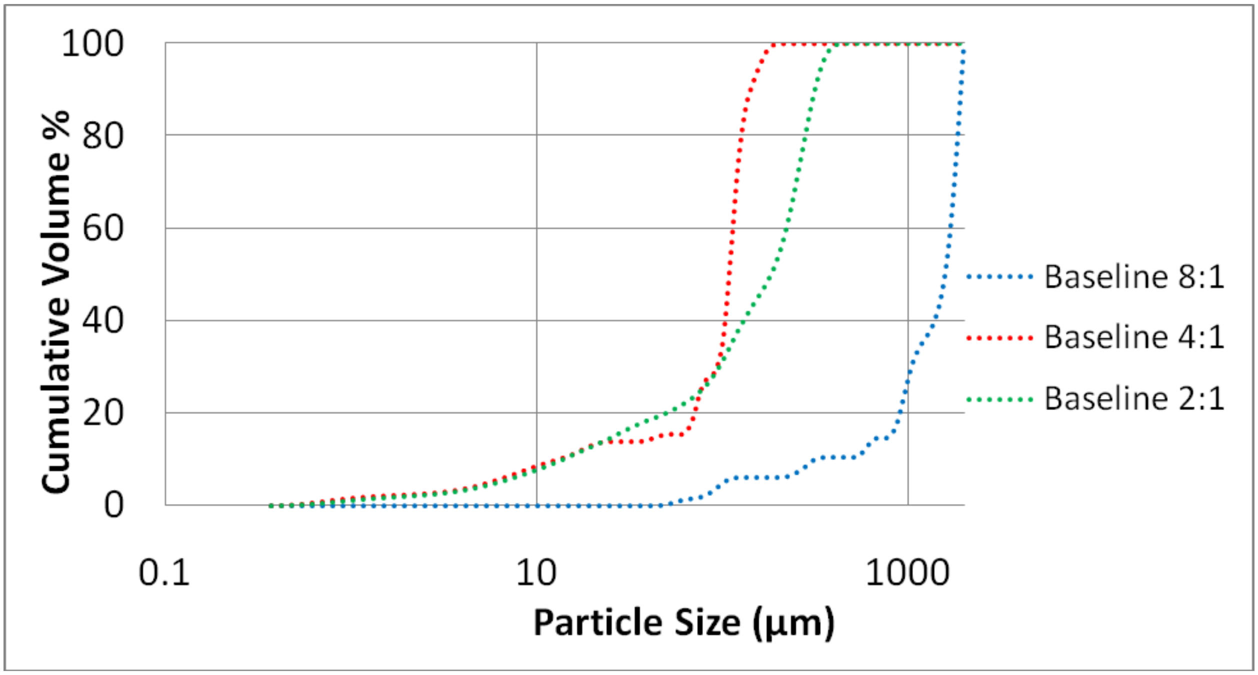


Figure 3. Particle size distribution of surface runoff from baseline samples from Bed 2 collected while the grass was dormant.

4 Medium Pollutant Concentration Experiments

In this series of tests, a medium concentration of contaminants, as described in Table 2 was delivered to the bed during an initial water quality event period (the first 0.75 in (19 mm) of the event), followed by a longer tailing period with a low concentration of contaminants and a lower flow rate. A total of three tests were conducted each at a medium flow rate which included the following: 1) an 8:1 slope (7.13°), 2) a 4:1 slope (14.0°), and 3) a 2:1 slope (26.6°). The simulation used an initial flow rate of 2.21 gpm (8.38 Lpm) for 15 min followed by a flow rate of 0.443 gpm (1.68 Lpm) for 45 min, as indicated in Table 3.

4.1 pH Results

The two stages of influent for all tests were mixed in separate drums to provide different concentrations of contaminants over the course of the simulated storms. After all the contaminants were mixed with tap water, pH was adjusted to 7.0±0.1 by addition of H_2SO_4, NaOH or KOH. During and after pH adjustment the pH would continue to drift. The pH data are tabulated in Table 6. Over the three tests influent pH averaged about 7.7 and 7.9 in the initial and tailing stages, respectively. The pH of the initial portion of the surface runoff was about 0.2 pH units higher than the corresponding influent.

Table 6. Average pH values during the medium concentration tests on Bed 2. Tailing surface runoff was either nonexistent or too low to get a good sample for pH measurement.

Test	Initial Influent	Tailing Influent	Initial Surface Runoff	Tailing Surface Runoff	Initial Underdrain Flow	Tailing Underdrain Flow
8:1	7.94	7.94	8.11	not measured	7.94	7.73
4:1	7.38	7.78	7.58	not measured	7.50	7.67
2:1	7.66	7.94	7.88	not measured	7.98	8.04

4.2 Suspended Solids Results

Figure 4 through Figure 6 depict suspended solids concentrations. Sieved soil (<0.841 mm (<33 mil)) was mixed with the two influent vessels at target concentrations of 207 mg/L for the initial medium concentration flow and 9 mg/L for the subsequent low concentration flow. Actual concentrations measured in the first portion of the influent flow as it sprayed onto the bed averaged for each slope 8:1, 4:1, and 2:1, respectively, 192 mg/L, 157 mg/L and 103 mg/L. Suspended solids concentrations during the lower flow rate tailing 45 min of the runoff averaged 23 mg/L, 28 mg/L, and 7 mg/L.

The majority of surface runoff was only generated during the first 15 min of the test or water quality portion; for the 8:1 and 2:1 slopes one sample was obtained 23 minutes into the event. The first captured surface samples for the 8:1, 4:1 and 2:1 slopes had concentrations of 67, 93 and 56 mg/L, respectively, with subsequent values declining; average concentrations during the first 15 minutes were 25.4, 34.4 and 18.6 mg/L, respectively. This contrasted with much lower concentrations obtained for the medium concentration application under active grass conditions which yielded average concentrations during the first 15 minutes of flow of 2 mg/L for the 8:1 slope, 7 mg/L for the 4:1 slope, and 4 mg/L for the 2:1 slope. The dormant experiment surface values can be contrasted with baseline suspended solids concentrations that averaged 13.4, 17.7 and 63.7 mg/L, respectively. The TSS surface values tracked the influent, declining with the influent and exhibiting higher concentrations with higher influent concentrations. When accumulated over the entire event, the percent removals at the 8:1, 4:1 and 2:1 slopes of the event mean concentrations were 85, 80 and 81 %, respectively, contrasted with removals of 98%, 96%, and 96% for the summer active grass.

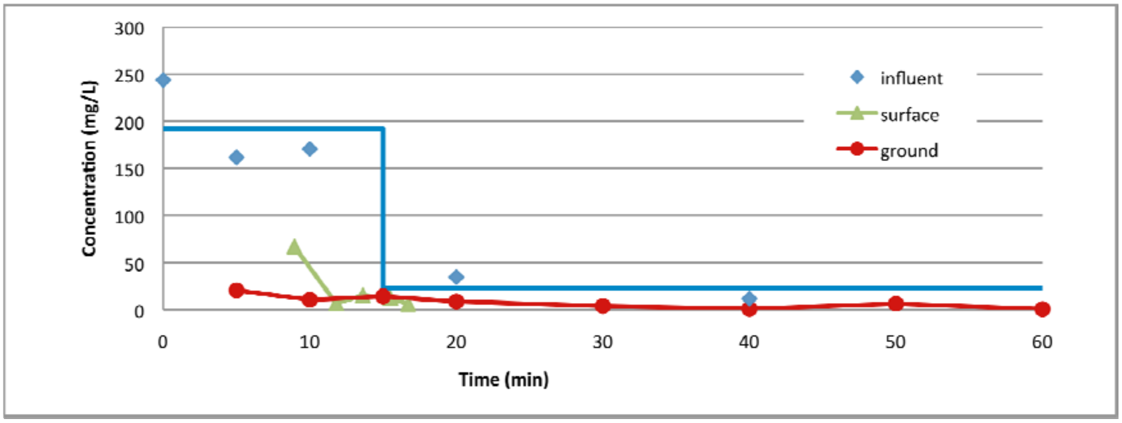


Figure 4. Concentration of suspended solids in 8:1 slope, medium flow rate.

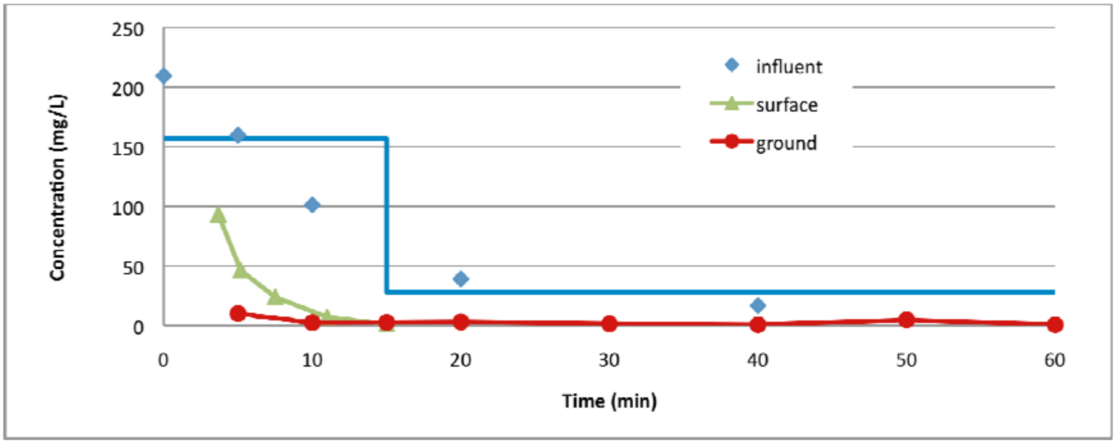


Figure 5. Concentration of suspended solids in 4:1 slope, medium flow rate.

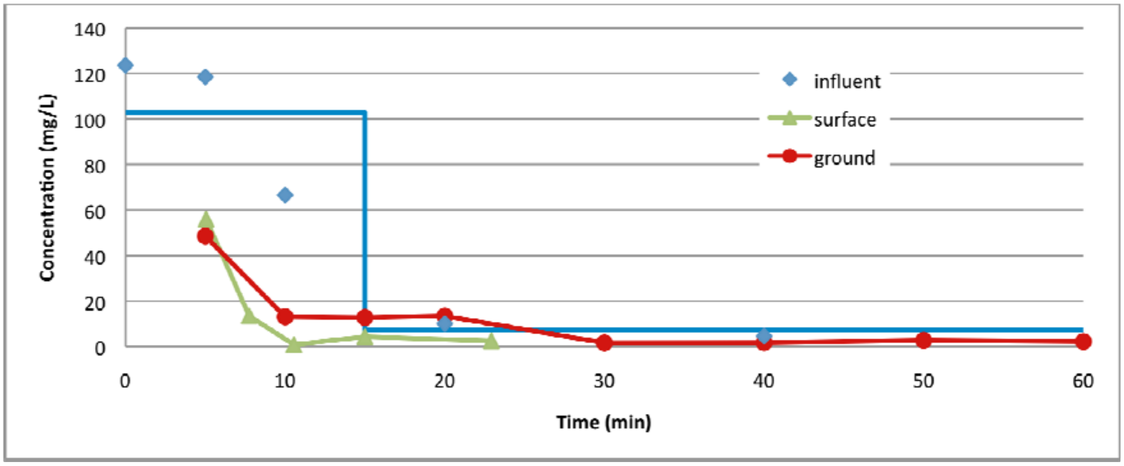


Figure 6. Concentration of suspended solids in 2:1 slope, medium flow rate.

4.2.1 Particle Size Analysis

Particle size analyses of sediment in the influent water and in the surface runoff were performed for each test, and results are shown in Figure 7. Influent samples varied considerably, two of them being dominated by small particles (mean diameters of 4.66±2.43 µm (0.183±0.096 mil) for 8:1 slope and 1.07±1.77 µm (0.042±0.070 mil) for 4:1 slope) and the other being dominated by larger particles (mean diameter 47.7±8.6 µm (1.88±0.34 mil) for 2:1 slope). The clay particles could have agglomerated in the influent mixing tank forming larger particle aggregations that entered the bed. Surface runoff distributions also varied considerably with two samples dominated by medium particles (mean diameter of 15.1±23.5 µm (0.59±0.92 mil) for 8:1 slope and 15.1±16.4 µm (0.59±0.65 mil) for 4:1 slope) and the remaining dominated by smaller particles (mean diameter 1.95±2.89 µm (0.077±0.114 mil) for 2:1 slope). These surface runoff particles were significantly smaller than observed in surface runoff samples from the baseline tests which were dominated by particles in the 100 µm to 2000 µm range.

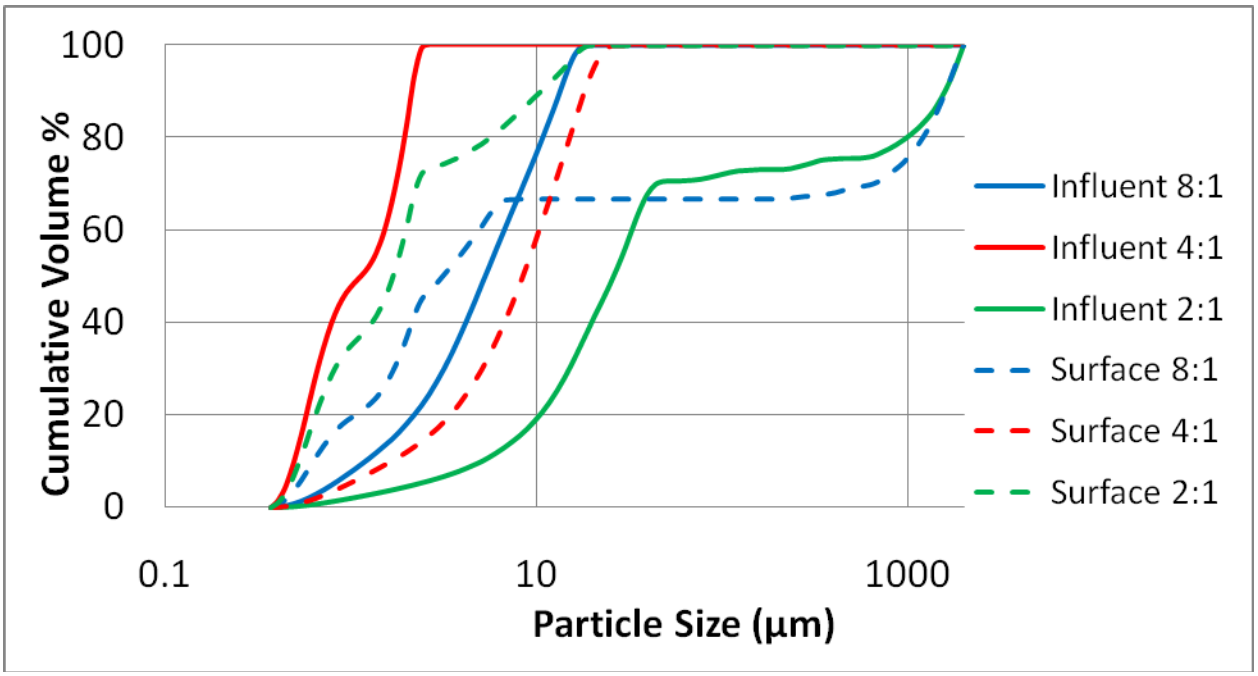


Figure 7. Particle size distribution of influent and surface samples from Bed 2.

4.3 Total Metals Results

For the 8:1 slope, total metals concentrations are displayed in Figure 8 through Figure 14. Measured influent concentrations for most metals were about 30 to 40 % less than the target concentrations for the water quality volume portion of the test and about double the target for the tailing portion of the event. Pb concentration was close to the target. Zn experienced an unexpected large increase in the second portion of the event. As noted in the baseline data, Zn concentrations were relatively high and about 10 times greater than in the previous baseline testing. In order to investigate this further, on August 23 three samples of tap water were obtained from the source used to prepare the artificial runoff (immediately after turning the tap on, after about 15 gallons of flow and then after about a total of 30 gallons of flow) and screened for metals concentration. Analysis of the samples yielded concentrations of total zinc of 4857 µg/l, 104.9 µg/l and 401.6 µg/l for the first, second and third samples of tap water. Dissolved metals were comparable for each of the samples, except the third which had a small dissolved fraction. Hence, the tap water was a source of zinc.

Surface runoff was primarily generated for the first fifteen minutes during the initial portion of the 8:1 medium flow test; one sample was collected at 16.75 minutes. (At the other two slopes one sample was collected at 20 minutes for the 4:1 and at 23 minutes for the 2:1.) For each metal, surface concentrations were well below the influent concentrations, and similar to baseline concentrations for all metals except for Fe concentrations which were higher in the performance test and Zn which had one measurement higher than baseline concentrations. This resulted in percent removals for Cd, Cr, Cu, Fe, Ni, Pb, and Zn of 85.2%, 94.7%, 94.5%, 65.6%, 93.6%, 98.8%, and 57.5%. Based on event mean concentration data, total metals removals were highest for Cr, Cu, Ni, and Pb and the lowest for Fe and Zn. For the previous active bed conditions, percent removals of the event mean concentration for Cd, Cr, Cu, Fe, Ni, Pb, and Zn were as follows: 76.2%, 79.3%, 89.3%, 98.5%, 91.4%, 94.1%, and 83.0%. Compared with the active growth tests, total metals removals were higher for the dormant tests for all metals except Fe and Zn.

Underdrain concentrations were low and relatively constant throughout the entire duration of the test for each metal, with all of the metals very similar to surface runoff concentrations.

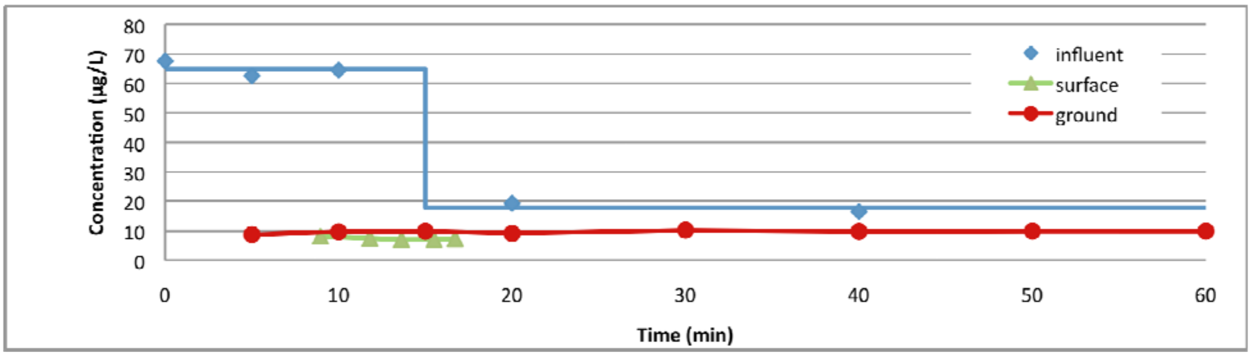


Figure 8. Total concentration of cadmium in 8:1 slope, medium flow rate.

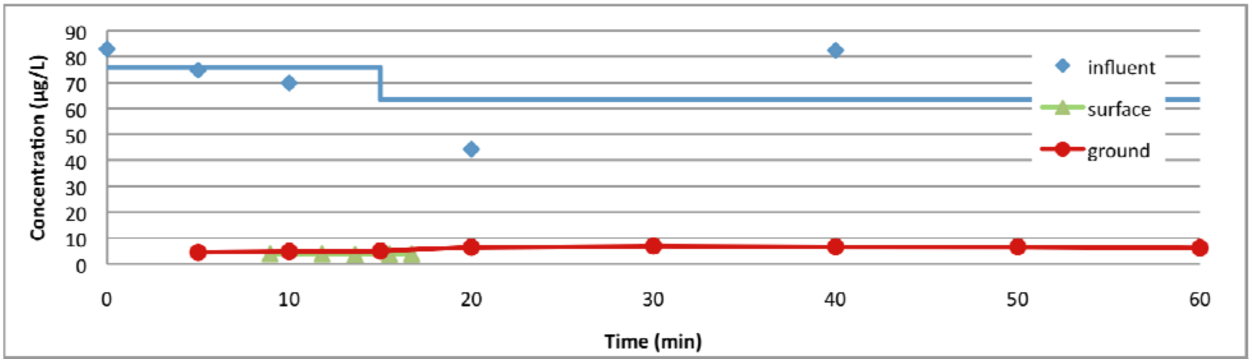


Figure 9. Total concentration of chromium in 8:1 slope, medium flow rate.

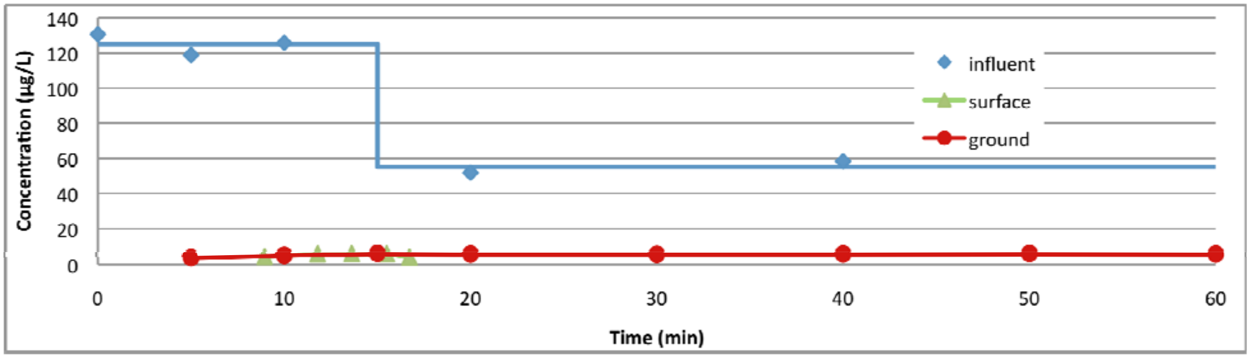


Figure 10. Total concentration of copper in 8:1 slope, medium flow rate.

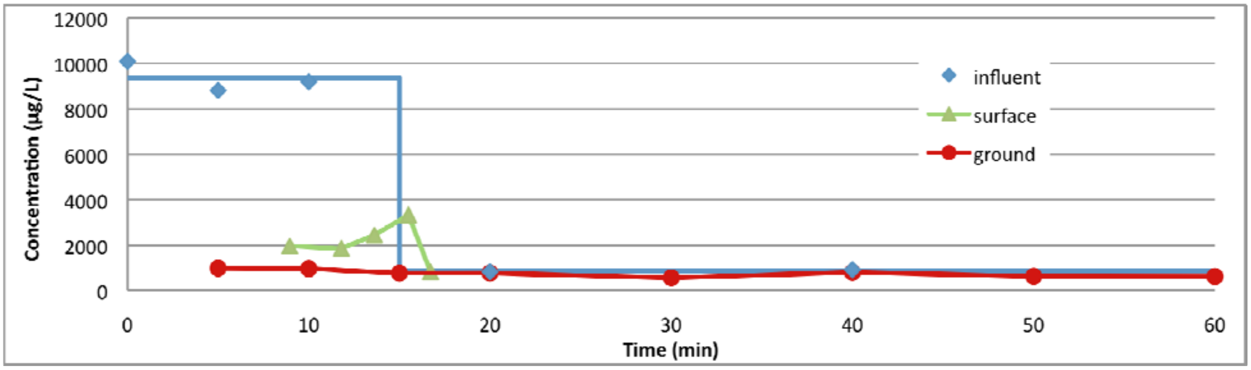


Figure 11. Total concentration of iron in 8:1 slope, medium flow rate.

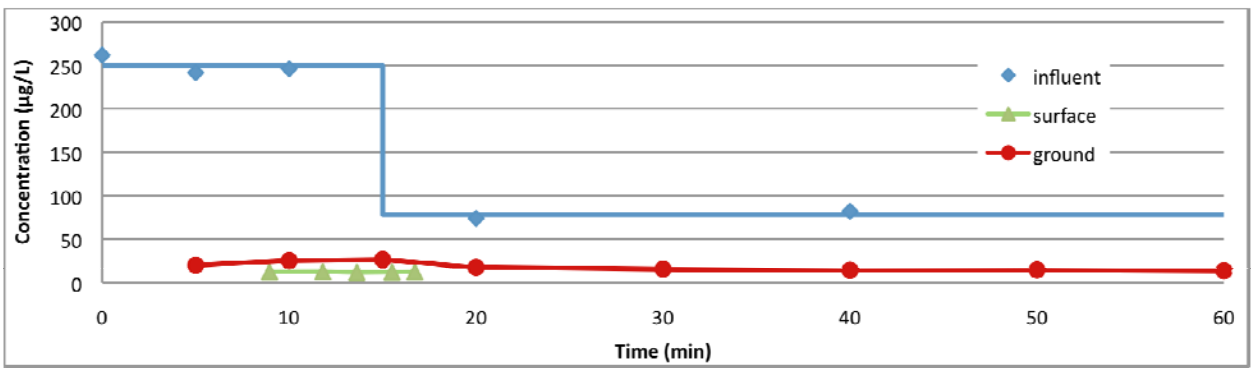


Figure 12. Total concentration of nickel in 8:1 slope, medium flow rate.

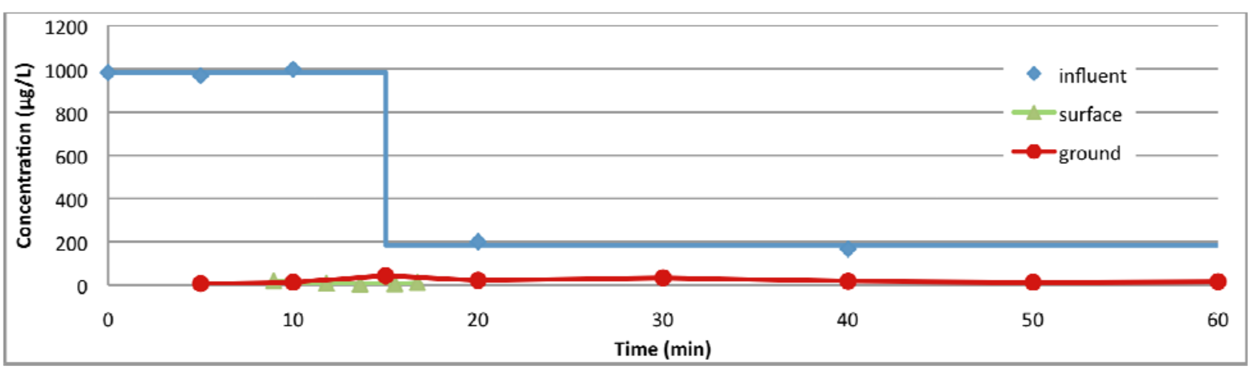


Figure 13. Total concentration of lead in 8:1 slope, medium flow rate.

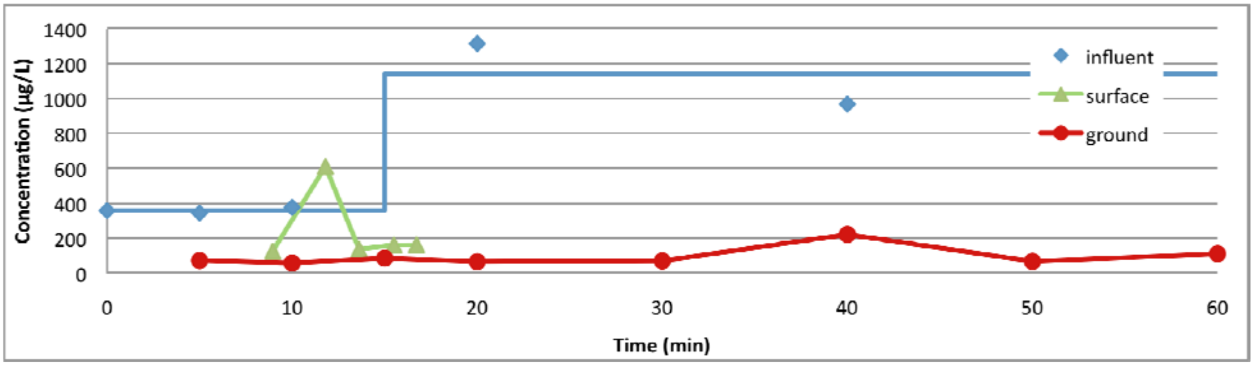


Figure 14. Total concentration of zinc in 8:1 slope, medium flow rate.

For the 4:1 slope, total metals concentrations are displayed in Figure 15 through Figure 21. For the water quality volume period of the test, all influent average metal concentrations were about 50% less than target values due primarily to a low concentration for the second sample obtained during the event. For the tailing portion of the test, Cd, Cr, Cu, and Pb had average influent concentrations close to low target concentrations; Fe and Zn had average influent concentrations higher than target concentrations while Ni was lower.

Surface runoff concentrations were all below about 20 µg/L, except for Fe with concentrations between 590 µg/L and 890 µg/L and Zn with a high spike for the first sample of nearly 800 µg/L, and the remaining samples between 25 µg/L and 69 µg/L. All of these metals' concentrations were similar to or below the concentrations detected during baseline experiments except for the single high Zn detection. This resulted in percent removals of the event mean concentrations for Cd, Cr, Cu, Fe, Ni, Pb, and Zn of: 80.5%, 88.3%, 94.8%, 76.8%, 91.5%, 97.9%, and 67.7%. Removals were highest for Cu and Pb and lowest for Fe and Zn. Under active grass conditions, percent removals of the event mean concentrations for Cd, Cr, Cu, Fe, Ni, Pb, and Zn were as follows: 97.6%, 97.2%, 91.7%, 99.2%, 97.5%, 94.8%, and 86.6%. Compared with the active growth tests, total metals removals were lower for the dormant tests for all metals except Cu and Pb. In both the active and dormant studies, removals were lowest with Zn.

Underdrain concentrations were very similar to surface runoff concentrations except for Fe, Ni, and Zn which had several detections higher than surface runoff concentrations.

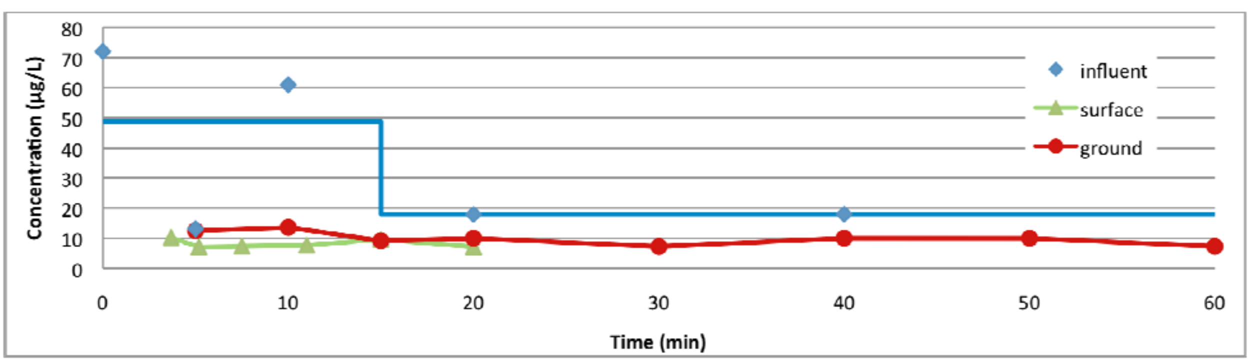


Figure 15. Total concentration of cadmium in 4:1 slope, medium flow rate.

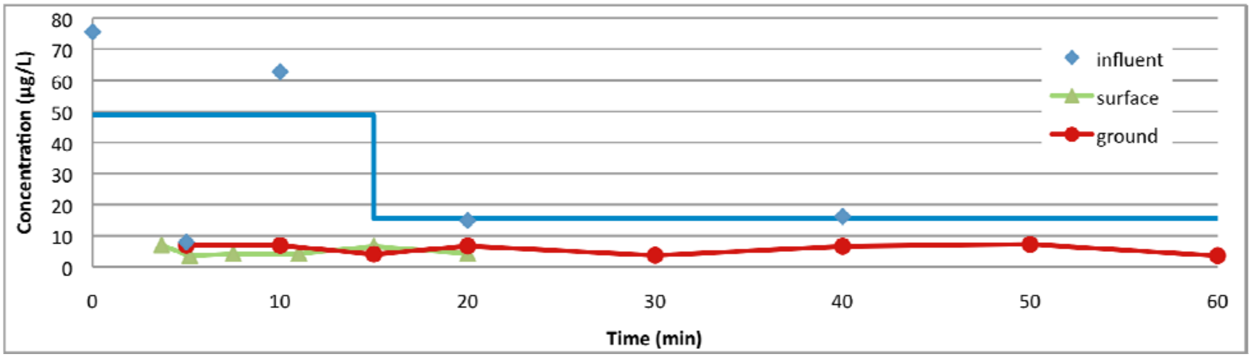


Figure 16. Total concentration of chromium in 4:1 slope, medium flow rate.

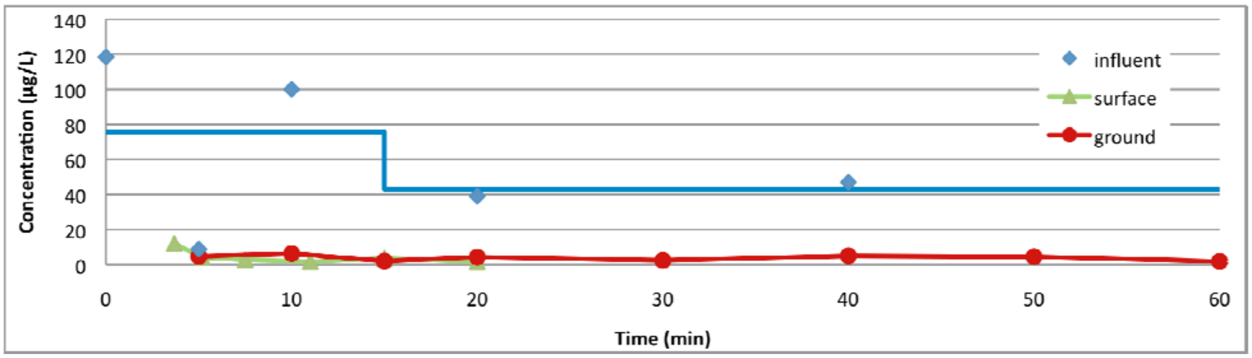


Figure 17. Total concentration of copper in 4:1 slope, medium flow rate.

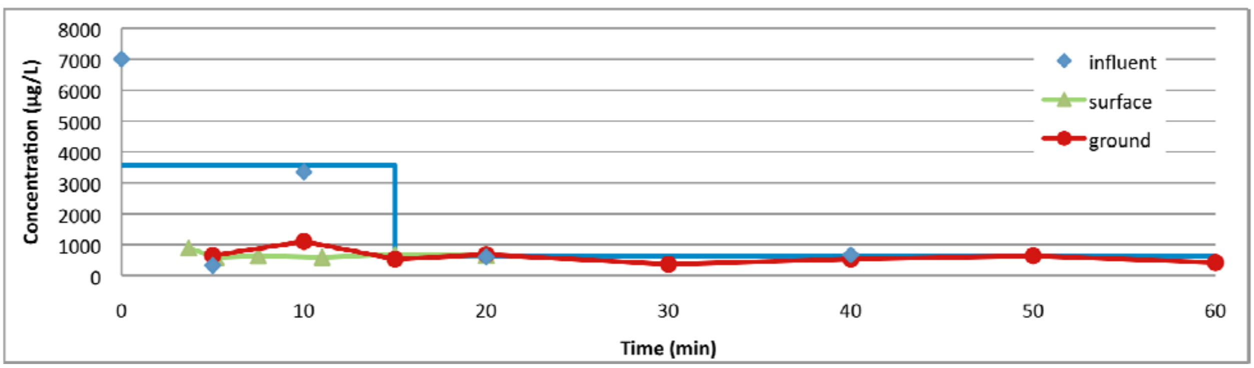


Figure 18. Total concentration of iron in 4:1 slope, medium flow rate.

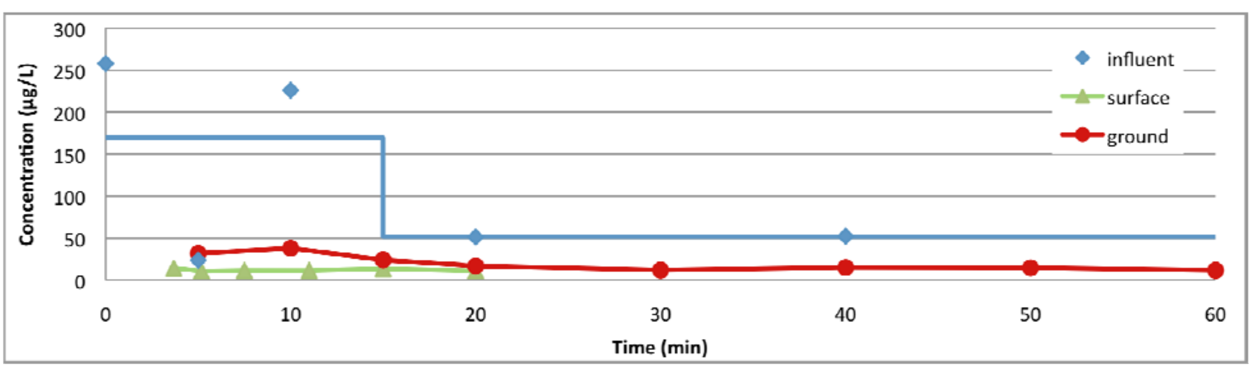


Figure 19. Total concentration of nickel in 4:1 slope, medium flow rate.

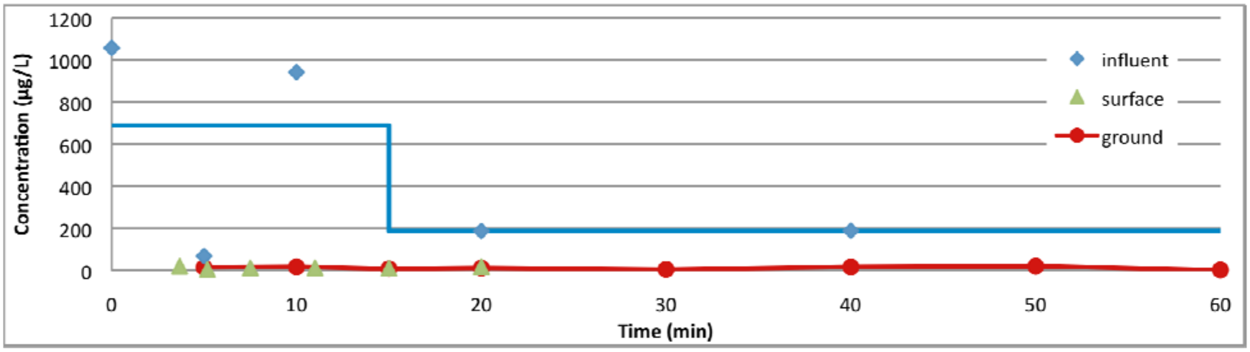


Figure 20. Total concentration of lead in 4:1 slope, medium flow rate.

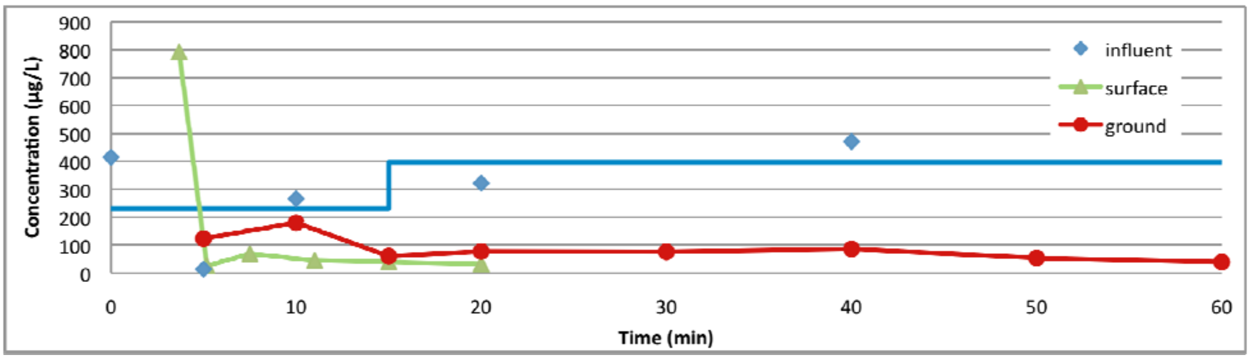


Figure 21. Total concentration of zinc in 4:1 slope, medium flow rate.

Figure 22 through Figure 28 portray the 2:1 slope test with a medium flow rate. For the water quality volume portion of the test, Cd, Cu, Ni, and Pb had average influent concentrations which were about 20-30% less than the medium target concentrations, while Cr was about 40% less, Zn 10 % higher and Fe about 28% higher. For the tail end portion of the test most all of the metals were within 20% of the low target concentrations, with the exception of Ni which was about half the target, while Zn as in the previous tests greatly exceeded the target and was similar in value to that of the 8:1 and 4:1 tests.

One sample of surface runoff was obtained during the tailing portion of the event at about 23 minutes into the event, although water was only dripping out of the trough at that point. All of the total metals concentrations in the surface runoff remained low, below 15 µg/L during the test, except Fe which had concentrations between 770 µg/L and 880 µg/L and Zn which had concentrations between 97 µg/L and 435 µg/L. All the metals in the surface flow except Zn remained fairly constant throughout the event. Percent removals, based on event mean concentrations, were for Cd, Cr, Cu, Fe, Ni, Pb, and Zn, respectively, 85.3%, 91.1%, 94.9%, 89.5%, 93.6%, 99.1%, and 50.9%. Removals were highest for Cu, Ni, and Pb and lowest for Zn. For the active grass, percent removals of event mean concentrations for Cd, Cr, Cu, Fe, Ni, Pb, and Zn were as follows: 93.8%, 89.4%, 98.2%, 97.0%, 92.6%, 97.1%, and 99.4%. Compared with the active growth tests, total metals removals were lower for the dormant tests for all metals except Cr and were substantially lower for Zn.

Underdrain concentrations were very similar to surface runoff concentrations except for Pb and Zn which each had one sample higher than surface runoff concentrations. Zn underdrain concentrations were high relative to influent concentrations as with the surface runoff concentrations.

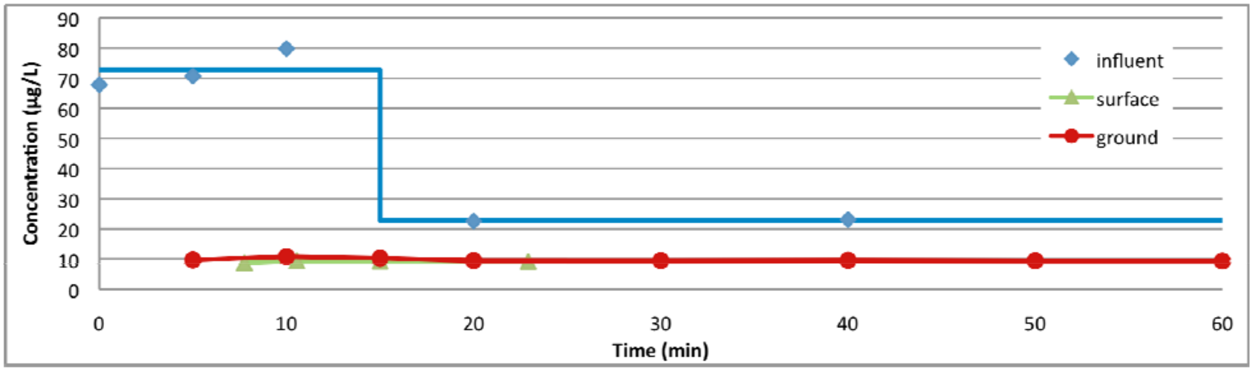


Figure 22. Total concentration of cadmium in 2:1 slope, medium flow rate.

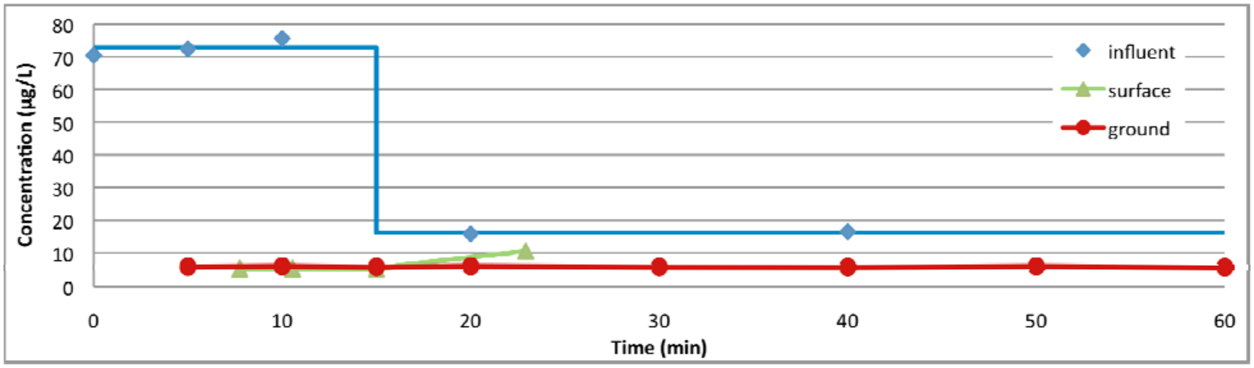


Figure 23. Total concentration of chromium in 2:1 slope, medium flow rate.

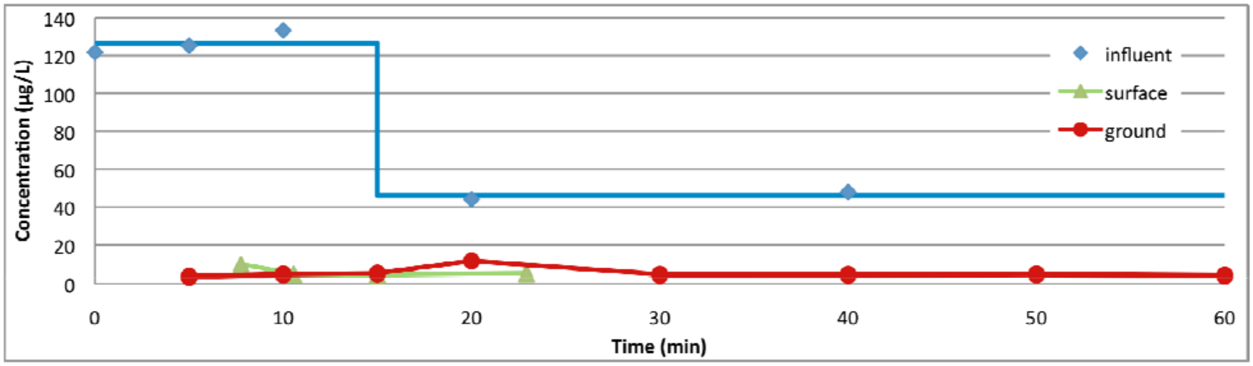


Figure 24. Total concentration of copper in 2:1 slope, medium flow rate.

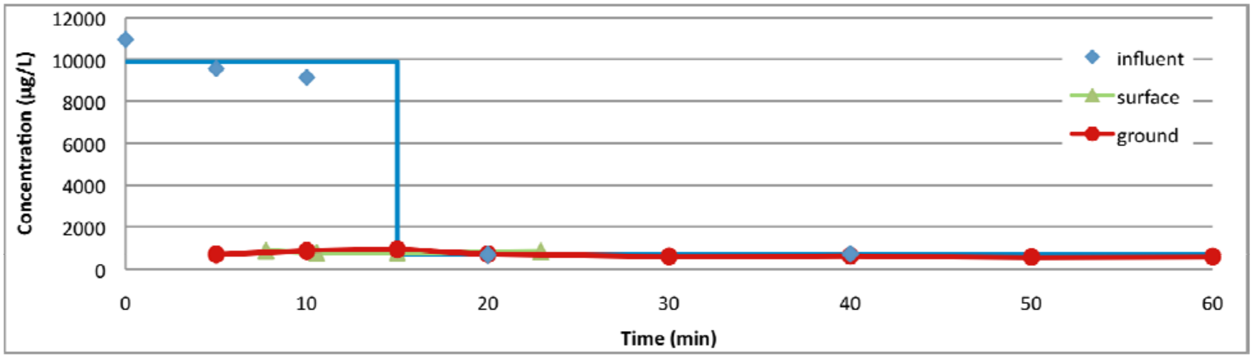


Figure 25. Total concentration of iron in 2:1 slope, medium flow rate.

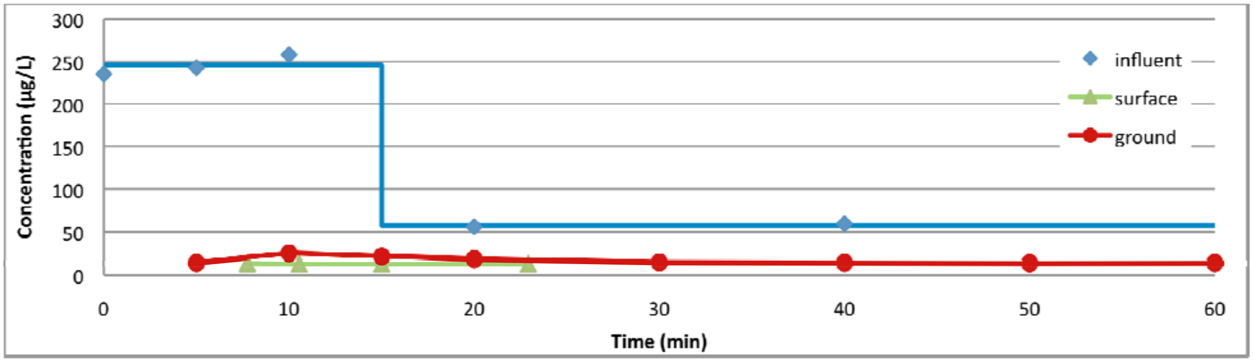


Figure 26. Total concentration of nickel in 2:1 slope, medium flow rate.

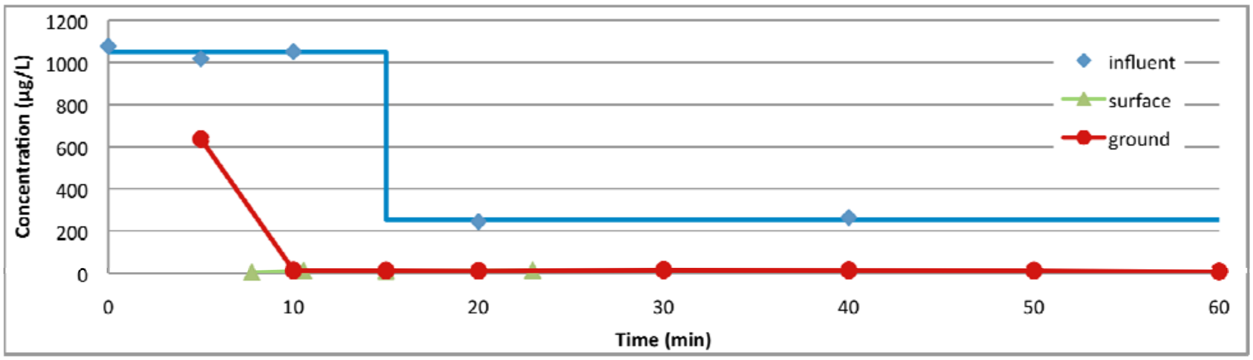


Figure 27. Total concentration of lead in 2:1 slope, medium flow rate.

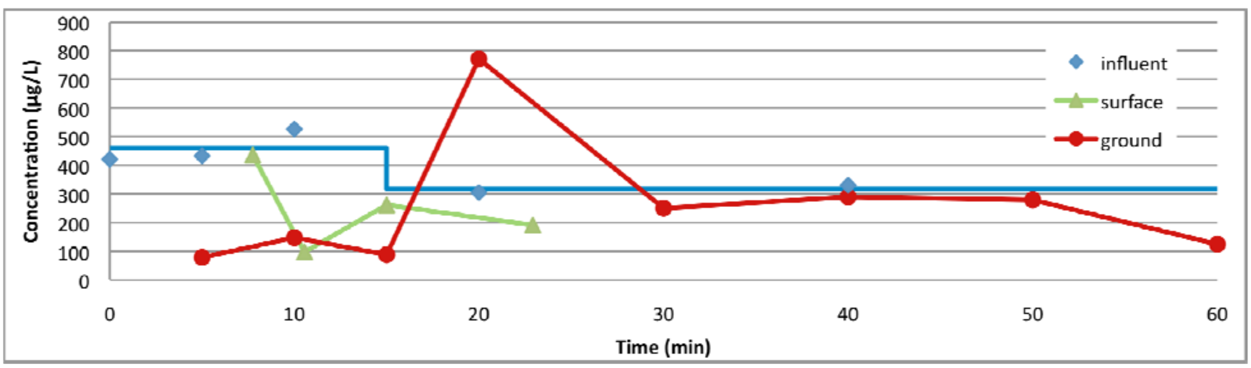


Figure 28. Total concentration of zinc in 2:1 slope, medium flow rate.

4.4 Dissolved Metals Results

Figure 29 through Figure 31 exhibit the dissolved metals for the 8:1 medium flow rate test for Cd, Ni, and Zn. Unfortunately, the ICP-MS failed during the analysis of these samples, so the analyses were continued with the ICP-AES. As a result, many of the samples have vastly different detection limits. This is apparent in Figure 29 where Cd was not detected in all of the surface runoff and underdrain samples, but the detection limit varied between 0.04 µg/L and 9 µg/L, which appears as fluctuating concentrations in the figure.

For Cr and Pb, metals were not detected in the dissolved phase for all but a few samples in the influent, surface runoff, and underdrain samples. For Cd and Ni, the influent dissolved metal concentrations were very similar to the total metal concentrations indicating complete dissolution of the metal in the influent. Dissolved Cd was not detected in any of the surface runoff or underdrain samples. Dissolved Ni was only detected in two of the surface runoff samples at concentrations near the total concentrations. Dissolved Ni was initially detected at near total concentrations in the underdrain but then transitioned to not detected for the tailing portion of the storm. Dissolved Cu was detected sporatically in the influent samples at low concentrations, but not detected in any surface runoff or underdrain samples. Dissolved Fe was detected in all samples with widely varying values, similar to the total Fe concentration, 1,040 µg/L, to a very small fraction of the total Fe concentration, 1.6 µg/L. These fluctuations in the fraction of Fe dissolved were sporatic and followed no trend for the influent and the surface runoff. In the underdrain, the dissolved Fe fraction began low, but midway in the tailing portion of the storm transitioned to the Fe being nearly entirely dissolved. Dissolved Zn was detected at high concentrations in the influent, similar to total Zn concentrations except one dissolved outlier that was very high, 3,200 µg/L. Dissolved Zn was detected in three of the five surface runoff samples again with one high outlier, 529 µg/L. Zn was only detected in three underdrain samples, much lower than total Zn concentrations.

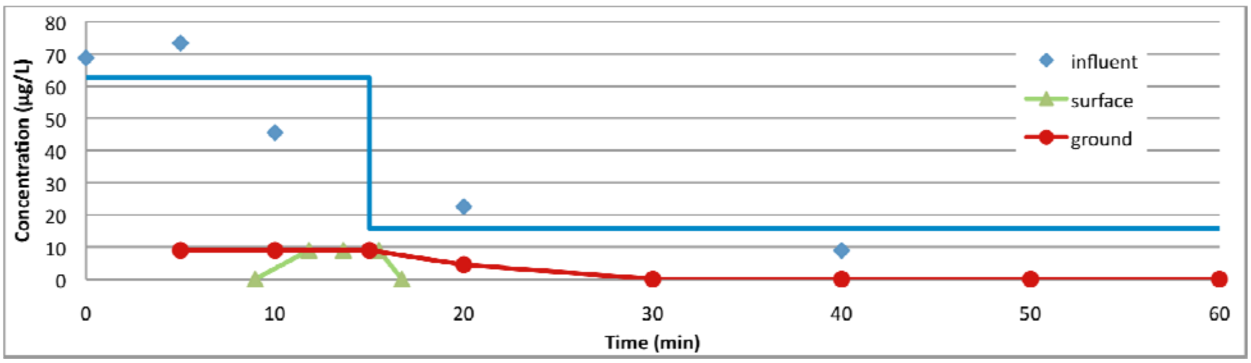


Figure 29. Dissolved concentration of cadmium in 8:1 slope, medium flow rate.

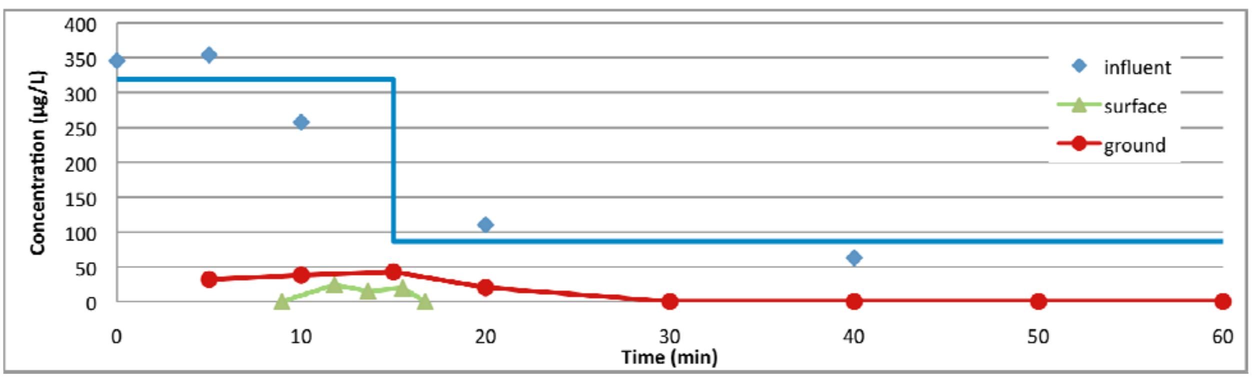


Figure 30. Dissolved concentration of nickel in 8:1 slope, medium flow rate.

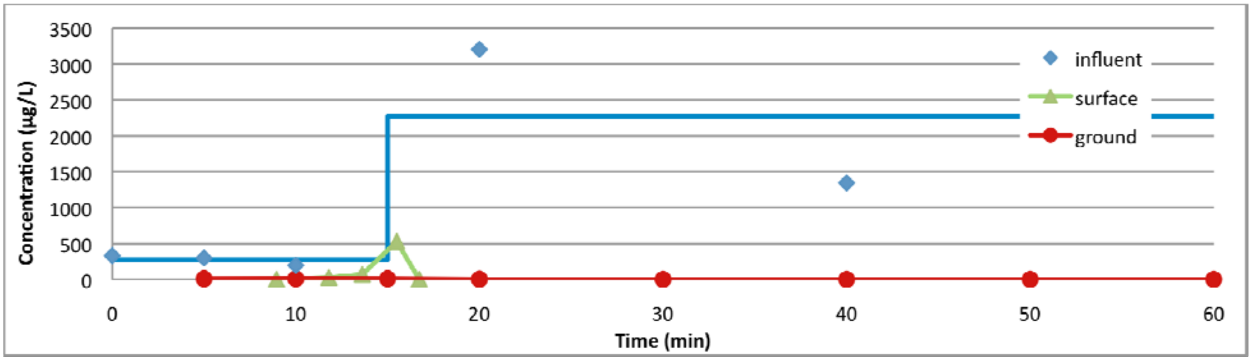


Figure 31. Dissolved concentration of zinc in 8:1 slope, medium flow rate.

Figure 32 through Figure 34 portray the dissolved Cd, Ni, and Zn concentrations for the 4:1 medium flow rate test. In the 4:1 test, metals partitioned between the dissolved and sorbed phase similarly to the 8:1 test. For Cr and Pb, metals were not detected in the dissolved phase for all but a few samples in the influent, surface runoff, and underdrain samples. For Cd and Ni, the influent dissolved metal concentrations were very similar to the total metal concentrations indicating complete dissolution of the metal in the influent. Dissolved Cd was not detected in any of the surface runoff or underdrain samples. Dissolved Ni was only detected in four of the six surface runoff samples at concentrations near the total concentrations. Dissolved Ni was initially detected at near total concentrations in the underdrain but then transitioned to not detected for the tailing portion of the storm. Dissolved Cu was detected sporatically in the influent samples at low concentrations, but not detected in any surface runoff or underdrain samples. Dissolved Fe was detected in half of the samples with widely varying values similar to the total Fe concentration, 825 µg/L, to a very small fraction of the total Fe concentration, 4.7 µg/L. These fluctuations in the fraction of Fe dissolved were sporatic and followed no trend for the influent and the surface runoff. In the underdrain, the dissolved Fe fraction began high, but midway in the tailing portion of the storm transitioned to a low fraction of the total metal. Dissolved Zn was detected at high concentrations in the influent, similar to total Zn concentrations. Dissolved Zn was detected in three of the six surface runoff samples again with one high outlier, 138 µg/L. Zn was only detected in one underdrain sample, much lower than total Zn concentration.

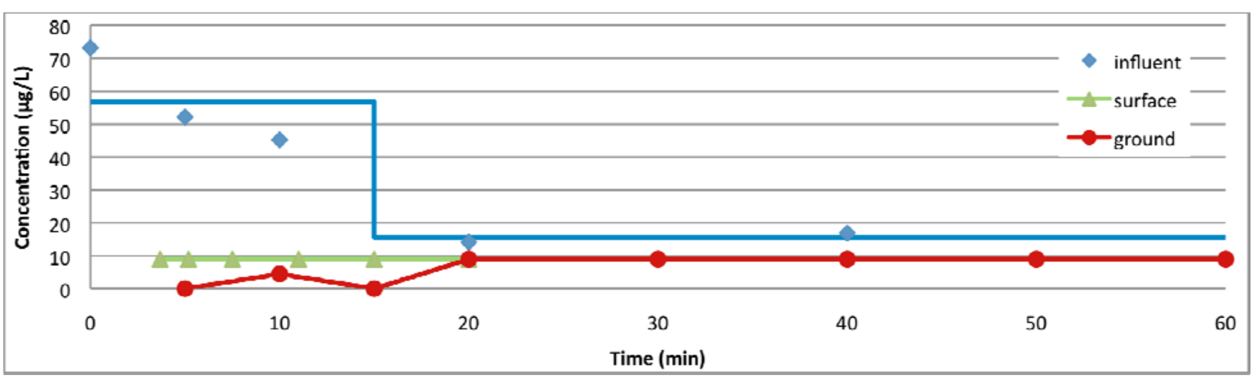


Figure 32. Dissolved concentration of cadmium in 4:1 slope, medium flow rate.

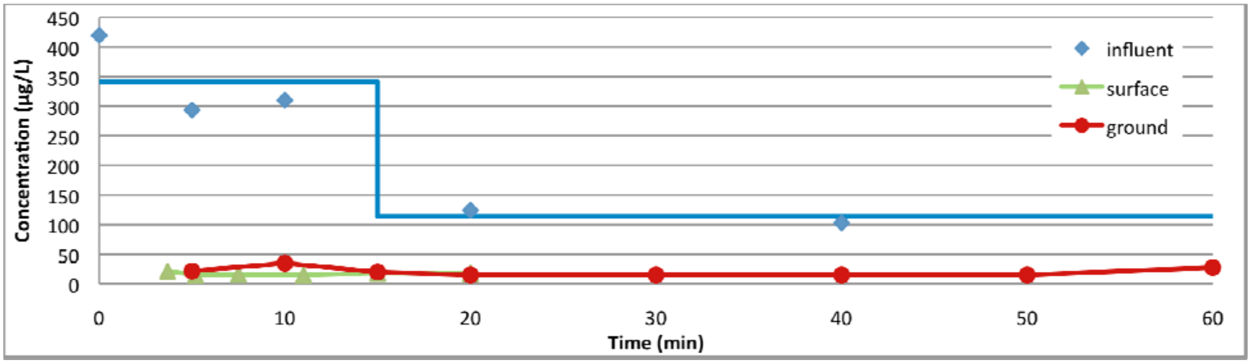


Figure 33. Dissolved concentration of nickel in 4:1 slope, medium flow rate.

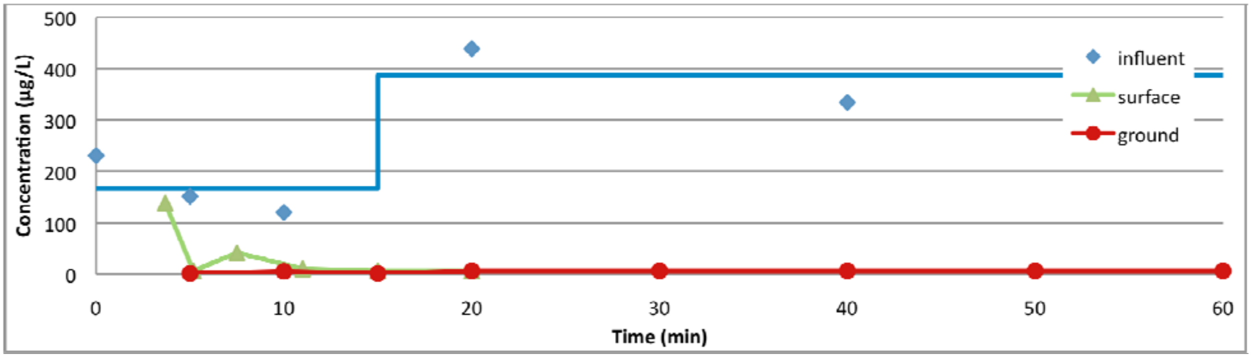


Figure 34. Dissolved concentration of zinc in 4:1 slope, medium flow rate.

Figure 35 through Figure 37 display the dissolved Cd, Ni, and Zn for the 2:1 slope and medium flow rate test. Dissolved Cu and Pb were not detected in any samples. For Cr and Pb, metals were not detected in the dissolved phase for all but a few samples in the influent, surface runoff, and underdrain samples. Dissolved Cr was detected in half of the samples in the influent and the surface runoff at low concentrations, < 5 µg/L. Dissolved Cr was detected in most underdrain samples again at low concentrations, < 6 µg/L, except for one outlier at 19 µg/L. Dissolved Cd was detected in all the influent samples at 25%-70% of the total Cd concentration, but was not detected in any surface runoff or underdrain samples. Dissolved Ni was detected in all influent samples at concentrations very similar to the total metal concentrations indicating complete dissolution of the metal in the influent. Dissolved Ni was not detected in any surface runoff samples and in only several underdrain samples at low concentrations. Dissolved Fe was detected in all samples at 10-20% of the total Fe concentration for influent samples and at concentrations similar to total Fe concentrations for surface runoff and underdrain samples. Dissolved Zn was detected in the influent samples, at 10-40% the total Zn concentrations and was only detected in two of all the surface runoff and underdrain samples.

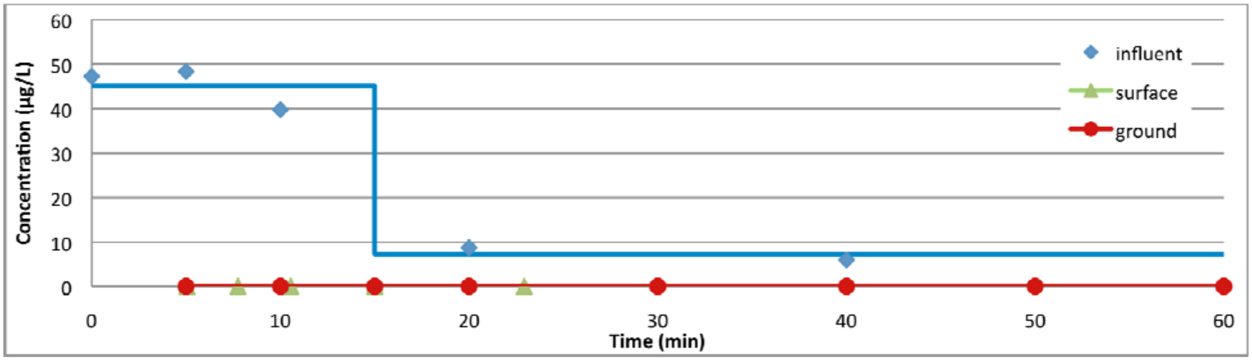


Figure 35. Dissolved concentration of cadmium in 2:1 slope, medium flow rate.

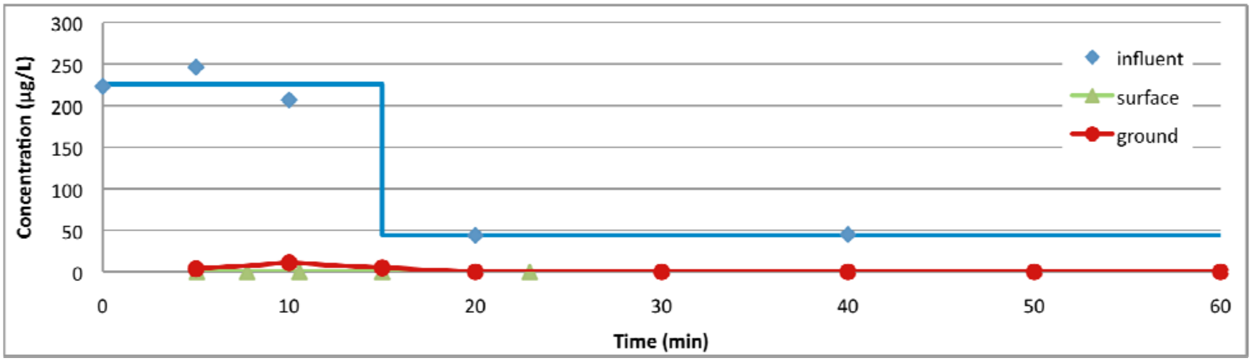


Figure 36. Dissolved concentration of nickel in 2:1 slope, medium flow rate.

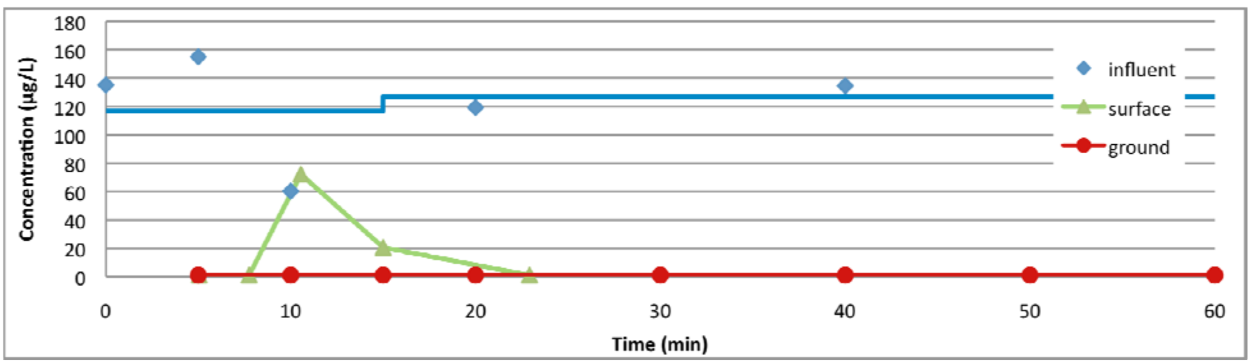


Figure 37. Dissolved concentration of zinc in 2:1 slope, medium flow rate.

4.5 Oil and Grease Results

Motor oil was added directly to the distributor plate as a pure phase with target concentrations after mixing with the influent water of 100 mg/L followed by 20 mg/L. Results are shown in Figure 38 through Figure 40. Average influent concentrations differed considerably from the target values and individual readings were erratic indicating the difficulty in monitoring the presence of a separate phase contaminant. Specifically, because motor oil floats on water it is transported chaotically and is difficult to capture a representative sample in a bottle, and results tend to be erratic. For the 8:1 slope the average was 68 mg/L dropping to 51 mg/L in the tailing portion. For the 4:1 and 2:1 tests, concentrations were about 80 and 100 mg/L, repectively, throughout the test. Surface runoff concentrations were low for all three tests with values below 20 mg/L. Percent removals for the dormant grass were 84%, 91%, and 96%, compared to percent decreases under active conditions of 99%, 85%, and 100% at 8:1, 4:1, and 2:1 slopes, respectively. Concentrations of oil and grease in the underdrain were often higher than in the surface runoff with several spikes but averaging below 20 mg/L. These spikes may be manifestations of oil/water emulsion micropackets carried into the subsurface, as noted by Berge and Ramsburg [2009]. Migration of other immiscible fluids such as gasoline and chlorinated solvents in groundwater has been well documented.

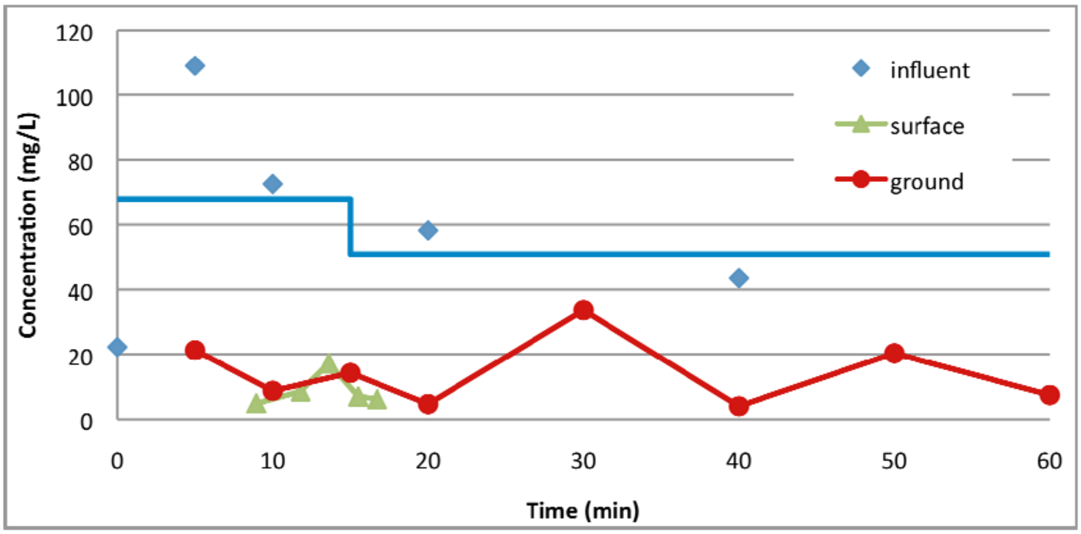


Figure 38. Concentration of oil and grease at 8:1 slope.

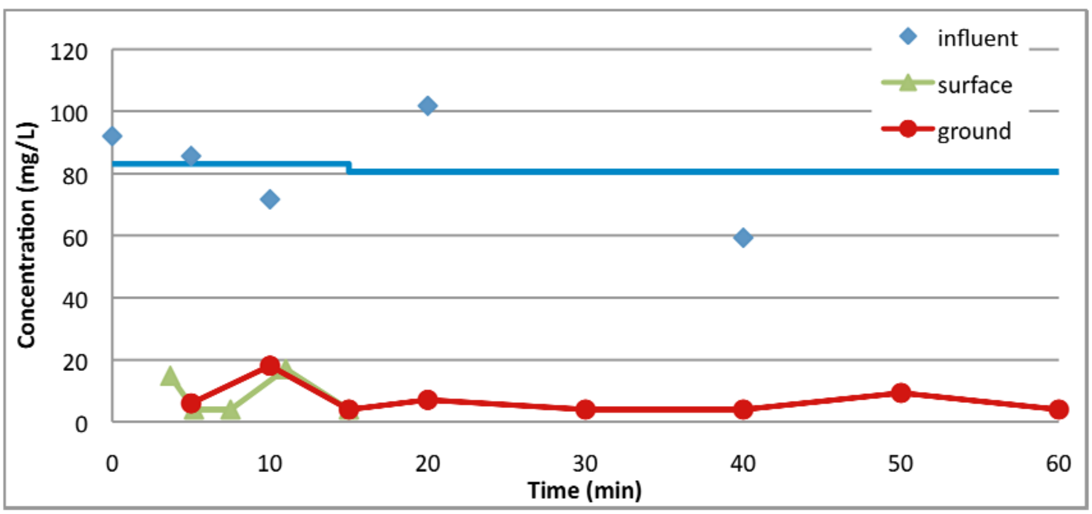


Figure 39. Concentration of oil and grease at 4:1 slope.

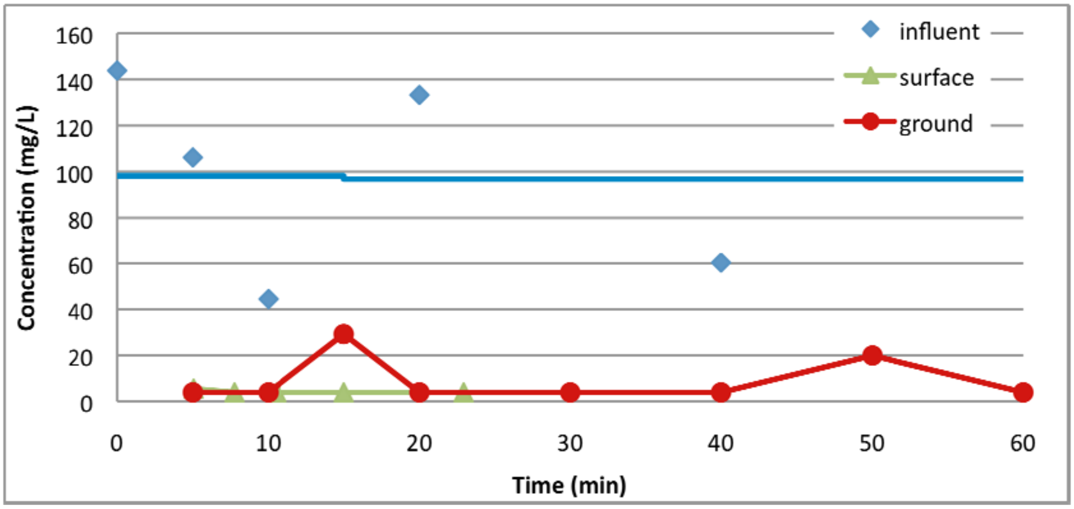


Figure 40. Concentration of oil and grease at 2:1 slope.

4.6 Chloride Results

Figure 41 to Figure 43 depict chloride concentrations for the three medium concentration tests. NaCl was added at a target concentration of 262 mg/L for the water quality portion of the event, and background tapwater chloride concentrations were used for the subsequent low concentration flow. Actual concentrations measured in the first portion of the influent flow as it sprayed onto the bed averaged 410 mg/L, 265 mg/L and 282 mg/L, for each slope of 8:1, 4:1, and 2:1, respectively. Chloride concentrations during the lower flow rate tailing 45 min of the runoff averaged 43 mg/L, 49 mg/L, and 51 mg/L.

For the 8:1 slope, surface runoff chloride concentrations averaged about half the influent concentration for the first portion of the event and continued at this level into the tailing portion. For the 4:1 and 2:1 events in general the chloride concentration was comparable to the influent concentration. In the underdrain for all three slopes chloride levels were below the influent for the water quality portion but slightly above the influent in the tailing portion. Only a 37% removal was calculated using event mean concentrations for the 8:1, and there were 0% removals for the 4:1 and 2:1 slopes.

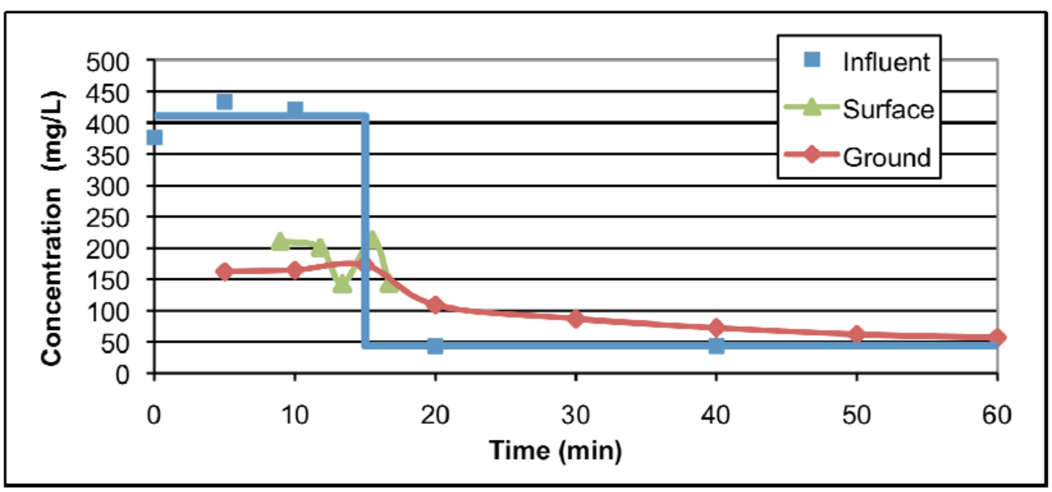


Figure 41. Concentrations of chloride at 8:1 slope.

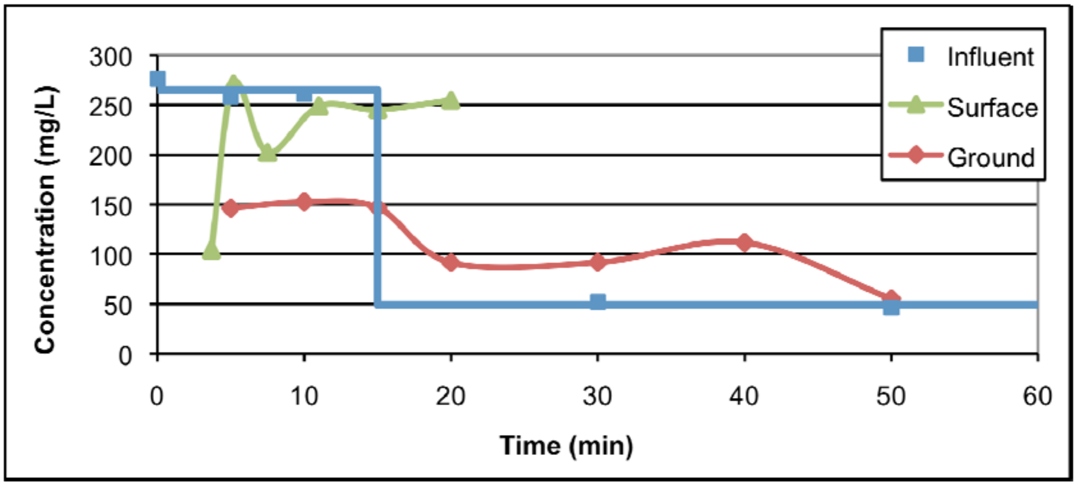


Figure 42. Concentrations of chloride at 4:1 slope.

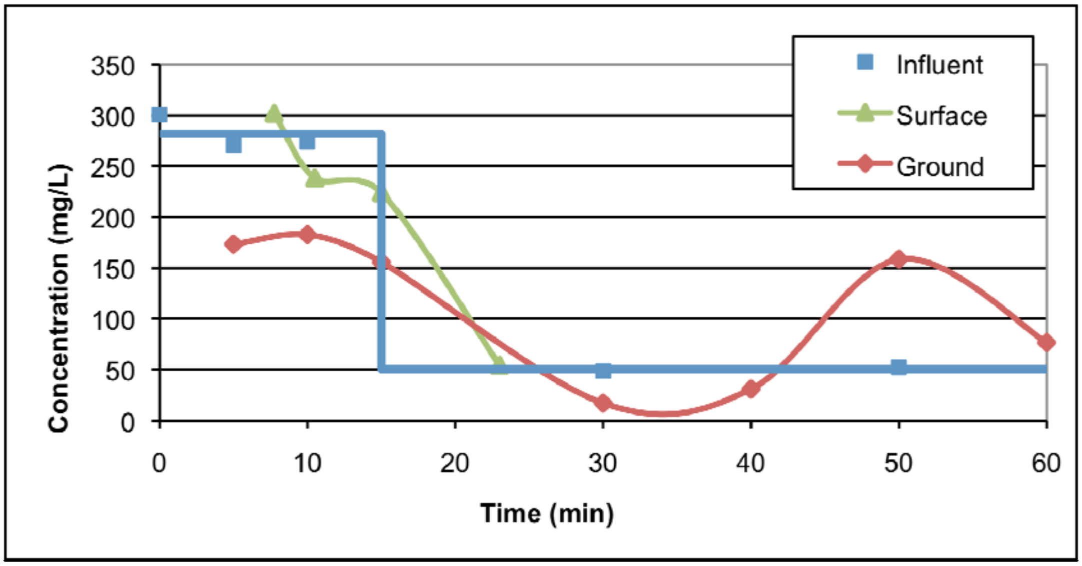


Figure 43. Concentrations of chloride at 2:1 slope.

4.7 Removals

Figure 44 displays the average percent removals of the event mean concentration for each total metal, total suspended solids, oil and grease, and chlorides for each dormant performance test. Percent removals were very high (>90%) for Cu, Ni, and Pb and high (>80%) for Cd, Cr, TSS, and oil and grease. Fe varied significantly from 66% to 89% removal, and Zn was low with percent removals of 51% to 68%. Chloride removal was minor ranging from 0% to 37%. There were no significant trends in removals associated with changes in slope. Results for total metals with the dormant bed were similar to percent removals observed for the active bed with overall slightly higher removal for the 8:1 slope and lower for the 4:1 and 2:1 slopes. Results for Fe, Zn, and TSS were consistently lower for the dormant bed.

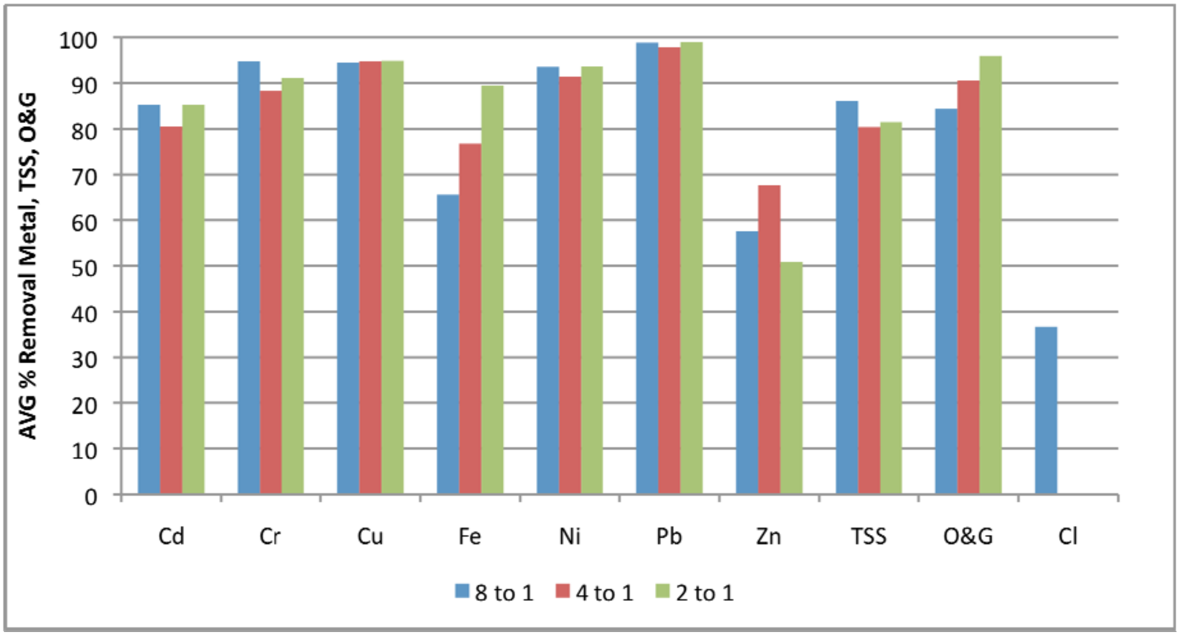


Figure 44. Percent removals of event mean concentration for total metals, TSS, and oil and grease from medium concentration influent tests on Bed 2.

Percent removals of contaminants from storm water were also determined for only the water quality event portion of the storm, event defined here as the first 0.75 in (19 mm) of runoff, and these are shown in Figure 45. Percent removals were higher for all constituents except Zn, because they did not include the tailing portion of the storm that has lower concentrations in the influent calculations. TSS and Cl^- removals were substantially higher when considering only the first flush; 86% to 90% for TSS and 14% to 56% for Cl^-

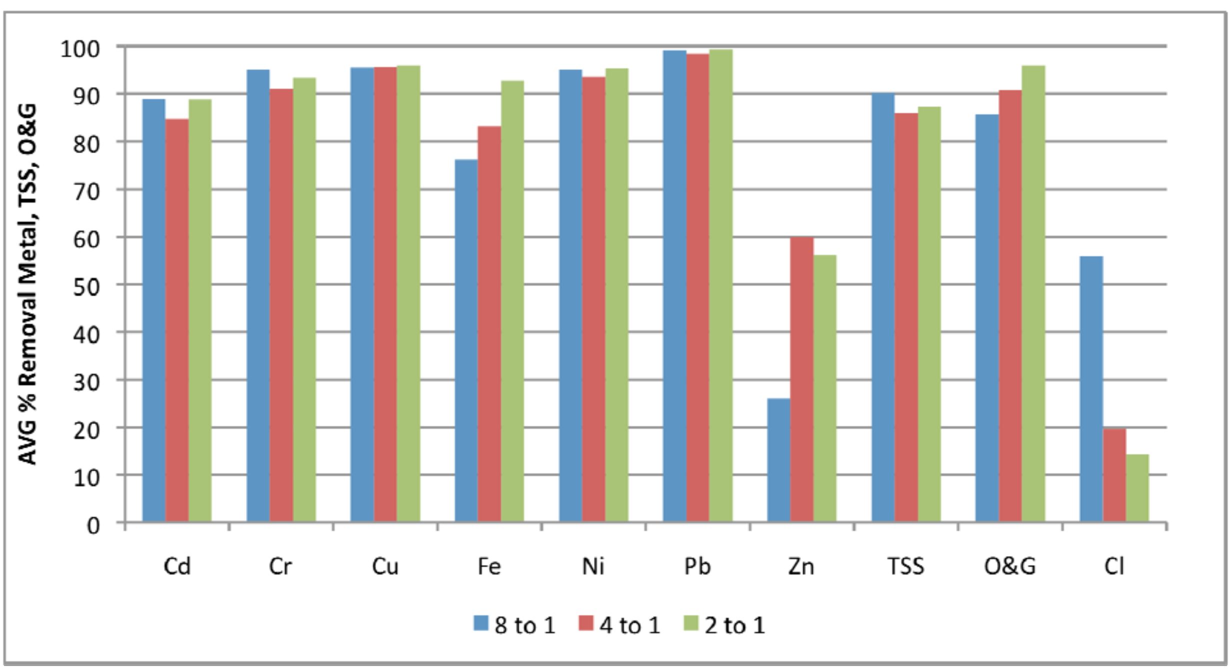


Figure 45. Percent removals of event mean concentration during the water quality volume of the storm event for total metals, TSS, and oil and grease for Bed 2.

4.8 Resuspension Results

For the initial 8:1 slope performance test, target concentrations of La tagged suspended solids were added to the influent; 207 mg/L for the water quality event portion and 9 mg/L for the tail end of the test. Subsequent tests did not tag the suspended solids that were added to the influent. As displayed in Figure 46, the initial influent samples exhibited tagged suspended solids concentrations higher than the target concentration averaging 255 mg/L with an average La concentration of 15,300 µg/L. For the tail end of the test, the collected influent samples exhibited tagged suspended solids concentrations very close to the target concentration, with an average tagged suspended solids concentration of 7 mg/L, and an average La concentration of 406 µg/L.

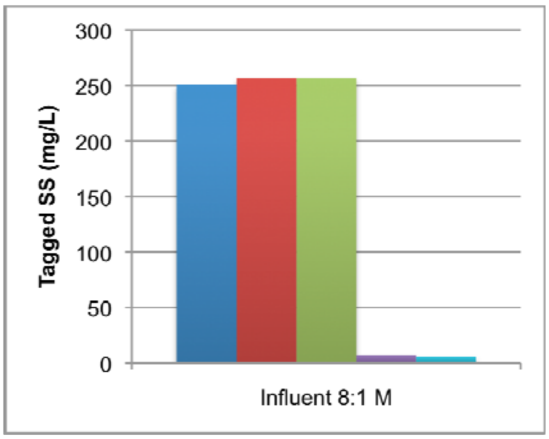


Figure 46. Influent tagged suspended solids concentration in 8:1 slope, medium flow rate for Bed 2. From left to right, the bars represent influent samples collected at times of 0 min, 5 min, 10 min, 30 min, and 50 min during the simulated storm event.

Figure 47 displays the tagged suspended solids concentrations in the surface runoff samples for each of the three performance tests. As seen from this figure, the tagged suspended solids concentrations were highest for the 8:1 medium flow test, with an average tagged suspended solids concentration of 0.21 mg/L and an average La concentration of 12.5 µg/L. The final collected sample was substantially higher than the others at a tagged suspended solids concentration of 0.80 mg/L and La concentration of 48.3 µg/L. It was during this test that the tagged suspended sediment was being released in the influent. These surface runoff concentrations were well below the average influent concentrations during the water quality event portion of the storm of 255 mg/L for tagged suspended solids concentration and 15,300 µg/L for La concentration. The fraction of La tagged soil in the samples greatly decreased from around 1.37 in the influent to 0.0307 in the surface samples. This low surface runoff concentration showed that the majority of the added suspended solids were settling within the bed, and a very small amount flowed over the bed without settling. The majority of the total suspended sediment in the runoff (average of 21.5 mg/L for this run, see Figure 4) was released from the bed itself and did not originate from the influent water. Additional evidence of this was the baseline TSS concentrations in surface runoff which averaged 13.4 mg/L for the 8:1 slope, 17.7 mg/L for the 4:1 slope, and 63.7 mg/L for the 2:1 slope with only tap water as influent. The other two performance tests resulted in very low concentrations of tagged suspended solids in surface runoff, averaging 0.027 mg/L for the 4:1 slope and 0.028 mg/L for the 2:1 slope. La concentrations averaged 1.6 µg/L and 1.7 µg/L, respectively.

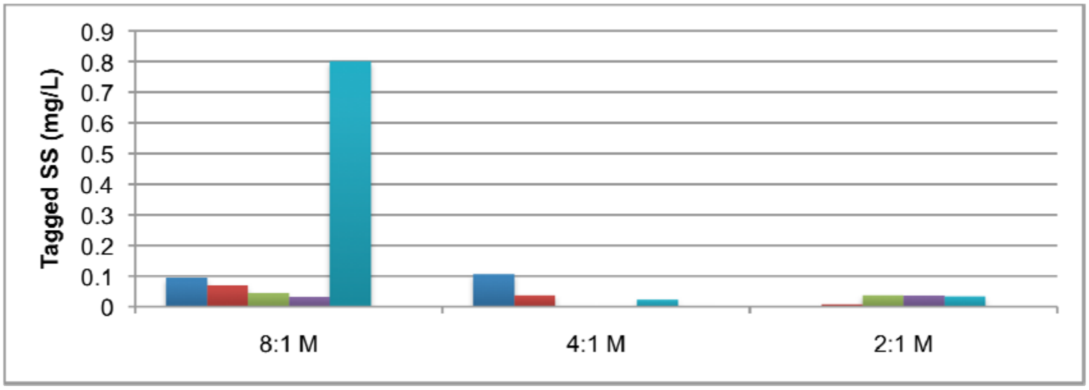


Figure 47. Tagged suspended solids concentrations for experimental and resuspension tests for Bed 2. Each bar represents a collected surface sample.

4.9 Metal Accumulation in Grass, Soil, and Roots

After completion of the dormant performance tests on bed 2, twenty cores were collected throughout the bed, five replicates at four different locations down the length of the bed. As previously described, the cores were separated into grass, root, and soil fractions, and each fraction was digested and analyzed for metals concentrations. The metals added to the influent included Cd, Cr, Cu, Fe, Ni, Pb, and Zn. Figure 48 through Figure 54 display the concentrations in mg of metal/kg of dry matter within the grass, soil, and roots down the length of the bed. Because five core samples were collected at each distance along the bed, average values were plotted and error bars at each point on the graph represent one standard deviation. The dashed lines on each graph represent the average concentrations of the grass, soil, and roots determined after the regular season performance on bed 2, the baseline condition for the dormant grass studies on bed 2.

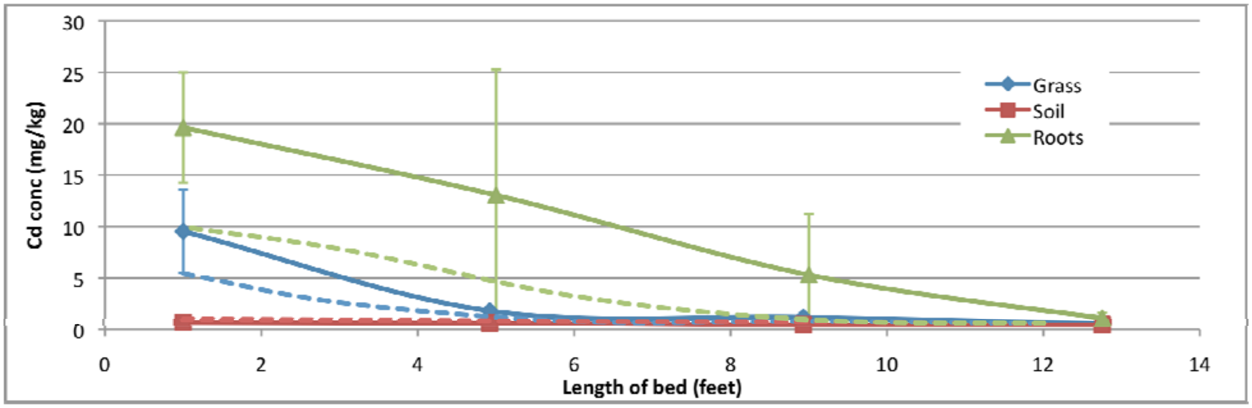


Figure 48. Concentration of Cd throughout length of Bed 2.

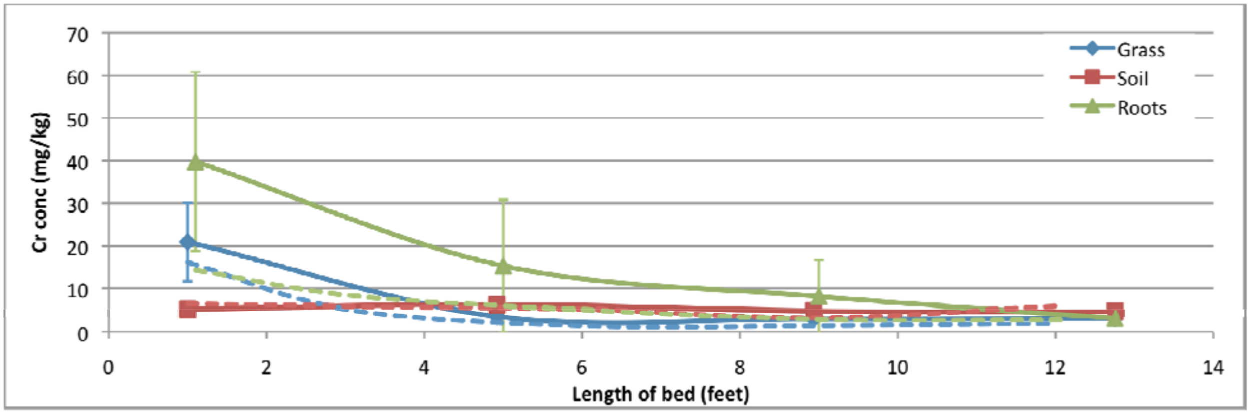


Figure 49. Concentration of Cr throughout length of Bed 2.

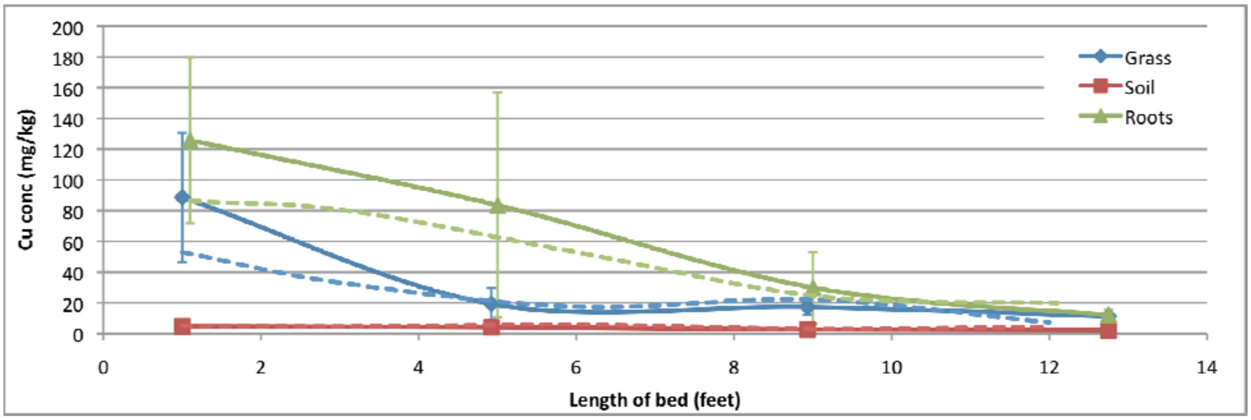


Figure 50. Concentration of Cu throughout length of Bed 2.

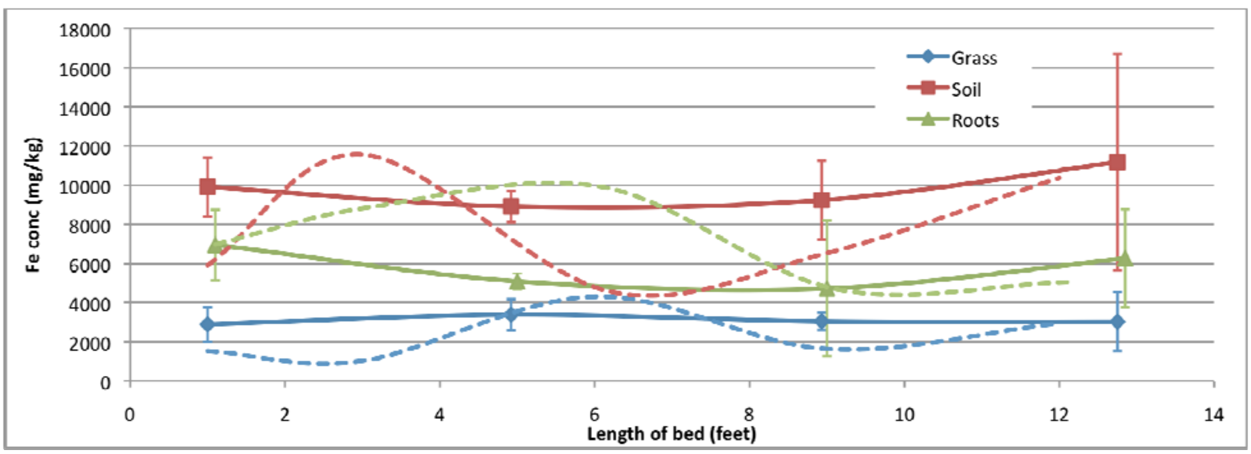


Figure 51. Concentration of Fe throughout length of Bed 2.

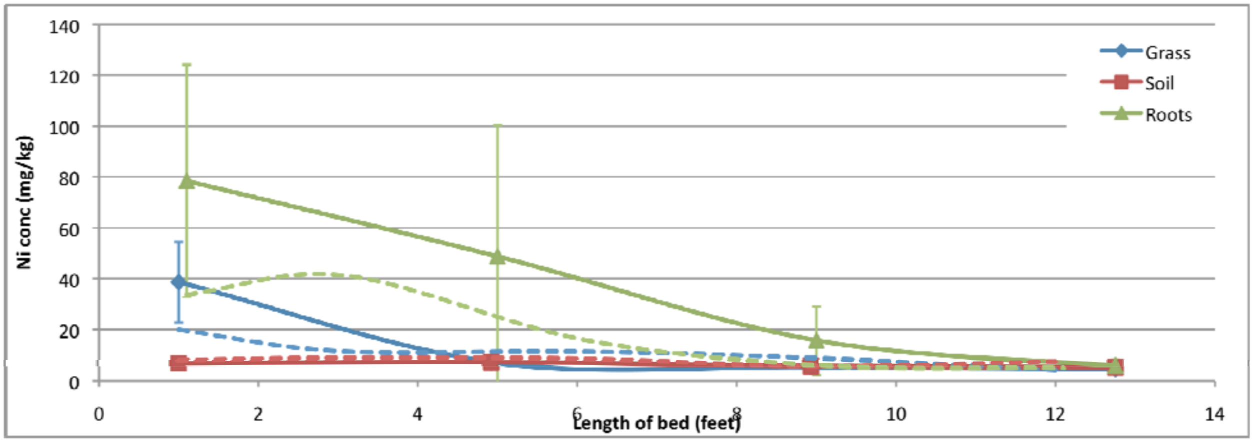


Figure 52. Concentration of Ni throughout length of Bed 2.

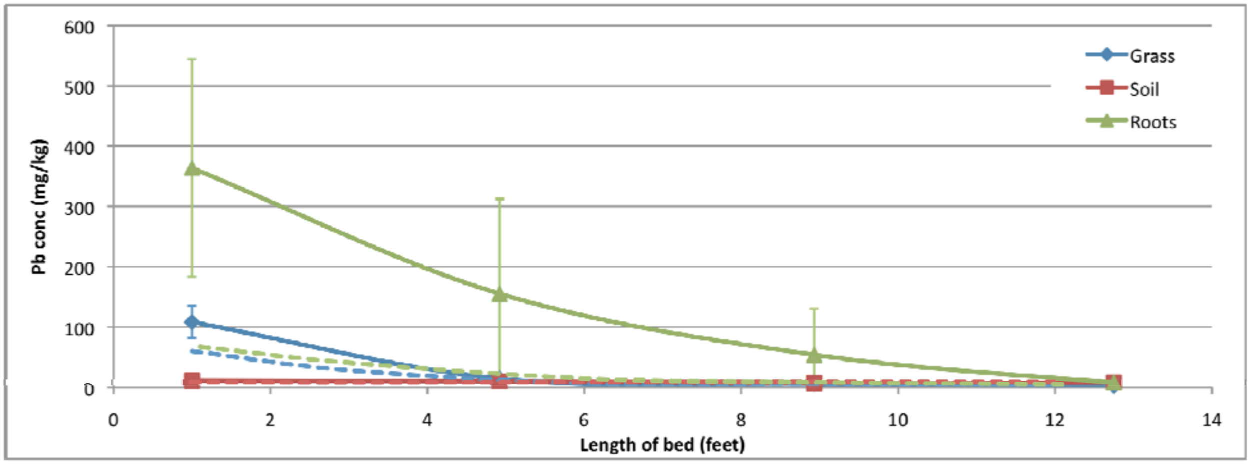


Figure 53. Concentration of Pb throughout length of Bed 2.

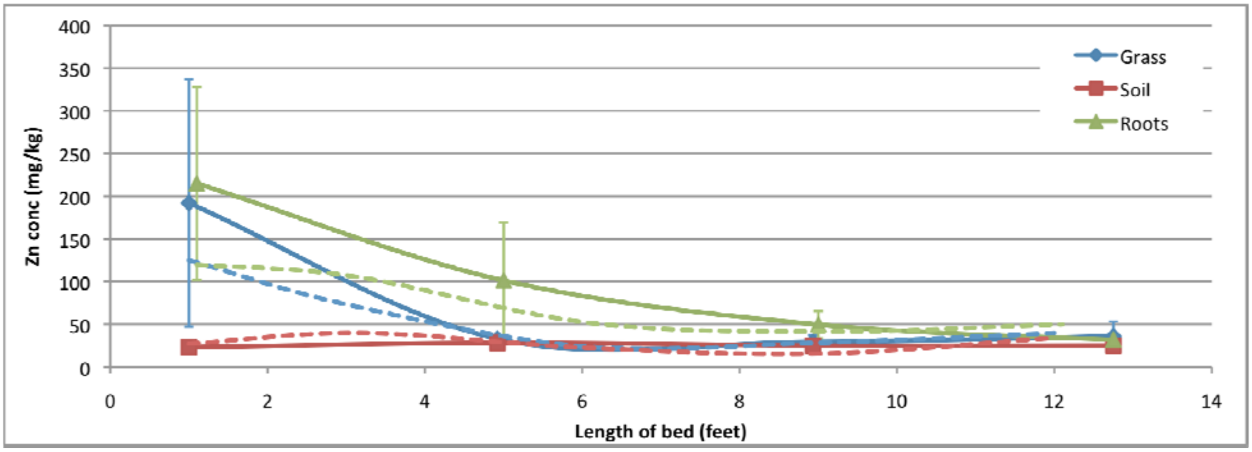


Figure 54. Concentration of Zn throughout length of Bed 2.

In terms of highest concentrations of metals accumulating within the media, all the metals except Fe exhibited the highest concentrations in the roots, next highest in grass, and low concentrations in soil. Fe was the only metal with highest concentrations detected in the soil, next highest in roots, and lowest concentrations detected in grass. In terms of spatial distribution of metals, concentrations decreased along the length of the bed for all metals except Fe with highest concentrations detected at a location of 1 ft (0.305 m) from the edge of the bed, corresponding to the drip line where the influent water encountered the bed. Distances in the following discussion are relative to the origin of the bed at 1 ft (0.305 m), 5 ft (1.52 m), 9 ft (2.74 m), and 12.8 ft (3.89 m); relative to the drip line, these positions are 0 ft (0.0 m), 4 ft (1.22 m), 8 ft (2.44 m), and 11.8 ft (3.58 m).

Metals were primarily detected at statistically significant levels above concentrations detected at the end of the previous summer performance tests ($\alpha = 0.05$ for all tests) in the roots at the location just under the dripline. This was true for Cd, Cr, Pb, Ni, and Zn, all the metals of concern save Cu. There were a number of other sporatic detections significantly above the previously measured values that were not readily apparent in the figures (Cr in grass at 9 ft (2.74 m) and 12.8 ft (3.89 m), Cr in soil at 5 ft (1.52 m) and 9 ft (2.74 m), Cu in grass at 12.8 ft (3.89 m), Pb in roots at 5 ft (1.52 m), Ni in grass at 1 ft (0.30 m), and Zn in soil at 9 ft (2.74 m)). However these were due primarily to fortuitously low standard deviations in the dormant and baseline replicate results and not to large differences in the averages, and they also conformed to no obvious trend. Fe was only significantly high in several seemingly random locations (grass at 1 ft (0.305 m) and 9 ft (2.74 m) and soil at 1 ft (0.305 m) and 9 ft (2.74 m)) due primarily to the high variability in the previous summer performance results.

Note that using the sampling results from the previous summer performance tests as the baseline for the dormant studies was not ideal because of the long time the bed sat idle. For the remainder of the season new grass grew and was periodically cut, and the bed was watered and received rain. All of these events might have led to migration of metals among the various media, like leaching of metals out of the soil by water, uptake of metals from soil into roots and grass, leaching of metals into soil from dead grass and root matter, and dilution of root and grass concentrations due to plant growth. However, a complete sampling of the bed before dormant testing was not possible, because the number of holes cored into the bed during a season when the bed was not actively growing would have created flow paths vertically down through the bed interfering with the performance tests. Also, preparing a new clean bed was not possible, because the additional dormant study was not approved until after the growing season had completed. As a result, there is some uncertainty interpreting the increase in concentrations compared to a baseline. Nevertheless, results were consistent with the previous active growth results, and average concentrations increased after the dormant study.

In the roots, every metal except Fe and Cu showed a statistically significant amount of accumulation at the first sampling location. Pb accumulated to the highest concentration in the roots at 364 mg/kg, but Pb was also at one of the highest concentrations in the influent water. As a fraction of the concentration in the roots to the concentration in the influent, Zn accumulated at the greatest proportion in the roots at 0.50, with Pb and Cr at the next highest proportions at 0.34 and 0.32. Although there were a handful of detections of metals in grass and soil at various locations, these were sporatic and followed no trend. Because of so few detections significantly above baseline, mass balance analysis of metals accumulation in the bed was not possible.

5 Comparisons of performance under dormant and active growth conditions

At the time of performance testing the dormant bed had about 60% vegetated coverage compared with about 83% coverage under summer conditions. Baseline concentrations were generally higher for all constituents for the dormant bed. Comparison of EMC removals of constituents show lesser removal for TSS, iron and zinc under dormant conditions. Comparisons of removals of other constituents under dormant versus summer vegetation did not appear to be statistically different. Removal of TSS was still above 80% for the dormant bed. Removal of Zn however declined to 50% to 65%, while iron exceeded 60%. Analysis of core data indicated that the roots were providing the greater uptake of metal constituents, which was the previous finding under active growth.

6 Summary and Conclusions

6.1 Summary

The Ohio Department of Transportation utilizes vegetated biofilters as one of several available post construction stormwater BMPs; "the vegetated biofilter consists of the vegetated portion of the graded shoulder, vegetated slope, and vegetated ditch." [ODOT 2009, Section 1117.3]. This supplemental study examined the slope portion of vegetated biofilters under dormant conditions to contrast to summer grass conditions relative to the capture and treatment of the water quality volume of highway storm runoff, defined by OEPA in the NPDES Construction General Permit as the volume of runoff from the first 0.75 in (19 mm) of precipitation that must be captured and treated [OEPA, 2008].

The prototype vegetated biofilter foreslope, labeled Bed 2, 4 ft (1.22 m) wide by 14 ft (4.27 m) long (direction of flow) and further described in the report [Mitchell, Riefler, and Russ, 2010b], was studied under dormant vegetation conditions. The foreslope, receiving a "medium" concentration influent (medium concentration during the water quality portion of the event followed by low concentration influent) storm water runoff, performed well at all slopes (8:1, 4:1, 2:1) under the medium flow storm event simulation. Based on EMC calculated data, removals of TSS and the total metals (Cd, Cr, Cu, Ni, and Pb) monitored in the influent flow were at or above 80%. Under dormant conditions removals of total metals from highest to lowest, averaged over the three slopes, were Pb, Cu, Ni, Cr, Cd, Fe and Zn. For the summer conditions, the highest removals were noted for Fe, Pb, Ni and Cu. Similar to the findings for summer conditions, dormant data indicated slightly lower overall removals for Cd and to a lesser extent for Cr compared to the other metals, such as Pb, Cu, and Ni. In the previous summer, tests for the medium concentration influent Ni, and to a somewhat lesser extent Cd, tended to predominate in the dissolved form. In the dormant tests, Ni, Cd, and Zn had dissolved concentrations similar to total concentrations for most of the influent samples.

Oil and grease removal for the three slopes was 82%-95%, and slightly higher under summer conditions for the medium flow rate.

Removals of constituents computed based only on the water quality volume as defined by OEPA [OEPA, 2008, ODOT, 2009], the runoff generated by the first 0.75 in (19 mm) of precipitation, in general, were the same or greater than those computed for the entire runoff event with the exception of zinc.

For the dormant bed, the baseline surface runoff particle sizes ranged from 100-1000 µm, and for the majority of the performance tests the influent and the surface runoff samples were in the range of 1-1000 µm and 1-10 µm, respectively. For the active bed, influent particle size ranged between about 1µm (0.039 mil) to 100 µm (3.9 mil) for the 8:1 and 4:1 slope, while the 2:1 slopes received particle sizes from 1µm (0.039 mil) to 1000 µm (39 mil) with over 80% above 100 µm (3.9 mil). The effluent surface particle sizes were predominately about 1000 µm (39 mil) for the three slopes at medium flow, but 1µm (0.039 mil) to 100 µm (3.9 mil) at the 2:1 high flow.

Analysis of the La tagged soil added in the first dormant performance test at 8:1 indicated that negligible material was transported to the surface effluent or resuspended. For the summer active grass study that had seven runoff events following the tagged suspended sediment deposition, negligible amounts of that original sediment were resuspended from the bed and released in the surface runoff.

Data indicate that the majority of uptake of metals occurred in the vegetated root structure, as was found previously for the summer active vegetation tests. For both the dormant and summer active grass, the highest concentration of metals occurred where the influent flow entered the bed and decreased along the length of bed in the direction of flow with the exception of Fe.

For the dormant vegetation sodium chloride was introduced into the artificial runoff to simulate winter maintenance on roadways. Over the entire event the chloride was reduced by about 35 % at the 8:1 slope with no reduction at the other two slopes. For the water quality portion of the event chlorides were slightly reduced at the 4:1 and 2:1 slopes.

In summary, the prototype vegetated biofilter foreslope under dormant conditions provided fair to excellent performance in removal of pollutants (seven metals, suspended material, and oil and grease) from a medium concentration simulated storm water runoff. Over 80 percent removal was achieved for all constituents except iron, zinc and chlorides. Iron removal averaged about 75%, while Zn was about 58%. Chlorides were only slightly removed at all slopes over the water quality portion of the event. TSS removal declined from a summer condition average removal of about 95% to 80% for the dormant condition. Results at slopes of 8:1, 4:1, and 2:1 did not indicate declining performance with increasing slope. For the dormant test vegetation coverage was about 60% contrasted to an average 83% during the summer. This reduced coverage which would be expected during winter conditions contributed to the reduction in removals. Overall within the parameters of this study, findings indicated that the foreslope portion of the vegetated biofilter even during a dormant condition significantly reduces the quantity of pollutants in the runoff with the exception of chlorides.

6.2 Recommendations

Removals, as expressed in EMC, under dormant conditions were less than that obtained with summer vegetation but overall were acceptable, particularly for TSS and most metals, 80% or greater. This was primarily attributed to the reduced vegetative coverage since this was the primary variable for the test conditions. Hence, establishment of good vegetative coverage prior to winter or dormant conditions is recommended. Some reduction in chlorides was observed, less than 30% averaged over the three slopes during the water quality portion of the events. If a high quantity of salt (NaCl) accumulated in the biofilter, this could possibly impair growth of the vegetation, however long term effects were beyond the scope of this project and were not investigated.

7 Implementation

ODOT can use the information in this supplement and report [Mitchell, Riefler, and Russ, 2010b] to begin assessing the selected versions of the vegetated biofilter as a best management practice suitable for meeting the OEPA permitting criteria. Some of the findings in the report and from the literature may have application in revising or adding to sections of ODOT's *Location and Design Manual* Volume 2 [ODOT 2009, Section 1117.3] and *Construction and Materials Specifications* regarding vegetated biofilters. These findings may also be applicable to revising ODOT's storm water and water quality research goals, and also to revising ODOT's Storm Water Management Program.

Items for consideration include the following:

- Recognition that the foreslope provides significant removal of storm runoff constituents.
- Restriction of foreslopes to less than 2:1.
- Establishment of a requirement of minimum coverage of vegetation. The impact of coverage on performance was outside the scope of this study. The vegetated foreslopes studied in this project performed well with a vegetative coverage above 80%; this coverage level is recommended. Tests of the foreslope prototype conducted under dormant conditions with vegetation coverage about 60 % indicated good performance also but less than that under summer conditions and greater vegetative coverage. Also, baseline concentrations were higher under dormant compared to summer conditions.
- Exclusion of the use of crown vetch.
- Establishment of a standard inspection schedule using a form similar to the field inspection record in [Mitchell, Riefler, and Russ, 2010b].
- Maximization of infiltration along the foreslope.

A field study is recommended to verify these results under actual roadside conditions and to consider long-term issues.

Ultimately changes in the *Location and Design Manual* Volume 2 and *Construction and Materials Specifications* will be distributed to the ODOT Districts so that vegetated biofilters conforming to the updated specifications can be designed and incorporated into future transportation system construction and repair projects.

Implementation will be limited to those sites with sufficient right of way to construct the vegetated biofilter, thus personnel in rural areas would be the primary users of the system. Other impediments could include the efficacy of the biofilter during prolonged salt application in winter seasons. Appropriate construction and maintenance will be important to the success of the BMP.

As discussed in [Mitchell, Riefler, and Russ, 2010b], cost components would include purchase of the vegetation and soils, construction of the biofilter, and site maintenance. Costs would be dependent on site characteristics and could be highly variable from site to site.

8 References

American Society of Civil Engineers (ASCE), et al., 1996 (ongoing), International Stormwater BMP Database, http://www.bmpdatabase.org/, accessed March 2010.

Athens Water Treatment Plant, 2009, "Laboratory Test Results", *2009 City of Athens Annual Drinking Water Consumer Confidence Report*, Athens, OH, 2009, pp. 12-13. Test dates 2008 for all metals and hardness.

Backstrom, Mattias, et al., 2004, "Mobilisation of heavy metals by deicing salts in a roadside environment", *Water Research*, 38: 720-732.

Barrett, M.E., L.B. Irish, J.F. Malina, Jr., and R. J. Charbeneau, 1998a, "Characterization of highway runoff in Austin, Texas, Area", *Journal of Environmental Engineering*, ASCE, Vol. 124, No. 2, 1998, p. 131-137.

Berge, ND, and CA Ramsburg, 2009, "Oil-in-Water Emulsions for Encapsulated Delivery of Reactive Iron Particles", *Environmental Science and Technology*, Volume: 43, Issue: 13, July, pp. 5060-5085.

Clescori, Lenore, Andrew Eaton, and Arnold Greenberg, eds., 2000, *Standard Methods for the Examination of Water and Waste Water*, 20th ed. American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2000.

Drapper, D., Tomlinson, R., Williams, P., 2000, "Pollutant concentration in road runoff: Southeast Queensland case study", *Journal of Environmental Engineering*,126(4): 313-320.

Driscoll, E.D., P.E. Shelley, and E.W. Strecker, 1990, *Pollutant Loadings and Impacts from Highway Stormwater Runoff, Vol. III: Analytical Investigation and Research Report*, Report No. USFHWA-RD-88-008, Office of Research and Development, Federal Highway Administration, Washington DC, 1990.

Flint, Kelly R., and Allen P, Davis, 2007, "Pollutant Flushing Characterization of Highway Stormwater Runoff from an Ultra-Urban Area", *J. Environmental Engineering*, 133(6): 616-626.

Gupta, M.K., Agnew, R.W., Gruber, D., and Kreutzberger, W., 1981, *Constituents of highway runoff Volume IV: Characteristics of highway runoff from operating highways*, Report No. USFHWA/RD-81/045, Office of Research and Development, Federal Highway Administration, Washington DC, 1981, 171 p.

Kayhanian, Masoud, Amardeep Singh, Claus Suverktopp, and Steve Borroum, 2003, "Impact of Annual Average Daily Traffic on Highway Runoff Pollutant Concentrations", *Journal of Environmental Engineering*, ASCE, Vol. 129, No. 11, pp. 975-990.

Kayhanian, M., and M.K. Stenstrom, 2005, "Mass Loading of First Flush Pollutants with Treatment Strategy Simulations", *Transportation Research Record* 1904, pp. 133-143.

Mesfin, B. D., M. Bruen, N. Higgins, and P. Johnston, 2007, *J. Environ. Monit*., 2007, 9, 366 - 371.

Mitchell, Gayle F., Christopher L. Hunt, and Yuming Su, 2002, "Mitigating Highway Runoff Constituents via a Wetland", Paper No, 02-3734, *Transportation Research Record* 1808, p. 127-133.

Mitchell, Gayle F., R, Guy Riefler, and Andrew Russ, 2010a, "Removal of pollutants from simulated highway runoff using a vegetated biofilter", Paper No. 10-3615 presented at the 89th Annual Meeting of the Transportation Research Board, Washington DC, January 2010.

Mitchell, Gayle F., R. Guy Riefler, and Andrew Russ, 2010b, *Vegetated Biofilter for Post Construction Storm Water Management for Linear Transportation Projects*, Final Report No. FHWA/OH-2010/7, for the Ohio Department of Transportation, Ohio Research Institute for Transportation and the Environment, Civil Engineering Department, Ohio University, May 2010.

Munster, Jennie, and Gilbert N. Hanson, 2009, "Perchlorate and ion chemistry of road runoff", *Environ. Chem.*, 6: 28-35.

Novotny, Eric V., Dan Murphy, and Heinz G. Stefan, 2008, "Increase of urban lake salinity by road deicing salt", *Science of the Total Environment* 406: 131-144.

Ohio Department of Transportation (ODOT), 2009, *Location and Design Manual*, Volume 2 Drainage Design, April 2009, http://www.dot.state.oh.us/Divisions/HighwayOps/Structures/Hydraulic/LandD/Pages/TableofContents.aspx, accessed October 1, 2009.

Ohio Department of Transportation (ODOT), 2010, *Construction and Material Specifications*, January 2010, http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Pages/2010CMS.aspx, accessed May 10, 2010.

Ohio Environmental Protection Agency (OEPA), 2008, "Authorization for Storm Water Discharges Associated with Construction Activity under the National Pollution Discharge Elimination System", Ohio EPA Permit No.: OHC000003, April 2008. Available at http://www.epa.ohio.gov/dsw/permits/GP_ConstructionSiteStormWater.aspx, accessed January 20, 2010.

Polyakov, V.O., and M.A. Nearing, 2004, "Rare earth element oxides for tracing sediment movement", *Catena* 55: 255-276.

Sansalone, John J., and Steven G. Buchberger, 1995, "An Infiltration Device as a Best Management Practice for Immobilizing Heavy Metals in Urban Highway Runoff", *Water Science and Technology*, Volume 32, No. 1, pp. 119-125.

Sansalone, John J., and Steven G. Buchberger, 1997, "Partitioning and First Flush of Metals in Urban Roadway Storm Water", *Journal of Environmental Engineering*, Volume 123, No. 2, pp. 134-143.

Sansalone, John J., and Donald W. Glenn III, 2002, "Accretion of Pollutants in Snow Exposed to Urban Traffic and Winter Storm Maintenance Activities I", *Journal of Environmental Engineering*, Volume 128, No. 2, pp. 151-165.

Sansalone, John J., and Zheng Teng, 2005, "Transient Rainfall-Runoff Loadings to a Partial Exfiltration System: Implications for Urban Water Quantity and Quality, *J. Environ. Engineering*, 131(8): 1155-1167.

United States Environmental Protection Agency (USEPA), 1993b, "Method 300.0: Determination of Inorganic Anions by Ion Chromatography." Environmental Protection Agency, Washington DC, available online at http://www.epa.gov/waterscience/methods/method/files/300_0.pdf, accessed August 19, 2010.

United States Environmental Protection Agency (USEPA), 1996, "Method 3050B: Acid Digestion of Sediments, Sludges, and Soils", Environmental Protection Agency, Washington DC, December 1996, available online at http://www.epa.gov/sw-846/pdfs/3050b.pdf, accessed August 2, 2008.

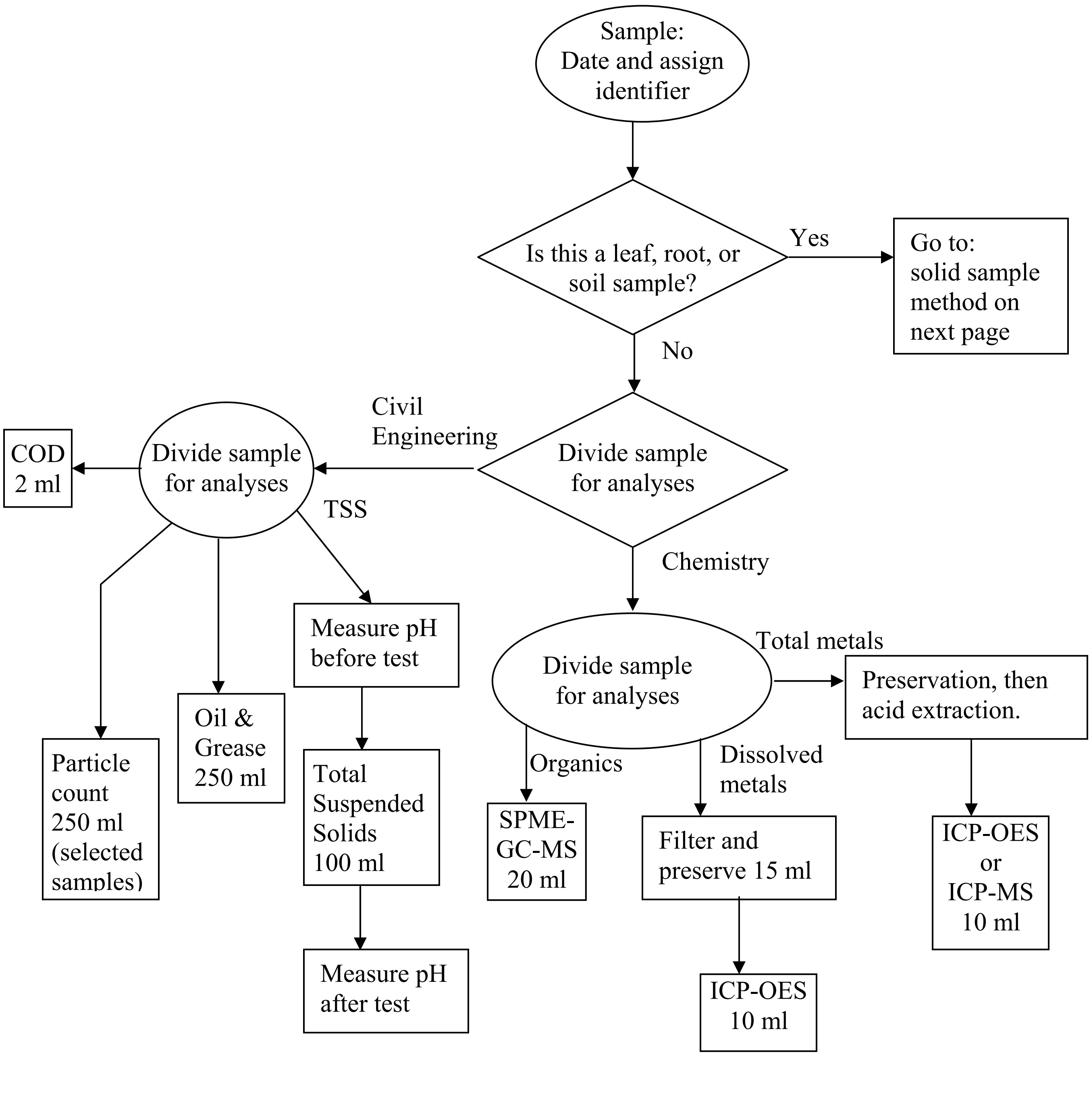
United States Environmental Protection Agency (USEPA), February 2007, "Method 6010C: Inductively Coupled Plasma-Atomic Emission Spectrometry", Environmental Protection Agency, Washington DC, available online at http://www.epa.gov/sw-846/pdfs/6010c.pdf, accessed April 4, 2008.

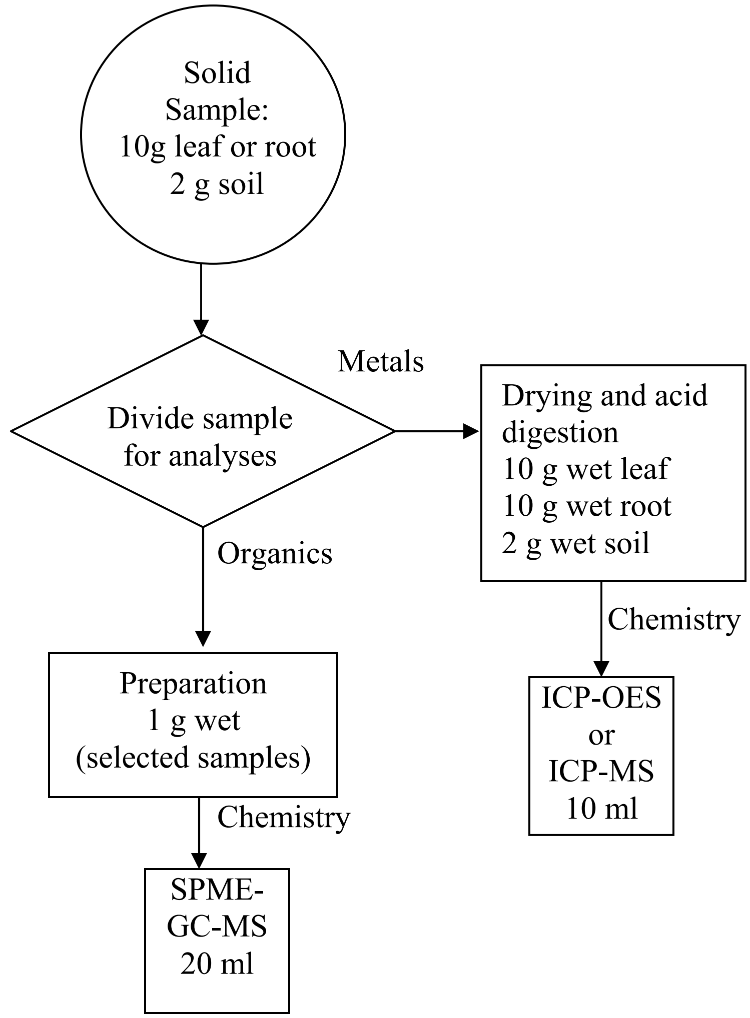
United States Environmental Protection Agency (USEPA), 2008a, "Clean Water Act Analytical Test Methods: Approved Clean Water Act Methods", Environmental Protection Agency, Washington DC, available online at http://www.epa.gov/waterscience/methods/method/index.html, accessed April 4, 2008.

United States Environmental Protection Agency (USEPA), 2008b, "Clean Water Act Analytical Test Methods: Method 1664, Revision A: N-Hexane Extractable Material (HEM; Oil and Grease) and Silica Gel Treated N-Hexane Extractable Material (SGT-HEM; Non-polar Material) by Extraction and Gravimetry", Environmental Protection Agency, Washington DC, available online at http://www.epa.gov/waterscience/methods/method/oil/1664.html, accessed February 5, 2008.

Wu, J., D.J. Allan, and W.L. Saunders, 1998, “Characterization and Pollutant Loading Estimation for Highway Runoff”, *Journal of Environmental Engineering*, ASCE, Vol. 124, No. 7, 1998, p. 584-592.

Appendix A: Sample analysis protocol




Solid
Sample:
10g leaf or root
2 g soil
Divide sample
for analyses
Metals
Drying and acid
digestion
10 g wet leaf
10 g wet root
2 g wet soil
Organics
Chemistry
Preparation
1 g wet
(selected samples)
ICP-OES
or
ICP-MS
10 ml
Chemistry
SPME-
GC-MS
20 ml

Appendix B: Updated Implementation Plan

OHIO DUSEPARTMENT OF TRANSPORTATION
OFFICE OF PRODUCTION
RESEARCH IMPLEMENTATION PLAN

Title: Vegetated Biofilter for Post Construction Storm Water Management for Linear Transportation Projects

State Job Number: 134349
PID Number:
Research Agency: Ohio University
Researcher(s): Gayle F. Mitchell, R. Guy Riefler
Technical Liaison(s): Robert Lang, Mike Wawszkiewicz
Research Manager: Jennifer Gallagher
Sponsor(s): ODOT
Study Start Date: October 15, 2007
Study Completion Date: December 31, 2010
Study Duration: 38.5 Months
Study Cost: $432,922.05
Study Funding Type:

STATEMENT OF NEED:

The use of Best Management Practices (BMPs) is required for all Ohio Department of Transportation (ODOT) maintained facilities where an improvement project results in a land disturbance greater than one acre (0.4 ha). Current ODOT policy requires 20% of existing impervious areas to be treated using a BMP, while 100% of new impervious areas are to be treated with BMPs. The various BMPs are generally designed to treat the water quality volume. In Ohio, the water quality volume volume is based on 0.75 in (1.91 cm) of precipitation. This water quality volume is defined in the Ohio Environmental Protection Agency (OEPA) National Pollutant Discharge Elimination System (NPDES) Construction General Permit (CGP) as the volume of storm runoff that must be captured and treated from the site after construction is complete. As specified by law, the Ohio Environmental Protection Agency (OEPA) requires that ODOT implement best management practices (BMPs) that reduce pollution from storm water runoff on linear transportation systems sold after March 10, 2006.

The Ohio Department of Transportation utilizes vegetated biofilters as one of several available post construction stormwater BMPs to implement the OEPA NPDES CGP requirements via provisions in ODOT's *Location and Design Manual*. "The vegetated biofilter consists of the vegetated portion of the graded shoulder, vegetated slope, and vegetated ditch." Pollutants are removed through uptake into the plant matter and into the soils. Vegetated slopes and ditches are already common along Ohio's highways. Vegetated slopes can range from 8% to 50% gradient, and a given vegetated slope may be suitable as part of a vegetated biofilter as is or with modification, or it may not be suitable. The conditions for making vegetated slopes suitable for integration into an acceptable biofilter need to be determined.

The research question is how the design of the vegetated biofilter can be optimized for the removal of pollutants from runoff, particularly the initial highway runoff that contains a high concentration of pollutants. Design parameters to be optimized include slope, length, ditch width, soil type, and vegetative cover. It should also be noted that pollutant removal is not the sole criterion for effectiveness, for instance recommended soil types must be maintainable, have proper slope stability properties, and promote the establishment of dense root mass from the vegetation. The vegetation itself is subject to similar criteria. Along with design criteria, maintenance and construction issues need to be addressed.

RESEARCH OBJECTIVES:

The goal of this project was to examine the slope portion of vegetated biofilters to evaluate capture and treatment of the water quality volume for highway storm runoff. This goal was accomplished through the following objectives:

- Performing a review and synthesis of the literature
- Conducting a survey of state DOTs
- Developing a biofilter foreslope prototype and conduct testing to determine:
  - Its ability to capture water quality volume
  - Its performance in removing typical roadway runoff contaminants
    - Its performance efficiency computed as the percent change between influent and effluent quality
  - The impact of its slope
  - The accumulation of contaminants in the foreslope soil and vegetation
  - The suitability of foreslope designs to accommodate different concentrations of runoff and/or intensity of storms
  - Potential resuspension of particles
- Examine the effectiveness and design of vegetated biofilters during conditions of dormancy that occur during winter months (December – March) in Ohio.

RESEARCH TASKS:
Task 1 – Literature search and synthesis
Task 2 – Develop and submit research plan
Task 3 – Determine and document performance validation criteria
Task 4 – Laboratory testing and development of prototype vegetated biofilters
Task 5 – Analyze and document performance issues
Task 6 – Prepare draft final report
Task 7 – Prepare final report and executive summary
Task 8 – Conduct dormant grass study and prepare report supplement.

RESEARCH DELIVERABLES:
Final Report, Executive Summary, Final Report Supplement

RESEARCH RECOMMENDATIONS:
Although this study did not indicate significant performance differences in terms of pollutant removal between the slopes at 8:1, 4:1, and 2:1, slopes less than 2:1 would be advisable with the varying rainfall-runoff events that may be experienced in the field. In addition, some of the tests had spikes in the surface effluent data for the 2:1 slopes, which indicated some variability in performance. Based on analysis of cores from the vegetated beds, break through of metals did not occur, and at an applied high concentration of influent, maximum accumulation occurred at about 2 ft (0.61 m) to 3 ft (0.91 m) from the inlet. It was beyond the scope of this study to determine the capacity of a typical biofilter which would provide guidance for longevity. Laboratory scale breakthrough tests (effluent concentrations = influent concentrations) could be performed to arrive at more definitive results, which could be used to develop a model to extrapolate to long range performance. Since maximum capacity of the biofilters was not reached, it would be speculative to provide recommendations on minimum length for the biofilter. The data from the literature indicated good correlation of percent suspended solids removal with slope length, and lengths greater than about 7 m (23 ft) to 8 m (26 ft) provide greater than 80% removal. The results in this experiment suggest that similar removals may be achievable at lesser lengths with full vegetative coverage.

Removals, as expressed in EMC, under dormant conditions were less than that obtained with summer vegetation but overall were acceptable, particularly for TSS and most metals, 80% or greater. This was primarily attributed to the reduced vegetative coverage since this was the primary variable for the test conditions. Hence, establishment of good vegetative coverage prior to winter or dormant conditions is recommended. Some reduction in chlorides was observed, less than 30% averaged over the three slopes during the water quality portion of the events. If a high quantity of salt (NaCl) accumulated in the biofilter, this could possibly impair growth of the vegetation, however long term effects were beyond the scope of this project and were not investigated.

PROJECT PANEL COMMENTS:

IMPLEMENTATION STEPS & TIME FRAME:
ODOT can use the information in this supplement and report to begin assessing the selected versions of the vegetated biofilter as a best management practice suitable for meeting the OEPA permitting criteria. Some of the

findings in the report and from the literature may have application in revising or adding to sections of ODOT's *Location and Design Manual* Volume 2, Section 1117.3 and *Construction and Materials Specifications* regarding vegetated biofilters. These findings may also be applicable to revising ODOT's storm water and water quality research goals, and also to revising ODOT's Storm Water Management Program.

Items for consideration include the following:

- Recognition that the foreslope provides significant removal of storm runoff constituents.
- Restriction of foreslopes to less than 2:1.
- Establishment of a requirement of minimum coverage of vegetation. The impact of coverage on performance was outside the scope of this study. The vegetated foreslopes studied in this project performed well with a vegetative coverage above 80%; this coverage level is recommended. Tests of the foreslope prototype conducted under dormant conditions with vegetation coverage about 60 % indicated good performance also but less than that under summer conditions and greater vegetative coverage. Also, baseline concentrations were higher under dormant compared to summer conditions.
- Exclusion of the use of crown vetch.
- Establishment of a standard inspection schedule using a form similar to the field inspection record in [Mitchell, Riefler, and Russ, 2010b].
- Maximization of infiltration along the foreslope.

A field study is recommended to verify these results under actual roadside conditions and to consider long-term issues.

Ultimately changes in the *Location and Design Manual* Volume 2 and *Construction and Materials Specifications* will be distributed to the ODOT Districts so that vegetated biofilters conforming to the updated specifications can be designed and incorporated into future transportation system construction and repair projects.

Implementation will be limited to those sites with sufficient right of way to construct the vegetated biofilter, thus personnel in rural areas would be the primary users of the system. Other impediments could include the efficacy of the biofilter during prolonged salt application in winter seasons. Appropriate construction and maintenance will be important to the success of the BMP.

As discussed in the project report, cost components would include purchase of the vegetation and soils, construction of the biofilter, and site maintenance. Costs would be dependent on site characteristics and could be highly variable from site to site.

EXPECTED BENEFITS:

EXPECTED RISKS, OBSTACLES, & STRATEGIES TO OVERCOME THEM:

OTHER ODOT OFFICES AFFECTED BY THE CHANGE:

PROGRESS REPORTING & TIME FRAME:

TECHNOLOGY TRANSFER METHODS TO BE USED:

IMPLEMENTATION COST & SOURCE OF FUNDING:

Approved By: (attached additional sheets if necessary)

Office Administrator(s):

Signature: ______________________________ Office: ____________ Date: _______________

Signature: ______________________________ Office: ____________ Date: _______________

Division Deputy Director(s):

Signature: ______________________________ Division: ____________ Date: _______________

Signature: ______________________________ Division: ____________ Date: _______________

ORITE • 141 Stocker Center • Athens, Ohio 45701-2979 • 740-593-2476
Fax: 740-593-0625 • orite@ohio.edu • http://www.ohio.edu/orite/