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

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

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<tr><td colspan="4">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. A 4 ft (1.2 m) wide by 14 ft (4.3 m) long prototype vegetated biofilter was constructed on a moveable frame. Artificial runoff was delivered to each of three grass beds for comprehensive tests at slopes and flow rates as follows: 8:1, medium; 4:1, medium; 2:1, medium; and 2:1, high. The medium and high flows represented storm runoff events typical in Ohio. First, baseline tests were performed to obtain concentrations of constituents native to the biofilter. Artificial runoff, formulated with metals, native soil, and motor oil, was applied to one bed at a "high" concentration for the first part of the event, followed by a "medium" concentration; a second bed received "medium" followed by "low" concentration runoff, and the third bed received "low" concentration followed by tap water. During the simulated storm events, samples were obtained from the inlet, surface runoff, and underdrain and analyzed for total and dissolved metals, TSS, and oil and grease. Prior to and at the end of testing, cores were extracted from the bed, separated into soil, roots and grass, and each component analyzed for metal content per mass of material. The two beds receiving the initial high and medium concentration flow performed well and removal of 7 total metals and TSS was above 75%. Removal of oil ranged from 30% to over 90%. The bed receiving low concentration runoff, which was near the baseline levels for constituents, had mixed performance of removals ranging from none to above 90%, illustrating the difficulty of any BMP to treat a relatively clean influent. Metals above background levels were found primarily in the first half (7 ft, 2.1 m) of each bed. Soil particles in the influent flow of the first test in each bed, tagged with La, were not resuspended in subsequent tests and were not measured at any significant concentration in the outlet surface flow.</td></tr>
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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)

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1 Introduction

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 [OEPA, 2008]. 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* [ODOT, 2009]. "The vegetated biofilter consists of the vegetated portion of the graded shoulder, vegetated slope, and vegetated ditch." [ODOT 2009, Section 1117.3] 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 current design process for the vegetated ditch component of the biofilter involves calculating the width of the ditch in the traditional manner used in Section 1102 of the *Location and Design Manual* [ODOT, 2009], then computing the Enhanced Bankful Width (*EBW*) in feet using this equation:

$$EBW = 5.4A^{0.356}$$

Where A is the total drainage area, in acres, served by the ditch. Then the width to be used in the plans will be the larger of the two, with a maximum of ten feet (3.05 m).

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.

This study focuses on the efficacy of the foreslope, using standard ODOT vegetation and soil that have proven themselves suitable in terms of maintenance and slope stability. This first phase includes gathering and integrating information from the literature, from other DOTs, and a laboratory prototype study of foreslope properties. The results obtained will guide subsequent phases, to address ditch properties and other issues determined to be relevant, and a field evaluation to further document effectiveness of the vegetated biofilter as a BMP.

1.1 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 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

2 Literature Review and Synthesis

2.1 Constituents in Highway Runoff

Transportation pollutants including oil and grease, brake dust, heavy metals, and deicing chemicals degrade the quality of highway stormwater runoff. Increasing lanes of traffic and adjacent development cause an increase in the quantity of stormwater runoff to be handled. The problems associated with large volumes of polluted stormwater runoff must be properly addressed to minimize the impact to the environment.

Typical constituents of stormwater and snowmelt runoff include both dissolved and particulate heavy metals, nutrients, and organic chemicals. Heavy metals may originate from automobile exhaust and degradation of vehicle components, particularly tires, brake linings, and bearings and fuel combustion [East-West Gateway Coordinating Council, 2000; USEPA, 2000]; a review of the highway runoff literature on heavy metals is provided by Barber et al [2006]. Other sources of pollutants include pavement surface wear, lubrication and petroleum additives, and deicing materials such as salt and sand. A study for the Michigan Department of Transportation reported that rainfall was also a source of metals in highway runoff [CH2MHILL, 1998].

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.

2.1.1 Heavy Metals

Cadmium, chromium, copper, iron, lead, nickel, and zinc are noted by United States Federal Highway Administration (USFHWA) as metals typically associated with highway runoff [USFHWA, 1999; USFHWA, 1984]. Wear and tear of various vehicle components such as tires, engine parts, brake pads; auto body rusting; lubricants; and fuel combustion are cited as primary sources [USEPA, 1995a]. As the use of lead in gasoline products was phased out beginning in 1973, lead concentrations in highway runoff decreased significantly [USEPA, 1983]. Other sources, such as paints used on right of ways, atmospheric deposition, tires, and automotive lead acid batteries still contribute lead to the runoff [USFHWA, 1999]. Table 1 shows a summary of the sources of metals pollutants on highways, as presented by Barber et al. [2006].

Breault and Granato [2000] presented tabular and graphical hierarchy of relative fractions of trace metals in the dissolved fraction and ratio of dissolved to total for cadmium, chromium, copper, nickel, lead and zinc. For example, the dissolved copper fraction ranged from 34% to 100% and dissolved zinc from 14 to 90% of total; dissolved fraction of various metals measured in various studies is reproduced in Figure 1, from Breault and Granato [2000]. The ratio of dissolved to total metals varies based on pH, hardness, water temperature, concentrations of competing cations, particulate and dissolved organics, presence of anions, and characteristics of metal binding sites. As noted by Barber et al. [2006], “event mean concentrations of dissolved copper and zinc were found to decrease with higher total event rainfall and seasonal cumulative precipitation and to increase with respect to duration of the antecedent dry period and [Annual Average Daily Traffic] AADT.”

For the metals cadmium, copper, lead, nickel, and zinc, acute and chronic criteria are expressed in terms of aqueous hardness. Regulatory allowable concentrations of metals increase with hardness since bioavailability and thus toxicity of a particular metal decreases with increasing hardness; nontoxic cationic compounds of hardness are absorbed preferentially by organisms [HydroQual, 2003].

Table 1. Sources of metals from highway operations. From Barber et al. [2006].

Pollutant	Source
Cadmium	Tire wear, lubricants, and insecticide application
Chromium	Metal plating, moving engine parts and brake lining wear
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, deicers, fungicides and insecticides
Iron	Auto body rust, steel highway structures such as bridges and guardrails, brake lining wear, deicers, and moving engine parts
Lead	Leaded gasoline from auto exhaust, tire wear, lubricating oil and grease, bearing wear and atmospheric deposition
Manganese	Moving engine parts and fuel additive
Nickel	Diesel fuel and gasoline, lubricating oil, deicers, metal plating, bushing wear, brake lining wear and asphalt paving
Zinc	Tire wear, brakes, motor oil and grease

From Barber et al. [2006], originally summarized by East-West Gateway Coordinating Council [2000] and Granato et al. [2003]

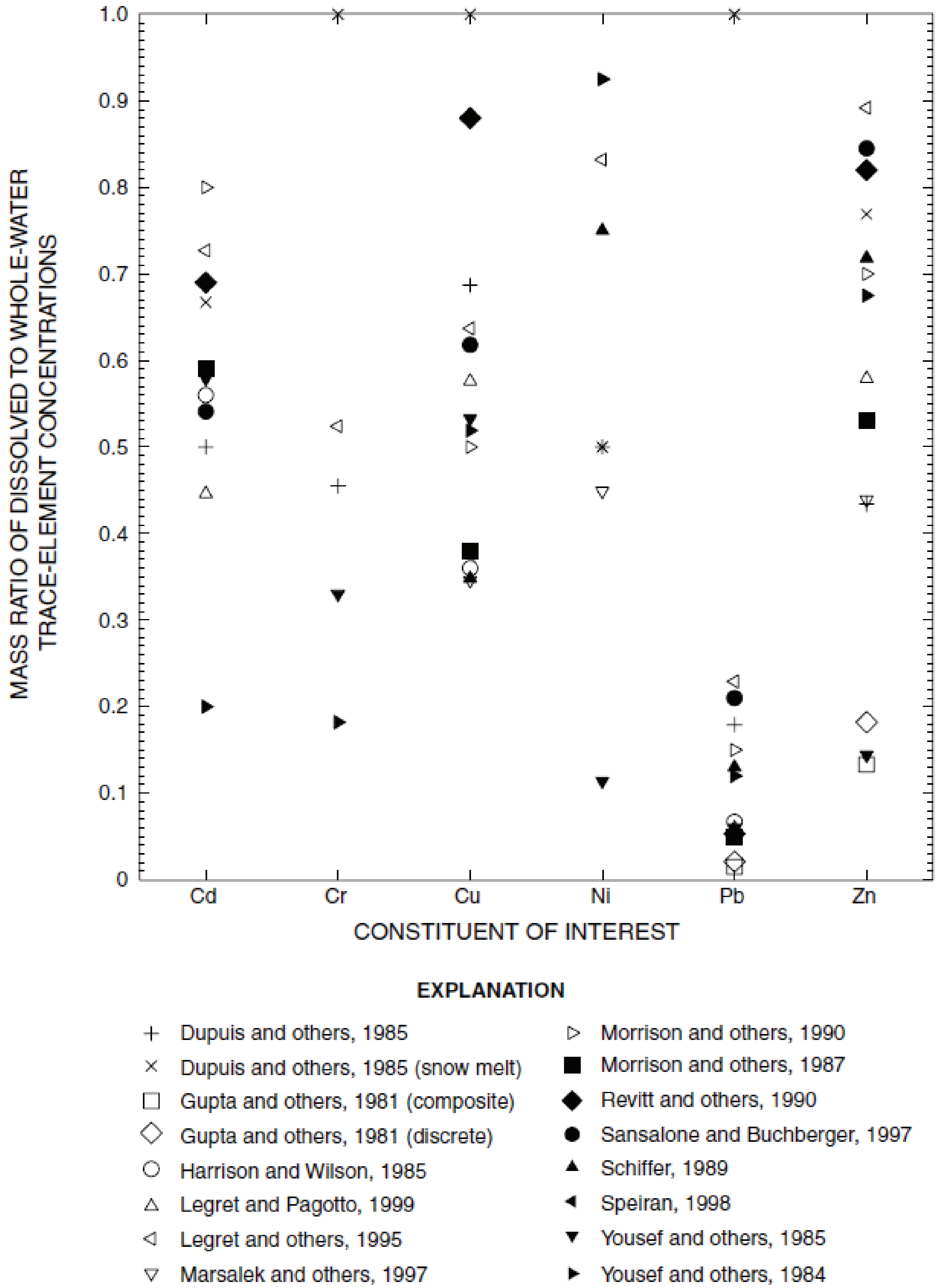


Figure 1. Ratio of dissolved to whole water concentrations of metals measured in pavement runoff in studies 1981-1997. From Breault and Granato [2000, p. 26].

2.1.2 Variability and Relationships of Constituents with Other Factors

Constituent concentrations may vary considerably from one site to another, between different storm events, or even at different times or locations in a single event. Factors seen to contribute to large amounts of pollutant buildup and removal include annual average daily traffic (AADT), antecedent dry period (ADP), number of vehicles during the storm, average traffic counts during the ADP, and rainfall amount [For example, Irish et al, 1998; Barrett et al. 1998a; and Hewitt and Rashed, 1992]. AADT over 30,000 has been heavily associated with significant pollutant concentration, e.g. by Driscoll et al [1990] and Wu et al [1998]. However, several studies have indicated that use of AADT alone is not predictive of pollutant loading of highway runoff, e.g. CH2M Hill [1998] and Kayhanian et al. [2003]. Kayhanian, et al [2003] reported that for highway runoff at several sites in California, in general, urban highways (AADT>30,000 vehicles per day) had higher pollutant concentrations than did nonurban highways, though there were some exceptions, such as COD, TSS, turbidity, and NH_3. Beyond some rough divisions between the two classes of highways, no simple linear correlations were observed between AADT and pollutant concentration, even for pollutants known to be related to transportation, such as lead, zinc, or oil; this suggests that other factors are also important in determining runoff concentrations. As found by Kayhanian et al. [2003] total event rainfall, seasonal cumulative rainfall, and antecedent dry days, along with AADT accounted for over 70% of observed contaminant levels in their multiple linear regression analysis. The relationships between the other factors and pollutant runoff are either not as well established or not as strong. However, Barber et al. [2006] noted uncertainty and variability in using multiple regression models for prediction of pollutant concentrations and that "models are only applicable in the geographic region and range of conditions represented by the original data set".

2.2 First Flush

The term "first flush" has been used to refer to the initial stage of a storm event which contains a large percentage of total pollution in a relatively small percentage of runoff volume [Maestri et al, 1988; Gupta and Saul, 1996; Hager, 2001]. It is generally agreed that the first flush from the initial stages of the storm contains the largest percentage of the pollution load, including suspended solids (SS), chemical oxygen demand (COD), and metals [Chui, 1997; Krebs et al., 1999; Sansalone and Buchberger, 1996; Larsen et al., 1998; Stenstrom et al., 2000]. Characterization and treatment of the first flush runoff can minimize adverse water quality effects, while requiring less volume to be treated. To illustrate, Kayhanian and Stenstrom [2005] report the improved performance that some BMPs exhibit when they treat only first flush, noting that the capture of the first 20% of the storm volume is more effective for infiltration basins than treating 20% of the storm volume throughout the entire period of runoff.

The definition of first flush utilized in data analysis and comparison vary significantly. For example, in Florida multiple study sites have shown that the first 2.5 cm (1 in) of runoff, defined as the first flush, carried 90% of the pollutant load from the entire storm event in urban drainage areas [Schiffer, 1989]. Bertrand-Krajewski et al. [1998] defined first flush as an event in which 80% of the total pollutant load was discharged during 30% (80:30) of the runoff volume. The Bertrand-Krajewski group investigated other definitions and indicated that Stahre and

Urbonas [1990] utilized an 80% loading in 20% (80:20) flow definition, and they noted Wanielista and Yousef [1993] proposed a 50% loading in 25% (50:25) flow.

Relative to Ohio storm water runoff from highways, Mitchell and Hunt [2000] monitored an asphalt concrete 4-lane section with grassy median on U.S. 33 with 30,000 AADT near Lancaster, OH, during 25 rainfall-runoff events. Most constituents exhibited first flush characteristics; metal concentration in the runoff consisted primarily of Fe, Zn, Pb, Ni and Cu with magnitude decreasing in order listed; and more than 60% of the metals were in the dissolved phase. Assuming an exponential decreasing concentration during a storm event, concentration was modeled as a function of a first order wash-off coefficient, K_w, cumulative rainfall depth and initial pollutant concentration. Using this model, statistical analysis of the runoff data indicated a moderate first flush occurring from this low volume traffic highway with the significance of the TSS at this site higher than metals and COD [Hunt, et al., 2002; Mitchell and Su, 2003].

A study by Sansalone and Buchberger [1997] examined first flush metal concentrations from five storm events on a four-lane asphalt pavement with asphalt overlay and grassy median near Cincinnati, OH, experiencing 150,000 AADT. The authors reported that dissolved fractions of Zn, Cd, and Cu exhibited strong first flush in the lateral sheet flow, while Pb had a weak first flush. Event mean concentrations of Zn, Cd, and Cu exceeded both USEPA and OEPA criteria for discharge to modified warmwater habitat streams. Predominantly dissolved metals included cadmium, copper, manganese, and zinc; particulates included aluminum, chromium, iron, and lead.

2.3 Treatment of Highway Runoff

Current treatment strategies include the use of vegetated swales, infiltration trenches, porous pavements, partial exfiltration trenches, detention basins, and wetlands, among others. In Ohio, currently approved BMPs include exfiltration trench, manufactured systems, vegetated biofilter, detention basin, underground detention conduit, retention basin, bioretention cell, infiltration trench, infiltration basin, and constructed wetlands [ODOT, 2009, Section 1117].

A U.S. Environmental Protection Agency (USEPA) report summarized typical pollutant removal percentages for various BMPs [Strassler, Pritts, and Strellac, 1999]. Grassy swales were indicated to achieve 30-65% removal for suspended solids and 15-45% for metals; vegetated filter strips achieved 50-80% suspended solids removal and 30-65% metals removal. Nitrogen and phosphorus removal were 15-45% for the former and 50-80% for the latter. Natural processes that remove pollutants make plant-based BMPs [Clar et al., 2004] attractive elements in stormwater remediation in Low-Impact Development (LID) [Keating, 2009]. Federal Highway Administration (USFHWA) fact sheets [USFHWA, 2006a and 2006b] provide guidance on the design and construction of filter strips and vegetated swales. NCHRP Report 565 [LID Center, 2006] provides guidance for BMP and LID evaluation, design and implementation for linear transportation projects. Among several other practices, the report provides graphical comparisons of filter strip effectiveness at various locations in the U.S. as a function of infiltration rate and slope. LID practices employing vegetation and infiltration such as bioslopes, swales and bioretention are covered in some detail. A synthesis report on grass swales for Wisconsin DOT also summarizes recent literature on pollutant removal efficiencies [CTC and Assoc. LLC and WisDOT Research & Library Unit, 2007].

Over the last 15-20 years, the use of plants in removing pollutants from sludges, sewage waters, spillage sites and polluted areas has been studied, particularly the transformation of these contaminants by plants [Harvey et al., 2002]. There are five possible mechanisms involved in the stabilization and degradation of roadway runoff contaminants, including phytoaccumulation, phytodegradation, phytovolatilization, phytostabilization and rhizodegradation [Nzengung et al., 1999]. Phytoaccumulation involves the accumulation of contaminants in the harvestable part of plants; i.e., seeds, fruits or roots. In phytodegradation, plants, along with microorganisms, degrade the contaminant present in the soil. Degradation in the plant is carried out by enzymes present in the plant tissue or by bacteria that inhabit the plant. Phytovolatilization is the use of plants to volatilize the contaminants present in the soil; volatilization of contaminants may also occur during transpiration of water by plants. Phytostabilization reduces the bioavailability of a contaminant, thus preventing its entry into the groundwater or food chain, by adsorbing or precipitating it into the soil [Nzengung et al., 1999].

Biodegradation of contaminants may occur in the root zone or rhizosphere of some plants due to the presence of plant enzymes, plant exudates, and bacteria. A thriving bacterial community often forms in the rhizosphere with populations and activities over ten times greater than surroundings [Nzengung et al., 1999]. This relationship is often symbiotic with the plant releasing exudates to provide growth substrate to the bacteria and the bacteria providing nutrients to the plant. Biodegradation by these processes is called rhizodegradation [Nzengung et al., 1999].

Further, sediments/soils can aid in removal of runoff constituents, for example by adsorbing metals to the organic fraction of hydrolytic soils and/or by ionic exchange. Mitchell et al [2002] investigated a naturally occurring wetland receiving runoff from a 30,000 AADT highway in Ohio and analysis indicated metals were removed in the soils/sediments of the wetland.

As pointed out in a recent publication prepared for AASHTO and as part of NCHRP Project 25-25 [Storey, et al., 2009], standardized/uniform terminology and more “consistent design criteria” are needed for vegetation-based BMPs. This also leads to ambiguity in comparing pollutant removal performance. It was also noted that “many state agencies use or adopt other states’ manuals, documents and design criteria”, which, “tend to perpetuate outdated research data.” Their summary of pollutant removal efficiency states that “studies on vegetated roadsides suggest relatively high removal rates for TSS and heavy metals and fair performance for soluble nutrients, such as phosphorus and nitrate”, and that “there can be consistent performance within a lesser treatment distance than most agencies’ design criteria.”

The sections below summarize information on the vegetated BMPs that are currently used with linear transportation systems; the LID [LID Center, 2006] publication definitions were primarily used for this discussion.

2.3.1 Vegetated Filter Strips or Vegetated Buffer Strips

As storm water flows in a sheet across the vegetated area, the filter strips or vegetated buffer strips provide infiltration into the soil and uptake by plants through biological and chemical processes. USFHWA [2002] guidance suggests designers should “estimate they need a filter strip 177 m (580 ft) wide by 23 m (75 ft) long (uphill to downhill) to manage a 0.4 ha (1 ac) service area (100% impervious). WSDOT [1995] guidance notes the strips are typically considered a pre-treatment BMP and are primarily applicable along rural roadways, suggesting their application for a maximum of two lanes and AADT of less than 30,000; Colorado DOT [1992] notes a maximum depth of 0.64 cm (0.25 in) on the strip. Recommended surface slopes are between 2% and 6% and minimum flow length of 7.6 m (25 ft) [Claytor and Schueler, 1996].

However, a study by Bren et al. [1997] reported “excellent suspended solids removal with slopes of up to 23% and good uniform flow.”

2.3.2 Bioretention

Located in the median or roadway setback, bioretention cells “are vegetated depressions that treat runoff by rapid filtering through bioretention soil media (typically 50% sand, 30% planting soil and 20% mulch)” [LID Center 2006]. The variable width cell is located at least 5 ft (1.5 m) down gradient from the edge of the roadway, the slope immediately adjacent to the cell is between 2% and 20%, with a maximum ponding depth of 1 ft (0.3 m). The cross-section consists of about 3 in (7.6 cm) of mulch above about 2 ft (0.6 m) of bioretention soil media that extends to the top and peripherally around a fabric covered trapezoidal-shaped under drain consisting of aggregate, placed at a 1:1 slope, and perforated drainage pipe [LID Center, 2006].

2.3.3 Bioslope

Located in the median embankment or side slope, “bioslopes are embankments that treat runoff by rapid filtering through an engineered soil media” or ecology mix [LID Center, 2006]. For typical bioslopes flow exits the pavement onto the base course and then downslope to the prepared subgrade, the no -vegetation zone (e.g. gravel), followed by the ecology mix zone, and finally exiting through a perforated underdrain pipe encased in gravel backfill. The NCHRP Report 565 [LID Center, 2006] recommends side slopes between 15% and 25%, longitudinal gradients 4% or less, total flow path length 30 ft (9.1 m) or less to the top of the bioslope (no-vegetation zone.) The ecology mix consists of crushed mineral aggregate screenings, perlite, dolomite, and gypsum, planted with grass.

2.3.4 Swales

Swales, located in medians and roadway setbacks, are vegetated “broad, shallow channels designed to convey storm water runoff and treat it by vegetative filtering and infiltration” [LID Center, 2006]. Design guidelines include drainage area 5 ac (2 ha) or less, longitudinal slope 1% to 4%, side slopes 2:1 or flatter, and bottom width 2 ft (0.6 m) to 8 ft (2.4 m). [LID Center, 2006] The swale bottom consists of about 30 in (76 cm) depth of permeable soil over 6 in (15 cm) of gravel around a perforated underdrain pipe. The “side vegetation is at a height greater than the maximum design flow depth.”

2.3.5 Maintenance

Periodic maintenance priorities include ensuring excellent plant growth, mowing (perpendicular to the slope), prevention of rills and gullies and removal of debris and litter. Herbicides and fertilizers are not recommended since they can contribute to pollutant load [LID Center, 2006].

2.4 Field Studies

A study conducted for the Michigan Department of Transportation assessed source, fate, and potential effects of metals in highway runoff [CH2MHILL, 1998]. Three sites were sampled; two discharged through a grassed swale and one directly from the roadway to the stream. In terms of reduced pollutants, results demonstrated the benefits of the grassed swales. Sampling for metals in soils indicated that swales effectively removed metals from the runoff; metal concentrations in soils were below cleanup criteria.

Field studies were conducted by Walsh et al. [1997] on two different v-shaped rounded bottom vegetated channels, located in highway medians in Austin, Texas. AADT was 47,000 and 111,000; width of entire median 15.5 m (50.8 ft) to 16.2 m (53.1 ft) and 14.9 m (48.9 ft) to 19.5 m (64.0 ft); drainage area 104,600 m^2 (25.84 ac) and 13,000 m^2 (3.2 ac); centerline length 1055 m (3461 ft) and 356 m (1168 ft); average median side slope of 9.4% and 12.1%, filter strip treatment length 7.8 m (25.6 ft) to 8.1 m (26.6 ft) and 7.5 m (24.6 ft) to 8.8 m (28.9 ft); and average centerline profile grade of 1.7% and 0.73%, respectively. Reported pollutant mass reductions were above 85% for TSS; 68% -93% for turbidity, COD, zinc and iron; and 36%-61% for TOC, nitrate, TKN, total phosphorus and lead with similar removal for the two dissimilar strips. The authors reported that "removal of constituents occurred down the sides of the median and not down its longitudinal length" further adding that "a longitudinally long median is not required for effective removal of constituents from highway runoff." They recommended that "filter strips have a maximum slope of 9 to 12 percent and a minimum length of 8 meters" (26 ft). This study was documented further by Barrett et al. [1998b].

Based on a two-year study of eight vegetated slope sites adjacent to highways in California, Barrett et al. [2004] concluded that "buffer strips consistently reduced the concentration of suspended solids and total metals in storm water runoff" and that "steady state levels were generally achieved within 5 meters (16 ft) of the pavement edge from slopes commonly found on highway shoulders and when the vegetation coverage exceeded 80%".

Deletic and Fletcher [2006] summarized statistics from seven researchers' studies of swale performance. The mean removals computed were: 72% for TSS based on 18 studies, 52% for total phosphorus based on 20 studies, and 45% removal for total nitrogen based on 13 studies. Deletic and Fletcher [2004] previously reported on a field study of a grass filter strip in Aberdeen, Scotland, and a grass swale in Brisbane, Australia. TSS removals were 61% - 86% in Aberdeen and 69% in Brisbane. A computer program named TRAVA was used to model the strip behavior and was found to be in reasonable agreement, with sediment loading rates in Aberdeen within 25% of measured values, and concentrations in Brisbane within 17%. The predicted mass of sediment removed was modeled within 50% and 11% of measured values for the two locations, respectively.

Barrett et al. [2006] combined data from 42 events at 6 sites in Austin and College Station, TX, to demonstrate further the benefits of vegetated side slopes or filter strips showing statistically significant removal of total copper at all sites, and TSS and total lead at the three Austin sites. Majority of removal of these three pollutants occurred within 8 m (26 ft), 4m (13 ft), and 8 m (26 ft), respectively, as measured from the edge of the pavement. Removals of 54% for zinc, 24% for copper, and 48% for TSS were reported, but negative removal was seen for nutrients. Elevated concentrations of total and dissolved zinc were attributed to leaching from galvanized metal flashing used in the collection apparatus. They recommended for "Texas highways with rural type cross sections" to use "strips with a minimum width of 4 m (13 ft) and a minimum vegetation density of 80%".

Han et al. [2005] constructed a 4% slope vegetated filter strip 24 ft (7.3m) wide by 55 ft (16.7 m) long adjacent to a 30,000 AADT state road in North Carolina. For two storm events with an average of ~50 mg/L TSS entering the strip, about 85% of the incoming TSS was removed, particularly aggregates larger than 8 µm (0.3 mil). The first 10 m (30.5 ft) removed the majority of sediment as an exponential function of length. As grass spacing increased from 2 to 7 cm (0.8–2.8 in), a 20% decline in TSS removal was reported.

Stagge and Davis [2006] studied two grass swales in the median of a four-lane highway in Maryland for 18 storm events. The swales had the same cross-section design, which included a 33% side slope and a 0.61 m (2 ft) bottom width with 1% channel slope. One swale had a 15.2 m (50 ft) wide (roadway to channel center), 6% slope pretreatment area. Both swales achieved similar removals of 65%-71% TSS with a mean applied concentration of 107 mg/L. Zinc removal was 30%-60%. The swale without the pretreatment area performed better, which was attributed to the greater channel length of 198 m (650 ft) contrasted to 137 m (449 ft) for the one with the pretreatment area.

The effectiveness of 18 ft (5.5 m) long vegetated highway embankments to retain metals, polycyclic aromatic hydrocarbons (PAHs) and particulates was investigated for three field sites in eastern Kansas with slopes of 7.7%, 11%,and 13% [Tatsuji Ebihara et al., 2009]. Retention of zinc, copper and PAH was reported at 41.6% to 114%, 8.9% to 15.6 %, and 11% to 109%, respectively, while “the margin of experimental uncertainty places the retention rates near 100%”. Controlled field experiments on six replicate 4 ft (1.2 m) long by 1 ft (0.3 m) wide vegetated strips using fluorescent polystyrene microspheres yielded 60% to 94% removal and less than 10% of captured particles were resuspended and released.

2.5 Studies with Simulated Runoff Events

Deletic and Fletcher [2006] reported on controlled field tests on a 7.8% slope grass filter strip 0.3 m (1 ft) wide and 6.2 m (20 ft) long in Aberdeen, Scotland. Six deposition experiments were conducted using natural silt passing a 1 cm (0.4 in) sieve; median diameter of about 50 µm. The majority of large particles were trapped within a distance of about 0.5 m (1.6 ft). However only a small percentage of particles with size less than 5.8 µm (0.23 mil) were removed. Sediment inflow concentrations were reduced by 61% to 86% by the strip.

Newberry and Yonge [1996] conducted a laboratory study of heavy metal retention by grass strips. A grass strip was constructed in a test bed of width 1.2 m (3.94 ft) and length 3 m (9.8 ft). The bed was filled with 25 cm (9.8 in) of compacted local Palouse topsoil with a 15.24 cm (6.0 in) layer of gravel in the first 1.22 m (4.0 ft), in accordance with Washington State Department of Transportation (WSDOT) specs. Standard WSDOT seed mix (40% Red Fescue, 40% Perennial Rye, 10% Colonial Bentgrass, and 10% White Dutch Clover) was planted in the bed. The entire test bed was mounted on a frame that could be tilted to form slopes from 0% to 50%. Sampling was conducted using 15 sub-surface sampling wells and surface sampling cup units distributed at 0.61 m (2 ft) intervals along the length of the test plot, with three units across the width of the plot at each interval. Flow was administered at the top end of the slope and collected in a collection tank at the bottom end; a distribution plate at the top guaranteed administration of a sheet flow onto the test bed. The flow consisted of artificial stormwater containing 250 mg/l suspended solids (soil from an alluvial fan in Oregon), 2.425 mg/l lead, 0.075 mg/l cadmium, 0.199 mg/l copper, and 2.055 mg/l zinc to mimic values observed in western Washington. Experimentation concerned the following: storm flow and contaminant selection, characterization of the soil, hydraulics of the test bed, metal migration, and determination of metal sinks. The study concluded that grass strips can be effective metal retention mechanisms. For six simulated storm events with average storm length of 208 minutes and a total application time of approximately 1350 minutes, retention percentages over the full length of the plot for contaminants exceeded the following values: Zn 84%, Pb 93%, Cu 99%, Cd 99%. Concentration of metals in the discharge did not significantly increase by the end of the experiment, so the retention times for each metal could not be estimated accurately. Indeed, significant metal breakthrough was not observed even at the first station, located at 0.61 m (2 ft). The stormwater sediment appeared to have a high affinity for the contaminant metals and thus most metals were trapped with the suspended solids. The seed mix plants tended to exclude the metals, with the clover absorbing the most during inert tracer experiments. The clover deteriorated over time as more metal migration experiments were conducted. Hydraulic detention times for different slope/flow combinations were calculated to range from 8.8 minutes for slope of 17% and flow 3.8 l/min (1.0 gal/min) to 78.4 min for 5% slope and 0.38 l/min (0.10 gal/min). Detention times were more sensitive to changes in flow than to changes in slope. Dispersion coefficients agreed with published field data. The procedures and set-ups utilized in this study were used to guide the study for this project.

Paul Hook [2003] examined the retention of sediment from artificial runoff in riparian buffers typical of rangelands in Montana. There were 13 plots in the experiment, each 6 m (19.6 ft) by 2 m (6.6 ft); 4 plots had "upland" vegetation with low plant cover (55%-60% bare area), 5 plots with "transition" vegetation (10%-14% bare area), and 4 plots with "wetland" vegetation (7% or less bare area). The artificial runoff was formulated containing suspended solids taken from dry, sieved sediment byproducts of sand and gravel mining that contained roughly equal proportions of silt, very fine sand, and fine sand, with a smaller amount of clay. On each plot, a standard amount of the artificial runoff was applied at lengths of 1 m (3.3 ft), 2 m (6.6 ft) and 6 m (19.6 ft) above the base of the slope, which ranged from 2% to 20%. Sediment retention was measured as functions of flow length, vegetation type, clipping treatment (moderate (10-15 cm (4-6 in) height) or severe (2-5 cm (0.8-2 in) height)), and slope. It was found that the worst mean sediment retention, about 63% was observed for 1 m (3.3 ft) of upland vegetation with severe clipping; the same conditions with moderate clipping was slightly better (66%), while the other types of vegetation retained 80-90% of the sediment. For 2 m (6.6 ft) lengths, upland vegetation retained 86-88% of the sediment, on average, and the other two types retained about 95%. For 6m (19.6 ft) plots, the retained sediment exceeded 97% for all types of vegetation. The difference in effectiveness between the two clipping treatments was minimal. In their discussion, the author notes that reducing buffer width from 6m (19.6 ft) to 1m (3.3 ft) reduces sediment retention from 99% to 83% on average, leading to a factor of 13 increase in runoff sediment. Increasing slope from 2% to 20% reduced retention from 96% to 91%, leading to a factor of 2.5 increase in runoff sediment. Thus the author suggests that the easiest way to assure effective rangeland buffers around bodies of water is to specify a minimum buffer width, say 6 m (19.6 ft), with some allowance for a smaller buffer if the land is flat (<2% slope) and strong vegetation coverage (e.g. 1000 g/m^2 (3.25 oz/ft^2) of biomass).

Walsh et al. [1997], constructed a 40 m (130 ft) long channel that was 0.76 m (2.5 ft) wide that was filled with up to 7.6 cm (3 in) gravel, then 15 - 17.8 cm (6 -7 in) soil, and planted with buffalo grass sod native to Texas that was trimmed to a height of about 7.6 cm (3 in). The average slope was 0.44%, thus simulating a swale that acted more as a ditch than as a slope. The experiment consisted of the application of 5000 gal (18,900 L) of well water mixed with the following soil contaminants: 500 mg/L detention pond sediment (filtered with 250 µm), 40 mg/L Gleason clay, 60 mg/L Velvacast kaolin, and 20 mg/L coarse clay, for a total of 620 mg/L suspended sediment. Metals were added at 0.16 mg/L $Pb(NO_3)_2$, 0.113 mg/L $Cu(NO_3)_2$ $3H_2O$, 0.91 mg/L $Zn(NO_3)_2$ $6H_2O$, and 0.9 mg/L Na_2CO_3. The influent was administered to flood the channel to depths of 3 cm (1.2 in), 4 cm (1.6 in), 7.5 cm (3.0 in), and 10cm (3.9 in). Samples were collected at the influent, at every 10 m (32.8 ft) along the channel, and from the underdrain. Experiments were conducted between October and May, including periods of dormancy and growth. Removal efficiencies were computed as a function of sample position and depth of water in channel. Results are tabulated in Table 2. TSS removal percentages were higher from the underdrain (73%-87%) than from the surface, and lower at 10 m (3.3 ft) (35%-59%) than at longer distances (50%-77%). Zinc and iron removals had a similar, but less pronounced pattern; zinc removal was 47-86% from the underdrain and 22-86% from the surface (excluding the 10 m (3.3 ft) position); iron removal was 75% from the underdrain, and 72% at 30 m (98 m) and 76% at 40 m (131 ft). It was also shown that the highest removal values from surface samples occurred at the lower depths of 3 cm (1.2 in) and 4 cm (1.6 in). From active to the dormant season, removal efficiency was similar except for TSS, which was "best in the growing season."

Table 2. Removal of constituents as a function of distance from source observed by Walsh, et al. [1997] (1 m = 3.28 ft).

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

2.5.1 Artificial stormwater in the literature

Most simulated storm events are conducted using artificial stormwater runoff (also called "simulated runoff" in the literature). The Washington State DOT study [Newberry and Yonge 1996] included the application of artificial stormwater to grass plots in a laboratory setting. Their formulation included suspended solids and the metals lead, cadmium, copper, and zinc in the concentrations shown in Table 3.

Table 3. Artificial stormwater mix used by Newberry and Yonge [1996].

Contaminant	Concentration (mg/L)
Suspended Solids	250
Pb	2.425
Cd	0.075
Cu	0.199
Zn	2.055

Paul Hook [2003] created an artificial runoff containing suspended solids taken from dry, sieved sediment byproducts of sand and gravel mining that contained roughly equal proportions of silt, very fine sand, and fine sand, with a smaller amount of clay. The runoff was applied to 6 m × 2 m (19.7 ft × 6.6 ft) plots. The particle size distribution of the sediment is given in Table 4. Hook did not provide TSS concentration information in his paper. Instead, he added 50 kg (or 36 l) of his sediment mix to an unspecified quantity of water, measured the total mass of solids in the entire collected effluent, and computed the removal by dividing the difference in the two masses by the 50 kg influent mass.

Table 4. Particle size distribution in sediment applied to vegetation by Hook [2003].

USDA particle size class	Size (mm)	% by mass	Cumulative % by mass
Coarse fragments	>2	0.0	0
Very coarse sand	1-2	0.5	0.5
Coarse sand	0.5-1	0.6	1.1
Medium sand	0.25-0.5	2.6	3.7
Fine sand	0.1-0.25	28.2	31.9
Very fine sand	0.05-0.1	27.5	59.4
Coarse silt	0.02-0.05	16.1	75.5
Medium silt	0.005-0.02	10.9	86.4
Fine silt	0.002-0.005	2.0	88.4
Clay	<0.002	11.6	100

Walsh et al. [1997], created an artificial runoff "cocktail" for testing a laboratory-scale (0.76 m (2.5 ft) wide by 40 m (131 ft) long) grassy swale in Texas. A list of the constituents and their concentrations is given in Table 5. The metal contaminants are listed in their chemical compound form as added, all as nitrates.

Table 5. Constituents in the roadway runoff "cocktail" applied to biofilters by Walsh et al. [1997].

Contaminant	Concentration (mg/L)
Detention pond sediment	500
Gleason clay	40
Velvacast kaolin	60
Coarse clay	20
$Pb(NO_3)_2$	0.16
$Cu(NO_3)_2\ 3H_2O$	0.113
$Zn(NO_3)_2\ 6H_2O$	0.91
Na_2CO_3	0.9

Davis et al. [2001] conducted laboratory scale studies on a bioretention cell. The synthetic runoff, based on sampling data obtained by Prince George County, Maryland's Department of Environmental Resources, was formulated using cupric sulfate 0.08 mg/l, lead chloride 0.08 mg/l, zinc chloride 0.6 mg/l, calcium chloride as dissolved solids 120 mg/l and nutrients of nitrate, organic nitrogen and phosphorus. Tap water was the solvent with pH at 7.0.

2.6 Event Mean Concentration (EMC) versus Annual Average Daily Traffic (AADT)

Data from five researchers [Barrett et al., 1998a; Driscoll et al., 1990; Gupta, et al., 1981; Kayhanian et al., 2005; Sansalone and Teng, 2004; and Wu et al., 1998] were harvested from the literature that give concentrations of selected contaminants in road runoff as well as AADT or other traffic estimates at 10 sites. Results are mixed because correlations are variable, limited, or insignificant, as shown in Figure 2, Figure 3, and Figure 4. This suggests other variables are significant, e.g. rainfall amount/rate, antecedent dry days, etc. [Clar, Barfield, and O'Connor, 2004], and as indicated previously, AADT is not indicative alone of pollutant loading.

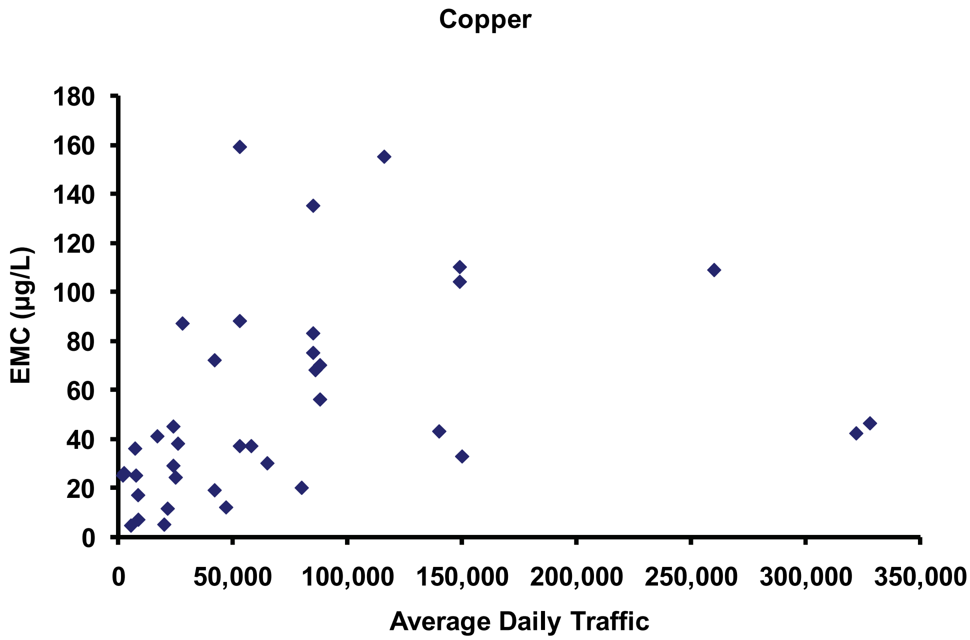


Figure 2. Plot of copper concentration in runoff as reported in literature versus AADT. Note lack of strong correlation.

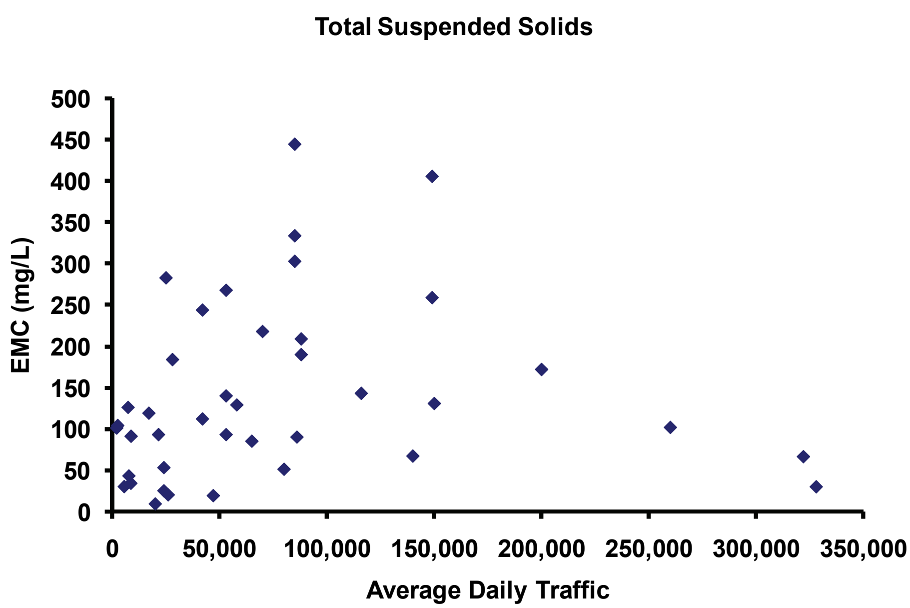


Figure 3. Plot of total suspended solids (TSS) concentration in runoff as reported in literature versus AADT. Note lack of strong correlation.

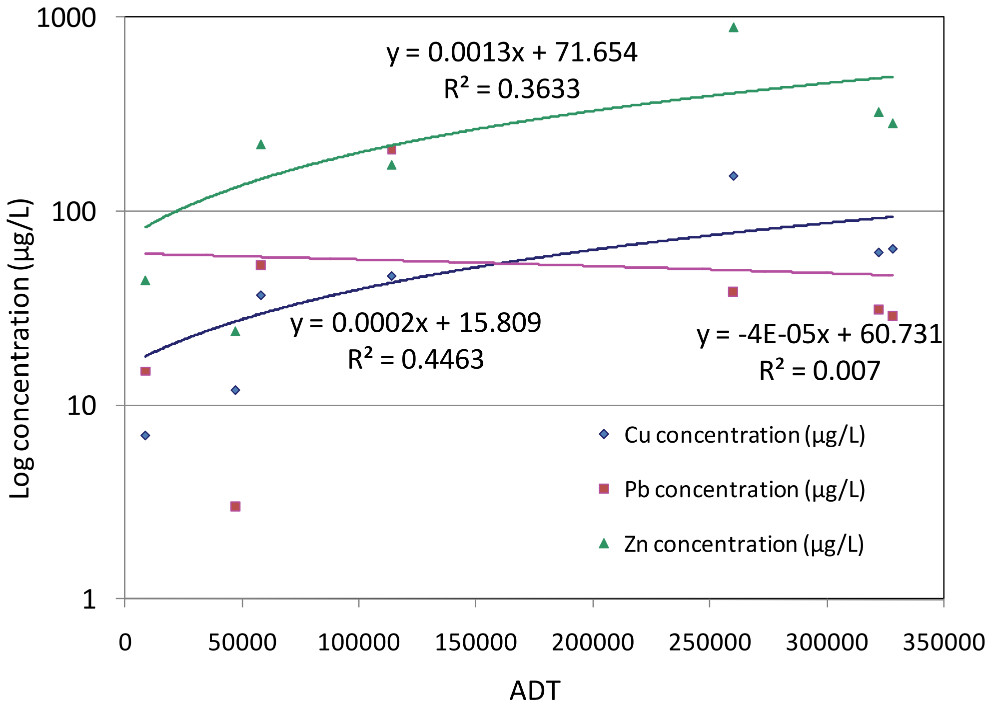


Figure 4. Plot of concentration in highway stormwater runoff for copper, lead, and zinc as reported in literature versus AADT, with fits. Note lack of strong correlations ($R^2 \leq 0.45$).

2.7 Synthesis of Literature Data on TSS Removal by Vegetated Areas

The removal results of vegetation, as reported by various sources, were gathered into a spreadsheet for graphing as a function of vegetated area length (along flow) and slope. By far the most commonly measured pollutant was total suspended solids (TSS), which is common to both agricultural and roadway runoff; agricultural data were included to expand the data set. A list of the references consulted to build the spreadsheet is in Table 6. TSS was the only pollutant measured and reported in enough sources with slope and length data to enable graphing of results to search for a correlation between TSS removal and slope or length. It is worth noting that the definition of removal used in these sources may vary (e.g. 1-(effluent concentration /influent concentration) or event mean concentration (EMC)), and no attempt was made to control for these various definitions, which were not always disclosed. Data were read off tables or estimated from graphs in the references; on occasion data were collected from secondary sources, such as review papers.

The various studies were then grouped by how the TSS was applied, whether by natural events in the field or by applying artificial stormwater in a controlled setting. Some studies were excluded based on various criteria, including outlier data, unclear identification of the source of the TSS or nature of the application events, or unrealistic conditions; the reasons for specific studies being excluded are given in the rightmost column of Table 6. The data gathered from the remaining studies using natural events are graphed in Figure 5 along with linear and power law fits. Data from those using simulated events are graphed in Figure 6 with fits. The lower correlations for the simulated events may reflect a variety of experimental set-ups and conditions that may have affected results.

Table 6. Vegetated stormwater controls references consulted while preparing Figure 5 through Figure 7, including reasons for excluding certain of these references from the fits in the figures.

Lead author	Publication date	Runoff source (Road or agricultural)	Length range	Slope range	Event type (Natural or simulated)	Pollutants	Reason if excluded from fits
Abu-Zreig	2004	Ag	2-15 m (6.6 - 49 ft)	2.3% - 5%	Simulated	TSS	
Barrett	2004	Road	4.2-13 m (14 -43 ft)	10%-52%	Natural	TSS, Cu, Pb, Zn	
Castelle	1994	various	4.6- 91.5 m (15 - 300 ft)	-	-	TSS	Review paper of earlier data
Daniels	1996	Ag	3-6 m (9.8 - 19.7 ft)	2.1%-4.9%	Natural	TSS	
Han	2005	Road	4.18-16.76 m (13.7 - 55.0 ft)	4%	Natural	TSS	Low outliers, wide variability
Blanco-Canqui	2004a	Ag	0.7 - 8 m (2.3 - 26 ft)	5%	Simulated	TSS	High outlier
Schoonover	2006	Ag	3.3 - 10 m (10.8 - 32.8 ft)	1%	Simulated	TSS	Cane and Forest only
Lee	1999	Ag	3-6 m (9.8 - 19.7 ft)	3%	Simulated	TSS, P, TN	
Mankin	2007	Ag	8.3 - 16.1 m(27.2 - 52.8 ft)	3.7%-4.3%	Simulated	TSS, TP, TN	High outlier
Patty	1997	Ag	6 - 18 m (19.7 - 59 ft)	7%-15%	Simulated	TSS	High outlier
Hook	2003	Sediment	1 - 6 m (3.2 - 19.7 ft)	8.7%-9.8%	Simulated	TSS	No concentration values
Yu	2001	Road & Ag	15 - 275 m (49 - 902 ft)	1%-3%	Natural	TSS,TP, TN, COD	Excessive length
Schmitt	1999	Ag	7.5 - 15 m (24.6 - 49 ft)	5%-7%	Simulated	TSS	
Shiono	2007	Ag	0.5 - 3 m (1.6 - 9.8 ft)	2%	Natural	TSS	
Syversen	2005	Ag	5 - 10 m (16.4 - 32.8 ft)	12%-17%	Simulated	TSS	
Van Dijk	1996	Ag	1 - 10 m (3.3 - 33 ft)	2.3%-5.2%	Simulated	TSS	
Deletic	2006	Ag	16.25 m (53.3 ft)	1.60%	Simulated	TSS	One point, low outlier
Helmers	2005	Ag	13 m (43 ft)	1%	Simulated	TSS	
Mendez	1999	Ag	4.3 - 8.5 m (14 - 28 ft)	18%	Natural	TSS, TKN	
Sheridan	1999	Ag	8 m (26 ft)	2.50%	Natural	TSS	Forest buffers
Stagge	2006	Road	137-198 m (449 - 650 ft)	1.2%-1.6%	Natural	TSS, Zn	Excessive length

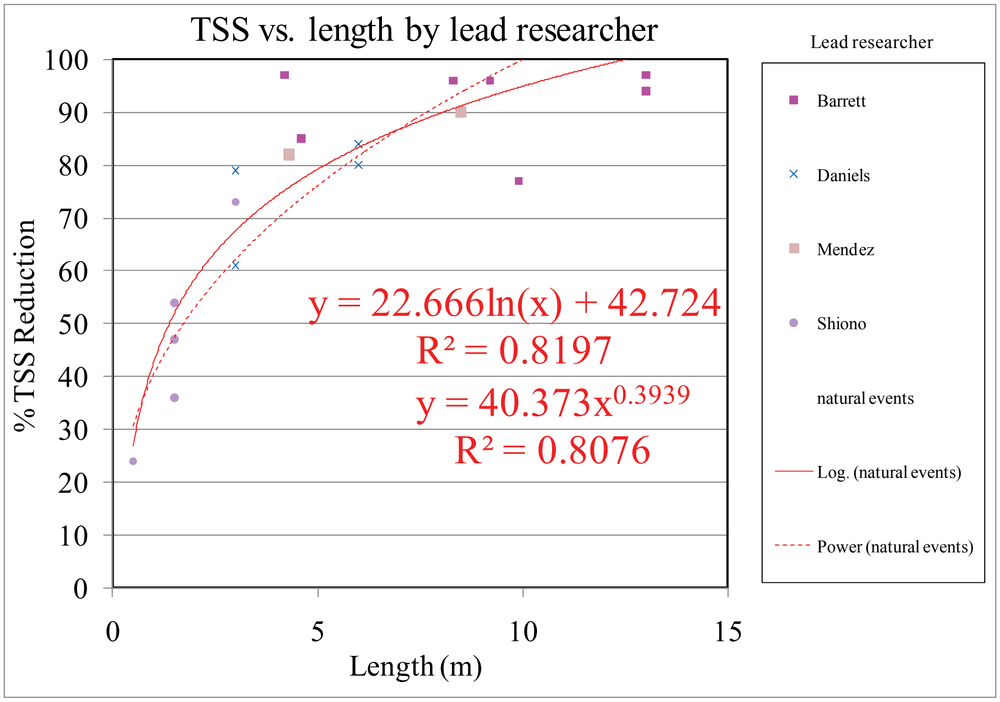


Figure 5. Total Suspended Solids (TSS) removal as a function of length taken from various sources in the literature. Includes only data based on natural rainfall events and excludes a few outliers. Includes logarithmic and power law fits. (1 m = 3.3 ft)

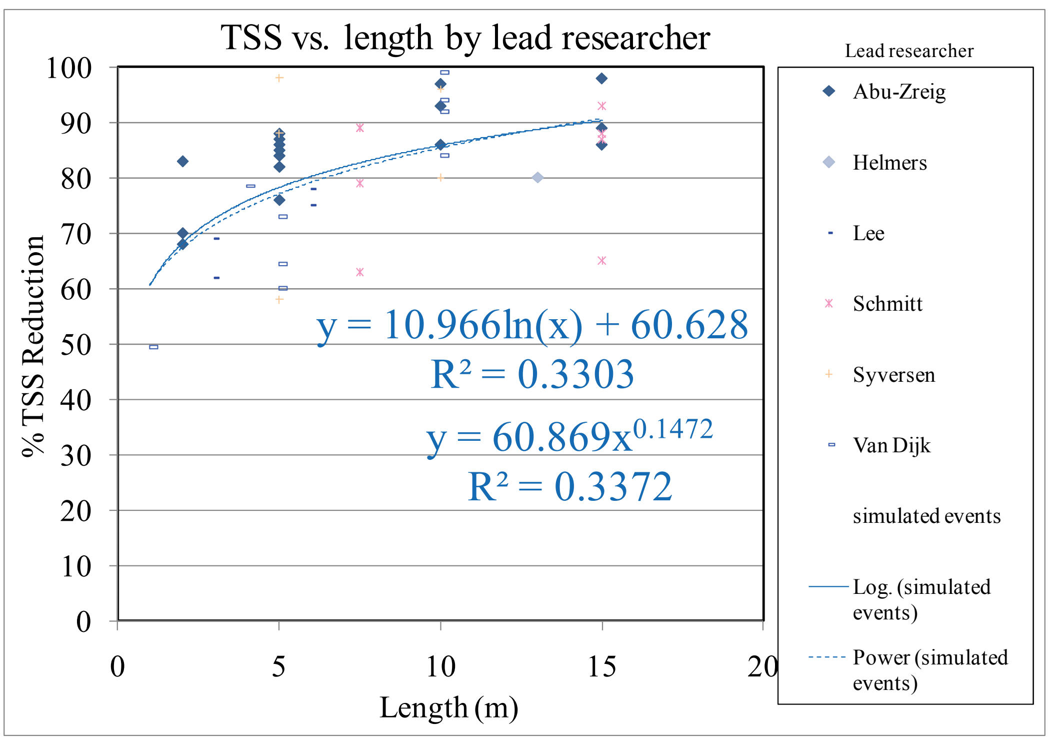


Figure 6. Total Suspended Solids (TSS) removal as a function of length taken from various sources in the literature. Includes only data based on simulated rainfall events and excludes a few outliers. Includes logarithmic and power law fits. (1 m = 3.3 ft)

The other major variable to consider is the slope of the vegetated area. TSS removal data are plotted as a function of slope in Figure 7, this time including both natural and simulated event results. Some studies were not included if slope data were not provided. Slope values were as reported, and may represent averages for some studies. Data were heavily concentrated in shallow slopes of 5% or less, which are considerably lower than the 12.5% (8:1) minimum slope used in this project. The correlations in the data (as estimated by R^2) are extremely low, indicating a weak relationship. Perhaps more disappointing is that the general trend of the fits in the graph is for increasing TSS removal with increasing slope, which is a counterintuitive result. However, both the lowest and the highest removals occur at the smaller slopes. For individual researchers, the highest removals at shallow slopes are at higher values than those at steeper slopes. There are many other variables that may affect this correlation, including length, vegetation coverage, number and type of storm event, and others.

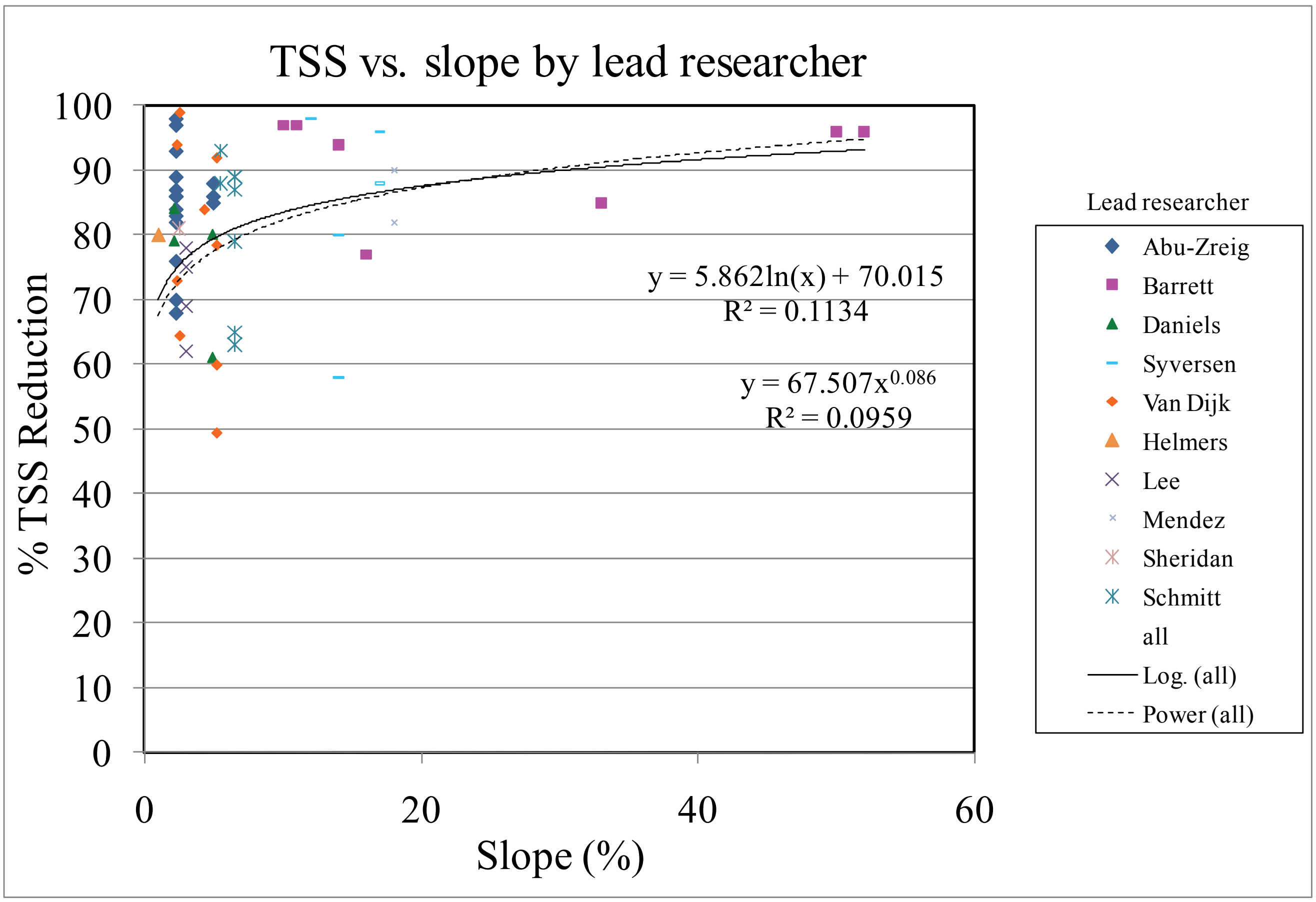


Figure 7. Total Suspended Solids (TSS) removal as a function of slope taken from various sources in the literature. Includes natural and simulated storm event data. Includes logarithmic and power law fits. Note lack of good fit to data as indicated by very low R^2 values.

3 Survey of State Departments of Transportation

As part of this project, a survey was sent electronically to representatives of all 49 other (excluding Ohio) state Departments of Transportation (DOTs) by ODOT's Office of Research and Development on behalf of the Ohio Research Institute for Transportation and the Environment (ORITE). ORITE had developed the survey in consultation with ODOT and the projects subcontractors at E. L. Robinson, CDM, and URS, Inc. The survey form is reproduced in Appendix A.

Survey participants were told in the preface to the survey that these questions regarded post-construction Best Management Practices (BMPs) used to reduce pollutant loads in stormwater runoff from linear transportation infrastructure, such as highways and roads whether in urban or rural settings. The designation "Post-construction" is for those devices used to treat stormwater pollutants (e.g. metals, petroleum residue, etc.) washed off the roads in the course of regular traffic and other designed uses, such as anti-icing and ordinary maintenance, as opposed to treating and preventing the loss of soil during construction work. The survey preface also told respondents that the survey was conducted as part of an ODOT sponsored research project.

3.1 Procedure

The survey was sent electronically all 49 states, excluding Ohio, by ODOT's Office of Research and Development in January 2008, with some follow-up email reminders. Additionally, ORITE staff contacted certain respondents via email or telephone to clarify selected responses. Follow-up requests for responses continued through May, 2008. In the final tally, 38 states responded, and a manual covering some of the same areas was found online for a 39th state (Pennsylvania). The Canadian province of Alberta also responded. A list of respondents from each state, including titles, affiliations, and contact information, is given in Appendix B. After all responses were tabulated, the relevant manuals from each of the responding states were consulted (one of the questions asked for a copy of or web link to the relevant manual) and responses were updated, particularly in instances where the respondents had referred to their manuals. Thus for most questions there are a maximum of 39 responses, but occasionally 40 where information from Pennsylvania was located in its manual.

In order to improve the rate of return by reducing the amount of effort requested from respondents, the survey was limited in length to 12 questions, some with multiple parts. In part because of the enforced brevity of the survey and because of the newness of the subject to highway engineering, several questions were of the open-ended "fill-in-the-blank" type, and some had multiple parts. Tabulating the responses to such questions requires some judgment to identify how to bin answers into useful categories for plotting. There were two groups of questions in the survey form in Appendix A. The first group of three questions, numbered 1 through 3, were broadly focused on the use of all types of best management practices (BMPs) for managing roadway runoff contamination and on the existence of manuals for design or maintenance. The second set of questions, numbered 1 through 9 on the questionnaire because the word processing program restarted the numbering of the questions, concerned details of roadside vegetation as a stormwater BMP. Because of the duplicate numbering, it is necessary to distinguish one set of questions from the other in this discussion; thus the first three questions are designated as “BMP Questions”, while the others are designated “Biofilter Questions” or simply “Questions”.

The graphs below present the responses to each question, beginning with the BMP questions and then the biofilter questions. For open-ended fill-in-the-blank questions, the responses have been binned to aggregate similar answers. These graphs reflect the direct responses given to survey questions with modifications where the manual provided additional information. Follow-up questions were often worded “If yes, then . . .”, but were sometimes completed by respondents who did not answer yes to the previous part or relevant information was obtained from the manuals consulted for this survey, thus the number of respondents to these follow-up questions may be larger than expected.

3.2 General BMP Question Responses

The first BMP Question asked states to supply a copy or web link for a design manual to address post-construction stormwater BMPs. Responses are shown in Figure 8. Slightly over half (21, 52%) provided the link or manual (typically as a pdf attachment). Two states (5%) used some alternate manual, while two more (5%) indicated a manual was forthcoming, but not yet adopted.

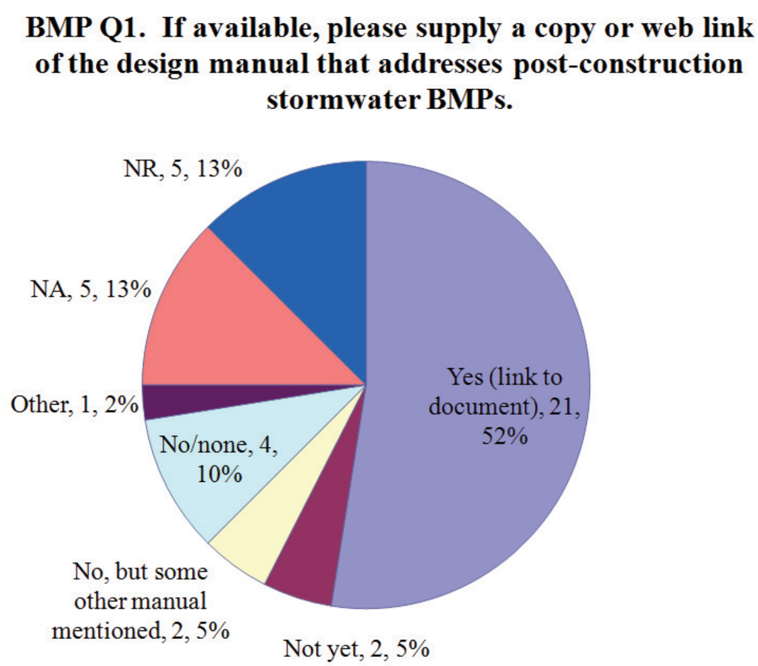


Figure 8. Responses to BMP Question 1 of survey of state DOTs.

BMP Question 2 asked if pollutant load was used as a design factor for BMPs. Only 11 states (28%) said yes, two more (5%) said “not yet”, indicating that such a policy was coming, and 21 states (52%) said no. BMP Question 2a was a followup that asked respondents to check off or enter BMP design factors. More than one could be chosen, and responses are shown in Figure 10. The most commonly chosen design criteria, in order of popularity, were typical first flush volumes, drainage area, urban location, rural location, event rainfall, and rainfall/runoff amounts.

The seven respondents who chose typical first flush volumes represented 54% of the 13 states that responded to this part of the question, two of which were states that selected "no" with some qualifications to BMP Question 2, and answered this part of the question anyway.

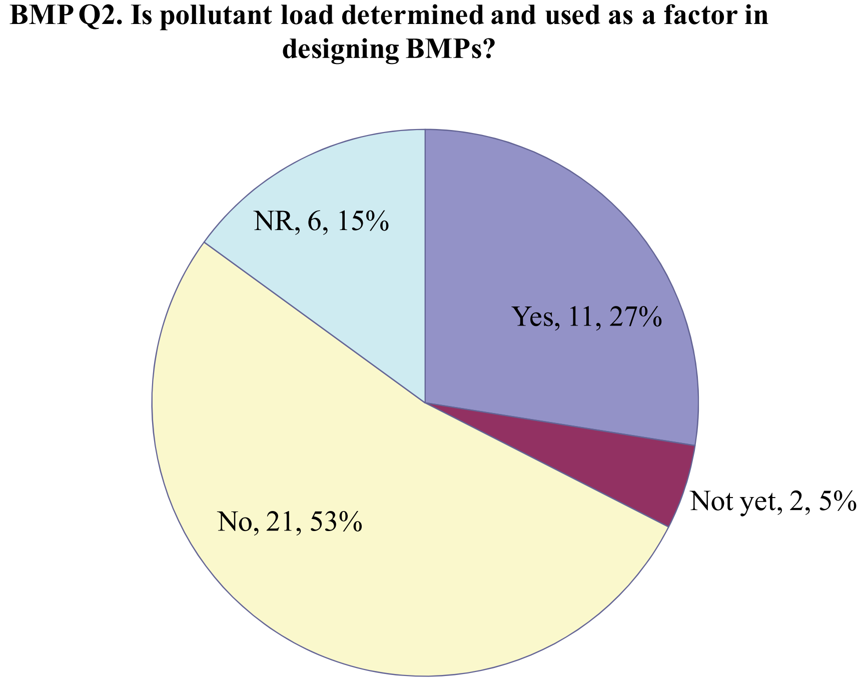


Figure 9. Responses to BMP Question 2 of survey of state DOTs.

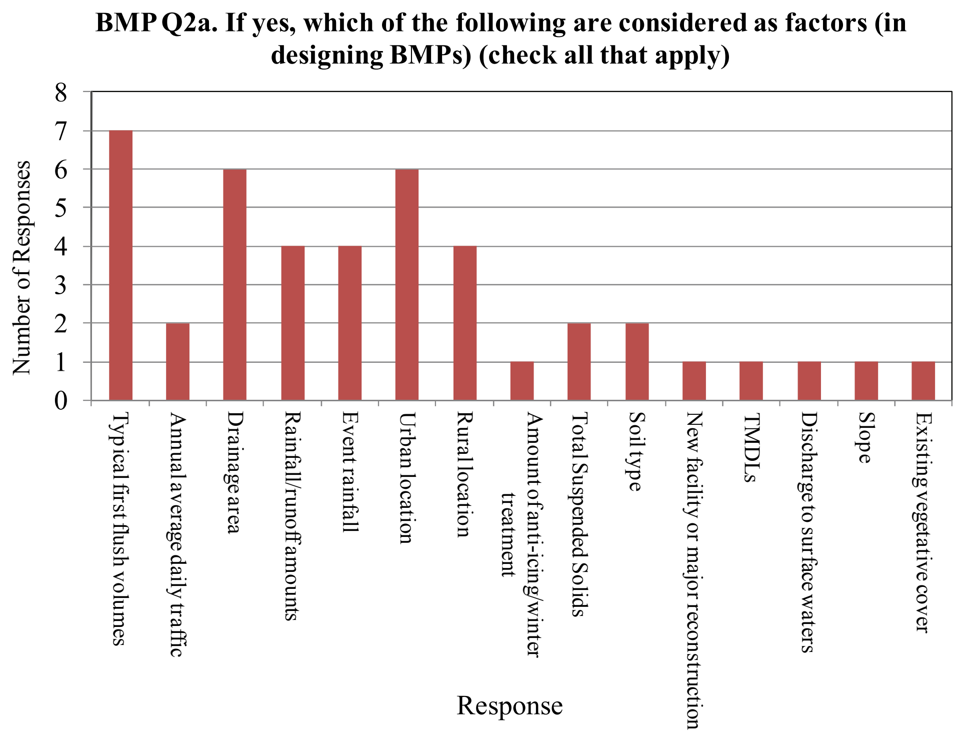


Figure 10. Responses to BMP Question 2a of survey of state DOTs.

BMP Question 3 is similar to BMP Question 1, except that it asks for a copy or web link of a manual for maintenance of post-construction stormwater BMPs. Positive responses were considerably lower on this question, only 11 (27%) supplied the document, 6 (15%) indicated one was still under development, and 2 (5%) referred to some other manual or unofficial procedure.

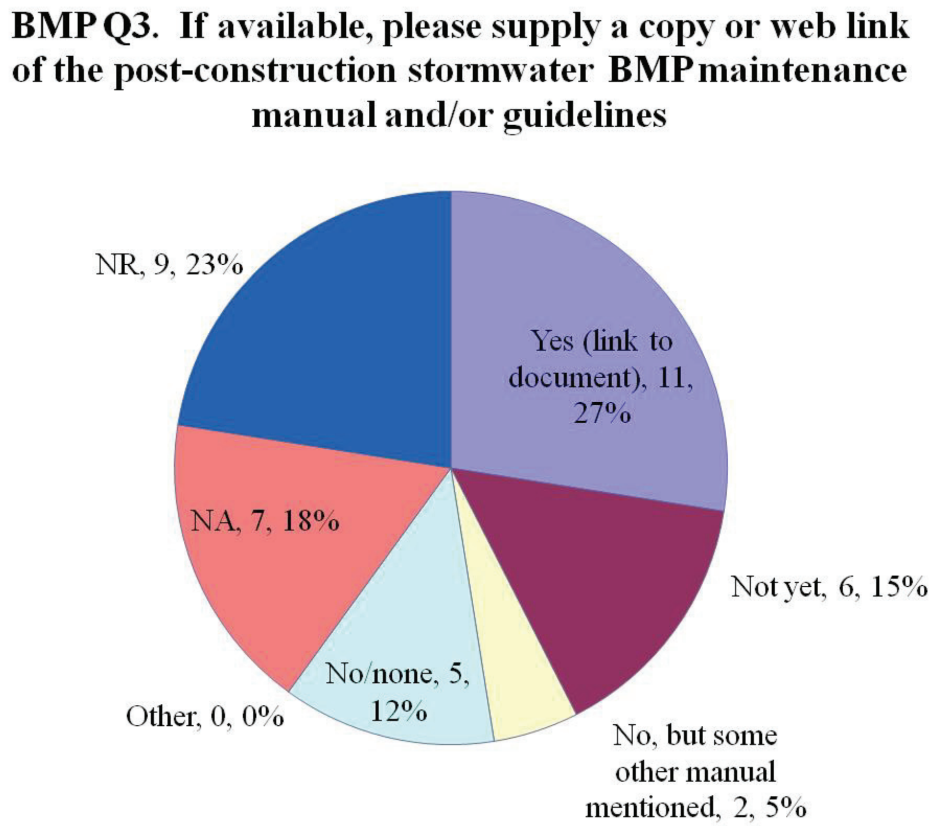


Figure 11. Responses to BMP Question 3 of survey of state DOTs.

3.3 Vegetated Biofilter Question Responses

After the three BMP Questions, the survey had a series of eight questions specifically regarding vegetated BMPs. The first question asks whether the state's environmental resource agency permits or is considering the use of vegetated filters as a post-construction BMP for treatment of highway storm water runoff. The follow up questions, Question 1a asks if vegetated surfaces can be used without other BMPs, and Question 1b asks if biofilters are used as a stand-alone BMP. Responses to these three parts of Question 1 are in Figure 12, Figure 13, and Figure 14 respectively. Figure 12 shows that nearly three-fourths (29, 74%) of responding states permit the use of vegetated surfaces for post-construction BMPs and three more (8%) are considering their use. About two-thirds (24, 64%, and 25, 66%) of those who responded yes or is considering to the first part of the question responded yes that vegetated biofilters could be used without other BMPS and that they could be used as a stand-alone BMP.

Q1. Does your state's environmental resource agency permit or is it considering the use of vegetated surfaces as a post-construction BMP to provide treatment of storm water runoff?

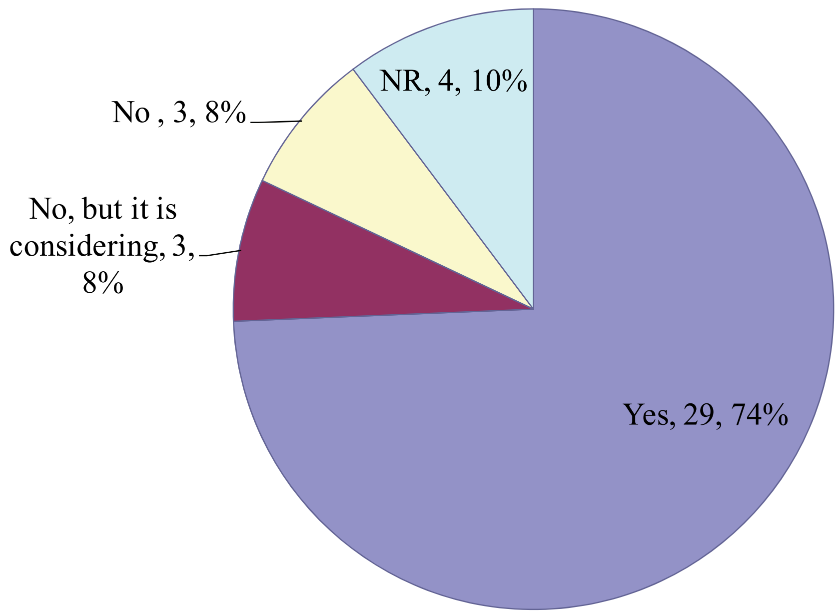


Figure 12. Responses to Question 1 of survey of state DOTs.

Q1a. If yes, is it acceptable to use vegetated surfaces without incorporating other storm water post-construction BMPs?

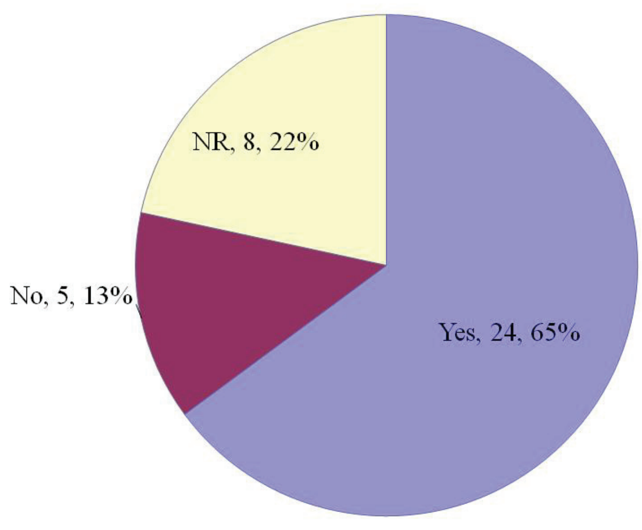


Figure 13. Responses to Question 1a of survey of state DOTs.

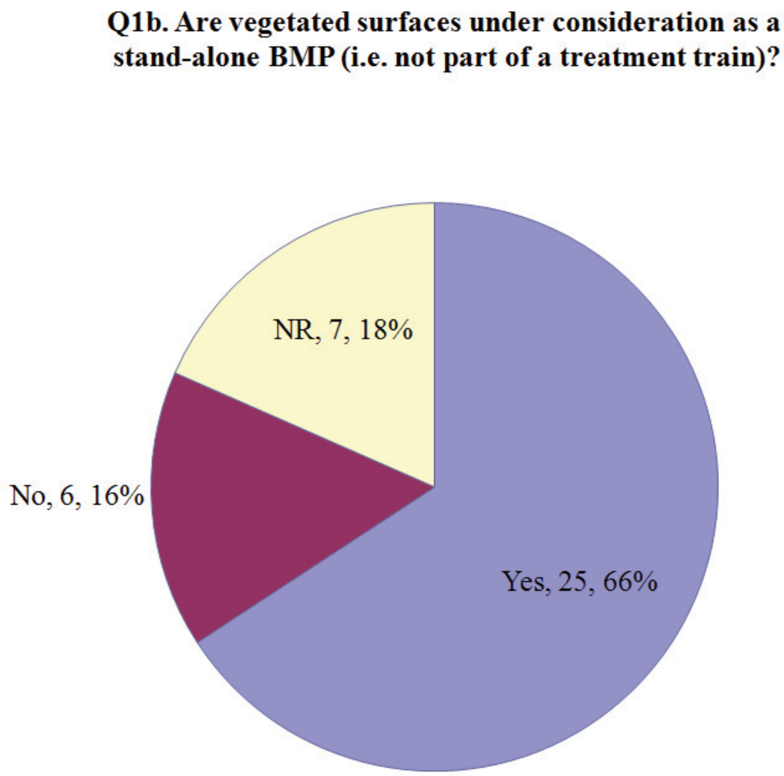


Figure 14. Responses to Question 1b of survey of state DOTs.

Question 2 asked what foreslope or backslope slopes and lengths are considered acceptable for pollutant removal. Many respondents indicated a specific number or range, or their state's manual had a range. The variety of numerical answers made it difficult to bin the responses by number, but for the slope responses this was possible. The results are shown in Figure 15. Not counting "unspecified" (9 responses, 23%), the top category was ≤10% with 8 responses (21%). Four states (11%) each selected 10-20% and 25-33%, and three states (8%) selected 50% (2:1) as the maximum slope. The length responses, shown in Figure 16, were if anything, more varied. Again, the plurality (9 responses, 23%) selected "unspecified", and the next largest category, 8 responses (21%) had specified both a minimum and maximum length. Six states (16%) specified a minimum length and one state (3%) specified only a maximum. For a few states, the slope length depended on the slope, the drainage area, or site characteristics.

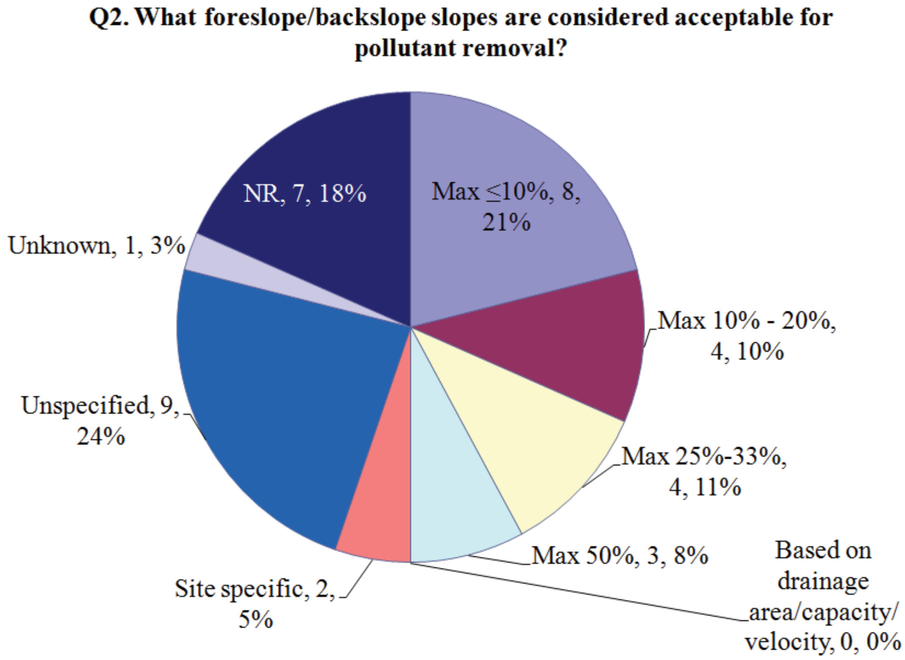


Figure 15. Responses to Question 2 of survey of state DOTs regarding foreslope slope angles.

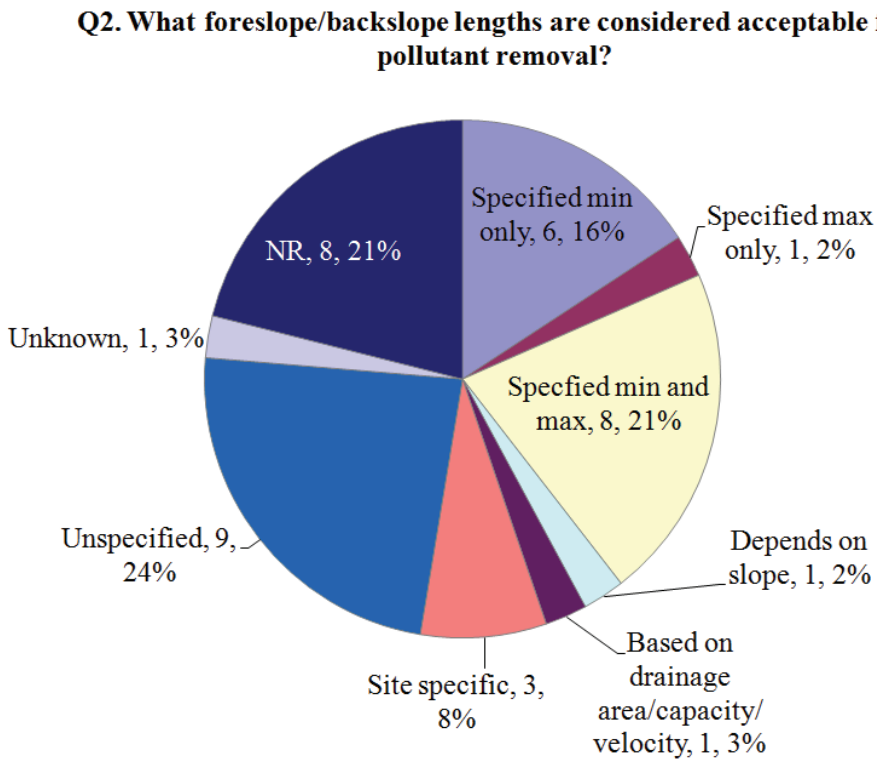


Figure 16. Responses to Question 2 of survey of state DOTs regarding foreslope lengths.

Figure 17 shows specific slope lengths from those respondents that provided them. Note that there may have been confusion about whether length is perpendicular to the direction of traffic (the intended meaning) or parallel, hence some of numbers given by respondents are very large.

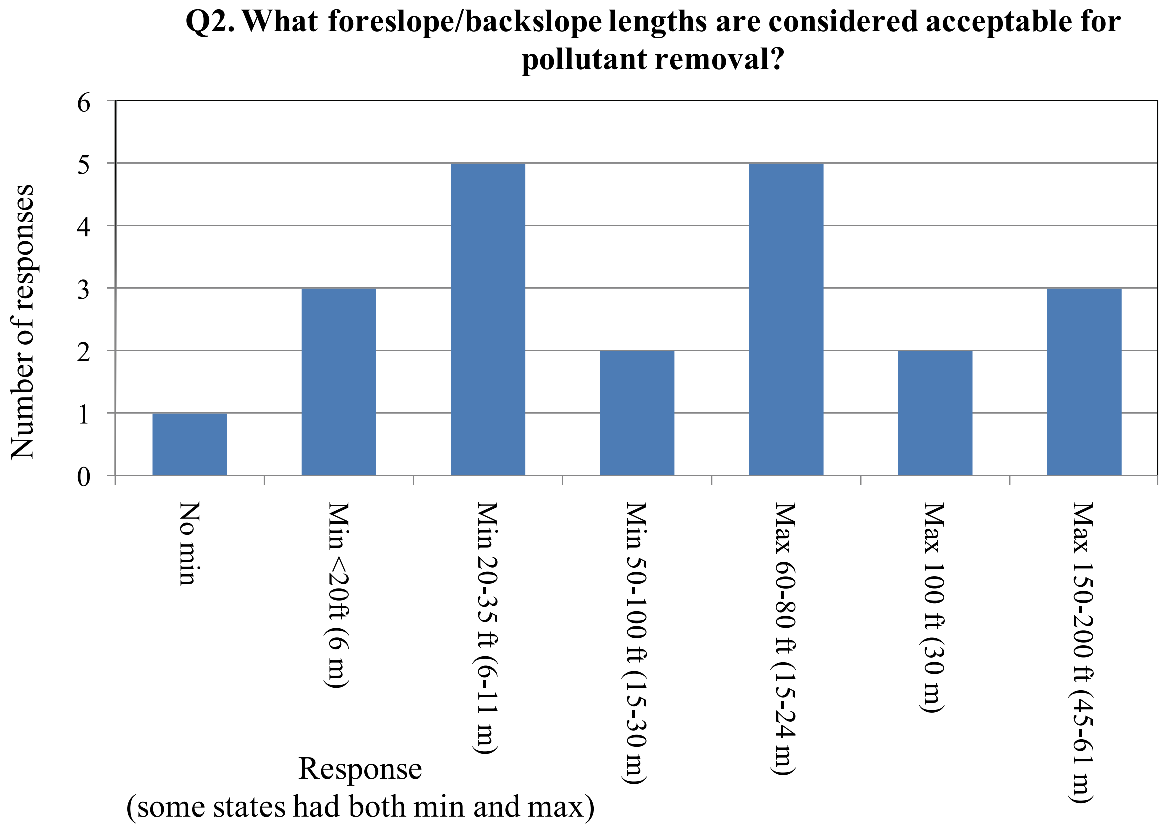


Figure 17. Responses to Question 2 of survey of state DOTs showing breakdown of specified values for foreslope lengths.

Question 3 asked about the grade and width of ditches receiving the flow from backslopes and foreslopes. Responses regarding ditch grades are compiled in Figure 18. The most common response was that the grade was unspecified, chosen by 8 states (21%), followed by 5 states (14%) that had a maximum and minimum and another 5 (14%) that said the grade was site specific. Specific numerical values given for grades are collected in the bar chart in Figure 19. The plurality of responses included a minimum slope ≤0.5% and a maximum slope of 4%. The one response indicating a maximum slope of 50% may reflect some confusion over terminology, as mentioned before. Figure 20 shows the responses regarding ditch widths. The largest response group (not counting no response (NR)) was again unspecified (9, 24%), followed by site specific at 6 responses (16%). Various numerical values are collected in Figure 21. Three respondents said the minimum width in their state was 2 ft (0.6 m) and two respondents said the maximum width was 8 ft (2.4 m). Other responses were unique, including one state that indicated the minimum width should be 50 ft (15 m).

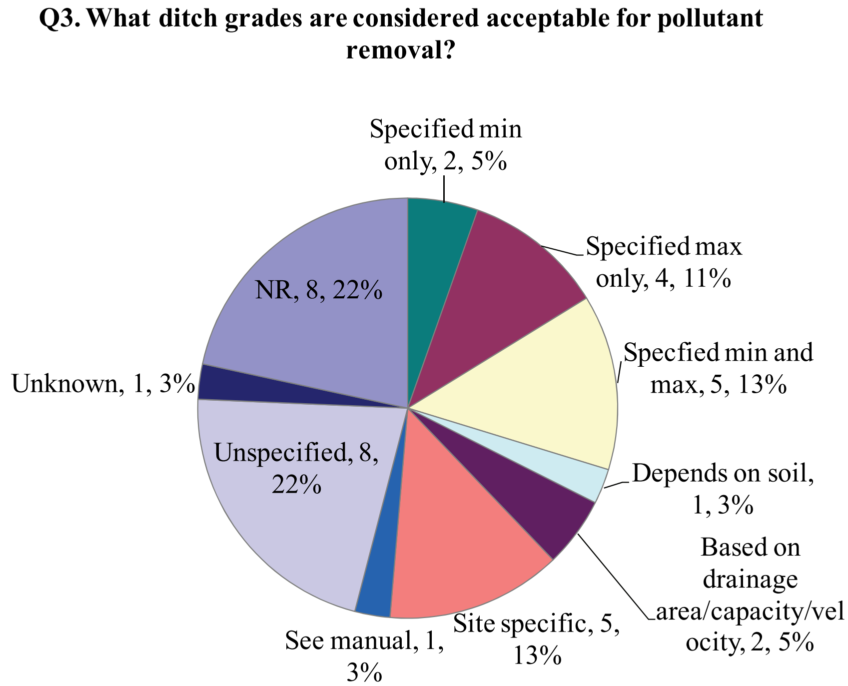


Figure 18. Responses to Question 3 of survey of state DOTs regarding ditch grades.

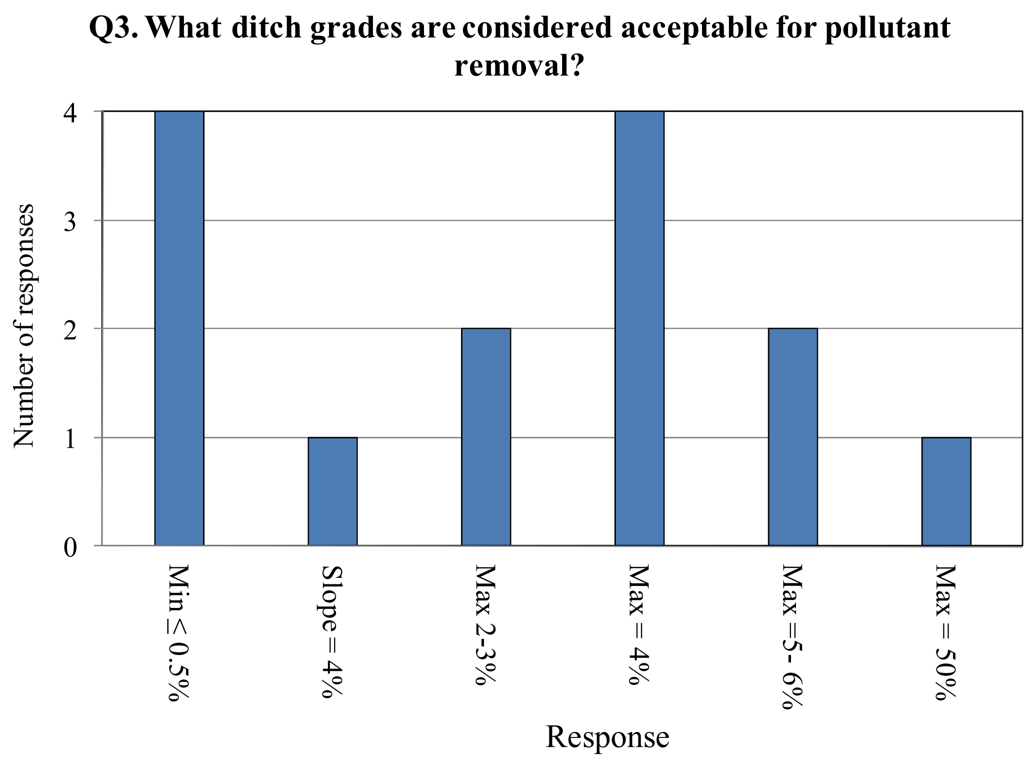


Figure 19. Responses to Question 3 of survey of state DOTs from those who provided specific values for ditch grades.

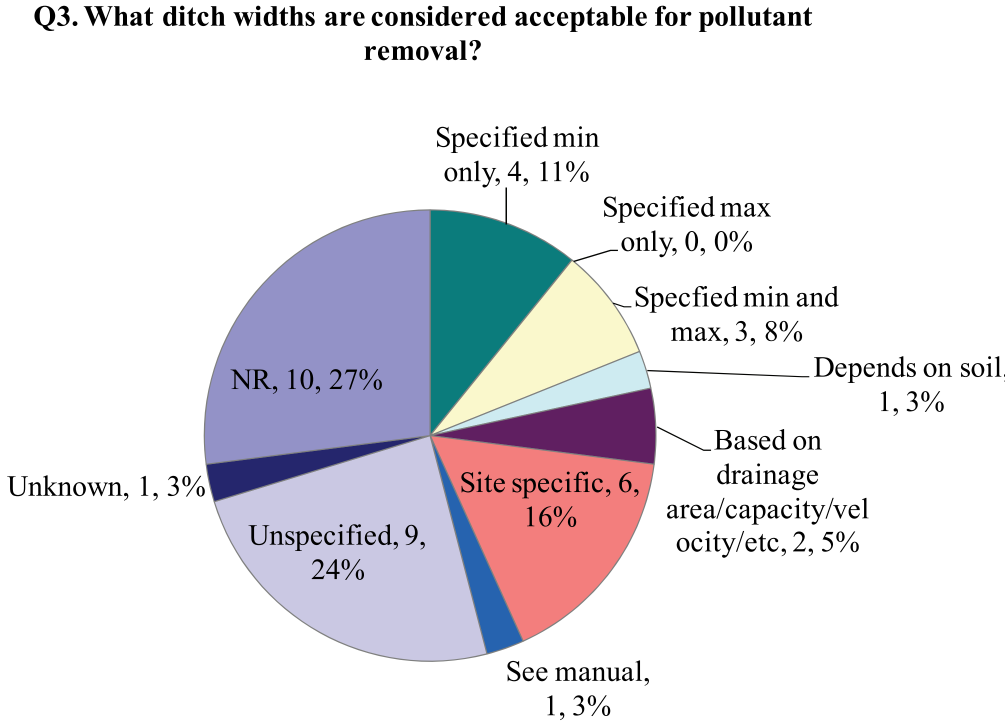


Figure 20. Responses to Question 3 of survey of state DOTs regarding ditch widths.

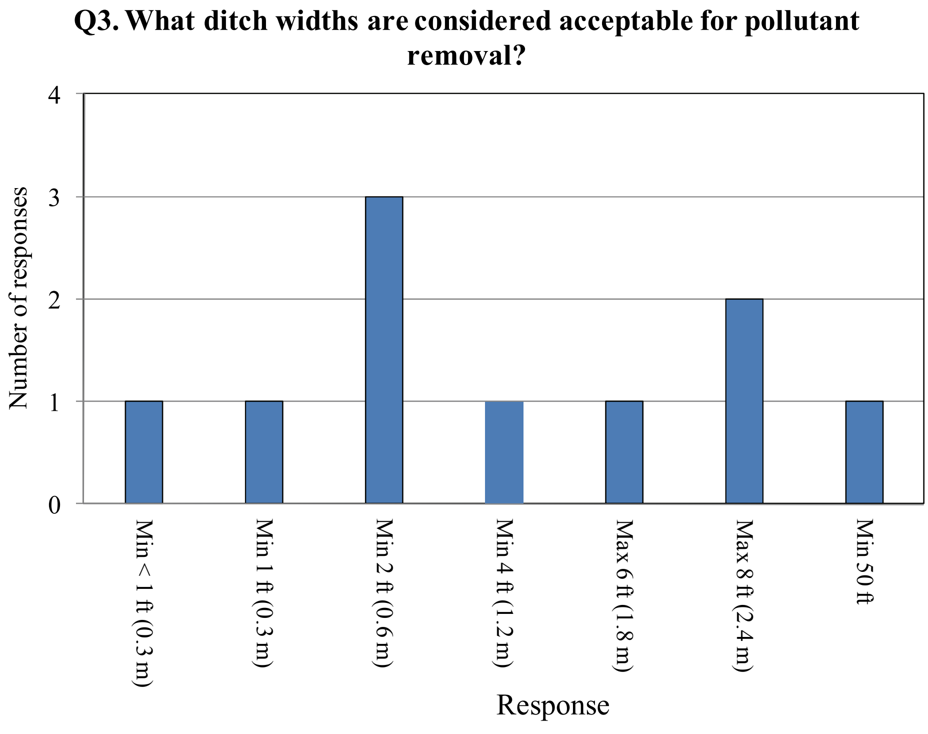


Figure 21. Responses to Question 3 of survey of state DOTs with responses indicating specific ditch widths.

Question 4 asked if a specific type of vegetation was specified for BMP use, and if so, what type. A clear majority of 27 (71%) indicated that no special mix was used for vegetated BMPs, as shown in Figure 22. Several states responded to Question 4a regarding specifics of the vegetation, including some that chose "no" to Question 4. By far the most common responses were native vegetation with 6 responses (30%), which probably could be conflated with "existing vegetation" which had one response (5%), followed by "site-specific" with 4 respondents (20%). Responses are shown in Figure 23.

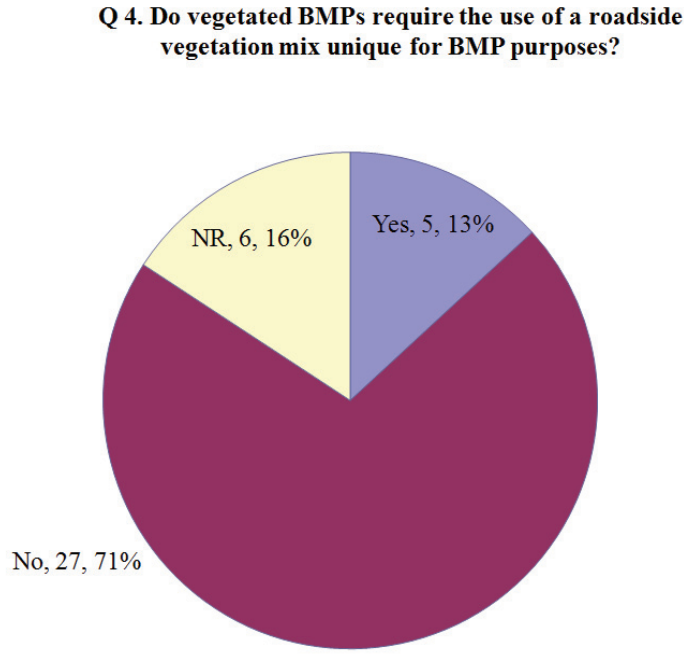


Figure 22. Responses to Question 4 of survey of state DOTs.

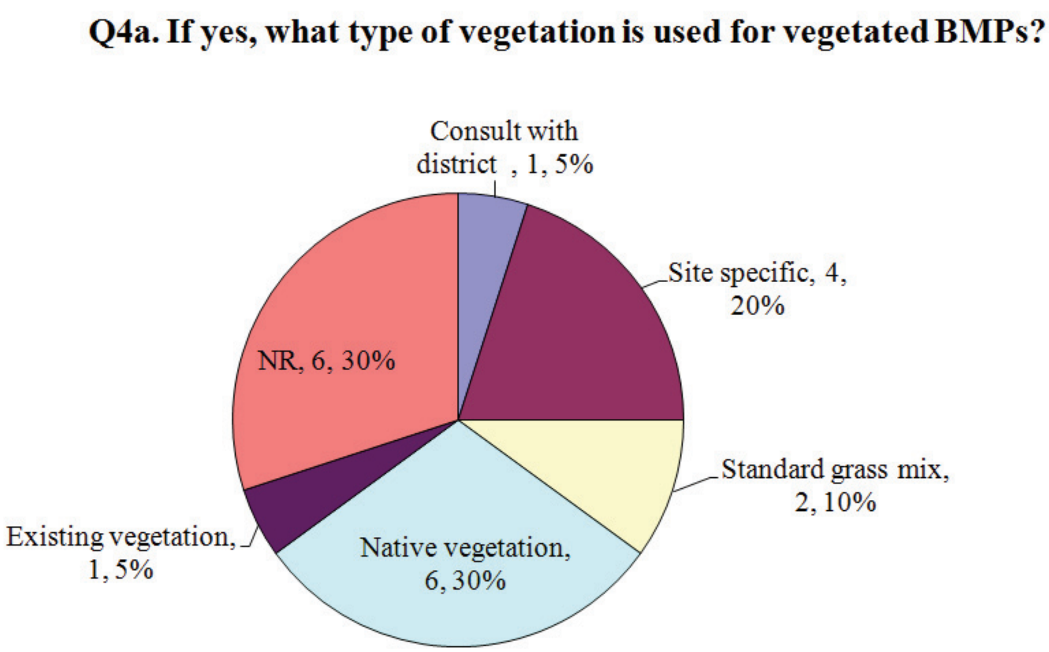


Figure 23. Responses to Question 4a of survey of state DOTs

Question 5 asked if there was a specific soil type used for BMPs, and if so, what type of soil. Again, about two-thirds of the respondents (26, 69%) indicated no special soil type was used. Responses are shown in Figure 24. Figure 25 shows the responses on type of soil used, which includes more than those states that answered “yes” to Question 5. Three states (19%) indicated they used a special soil mix, two (13%) indicated the soil choice was site specific, and other choices by 1 respondent (6%) each included “consult with district”, local soil, or a specification based on pH and other measures.

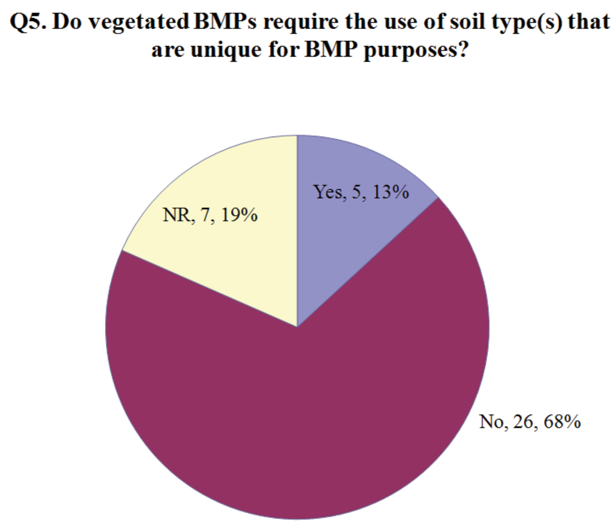


Figure 24. Responses to Question 5 of survey of state DOTs.

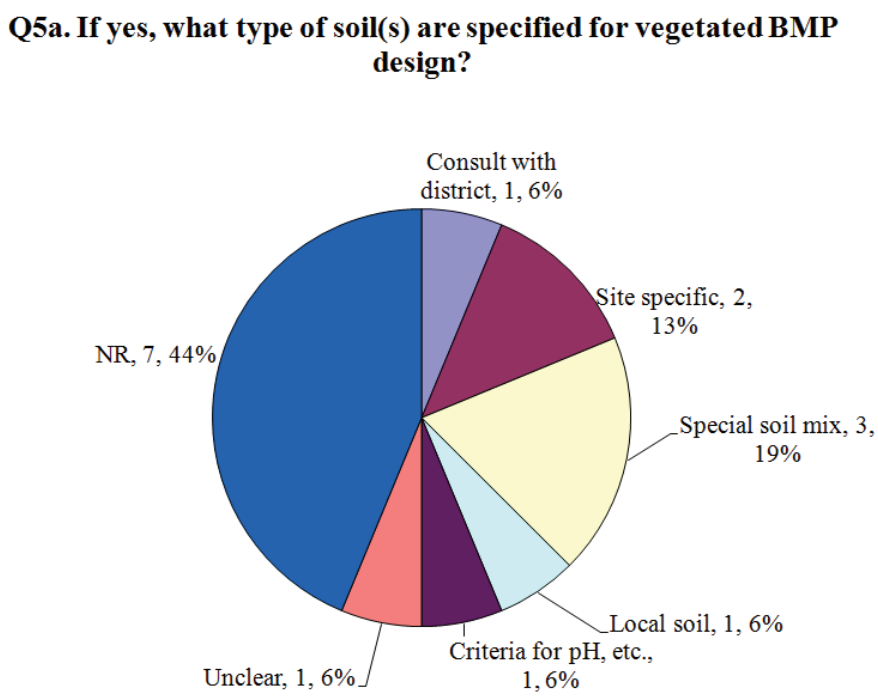


Figure 25. Responses to Question 5a of survey of state DOTs.

Question 6 asked if there were maintenance procedures specific to BMPs, with a follow-up asking for details. Responses are shown in Figure 26. A majority of 21 (56%) said that no special maintenance was required. Specific maintenance activities are given in Figure 27. The most common maintenance step was conducting periodic inspections, which was selected by 5 respondents (25%).

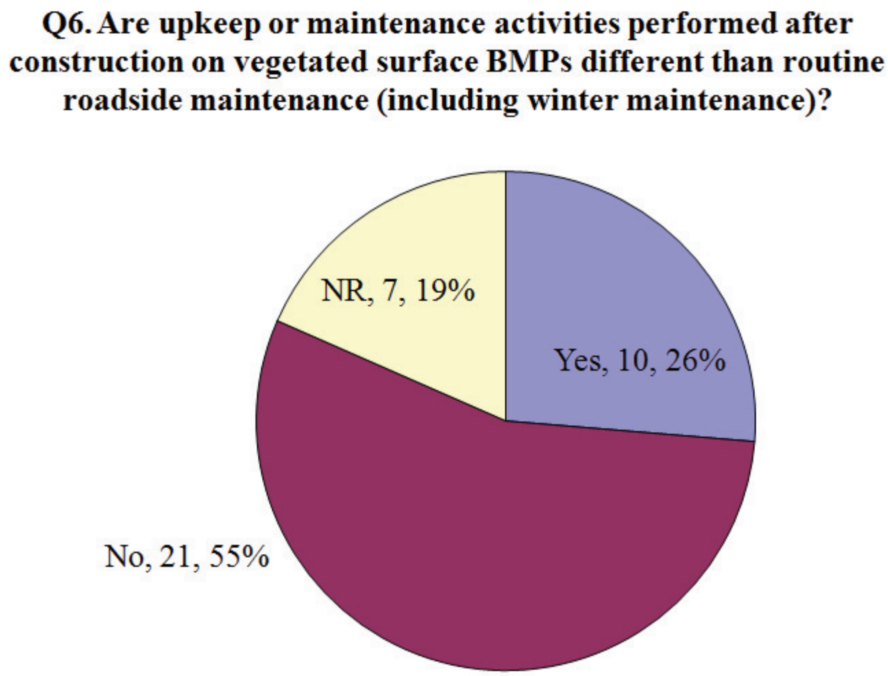


Figure 26. Responses to Question 6 of survey of state DOTs.

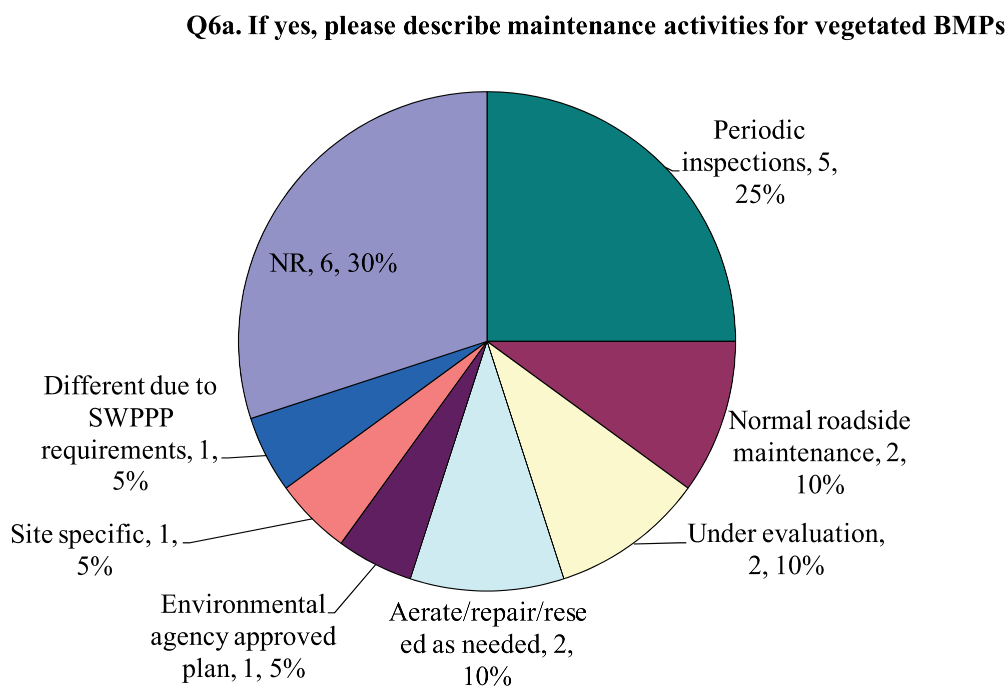


Figure 27. Responses to Question 6a of survey of state DOTs.

Question 7 asked if there are criteria to establish a pollutant saturation level for vegetated BMPs. Responses are shown in Figure 28. Three-fourths of respondents (29, 77%) said there were not, and only two (5%) said there were. Question 7a asked what the criteria were, to which four (31%) indicated the criterion was sediment accumulation, as shown in Figure 29, and one more state (8%) said pollutant criteria were under consideration. Question 7b asked what steps were taken to remedy the pollutant saturation condition. As shown in Figure 30, the only specific step notes was the replacement of vegetation and soil, chosen by four respondents (36%), while other eligible states did not respond (7, 64%). A variety of possibilities for disposal of the contaminated material were cited for Question 7c, as shown in Figure 31.

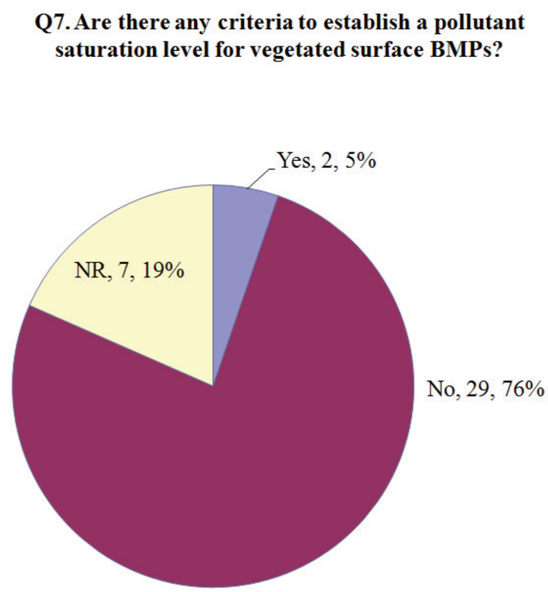


Figure 28. Responses to Question 7 of survey of state DOTs.

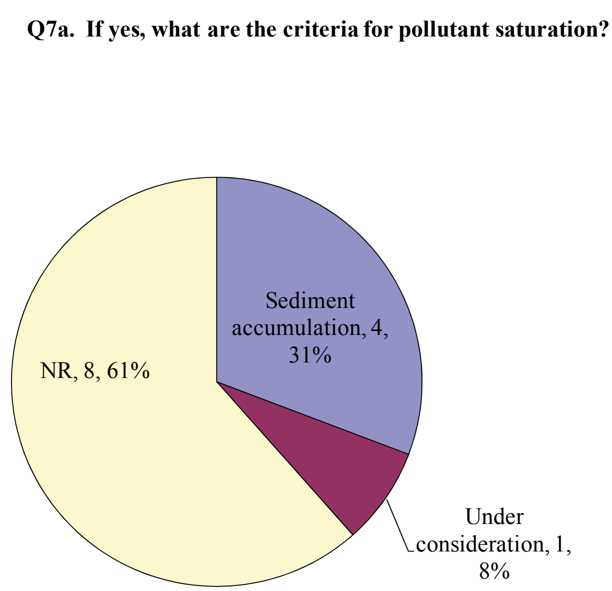


Figure 29. Responses to Question 7a of survey of state DOTs.

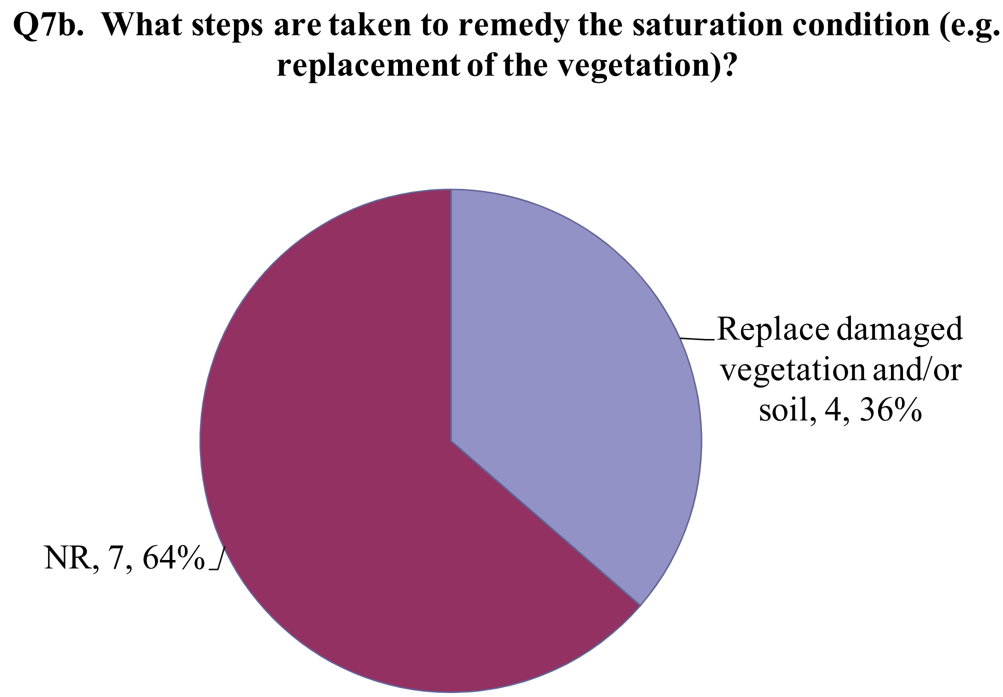


Figure 30. Responses to Question 7b of survey of state DOTs.

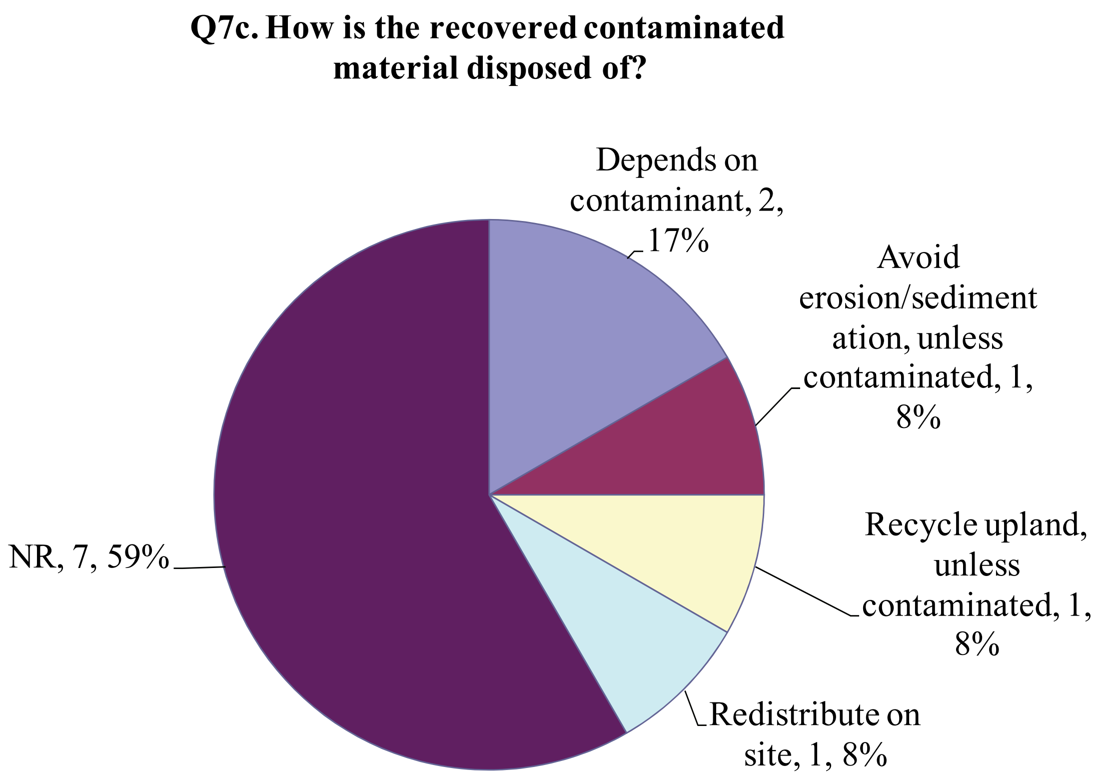


Figure 31. Responses to Question 7c of survey of state DOTs.

Question 8 asked if states documented BMP effectiveness. Figure 32 shows that 11 states (29%) did, but most states (20, 53%) did not. The remainder (7, 18%) did not respond to the question. The follow up in Question 8a was to ask how effectiveness was documented. A variety of responses were given in Figure 33. The most popular method was to measure pollutant removal or a similar criterion, chosen by 4 states (18%).

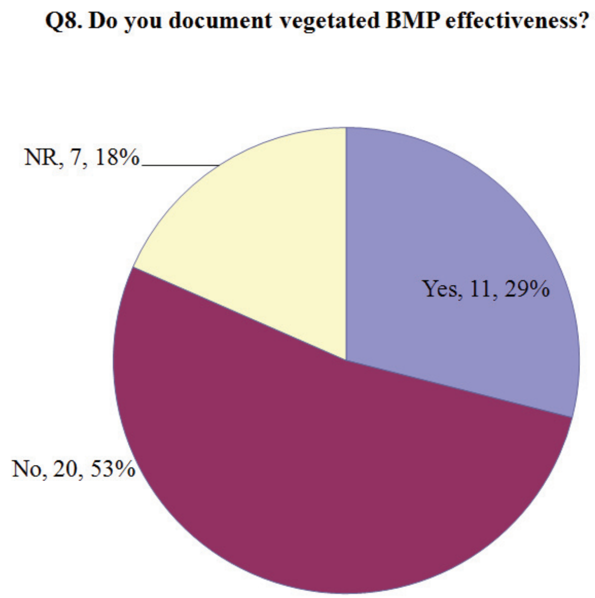


Figure 32. Responses to Question 8 of survey of state DOTs.

Q8a. If yes, how is BMP effectiveness documented?

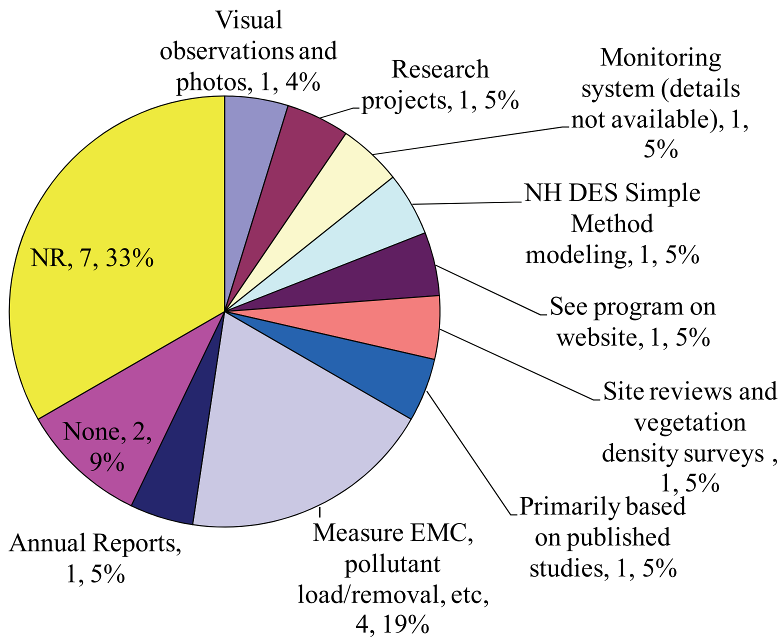


Figure 33. Responses to Question 8a of survey of state DOTs.

Lastly Question 9 asked if respondents would like to see the survey results, to which the overwhelming majority (36, 92%) said they would, as shown in Figure 34.

Q9. Would you like to see a copy of the survey results?

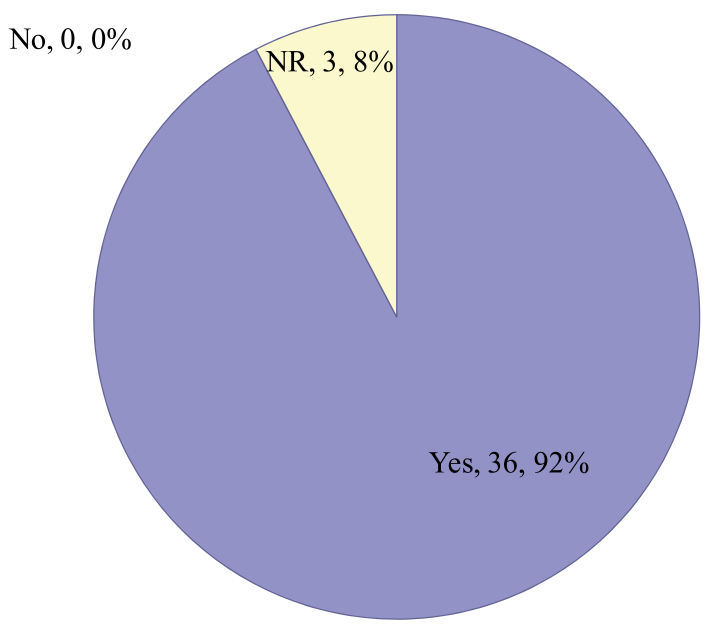


Figure 34. Responses to Question 9 of survey of state DOTs.

4 Field Inspections

Field inspections of existing ODOT vegetated biofilter installations were conducted to assess the current state of practice in the field. Field inspections were limited primarily to a visual examination with photographic documentation. An inspection sheet was prepared in cooperation with ODOT technical liaisons and the subcontractors, and a blank form is shown in Appendix D. A list of prospective sites to visit was obtained from the ODOT Districts, from which sites were selected for inspection. Inspections were conducted by at least two members of the research team, and their responses on the forms were compared and reconciled to generate a final assessment of the state of the biofilter(s) at the site.

4.1 Field Inspection Observations and Findings

Note: This section was written by Mark McCabe of CDM, Jay Mosley of URS, Inc., and Kevin White of E.L. Robinson.

This section provides information on the vegetated biofilters visited and inspected in the field. During information collection, the research team learned some key pieces of information:

- ODOT has projects where vegetated biofilters have been included in the design design of the improvement project. However, many of the projects have not been bid for construction or construction has not yet been initiated.
- ODOT is just beginning to collect and store information on the location of the vegetated biofilters that have been included in project bid sets, in projects under construction, or in projects that have been constructed.

The research team identified two locations to conduct field visits. These sites were selected in part because there was considerable difficulty locating constructed projects that had vegetated biofilters specifically itemized as a post-construction BMP. A third site was inspected to gather addition information on the in-situ quality of the median foreslope and fill section foreslope of a four-lane divided highway. The three locations provide both geographic and functional variety. The main focus of the field inspection was to make visual field observations on conditions, maintenance issues and general comments associated with performance.

State Route 422 – Geauga/ Portage County - General Field Information: The three locations along SR 422 that were inspected, were not specifically itemized as post-construction BMP vegetated biofilters. However, current ODOT design practice for vegetated biofilters does not affect the embankment slope, but rather the ditch bottom width. Therefore, the site was included because of the gereral nature of information to be gathered during the field inspections. A picture of the ditch of the vegetated biofilter is shown in Figure 35.

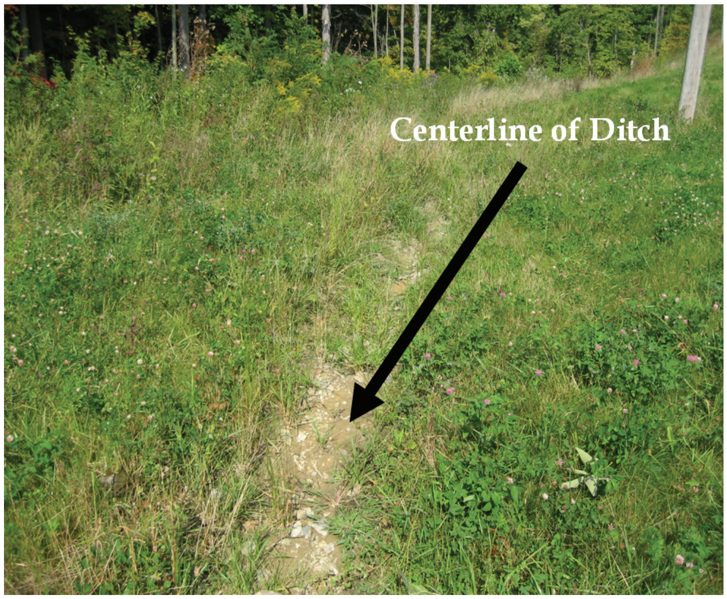


Figure 35. Modified vegetated biofilter- Flow line down cutting at SR 422.

The following represents a summary of field observations for the SR 422 field visit.

- It is unknown if the roadside ditches inspected on State Route 422 meet vegetated biofilter cross section design. The project was designed and sold prior to March 2006 which was the deadline to begin implementing vegetated biofilters and exfiltration trenches into project design drawings. However, as stated previously, the current vegetated biofilter design procedure only affects the ditch bottom width.
- Mowing Maintenance – Mower tracks were observed in the centerline of the swale and there was evidence that the mower had become stuck while mowing that part of the control.
- Placement of rolled erosion control product (RECP) was inconsistent, and the RECP appeared to have been placed incorrectly.
- Maintenance was performed to reestablish the hydraulic grade line and flow, but little or no stabilization was performed after the maintenance.
- Erosion and the beginning of channel down cutting was documented in the centerline of the three swale locations inspected.
- Recommendation for 2 of the 3 swales inspected: It appeared that with minimal regrading and shaping and proper post-grading stabilization that the evidenced down cutting could be eliminated. This would allow for both the foreslope and bottom width of the ditch to provide water quality benefits.
- Several of the swales exhibited uneven settlement creating pools which trapped water that had become stagnant.

Post Road Roadway Improvements, Painesville Township, Lake County – General Field Information – These BMPs are descriped in the Post Road plan set as Bioretention Swales. A picture of one of the swales is in Figure 36.

Figure 36. Post Road Bioretention Swale.

The following represents a summary of field observations for the Post Road field visit.

- These biorentention swales are similar in surficial configuration to ODOTs vegetated biofilters. The two BMPs inspected had bottom widths of 9.5 ft (2.89 m) and 8.5 ft (2.59 m) with longitudinal slopes of 0.74% and 0.76%. Side slopes were 2:1. Both swales had good grass coverage with only moderate amounts of weeds present and generally appeared to be well constructed.
- The bioretention swales include a perforated underdrain pipe surrounded by gravel, sand and filter fabric in the center of the swale. This is not a component of an ODOT vegetated biofilter.
- No evidence of erosion or sediment deposition was observed except for one location where a small amount of road berm gravel had washed into one of the swales.
- The biorentention swales were installed in September of 2009 therefore it was unclear if enough time had passed to warrant the need for any maintenance of the BMPs. Neither swale appeared to require any maintenance.
- The largest biorentention swale had some additional raingarden plantings immediately upstream of the catch basin outlet. This is not a component of an ODOT vegetated biofilter.

US Route 33 – Fairfield County - General Field Information: Various locations along the Lancaster Bypass were inspected. The locations include 6:1 median foreslopes and high fill embankment foreslopes with 2:1 slopes. The locations along US 33 that were inspected were not specifically itemized as being post construction BMP vegetated biofilters. However, current ODOT design practice for vegetated biofilters does not affect the embankment foreslope, but rather the ditch bottom width.

The following represents a summary of field observations from the US 33 field visit.

- Grass coverage along the median was quite poor. There was excessive weed growth. Weed growth was choking out grass growth. Even though the foreslope is a 6:1 slope the lack of grass coverage was resulting in the formation of rills.
- Typically, ODOT uses a crown vetch seed mixture for high embankments. Many of the US 33 fill areas utilize this mix. Experience has shown that the crown vetch mixture is well suited for the steep 2:1 slopes. The dense root structure of the crown vetch is an excellent soil binder. However, overall ground coverage is relatively poor when using crown vetch. This was consistent with the field observations.
- Maintenance of the roadway median is necessary for the foreslope to act as a vegetated biofilter. Weed control and seeding and mulching are necessary to establish a good stand of grass.

5 Method and Equipment Overview

5.1 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 and had grass planted on them. 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 Section 6.2. There were four beds planted, one each for testing with high concentration, medium concentration, and low concentration runoff, and one as a spare. The method for creating the artificial runoff and the setting of pollutant concentrations is described in Section 7.1. The application of artificial runoff using a specially devised apparatus is described in Section 6.3, and the application rate, which involved using a portion of the event that was equivalent to the water quality volume precipitation depthwater quality volume of 0.75 in (19 mm) of polluted runoff at the selected concentration level (high, medium or low) lasting for 15 min for medium flow (9 min for "medium flow" on bed 3) or 6 min for high flow followed by a tailing portion that was a step lower in concentration (medium, low, or tap water) at a lower flow rate for the remaining 45 min (51 min for Bed 3) for medium flow or 24 min for high flow events. The flow levels and details of the simulated storm events are described in detail in Section 7.2. For each bed that was used, the following sequence of experiments was conducted:

- Baseline soil cores, followed by a week of bed recovery
- Hydraulic testing with tap water to insure that the artificial runoff delivery and collection systems were fully operational and to determine the amount of runoff produced.
- Baseline flow data using tap water at medium flow rate at 8:1 slope, with influent, surface, and ground samples collected at 5 minute intervals
- Pollutant removal test at 8:1 slope with medium intensity simulated storm event
- Pollutant removal test at 4:1 slope with medium intensity simulated storm event
- Pollutant removal test at 2:1 slope with medium intensity simulated storm event
- Pollutant removal test at 2:1 slope with high intensity simulated storm event
- Resuspension tests at each slope using tap water
- Bromide tracer tests at each slope and simulated storm intensity
- Final set of soil cores

The procedures used to analyze the collected samples are given in Section 8.7. In brief, the soil cores were collected to determine the presence of metals before applying any runoff (baseline cores) or after all events (final cores). Once the beds had recovered from the initial core collection, hydrological and baseline tests using tap water were conducted, using an application apparatus described in Section 6.3. The pollutant removal tests involved applying artificial runoff using the same apparatus. The artificial runoff was produced as described in Section 7.1, and applied in specified simulated storm events, details of which are provided in Section 7.2. The research aim was to look for pollutant concentrations in the effluent that came off the surface and the effluent that migrated through the soil and was collected from the underdrain (labeled as "ground" to distinguish from "surface"), following the sample collection procedures described in Chapter 8, and compare those 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. The resuspension tests involved tagging soil particles used in the first pollutant removal test with the rare earth metal Lanthanum (La) and then analyzing for the metal in subsequent tests, including specific resuspension tests at the end using tap water, to see how and when the tagged soil particles emerged from the biofilter. The method for the resuspension study is described in 8.6. The bromide tracer tests involved application of sodium bromide as a detectible tracer that could be measured with a probe to determine flow paths in the bed; these tests were conducted during the same period as the resuspension tests. The bromide tracer test method is described in Section 8.4.

High pollutant concentration tests were conducted on Bed 1 in September and October 2008; medium concentration tests were conducted on Bed 2 in May and June 2009; low pollutant concentration tests were conducted on Bed 3 in July and August 2009. The high pollutant concentration tests were conducted in early autumn once the grass reached 80% coverage after initial seeding in June 2008. The remaining tests were conducted following the dormant season during the next spring and summer.

Table 7 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. 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, pollutant removal, and resuspension tests followed at the dates in each row of Table 7. The bromide tracer tests were conducted at slopes of 8:1, 4:1, and 2:1with medium intensity storm events, and at 2:1 slope with high intensity storm events during the same period as the resuspension testing. The last step with each bed was final core removal, which followed shortly after the last resuspension test.

Table 7. Test matrix for the vegetated biofilter experiment, including dates of experiments.

	Slope:	8:1 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

6 Construction of Vegetated Biofilter Prototype

6.1 Bench Scale Laboratory Grass Patch Experiments

To provide guidance for subsequent tests and sampling using the full scale vegetated biofilter prototype, bench tests were conducted in the laboratory. Two rectangular (each 21.75 in (55.2 cm) × 10.25 in (26.04 cm)) samples of sod were obtained from a local vendor and placed in appropriate containers under grow lights in the OU CE Environmental Laboratory. One sample served as the control and was watered with tap water, and the other was watered with a solution of ultrapure water containing 10 mg/L Zn. The ultrapure water was created by placing tap water through a reverse osmosis filter (Millipore Milli-Q Type I) to create reagent grade with a resitivity of 18.2 MΩ/cm. The samples were watered during the period of June 26, 2008, to July 9, 2008. After watering each sample with 1 liter (1.06 qt) of water a total of 6 times, 10 cores of soil, grass, and root samples were extracted for analysis: 5 from the contaminated sample and 5 from the sample that was watered with tap water. The extracted cores were divided into grass, roots and soil, which were oven dried, ground, and passed through a USS #10 sieve before analysis. Then, USEPA Method 3050B [USEPA 1996] was applied and the subsequent samples analyzed by ICP-OES.

Figure 37 summarizes the average data for the contaminated (with Zn) and uncontaminated samples of sod for the grass, roots and soil. As shown in the graph, only the grass had a statistically significant difference in zinc concentration between the contaminated and uncontaminated sample. An estimate of the dry matter in each sample was as follows: 0.085 kg (0.19 lb) of grass, 1.90 kg (4.19 lb) of soil, and 0.084 (0.19 lb) kg of roots for a total of 2.07 kg (4.56 lb) of dry mass. Based on this data, the uncontaminated sample contained 42.17 mg (0.6508 grains) of Zn and the contaminated sample contained 61.87 mg (0.9548 grains) of Zn. Thus the amount of Zn in the contaminated plot increased by 46.72% relative to the control.

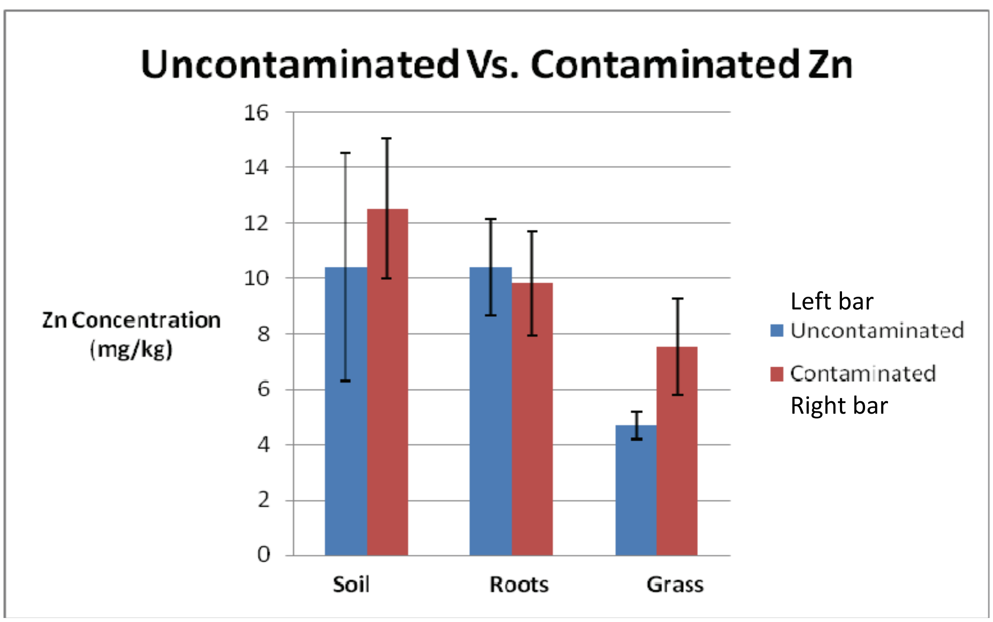


Figure 37. Zinc concentration in sod sample watered 6 times with ultrapure water with 10 mg/L zinc ("contaminated") versus a control sample watered 6 times with tap water ("uncontaminated").

This test provided guidance for the large scale prototype testing by indicating that relatively high concentrations of metals in the influent as well as 5 replicate samples would be needed in order to discern concentrations above background and have reliable results.

6.2 Design and Development of Test Site and Full Scale Prototype Frame and Test Beds

The construction of the steel frame and test beds was completed by a subcontractor, using an ORITE design. They were delivered to the laboratory test site in early June 2008. The delivered test beds included reinforcement in the corners. The vegetated biofilter bed measured 4 ft (1.2 m) wide by 14 ft (4.3 m) long or area 56 ft^2 (5.2 m^2), with an effective size of 3.17 ft (0.97 m) wide by 12.67 ft (3.8 m) long. A chain hoist was used to adjust the frame slope from horizontal to 2:1 (50%).

The test site was configured as shown in Figure 38. The site was established with fencing and a gate. Water and electrical connections were supplied to the site. Overviews of the test site with the frame, mobile platform, and grass growing in test beds, are in Figure 39 and Figure 40. A view of the empty test frame is in Figure 41.

A wooden bottom, which was slightly sloped, and sides were inserted into each test bed, which was then lined with plastic. This was followed by adding retention rods covered with plastic pipes (to prevent steel from the rods contaminating the analysis), and a plastic drainline down the center bottom. A 4 inch (10 cm) layer of gravel and stones was placed above the drainline, followed by one foot (30cm) depth of screened A-6 soil. The soil was screened with 0.5 in (1.27 cm) mesh, and organic material (roots and plants) and soil clods were removed from the screened out gravel and stones. Figure 42 depicts the test beds at various stages in the process of adding the liner, piping, soil retainers, and soil. Figure 43 shows the vegetated biofilter bed in the frame tilted at the three angles used in the experiment.

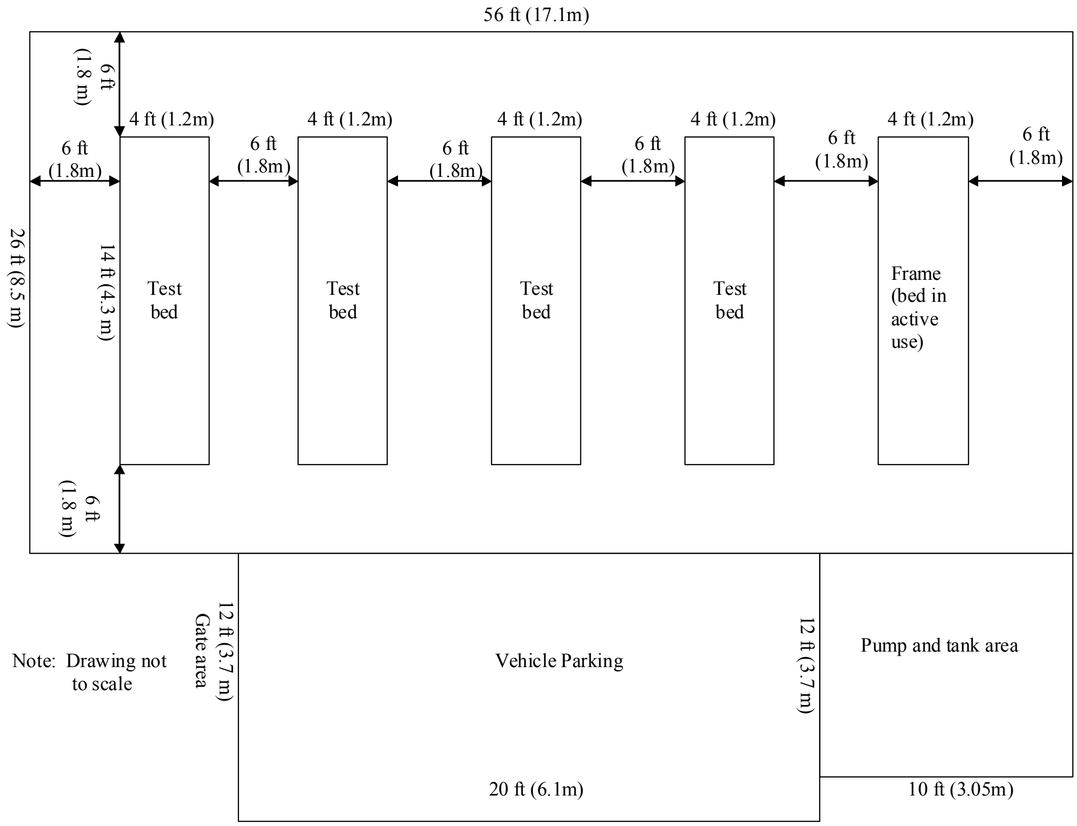


Figure 38. Planned layout of test beds and frame at laboratory study site and space requirements, as detailed in project proposal.

Figure 39. Overview of test site in late July 2008 showing grass growing in test beds, empty test frame, mobile access ladder/platform, and fence surrounding test area.

Figure 40. Second overview of test site in Early August 2008 showing grass growing in test beds, empty test frame, mobile access ladder/platform, and fence surrounding test area.

Figure 41. A view of the empty laboratory test frame at the test site.

Bare test bed. Note slightly sloped bottom.

Test bed with plastic liner, drainpipe, and gravel

Drainline under gravel

Soil retainers (steel rods inside PVC piping)

Test bed with soil

Test bed with soil and seed planted

Figure 42. Pictures of the test bed during stages of liner construction and soil placement.

a) 8:1 slope, 7.12°

b) 4:1 slope, 14.0°

c) 2:1 slope, 26.6°

Figure 43. Three inclined positions of the vegetated biofilter bed in frame as used in pollutant removal experiments: a) 8:1 slope, 7. 12°, b) 4:1 slope, 14.0°, c) 2:1 slope, 26.6°.

6.2.1 Soil Selection, Preparation and Analysis

Samples were obtained from prospective soil sources at three locations from the Nelsonville bypass project in ODOT District 10, one of which had AASHTO type A-6 soil. This A-6 soil was obtained in Hocking County near Twp Rd 336. The classification of the soil was confirmed using tests that included ASTM D 4318 (Liquid Limit, Plastic Limit, and Plasticity Index) and AASHTO T89 and T 90. The soil was delivered to the test site, screened, as discussed above, and placed into the test beds. Prior to placement soil pH of 5.3 was measured, using a Denver instrument, model 225. To improve the soil, lime ($CaCO_3$) was introduced into the soil and mixed to achieve a pH of 6.5, as per ODOT specification 659.02. Four 50 lb (22.7 kg) bags of lime were used in each bed. Samples of soil were also obtained, and metals' concentrations were determined and recorded in Table 8.

Table 8. Concentrations of metals in ppb found in samples of soil used in test beds.

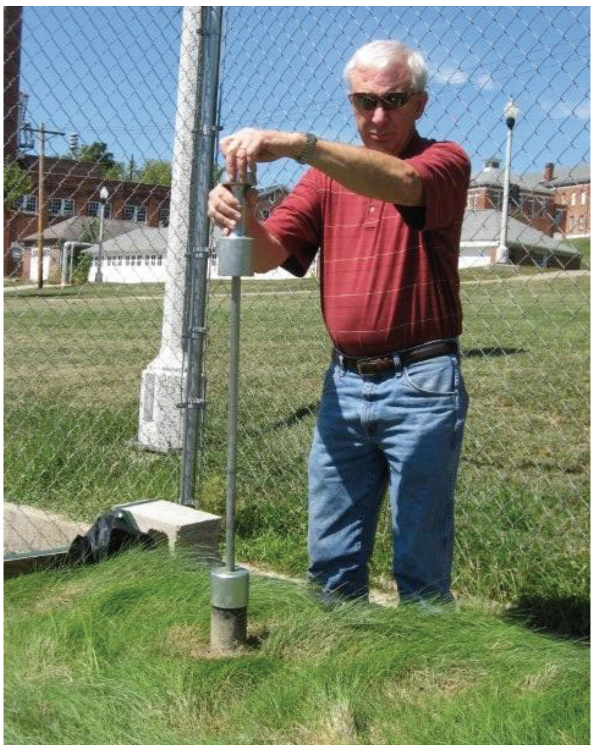
Metal	Soil sample A	Soil sample B	Avg.	Standard deviation	R^2
Mg	132	123	128	6.36	0.052
Mn	37	29	33	5.66	0.165
Al	590	674	632	59.40	0.094
Ca	595	427	511	118.79	0.233
Cd	<0.03	<0.03	<0.03	<0.03	0
Cr	0.556	0.485	0.521	0.05	0.096
Cu	1.12	0.641	0.881	0.34	0.385
Fe	950	935	943	10.61	0.011
Ni	0.972	0.819	0.896	0.11	0.12
Pb	0.582	0.848	0.715	0.19	0.263
V	0.884	1.016	0.950	0.09	0.098
Zn	4.829	5.402	5.116	0.41	0.079

The bed was filled about half full of soil and half of the lime was mixed in using shoves and hoes. A 3 ft by 3 ft (91 cm x 91 cm) board was placed on top of the soil and manual compaction followed; the board was moved to obtain full coverage of the bed. The second half of the soil was placed into the bed on top of the compacted material and mixed with lime. The 3 ft by 3 ft (91 cm x 91 cm) board was placed on top of the bed and manual compaction followed over the entire bed as before. A manually compacted soil depth of one foot (30.5 cm) was achieved at about 100 pcf density. Because ODOT specifications for seeding (Spec. 659.11 and 659.12) require loosening the soil to allow the seed to germinate and the grass to grow, there is not a clear-cut soil density criterion at the time of planting. It should also be noted that as a practical matter, seeding is the last operation performed by the contractor on a project, and the density of soil on the shoulder is never monitored in the field.

In this project, however, the density of the soil was measured, using cores obtained with the device shown in Figure 44. The procedure involved measuring the depth and diameter of the core at the site before inserting the core into a plastic bag. At the laboratory, the vegetation was cut off and the remaining soil weighed. The wet density was this weight divided by the volume of the core. The soil was then dried for 24 hours and then weighed again to measure dry density.

The wet density of the soil in Bed 1 was 99.1±8.7 pcf (1590±140 kg/m^3). In Bed 2 the wet density was 90.8±6.7 pcf (1455±107 kg/m^3), and in Bed 3 it was 78.1±1.7pcf (1251±27 kg/m^3). These are slightly lower than the densities measured at an actual roadside location on State Route 32 in Februrary 2010, which were 117±16 pcf (1876±256 kg/m^3).

In the test beds, the A-6 soil dried and cracked, as it generally does. When saturating the soil (bringing to field capacity) before the test, some cracks did not close completely, which left paths for influent to migrate to the underdrain. Despite the sources of uncertainty mentioned above, the compaction and infiltration should not affect the results, since the constituent removal is based on comparing measurements from the influent at the point of entry to measurements from the surface effluent at the point of exit.



a) Collecting a sample to measure soil density

b) Density core collector in place

Figure 44. Collection of soil samples for density measurements using a coring device: a) collection method for density samples; b) density core collector in place.

6.2.2 Seeding of Test Beds and Measurements of Grass Growth

Standard ODOT grass seed mix (ODOT specification 659.09, Slope Mixture 3B) was added at twice the specified rate to ensure dense growth. A quantity of 119 g (4.2 oz.) of seed mix was used in each bed; the bed area was 4x14=56 ft^2 (1.22 x 4.27 = 5.20 m^2). Grass species and the amounts of seed used of each are given in Table 9. Weed species identified in the ODOT fill by Dr. Glenn Matlack, Professor of Environmental and Plant Science at Ohio University, included pokeweed (Phytolacca Americana), tulip poplar (Liriodendron tulipfera), panic grass (Panicum species), maples (Acer species), and Virginia creeper (Parthenocissus quinquifolia). The percentage of weed growth was about 1% or less.

The seeded soil was lightly tamped down and spread with loose straw mulch. The test beds were seeded between June 20 and July 11, 2008; details of planting and sprouting dates for each test bed are given in Table 10. Until July 22, 2008, plots were watered with tap water every 12 hours except when there was rain. After July 22, watering frequency was every three days, as recommended by Professor Matlack. The final test bed with sprouted grass after 17 days is shown in Figure 45.

Table 9. Types and amounts of grass seeds planted in vegetated biofilter test beds.

Grass type	Species	Amount of seed planted		
		%	(lb/1000 ft^2)	(g/m^2)
Annual Rye Grass	lolium multiflorum	10%	0.46	2.24
Creeping Red Fescue	festuca rubra	34%	1.6	7.82
Hard Fescue	festuca longifolia	56%	2.6	12.7

Table 10. Dates of planting and sprouting of seeds in test beds. All dates are in 2008.

	Event date			
Bed No.	Seed planted	Annual rye grass sprouted	Hard fescue sprouted	Creeping red fescue sprouted
1	June 20	June 30 (10 days)	June 25 (5 days)	June 27 (7 days)
2	June 27	July 5 (8 days)	July 1 (4 days)	July 3 (6 days)
3	July 7	July 16 (9 days)	July 12 (5 days)	July 14 (7 days)
4	July 11	July 19 (8 days)	July 15 (4 days)	July 16 (5 days)

Figure 45. Grass growing in first Bed 17 days after planting.

Development of grass was assessed by measurement of density and coverage. Density of grass growth was measured as follows: each test bed was divided into a grid of approximately 39 1 ft × 1 ft (30.5 cm × 30.5 cm) squares, one of which is shown marked off in Figure 46. Thirteen of the squares were randomly selected for measurement. The grass density was determined by counting the number of individual grass plants (tillers) in the selected area. Although the two fescue species were virtually indistinguishable, the number of rye plants and fescue plants was determined. Density reflects the percentage of seed that sprouted and tends to decrease over time as large plants outcompete other plants. As a result this density assessment was performed only once on each bed. Prior to the first test in Bed 1, the density was estimated at greater than 1500 tillers/ft^2 (16,000 tillers/m^2).

Coverage was also measured by randomly selecting thirteen of the 39 marked squares, but the percentage of area covered with live plant matter is estimated. With training from Professor Matlack, these measurements were accurate and repeatable. This assessment was repeated weekly to assess coverage as a function of time through the point at which the bed was used for a pollutant removal study. Pollutant removal tests began on each bed only when coverage was at least 80%. Figure 47 shows grass coverage in all three beds as a function of time; the rectangular windows indicate times and approximate coverage values when pollutant removal tests were conducted on each bed. The grass coverage for Bed 1, Bed 2, and Bed 3 during the time of the tests was 83%-85%, 76%-97%, and 94%, respectively.

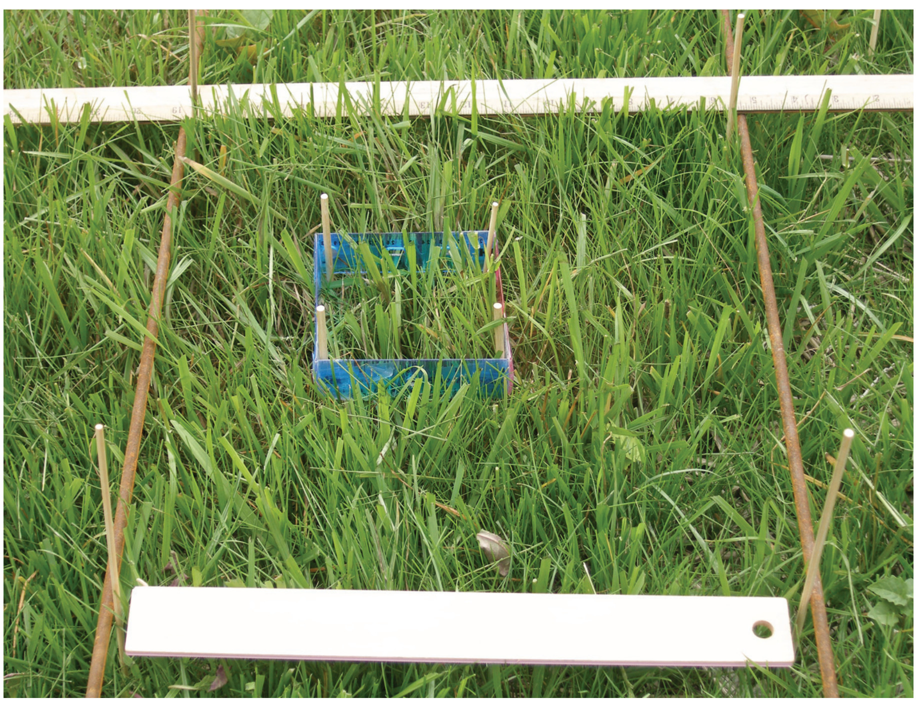


Figure 46. Measurement of grass density in a square marked with wooden slats and rods. The blue square (10cm (3.94 in) on a side) was considred for an experimental measurement method that was ultimately rejected.

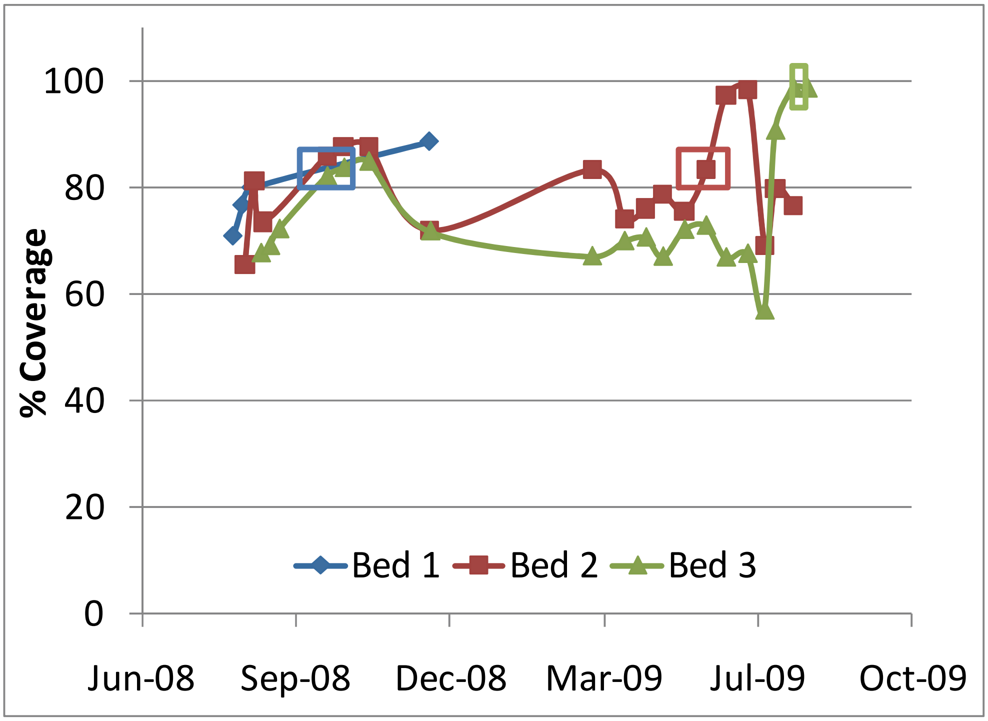


Figure 47. Grass coverage in test beds as function of time. Rectangular areas indicate when pollutant removal tests were conducted on each bed.

6.2.3 Maintenance of Test Beds

Mowing and trimming of the grass was conducted to simulate typical field maintenance of a biofilter slope. ODOT specifies mowing to a minimum height of 6 in (150 mm) [ODOT 2010 specification 659.19]. In order to maintain an approximately uniform height, the grass was trimmed to a height of 4-5 in (10-13 cm), which was a level equal to the top of the test bed.

Before each pollutant removal test, the bed was leveled and tap water was applied using a sprinkler, as shown in Figure 48, until the bed was brought to field capacity, and a steady constant flow could be observed from the ground drainpipe.

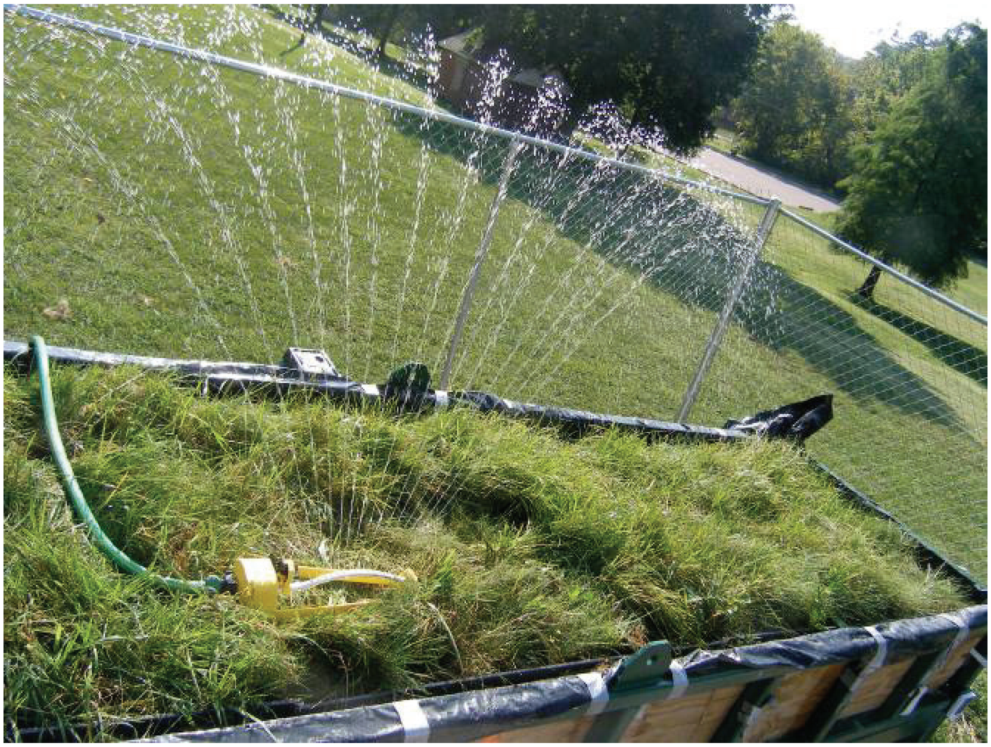
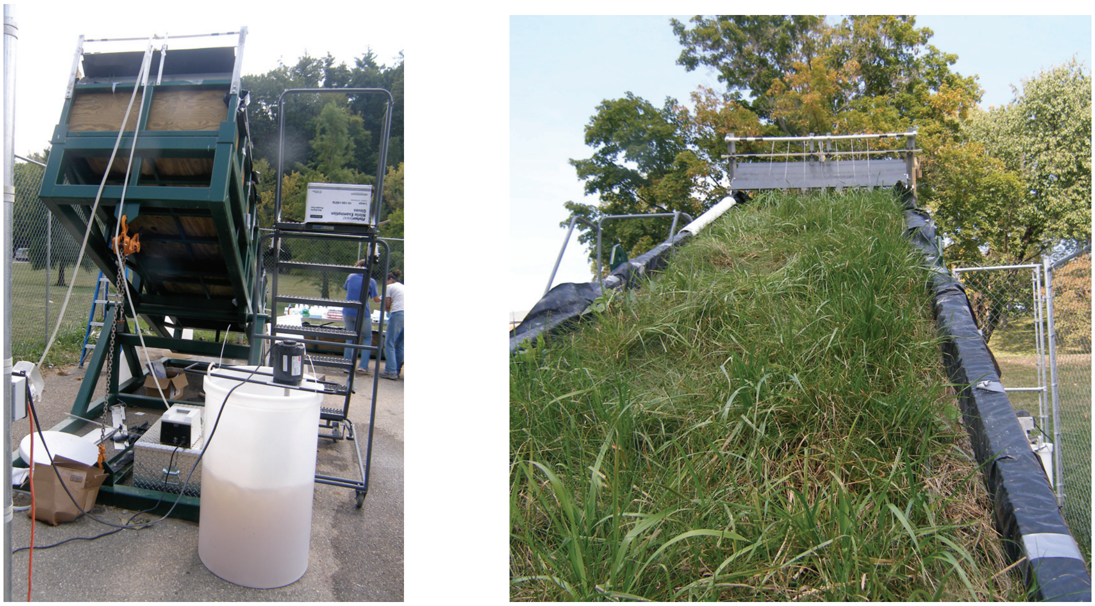


Figure 48. Application of water to bed to bring plot to field capacity prior to pollutant removal test.

6.3 Delivery of artificial runoff to bed

The artificial runoff, consisting of tap water mixed with selected metals, suspended solids, and oil and grease as described in Section 7.1, was applied in simulated storm events as determined in Section 7.2. These simulated storm events were delivered in two stages, a higher intensity period lasting for the first 15-25% of the storm time followed by a lower intensity period. The runoff was applied to the bed during the simulated storm using a system of drums and pumps delivering to spray bars mounted at the top of the bed. This system as originally configured is shown in Figure 49. There were two drums of artificial runoff, formulated for use in the first and second part of the storm event, each with an electronic stirrer to maintain uniformity of the artificial runoff. Each drum had a line leading to a drip bar at the head of the bed. The drip bars can be seen in both parts of Figure 49: from the rear in part a, and from the front, with runoff coming from the top bar, in part b. The artificial runoff coming out of the drip bar would hit a plastic barrier that would mimic the effect of the road pavement surface in converting the drip flow of liquid to a sheet flow.

Plastic "railings" (0.25 in (6.4 mm) wide by 5 in (12.7 cm) deep) were placed along the longitudinal edges of the bed to prevent water flowing preferentially along the sides of the bed.



a) b)

Figure 49. Delivery mechanism of artificial stormwater to grass bed. In a) the artificial stormwater is pumped from the continuously stirred drum through one of the white tubes to the selected drip bar at the top of the plot, also shown in b). The artificial stormwater hits the plastic plate before running off into the grass. Note that the high and medium concentration artificial stormwater used in the first and second parts of the simulated storm event are delivered from separate drums through separate tubing into separate drip bars; one of the drums is not shown in a).

After the first set of experiments with high concentration runoff on Bed 1, it became apparent that the oil and grease components were not staying completely mixed with the artificial runoff, so a parallel delivery system for oil was devised and added to the drip bar arrangement for the Bed 2 (medium concentration) and Bed 3 (low concentration) experiments. The oil mixture consisted of new motor oil (Mobil Clean 5000 10W-30) mixed with the deuterated alkanes. The oil delivery system is shown in Figure 50.

a) b)

Figure 50. Views of oil distribution system added for experiments on Bed 2 and Bed 3: a) pump and reservoir, b) yellow oil drip tubes in front of drip bars over splash plate.

Other improvements made between the high and medium concentration experiments (Bed 1 and Bed 2) included the introduction of a flow meter in a reworked pump system, shown in Figure 51 and a wider surface runoff collection pipe, shown in Figure 52.

a) Reading flow meter in new pump system b) Close-up of flow meter

Figure 51. Flow meter and redesigned stormwater pump system: a) reading flow meter as mounted in flow line, b) close-up of meter.

a) Collecting surface runoff b) Mouth view of wider pipe

Figure 52. Views of new wider surface runoff pipe in use: a) collecting runoff, b) mouth view.

7 Artificial Runoff Formulation and Simulated Storm Events

7.1 Formulation of artificial stormwater runoff for this project

A formulation for artificial runoff was proposed at low, medium, and high concentrations. 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, et al., 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, have 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 11, including metals, total suspended solids (TSS), chemical oxygen demand (COD), and oil and grease (O&G).

Table 11. 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
	O&G	(mg/L)	0.4	5	17	-	0.4*	5*	20
Deuterated alkanes	$C_{20}D_{42}$	(mg/L)	-	-	-	-	0.01*	0.05*	0.1
	$C_{24}D_{50}$	(mg/L)	-	-	-	-	0.01*	0.05*	0.1
	$C_{30}D_{62}$	(mg/L)	-	-	-	-	0.01*	0.05*	0.1
	total	(mg/L)	-	-	-	-	0.03*	0.15*	0.3
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

*O&G and Deuterated alkane values applied to Bed 2 and Bed 3 differ from these original target values. See Section 7.1.5 for details.

Because the minimum concentrations in Table 11 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 11, such as pH and alkalinity, were controlled to achieve an appropriately buffered solution. The constituents $C_{20}D_{42}$, $C_{24}D_{50}$, and $C_{30}D_{62}$ are deuterated alkanes – hydrocarbon chains where the hydrogen atoms are replaced with atoms of the isotope deuterium. The deuterated alkanes were intended to provide a more accurate means to track the movement of the oil and grease, which were less susceptible to interference from organic material from the bed itself. They were added at concentrations of at most a few percent of the total oil and grease content. The deuterated alkanes and some of the other constituents are discussed in more detail below. It should also be noted that because of difficulties with consistently adding oil and grease to the influent, the actual concentrations applied varied from the values listed in Table 11 for Bed 2 and Bed 3. Actual oil and grease concentrations are given in Table 14 in Section 7.1.5.

7.1.1 Tap Water Solvent

Since a large volume of water was needed to conduct this study, it was impractical to use ultrapure water. Hence, the biofilter test beds were watered with tap water, and tap water was also used as the solvent to prepare the artificial runoff.

Table 12 and Table 13 show concentrations of selected metals in tap water taken from the test site at the Ridges and from a sink in the chemistry laboratory. Concentrations of magnesium and calcium, the hardness metals, are typical, and there are detectable levels of iron in the Ridges water, and small amounts of zinc in both. Otherwise all the constituent and other metals listed are below detection limits. The *2009 City of Athens Annual Drinking Water Consumer Confidence Report* [Athens Water Treatment Plant, 2009] gives the average hardness of the city tap water as 144 ppm.

Table 12. Metals concentrations observed in tap water taken from Ridges tap at laboratory study site. Concentrations preceded by < are values below detection limits.

Metal	Ridges Tap 1 (ppb)	Ridges Tap 2 (ppb)	Ridges Tap 3 (ppb)	**Ridges Tap Average (ppb)**	**Ridges Tap Std Dev (n=3) (ppb)**	**Athens Water Treatment Plant [2009] (ppb)**
Mg	15155.3	7497	7495	**10049**	**4422**	**-**
Mn	< 1	< 1	< 1	< 1		10
Al	<39	<39	<39	<39		-
Ca	50324.3	26278	26550	**34384**	**13805**	**-**
Cd	<5	<5	<5	<5		<1.0
Cr	<5	<5	<5	<5		<2.0
Cu	<9	<9	<9	<9		210
Fe	91	82	80	**84**	**6**	**40**
Ni	<18	<18	<18	<18		<10.0
Pb	<43	<43	<43	<43		4.7
V	<1	<1	<1	<1		-
Zn	15	18	13	**16**	**3**	**-**

Table 13. Metals concentrations observed in tap water taken from taps in chemistry laboratory, Clippinger room 194. Concentrations preceded by < are values below detection limits.

Metal	Lab Tap 1 (ppb)	Lab Tap 2 (ppb)	Lab Tap 3 (ppb)	Lab Tap Average (ppb)	Lab Tap Std Dev (n=3) (ppb)	Athens Water Treatment Plant [2009] (ppb)
Mg	8092	7794	7957	**7948**	**149**	**-**
Mn	< 1	< 1	< 1	< 1		10
Al	<39	<39	<39	<39		-
Ca	27553	26645	27552	**27250**	**524**	**-**
Cd	<5	<5	<5	<5		<1.0
Cr	<5	<5	<5	<5		<2.0
Cu	<9	<9	<9	<9		210
Fe	<3	<3	<3	<3		**40**
Ni	<18	<18	<18	<18		<10.0
Pb	<43	<43	<43	<43		4.7
V	<1	<1	<1	<1		-
Zn	22	27	22	**24**	**3**	**-**

7.1.2 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 170.3 L (45.0 gal) prior to use and mixed for three hours before beginning the experiment. Details on the preparation of the stock solutions are given in Appendix E.

7.1.3 pH

Partitioning and other attributes of metals are strongly affected by pH. Rainwater in Ohio has an average pH of 4.5 with alkalinities typically below 10 mg $CaCO_3$/L [NADP, 2008]. However, samples of storm water runoff measured in the Columbus area in 2007 had an average pH of 7.0 and an average alkalinity of 109 mg $CaCO_3$/L [Cox, 2007]. It is likely that the low pH rainwater that is poorly buffered is rapidly neutralized while being conveyed to stormwater outfalls. Concrete highways, concrete pipes, and limestone aggregate in pavement and shoulder lanes likely all contribute to neutralizing the acidic rainfall. The background alkalinity of the tap water of about 170 mg $CaCO_3$/L was used for the simulated/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.

7.1.4 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 11, 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 Section 6.2.1.

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 particle distribution is shown in Figure 53, along with those reported in the literature by Hook [2003] (average particle diameter = 48.7 µm, for artificial runoff) and by Sansalone and Buchberger [1997] (average particle diameter = 592 µm, natural pavement runoff near Cincinnati, Ohio).

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].

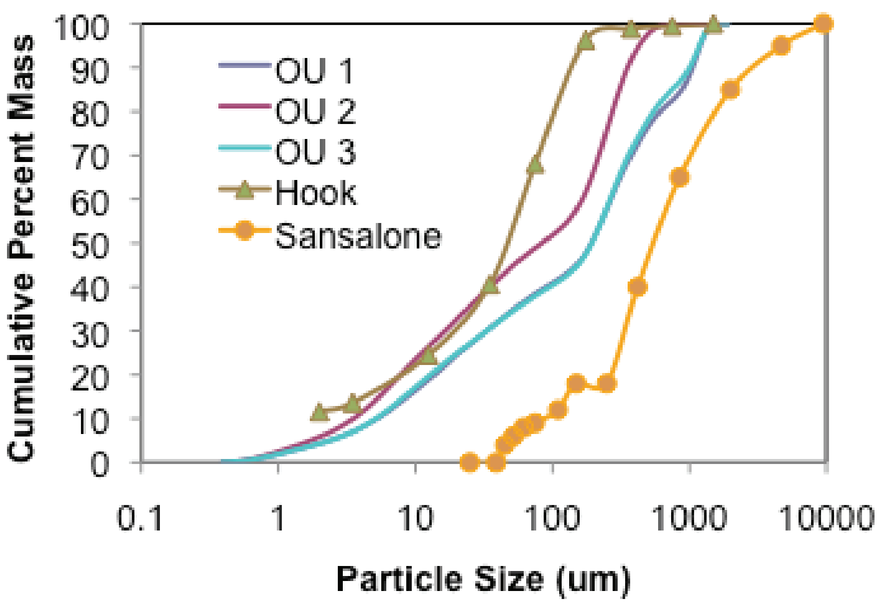


Figure 53. Particle size distribution of suspended solids added to artificial runoff, compared to those of two studies in the literature [Hook, 2003, and Sanasalone and Buchberger, 1997].

7.1.5 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]. From the literature oil and grease concentrations average 5 mg/L with 95% confidence intervals of 0.4 and 17 mg/L. To determine the appropriate addition of oil and grease components to simulate these constituents, actual samples of runoff and diluted motor oil were analyzed with solid-phase microextraction gas chromatography-mass spectrometry (SPME-GC-MS). These results indicated the presence of petroleum hydrocarbons in the runoff typical of motor oil with very little diesel fuel or gasoline present. Initially, it was expected that several n-alkanes would predominate and that the formulation would be based on the prevalence of these. Observed results from samples analyzed could be due to evaporation and other weathering effects on the petroleum residues. The analytical procedure does not detect alkane chains longer than about n=35; lighter chains (n=13 or less) that might be associated with gasoline (n=8) are highly volatile and would have evaporated from samples.

New motor oil (Mobil Clean 5000 10W-30) was added to the artificial runoff at the concentrations listed in Table 11 for high concentration experiments on Bed 1, and was tracked using the oil and grease standard analysis method. Based on additional laboratory tests conducted, the oil and grease application method was modified and concentrations increased on Bed 2 and Bed 3 to better discern removal rates.

In addition, in order to better track the fate of hydrocarbons in the biofilter, a mixture of three fully deuterated n-alkanes was prepared and added to the runoff solution. This combination of hydrocarbons with chain lengths of 20, 24, and 30 carbon atoms constitutes some molecules found in high concentrations in analyzed local storm water and is typical of motor oil. These deuterated n-alkane standards were initially to be added at low, medium and high concentrations of 0.1, 1, and 2 ppb; however, after difficulty with differentiating removals in preliminary tests at these low concentrations, the higher concentrations shown in Table 11 were added for Bed 1; these in turn were further modified for Bed 2 and Bed 3, as discussed below. These molecules were individually identified using SPME-GC-MS so that selective removal of different size molecules could be determined.

In the experiments with high concentration runoff on Bed 1, the oil and grease components were mixed with the other artificial runoff components. During runs, the oil and grease tended to separate and rise to the surface of the fluid in the drum, despite the vigorous constant mechanical mixing. For Bed 2 and Bed 3 a separate parallel oil and grease application system was constructed, as described in Section 6.3. The amount of oil and deuterated alkanes that would have been added to the artificial runoff was then applied through the parallel delivery system. The influent flow rates for the storms were also adjusted for Bed 2 and Bed 3, as discussed in Section 7.2.2, so the concentrations of motor oil and deuterated alkanes were different on each bed. The actual concentration of oil and grease (Mobil Clean 5000 10W-30 motor oil) added to each bed is given in Table 14, along with the flow rates used in the parallel oil application system discussed in Section 6.3 and shown in Figure 50. The "first portion" and "second portion" refers to the two parts of the simulated storm events discussed in Section 7.2.2.

Table 14. Effective concentration of oil and grease applied to each bed, along with flow rates for Bed 2 and Bed 3.

		Oil and grease concentration in influent (mg/L)		Flow rate (including deuterated alkanes) (ml/min)	
Bed	Flow rate	First Portion	Second portion	First Portion	Second portion
1	Medium	20	5	In influent	In influent
1	High	20	5	In influent	In influent
2	Medium	100	20	0.919	0.0368
2	High	100	20	2.3	0.1
3	Medium	100	20	1.66	0.0925
3	High	100	20	2.3	0.1

7.1.6 Chemical Oxygen Demand

Chemical oxygen demand (COD) in stormwater was estimated to average 111 mg/L with a standard deviation of 81 mg/L. Since the standard deviation is quite large, additional organic compounds beyond the amount added for oil and grease were not added. COD was monitored in the first experiment using the "high" concentration runoff, but was not monitored in the medium and low concentration experiments, since the high concentration data were inconsistent, primarily due to the presence of the organic material in the vegetation itself. Hence, COD data results are not reported.

7.2 Determination of flow rates during simulated storm events

High, medium, and low runoff flow rates were originally considered for the test matrix. After discussion with the ODOT technical liaisons, the matrix was revised to include only medium flow rate events, along with a high flow rate event at the steepest (2:1) slope. The definition of what constitutes a medium or high flow rate was then 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 was the water quality depth. The following presents a discussion of the rationale for the determination of the medium and high flow rates.

7.2.1 Regional Storm Events

Rainfall events are highly variable with durations from several minutes to several days and total precipitation from tenths of an inch (a few mm) to multiple inches (as much as 9.27 in (235 mm) for the 100-yr 10-day storm in central Ohio) [Huff and Angel, 1992]. For the study of road runoff, contaminants accumulated on the road are transported normally within the first portion of the storm. Consistent with ODOT specifications for Water Quality Volume, the first 0.75 in (19 mm) of rain was used to depict the contaminated portion of the runoff event [ODOT 2009, Section 1115.3]. Storms of rainfall depths smaller than 0.75 in (19 mm) were not considered. In addition, because rainfall beyond 0.75 in (19 mm) are thought to transport comparatively little additional contamination, large storms with durations greater than 3 hr or total precipitation greater than 2.00 in (51 mm) were not considered. Data for storms in central Ohio are shown in Table 15, with the storms considered applicable to this study highlighted.

Table 15. Rainfall in inches for storms in central Ohio [Huff and Angel, 1992]. (1 in =25.4 mm)

Duration	Recurrence time (yr)											
(min)	0.17	0.25	0.33	0.5	0.75	1	2	5	10	25	50	100
360	0.90	1.04	1.14	1.32	1.50	1.63	2.03	2.51	2.89	3.48	4.00	4.55
180	**0.76**	**0.89**	**0.97**	**1.13**	**1.28**	**1.39**	**1.73**	2.14	2.47	2.97	3.41	3.88
120	0.69	**0.81**	**0.88**	**1.02**	**1.16**	**1.26**	**1.57**	**1.94**	2.24	2.69	3.09	3.51
60	0.56	0.65	0.71	**0.83**	**0.94**	**1.02**	**1.27**	**1.57**	**1.81**	2.18	2.51	2.85
30	0.44	0.51	0.56	0.65	**0.74**	**0.80**	**1.00**	**1.24**	**1.43**	**1.72**	**1.97**	2.24
15	0.32	0.38	0.41	0.48	0.54	0.59	**0.73**	**0.90**	**1.04**	**1.25**	**1.44**	**1.64**
10	0.25	0.29	0.32	0.37	0.42	0.46	0.57	0.70	**0.81**	**0.97**	**1.12**	**1.27**
5	0.14	0.17	0.18	0.21	0.24	0.26	0.32	0.40	0.46	0.56	0.64	**0.73**

In the Midwest region heavy storms typically develop with high intensity rainfall initially, gradually tailing off over time (see Figure 54). Additionally, the intensity of rainfall during the initial portion of the storm is normally much higher than might be expected when simply considering total rainfall and duration for the event.

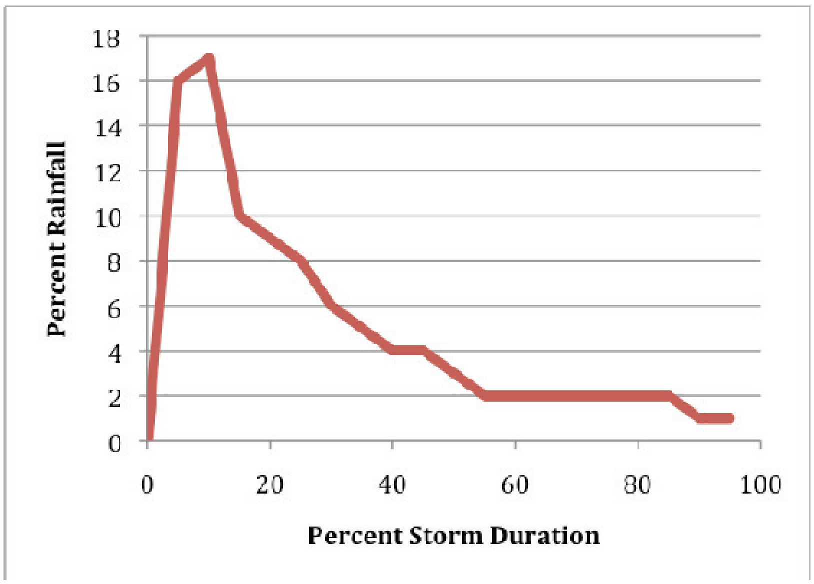
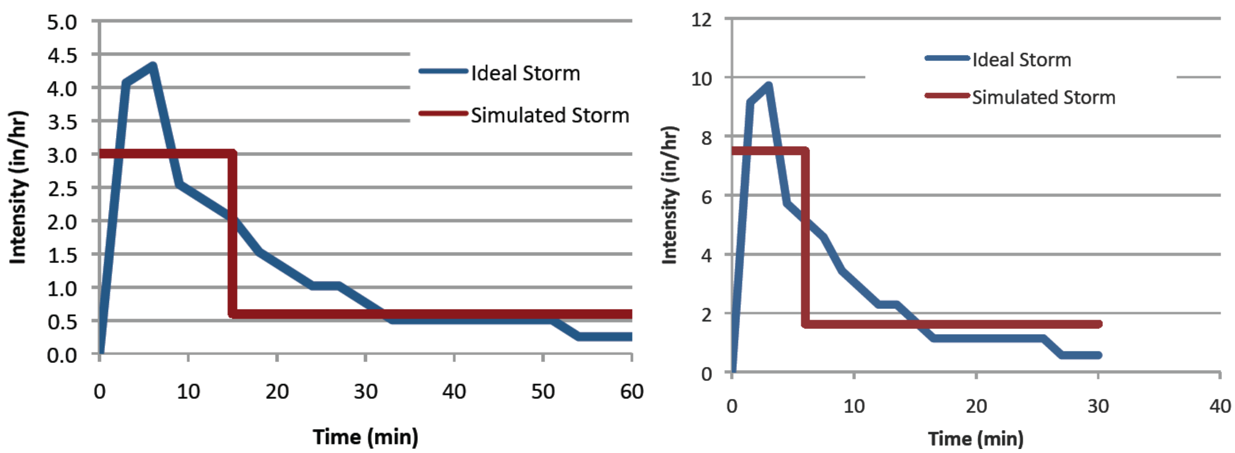


Figure 54. Median time distribution of heavy storm rainfall at a point, 1st quartile [Huff and Angel, 1992].

7.2.2 Model Storm Events

A rural, high speed, high-volume roadway was considered to determine the volume of runoff tributary to the vegetated biofilter prototype for the simulated event. This type of roadway typically includes up to two 12 ft (3.6 m) wide lanes plus two 10 ft (3.0 m) wide shoulders. Since the road is crowned along the middle, only one lane and one shoulder drain to a single biofilter. OEPA’s definition of water quality volume and the associated water quality volume precipitation depth of 0.75 inches (19 mm) was then used to establish a volume of water to be applied to the biofilter prototype.[ODOT 2009, Section 1115.4]. With the assumptions that all the water would run off the assumed roadway surface and flow into the effective width of the biofilter prototype (38 in (96.5 cm) for the prototype), this corresponds to 33 gal (125 l) of runoff.

Two types of storm conditions were simulated, described as "medium" and "high" intensity or flow. Historical data for Ohio [Huff and Angel, 1992] indicate that 0.75 in (19 mm) of rainfall is rarely produced in time intervals less than 30 min, but does occur occasionally. For the medium intensity storm a recurrence interval of approximately 2 years was selected, which would deliver 0.75 in (19 mm) of runoff to the vegetated biofilter in the first 15 min of a 60 min storm. Using the median time distribution, this storm would produce a maximum intensity of 4.3 in/hr (109 mm/hr) and an average intensity of 1.3 in/hr (33 mm/hr) (see Figure 55a). For a high concentration medium intensity event, this storm was simulated by 15 minutes of high intensity runoff at 3.0 in/hr (76 mm/hr) at high concentration ("High" artificial runoff values from Table 11) followed by 45 minutes at 0.6 in/hr (15 mm/hr) at medium concentration ("Med" artificial runoff values from Table 11), delivering 0.75 in (19 mm) or 33 gal (125 l) of high concentration runoff in the first 15 min and 0.45 in (11 mm) or 20 gal of medium concentration runoff in the remaining 45 min. The flow rate was 2.2 gpm (8.3 L/min) for 15 min followed by 0.44 gpm (1.67 l/min) for 45 min.



a) medium intensity storm event b) high intensity storm event

Figure 55. Simulated storm events for vegetated biofilter testing: a) medium flow, b) high flow.

For the high flow simulation a 30-min, 10-yr storm that generates 1.4 in (35.6 mm) of rainfall was used, which has a maximum intensity of 9.72 in/hr (247 mm/hr) and an average intensity of 2.94 in/hr (74.7 mm/hr). The 0.75 in (19 mm) WQv of high concentration runoff is delivered in the first 6 min of rainfall (see Figure 55b). This high concentration high intensity event was modeled with 6 min of 7.50 in/hr (190 mm/hr) rainfall generating high concentration runoff, followed by 1.63 in/hr (41.4 mm/hr) rainfall generating medium concentration runoff. This corresponded to 33 gal (125 l) delivered to the biofilter test section in 6 min at a flow rate of 5.4 gpm (20.44 l/min), followed by 28 gal (106 l) delivered in 24 min at a flow rate of 1.2 gpm (4.54 l/min). The flow parameters for the medium and high flow storm events at high concentration applied to Bed 1 are given in Table 16, along with the corresponding parameters from the literature at the bottom. The bed parameters are tweaked slightly between the high and medium concentration experiments. The flow parameters for the medium concentration experiments on Bed 2 are given in Table 17; those for the low concentration experiments on Bed 3 are given in Table 18. For Bed 3, the medium flow event was modified to an alternate 10 year storm with a portion of the event that was equivalent to the water quality volume precipitation depth of 0.75 in (19 mm) of polluted runoff delivered in 9 minutes followed by 51 minutes of tailing flow of tap water. The literature values in all three tables are based primarily on Huff and Angel [1992]. The first portion of the event is sometimes referred to as the "initial" flow or portion, and the second portion as the "tailing" flow. The first or initial portion also represents the water quality volume specified previously.

Table 16. Parameters for simulated storm events at high concentration on Bed 1.

		English units			Metric units		
	Intensity or flow rate		Medium	High		Medium	High
	Recurrence rate	(yr)	2	10	(yr)	2	10
First Portion	Contaminant concentration level		High	High		High	High
	Rainfall rate	(in/hr)	3.00	7.50	(mm/hr)	76.2	190.5
	Flow rate	(gal/min)	2.17	5.43	(l/min)	8.22	20.55
	Duration	(min)	15	6	(min)	15	6
	Rainfall	(in)	0.75	0.75	(mm)	19.1	19.1
	Volume	(gal)	32.6	32.6	(l)	123.3	123.3
Second Portion	Contaminant concentration level		Medium	Medium		Medium	Medium
	Rainfall rate	(in/hr)	0.60	1.63	(mm/hr)	15.2	41.4
	Flow rate	(gal/min)	0.43	1.18	(l/min)	1.64	4.47
	Duration	(min)	45	24	(min)	45	24
	Rainfall	(in)	0.45	0.65	(mm)	11.4	16.6
	Volume	(gal)	19.5	28.3	(l)	74.0	107.2
Overall	Average rainfall rate	(in/hr)	1.20	2.80	(mm/hr)	30.5	71.2
	Average flow rate	(gal/min)	0.87	2.03	(l/min)	3.29	7.68
	Total duration	(min)	60	30	(min)	60	30
	Total rainfall	(in)	1.20	1.40	(mm)	30.5	35.6
	Total volume	(gal)	52.1	60.9	(l)	197.3	230.5
Literature	Maximum rainfall rate	(in/hr)	4.32	9.72	(mm/hr)	109.7	246.9
	Average rainfall rate	(in/hr)	1.26	2.94	(mm/hr)	32.0	74.7
	Water quality volume precipitation depth	(in)	0.75	0.75	(mm)	19.1	19.1
	Water quality volume	(gal)	32.57	32.57	(l)	123.3	123.3

Table 17. Parameters for simulated storm events at medium concentration on Bed 2.

		English units			Metric units		
	Intensity or flow rate		Medium	High		Medium	High
	Recurrence rate	(yr)	2	10	(yr)	2	10
First Portion	Contaminant concentration level		Medium	Medium		Medium	Medium
	Rainfall rate	(in/hr)	3.00	7.50	(mm/hr)	76.2	190.5
	Flow rate	(gal/min)	2.21	5.54	(l/min)	8.38	20.95
	Duration	(min)	15	6	(min)	15	6
	Rainfall	(in)	0.75	0.75	(mm)	19.1	19.1
	Volume	(gal)	33.2	33.2	(l)	125.7	125.7
Second Portion	Contaminant concentration level		Low	Low		Low	Low
	Rainfall rate	(in/hr)	0.60	1.63	(mm/hr)	15.2	41.4
	Flow rate	(gal/min)	0.44	1.20	(l/min)	1.68	4.55
	Duration	(min)	45	24	(min)	45	24
	Rainfall	(in)	0.45	0.65	(mm)	11.4	16.6
	Volume	(gal)	19.9	28.9	(l)	75.4	109.3
Overall	Average rainfall rate	(in/hr)	1.20	2.80	(mm/hr)	30.5	71.2
	Average flow rate	(gal/min)	0.89	2.07	(l/min)	3.35	7.83
	Total duration	(min)	60	30	(min)	60	30
	Total rainfall	(in)	1.20	1.40	(mm)	30.5	35.6
	Total volume	(gal)	53.1	62.1	(l)	201.2	235.0
Literature	Maximum rainfall rate	(in/hr)	4.32	9.72	(mm/hr)	109.7	246.9
	Average rainfall rate	(in/hr)	1.26	2.94	(mm/hr)	32.0	74.7
	Water quality volume precipitation depth	(in)	0.75	0.75	(mm)	19.1	19.1
	Water quality volume	(gal)	33.2	33.2	(l)	125.7	125.7

Table 18. Parameters for simulated storm events at low concentration on Bed 3.

		English units			Metric units		
	Intensity or flow rate		Medium	High		Medium	High
	Recurrence rate	(yr)	10	10	(yr)	10	10
First Portion	Contaminant concentration level		Low	Low		Low	Low
	Rainfall rate	(in/hr)	5.40	7.50	(mm/hr)	137.2	190.5
	Flow rate	(gal/min)	3.99	5.54	(l/min)	15.09	20.95
	Duration	(min)	9	6	(min)	9	6
	Rainfall	(in)	0.81	0.75	(mm)	20.6	19.1
	Volume	(gal)	35.9	33.2	(l)	135.8	125.7
Second Portion	Contaminant concentration level		Tap water	Tap water		Tap water	Tap water
	Rainfall rate	(in/hr)	1.50	1.63	(mm/hr)	38.1	41.4
	Flow rate	(gal/min)	1.11	1.20	(l/min)	4.19	4.55
	Duration	(min)	51	24	(min)	51	24
	Rainfall	(in)	1.28	0.65	(mm)	32.4	16.6
	Volume	(gal)	56.5	28.9	(l)	213.7	109.3
Overall	Average rainfall rate	(in/hr)	2.09	2.80	(mm/hr)	53.0	71.2
	Average flow rate	(gal/min)	1.54	2.07	(l/min)	5.83	7.83
	Total duration	(min)	60	30	(min)	60	30
	Total rainfall	(in)	2.09	1.40	(mm)	53.0	35.6
	Total volume	(gal)	92.3	62.1	(l)	349.5	235.0
Literature	Maximum rainfall rate	(in/hr)	6.15	9.72	(mm/hr)	156.2	246.9
	Average rainfall rate	(in/hr)	1.79	2.94	(mm/hr)	45.5	74.7
	Water quality volume precipitation depth	(in)	0.75	0.75	(mm)	19.1	19.1
	Water quality volume	(gal)	33.2	33.2	(l)	125.7	125.7

8 Experimental Method

With the test equipment described along with the formulation of the artificial runoff and the simulated storm events, the sequence of tests performed using each bed and the methods for each can be presented. Reviewing the test matrix in Table 7, the sequence of tests for each bed is the same:

- Initial or baseline cores were taken to determine metals embedded in the soil, foliage, and roots before application of any contaminated artificial runoff
- Hydraulic testing was conducted to ensure the artificial runoff pumping and drainage systems were operational. Some trial and error adjustment of the equipment was conducted, so the amount of hydraulic testing varied from bed to bed.
- Baseline flow tests were conducted using tap water to determine what contaminants, if any, would emanate from the bed. A water quality volume (0.75 in or 19 mm) of tap water was administered as per the first part (first 15 minutes (9 minutes for Bed 3)) of a medium flow event, with samples collected every five minutes from influent, surface, and ground.
- Pollutant removal tests followed with the artificial runoff concentration assigned to that bed (Bed 1 = high, Bed 2 = medium, Bed 3 = low), beginning one to three weeks after cores were collected, depending on the amount of adjustments during the hydraulic tests and the weather conditions. Pollutant removal tests occurred at the following flow rates and simulated storm event intensities:
    - 8:1 slope, medium flow
    - 4:1 slope, medium flow
    - 2:1 slope, medium flow
    - 2:1 slope, high flow
- Resuspension tests involved tilting the bed to the same angles (8:1, 4:1, and 2:1) with the same flow rates applied with tap water to see if any of the lanthanum-tagged sediment added in the first pollutant removal test would become dislodged and reappear in the effluent. These were conducted within a week after the final pollutant removal test.
- Flow paths were mapped using sodium bromide tracer at all three slopes with medium flow and at 2:1 slope with high flow.
- Collection of a final set of cores to determine metals embedded in the soil, foliage, and roots after the application of the contaminated artificial runoff. From Bed 1, 20 cores were collected; from Bed 2 and Bed 3, 25 cores were collected. Cores were taken within a week after the final resuspension test and the bed was repaired.

The general method for all these experiments, excepting the core collection and tracer tests is similar. An influent is applied via the drip bar at a flow rate and concentration indicated in the test matrix, and two types of effluent are collected at the base of the bed: surface flow was collected across the width of the bed and 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, 20 ml for SPME analysis (deuterated alkanes), 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 Mulri-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 for medium intensity simulated storm events. For high intensity events the times were 0 min, 5 min, 10 min, 15 min, and 25 min. For surface and ground data, for high concentration events, samples were first collected at 5 minutes and then every 5 minutes thereafter, though for shallower slopes, surface flow typically stopped after the first part of the simulated storm. For Bed 2 (medium concentration) and Bed 3 (low concentration), collection of surface samples started when flow started and was collected at approximately 5 minute intervals afterwards, with the exact times recorded.

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, SPME, TSS, O&G). Samples were collected and immediately preserved in coolers for subsequent chemical analysis.

Influent samples were collected with the aid of a collection pipe held under the drip bar, as shown in Figure 56. The collection of effluent samples at the base of the bed is shown in Figure 57. Figure 58 shows the organization and handling of bottles before and after actual sample collection. Figure 59 shows the probe data collection.

a)

b)

c)

Figure 56. Collection of influent samples: a) and b) collection of samples was facilitated using a hand-held open collection pipe; c) experimenter collecting samples in bottles stored temporarily on blue stryofoam carrying rack.

Figure 57. Collection of effluent samples at the base of the bed. On the right a groundwater oil and grease specimen is being collected from the central drainage pipe. The white pipe pointing out of the page is for collection of surface effluent. Underneath that pipe is a digital clock used to track times when effluent was collected and to measure flow rates. The large white drums held excess effluent not collected for the contaminant analysis.

a)

b)

Figure 58. a) labelled bottles were placed in holders by type. Experimenters collected a set of bottles and placed them in a styrofoam holder for transport to the bed for collection; b) an experimenter crimping a cap on a SPME vial. Once metal and deuterated alkane samples were collected, preserved with nitric acid, and sealed, they were stored in coolers such as those in the foreground.

Figure 59. An experimenter, holding a beaker, about to measure probe data using the instrument on the table. On the right are labelled empty bottles ready for influent sample collection.

8.1 Hydraulic and Slope Mechanism Tests

In order to ensure that the slope mechanism adjustment operated as designed and to test all of the hydraulics of the system, an initial test run was conducted prior to testing with the contaminated/artificial water. Test Bed 1 was placed on the frame and adjusted to the 8:1 slope. Clean tap water was applied to the bed at the different flow rates listed above for medium and high flow storms to test the hydraulic delivery and collection systems. Visual inspections were used to examine vertical flow pathways along the walls of the bed. Repairs were made to the bed using expanding clays along the bed perimeter. These tests also served as trial runs for the methods the research team used for gathering samples during tests and preparing them for chemical analysis.

8.2 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 admitting 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 with this equipment, the test bed on the frame was leveled horizontally. Clay material 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 sprinkler, as in Figure 48, 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.

8.3 Soil and Grass Sampling

The primary goal of this research is to establish removal efficiencies of the vegetated biofilter for various contaminants under different conditions. However, the fates of these contaminants are also of interest, including sorption of contaminants into the soil or organic matter, and uptake of the contaminants into the grass. Prior to testing with contaminated water, baseline sampling was conducted. Five samples of soil and vegetation was collected from throughout the test bed using a coring device, as shown in Figure 60a, which was advanced about 2 in (5 cm) into the soil below the bottom of the sod. The core holes were replaced with cores from the fourth extra test bed grown as a backup. The core holes on the fourth test bed were then filled with soil and reseeded. The extracted cores were analyzed and considered baseline conditions for the test bed. Five samples were collected because of expected heterogeneity in the soil and grass, and results averaged. Then, baseline, pollutant removal, and resuspension tests were conducted according to the test matrix in Table 7.

At the end of the testing on Bed 1, 20 final cores were extracted: four across the width of the bed at distances of 2.2, 4.4, 6.6, 8.8, and 10.1 ft (0.67, 1.34, 2.01, 2.68, and 3.08 m) as measured from the top edge of the bed. The first sampling location was under the location of the drip line, where flow from the splash plate hit the bed. Relative to the drip line, the sampling distances on Bed 1 were 0, 2.2, 4.4, 6.6, and 7.9 ft (0, 0.67, 1.34, 2.01, and 2.41 m).

At the end of the testing on Bed 2 and Bed 3, 25 final cores were extracted from each bed: five across the width of the bed at distances of 1, 3, 6, 9, and 12 ft (0.305, 0.91, 1.83, 2.74, and 3.66 m) as measured from the top edge of the bed. The first sampling location was again under the drip line, which was repositioned following the modifications to the flow apparatus after the high concentration tests on Bed 1. Relative to the drip line, the sampling distances on Bed 2 and Bed 3 were 0, 2, 5, 8, and 11 ft (0, 0.61, 1.52, 2.44, and 3.35 m).

After collection, soil cores were carefully divided into three portions: soil, roots, and grass. The grass was clipped with scissors and roots were gently washed with ultrapure water to remove soil. Samples were first oven dried, ground, and sieved to determine dry weight. Preliminary bench scale work indicated that 10 g (154 grains) of vegetation and 2 g (31 grains) of soil were needed to obtain the required 1 g (15.4 grains) dry matter required for digestion. Residue was digested with heat following USEPA Method 3050B [USEPA, 1996] using nitric acid, hydrochloric acid, and hydrogen peroxide. The remaining extract was analyzed for metals by ICP-OES.

a) Soil core collector for metals analysis b) The final specimen

Figure 60. Collection of soil and grass samples using a coring device: a) collection of core for analysis; b) a soil core specimen.

8.4 Bromide Tracer Tests

Tracer tests involved running tap water over the bed at the prescribed medium or high flow rates that was spiked with an initial slug of sodium bromide. Bromide was expected to behave as a conservative tracer, moving though the bed with very little uptake, adsorption, or other interaction with the bed. A bromide selective probe was used to determine bromide concentrations over time in the surface runoff and underdrain flow. Flow rates of the surface runoff and underdrain were also measured frequently.

8.5 Artificial Runoff Testing

As described above, each test bed was dedicated to a single runoff concentration. Tests began with the high concentration set of experiments on Bed 1. Baseline tests using tap water were obtained at8:1 slope and medium flow rate. Testing was then conducted using the polluted water at the 8:1 slope at medium flow, followed by the slope of 4:1 at medium flow, then the slope of 2:1 at medium flow and finally the slope of 2:1 at high flow, as per the test matrix in Table 7. The bed was brought to field capacity before each test. The test at each slope and flow condition was conducted on different days due to the time needed to prepare the artificial runoff and the large number of samples that had to be obtained and analyzed. Final core samples were then collected and analyzed. The process was repeated with the second bed with application of the medium concentration, and then the third bed with the low concentration.

Removal tests were conducted with medium flow at slopes of 8:1 (12.5%), 4:1 (25%), and 2:1 (50%), and with high flow at 2:1 (50%), in that order. Five cores of 1 in (2.5 cm) diameter by 2 in (5.1 cm) depth were obtained at random locations from the bed to analyze for baseline concentrations of metals in the soil, grass and roots. The holes were refilled with cores extracted from another bed and after a week testing began. The frame was leveled and brought to field capacity with tap water, then tilted to the specified incline. Flow was introduced at the specified rate and concentration, and sampling was periodically conducted from the influent, surface effluent, and groundwater. Flow rates were obtained from the surface runoff and the underdrain with each sample.

As shown in Figure 49, 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. For Bed 1 and Bed 2, the medium (high) flow rate the first 15 (6) minutes of high (Bed 1) or medium (Bed 2) concentration influent was provided from drum 1, while the next 45 (24) minutes of medium (Bed 1) or low (Bed 2) concentration influent came from drum 2 as the storm event proceeded according to the rates given in Table 16 for Bed 1 or Table 17 for Bed 2. For Bed 3, the medium (high) flow rate the first 9 (6) minutes of low concentration influent was provided from drum 1, while the next 51 (24) minutes of tap water influent came from drum 2 as the storm event proceeded according to the rates given in Table 18. 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 pollutant removal tests is as given in Table 19.

Table 19. Sample collection times during simulated storm events on each bed.

Bed	Conc.	Flow rate	First part (min)	Tailing part (min)	Influent sampling times (min)	Ground sampling times (min)	Surface sampling times (min)
1	high	medium	15	45	0, 5, 10, 30, 50	5, 10, 15, 20, 30, 40, 50, 60	5, 10, 15 (except 2:1 as below)
		high	6	24	0, 5, 10, 15, 25	5, 10, 15, 20, 25, 30, 35	When flow starts, then at various intervals afterwards
2	medium	medium	15	45	0, 5, 10, 30, 50	5, 10, 15, 20, 30, 40, 50, 60	
		high	6	24	0, 5, 10, 15, 25	5, 10, 15, 20, 25, 30	
3	low	medium	9	51	0, 4, 8, 30, 50	5, 10, 15, 20, 30, 40, 50, 60	
		high	6	24	0, 5, 10, 15, 25	5, 10, 15, 20, 25, 30	

The influent, surface water and ground water (underdrain) samples were each analyzed for TSS, oil and grease, dissolved metals, total metals, and deuterated alkanes. Because oil floats and is highly hydrophobic, it was not anticipated to be transported vertically downward though the bed. In addition, TSS is not relevant for groundwater samples. Several turbid samples of influent and surface water were selected for particle size analysis. Sample analysis protocol is presented in Appendix D. 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.

8.6 Resuspension Tests

Although it has been established that vegetated biofilters can capture suspended sediment, concern remains that the particles may be remobilized by following 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 an ideal tool 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 is 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 on each bed, 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.

8.7 Analytical Techniques

Samples collected, including all cores, baseline samples, pollutant samples, and resuspension test 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] augmented with solid-phase microextraction (SPME) with gas chromatography and mass spectrometry (GC-MS) further described below. 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) 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.

8.7.1 Inductively Coupled Plasma (ICP): Analysis of total and dissolved metals

On site 10-15 mL (about 0.3-0.5 fl. oz.) of water was collected, for both the dissolved and total metal analysis, for each sample. The dissolved metals samples were collected and prepared on site by filtering each sample through a 0.4 µm (0.016 mil) filter and nitric acid was added to keep the metals suspended in solution. Total metal samples were collected on site and taken to the lab for further preparation before analysis. Samples were digested with heat using nitric and hydrochloric acid as specified in USEPA method 6010b [USEPA, 2007]. Total and dissolved metal samples were stored in a refrigerator until they were ready to be analyzed.

To determine the concentration of each metal present in the sample a 13 point calibration curve was obtained from 0.001 ppm to 1 ppm using the multi-element ICP-MS calibration standard and the La ICP-MS calibration standard (catalog number CLMS-2N and PLLA2-3Y; Fisher Scientific, Waltham, MA) in 5% nitric acid; concentrations are given in Table 20. The metals of interest included: cadmium (Cd), calcium (Ca), chromium (Cr), copper (Cu), iron (Fe), lanthanum (La), lead (Pb), magnesium (Mg), manganese (Mn), nickel (Ni), and zinc (Zn). The total and dissolved metals were then analyzed using a Vista-MPX ICP-OES (Varian, Palo Alto, CA).

Quality control was obtained by running the standards after every 30 samples. If any extreme fluctuation from this calibration in comparison to the first calibration were to occur, sample analysis would be stopped. Troubleshooting would commence and the problem that caused the fluctuation off the curve would be resolved before resuming sample analysis.

Table 20. Concentrations of standards used for ICP-OES calibration.

Concentration of standards (ppm)						
Multi-elemental standard (Cd, Cr, Cu, Fe, Ni, Pb, Zn)	**Lanthanum standard (La)**	**Initial concentration (ppm)**	**Initial volume (mL)**	**Final concentration (ppm)**	**Final volume (mL)**	**Volume of nitric acid added (mL)**
1.000	**1.000**	10	*5*	1.000	50	2.5
0.750	**0.750**	10	*3.750*	0.750	50	2.5
0.500	**0.500**	10	*2.500*	0.500	50	2.5
0.250	**0.250**	10	*1.250*	0.250	50	2.5
0.100	**0.100**	10	*0.500*	0.100	50	2.5
0.075	**0.075**	10	*0.375*	0.075	50	2.5
0.050	**0.050**	10	*0.250*	0.050	50	2.5
0.025	**0.025**	10	*0.125*	0.025	50	2.5
0.010	**0.010**	10	*0.050*	0.010	50	2.5
0.0075	**0.0075**	10	*0.0375*	0.0075	50	2.5
0.005	**0.005**	10	*0.0250*	0.005	50	2.5
0.0025	**0.0025**	10	*0.0125*	0.0025	50	2.5
0.001	**0.001**	10	*0.005*	0.001	50	2.5
Blank	**Blank**	10	*0.000*	0.000	50	2.5

8.7.2 Solid Phase Microextraction (SPME): Analysis of deuterated standards

Solid-phase microextraction (SPME) is a common and simple method that is used to extract and pre-concentrate analytes from gaseous or aqueous samples [Boyd-Boland, A. A. et al., 1994], using an approach similar to Langenfeld et al [1996]. On site approximately 20 ml (0.68 fl oz) of water was collected, for the deuterated standard analysis, for each sample. No further preparation of these samples was needed so the samples were collected and capped on site and stored in a refrigerator until they were ready to be analyzed.

To determine the concentration of each metal present in the sample a 3 point calibration curve was obtained with concentrations of 50 ppb, 5 ppb, and 0.5 ppb of the three deuterated standards: N-Eicosane ($C_{20}D_{42}$), N-Tetracosane ($C_{24}D_{50}$), N-Triacontane ($C_{30}D_{62}$). Each of the standards was prepared in 20 ml (0.68 fl oz) of water.

A TriPlus autosampler (Thermo Scientific, Waltham, MA) was used to handle direct insertion solid phase microextraction (DI-SPME) measurements which included preheating the samples, DI adsorption with agitation and desorption into GC injection port. Each sample was preheated and agitated for 10 min at 90°C (194°F). DI-SPME was then performed on each sample for 30 minutes, while agitation continued at a constant temperature of 90°C (194°F). DI HS-SPME analysis was performed using a 100 μm (3.94 mil) polydimethylsiloxane (PDMS) fiber (Sigma-Aldrich, St. Louis, MO). GC tandem MS analysis was performed using a Trace GC (Thermo Scientific) coupled with a Finnigan Polaris Q (Thermo Scientific) quadrupole ion trap in electron ionization (EI) mode. Samples were analyzed on a 28m × 0.25mm × 0.25 mm (92 ft × 9.8 mil × 9.8mil) RTX®-5MS fused silica capillary column (Restek Cooperation, Bellefonte, PA). The carrier gas was ultrapure (99.999%) helium (Airgas, Radnor, PA) at a constant flow of 2.0 ml/min. The initial column temperature was 50°C (122°F) for 5 minutes. The temperature was then increased by 10°C/min (18°F/min) to a final temperature of 280°C (536°F) and held for 5 minutes. The 100 μm (3.94 mil) PDMS SPME fiber was exposed in the injection port at 250°C (482°F) for 2 minutes to desorb the analytes and begin the GC separation. The transfer line temperature was 280°C with an ion source temperature of 250°C (482°F).

For quality control, a 3-point calibration curve was run with concentrations of 50 ppt, 250 ppt, and 500 ppt for each deuterated standard for every batch of samples run. Each standard was run in quadruplicate. These deuterated standard concentrations were in the expected concentration range of the samples. To verify the quality of the SPME fiber and method, the standards were placed randomly throughout the samples. If any major deviations were to occur in the calibration standards the analysis would be stopped for troubleshooting before sample analysis could proceed.

Each fiber has a different adsorption coefficient due to the fiber use. If a fiber were to break in the middle of a run, a new fiber must take its place. Thus due to this different adsorption coefficient of the SPME fibers, the samples were analyzed according to the standard that was before or after the breakage of the fiber. Samples that were run before the fiber broke were analyzed to the standards before fiber breakage, and samples that were run with the new fiber were analyzed to the standards that were run with the new fiber.

8.8 Determination of Percent Removals for Contaminants

Percent removals of contaminants from the simulated storm water runoff were calculated using three methods: average concentrations, event mean concentrations, and mass loading. For each method removal was calculated separately for the water quality event (defined here as the first

0.75 in (19 mm) of the simulated storm) and then the tailing portion of the event. Using the method of average concentrations, the surface runoff concentration C_{Si} of a particular contaminant in the ith sample is compared to the average influent concentration C_{IMi} for that stage of each test (8:1 M, 4:1 M, 2:1 M and 2:1 H). The percent removal R_c for that test is calculated by averaging the percent removal for each sample:

$$R_c = \left(\frac{\sum_{i=1}^{N_S} \left(1 - (C_{Si}/C_{IMi})\right)}{N_S} \right) \times 100\%$$

Where N_S is the number of surface samples. The influent mean concentration C_{IMi} is computed by averaging the concentration measurements in each of the two phases of the storm (water quality event initial phase and tailing phase), and the small i subscript is used to match this concentration with the stage of flow during which the surface sample was collected, allowing for up to 5 minutes lag time between the change at the input and that in the effluent. The volume of flow in and out of the system is not taken into account.

For the EMC method, the average flow rates during the event were incorporated and the removal R_{EMC} calculated as follows:

$$R_{EMC} = \left(1 - \frac{\left(\sum_{i=1}^{N_S} C_{Si} \times V_{Si}\right)/V_S}{\left(\sum_{j=1}^{N_I} C_{Ij} \times V_{Ij}\right)/V_I} \right) \times 100\%$$

Where V is the volume; specifically V_{Si} is the volume of flow represented by the ith surface sample during which the concentration was C_{Si}, and V_S is the total surface volume:

$$V_S = \sum_{i=1}^{N_S} V_{Si}$$

A similar equation was used for the total influent volume V_I in terms of the influent samples V_{Ij}. Since each $C_{Si} \times V_{Si}$ term represents the mass of the contaminant in the volume V_{Si}, the sum represents the total mass of contaminant in the surface runoff; when this is divided by the total surface flow volume V_S, one gets the event mean concentration (EMC) for the surface flow. Similarly, the influent term in the denominator gives the influent flow EMC.

Using the mass loadings method, the total influent mass loading and effluent mass are calculated using volume of flow and then compared to determine the percent removal of mass. The calculation of the removal R_m is as follows:

$$R_m = \left(1 - \frac{\left(\sum_{i=1}^{N_S} C_{Si} \times V_{Si}\right)}{\left(\sum_{j=1}^{N_I} C_{Ij} \times V_{Ij}\right)} \right) \times 100\%$$

Which is simply the ratio of the total contaminant mass in the surface flow to that in the influent, subtracted from 1.

In reporting the percent removals from the prototype vegetated biofilter, the EMC method was chosen, partly because it is already the predominant method in the literature, and partly to avoid issues with the other computational methods, such as sensitivity to outliers. A comparison of the removals using the three formulas in this section is given in Section 13.1.

8.8.1 Handling of nondetections

Determination of removals will also vary depending on how samples in which a constituent was not detected are interpreted. There does not appear to be a consensus among researchers as to the best way to report and utilize data that are below a given detection limit, which is based on the limitations of the particular instrumentation used to analyze a constituent of interest. For example with the ICP-EOS instrumentation, different detection limits are determined for each constituent for each batch of samples analyzed, and the range of the detection limits among various metals are fairly broad. For a particular constituent that is below a given detection value, some references use zero as the concentration, others use one-half the detection value, and others the detection limit itself. As reported in the NCHRP Report 565 [LID Center, 2006], within the International BMP Database "nondetects are assigned one-half the reported detection limit." Using zero yields the highest removal values. For this study it was decided to use half the detection limit for all calculations.

9 Baseline Test Results

Preceding any performance testing, a baseline run at a slope of 8:1 with medium flow was performed using tap water on each of the beds to determine background concentrations released from the bed with clean influent water. Average values for three samples collected at 5 min intervals using the three beds are shown in Table 21; 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 between Bed 1 and Bed 3; however, metal results for Bed 2 were high. It is possible that influent tanks, piping, or distributor pipes were not completely decontaminated after the high concentration tests performed on Bed 1, leading to carryover of low levels of contaminants for the Bed 2 baseline test. As a result, metals performance results for Bed 2 were compared against the average baseline metals results from Beds 1 and 3, and not the elevated baseline metals results from Bed 2.

Table 21. Average concentrations in baseline tests. Values preceded by "<" were below detection limits.

		Bed 1 Surface	Bed 1 Underdrain	Bed 2 Surface	Bed 2 Underdrain	Bed 3 Surface	Bed 3 Underdrain
Dissolved Metals	Cd (μg/L)	2.7	3.0	19.7	20.3	< 2	< 8
	Cr (μg/L)	< 7	< 7	21.0	19.0	< 9	< 9
	Cu (μg/L)	14.3	11.3	24.7	26.3	< 12	< 7
	Fe (μg/L)	< 6	13.3	23.3	76.4	< 8	81.0
	Ni (μg/L)	< 17	< 17	14.7	17.9	< 18	< 7
	Pb (μg/L)	< 55	< 55	< 53	< 53	< 77	< 71
	Zn (μg/L)	< 5	< 5	24.0	26.2	< 7	< 5
Total Metals	Cd (μg/L)	< 3	1.7	19.3	19.7	< 8	< 8
	Cr (μg/L)	< 7	< 7	20.3	20.3	< 6	< 6
	Cu (μg/L)	15.3	15.0	33.3	36.1	< 12	< 12
	Fe (μg/L)	139	779	125	579	82	332
	Ni (μg/L)	< 17	< 17	20.0	29.4	< 18	< 18
	Pb (μg/L)	< 55	< 55	< 53	< 53	< 77	< 77
	Zn (μg/L)	27.0	36.7	117	67.9	25.9	31.9
TSS (mg/L)		14.4	55.4	7.2	11.5	1.8	10.2
O&G (mg/L)		1.5	2.5	1.2	< 0.4	< 0.4	0.28

In the baseline Bed 1 and Bed 3 tests, the metals Cd, Cr, Cu, Ni, and Pb were not detected or detected at concentrations near the detection limits. Elevated Fe concentrations were detected in surface runoff at concentrations somewhat higher than tap water (84 mg/L), but in the underdrain at concentrations far above tap water concentrations indicating natural leaching of Fe from the soil. Elevated Zn concentrations were found in both surface runoff and underdrain samples at concentrations higher than tap water (24 mg/L). For both Fe and Zn in baseline tests, the majority of the metals was sorbed to soil rather than dissolved. Baseline TSS concentrations averaged 1.8 to 14.4 mg/L in the surface runoff and 10.2 to 55.4 mg/L in the underdrain. Not surprisingly biofilters release some TSS naturally in the effluent, even when the stormwater entering the biofilter has no TSS. Oil and grease was detected in many of the baseline samples, although at low concentrations, indicating the presence of hexane extractable compounds even in a clean biofilter system.

Particle size analyses were performed on baseline samples for Bed 2, and results are shown in Figure 61. In this test, tap water with no added sediment was introduced to the bed, so sediment in the surface runoff was all eroded from the bed itself. Initially, particle sizes were fairly uniform and small with mean diameters of 8.6 µm (0.33 mil) and 10.9 µm (0.43 mil). At fifteen minutes after the start of the runoff, larger particles were eroded from the bed resulting in a mean diameter of 164 µm (6.5 mil).

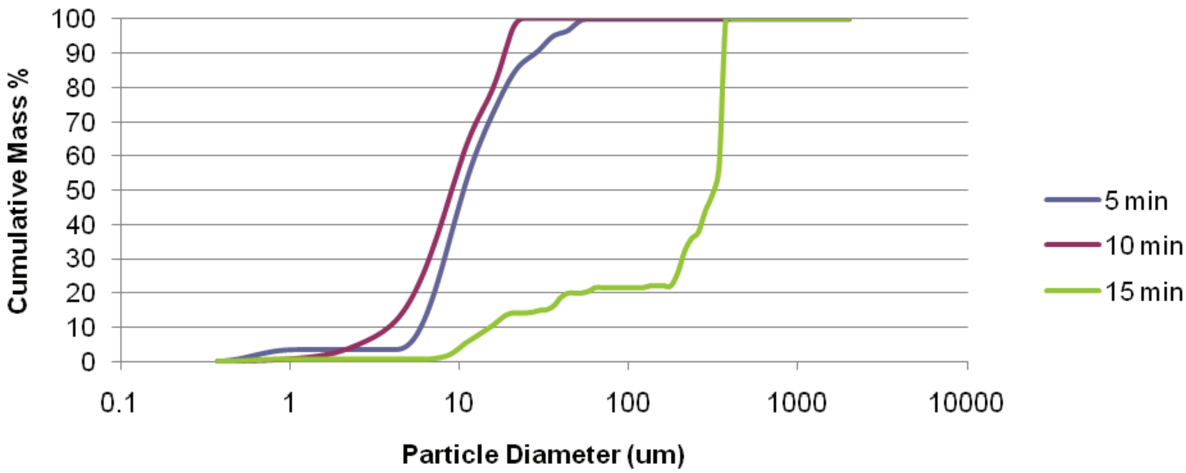


Figure 61. Particle size distribution of surface runoff from a baseline test of Bed 2.

10 High Pollutant Concentration Experiments

In this series of tests, a high concentration of contaminants was delivered to the test biofilter 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 medium concentration of contaminants at a lower flow rate; the concentrations of each contaminant are listed in Table 11 in Section 7.1. As per the test matrix in Table 7 in Section 5.1, a total of four pollutant removal tests were conducted which included the following: 1) an 8:1 slope (7.13°) with a medium flow rate, 2) a 4:1 slope (14.0°) with a medium flow rate, 3) a 2:1 slope (26.6 °) with a medium flow rate, and 4) a 2:1 slope (26.6 °) with a high flow rate. The first pollutant removal test was preceded by baseline core collection and a baseline flow test as described in Chapter 9. The last pollutant removal test was followed by resuspension and bromide tracer tests followed by final core collection. The medium flow simulations used an initial flow rate of 2.17 gpm (8.22 lpm) for 15 min followed by a flow rate of 0.43 gpm (1.64 lpm) for 45 min. The high flow simulation used an initial flow rate of 5.43 gpm (20.6 lpm) for 6 min followed by a flow rate of 1.18 gpm (4.47 lpm) for 24 min. The flow rates for both medium and high flow events are given in Table 16 in Section 7.2.2. All tests were performed on the same test plot, designated Bed 1. After completion of the performance tests, a series of tracer and resuspension tests were performed at all slopes with tap water to evaluate flow through the bed in more detail and investigate the release of contaminants laid down from previous tests. Results from all tests on Bed 1 are discussed in this chapter.

10.1 Tracer Tests

Tracer tests, conducted after the completion of pollutant removal tests, involved running tap water over the bed at the prescribed medium or high flow rates that was spiked with an initial slug of sodium bromide. Bromide was expected to behave as a conservative tracer, moving though the bed with very little uptake, adsorption, or other interaction with the bed. A bromide selective probe was used to determine bromide concentrations over time in the surface runoff and underdrain flow. Flow rates of the surface runoff and underdrain were also measured frequently.

Tracer results for the 8:1 slope are shown in Figure 62. Bromide moved directly with the overland flow, and highest bromide concentrations were detected in the water that first emerged from the bed, 6 min after initiation of the runoff flow. Concentrations then decreased rapidly until surface flow stopped. In the underdrain, initial bromide concentrations were close to zero, and flow at this point was due to draining of the bed from bringing the bed to field capacity in preparation for the test. Concentrations increased rapidly after 6 min indicating the time required for water to seep through the soil layer and into the underdrain. Concentrations decreased rapidly until the tailing portion of the storm began, when concentrations increased again somewhat. This was possibly due to overland flow seeping into the underdrain due the decrease in inflow providing additional bromide to the underdrain. Surface runoff began at 6 min after initiation of the storm, remained fairly constant at 0.55 gpm (2.08 lpm), and then stopped rapidly at 19 min after the tailing portion of the storm began. Underdrain flow increased from base flow at 6 min, remained constant through the initial portion of the storm at 0.80 gpm (3.03 lpm), and then decreased to match the inflow rate of 0.49 gpm (1.85 lpm). After inflow ceased completely, the underdrain continued to flow, decreasing linearly for 8 min. 94% of the inflow added to the bed was recovered in the surface runoff and underdrain flow, and only 15% of the inflow resulted in surface runoff, the rest seeping into the soil and emerging as underdrain flow.

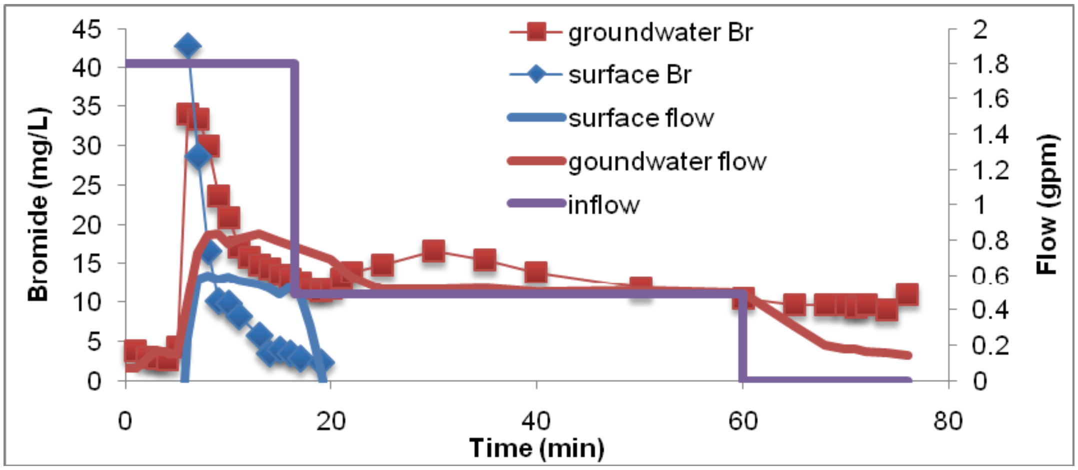


Figure 62. Tracer Test Results for 8:1 Slope, Bed 1.

Tracer results for the 4:1 slope, 2:1 slope medium flow, and 2:1 slope high flow are shown in Figure 63, Figure 64, and Figure 65, respectively. Results were similar to those for the 8:1 slope, although runoff began at increasingly earlier times, and a larger proportion of inflow ran off the surface. Surface flow first appeared after 4 min for the 4:1 slope, 3 min for the 2:1 slope medium flow, and 1.5 min for the 2:1 slope high flow. Increased flow emerged from the underdrain at nearly the same intervals as the 8:1 slope, but no longer coincided with the surface flow, after 5 min for both the 4:1 slope and the 2:1 slope medium flow. For the 2:1 slope high flow test, high bromide was first seen in the underdrain flow at 2 min, but water was spilling over the surface flow collection trough into the underdrain leading to a false reading. This problem was corrected for beds 2 and 3. Surface runoff continued through the tailing portion of the storm for the 4:1 and 2:1 medium flow tests, though at very low flow rates. For the 2:1 high flow test, significant surface runoff was observed throughout the simulated storm. During the initial portion of these three events, surface runoff exceeded underdrain flow. Over the entire storm, the percent of inflow that ran off the surface was 36% for the 4:1 slope, 41% for the 2:1 slope medium flow test, and 70% for the 2:1 slope high flow test. Percent recoveries of water for the tests were 99%, 95%, and 91%, respectively.

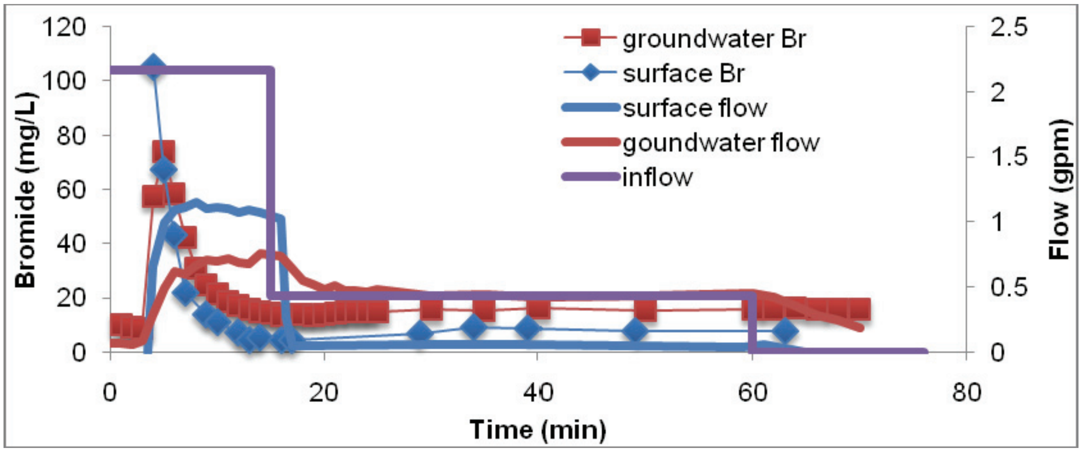


Figure 63. Tracer Test Results for 4:1 Slope, Bed 1.

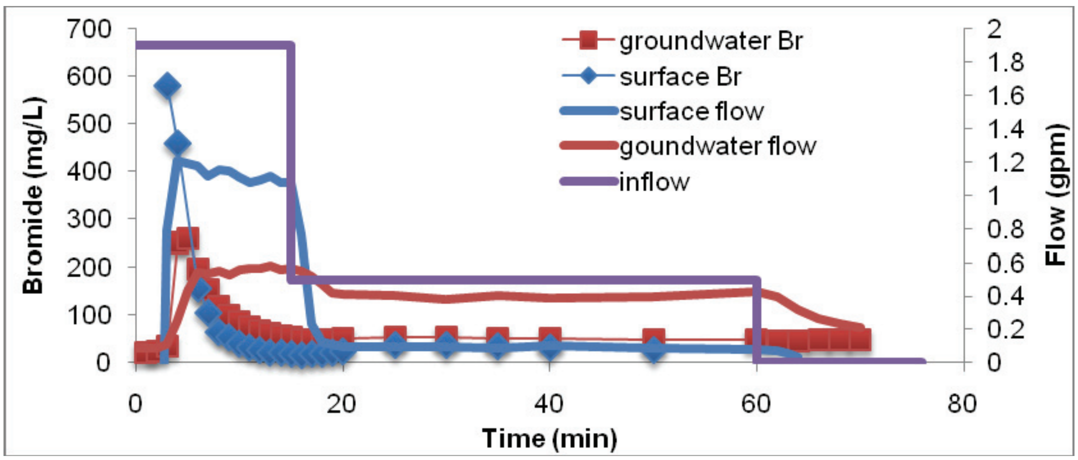


Figure 64. Tracer Test Results for 2:1 Slope, Medium Flow, Bed 1.

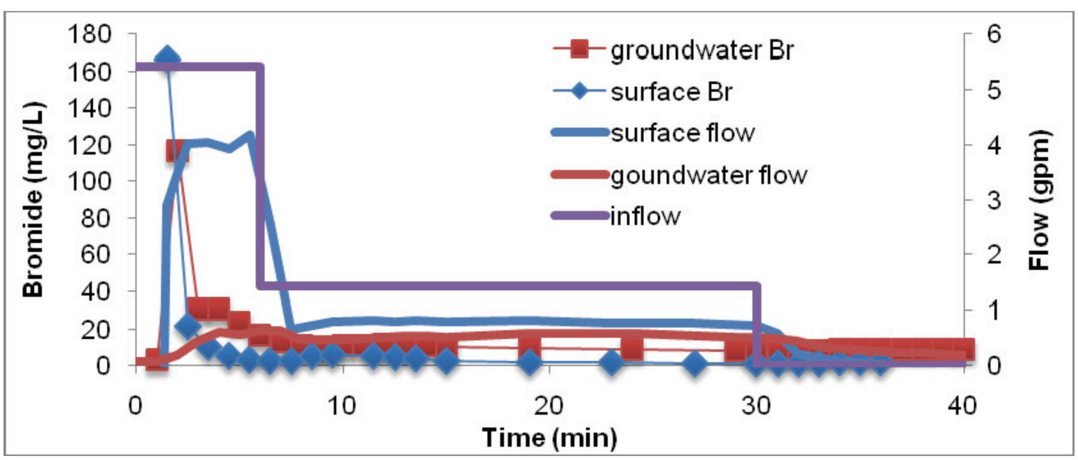


Figure 65. Tracer Test Results for 2:1 Slope, High Flow, Bed 1.

10.2 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 of the contaminants were mixed with tap water, pH was adjusted to 7.0±0.1 by addition of H_2SO_4 or NaOH and/or KOH. This proved to be extremely challenging with the large volume of complex solutions open to the atmosphere. During and after pH adjustment, the pH would continue to drift over several hours. Although pH was adjusted to 7 after the solutions were mixed, by the time the other preparation steps were completed, the pH had increased to as high as 7.80 in the influent water. The pH in the surface runoff was not significantly different from the influent water. The pH from the underdrain however was lower than the influent, likely due to leaching of acidity from the soil. The native soil initially had a pH of 5.3 and was mixed with lime to raise the pH to 6.5. Average measurements of the pH in influent and effluent from each test are given in Table 22.

Table 22. Average pH values during the high concentration tests on Bed 1.

Test	Initial Influent	Tailing Influent	Initial Surface Runoff	Tailing Surface Runoff	Initial Underdrain Flow	Tailing Underdrain Flow
8:1	7.41	7.80	7.83	no flow	6.98	6.86
4:1	7.50	7.78	7.90	no flow	6.98	6.71
2:1 Medium	7.57	7.37	7.65	no flow	7.18	6.94
2:1 High	7.52	7.46	7.68	7.49	7.34	7.19

10.3 Suspended Solids Results

Figure 66 through Figure 69 depict the suspended solids concentrations for the four high concentration tests. Sieved soil (<0.841 mm) was mixed with the two influent drums at target concentrations of 737 mg/L for the initial high concentration flow and 207 mg/L for the subsequent medium concentration flow. Actual concentrations measured in the influent flow as it sprayed onto the distributor plate varied from the target concentration on more than one occasion, which is attributed to particles settling in the influent mixing container and concentration gradients. Specifically, particulate concentrations appeared to decrease over time during the initial high concentration flow. Despite this problem, most average concentrations were reasonably close to the target values, and the variability in concentration would be more representative of actual runoff. For the high concentration tests with a medium flow, influent concentrations averaged 695 mg/L, 721 mg/L, and 851 mg/L for the first three tests. These values were within 15% of the target concentration of 737 mg/L. For the high concentration test with a high flow, the average influent concentration was 419 mg/L, which was significantly below the target concentration of 737 mg/L. Suspended solids concentrations decreased during the lower flow rate for the tailing 45 min for the first three tests and for the tailing 24 min for the last test. Concentrations averaged 163 mg/L, 122 mg/L, 232 mg/L, and 175 mg/L, respectively for the four tests, which were within a 20% margin of the target value of 207 mg/L for three of the tests.

For the first three medium flow tests, surface runoff was only generated during the first 15 min of the test during the high concentration and initial high flow. Once the concentration and flow decreased for the tailing 45 min, all the water delivered to the bed infiltrated and no surface samples could be collected. Overall, the suspended sediment concentrations were low in the surface runoff and decreased over time, with average concentrations of 47.0 mg/L for the 8:1 slope, 57.9 mg/L for the 4:1 slope, and 22.2 mg/L for the 2:1 slope with medium flow. The high flow run generated surface runoff throughout the entire test. Suspended sediment concentrations were also low for this test, with an average initial concentration of 62.4 mg/L for the first 6 min and an average tailing concentration of 16.4 mg/L for the last 24 min. Baseline suspended solids concentrations averaged 14.4 mg/L at the 8:1 slope and represent the lower limit of TSS concentrations that can be achieved in runoff concentrations even with clean influent flowing over the grassy slope. When accumulated over the entire runoff event, the percent removals of the event mean concentrations (EMCs) were 91.9% for the 8:1 test, 88.0% for the 4:1 test, 96.6% for the 2:1 medium flow rate test, and 87.8% for the 2:1 high flow rate test. Based on these percent removals, the change in slope of the bed did not significantly affect the percent removals of the suspended solids at the high concentration level.

In addition to collecting surface samples, groundwater samples were also collected from the underdrain. Suspended sediment concentrations in the underdrain were very low for the first three medium flow tests averaging 18.2 mg/L for the 8:1 slope, 38.5 mg/L for the 4:1 slope, and 72.0 mg/L for the 2:1 slope. For all three tests, suspended sediment concentrations decreased over time. These values were similar to baseline underdrain suspended solids concentrations that averaged 55.4 mg/L and indicate, that suspended sediment results in the underdrain were no different than when infiltrated with clean water. Water flowing through soil will suspend and transport solids. The 2:1 test had a very high initial suspended sediment value of 311 mg/L in the underdrain, while the remaining values were similar to baseline concentrations.

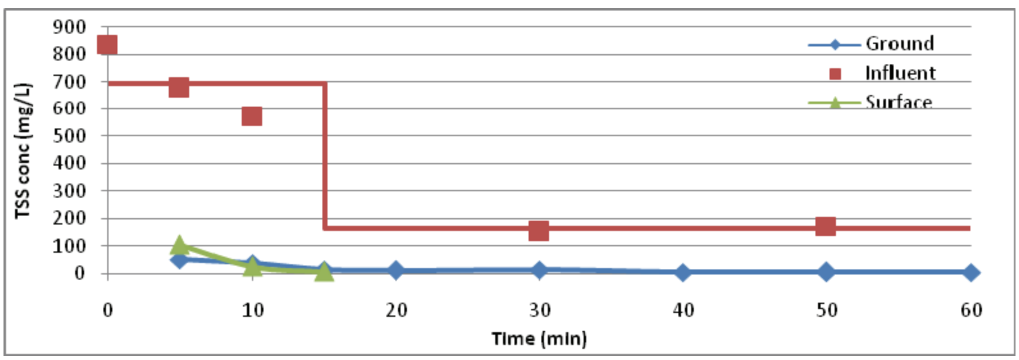


Figure 66. Concentration of suspended solids in 8:1 slope, medium flow rate.

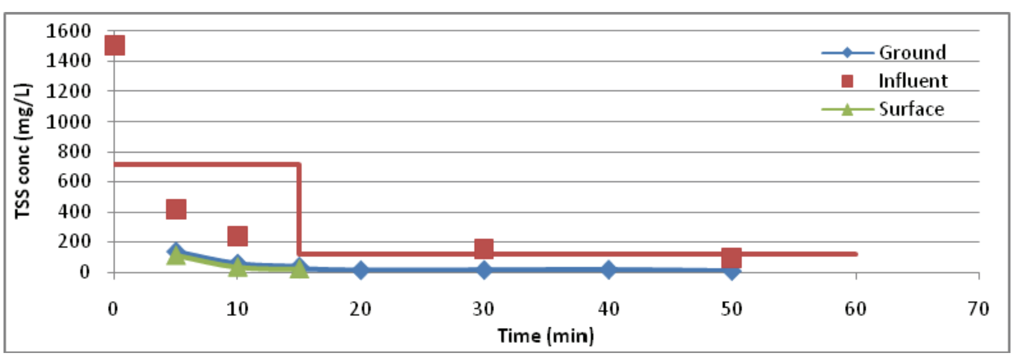


Figure 67. Concentration of suspended solids in 4:1 slope, medium flow rate.

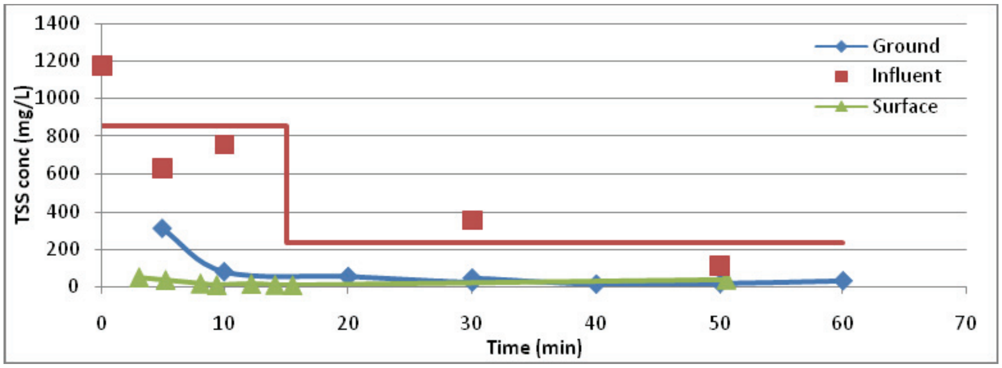


Figure 68. Concentration of suspended solids in 2:1 slope, medium flow rate.

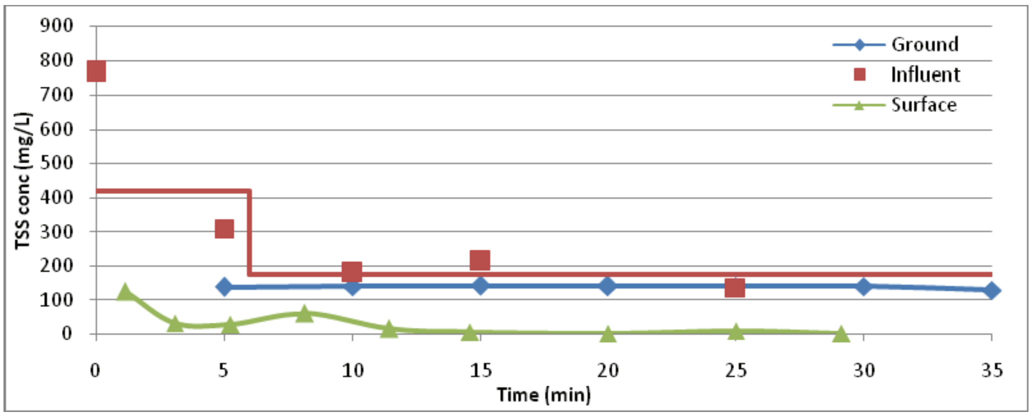


Figure 69. Concentration of suspended solids in 2:1 slope, high flow rate.

10.3.1 Particle Size Analysis

Several samples from each performance test were analyzed for particle size analysis. Because of the high volume of water required, this analysis was not performed at every sampling interval. One particle size analysis of sediment in the influent water and in the surface runoff was performed for each test, and results are shown in Figure 70 for influent and in Figure 71 for surface effluent. Samples from the 2:1 slope, high flow rate test were not collected. Particle sizes from the influent were very consistent. For all three samples, less than 15% of particles below 20 μm (0.79 mil) were detected, but the majority of particles were much larger, with mean particles sizes of 1,094 μm (43.1 mil) to 1,223 μm (48.1 mil). This was unexpected, because the clayey soil used as suspended matter in the influent was sieved to a diameter of less than 841 μm (33.1 mil), smaller than the majority of particles detected. It is likely that the clay particles agglomerated in the influent mixing tank forming larger particle aggregations that entered the bed. Further, high levels of Fe were added to the solution to match literature values. The water turned an obvious orange color after metal addition and pH adjustment to 7.0, indicating the presence of $Fe(OH)_{3(s)}$, which may have contributed to the aggregation of clay particles. Surface runoff particle size distributions were extremely uniform comprising almost entirely of a narrow size range, and was very consistent among the three samples overlaying on top of each other on the figure. Suspended sediment in surface runoff had virtually no small particles with mean diameters of 1,380 μm (54.3 mil) to 1,514 μm (59.6 mil). This was again unexpected, because larger particles should be easier to capture than the fine particles, however, the opposite was observed here. These sizes were also considerably larger than observed in baseline runs with mean diameters of 8.6 µm (0.34 mil) to 164 µm (6.56 mil), as seen in Figure 61.

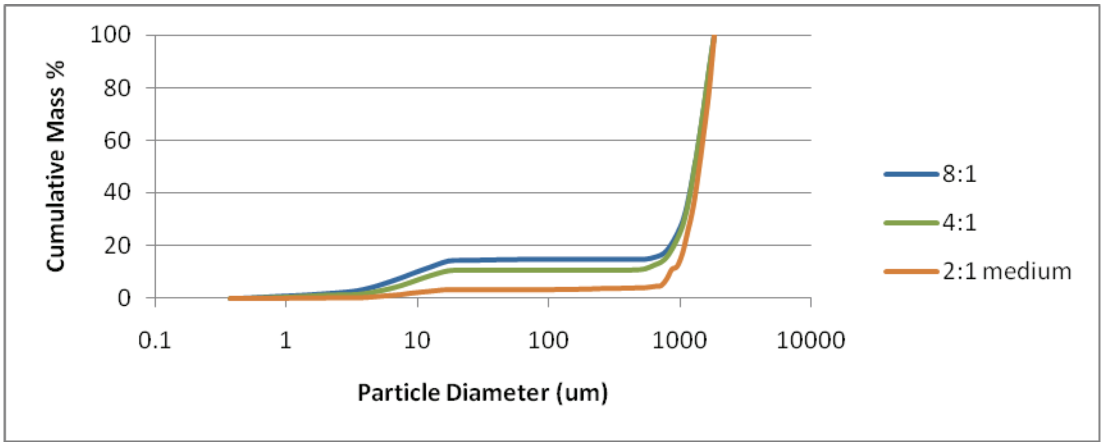


Figure 70. Particle Size Distribution of Influent Samples from Bed 1.

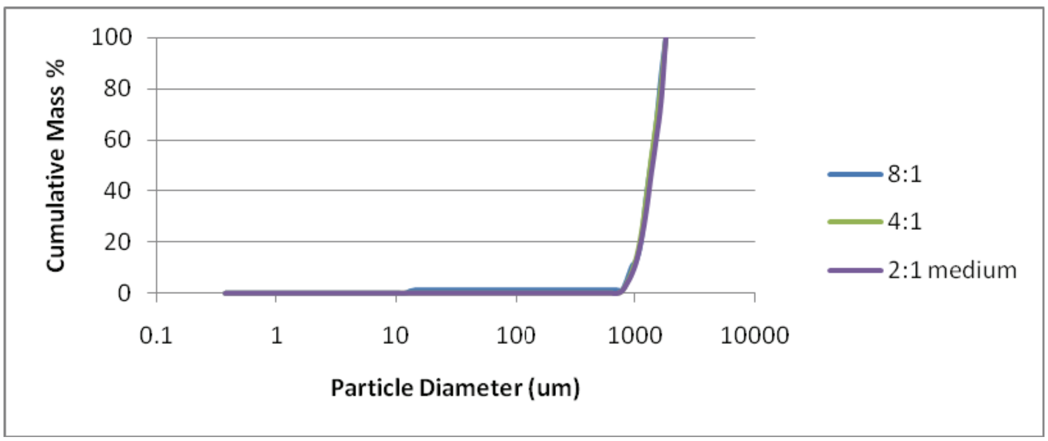


Figure 71. Particle Size Distribution of Surface Runoff Samples from Bed 1.

10.4 Total Metals Results

Total metals were determined by ICP-OES analysis following acid digestion. These samples were not filtered prior to digestion, and results represent the combined total of metals dissolved in the water, precipitated, and sorbed to suspended solids. Table 11 displays the high and medium target concentrations. For the medium flow rate test with an 8:1 slope, total metal concentrations are displayed in Figure 72 (Cd) through Figure 78 (Zn), in alphabetical order by element symbol (Cd, Cr, Cu, Fe, Ni, Pb, Zn). Measured influent concentrations of each metal were somewhat lower in both the high and medium concentrations than the target concentrations. For example, the high target concentration for cadmium was 500 µg/L, and the average measured concentration was 409 µg/L. The medium target concentration was 100 µg/L and the average measured concentration was 83 µg/L. Nevertheless, all metals except Pb were within a 20% margin of the target values. Pb concentrations were 75% of the target values. Influent concentrations remained constant over time for every metal.

Collected surface runoff was only generated for the first 15 min during the initial higher flow rate of the 8:1 medium flow test. Surface runoff concentrations were very low for each metal, and removal of metals from the surface runoff was excellent. Cr and Pb were not detected in all surface runoff samples with detection limits of 7 µg/L and 55 µg/L, respectively. Cd and Cu were detected at concentrations below 30 µg/L, Ni and Zn below 100 µg/L, and Fe between 100 µg/L and 1,000 µg/L. In the surface baseline samples, Cd, Cr, Ni, and Pb were not detected with detection limits of 2 µg/L, 7 µg/L, 17 µg/L, and 30 µg/L, respectively. Cu, Fe, and Zn were detected in the baseline samples at average concentrations of 15 µg/L, 139 µg/L, and 27 µg/L, respectively. These concentrations were similar to the experimental surface concentrations, so a portion of these metals in the surface runoff originated from the original grassy slope itself and not the influent. Percent decreases in the event mean concentration for Cd, Cr, Cu, Fe, Ni, Pb, and Zn were as follows: 86.0%, 99.1%, 93.2%, 97.7%, 96.2%, 99.1%, and 94.3%. In the 8:1 slope test, Cr and Pb had the highest percent removals out of the metals.

Underdrain samples had even lower metal concentrations for each metal. Cr and Pb were not detected, with detection limits of 7 µg/L and 55 µg/L, and Ni was only detected twice near the detection limit of 17 µg/L. Cd remained below 5 µg/L, Cu below 30 µg/L, Zn below 65 µg/L, and Fe below 1,000 µg/L. Each individual metal concentration remained reasonably consistent over time, except Cu and Fe, which had the highest concentrations in the initial sample. In the underdrain baseline samples, Cr, Ni, and Pb were also not detected, with the same detection limits. Cd was detected at 3 µg/L in the first collected underdrain sample, but was not detected in the other two samples with a detection limit of 2 µg/L. Cu and Zn were detected at average concentrations of 15 µg/L and 37 µg/L, respectively. Fe was higher in the first underdrain sample at 1370 µg/L and an average of 484 µg/L in the other two samples. Compared with baseline samples, none of the total metals concentrations in the underdrain from the high concentration tests exceeded what would be expected from tap water leaching through soil.

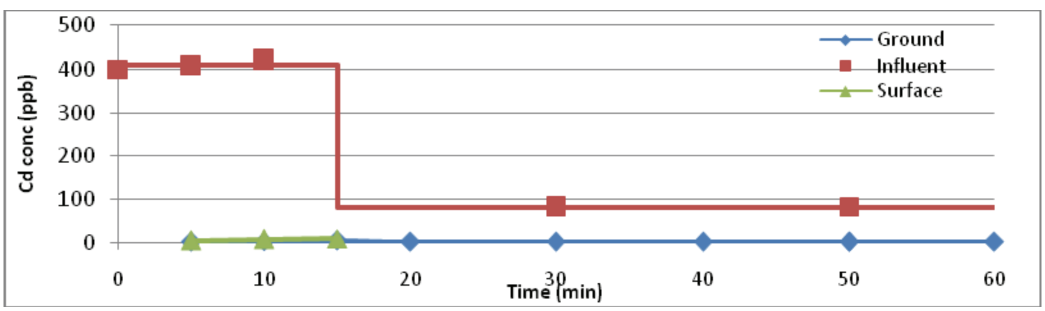


Figure 72. Total concentration of cadmium in 8:1 slope, medium flow rate.

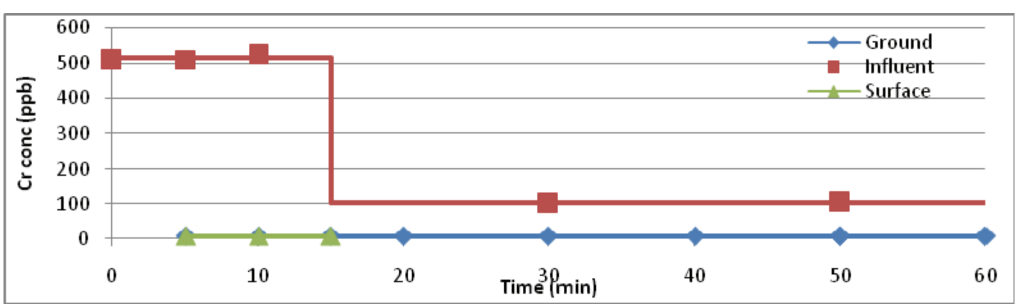


Figure 73. Total concentration of chromium in 8:1 slope, medium flow rate.

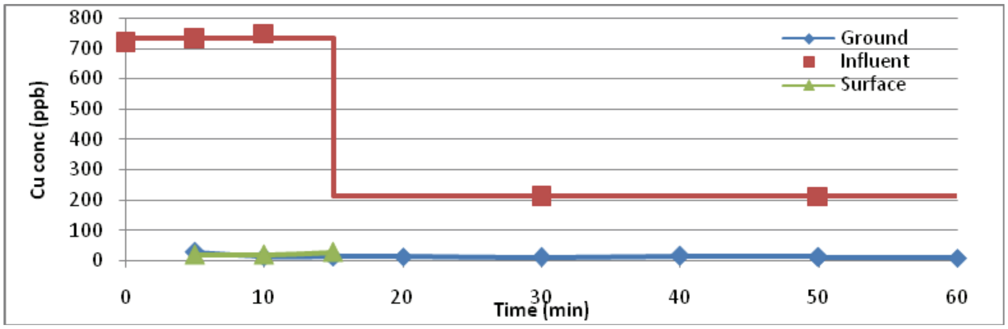


Figure 74. Total concentration of copper in 8:1 slope, medium flow rate.

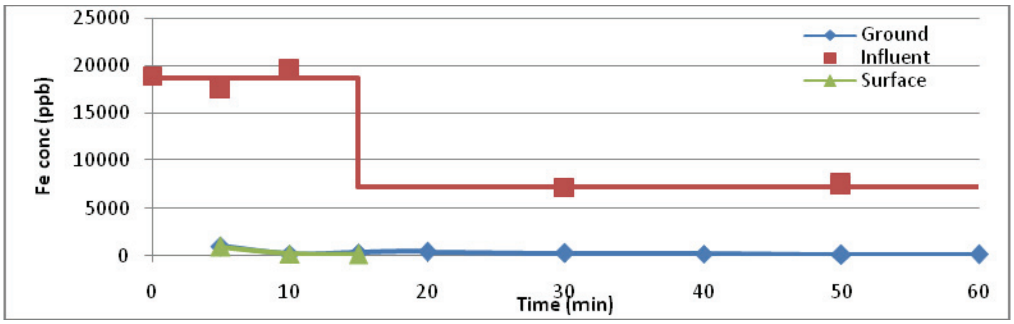


Figure 75. Total concentration of iron in 8:1 slope, medium flow rate.

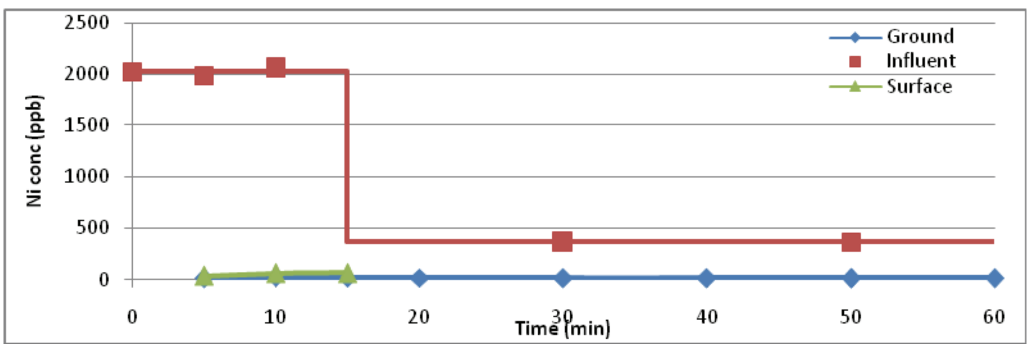


Figure 76. Total concentration of nickel in 8:1 slope, medium flow rate.

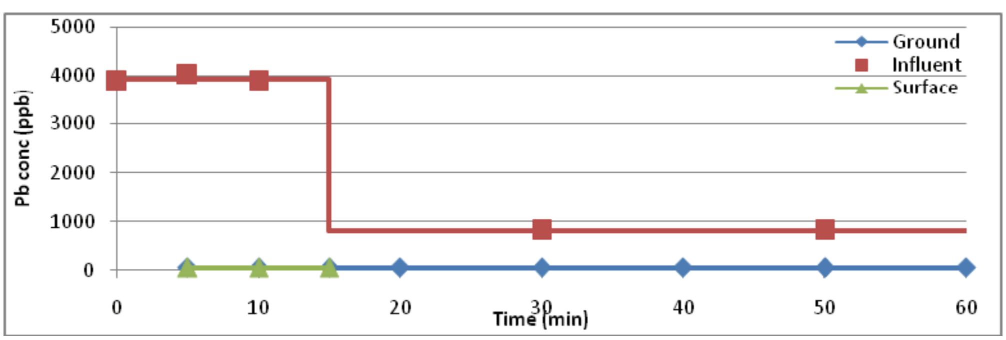


Figure 77. Total concentration of lead in 8:1 slope, medium flow rate.

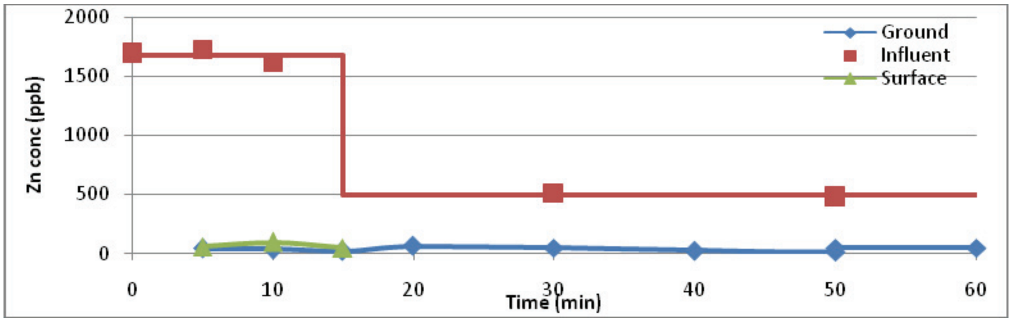


Figure 78. Total concentration of zinc in 8:1 slope, medium flow rate.

For the medium flow rate test with a 4:1 slope, total metal concentrations are displayed in Figure 79 through Figure 85, again in alphabetical order by elemental symbol. When compared with the 8:1 slope test, the influent metal concentrations vary slightly. Instead of being consistent for the initial high concentration, there is a slight decrease over time for every metal except Zn, where Zn remained consistent throughout. The tailing portion of the test had consistent concentrations for each metal. Similar to the 8:1 slope test, several of the metals had lower average concentrations than the target values, but all were within a 20% margin except Pb which was 72% of the target value.

The surface and underdrain samples exhibited similar trends to the 8:1 slope test with low metals concentrations and excellent removals of metals from the surface runoff. In the surface runoff, Cr and Pb were not detected with detection limits of 7 µg/L and 55 µg/L respectively. Concentrations for Cd, Cu, Fe, Ni, and Zn remained low and consistent, except Ni which increased over time from 39 µg/L to 135 µg/L. A large portion of the metal detected in surface runoff for Fe and Zn in the performance tests could be explained by significant concentrations in the baseline surface samples. Percent removals of the event mean concentration for Cd, Cr, Cu, Fe, Ni, Pb, and Zn were as follows: 97.1%, 99.0%, 97.4%, 98.2%, 94.6%, 99.0%, and 95.6%. As with the 8:1 slope, Cr and Pb had the highest percent removals out of all the metals. Overall, the increase in slope from 8:1 to 4:1 did not have a significant effect on metal removals.

The underdrain samples also contained consistently low metal concentrations, with Fe, Zn, and Ni decreasing over time. Zn had a large spike in concentration at 50 min, much unlike any of the other metals. Cr and Pb were not detected throughout the entire test in the underdrain samples, while Cd and Ni were initially detectable near detection limits in the first 15 min with the high concentration flow, but then became undetectable with limits of 2 µg/L and 17 µg/L when the medium concentration was pumped onto the bed.

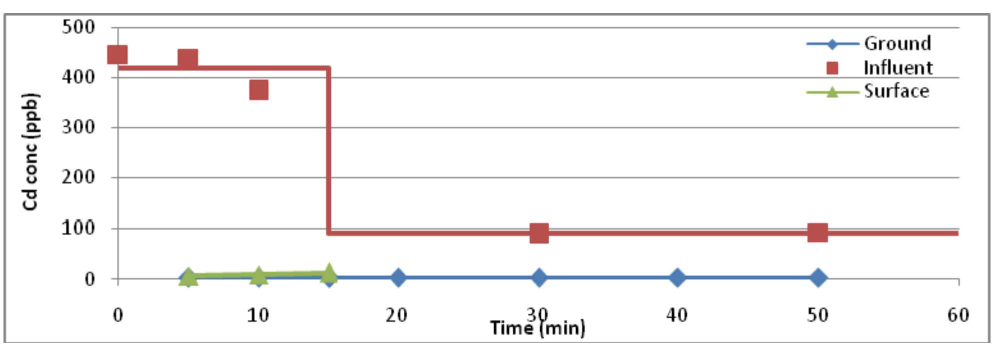


Figure 79. Total concentration of cadmium in 4:1 slope, medium flow rate.

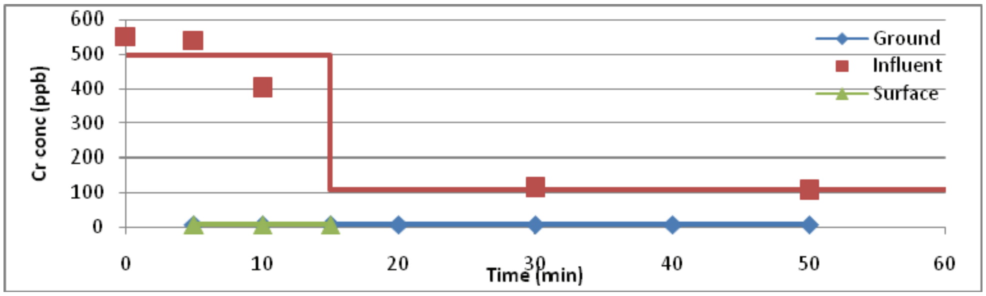


Figure 80. Total concentration of chromium in 4:1 slope, medium flow rate.

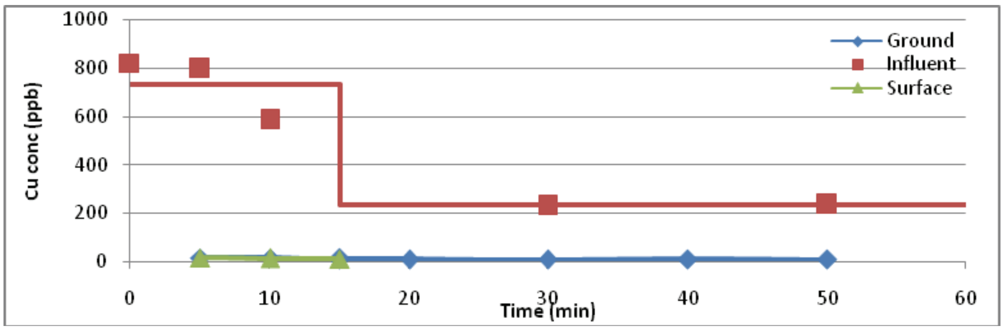


Figure 81. Total concentration of copper in 4:1 slope, medium flow rate.

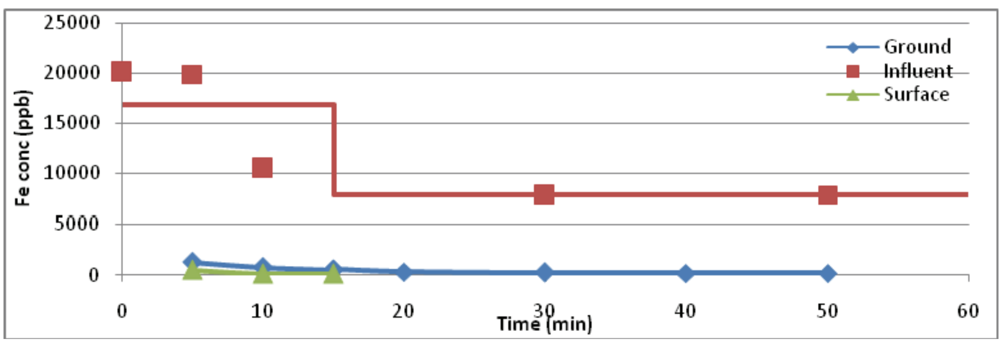


Figure 82. Total concentration of iron in 4:1 slope, medium flow rate.

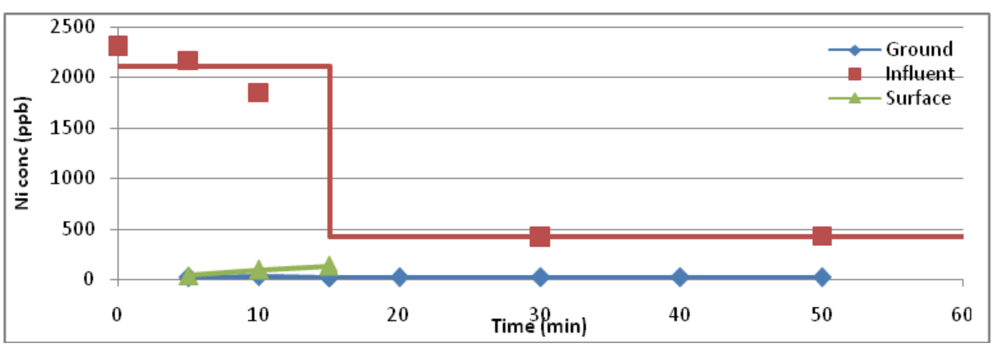


Figure 83. Total concentration of nickel in 4:1 slope, medium flow rate.

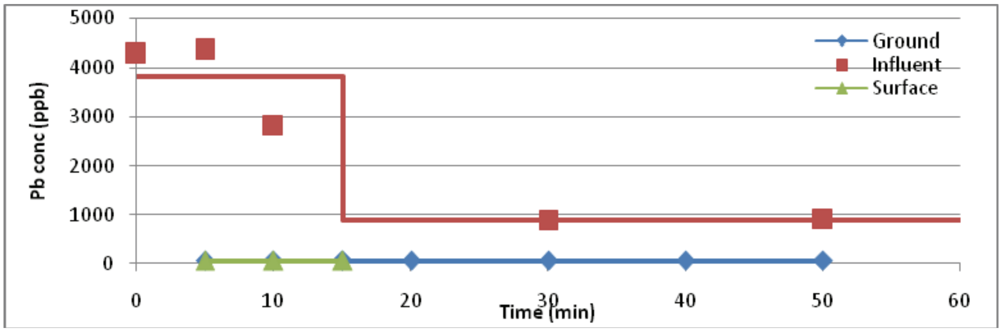


Figure 84. Total concentration of lead in 4:1 slope, medium flow rate.

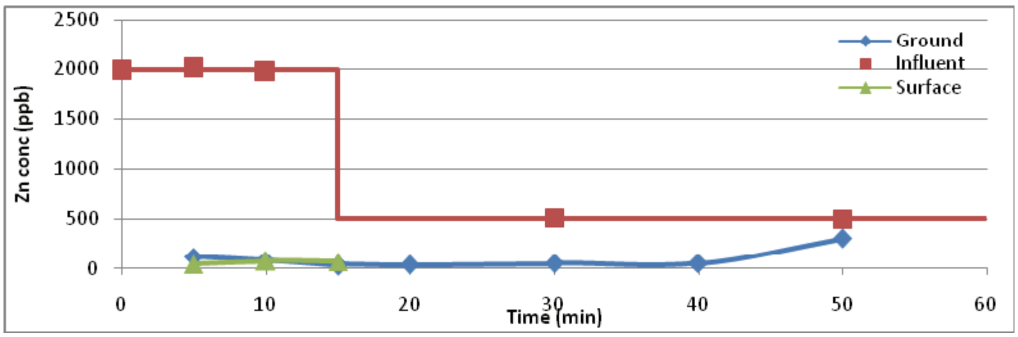


Figure 85. Total concentration of zinc in 4:1 slope, medium flow rate.

Figure 86 through Figure 92 portray the total metals concentrations from the 2:1 slope test with a medium flow. The influent samples exhibited similar trends as the 8:1 slope test for Cd, Cr, Cu, and Zn, because these influent concentrations were slightly lower than their target concentrations, but within a 15% margin except for Ni and Pb, which were only 58% and 70% of the target values. This was due to a low sample concentration for both metals at 10 minutes. The tailing end of the test had the same consistently low metal concentrations as the other two tests.

Even with the 2:1 slope, surface runoff virtually ceased after the initial 15 min high flow period. Water was dripping into the surface collection trough throughout the tailing portion of the storm, but at such a slow rate that only one set of sampling bottles could be collected. One significant trend for each metal within the surface runoff samples was at 5 min into the test each metal was detected at its highest concentration, even Pb which was rarely detected in all tests. Cr was not detected in the surface runoff for the 4:1 slope but was detected with the 2:1 slope. This difference could be from the storm water having less time to infiltrate into the bed at the higher slope. The only metal that was not detected in the surface runoff after the 5 min sample was Pb with a detection limit of 48 µg/L. During the tailing portion of the storm event, metal concentrations were low. Overall, the surface runoff concentrations were low, and still resulted in excellent percent removals of event mean concentration for Cd, Cr, Cu, Fe, Ni, Pb, and Zn as follows: 96.7%, 96.6%, 95.7%, 90.1%, 94.9%, 97.1%, and 92.4%. As with the first two slopes, Cr and Pb exhibit the highest percent removals, with Cd high as well. These percent removals are slightly lower than the 4:1 test.

The underdrain samples had consistently low concentrations for every metal over time except Fe and Zn. Fe had a spike in concentration at 10 min during the initial high flow with a concentration of 1800 µg/L versus the average concentration of 840 µg/L. Zn had a slight increase in concentration at the tail end of the flow during 30 min and 40 min from 76 µg/L to 150 µg/L with an average of 105 µg/L. Cd and Pb were not detected throughout the run, with limits of 5 µg/L and 48 µg/L respectively. Cr and Ni were detected for up to 20 min, and then were not detected after 20 min with limits of 2 µg/L and 13 µg/L, respectively.

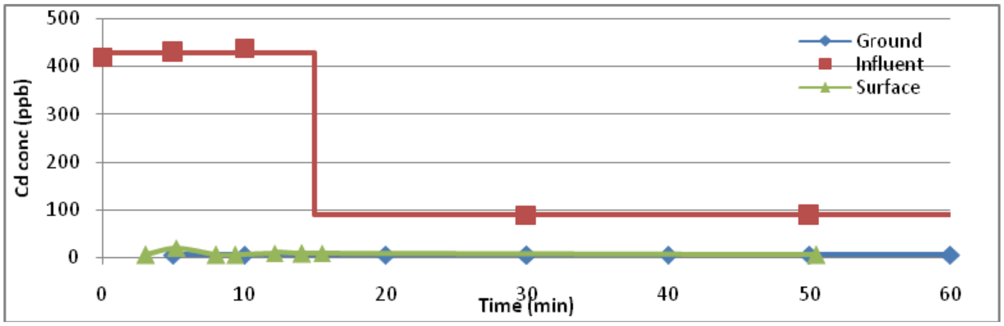


Figure 86. Total concentration of cadmium in 2:1 slope, medium flow rate.

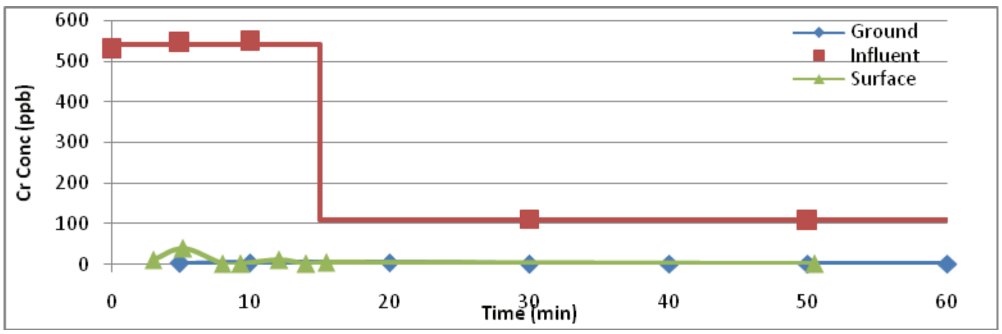


Figure 87. Total concentration of chromium in 2:1 slope, medium flow rate.

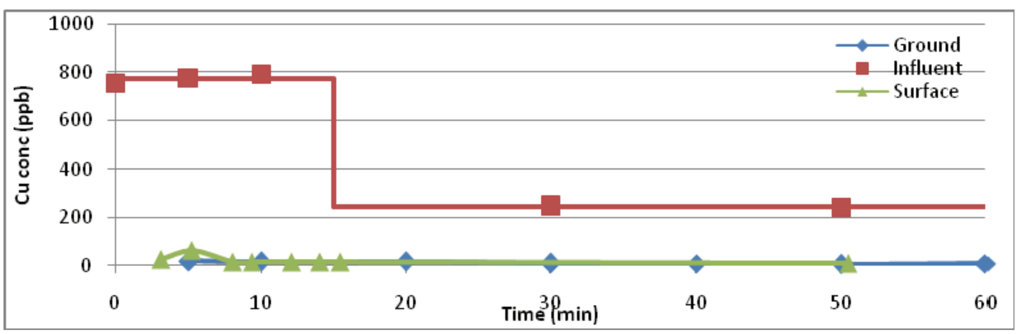


Figure 88. Total concentration of copper in 2:1 slope, medium flow rate.

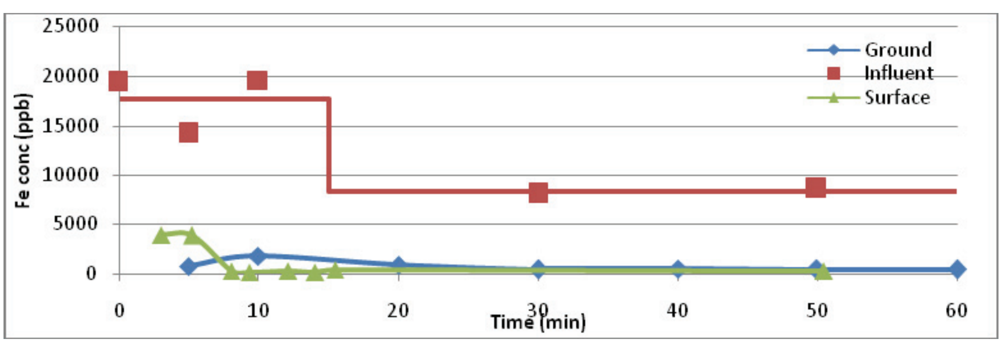


Figure 89. Total concentration of iron in 2:1 slope, medium flow rate.

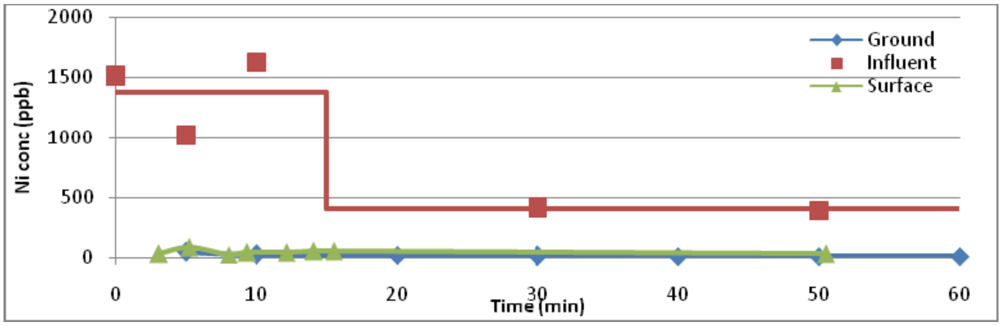


Figure 90. Total concentration of nickel in 2:1 slope, medium flow rate.

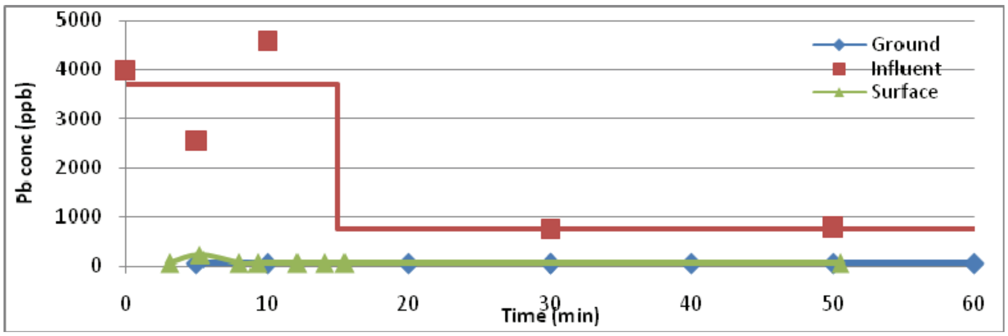


Figure 91. Total concentration of lead in 2:1 slope, medium flow rate.

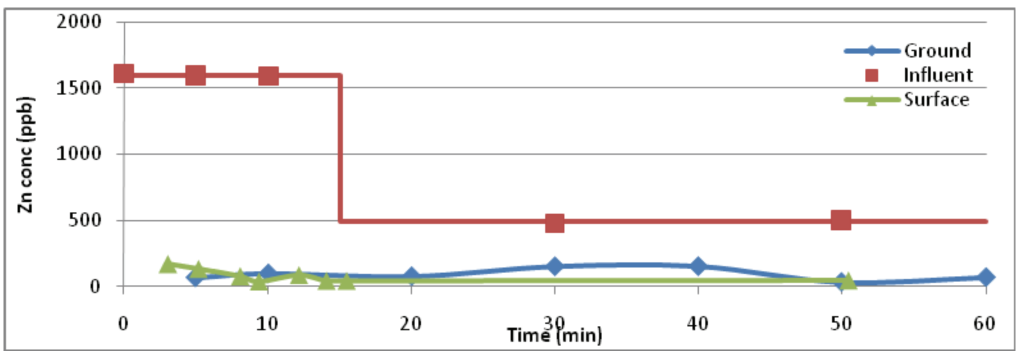


Figure 92. Total concentration of zinc in 2:1 slope, medium flow rate.

Figure 93 through Figure 99 portray the total metals concentrations from the high flow rate test at a 2:1 slope. The initial flow rate of 5.43 gpm (20.55 lpm) was maintained for 6 min and then followed by a flow rate of 1.18 gpm (4.47 lpm) for 24 min. The initial influent flow had lower concentrations than the target values listed in Table 11 but within a 20% margin, except for Zn which had an initial average concentration 190% of the target value due to a single, very high detection. For the first 5 min, the influent concentration slightly decreased for every metal, but stayed consistent throughout, except Zn, which had a large decrease from 4790 μg/L to 1672 μg/L. The tail end of the influent flow was consistent for every metal as was the case for the other three tests.

Surface runoff was generated throughout the entire test, and metal concentrations were highest during the first 5 min of the test, and then decreased at the tail end for the remainder of the run. The only metal that did not display this trend was Pb, because it was not detected throughout the run at a detection limit of 58 μg/L. Cr was not detected after the first 5 min at a detection limit of 6 μg/L. Overall, the surface runoff concentrations were low, and gave average percent removals for Cd, Cr, Cu, Fe, Ni, Pb, and Zn as follows: 91.7%, 98.2%, 96.5%, 96.9%, 86.1%, 98.9%, and 94.3%. As with the other three slopes, Cr and Pb had the highest percent removals. These removals were similar to removals at the other slopes and flow rates for the high concentration performance tests and show no consistent trend.

Different metals were detected in underdrain samples from the 2:1 high flow test than in previous tests. For the 2:1 medium flow test, Cd, Cr, Ni, and Pb were not detected, while for the 2:1 high flow test, Cr, Cu, and Pb were not detected, with detection limits 6 µg/L, 8 µg/L, and 58 µg/L. This was the only test, where Cu was not detected in several samples. Cu was detected at concentrations of between 9 µg/L and 16 µg/L in four samples. Every metal except Pb had a higher concentration in the beginning of the run, and then the concentrations decreased during the tail end of the test. Cr and Pb were not detected in the underdrain samples. Overall, the concentrations were low compared to the influent samples.

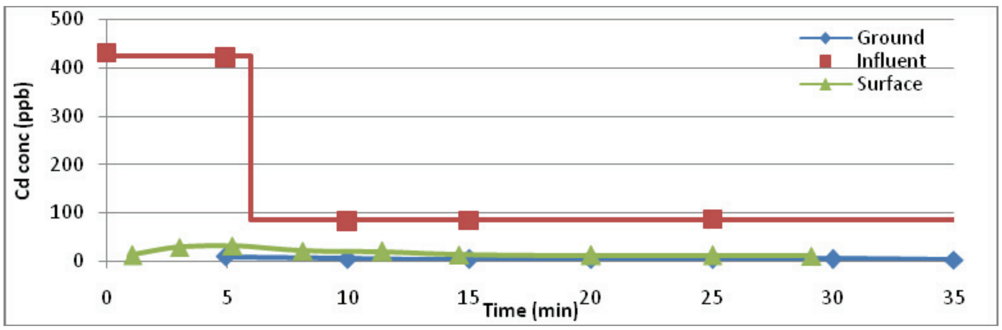


Figure 93. Total concentration of cadmium in 2:1 slope, high flow rate.

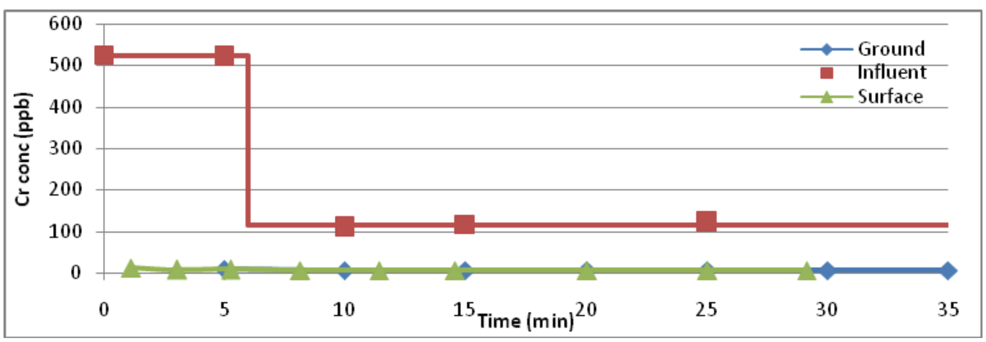


Figure 94. Total concentration of chromium in 2:1 slope, high flow rate.

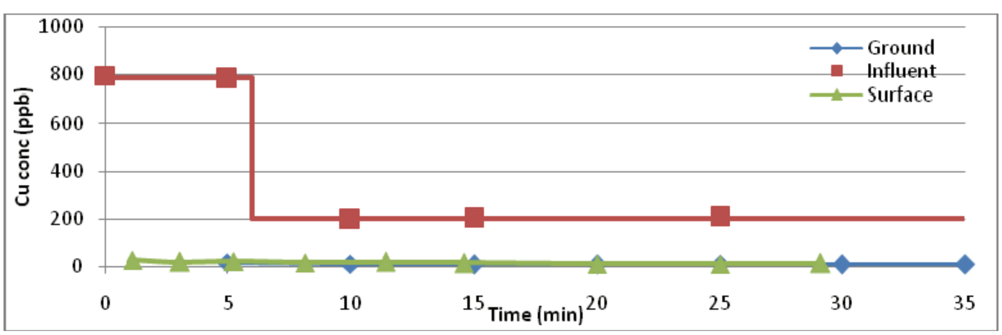


Figure 95. Total concentration of copper in 2:1 slope, high flow rate.

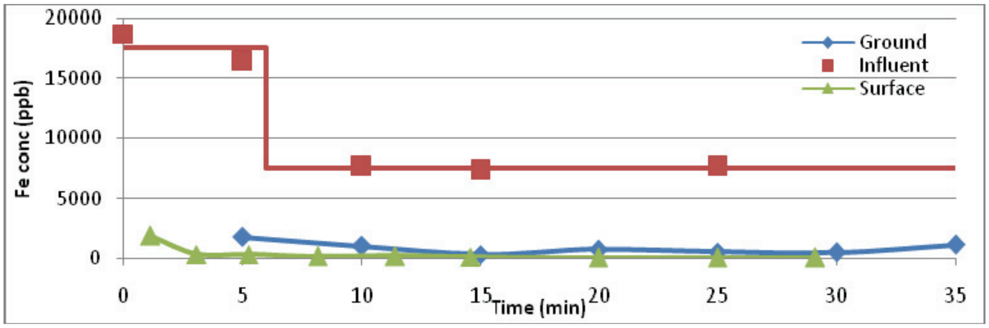


Figure 96. Total concentration of iron in 2:1 slope, high flow rate.

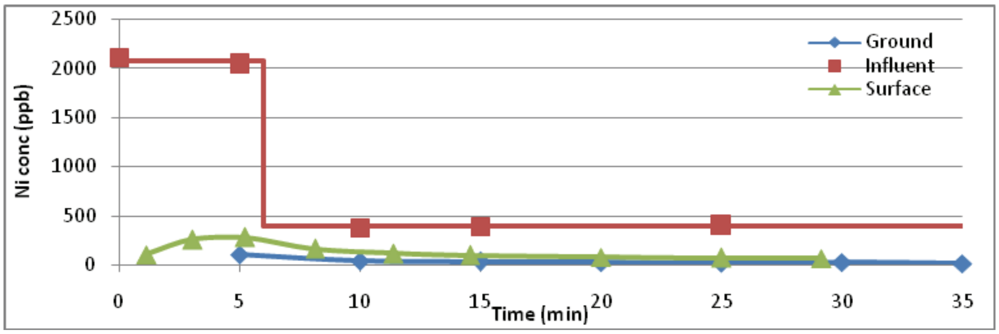


Figure 97. Total concentration of nickel in 2:1 slope, high flow rate.

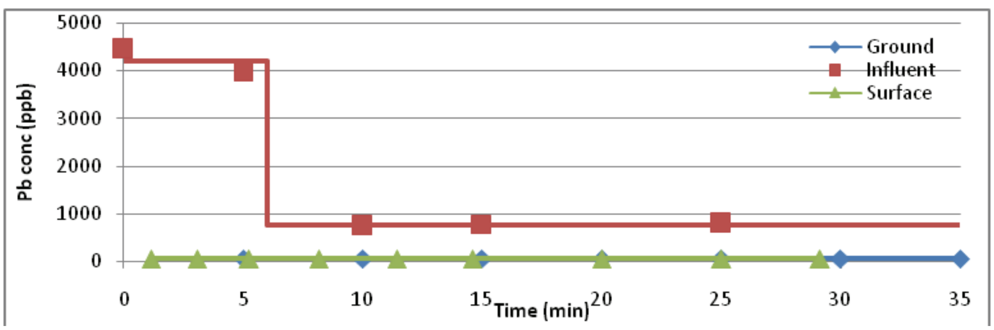


Figure 98. Total concentration of lead in 2:1 slope, high flow rate.

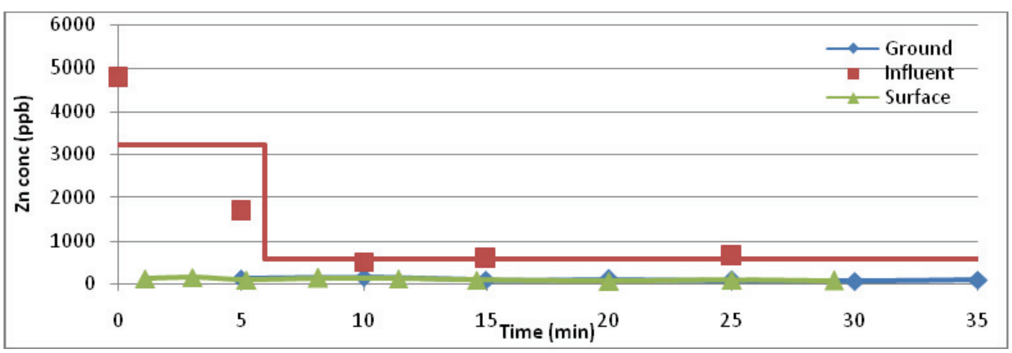


Figure 99. Total concentration of zinc in 2:1 slope, high flow rate.

10.5 Dissolved Metals Results

Dissolved metal samples were collected on site by filtering the samples with a 0.45 µm (0.018 mil) syringe filter. These samples were preserved with acid and analyzed by ICP-OES. Cr, Cu, and Pb were not detected in all influent, surface, and underdrain samples for both 8:1 and 4:1 slope tests with detection limits of 7 µg/L, 9 µg/L, and 55 µg/L. Influent dissolved iron results were very erratic varying from 126 µg/L to not detected at a detection limit of 6 µg/L, indicating inconsistent partitioning between the dissolved, precipitate, and sorbed phases in the influent solution. Surface runoff concentrations of Fe were not detected at a detection limit of 6 µg/L or close to that limit, while underdrain concentrations averaged 32 µg/L higher than the average baseline concentration of 13 µg/L seen in Table 21. It should be noted, however, that even the highest dissolved Fe concentration values are less than 1% of the total Fe concentration, which was about 18,000 µg/L; these dissolved Fe results may be more sensitive to subtle changes in aquatic chemistry. Figure 100 through Figure 102 display the dissolved metals results for the 8:1 medium flow test for Cd, Ni, and Zn; those for the 4:1 medium flow test are shown in Figure 103 through Figure 105. For both tests, influent concentrations for dissolved Cd, Ni, and Zn were consistent and tracked the total metals concentrations. The fraction of total metals that were dissolved in the influent varied from 0.11 to 0.62 for Cd, 0.40 to 0.89 for Ni, and 0.01 to 0.22 for Zn. Cd and Zn were not detected in the underdrain and surface samples or were very close to the detection limits of 2 µg/L and 5 µg/L. Ni was detected in surface runoff, with an average concentration of 46.7 µg/L for the 8:1 test and 96.7 µg/L for the 4:1 test, far below dissolved influent concentrations of 1,100 µg/L to 1,600 µg/L. The fraction of total Ni that was dissolved in the surface runoff samples varied from 0.80 to 1.00.

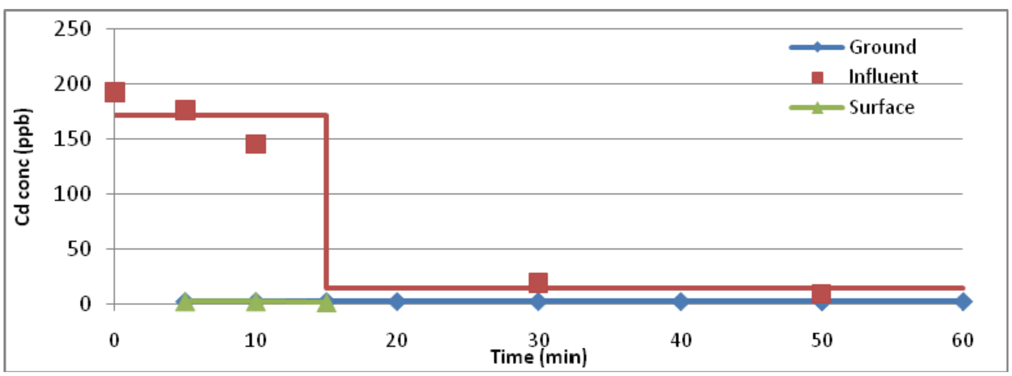


Figure 100. Dissolved concentration of cadmium in 8:1 slope, medium flow rate.

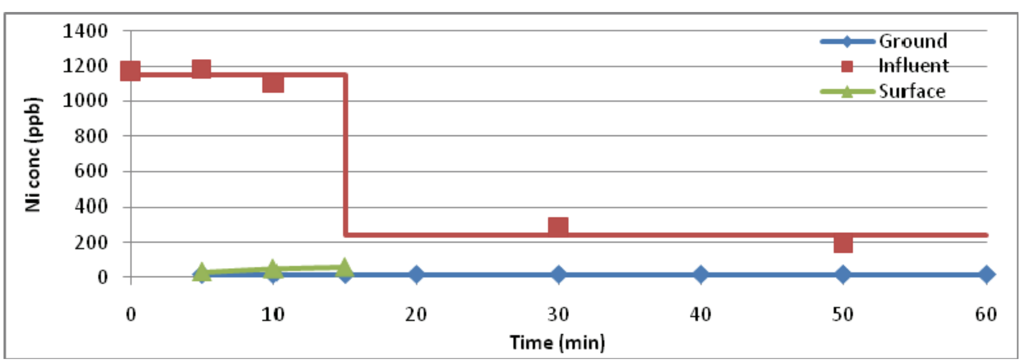


Figure 101. Dissolved concentration of nickel in 8:1 slope, medium flow rate.

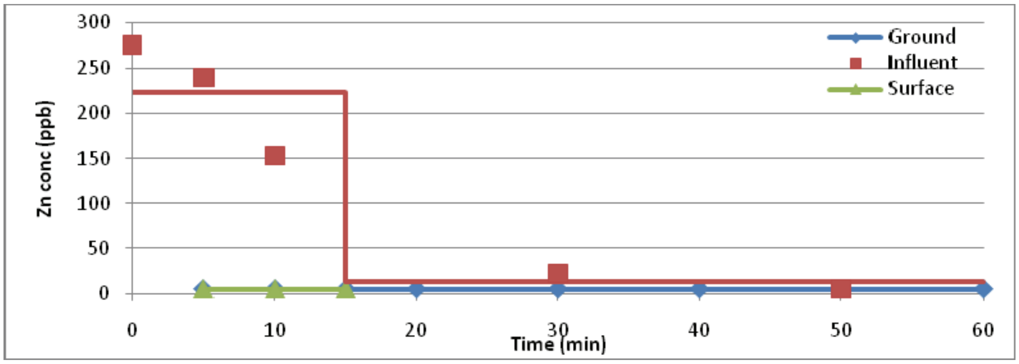


Figure 102. Dissolved concentration of zinc in 8:1 slope, medium flow rate.

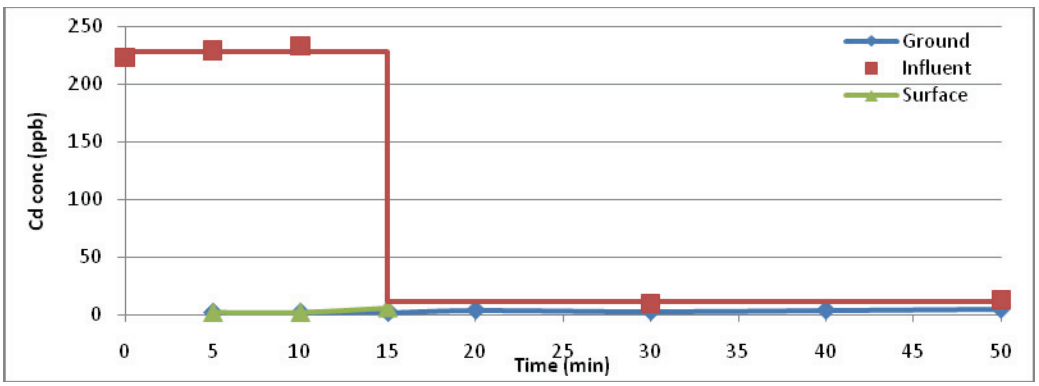


Figure 103. Dissolved concentration of cadmium in 4:1 slope, medium flow rate.

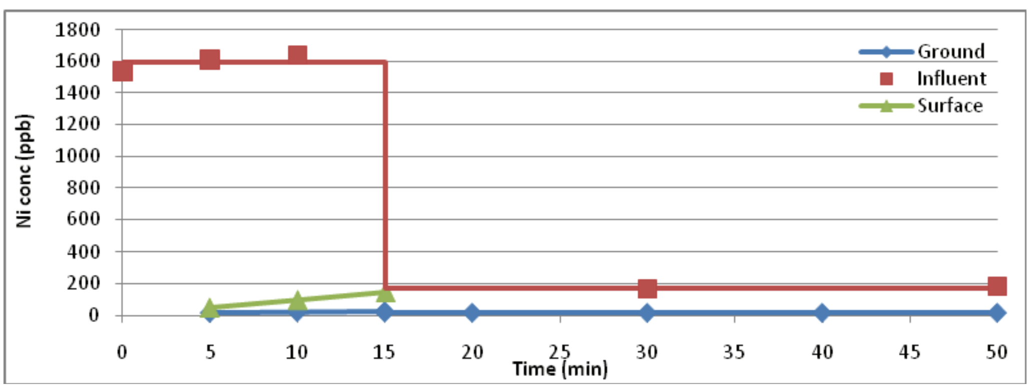


Figure 104. Dissolved concentration of nickel in 4:1 slope, medium flow rate.

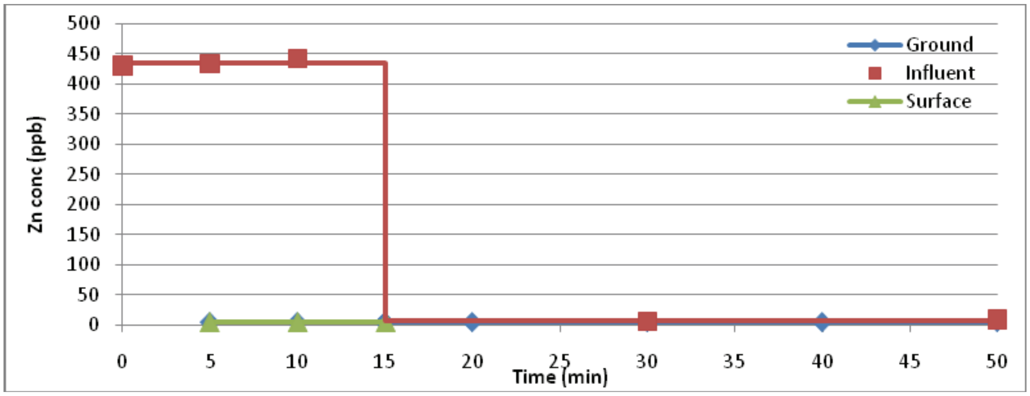


Figure 105. Dissolved concentration of zinc in 4:1 slope, medium flow rate.

Dissolved Cr and Pb were not found in any samples in the 2:1 slope medium flow tests with detection limits of 2 µg/L and 48 µg/L, as was the case with the 8:1 and 4:1 tests. Dissolved Cu was detected in all samples between 4 µg/L and 17 µg/L, similar to baseline concentrations. Dissolved Fe was again detected sporadically in the influent and surface runoff, but consistently in the underdrain at an average concentration of 40.6 µg/L. Figure 106 through Figure 108 display the dissolved metals results for the 2:1 medium flow test for Cd, Ni, and Zn. Dissolved Cd, Ni, and Zn were detected in all influent samples, though the concentrations did not track the total metals trends, with concentrations in the tailing portion of the storm similar or higher than in the initial portion of the storm. Sorption is a nonlinear process, and the partitioning of metals is pH dependent, which contributes to the variability in dissolved metals concentrations. The fraction of total metal dissolved was 0.20 to 0.90 for Cd, 0.32 to 0.90 for Ni, and 0.03 to 0.57 for Zn. Dissolved Cd and Zn in surface and underdrain samples were not detected or close to detection limits of 5 µg/L and 3 µg/L. Dissolved Ni averaged 31.0 µg/L in the surface runoff, much lower than the average dissolved influent concentration of 640 µg/L, and was not detected or near the detection limit of 13 µg/L in the underdrain. The fraction of dissolved Ni in the surface runoff varied from 0.35 to 1.00.

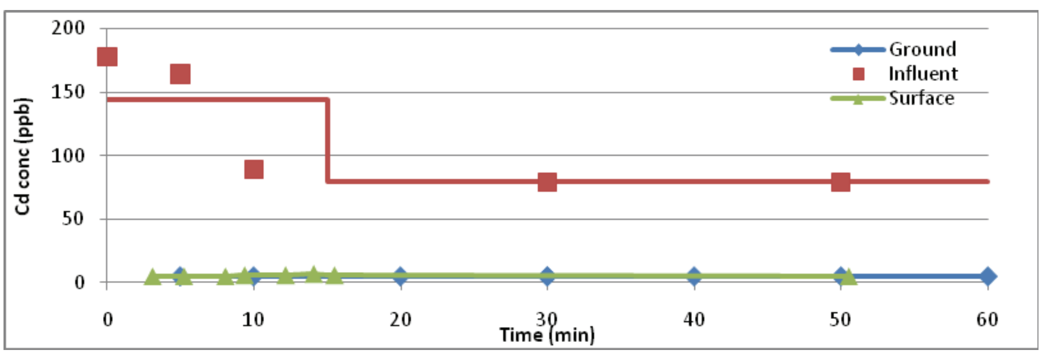


Figure 106. Dissolved concentration of cadmium in 2:1 slope, medium flow rate.

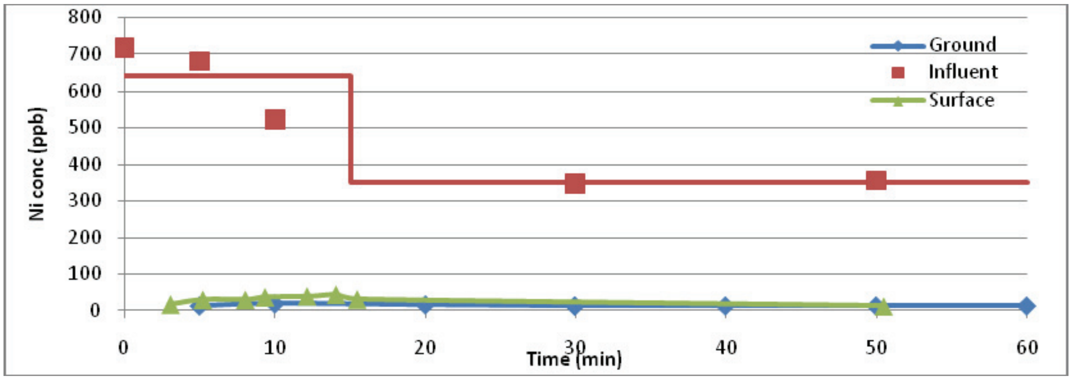


Figure 107. Dissolved concentration of nickel in 2:1 slope, medium flow rate.

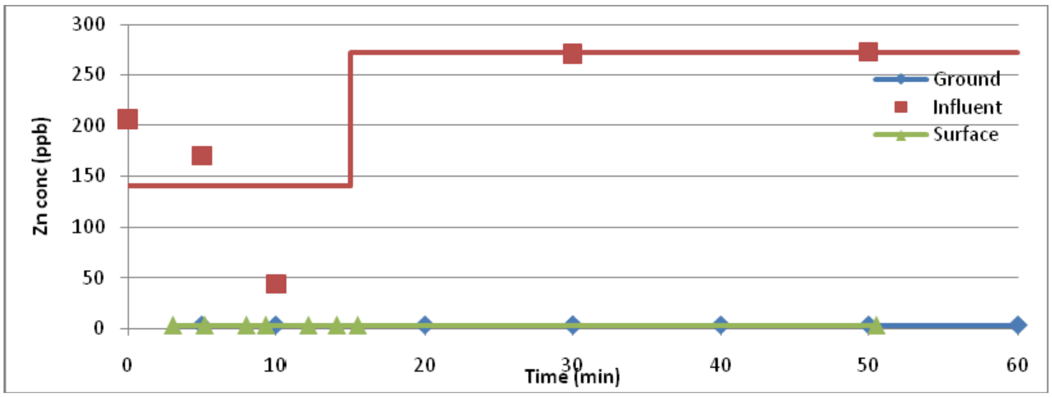


Figure 108. Dissolved concentration of zinc in 2:1 slope, medium flow rate.

The 2:1 high flow test metals results were similar to the 2:1 medium flow results, as displayed in Figure 109 through Figure 111. Concentrations of Cr, Cu, and Pb were near or at detection limits for the influent, surface, and underdrain samples; detection limits were 6 µg/L, 8 µg/L, and 58 µg/L respectively, except for the 5 min influent sample. This sample had uncharacteristically high levels of all dissolved metals indicating a problem with the sample, possibly failure of the filter to remove all particles. Dissolved Cd, Ni, and Zn were detected in all influent samples with lower concentrations in the tailing portion of the storm and dissolved fractions of 0.50 to 0.65 for Cd, 0.75 to 0.94 for Ni, and 0.08 to 0.47 for Zn. Different than the other tests, Cd and Zn were detected in nearly all of the surface runoff samples at average values of 17.4 µg/L and 17.7 µg/L, respectively. The fractions of dissolved metals in these samples were 0.62 to 1.00 for Cd and 0.10 to 0.49 for Zn. Dissolved Cd and Zn were not detected or were detected near detection limits in underdrain samples at limits of 3 µg/L and 4 µg/L. Dissolved Ni was detected in nearly all surface runoff and underdrain samples at average values of 231 µg/L and 107 µg/L during the first portion of the storm and 95.6 µg/L and 32.8 µg/L during the tailing portion of the storm. The fraction of dissolved Ni was 0.94 or greater for all of these samples.

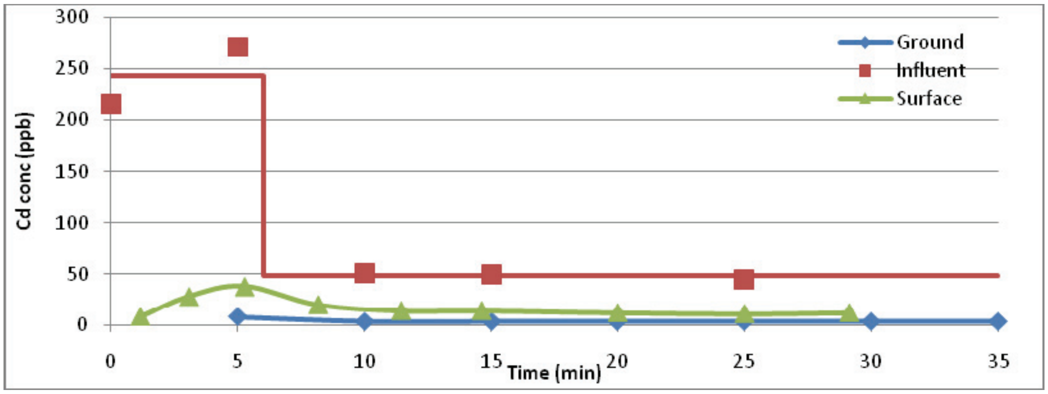


Figure 109. Dissolved concentration of cadmium in 2:1 slope, high flow rate.

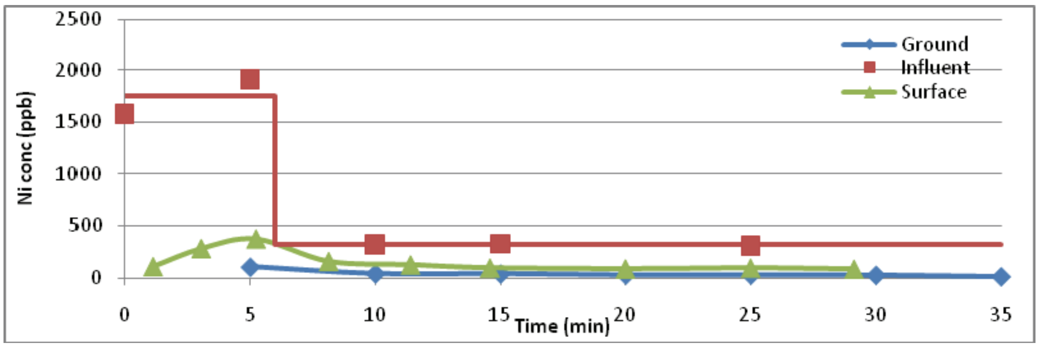


Figure 110. Dissolved concentration of nickel in 2:1 slope, high flow rate.

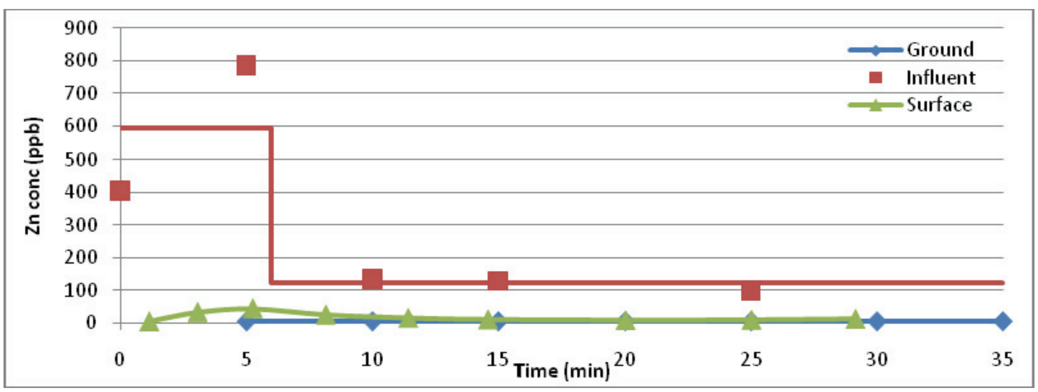


Figure 111. Dissolved concentration of zinc in 2:1 slope, high flow rate.

10.6 Oil and Grease Results

In the high concentration tests for Bed 1, motor oil was added to the influent mixture with target concentrations of 20 mg/L followed by 5 mg/L. Results for the 8:1, 4:1, 2:1 medium flow and 2:1 high flow tests are shown in Figure 112 through Figure 115. Influent concentrations differed considerably from the target values particularly for the tailing portion of flow. It was observed during the test that the motor oil floated in a separate phase on the surface of the well-mixed influent tank, and consequently was not uniformly delivered to the test bed. Because the oil was immiscible in water, the effluent results were also fairly erratic. The oil did not flow across the bed in a dispersed uniform concentration, but rather in highly concentrated droplets that migrated chaotically. As a result, most surface and underdrain concentrations were low interspersed with spikes of high concentration. It was also observed through QA/QC checks that analysis results below 20 mg/L were unreliable, with high percent errors using calibration standards. The oil and grease analysis method is highly dependent on operator experience and laboratory protocols. Because of these complications, the oil and grease experimental procedures for Bed 1 were changed to improve results for experiments with Bed 2 and Bed 3. Nevertheless, surface runoff and underdrain concentrations of oil and grease were lower than influent concentrations for most runs with percent decrease in event mean concentrations of 31%, 69%, and 43% for the 8:1, 4:1, and 2:1 medium flow tests. For the 2:1 high flow test, the first surface runoff concentration was much higher than the concentration in the influent samples, so the concentration appeared to increase through the bed. This illogical result is attributed to the erratic behavior of the oil in the bed.

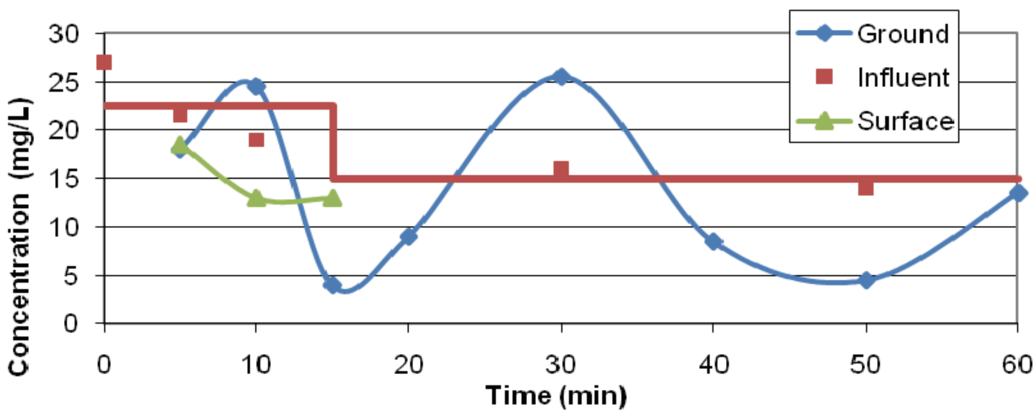


Figure 112. Concentration of oil and grease at 8:1 slope.

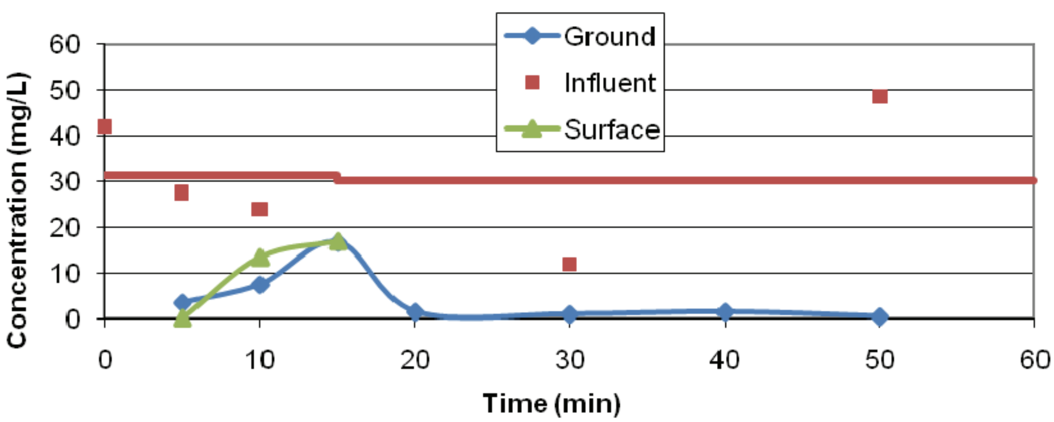


Figure 113. Concentration of oil and grease at 4:1 slope.

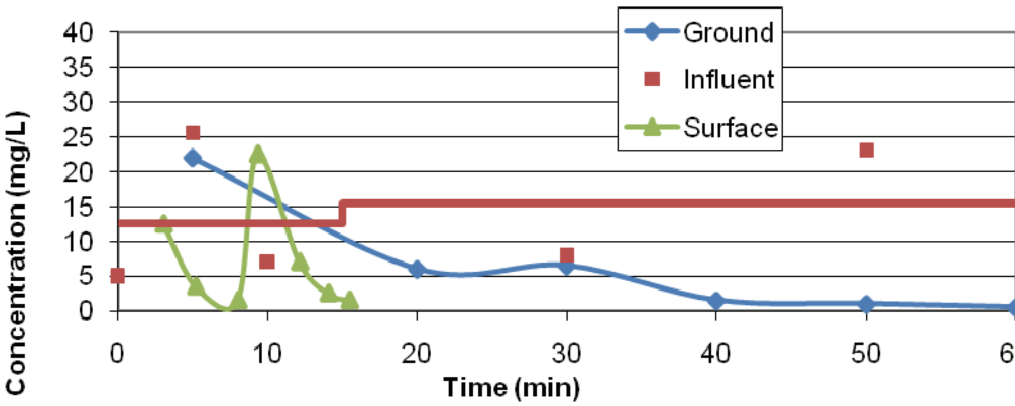


Figure 114. Concentration of oil and grease at 2:1 slope, medium flow.

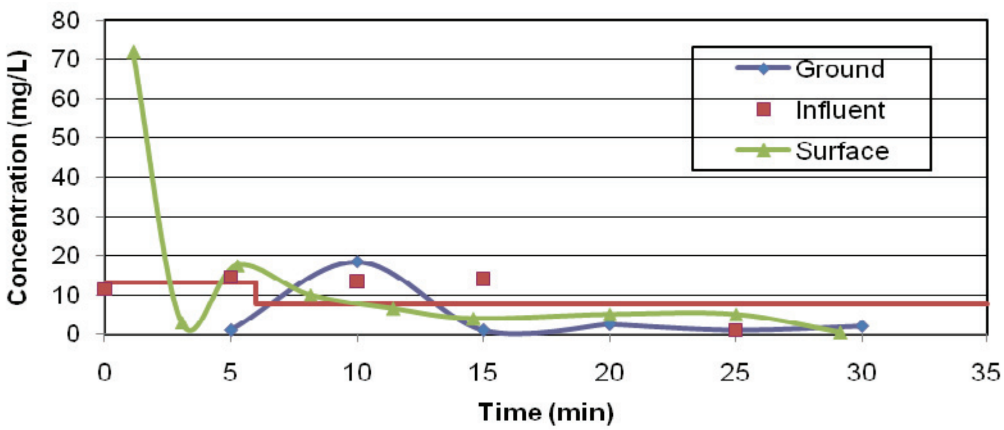


Figure 115. Concentration of oil and grease at 2:1 slope, high flow.

10.7 Deuterated Alkane Results

Three different deuterated alkanes, $C_{20}D_{42}$, $C_{24}D_{50}$, and $C_{30}D_{62}$, which are n-alkanes typically found in motor oil but with deuterium (D) substituted for hydrogen (H) in each molecule, were added to the motor oil before it was combined with the influent mixture for Bed 1, at concentrations given in Table 11. Because the alkanes, like oil, are also immiscible in water, these results were limited by the same problems discussed above for motor oil (see Section 10.6), namely poor delivery of the oil to the bed and erratic behavior of the motor oil flowing over the bed. The experimental methods were altered to improve results for tests on Bed 2 and Bed 3. Results for the deuterated alkanes analyses are shown in Figure 116 through Figure 119. In these figures, the total concentration of the three deuterated alkanes was summed and plotted. Deuterated alkanes were detected in the influent for most of the samples in the tests, except for the 2:1 medium flow test, where they were not detected in three of the influent samples. Further, influent concentrations measured in the 2:1 tests were much lower than the influent concentrations in the 8:1 and 4:1 tests. In the 8:1 test, the highest concentrations of alkanes were detected in the surface runoff, while no deuterated alkanes were detected in the underdrain with detection limits of 0.05 µg/L. Similarly, in the 4:1 test deuterated alkanes were detected in the initial surface and underdrain samples, but thereafter were not detected or were near the detection limit of 0.05 µg/L. All of the surface and underdrain samples from the 2:1 tests were below or near the detection limits of 0.002 µg/L for the medium flow test and 0.11 µg/L for the high flow test.

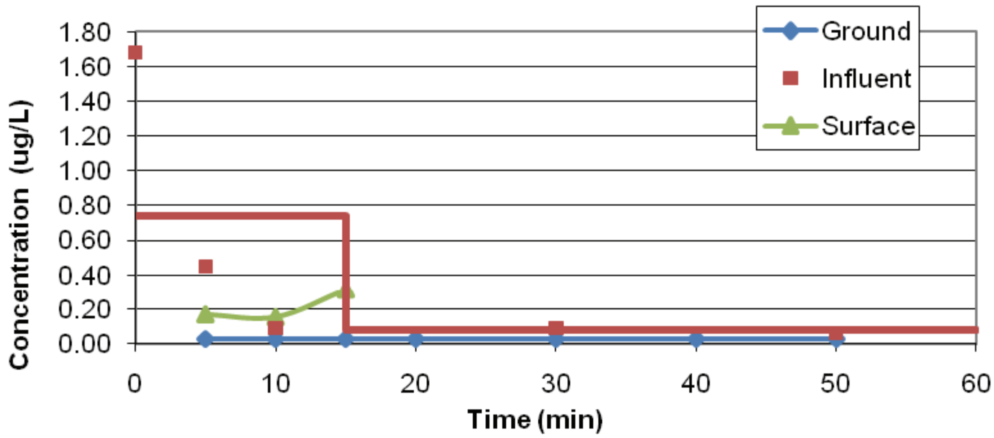


Figure 116. Total concentration of deuterated alkanes at 8:1 slope.

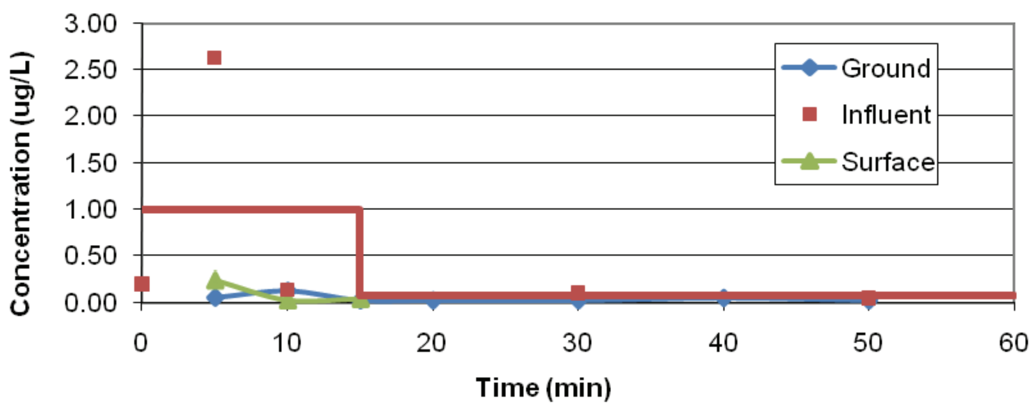


Figure 117. Total concentration of deuterated alkanes at 4:1 slope.

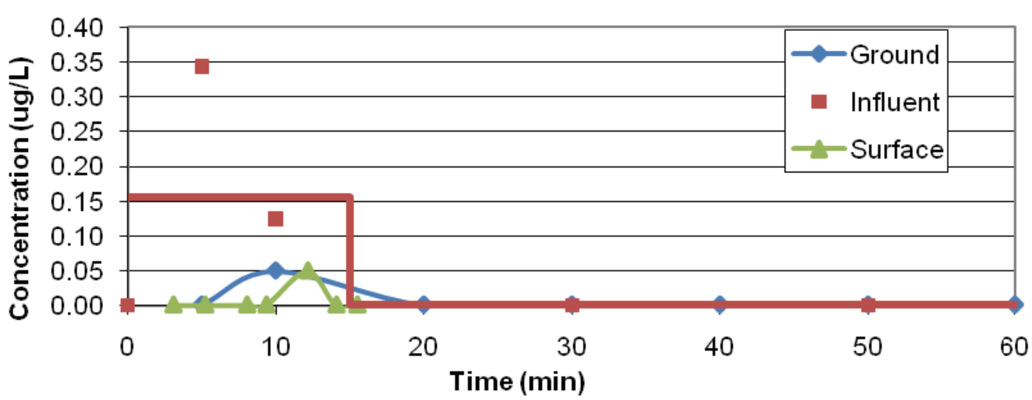


Figure 118. Total concentration of deuterated alkanes at 2:1 slope, medium flow.

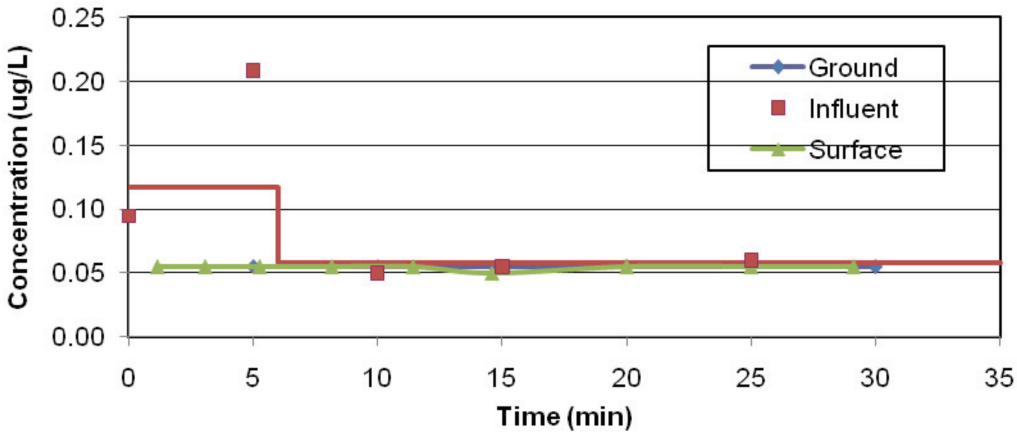


Figure 119. Total concentration of deuterated alkanes at 2:1 slope, high flow.

10.8 Removals

Figure 120 displays the percent removals based on the event mean concentration (EMC) for each total metal, total suspended solids, and oil and grease for each performance test with Bed 1. It can be seen from this figure that percent removals were above 80 % for every metal and suspended solids. Oil and grease had much lower percent removals, however as described above there were significant problems in working with the motor oil. A percent removal was not plotted for the 2:1 slope, high flow test, because the surface runoff event mean concentration exceeded the influent event mean concentration. As stated above, Cr and Pb, had the highest percent removals over all four performance tests. For the high concentration set of tests, no definitive trends were noted with changes in slope or flow rate.

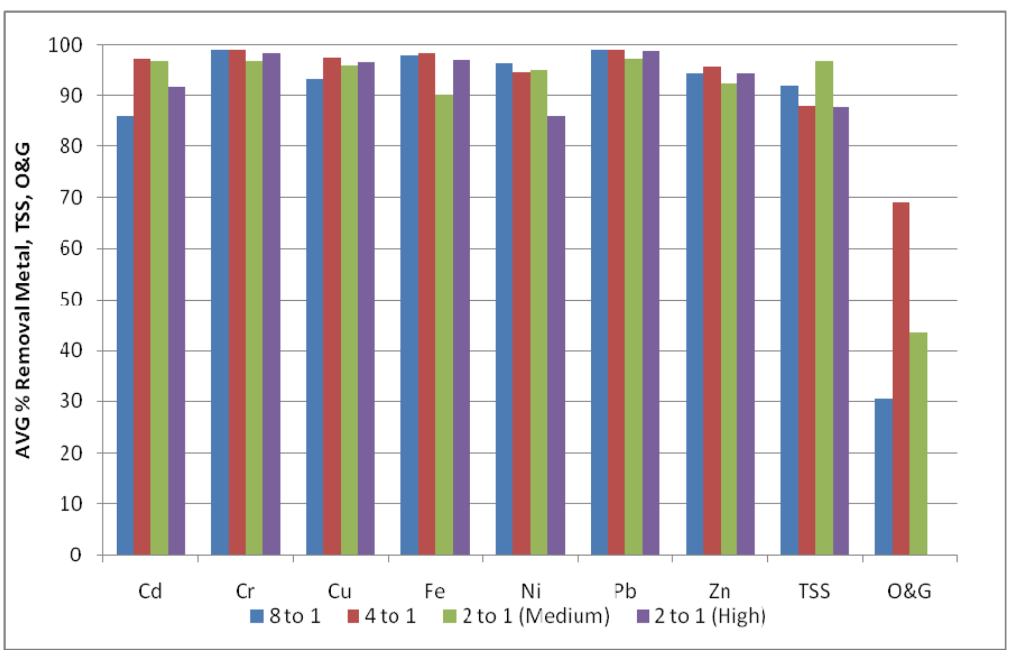


Figure 120. Percent removals of event mean concentration for total metals, TSS, and oil and grease from high concentration influent tests on Bed 1.

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 121. Percent removals were almost always slightly higher when considering only the water quality event portion, because the event mean concentration of the storm water influent was higher and did not include the tailing portion of the storm that has lower concentrations. For Bed 1, differences between using the complete storm and only the water quality event portion were no greater than 4.1% for all metals and TSS, and no greater than 8.6% for oil and grease.

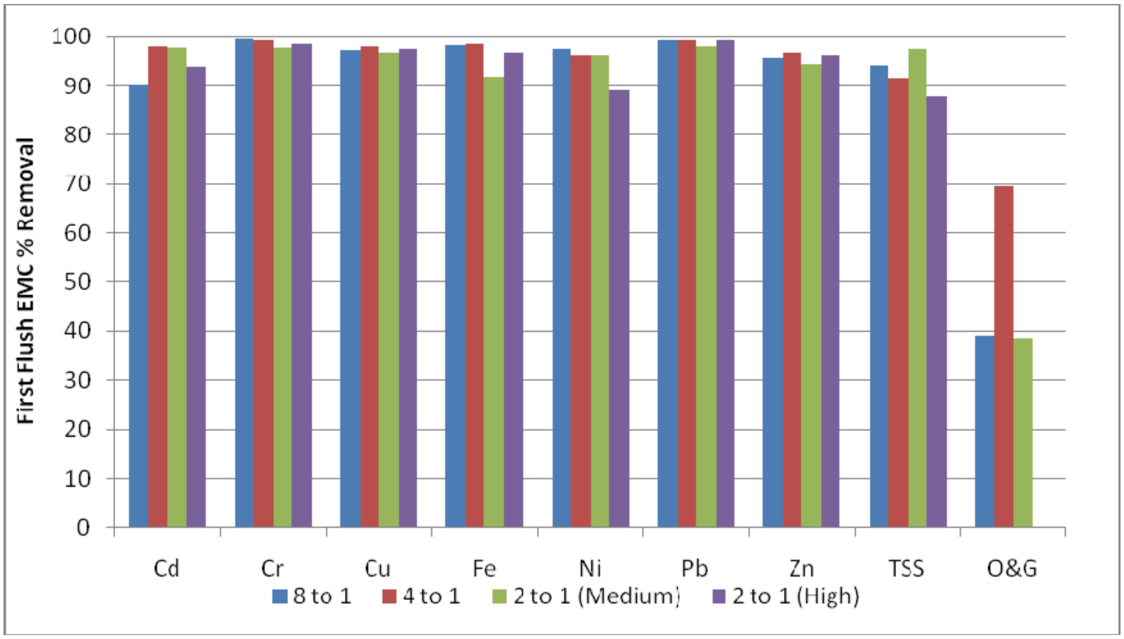


Figure 121. Percent removal of event mean concentration during the water quality volume of the storm event for total metals, TSS, and oil and grease for Bed 1.

10.9 Resuspension Results

After the four performance tests were completed on the bed, resuspension tests were conducted to determine if the tagged suspended solids could become remobilized. Four resuspension tests were conducted that represented each slope and flow rate used for the performance testing. For the initial 8:1 slope performance test, La tagged suspended solids were added to the influent with target values of 737 mg/L for the water quality event portion (defined here as the first 0.75 in (19 mm) of runoff) of the test and 207 mg/L for the tailing portion of the test. Subsequent tests did not tag the suspended solids that were added to the influent. As displayed in Figure 122, the first three collected influent samples exhibited tagged suspended solids concentrations near the target concentration for the water quality event portion, with an average tagged suspended solids concentration of 810 mg/L, and an average La concentration of 48,767 μg/L. The last two collected influent samples exhibited tagged suspended solids concentrations very close to the target concentration for the tailing portion of the test, with an average tagged suspended solids concentration of 208 mg/L, and an average La concentration of 12,550 μg/L.

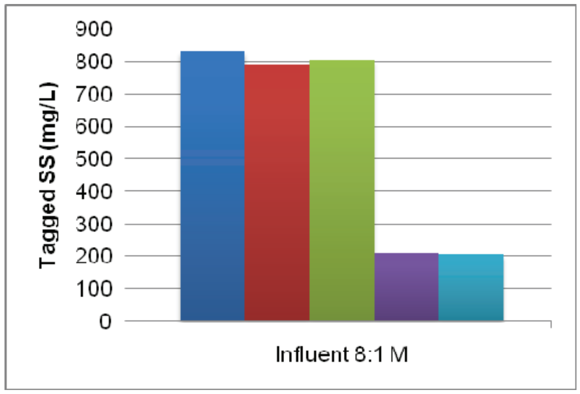


Figure 122. Influent tagged suspended solids concentration in 8:1 slope, medium flow rate. From left to right, the bars represent influent samples collected at times of 0 min, 5 min, 10 min, 30 min, and 50 min during the simulated storm event.

Figure 123 displays the tagged suspended solids concentrations in the surface runoff samples for each test on Bed 1, four performance tests and four resuspension 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 4 mg/L and an average La concentration of 226 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 tagged suspended solids concentration of 810 mg/L and average La concentration of 48,767 μg/L. The fraction of La tagged soil in samples greatly decreased from approximately 1.0 in the influent to 0.20 in the surface samples. This low tagged fraction in the surface runoff showed that the majority of the added suspended solids were settling within the bed, and only a fraction flowed over the bed without settling. Further, the majority of the total suspended sediment in the runoff (average of 47 mg/L for this run, see Figure 66) 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 14.4 mg/L with only tap water as influent. The other three performance tests resulted in very low concentrations of tagged suspended solids in surface runoff, averaging 0.29 mg/L for the 4:1 medium flow test, 0.24 mg/L for the 2:1 medium flow test, and 0.06 mg/L for the 2:1 high flow test. In the 4:1 medium flow test, La was detected, with an average concentration of 17 μg/L. In the 2:1 medium flow test, La was only detected for the first 8 min, and then was not detected for the remainder of the test, with a detection limit of 8 μg/L. In the 2:1 high flow test, La was not detected throughout the entire test.

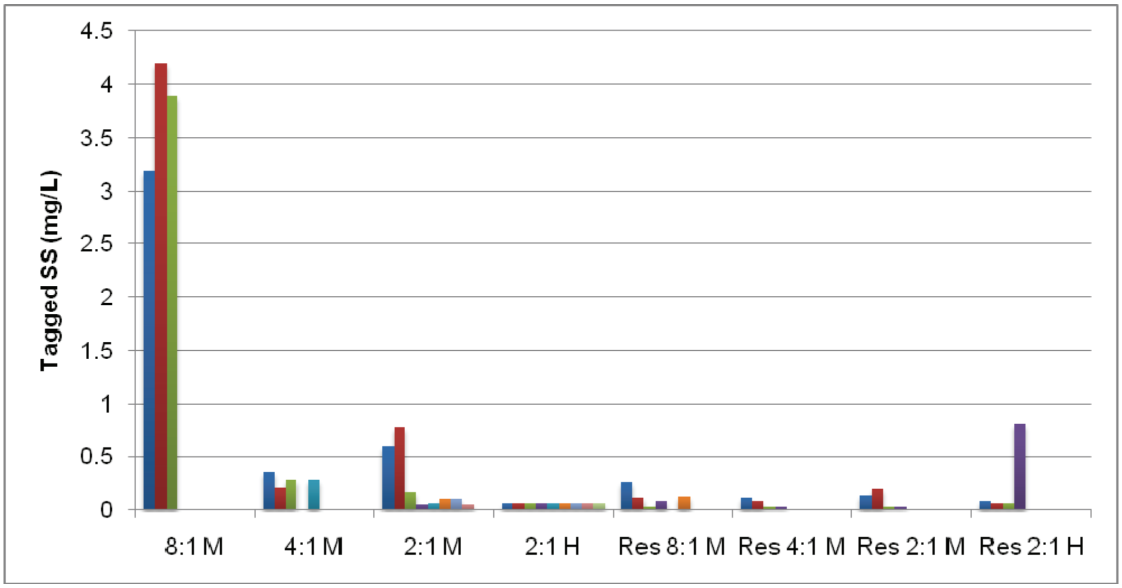


Figure 123. Tagged suspended solids concentrations for experimental and resuspension tests. Each bar represents a collected surface sample.

Each of the resuspension tests also had very low concentrations of tagged suspended solids, with average concentrations of 0.12 µg/L for the 8:1 medium flow test, 0.07 µg/L for the 4:1 medium flow test, 0.10 µg/L for the 2:1 medium flow test, and 0.26 µg/L for the 2:1 high flow test, which were all lower concentrations than the initial tests, except for one sample in the 2:1 high flow test. La concentrations remained low for each test, except a spike in surface La concentration for the 2:1 high flow test with a concentration of 49 µg/L, which was approximately the same concentration of the 2:1 medium flow spike for the performance tests, with a surface La concentration of 47 µg/L. Based on these data, it appears that the tagged suspended solids initially added to the 8:1 medium flow influent did not become resuspended, except when the slope and flow rate were higher, but even then these concentrations were approximately 1000 times lower than the average 8:1 medium flow influent La concentration.

10.10 Metal Accumulation in Grass, Soil, and Roots

Five soil cores were initially collected from the bed from random locations to determine the baseline metals concentrations in the soil, grass, and roots. After completion of all performance and resuspension tests, twenty cores were collected throughout the bed, four replicates at five different locations down the length of the bed. As described previously in Section 8.3, the cores were separated into grass, root, and soil fractions, and each fraction was digested and analyzed for metals concentrations using the ICP-OES as described in Section 8.7.1. The metals added to the influent included Cd, Cr, Cu, Fe, Ni, Pb, and Zn. Figure 124 through Figure 130 display the concentrations in mg of metal/kg of dry matter within the grass, soil, and roots down the length of the bed. Because four 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 solid horizontal lines on each graph represent the average baseline concentrations of the grass, soil, and roots before any tests were conducted. It should be noted that the drip line where the influent actually touched the bed was located 2.2 ft (0.67 m) from the origin of the bed. The distances in the following discussion are relative to the origin of the bed:

2.2 ft (0.67 m), 4.4 ft (1.34 m), 6.6 ft (2.01 m), 8.8 ft (2.68 m), and 10.1 ft (3.08 m); relative to the drip line, these positions are 0 ft (0.0 m), 2.2 ft (0.67 m), 4.4 ft (1.34 m), 6.6 ft (2.01 m), and 7.9 ft (2.41 m).

All of the metals except Fe show similar results, with the highest concentrations detected in root tissue, next highest in grass tissue, and low concentrations detected in soil. In terms of the spatial distribution of the metals, with the exception of Fe, the highest concentrations were detected at a distance of 4.4 ft (1.34 m) from the beginning of the bed, or 2.2 ft (0.67 m) from the drip line, and then decreased along the length of the bed. Grass and root concentrations varied considerably among the duplicate samples, so even though average concentrations were often above background levels, in many cases the differences were not statistically significant (α=0.5 for all tests). Average soil concentrations, though much lower than average grass and root concentrations, had much smaller standard deviations and in some cases were significantly different than background concentrations, even though it is not apparent in the figures. The one exception to all of these trends was Fe which had high background concentrations in all media, and all levels detected after testing were not significantly different from those background concentrations.

Cd was the only metal that had a statistically significant accumulation throughout the bed in the grass, soil, and root media (see Figure 124). Highest concentrations were found in the roots and grass. Even though concentrations in soil were only slightly above background concentrations, because the variability was low, the differences were statistically significant. Pb was also detected at elevated concentrations throughout the bed in the roots and soil (see Figure 129). Pb was found above background in grass at the 2.2 ft (0.67 m), 4.4 (1.34 m), and 6.6 ft (2.01 m) distances, but beyond that grass concentrations were not significantly different than background. Cu similarly had elevated concentrations in roots throughout the bed and in soil at the 2.2 ft (0.67 m), 4.4 (1.34 m), and 6.6 ft (2.01 m) locations (see Figure 126). All concentrations of Cu in grass were indistinguishable from background. Ni had elevated concentrations in the roots throughout the bed, but was only found at a significant level above background in the grass at the 2.2 ft (0.67 m) location (see Figure 128). Ni was not above background in soil. Cr was only above background concentrations in the roots at the 2.2 ft (0.67 m) and 4.4 ft (1.34 m) locations and in the grass at the 2.2 ft (0.67 m) location (see Figure 125). Cr was not above background in soil. Zn was only above background concentrations in the roots at the 2.2 ft (0.67 m) and 4.4 ft (1.34 m) locations, and was not above background in any of the soil or grass samples (see Figure 130). This was in part due to high background Zn concentrations, which may be due to the presence of Zn in tap water used to water the bed (see Table 12). Fe being a common element was present at high levels in background samples and consequently not detected at concentrations above background in any samples (see Figure 127). In addition, average concentrations of Fe did not decrease along the length of the bed like all the other metals.

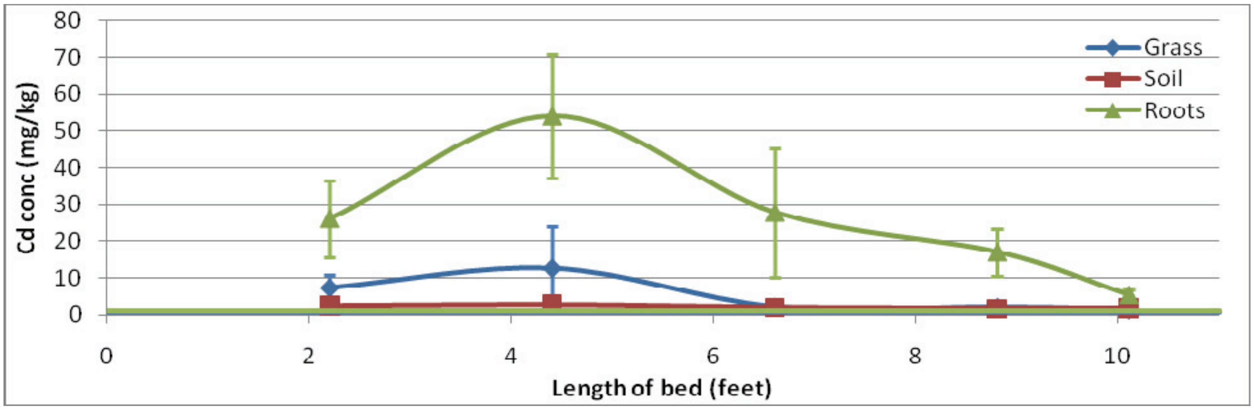


Figure 124. Concentration of Cd throughout length of Bed 1 after tests.

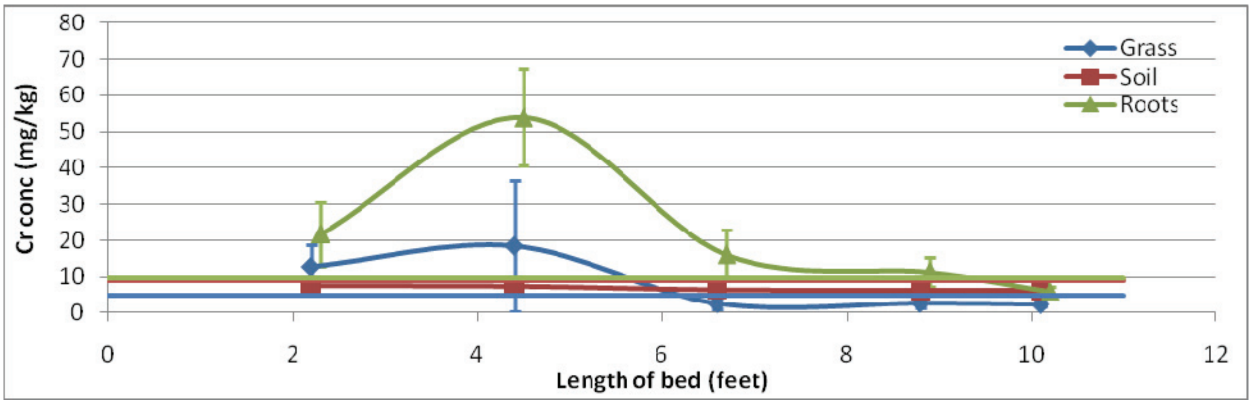


Figure 125. Concentration of Cr throughout length of Bed 1 after tests.

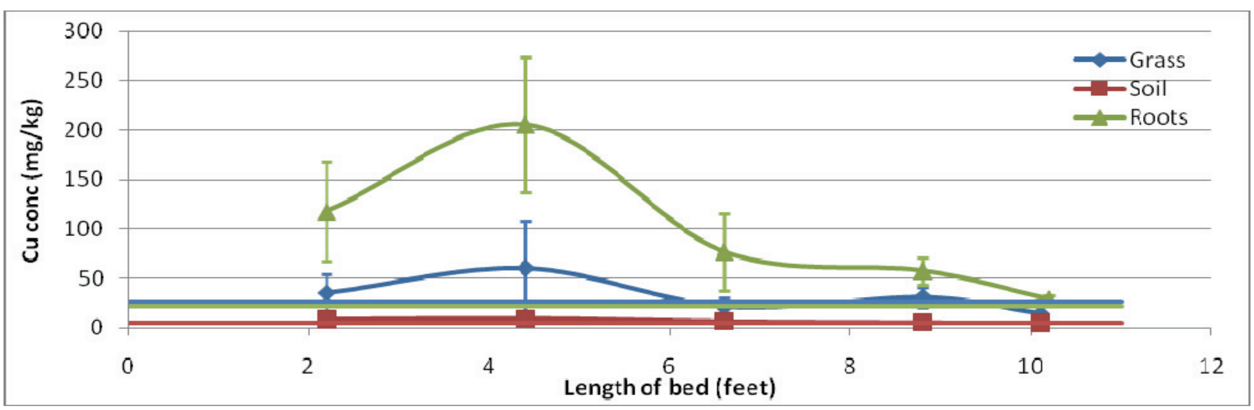


Figure 126. Concentration of Cu throughout length of Bed 1 after tests.

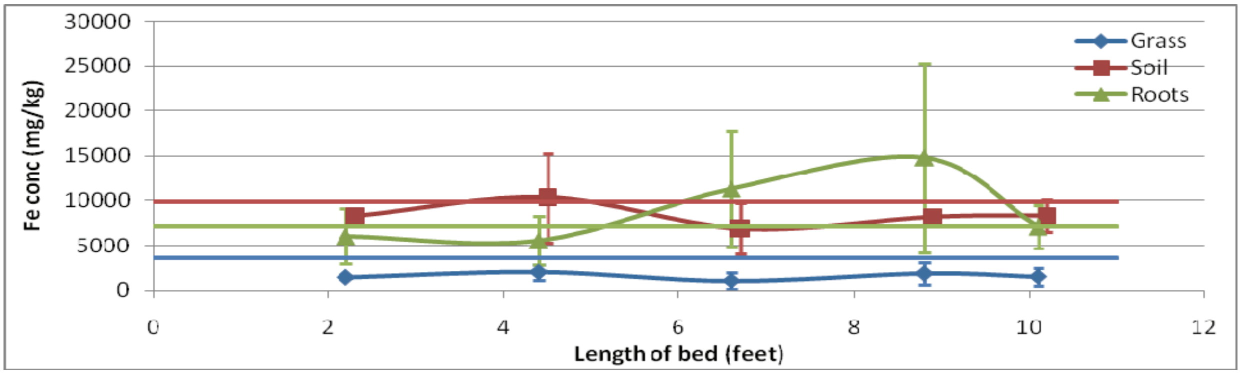


Figure 127. Concentration of Fe throughout length of Bed 1 after tests.

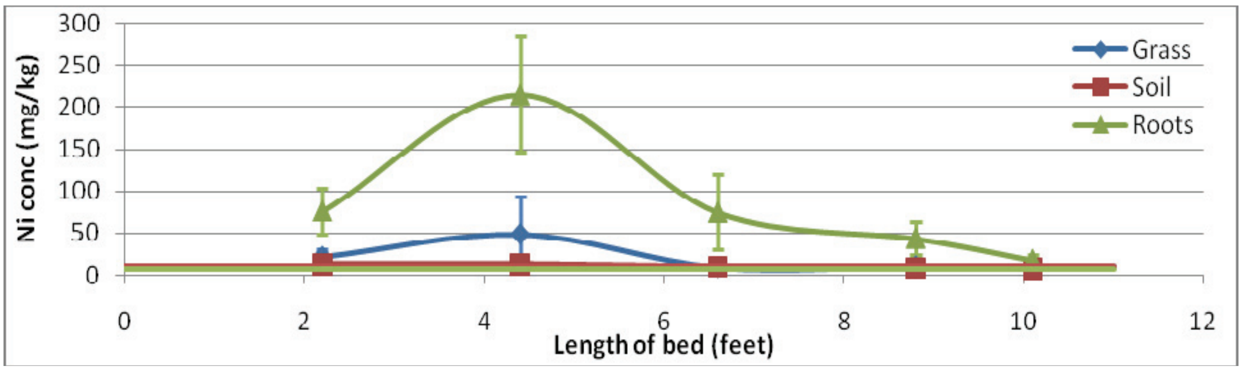


Figure 128. Concentration of Ni throughout length of Bed 1 after tests.

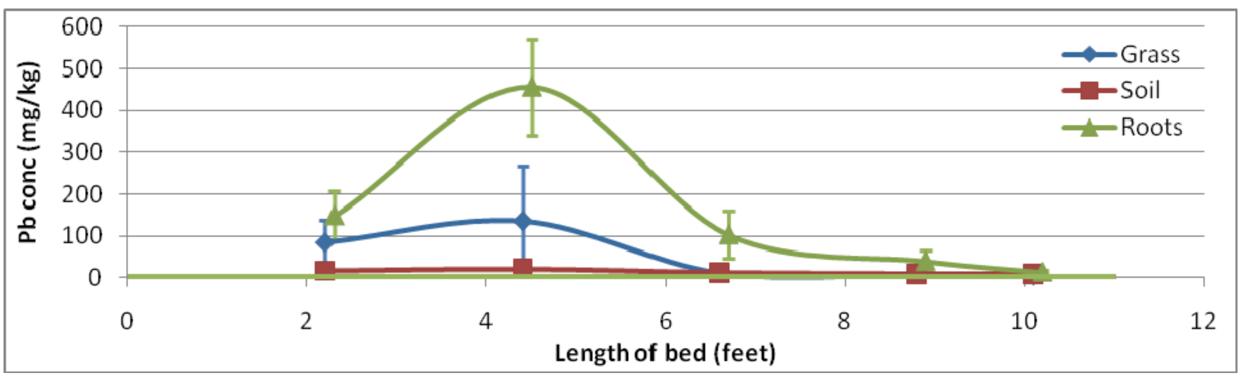


Figure 129. Concentration of Pb throughout length of Bed 1 after tests.

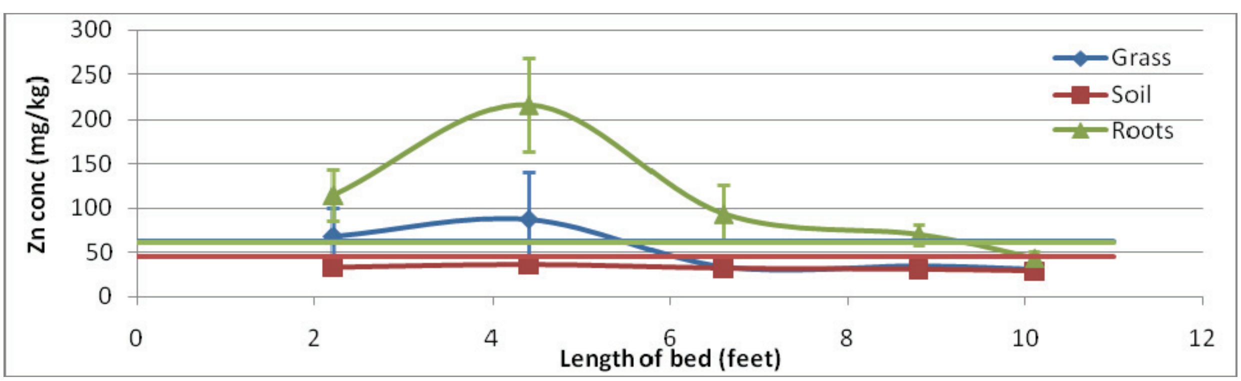


Figure 130. Concentration of Zn throughout length of Bed 1 after tests.

In the roots, every metal except Fe showed a statistically significant accumulation along the length of the bed. Cd, Cu, Ni, and Pb accumulated significantly down the entire length of the bed, but Cr and Zn only accumulated significantly at the 2.2 ft (0.67 m) and 4.4 ft (1.34 m) locations. Highest concentrations for all metals were found in the roots. Pb accumulated to the highest concentration of all the metals in the roots at 456 mg/kg, but Pb was also at the highest concentration in the influent water. As a fraction of the concentration in the roots to the concentration in the influent, Cu accumulated in the roots in the greatest proportion at 0.23, while the remaining metals accumulated in the proportion of 0.08 to 0.13. In the grass, Cd, Cr, Ni, and Pb accumulated significantly in the tissues, but only in the upper portions of the bed for most of these, at concentrations much higher than seen in the soil. There are two explanations for the higher concentrations in vegetation than in the soil. It appears metals were taken up into the plant and concentrated in the tissues as an active mechanism. However, this is exaggerated by reporting concentrations in terms of dry mass. Because vegetation has a much higher moisture content than soil, metals are greater concentrated in vegetation than soil during drying compared with the native conditions. On average the moisture content of the root, grass, and soil samples from Bed 1 were 83.1%, 64.4%, and 10.5%. This was used to convert concentrations of mg/kg dry mass to mg/kg wet mass for the highest concentrations found in the bed, shown in Table 23. After correcting for this distortion, root concentrations were still significantly higher than soil concentrations for Cd, Cr, Cu, Ni, and Pb, but not for Zn. Because of high standard deviations in the grass concentrations, there was no significant difference for any of the metals concentrations between the grass and the roots and between the grass and the soil. Therefore it is apparent that the vegetation preferentially took up the metals Cd, Cr, Cu, Ni, and Pb and concentrated them in their roots. Metals also accumulated in the tiller portion of the grass, although not at higher concentrations than seen in the soil.

Table 23. Maximum metal concentrations from Bed 1 per dry and wet mass.

mg/kg (ppm) dry mass						
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Grass	12.6	18.5	60.4	48.7	135.0	87.1
Roots	54.1	54.0	205.4	215.2	456.2	216.6
Soil	2.8	7.4	9.3	12.7	20.7	35.9
mg/kg (ppm) wet mass						
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Grass	4.5	6.6	21.5	17.3	48.0	31.0
Roots	9.2	9.1	34.8	36.4	77.2	36.7
Soil	2.5	6.6	8.3	11.3	18.5	32.1

In the soil, Cd, Cu, and Pb accumulated significantly at maximum concentrations of 2.8, 9.3, and 20.7 mg/kg, but still an order of magnitude lower than concentrations observed in vegetation. Again, Pb was found at the highest concentration, but it was also at the highest concentration in the influent. As a fraction of the concentration in the soil to the concentration in the influent, Cu accumulated in the greatest proportion at 0.011, as it did in roots, while Cd and Pb accumulated in the proportions of 0.0057 and 0.0038, respectively. The low concentrations of metals in the soil compared to the vegetation give the impression that the vegetation captured the majority of the metals. However, concentrations are based on mass of contaminant per mass of media, and the total mass of soil in the test bed greatly exceeds the mass of vegetation. An accurate mass balance could not be performed, because the total mass of grass, roots and soil in the bed could not be directly measured without destruction of the bed, and the variability of metals concentration with depth was not determined because of cost constraints. Nevertheless, extrapolating the relative mass of soil, roots, and grass from the cores over the extent of the bed, using average values, and assuming that the metals did not penetrate any deeper than the 2 in (5 cm) depth of the cores, the mass of contaminants collected by each media fraction was computed, and the results are given in Table 24. The majority of the metal mass was concentrated in the roots of the grass for all metals except Pb for which a clear majority of the mass accumulated in the soil, and Cd which was about evenly split between roots and soil.

Table 24. Estimated mass of metal accumulated in different media over the top 2 in (5 cm) over the entire area of Bed 1.

	Total dry mass in top 5 cm (2 in) of Bed 1 (kg)	**Cd (g)**	**Cr (g)**	**Cu (g)**	**Ni (g)**	**Pb (g)**	**Zn (g)**
Grass	52.1	0.22	0.13	0.28	0.42	2.18	0
Roots	32.8	0.82	0.4	2.41	2.62	4.96	1.48
Soil	778	0.74	0	1.4	0	8.91	0
	(lb)	**(oz)**	**(oz)**	**(oz)**	**(oz)**	**(oz)**	**(oz)**
Grass	114.9	0.0078	0.0046	0.0099	0.0148	0.0769	0.0000
Roots	72.3	0.0289	0.0141	0.0850	0.0924	0.1750	0.0522
Soil	1715.2	0.0261	0.0000	0.0494	0.0000	0.3143	0.0000
		(ppm)	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**
Grass		4.22	2.50	5.37	8.06	41.84	0.00
Roots		25.00	12.20	73.48	79.88	151.22	45.12
Soil		0.95	0.00	1.80	0.00	11.45	0.00
	(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
Grass	6.0%	12.4%	24.5%	6.8%	13.8%	13.6%	0.0%
Roots	3.8%	46.1%	75.5%	58.9%	86.2%	30.9%	100.0%
Soil	90.2%	41.6%	0.0%	34.2%	0.0%	55.5%	0.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

11 Medium Pollutant Concentration Experiments

In this series of tests, a medium concentration of contaminants, as described in Table 11 was delivered to a different 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 four tests were conducted which included the following: 1) an 8:1 slope (7.13°) with a medium flow rate, 2) a 4:1 slope (14.0°) with a medium flow rate, 3) a 2:1 slope (26.6°) with a medium flow rate, and 4) a 2:1 slope (26.6°) with a high flow rate. The medium flow 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 17. The high flow simulation used an initial flow rate of 5.54 gpm (20.95 lpm) for 6 min followed by a flow rate of 1.20 gpm for (4.55 lpm) 24 min. All tests were performed on the same test plot, designated Bed 2. After completion of the performance tests, a series of tracer and resuspension tests were performed at all slopes with tap water to evaluate flow through the bed in more detail and investigate the release of contaminants laid down from previous tests. In addition, preceding any testing a baseline run at a slope of 8:1 with medium flow was performed using tap water to determine background concentrations released from the clean bed with the clean influent water (see Chapter 9). The background levels for metals were quite high for this bed, because of probable contamination of the distribution equipment, as discussed earlier. The metals performance results for this bed were instead compared against the average baseline metals results from Beds 1 and 3, and not the elevated baseline metals results from Bed 2. Non metals baseline values from Bed 2 were used.

11.1 Tracer Tests

Tracer tests involved running tap water over the bed at the prescribed medium or high flow rates that was spiked with an initial slug of sodium bromide. Bromide was expected to behave as a conservative tracer, moving though the bed with very little uptake, adsorption, or other interaction with the bed. A bromide selective probe was used to determine bromide concentrations over time in the surface runoff and underdrain flow. Flow rates of the surface runoff and underdrain were also measured frequently.

Tracer results for the 8:1 slope are shown in Figure 131. Bromide moved directly with the overland flow, and highest bromide concentrations were detected in the water that first emerged from the bed, 5.6 min after initiation of the simulated runoff. Concentrations then decreased rapidly until surface flow stopped. In the underdrain, initial bromide concentrations were low, and flow at this point was due to draining of the bed from the saturation step in preparation for the test. Concentrations increased rapidly peaking at 6 min indicating the average time required for water to seep through the soil layer and into the underdrain. Concentrations decreased rapidly until the tailing portion of the event began, when concentrations increased again somewhat. Surface runoff began at 5.6 min after initiation of the event, remained fairly constant at 0.61 gpm (2.31 lpm), and then stopped rapidly at 17 min after the tailing portion of the storm began. Underdrain flow increased from base flow at 6 min, peaking at 2.0 gpm (7.57 lpm), and then decreased slowly to eventually match the inflow rate of 0.44 gpm (1.68 lpm). After inflow ceased completely, the underdrain continued to flow, decreasing linearly for 10 min. Of the inflow added to the bed, 92% was recovered in the surface runoff and underdrain flow, and only

13% of the inflow resulted in surface runoff, the rest seeping into the soil and emerging as underdrain flow.

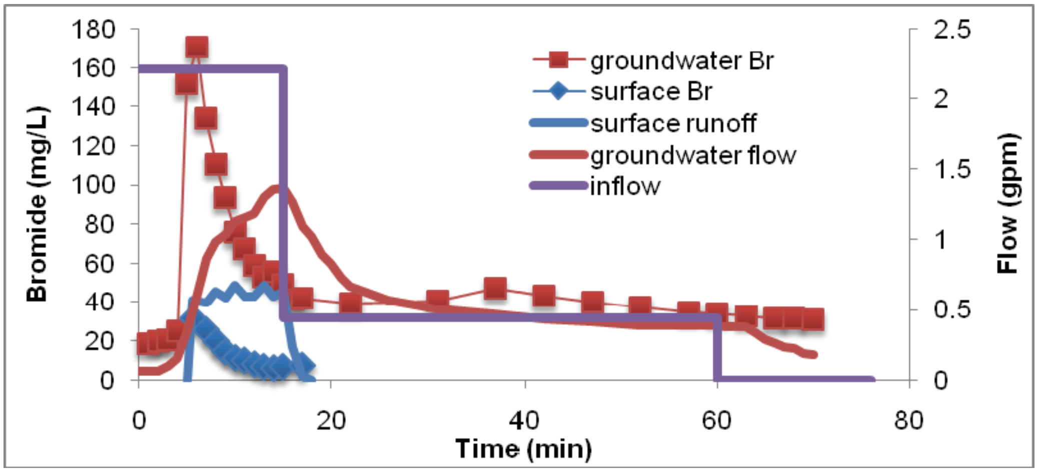


Figure 131. Bromide tracer test results for 8:1 slope, Bed 2.

Tracer results for the 4:1 slope, 2:1 slope medium flow, and 2:1 slope high flow are shown in Figure 132 through Figure 134. Results were similar for the 8:1 slope, although runoff began at increasingly earlier times, and an increasing high proportion of inflow ran off the surface. Surface flow first appeared after 4.5 min for the 4:1 slope, 3.9 min for the 2:1 slope medium flow, and 1.0 min for the 2:1 slope high flow. Increased flow emerged from the underdrain at nearly the same intervals as the 8:1 slope, but no longer coincided with the surface flow, after 5 min for the 4:1 slope, 3 min for the 2:1 slope medium flow, and 4 min for the 2:1 slope high flow. Surface runoff continued through the tailing portion of the event only for the 2:1 high flow test and at much lower flow rates than observed for Bed 1 (see Figure 65). During the initial portion of the events, surface runoff only measurably exceeded underdrain flow during the high flow test, also different than Bed 1 performance. Over the entire event, the percent of inflow that ran off the surface was 24% for the 4:1 slope, 27% for the 2:1 slope medium flow test, and 58% for the 2:1 slope high flow test. These were significantly lower than observed in Bed 1. Based on the quantity of surface runoff generated in these tests, it was quite clear that Bed 2 produced less runoff than Bed 1. Although the beds appeared identical, this may be due to Bed 2 weathering over a winter before testing, resulting in freeze thaw of the soil and more mature second-year plant growth. It was also observed that overland flow was greatly vulnerable to slight undulations in the bed surface. Very slight rises in the soil can result in a barrier to overland flow. Although prepared with the same materials and in the same manner (see Section 6.2) as Bed 1, Bed 2 may have had more surface undulations. Spatial heterogeneity in the soil surface elevation and grass coverage may play a large role in the amount of surface runoff generated, particularly at low slopes. Percent recoveries of water for the tests were 80%, 74%, and 74%, respectively.

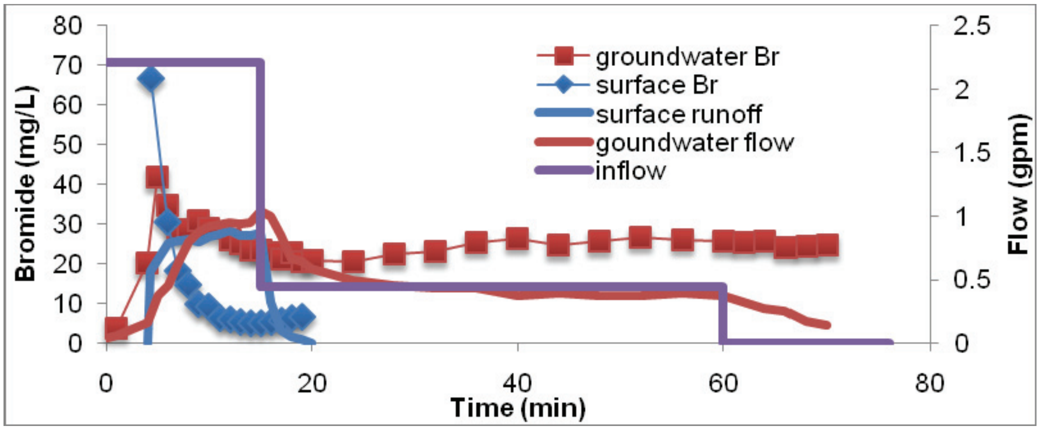


Figure 132. Bromide tracer test results for 4:1 slope, Bed 2.

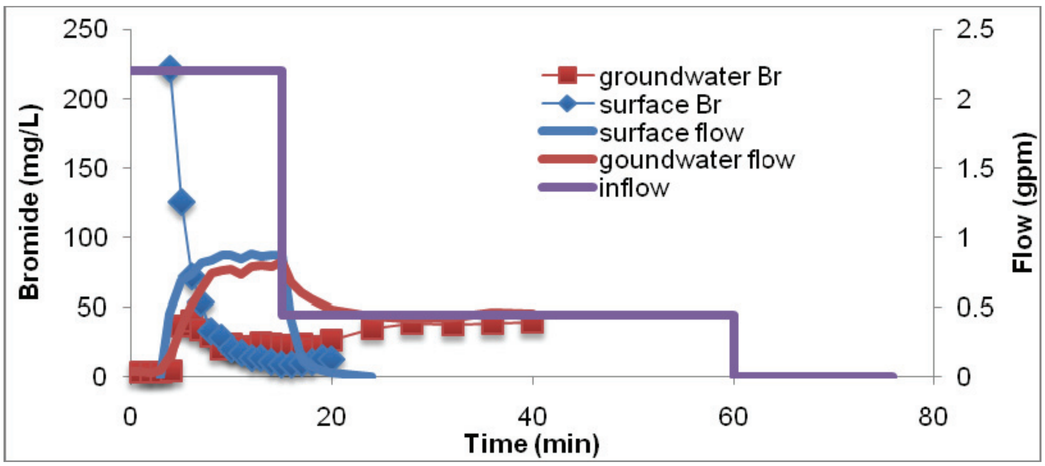


Figure 133. Bromide tracer test results for 2:1 slope, medium flow, Bed 2.

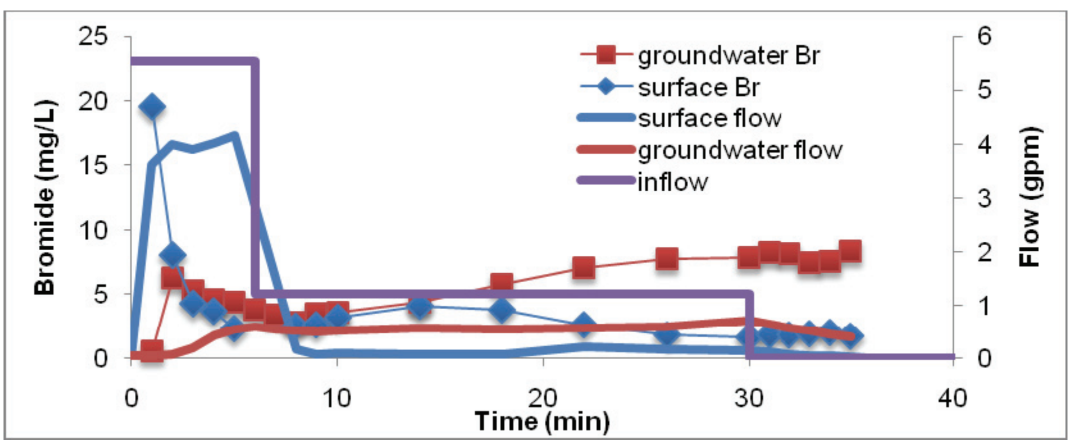


Figure 134. Bromide tracer test results for 2:1 slope, high flow, Bed 2.

11.2 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 or

NaOH. During and after pH adjustment the pH would continue to drift over several hours. Although pH was adjusted to 7 after the solutions were mixed, by the time the other preparation steps were completed, the pH had decreased to as low as 6.51 in the influent water. The pH in the surface runoff and the underdrain flow were not significantly different from the influent water. The pH data are tabulated in Table 25.

Table 25. Average pH values during the medium concentration tests on Bed 2.

Test	Initial Influent	Tailing Influent	Initial Surface Runoff	Tailing Surface Runoff	Initial Underdrain Flow	Tailing Underdrain Flow
8:1	6.71	6.51	6.84	no flow	6.76	6.50
4:1	6.75	6.57	6.84	no flow	6.63	6.40
2:1 Medium	7.23	6.58	7.26	no flow	7.01	6.51
2:1 High	6.79	6.84	6.86	no flow	6.14	6.77

11.3 Suspended Solids Results

Figure 135 through Figure 138 depict suspended solids concentrations for the four medium concentration tests. 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 influent flow as it sprayed onto the bed were somewhat lower than the target concentrations for each slope, averaging 131 mg/L, 119 mg/L, 84 mg/L, and 92 mg/L. These values were significantly lower than the target concentration of 207 mg/L. Suspended solids concentrations decreased during the lower flow rate for the tailing 45 min for the first three tests and 24 min for the last test, and averaged 11 mg/L, 4 mg/L, 3 mg/L, and 2 mg/L. For each of the four tests except the 4:1 medium flow test, the influent concentrations remained consistent around the average concentration for the initial medium concentration flow. This consistency shows that the suspended solids were being evenly pumped out of the influent tank, and settling was not a problem as in the high concentration tests.

For the first three tests, surface runoff was only generated during the first 15 min of the test during the medium concentration and initial water quality volume portion, similar to the high concentration tests. Once the concentration and flow decreased for the tailing 45 min, all water delivered to the bed infiltrated and no surface runoff samples could be collected. For all three medium flow tests, the surface runoff had very low suspended solids concentrations (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 and medium flow) that remained well below average influent concentrations. The 2:1 slope and high flow generated more surface runoff throughout the duration of the test, similar to the high concentration test. The suspended solids concentrations in the surface flow were also low with an initial average concentration of 4 mg/L for the first 6 min and an average tailing concentration of 5 mg/L for the last 24 min. These values can be contrasted with baseline suspended solids concentrations that averaged 7.2 mg/L. When accumulated over the entire storm, the percent removals of the event mean concentrations were 98.3% for the 8:1 test, 95.7% for the 4:1 test, 96.3% for the 2:1 medium flow test, and 83.73% for the 2:1 high flow test. The lowest TSS removal, which was still above 80%, occurred in the 2:1 high flow test.

In the underdrain, the first collected sediment sample for each of the tests had a much higher suspended solids concentration than the other samples. For example, in Figure 135, the first underdrain sample had a suspended solids concentration of 242 mg/L, while the other two initial samples averaged 4 mg/L. It appears that some material loosened and migrated out the underdrain. The remaining 45 min of the test had low suspended solids concentration, much like the surface runoff, although some sediment concentrations were above average influent concentrations the values were consistent with the average baseline concentration of 11.5 mg/L (see Table 21).

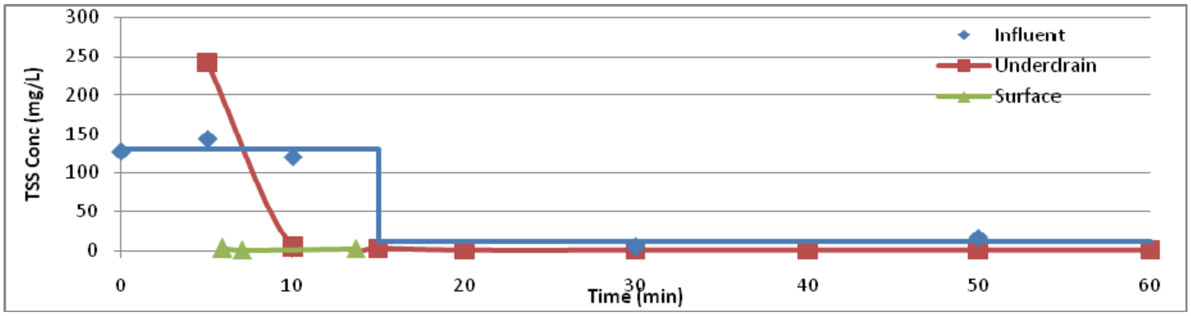


Figure 135. Concentration of suspended solids in 8:1 slope, medium flow rate.

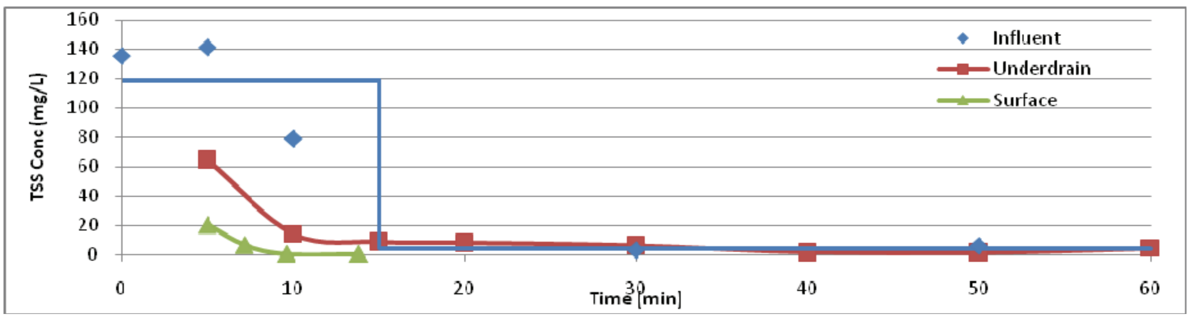


Figure 136. Concentration of suspended solids in 4:1 slope, medium flow rate.

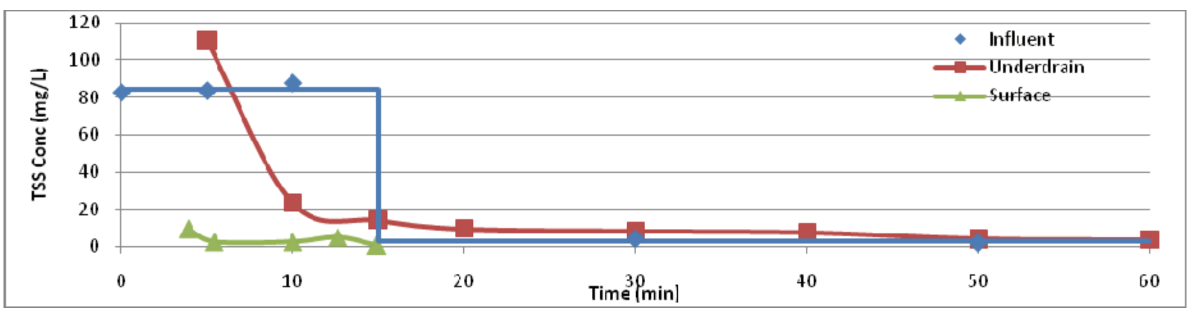


Figure 137. Concentration of suspended solids in 2:1 slope, medium flow rate.

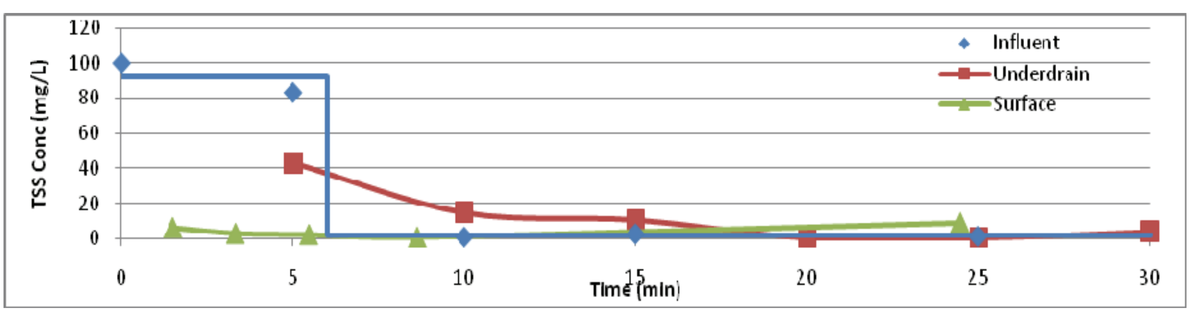


Figure 138. Concentration of suspended solids in 2:1 slope, high flow rate.

11.3.1 Particle Size Analysis

One particle size analysis of sediment in the influent water and in the surface runoff was performed for each test and results are shown in Figure 139 and Figure 140. Influent samples varied considerably, two of them being dominated by small particles (mean diameters of 9.9 µm (0.39 mil) and 15.4 µm (0.61 mil)) and the other two being dominated by larger particles (mean diameters of 545 µm (21.5 mil) and 1230 µm (48.4 mil)). The influent particle size distribution from the 2:1 slope, medium flow test was unexpected, because the mean suspended sediment size was larger than the soil added to the influent (sieved to be smaller than 841 µm (33 mil)) and the baseline sediment distributions (see Figure 61). As noted previously, it is likely that the clay particles agglomerated in the influent mixing tank forming larger particle aggregations that entered the bed. Surface runoff distributions also varied considerably with one sample dominated by small particles (mean diameter of 15.4 µm (0.61 mil)) and the remaining three dominated by large particles (mean diameters of 649 µm (25.6 mil) to 1126 µm (44.3 mil), which were again larger than particles added to the influent and observed during baseline tests.

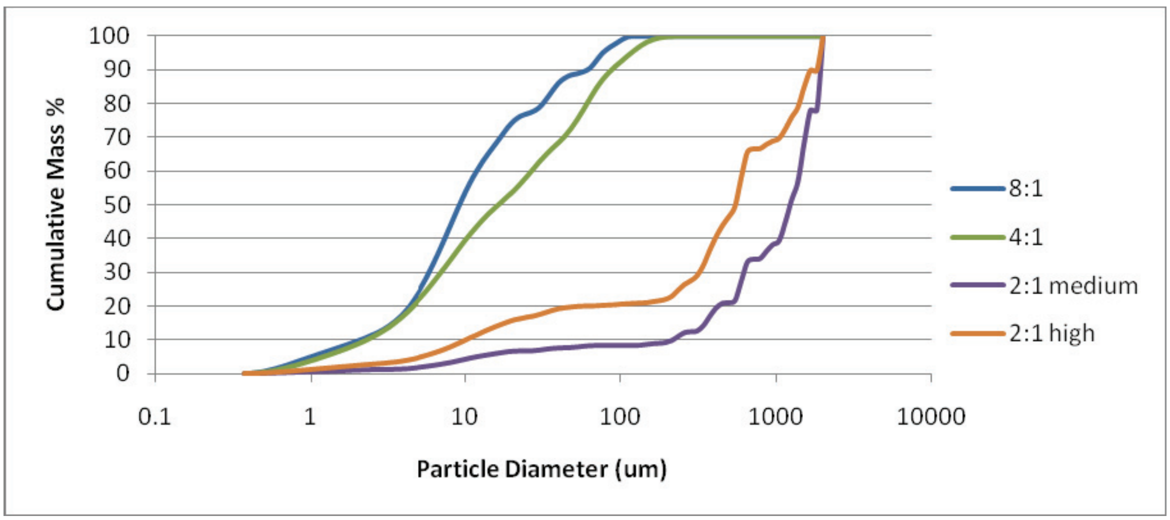


Figure 139. Particle size distribution of influent samples from Bed 2.

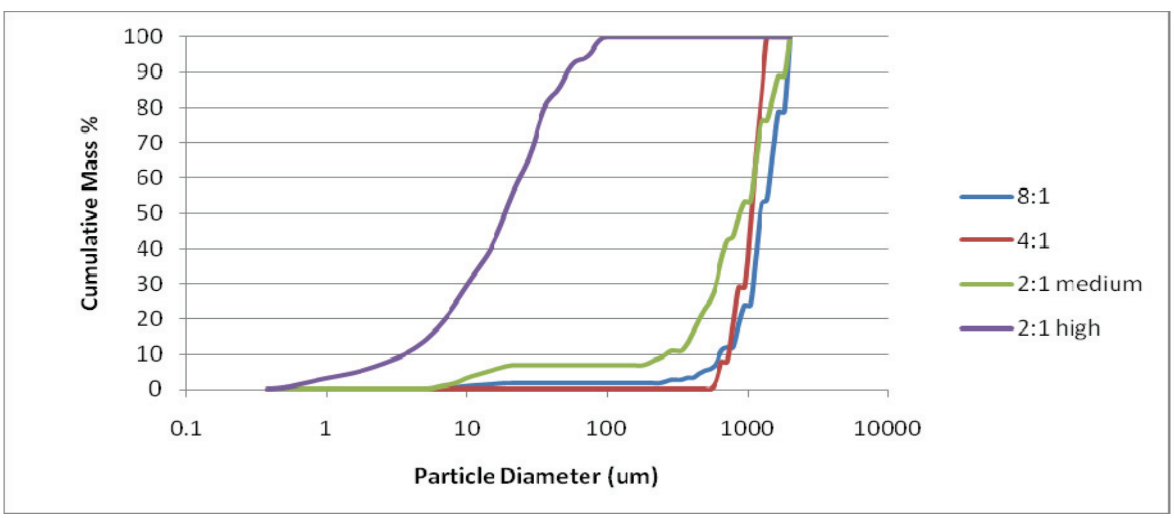


Figure 140. Particle size distribution of surface runoff samples from Bed 2.

11.4 Total Metals Results

For the medium flow rate test with an 8:1 slope, total metals concentrations are displayed in Figure 141 through Figure 147. Measured influent concentrations for the metals were relatively close to the target concentrations for the water quality volume portion of the test. For example, the medium target concentration for Ni was 475 µg/L, and the average measured influent concentration was 439 µg/L. For the remaining 45 min, each metal had concentrations higher than the target concentrations for each metal except Pb. For example, the Cd low target concentration was 20 µg/L, while the measured average influent concentration was 36 µg/L.

Surface runoff was only generated for the first fifteen min during the initial portion of the 8:1 medium flow test. For each metal, surface concentrations were well below the influent concentrations, but above background concentrations for all metals except Fe and Pb. 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%. These performance results were low compared to the other tests with this bed. In the 8:1 slope test, Fe and Pb had the highest percent removals out of the metals.

Underdrain concentrations were low and constant throughout the entire duration of the test for each metal, with all of the metals above detection limits, except Pb with a detection limit of 53 µg/L. The tailing portion of the test had very low and consistent concentrations for each metal.

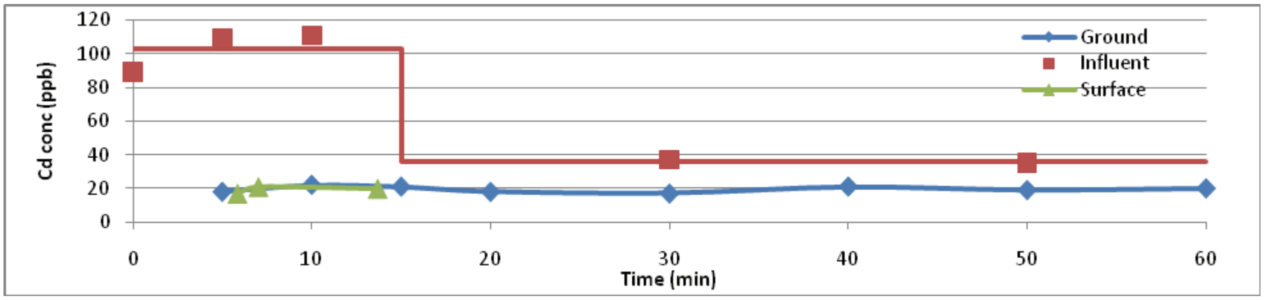


Figure 141. Total concentration of cadmium in 8:1 slope, medium flow rate.

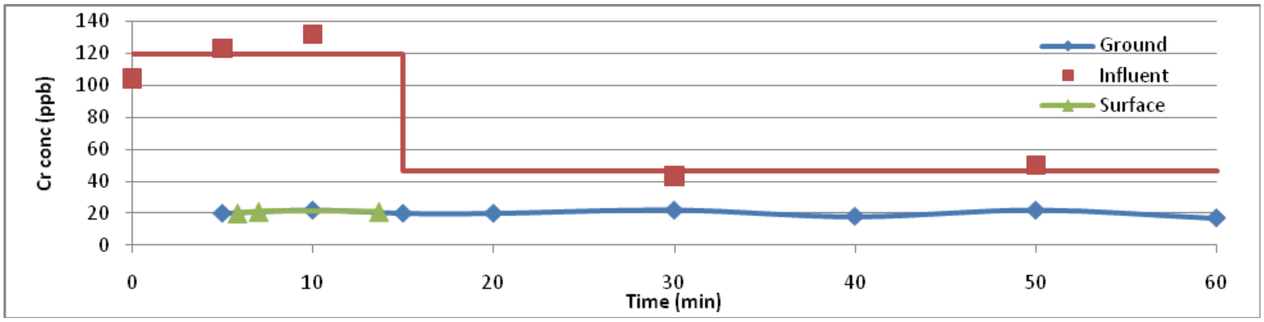


Figure 142. Total concentration of chromium in 8:1 slope, medium flow rate.

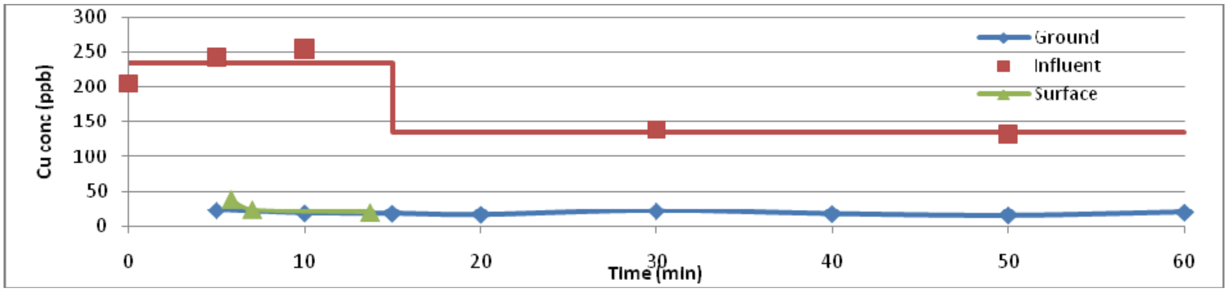


Figure 143. Total concentration of copper in 8:1 slope, medium flow rate.

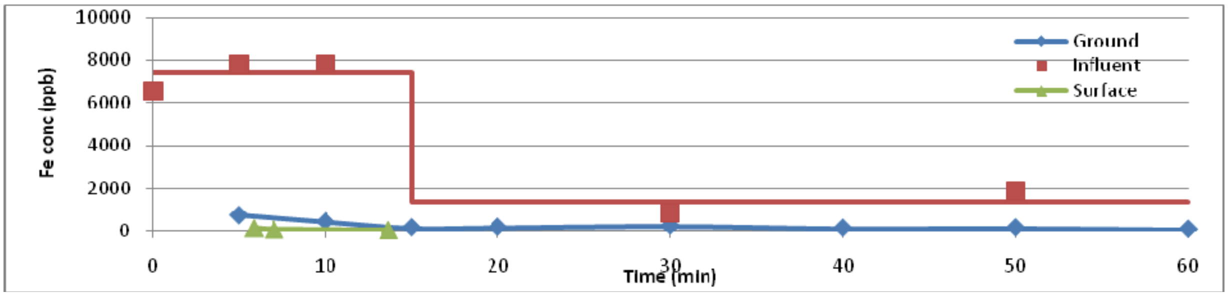


Figure 144. Total concentration of iron in 8:1 slope, medium flow rate.

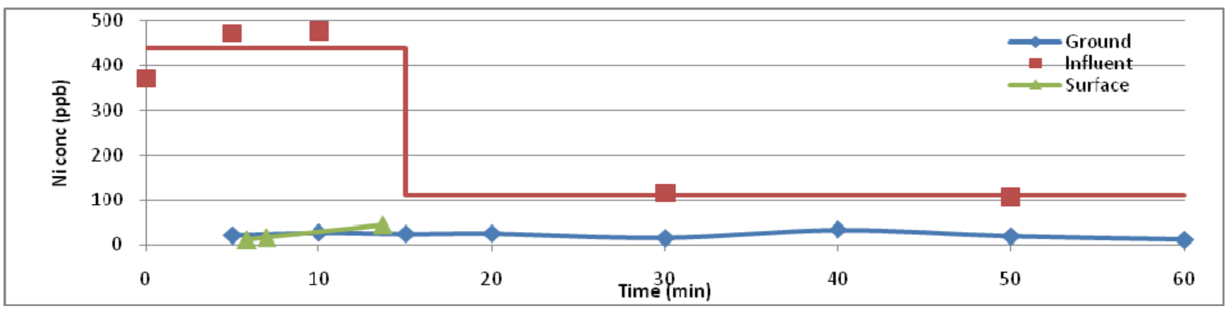


Figure 145. Total concentration of nickel in 8:1 slope, medium flow rate.

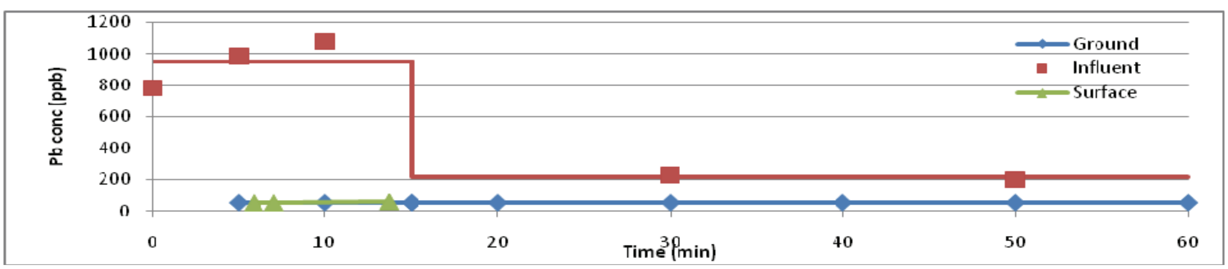


Figure 146. Total concentration of lead in 8:1 slope, medium flow rate.

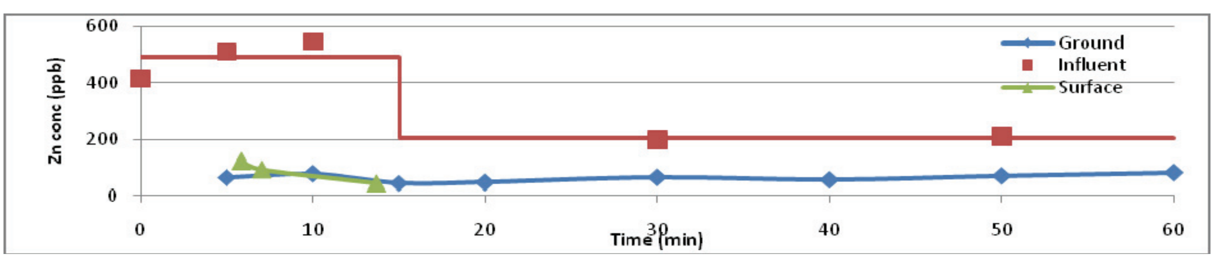


Figure 147. Total concentration of zinc in 8:1 slope, medium flow rate.

For the medium flow rate test with a 4:1 slope, total metals concentrations are displayed in Figure 148 through Figure 154. For the water quality volume period of the test, all influent metal concentrations were within a 25% margin of target values, except Zn that had average influent concentrations significantly higher than the target values. For the tailing portion of the test, Cd, Cr, and Ni had average influent concentrations close to low target concentrations; Cu, Fe, Pb, and Zn had average influent concentrations somewhat higher than target concentrations.

Unlike the 8:1 slope, surface runoff concentrations were not detected for nearly all samples except Fe and Zn, with concentrations below 105 µg/L and 95 µg/L, respectively. The Fe concentration was consistent with baseline concentrations, though Zn is significantly higher than baseline results. Cd, Cr, Cu, Ni, and Pb had detection limits of 2 µg/L, 2 µg/L, 7 µg/L, 6 µg/L, and 27 µg/L, respectively. In the first collected surface sample, Cu and Pb were detected but were not detected in the three following samples. 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%. For the 4:1 slope medium flow test, Fe had the highest percent removal, and Zn the lowest. In the underdrain, all the metals were nondetects except Fe and Zn, which had consistent concentrations below average influent concentrations.

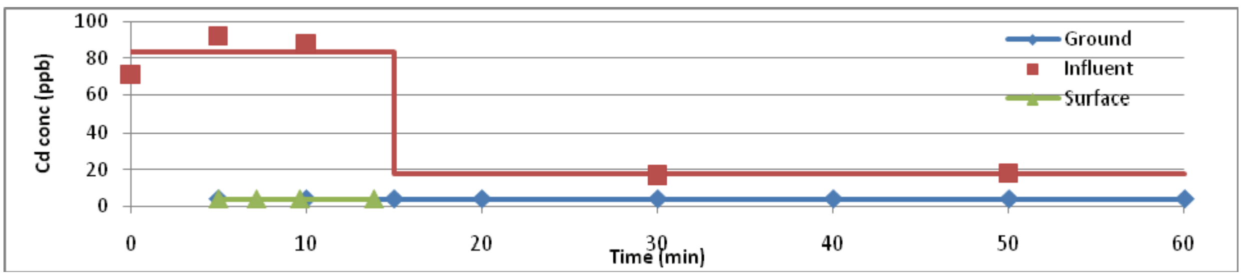


Figure 148. Total concentration of cadmium in 4:1 slope, medium flow rate.

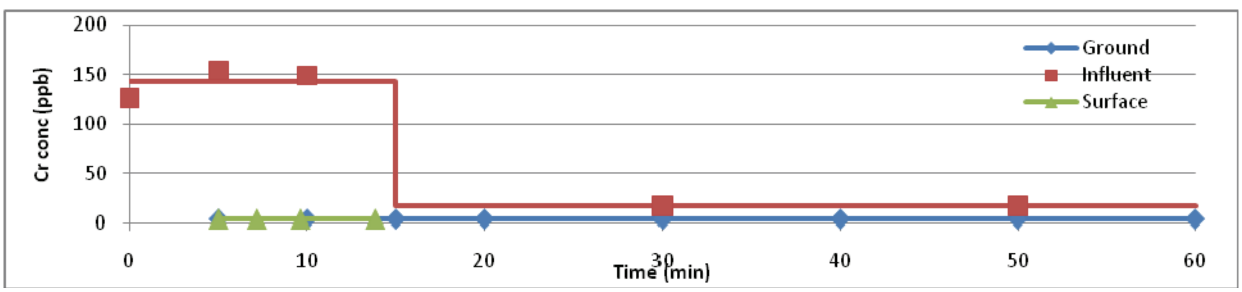


Figure 149. Total concentration of chromium in 4:1 slope, medium flow rate.

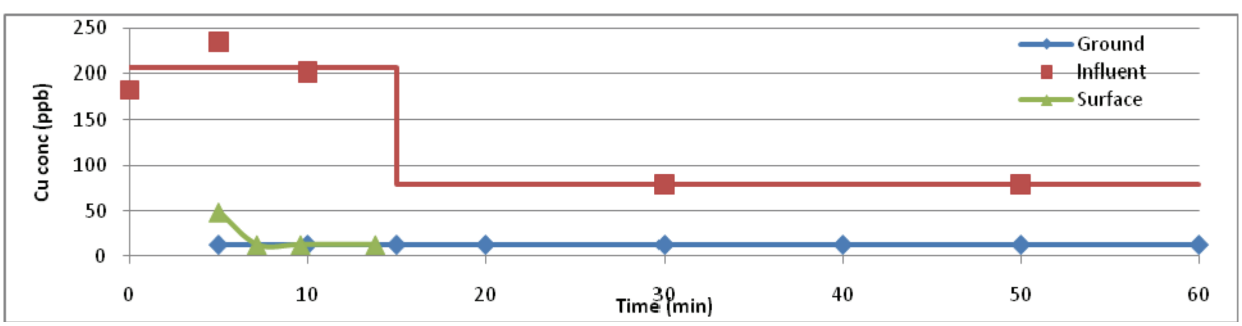


Figure 150. Total concentration of copper in 4:1 slope, medium flow rate.

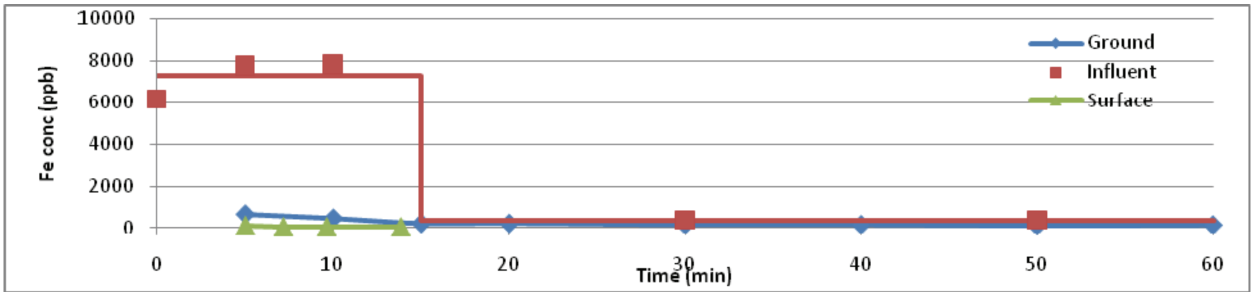


Figure 151. Total concentration of iron in 4:1 slope, medium flow rate.

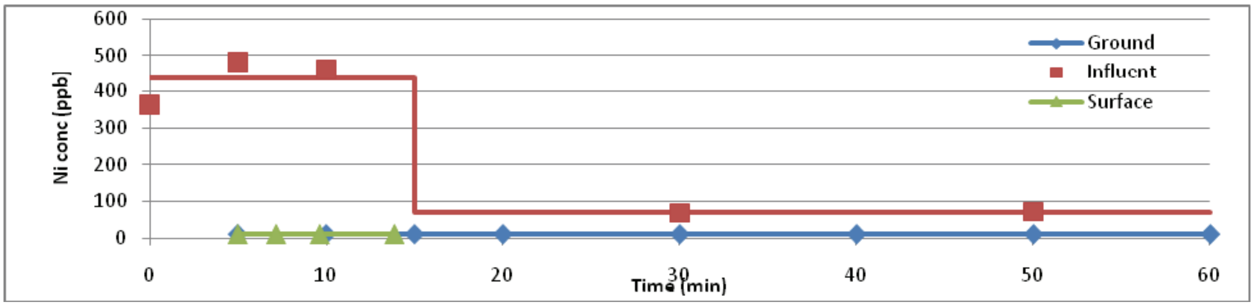


Figure 152. Total concentration of nickel in 4:1 slope, medium flow rate.

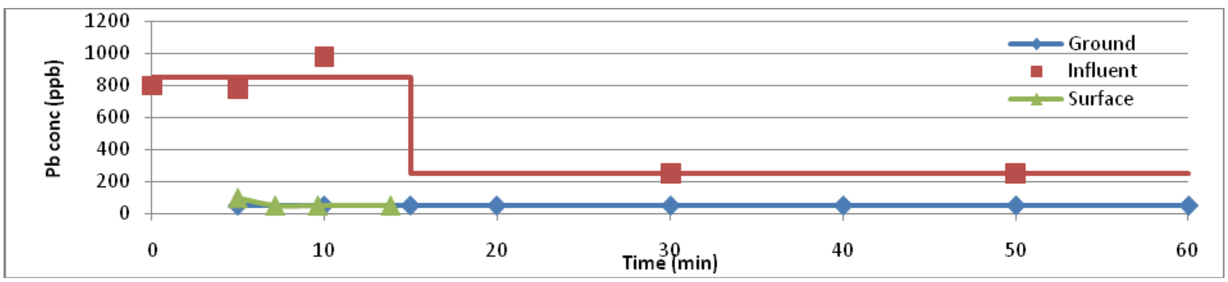


Figure 153. Total concentration of lead in 4:1 slope, medium flow rate.

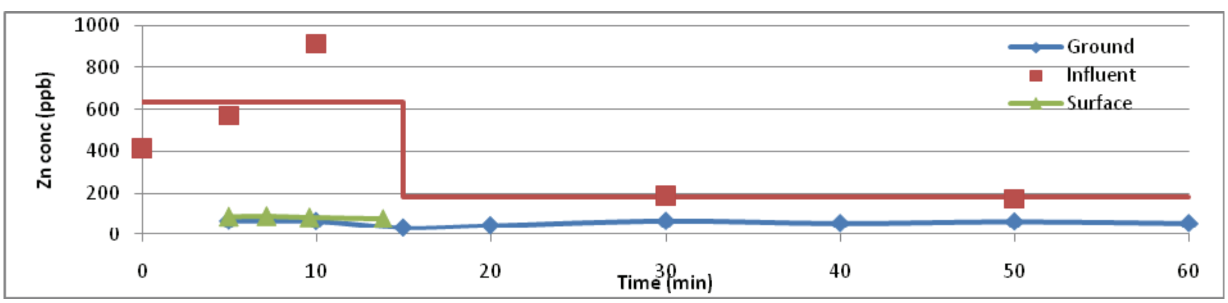


Figure 154. Total concentration of zinc in 4:1 slope, medium flow rate.

Figure 155 through Figure 161 portray the 2:1 slope test with a medium flow rate. For the water quality volume portion of the test, Cd, Cr, Ni, and Pb had average influent concentrations which were within a 20% margin of the medium target concentrations. Fe was within a 25% margin. For the tail end portion of the test, Cd, Ni, and Pb had lower average influent concentrations that were within 20% of the low target concentrations, while Cr was also lower, but within 40% of its low target concentration. Similar to the water quality volume portion of the test, Cu, Fe, and Zn had measured influent concentrations that were higher than the target concentrations. Zn was unusual compared to the other metals. For the water quality volume portion of the test, Zn displayed lower concentrations than at the tail end of the test (see Figure 161).

Even with the 2:1 slope, surface runoff virtually ceased to be generated after the water quality volume of the storm. Each of the metals was not detected in the surface runoff except Fe, with concentrations below 435 µg/L that remained below average influent concentrations. Cd, Cr, Cu, Ni, Pb, and Zn had detection limits of 3 µg/L, 6 µg/L, 4 µg/L, 16 µg/L, 13 µg/L, and 2 µg/L, respectively. Even with the higher 2:1 slope, there were excellent percent removals of event mean concentrations for Cd, Cr, Cu, Fe, Ni, Pb, and Zn as follows: 93.8%, 89.4%, 98.2%, 97.0%, 92.6%, 97.1%, and 99.4%. Zn exhibited the highest percent removal for the 2:1 medium flow test, while Cr had the lowest at 89.4%. When compared with the 4:1 medium flow test, there was a slight decrease in percent removals for Cd, Cr, Fe, and Ni, but a slight increase for Pb and Zn.

The underdrain flow was generated throughout the duration of the test, with nondetections recorded for each metal except Fe and Zn, similar to the 4:1 slope. Fe concentrations remained below 1850 µg/L and Zn concentrations below 40 µg/L. Much like the other tests, Fe had an initial spike in concentration at 5 min into the test (see Figure 158). Even past 5 min, Fe concentrations remained above average influent concentrations for the remaining 45 min of the test. Zn exhibited detectable concentrations mainly in the first-flush portion of the test, and was not detected past 30 min, with a detection limit of 3 µg/L. In the baseline samples, only Fe was detected in the underdrain, which could explain the higher concentrations of Fe.

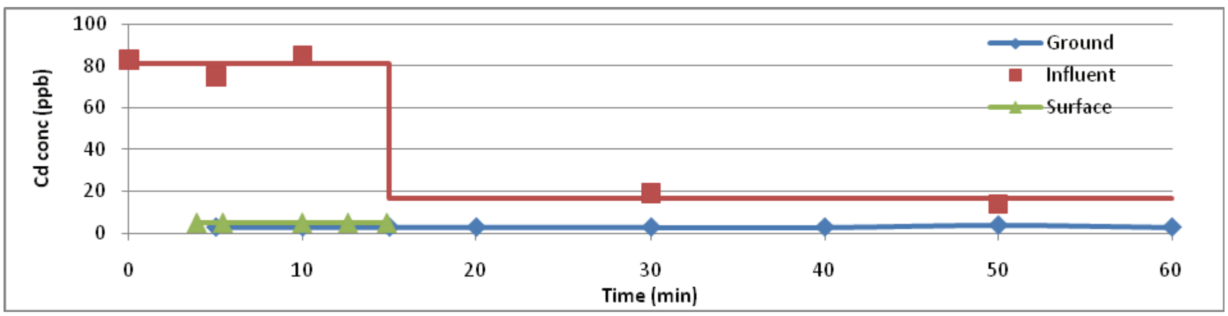


Figure 155. Total concentration of cadmium in 2:1 slope, medium flow rate.

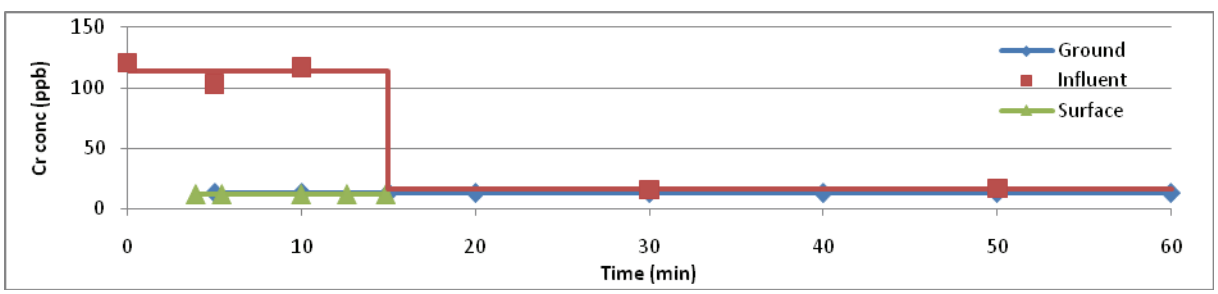


Figure 156. Total concentration of chromium in 2:1 slope, medium flow rate.

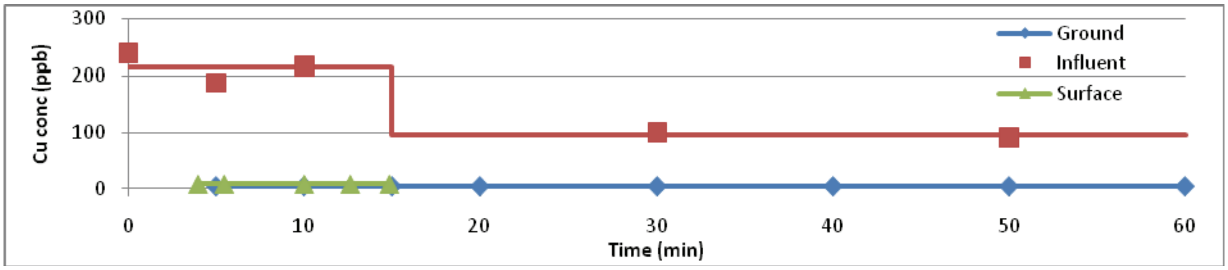


Figure 157. Total concentration of copper in 2:1 slope, medium flow rate.

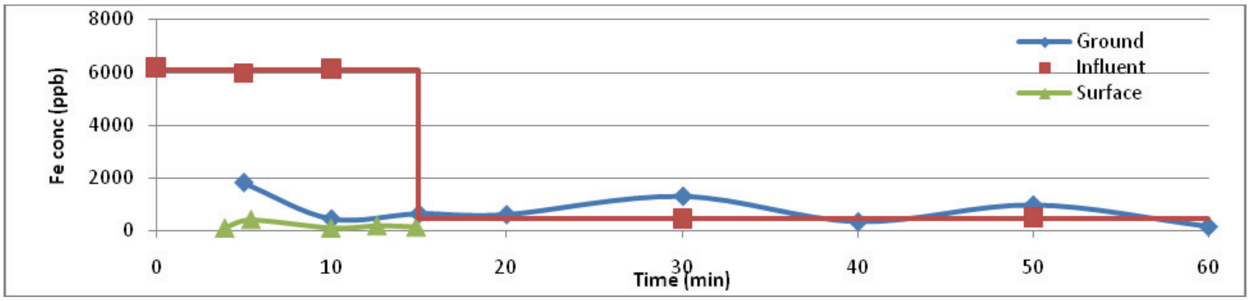


Figure 158. Total concentration of iron in 2:1 slope, medium flow rate.

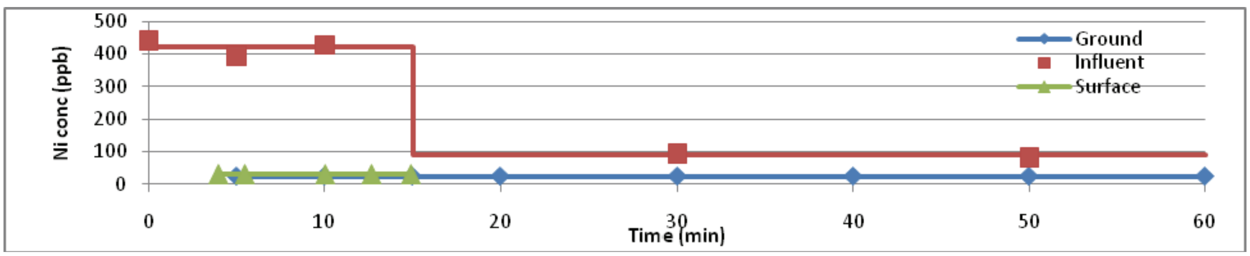


Figure 159. Total concentration of nickel in 2:1 slope, medium flow rate.

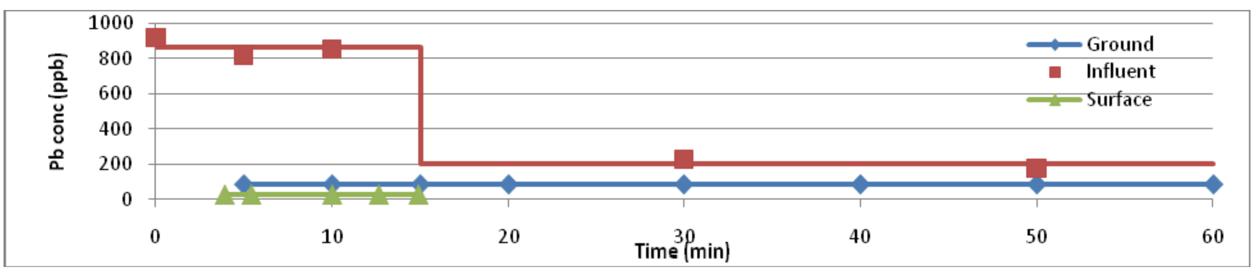


Figure 160. Total concentration of lead in 2:1 slope, medium flow rate.

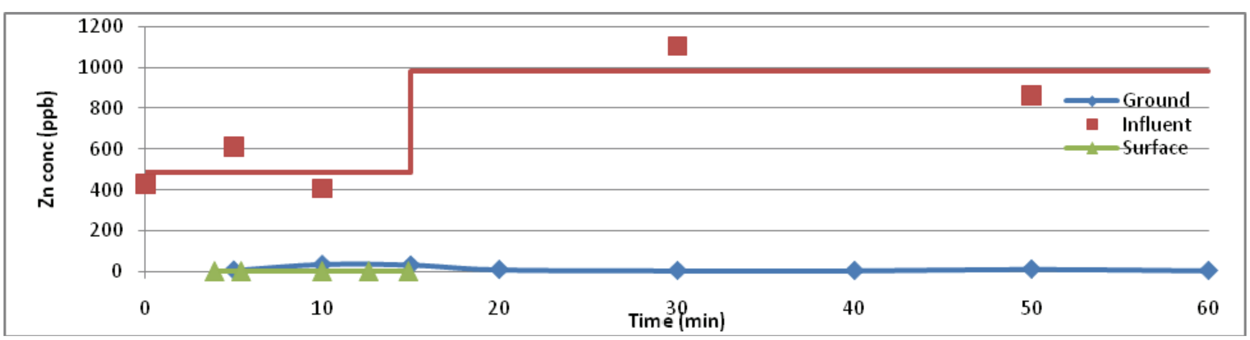


Figure 161. Total concentration of zinc in 2:1 slope, medium flow rate.

Figure 162 though Figure 168 portray the 2:1 slope test with a high flow rate. For the water quality volume portion of the test, Cd, Ni, and Pb had lower average influent concentrations than the medium target concentrations that were within a 40% margin of the target concentrations. Cr and Fe were also lower and were within a 20% margin of the target concentrations. Cu and Zn had average influent concentrations that were higher than target concentrations. For the tail end portion of the test, Cd, Cr, and Pb had lower average influent concentrations than the low target concentrations that were within a 40% margin of the target concentrations. Ni was also lower and was within a 20% margin of its target concentration. For example, the actual first-flush and tail end average Cd concentrations were 69 µg/L and 15 µg/L respectively, while the target concentrations were 100 µg/L and 20 µg/L, respectively.

Unlike the other three tests, the 2:1 high flow rate test generated surface runoff into the tail-end portion of the test for almost 25 min. Cd, Cr, Cu and Pb were nondetects, with detection limits of 2 µg/L, 7 µg/L, 3 µg/L, and 43 µg/L, respectively. Ni and Zn effluent concentrations registered below detection limits of 13 µg/L and 3 µg/L, excepting the surface sample collected at around nine minutes, with high concentrations of 580 µg/L and 185 µg/L for Ni and Zn, respectively, which were above the average tail end influent Ni and Zn concentrations (see Figure 166 and Figure 168). These spikes were unique to the 2:1 slope and are the reason why such large slopes are not recommended in this report. Percent removals of event mean concentration for Cd, Cr, Cu, Fe, Ni, Pb, and Zn were as follows: 89.1%, 79.9%, 98.2%, 85.8%, 92.5%, 86.4%, and 94.9%. Zn had the highest percent removal and Cr the lowest for the 2:1 high flow test. There was a slight decrease in percent removals for each metal from the 2:1 medium to 2:1 high flow test.

Similar to the other three tests, the metals in the underdrain samples were not detected except Fe and Zn, with concentrations below 805 µg/L and 15 µg/L, respectively. Past 20 min, Zn concentrations were not detected with a detection limit of 3 µg/L. Once again, Fe had an initial spike in concentration in the water quality volume portion of the test, with decreasing concentrations past 5 min (see Figure 165).

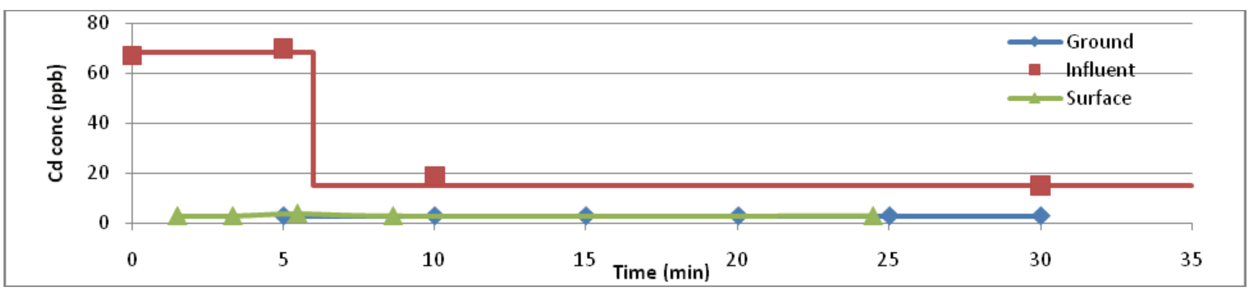


Figure 162. Total concentration of cadmium in 2:1 slope, high flow rate.

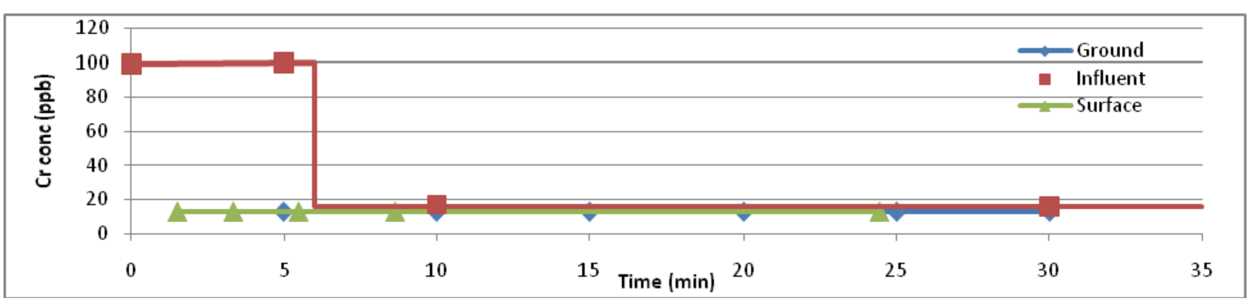


Figure 163. Total concentration of chromium in 2:1 slope, high flow rate.

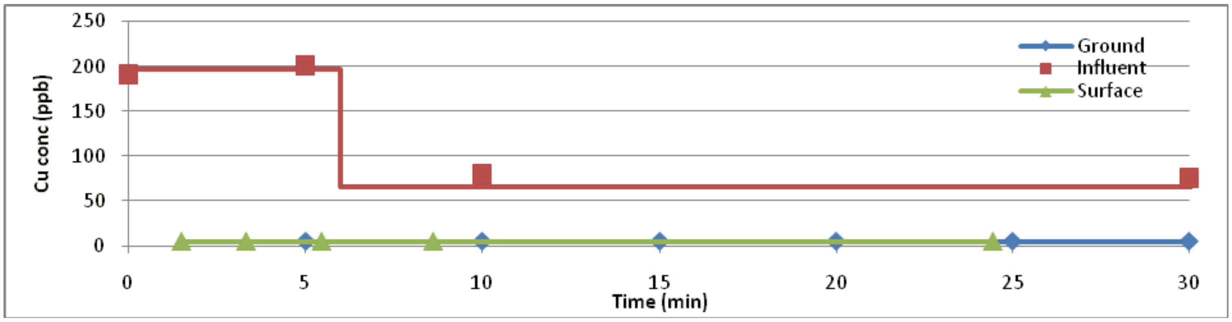


Figure 164. Total concentration of copper in 2:1 slope, high flow rate.

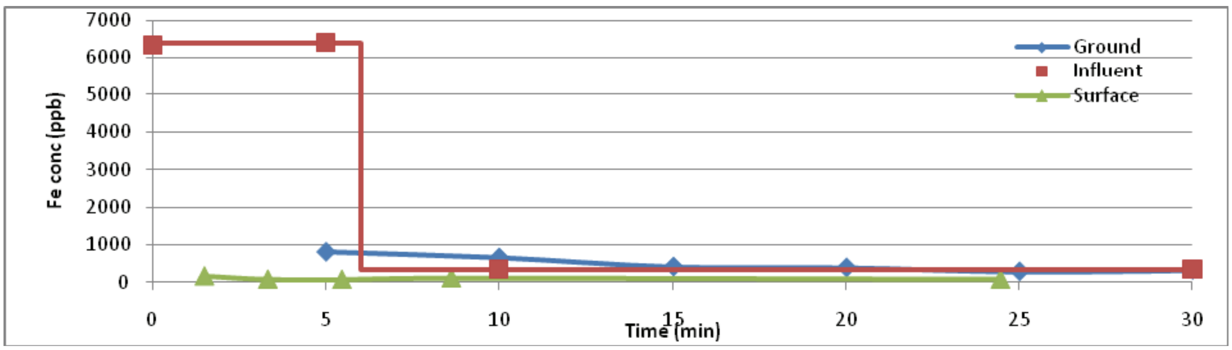


Figure 165. Total concentration of iron in 2:1 slope, high flow rate.

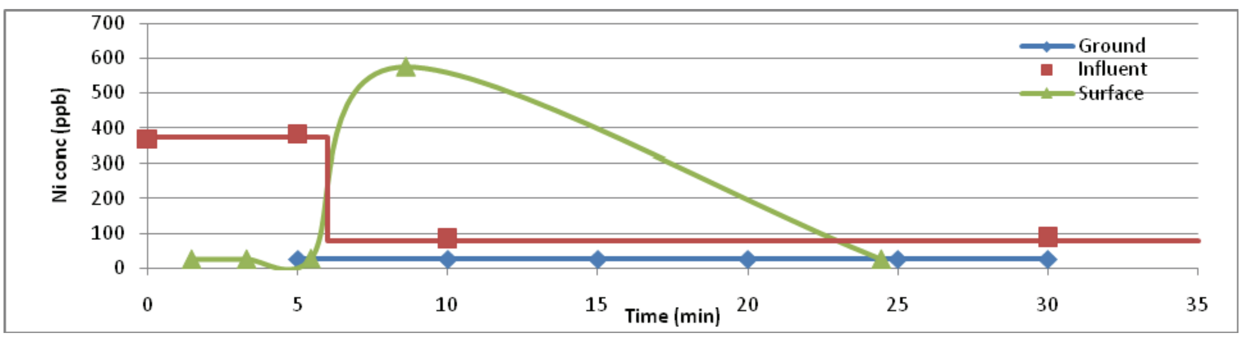


Figure 166. Total concentration of nickel in 2:1 slope, high flow rate.

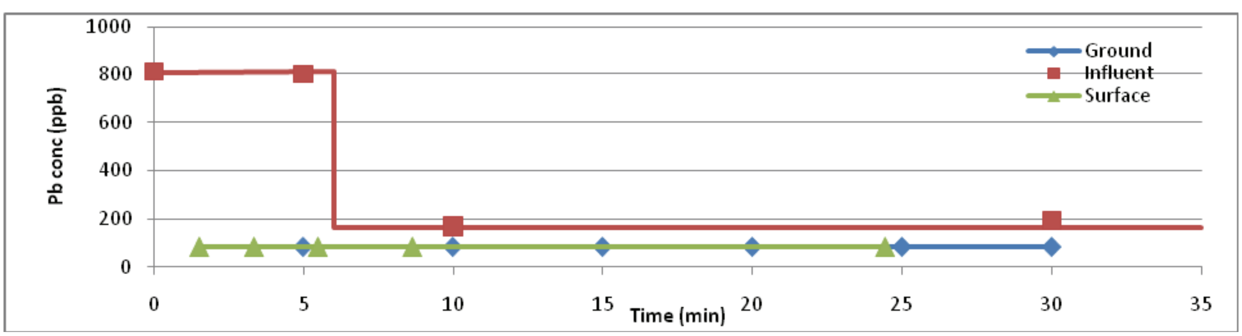


Figure 167. Total concentration of lead in 2:1 slope, high flow rate.

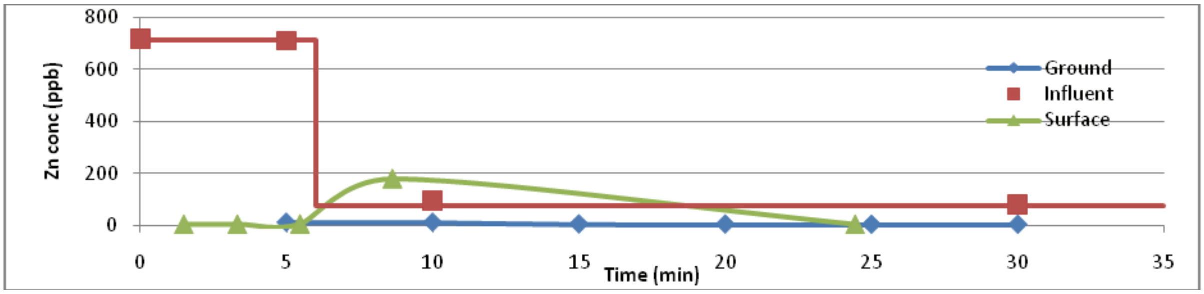


Figure 168. Total concentration of zinc in 2:1 slope, high flow rate.

11.5 Dissolved Metals Results

Figure 169 through Figure 171 exhibit the dissolved metals for the 8:1 medium flow rate test for Cd, Ni, and Zn. These three metals were detected at the highest concentrations. Dissolved Cr, Cu, and Pb were also detected but at concentrations near the detection limit. As with Bed 1, dissolved Fe results were erratic, and again the dissolved Fe was only a small percentage of the total concentration. Cd, Ni, and Zn had concentrations in the influent below 85 µg/L, 450 µg/L, and 235 µg/L, respectively, throughout the entire test. Dissolved Cd and Ni influent concentrations decreased significantly in the tailing portion of the storm, however dissolved Zn influent concentrations were nearly the same throughout the entire test.

In the surface runoff samples, Cd, Ni, and Zn, were lower than average influent concentrations, with concentrations below 25 µg/L, 25 µg/L, and 30 µg/L, respectively. In the underdrain, Cd, Cr, Cu, and Ni displayed similar trends. For the first 30 min, each of these metals were detected with concentrations below 25 µg/L, 25 µg/L, 30 µg/L, and 30 µg/L, respectively. After 30 min, these metals were not detected with detection limits of 2 µg/L, 2 µg/L, 7 µg/L, and 6 µg/L, respectively. Pb was not detected at all, while Fe and Zn were detected throughout the entire test, with concentrations below 195 µg/L and 35 µg/L, respectively. Fe was above influent concentrations, which indicates leaching out of the soil.

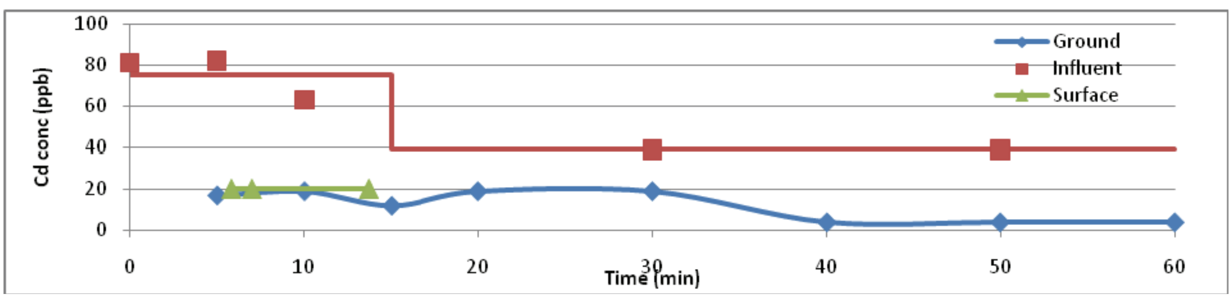


Figure 169. Dissolved concentration of cadmium in 8:1 slope, medium flow rate.

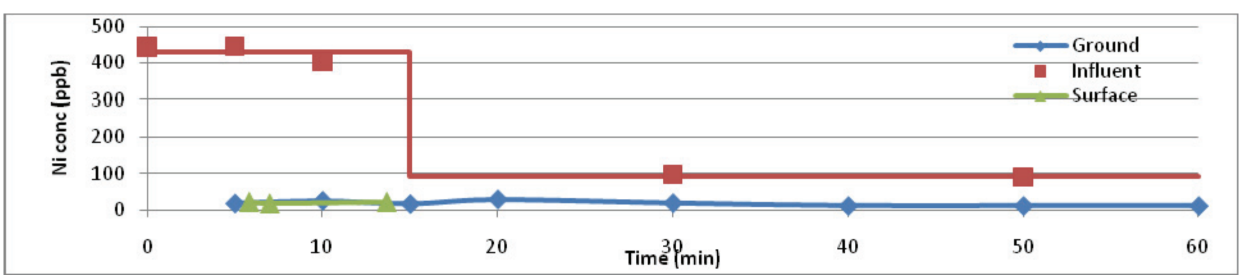


Figure 170. Dissolved concentration of nickel in 8:1 slope, medium flow rate.

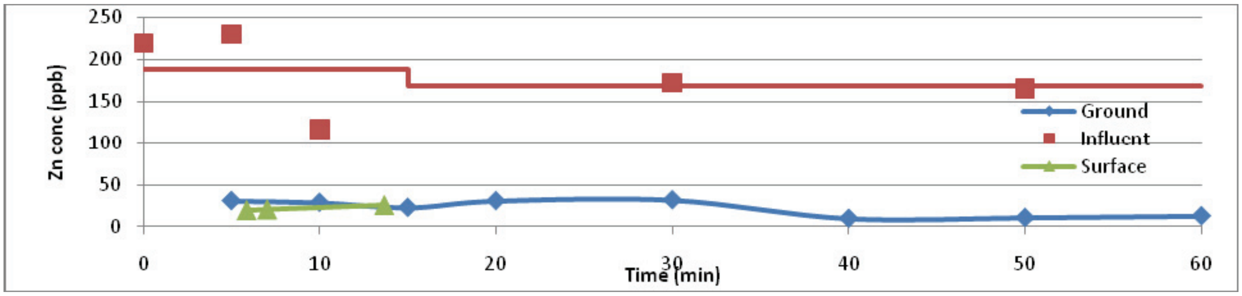


Figure 171. Dissolved concentration of zinc in 8:1 slope, medium flow rate.

Figure 172 through Figure 174 portray the dissolved Cd, Ni, and Zn concentrations for the 4:1 medium flow rate test. Influent concentrations for Cd, Ni, and Zn were below 85 µg/L, 455 µg/L, and 395 µg/L, respectively. Fe was also detected in the water quality volume of the test, with concentrations below 5470 µg/L. Cr, Cu, and Pb were only detected initially. Similar to the 8:1 slope, the third Zn sample in the influent has a lower concentration than the tail-end concentrations, which could mean there were a lot more suspended solids in that sample. The tail end portion of the test has low influent concentrations that are consistent with the average for Cd, Ni, and Zn. Cr, Cu, and Pb were not detected, with detection limits of 2 µg/L, 7 µg/L, and 27 µg/L, respectively.

Unlike the 8:1 slope, dissolved metals were below detection limits. In the underdrain, only Fe and Zn were detected with dissolved concentrations below 125 µg/L and 15 µg/L, respectively.

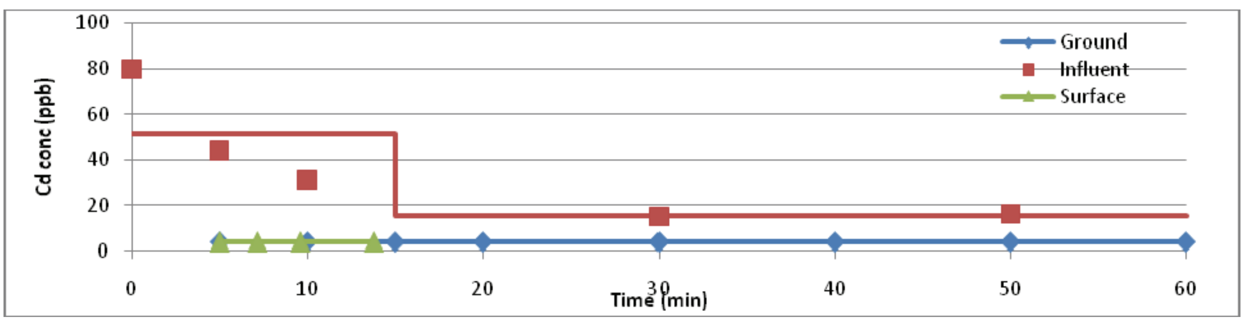


Figure 172. Dissolved concentration of cadmium in 4:1 slope, medium flow rate.

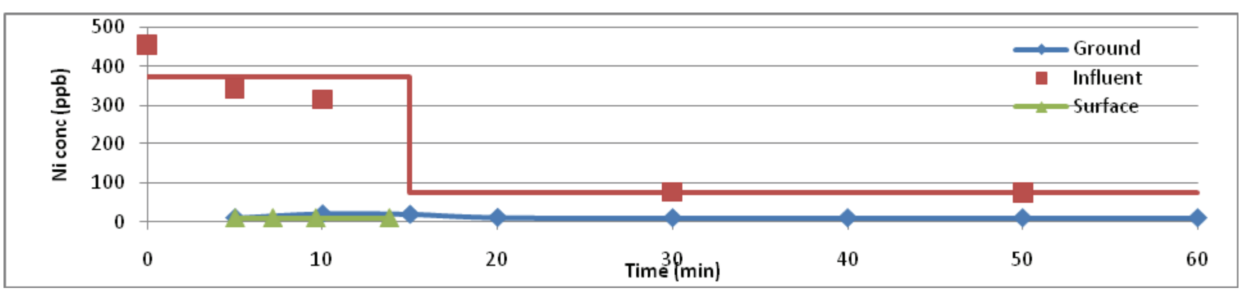


Figure 173. Dissolved concentration of nickel in 4:1 slope, medium flow rate.

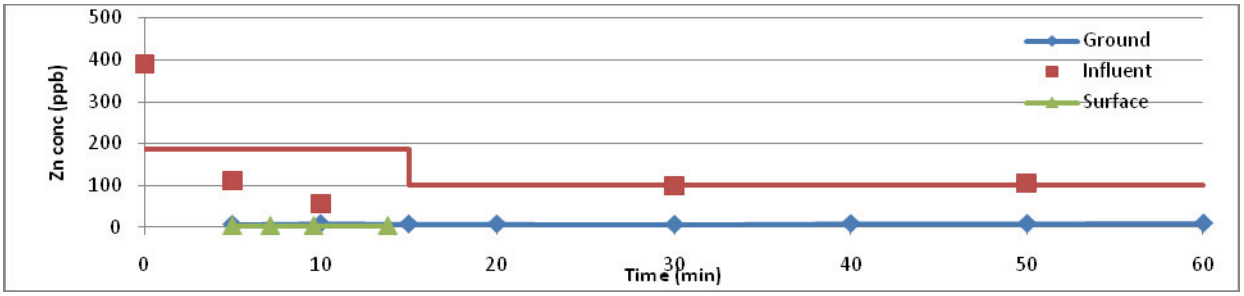


Figure 174. Dissolved concentration of zinc in 4:1 slope, medium flow rate.

Figure 175 through Figure 177 display the dissolved Cd, Ni, and Zn for the 2:1 slope and medium flow rate test. For this slope and flow rate, most of the metals were not detected in the influent throughout the entire test, except Cd, Ni, and Zn with concentrations below 55 µg/L, 370 µg/L, and 1310 µg/L, respectively. Fe was not detected throughout the test with a detection limit of 4 µg/L, except at 10 min with a concentration of 10 µg/L. For the water quality volume portion of the test, Cr, Cu, and Pb were not detected with detection limits of 2 µg/L , 7 µg/L , and 27 µg/L , respectively. Zn exhibited similar influent trends to total metals at this slope and flow rate, where the water quality volume influent concentrations were lower than the tail end influent concentrations (see Figure 177), and which again may be attributed to the nonlinearity of sorption and pH dependence of the partitioning of the metals. For the tail end portion of the test, Cu was detected with concentrations below 70 µg/L.

In the surface runoff, none of the metals were detected. In the underdrain, only Fe and Zn were detected, much like the 4:1 slope with concentrations below 245 µg/L and 15 µg/L, respectively.

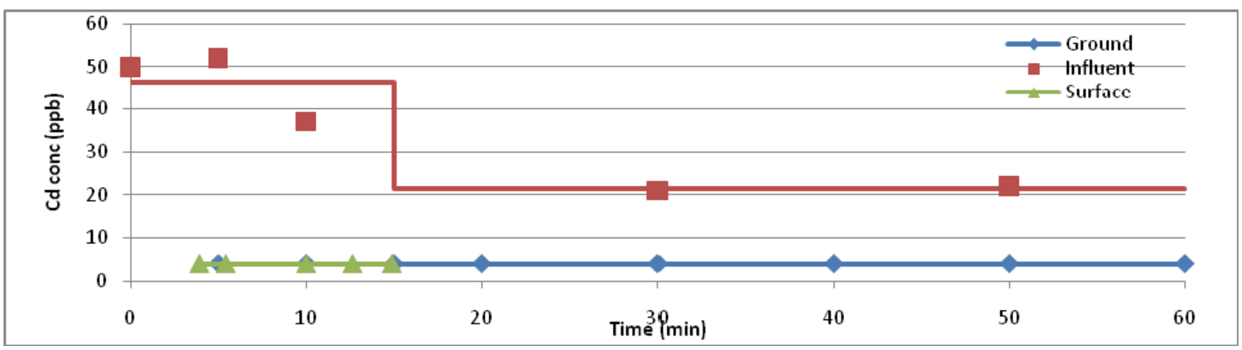


Figure 175. Dissolved concentration of cadmium in 2:1 slope, medium flow rate.

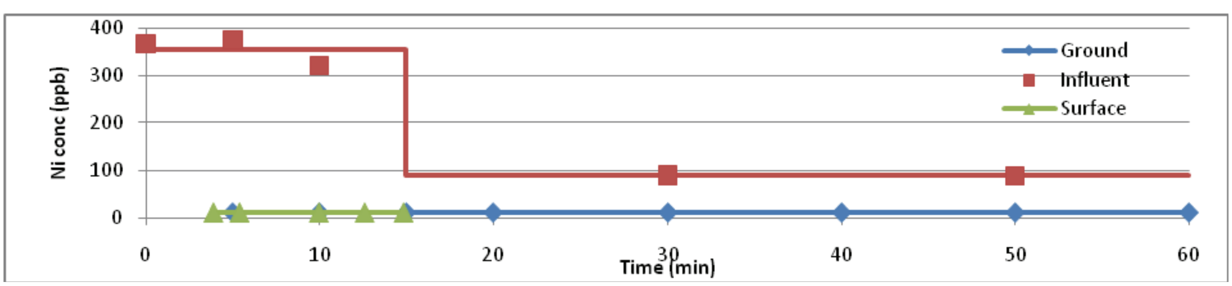


Figure 176. Dissolved concentration of nickel in 2:1 slope, medium flow rate.

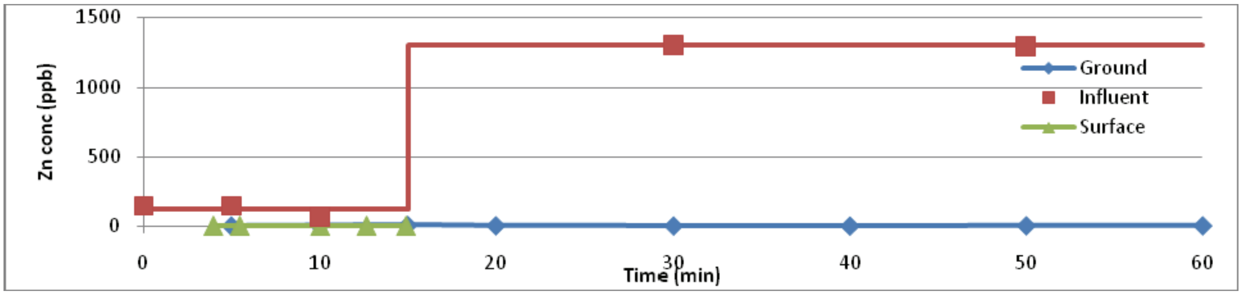


Figure 177. Dissolved concentration of zinc in 2:1 slope, medium flow rate.

Figure 178 through Figure 180 display the dissolved Cd, NI, and Zn concentrations for the 2:1 slope and high flow rate test. In the influent, the majority of the metals were detectable except Cr and Pb, with detection limits of 6 µg/L and 13 µg/L, respectively. Cd, Fe, Ni, and Zn were detected throughout the test with concentrations below 45 µg/L, 20 µg/L, 270 µg/L, and 260 µg/L, respectively. Cu was detected past 5 min, with concentrations below 25 µg/L . For the water quality volume and tail end portion of the test, the influent metal concentrations that were detected were consistent with the average influent concentrations. Surface runoff was generated throughout most of the test, but dissolved metals were not detected except for Fe, which had detectable concentrations during the tail end of the test with concentrations below 25 µg/L and a detection limit of 5 µg/L for the water quality volume portion of the test. In the underdrain, Fe was the only detected metal throughout the entire test, with concentrations below 135 µg/L, which further proves that it occurs in both particulate and dissolved forms.

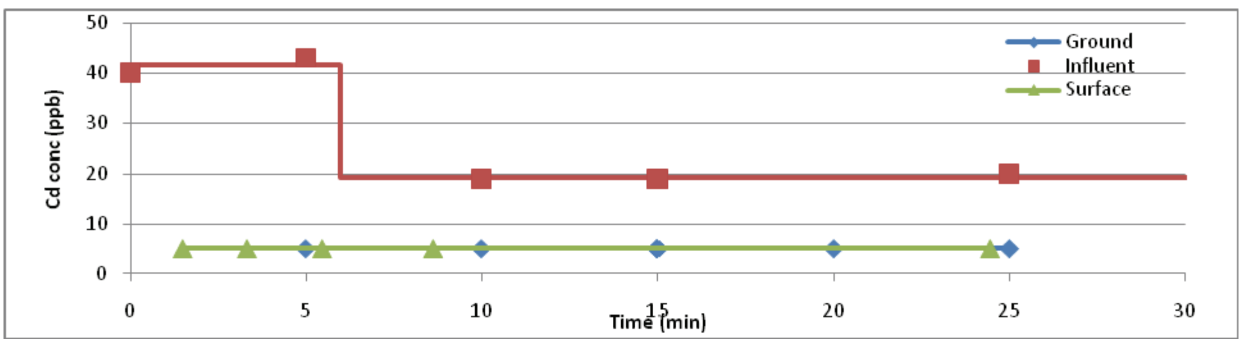


Figure 178. Dissolved concentration of cadmium in 2:1 slope, high flow rate.

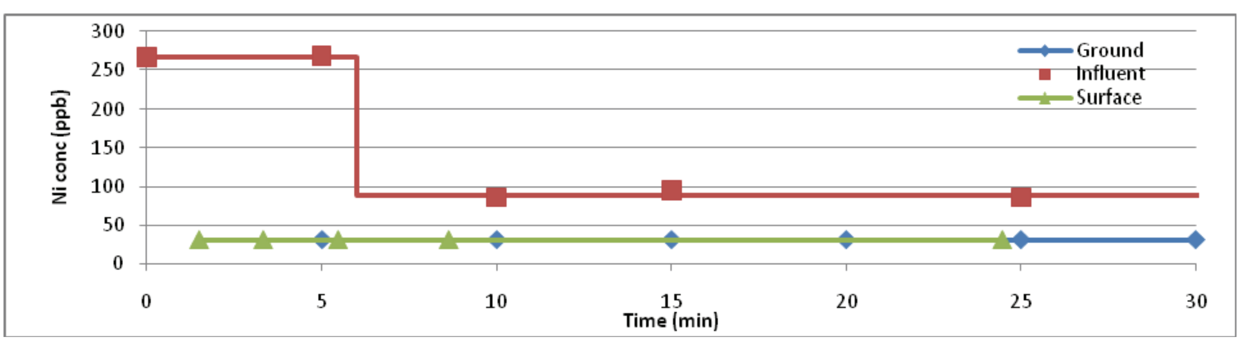


Figure 179. Dissolved concentration of nickel in 2:1 slope, high flow rate.

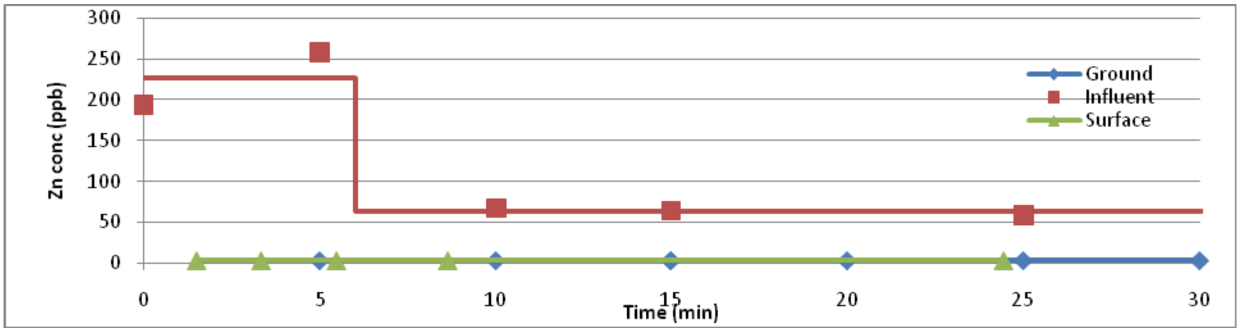


Figure 180. Dissolved concentration of zinc in 2:1 slope, high flow rate.

11.6 Oil and Grease Results

Based on the inadequate delivery of motor oil to Bed 1, several changes were made in the experimental methods, including changing the delivery of oil to the bed and raising the target concentrations, as discussed in Section 6.3 (see Figure 50). In the medium concentration tests for Bed 2, 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 for the 8:1, 4:1, 2:1 medium flow, and 2:1 high flow tests are shown in Figure 181 through Figure 184. 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 across the bed and is difficult to capture a representative sample in a bottle, and results tend to be erratic. Surface runoff concentrations were low for all four tests except for a single high detect near the influent concentration in the 2:1 slope, high flow test. Percent decrease in event mean concentrations were 99%, 85%, 100%, and 54% for the 8:1, 4:1, 2:1 medium flow, and 2:1 high flow tests. Concentrations of oil and grease in the underdrain were often higher than in the surface runoff with several high spikes. 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.

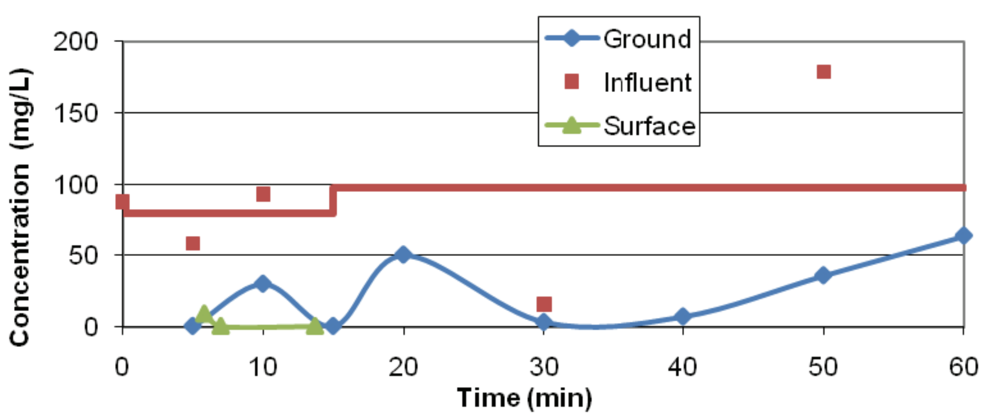


Figure 181. Concentration of oil and grease at 8:1 slope.

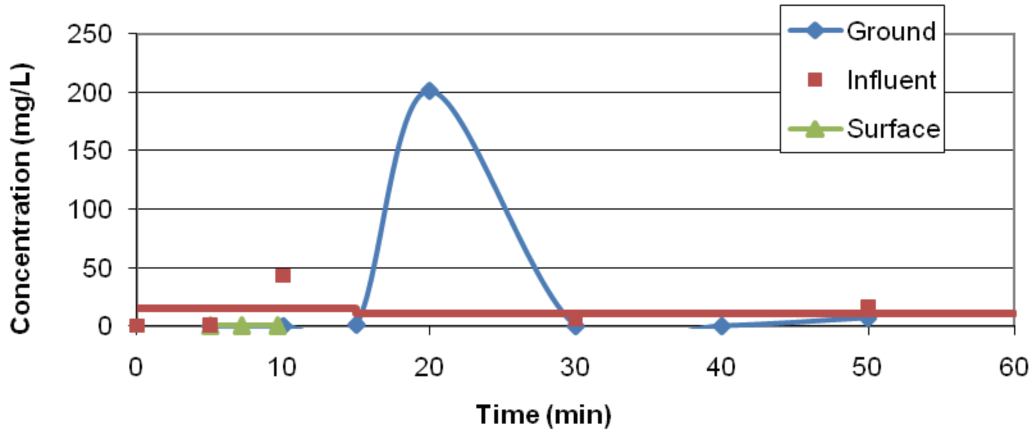


Figure 182. Concentration of oil and grease at 4:1 slope.

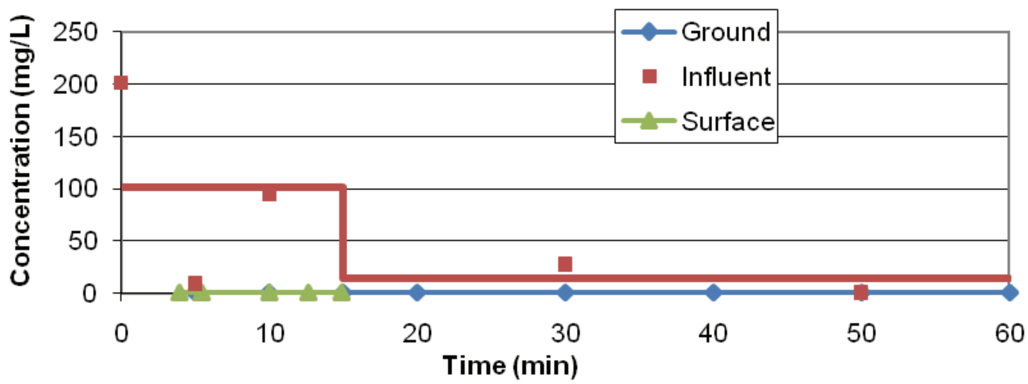


Figure 183. Concentration of oil and grease at 2:1 slope, medium flow.

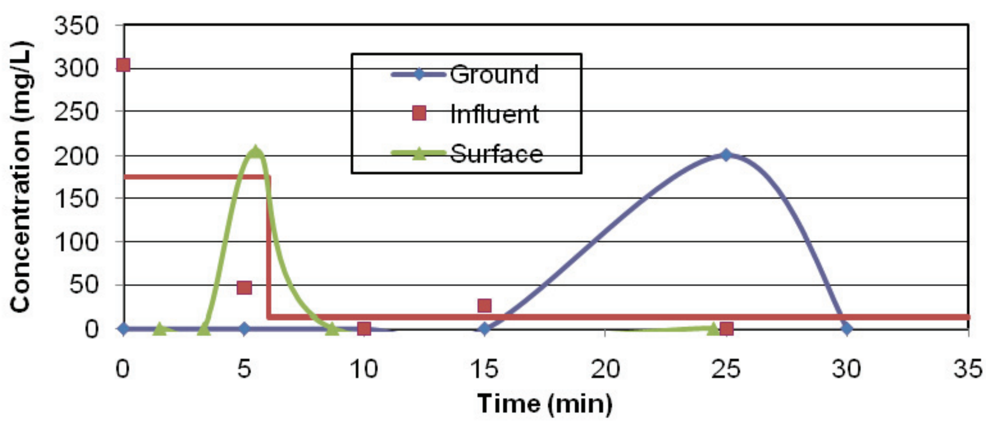


Figure 184. Concentration of oil and grease at 2:1 slope, high flow.

11.7 Deuterated Alkane Results

Results for the deuterated alkanes analyses are shown in Figure 185 through Figure 188. In these figures, the total concentration of the three deuterated alkanes was summed and plotted. Influent concentrations were an order of magnitude higher than in the Bed 1 performance test in order to discern removals. However, deuterated alkanes influent concentrations were still erratic and concentrations in the tailing portion of the storm in two of the test were higher than the water quality event portion of the storm. This behavior again illustrates the chaotic nature of oil transport. Surface runoff concentrations were uniformly low for the medium flow tests showing good removal, however, deuterated alkanes were detected near influent concentrations in the high flow test. Deuterated alkanes were not detected in underdrain samples at detection limits of 0.04 µg/L, except for four samples in both 2:1 tests, one result being close to the influent concentration.

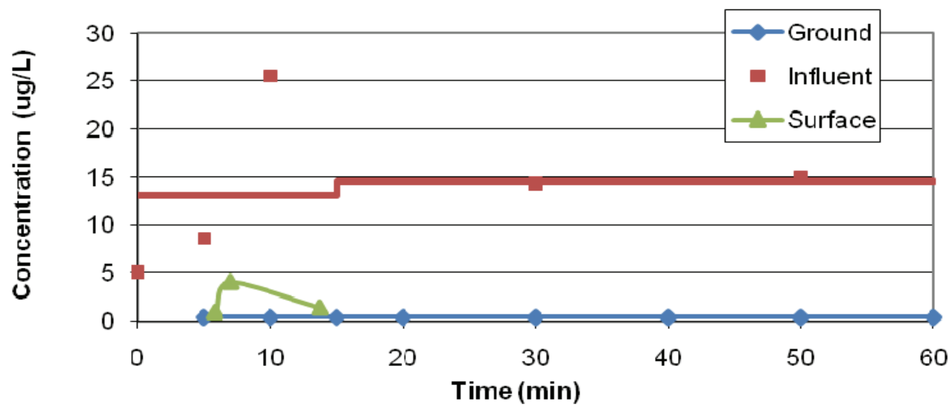


Figure 185. Total concentration of deuterated alkanes at 8:1 slope.

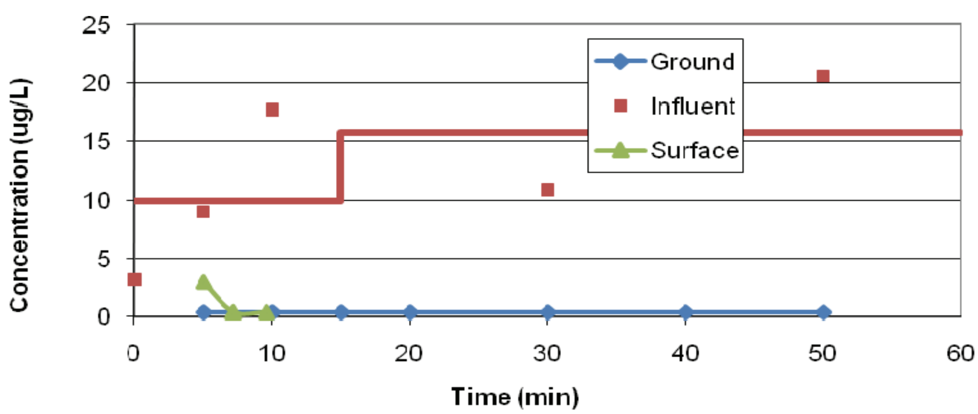


Figure 186. Total concentration of deuterated alkanes at 4:1 slope.

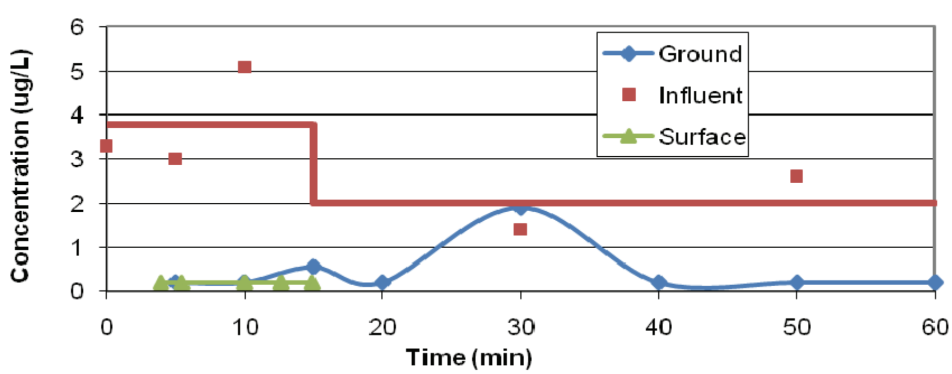


Figure 187. Total concentration of deuterated alkanes at 2:1 slope, medium flow.

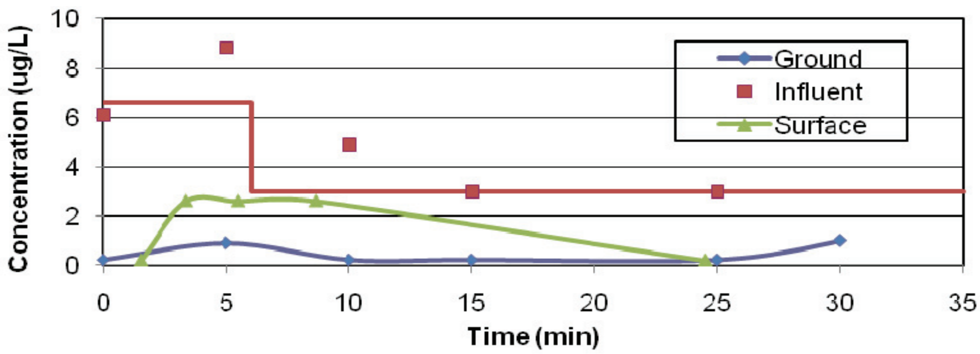


Figure 188. Total concentration of deuterated alkanes at 2:1 slope, high flow.

11.8 Removals

Figure 189 displays the average percent removals of the event mean concentration for each total metal, total suspended solids, and oil and grease for each performance test with Bed 2. Percent removals were fairly consistent and high for every metal, and particularly with the suspended solids. The 8:1 medium flow test exhibited the lowest percent removals for Cd, Cu, Ni, and Zn. For the medium concentration tests, no significant trends were noted with a change in slope. However, comparing the results for the 2:1 slope medium flow to the 2:1 slope high flow, removals were generally lower at the high flow. Overall percent removals were lower when compared with the high concentration tests.

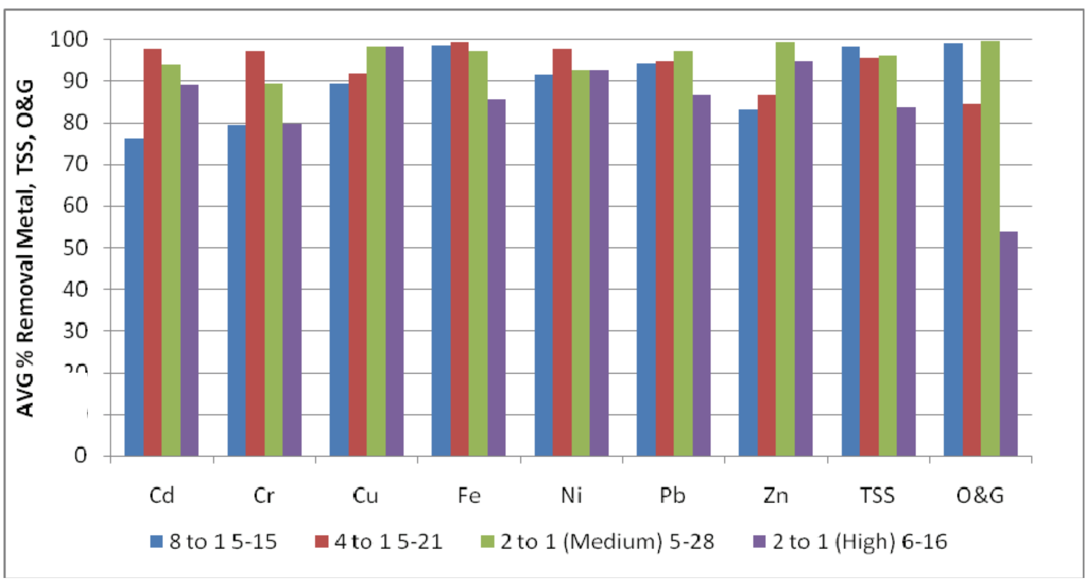


Figure 189. Percent removals of event mean concentration for total metals, TSS, and oil and grease from medium concentration influent tests on Bed 2.

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 190. Percent removals were higher for all except one point when considering only the water quality event portion, because the event mean concentration of the storm water influent was higher, because it did not include the tailing portion of the storm that has lower concentrations. For Bed 2, differences between using the complete storm and only the water quality event portion were less than 5% for tests except for seven points: Cd at 8:1

medium (5.9%), Cd at 2:1 high (7.9%), Cr at 2:1 medium (6.6%), Cr at 2:1 high (12.5%), Pb at 2:1 high (8.3%), TSS at 2:1 high (12.5%), and oil and grease at 2:1 high (20.4%).

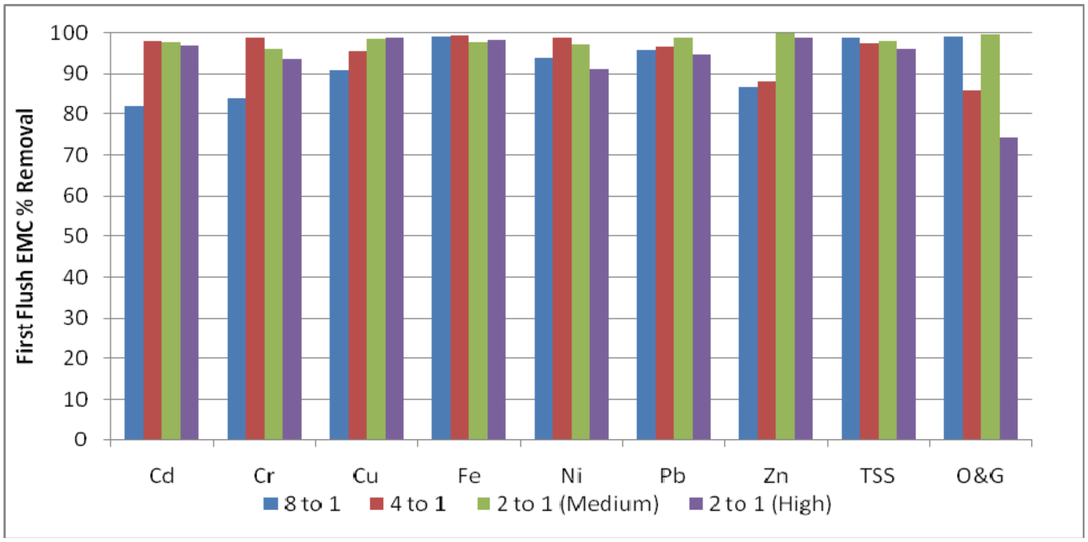


Figure 190. Percent removals of event mean concentration during the water quality volume of the storm event for total metals, TSS, and oil and grease for Bed 2.

11.9 Resuspension Results

After the four tests were completed on the bed, resuspension tests were conducted to determine the amount of tagged suspended solids that could become remobilized. Four resuspension tests were conducted that represented each slope and flow rate used for the initial testing. 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 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 191, the first collected influent sample exhibited a tagged suspended solids concentration slightly lower than the target concentration at 155 mg/L, while the other two influent samples were close to the target concentration, with an average tagged suspended solids concentration of 192 mg/L, and an average La concentration of 11,582 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 8 mg/L, and an average La concentration of 505 µg/L.

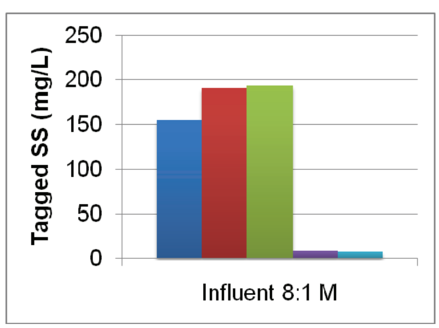


Figure 191. Influent tagged suspended solids concentration in 8:1 slope, medium flow rate for Bed 2. From left to right, the bars represent influent samples collected at times of 0 min, 5 min, 10 min, 30 min, and 50 min during the simulated storm event.

Figure 192 displays the tagged suspended solids concentrations in the surface runoff samples for each test on Bed 2, four performance tests and four resuspension 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 0.67 mg/L and an average La concentration of 40 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 tagged suspended solids concentration of 111 mg/L and average La concentration of 6,701 µg/L. The fraction of La tagged soil in the samples greatly decreased from around 1.3 in the influent to 0.2 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 4.8 mg/L for this run, see Figure 135) 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 7.2 mg/L with only tap water as influent. The other three performance tests resulted in very low concentrations of tagged suspended solids in surface runoff, averaging 0.01 mg/L for the 4:1 medium flow test, 0.05 mg/L for the 2:1 medium flow test, and 0.09 mg/L for the 2:1 high flow test. In the 4:1 medium flow test, La was detected with an average concentration of 8 µg/L. In the 2:1 medium flow test, La was not detected throughout the entire test, with a detection limit of 3 µg/L. In the 2:1 high flow test, La was not detected throughout the entire test, with a detection limit of 7 µg/L.

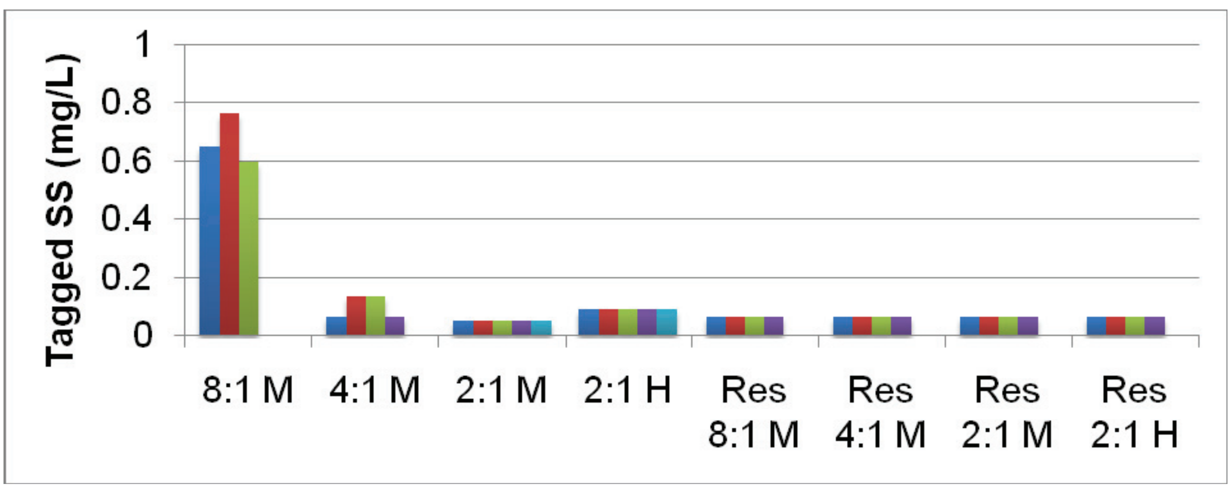


Figure 192. Tagged suspended solids concentrations for experimental and resuspension tests for Bed 2. Each bar represents a collected surface sample.

Each of the resuspension tests also had very low concentrations of tagged suspended solids, with average concentration of 0.07 mg/L for all four tests, which was a lower concentration than the initial tests. La concentrations were not detected for each test. Based on this data, it appears that the tagged suspended solids initially added to the 8:1 medium flow influent did not become resuspended at any slope or flow rate.

11.10Metal Accumulation in Grass, Soil, and Roots

Five soil cores were initially collected from the bed from random locations to determine the baseline metals concentrations. After completion of all performance and resuspension tests, twenty-five cores were collected throughout the bed, five replicates at five 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 193 through Figure 199 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 solid horizontal lines on each graph represent the average baseline concentrations of the grass, soil, and roots before any tests were conducted.

In terms of highest concentrations of metals accumulating within the media, each metal exhibited different trends. Cd, Cu, Ni, and Pb exhibited the highest concentrations detected in the roots, next highest in grass, and low concentrations detected in soil. Cr and Zn exhibited the highest concentrations detected in the grass, next highest in roots, and low concentrations detected in soil. Fe was the only metal with highest concentrations detected in the soil, next highest in roots, and low concentrations detected in grass. In terms of spatial distribution of metals, concentrations typically decreased along the length of the bed with highest concentrations detected at a location of 1 ft (0.305 m) from the origin or 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), 3 ft (0.91 m), 6 ft (1.83 m), 9 ft (2.74 m), and 12 ft (3.66 m); relative to the drip line, these positions are 0 ft (0.0 m), 2 ft (0.61 m), 5 ft (1.52 m), 8 ft (2.44 m), and 11 ft (3.35 m).

Metals were only detected at statistically significant levels above background concentrations ($\alpha = 0.05$ for all tests) in the roots and the grass. Cd was detected at statistically significant levels above background concentrations only in the root media and the grass at one location, 1 ft (0.305 m) along the length of the bed (see Figure 193). Cr likewise was only detected at significant levels above background in the root and grass at 1 ft (0.305 m) (see Figure 194). Cu was found significantly above background concentrations in roots along the entire length of the bed except at 9 ft (2.74 m), and in grass at the 1 ft (0.305) location (see Figure 195). Ni was found significantly above background concentrations in roots at 1 ft (0.305 m) and 3 ft (0.91 m) and in grass at 1 ft (0.305 m), 6 ft (1.83 m), and 9 ft (2.74 m) (see Figure 197). Pb was found significantly above background concentrations in roots at 1 ft (0.305 m) and 6 ft (1.83 m) and in grass at 1 ft (0.305 m) and 3 ft (0.91 m) (see Figure 198). Zn was detected significantly above background concentrations in the roots at 1 ft (0.305 m), 3 ft (0.91 m), and 12 ft (3.66 m) and in grass only at 1 ft (0.305 m) (see Figure 199). A high background concentration of Zn was obtained in all media compared to other metals, likely because Zn was at a high concentration in the tap water used for watering the bed. Fe was found in very high concentrations in background and post testing samples. Fe was only significantly high in grass at 12 ft (3.66 m), and no trend was apparent with concentrations varying randomly around the background concentration (see Figure 196).

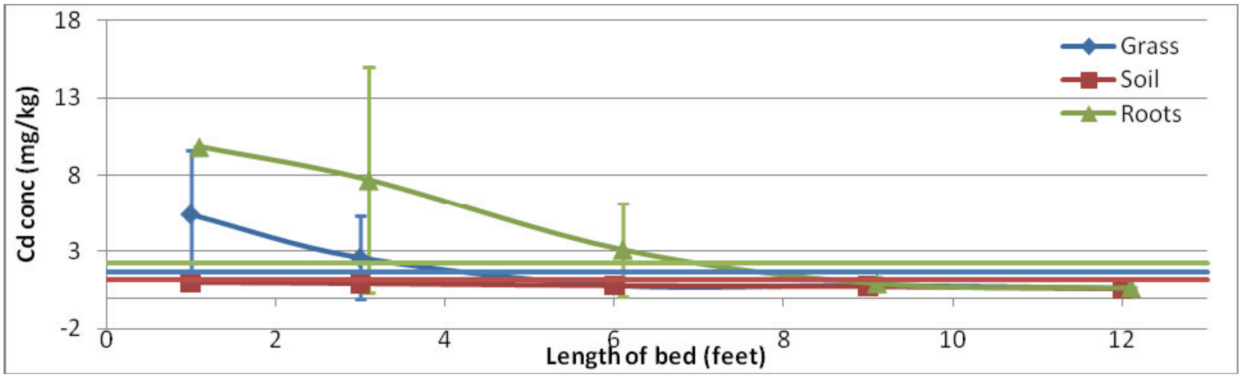


Figure 193. Concentration of Cd throughout length of Bed 2.

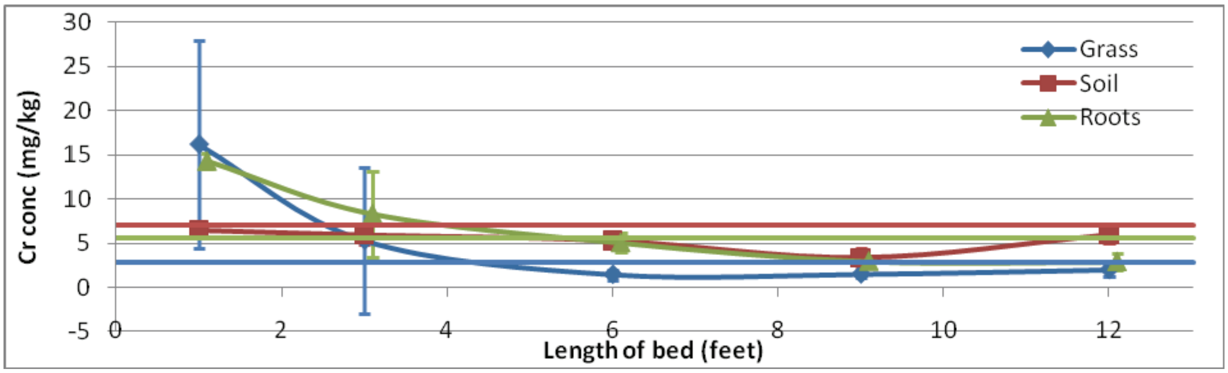


Figure 194. Concentration of Cr throughout length of Bed 2.

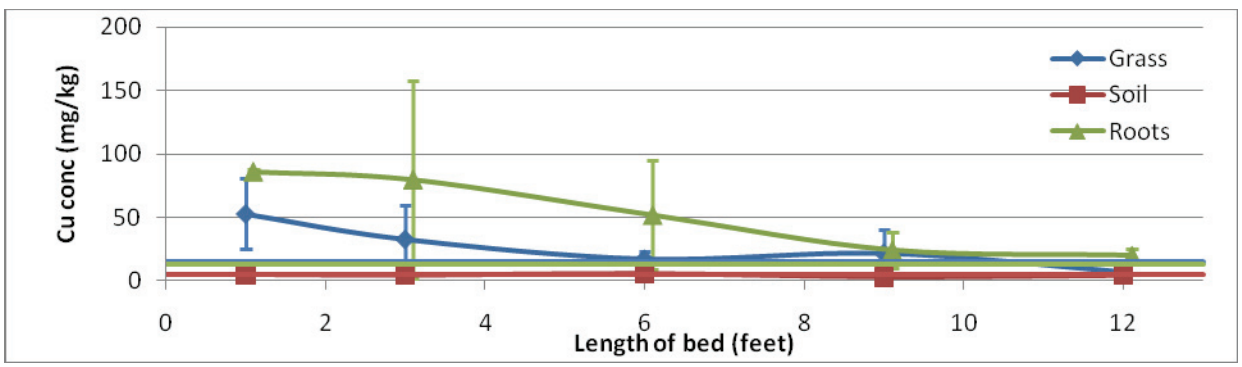


Figure 195. Concentration of Cu throughout length of Bed 2.

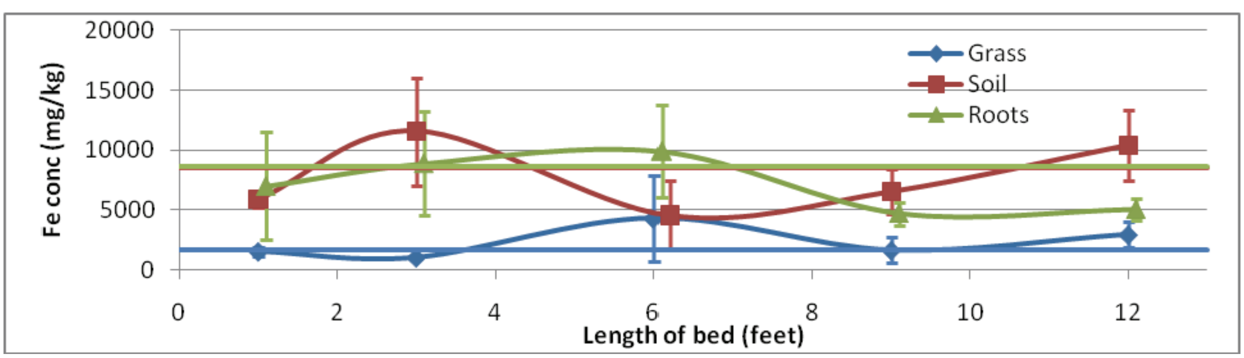


Figure 196. Concentration of Fe throughout length of Bed 2.

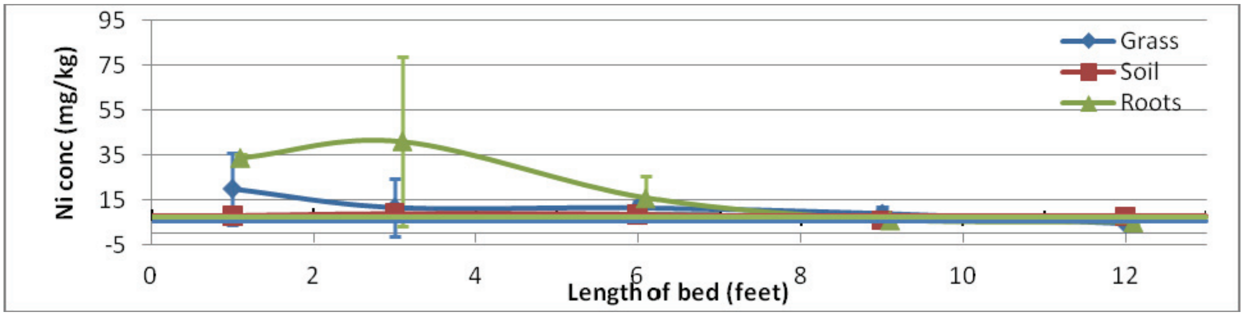


Figure 197. Concentration of Ni throughout length of Bed 2.

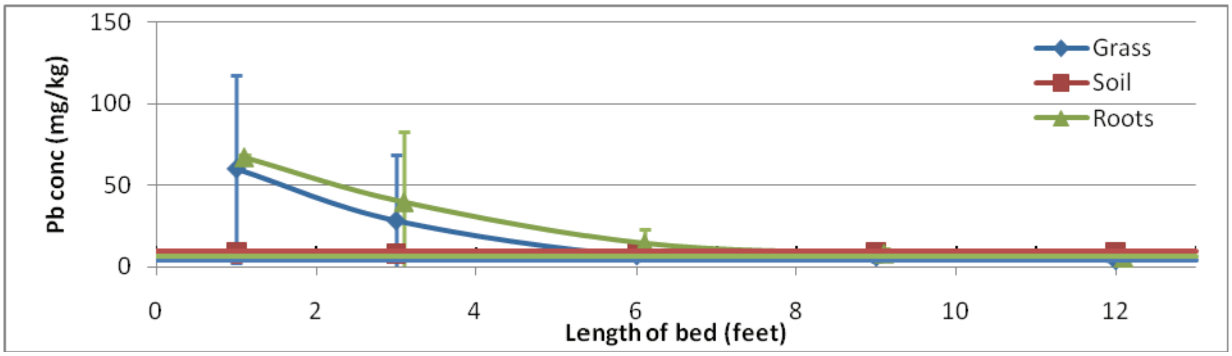


Figure 198. Concentration of Pb throughout length of Bed 2.

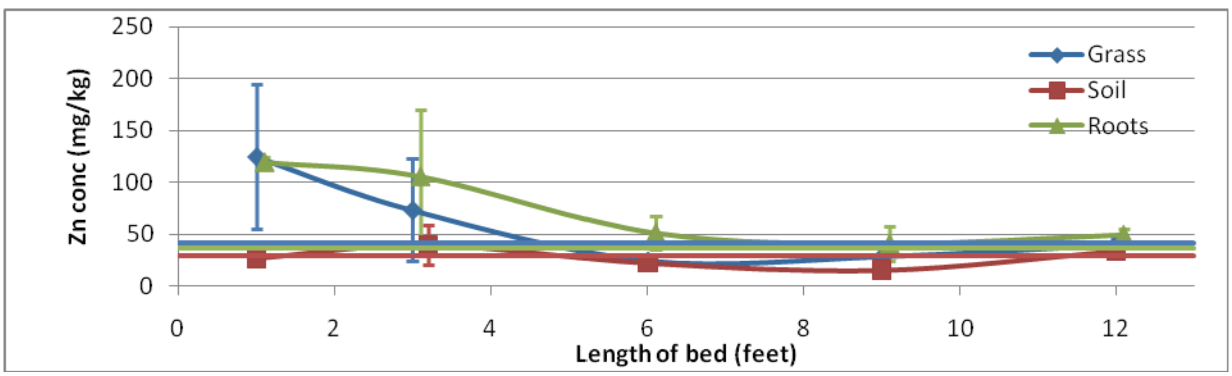


Figure 199. Concentration of Zn throughout length of Bed 2.

In the roots and grass, every metal except Fe showed a statistically significant amount of accumulation at the first sampling location. Cu, Ni, Pb, and Zn were also found in significant concentrations at several other locations. Zn accumulated to the highest concentration in grass at 125 mg/kg, and Cu accumulated to the highest concentration in the roots at 86.3 mg/kg, but Zn 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, Cu accumulated at the greatest proportion at 0.49 in the roots and at 0.30 in the grass. Zn accumulated in the proportion of 0.15 in the roots and 0.29 in the grass, while the remaining metals accumulated in the proportion of 0.01 to 0.13. As in Bed 1, metals accumulated at much higher concentrations in the grass tissues than in the soil. However, this is exaggerated by reporting concentrations in terms of dry mass. On average the moisture content of the root, grass, and soil samples from Bed 2 were 74.9.1%, 67.2%, and 17.0%. This was used to convert concentrations of mg/kg dry mass to mg/kg wet mass for the highest concentrations found in the bed (see Table 26). After correcting for this distortion, concentrations in the three media were very similar. Only Cu had a wet root concentration that was statistically significantly higher than the wet soil concentration. The Zn grass and soil concentrations were also significantly higher than the root concentration. Therefore it is unclear if the vegetation preferentially took up any of the metals, Cu being the most likely candidate. Cu also had the greatest uptake in Bed 1.

Table 26. Maximum metal concentrations in Bed 2 per dry and wet mass.

mg/kg (ppm) dry mass						
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Grass	5.4	16.1	52.9	19.8	60.0	125.0
Roots	9.8	14.3	86.3	41.1	67.1	64.2
Soil	1.0	6.5	5.1	8.8	9.3	39.9
mg/kg (ppm) wet mass						
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Grass	1.8	5.3	17.3	6.5	19.7	41.0
Roots	2.5	3.6	21.6	10.3	16.8	16.1
Soil	0.8	5.4	4.3	7.3	7.7	33.1

Because the total mass of grass, roots and soil in the bed could not be directly measured without destruction of the bed, and the variability of metals concentration with depth was not determined, a precise mass balance could not be performed. Nevertheless, extrapolating the relative mass of soil, roots, and grass from the cores over the extent of the bed, and assuming that the metals did not penetrate any deeper than the 2 in (5 cm) depth of the cores, the mass of contaminants collected by each media fraction was computed, and can be seen in Table 27. The majority of the metal mass was concentrated in the roots of the grass for all metals except Pb, which accumulated most significantly in the grass leaves. Cu, Zn, and Pb accumulated to the greatest extent. No net increase in metal mass in the soil was observed over the bed.

Table 27. Estimated mass of metal accumulated in different media over the top 2 in (5 cm) over the entire area of Bed 2.

	Total dry mass in top 5 cm (2 in) of Bed 2 (kg)	**Cd (g)**	**Cr (g)**	**Cu (g)**	**Ni (g)**	**Pb (g)**	**Zn (g)**
Grass	65.7	0	0.05	0.48	0.26	0.71	0.37
Roots	41.4	0.05	0	1.36	0.42	0.57	1.14
Soil	983	0	0	0	0	0	0
	(lb)	**(oz)**	**(oz)**	**(oz)**	**(oz)**	**(oz)**	**(oz)**
Grass	144.8	0.0000	0.0018	0.0169	0.0092	0.0250	0.0131
Roots	91.3	0.0018	0.0000	0.0480	0.0148	0.0201	0.0402
Soil	2167.1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		(ppm)	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**
Grass		0.00	0.76	7.31	3.96	10.81	5.63
Roots		1.21	0.00	32.85	10.14	13.77	27.54
Soil		0.00	0.00	0.00	0.00	0.00	0.00
	(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
Grass	6.0%	0.0%	100.0%	26.1%	38.2%	55.5%	24.5%
Roots	3.8%	100.0%	0.0%	73.9%	61.8%	44.5%	75.5%
Soil	90.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

12 Low Pollutant Concentration Experiments

In this series of tests, a low concentration of contaminants, as described in Table 11 was delivered to a different bed during an initial water quality event portion (the first 0.75 in (19 mm) of the event), followed by a longer flow period with tap water and a lower flow rate, as described in Table 18. A total of four tests were conducted which included the following: 1) an 8:1 slope (7.13°) with a medium flow rate, 2) a 4:1 slope (14.0°) with a medium flow rate, 3) a 2:1 slope (26.6°) with a medium flow rate, and 4) a 2:1 slope (26.6°) with a high flow rate. The medium flow simulation used an initial flow rate of 3.99 gpm (15.1 lpm) for 9 min followed by a flow rate of 1.11 gpm (4.20 lpm) for 51 min. The high flow simulation used an initial flow rate of 5.54 gpm (20.97 lpm) for 6 min followed by a flow rate of 1.20 gpm (4.54 lpm) for 24 min.

12.1 Tracer Tests

Tracer tests involved running tap water over the bed at the prescribed medium or high flow rates that was spiked with an initial slug of sodium bromide. Bromide was expected to behave as a conservative tracer, moving though the bed with very little uptake, adsorption, or other interaction with the bed. A bromide selective probe was used to determine bromide concentrations over time in the surface runoff and underdrain flow. Flow rates of the surface runoff and underdrain were also measured frequently.

Initial testing with the bed indicated no runoff would be generated using the same flow rates that were used in Bed 1 and Bed 2. For Bed 2, a significant decrease in runoff generated was observed, presumably because Bed 2 was about a year older than Bed 1 was and thus Bed 2 had been exposed to winter conditions, such as freezing and thawing, which may have resulted in Bed 2 being more porous with greater matting of vegetation. Bed 3 was even more likely to infiltrate water that Bed 2. Given the tremendous heterogeneity in soil (even though screened soil from a single source was used in this experiment), bed surface elevation after one year of exposure, and plant growth and development, this variability in the bed's ability to transmit water was expected. As a result, a more intense storm event was selected as the "medium flow" event in order to generate surface runoff for the performance tests.

Tracer results for the 8:1 slope are shown in Figure 200. Bromide moved directly with the overland flow, and highest bromide concentrations were detected in the water that first emerged from the bed, 3.5 min after initiation of the simulated storm event. Concentrations then decreased rapidly until surface flow stopped. In the underdrain, initial bromide concentrations were low, and flow at this point was due to draining of the bed from the saturation step in preparation for the test. Concentrations increased slightly, peaking at 6 min, indicating the average time required for water to seep through the soil layer and into the underdrain. Concentrations decreased rapidly until the tailing portion of the event began, when concentrations increased, peaking again at 20 min. Surface runoff began at 3.5 min after initiation of the event, increased slowly to 0.70 gpm (2.65 lpm), and then stopped rapidly at 11 min, 2 min after the tailing portion of the event began. Underdrain flow increased from base flow at 3 min, peaking at 3.9 gpm (14.8 lpm), and then decreased slowly to 0.68 gpm (2.57 lpm), below the inflow rate of 1.11 gpm (4.20 lpm). After inflow ceased completely, the underdrain continued to flow, decreasing linearly for 10 min. Of the inflow added to the bed, 71% was recovered in the surface runoff and underdrain flow, and only 5.3% of the inflow resulted in surface runoff, the rest seeping into the soil and emerging as underdrain flow.

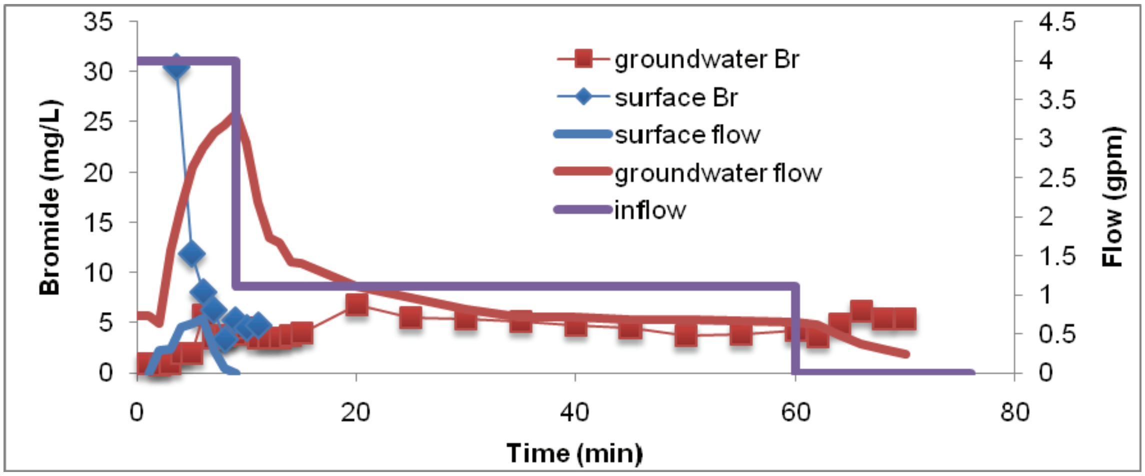


Figure 200. Bromide tracer test results for 8:1 slope, Bed 3.

Tracer results for the 4:1 slope, 2:1 slope medium flow, and 2:1 slope high flow are shown in Figure 201, Figure 202, and Figure 203, respectively. Results were similar for the 8:1 slope, although runoff began at increasingly earlier times, and an increasing higher proportion of inflow ran off the surface. Surface flow first appeared after 3.0 min for the 4:1 slope, 2.2 min for the 2:1 slope medium flow, and 1.7 min for the 2:1 slope high flow. Increased flow emerged from the underdrain at nearly the same intervals as the 8:1 slope, but did not coincide with the surface flow, after 4 min for all three tests. Surface runoff ceased after the end of water quality event flow for all three of the tests. During the initial portion of the events, surface runoff only measurably exceeded underdrain flow during the high flow test. Over the entire event, the percent of inflow that ran off the surface was 7.4% for the 4:1 slope, 15% for the 2:1 slope medium flow test, and 29% for the 2:1 slope high flow test. Percent recoveries of water for the tests were 74%, 67%, and 69%, respectively.

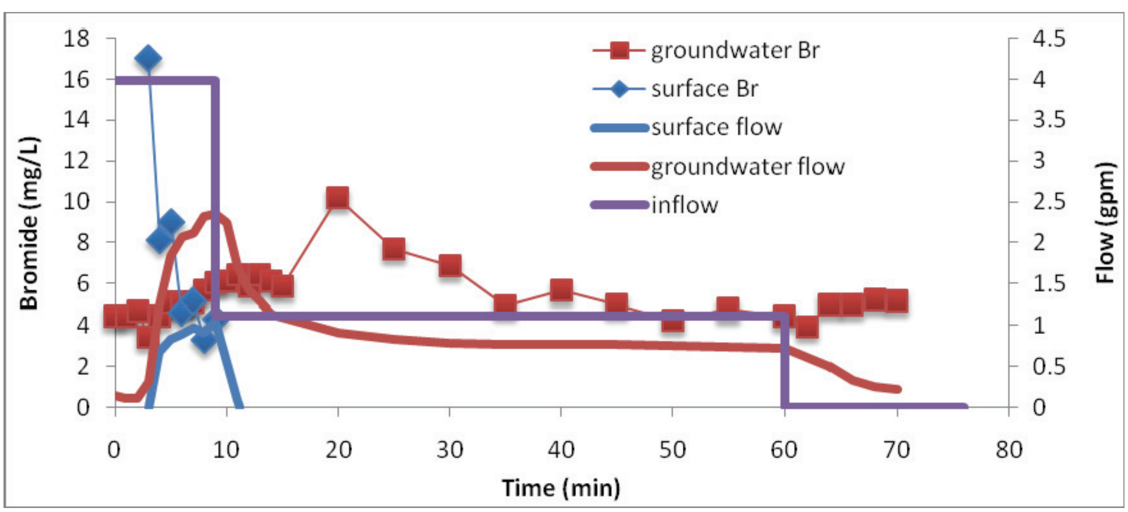


Figure 201. Bromide tracer test results for 4:1 slope, Bed 3.

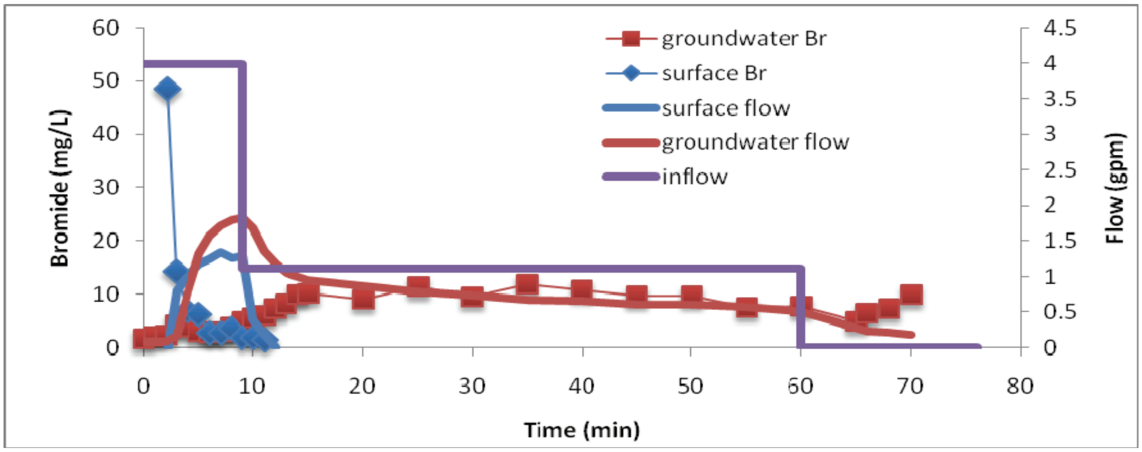


Figure 202. Bromide tracer test results for 2:1 slope, medium flow, Bed 3.

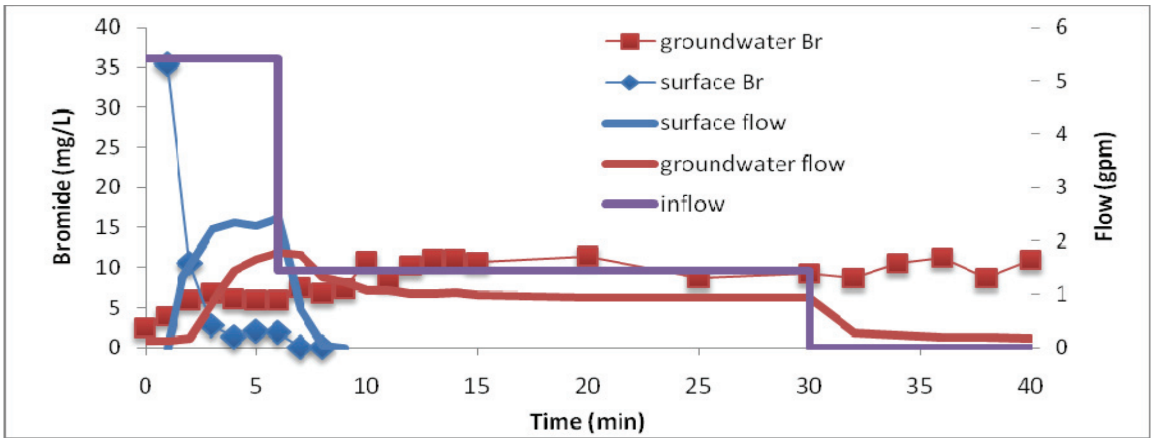


Figure 203. Bromide tracer test results for 2:1 slope, high flow, Bed 3.

12.2 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 or NaOH. During and after pH adjustment the pH would continue to drift over several hours. Although pH was adjusted to 7 after the solutions were mixed, by the time the other preparation steps were completed, the pH had increased to as high as 7.88 in the influent water. The pH in the surface runoff was not significantly different from the influent water. The pH from the underdrain however was lower than the influent, likely due to leaching of acidity from the soil. The native soil initially had a pH of 5.3 and was mixed with lime to raise the pH to 6.5. The average pH values recorded in each test are given in Table 28.

Table 28. Average pH values during the low concentration tests.

Test	Initial Influent	Tailing Influent	Initial Surface Runoff	Tailing Surface Runoff	Initial Underdrain Flow	Tailing Underdrain Flow
8:1	7.47	7.35	7.61	no flow	7.09	6.90
4:1	7.88	7.19	7.64	no flow	7.05	6.80
2:1 Medium	7.43	7.54	7.25	no flow	7.27	7.07
2:1 High	7.82	7.54	7.71	no flow	7.51	7.34

12.3 Suspended Solids Results

Figure 204 through Figure 207 depict the suspended solids concentrations for the four low concentration tests. Sieved soil (<0.841 mm (0.033 mil)) was mixed at a target concentration of 9 mg/L for the initial low concentration flow of 3.99 gpm (15.1 lpm); no soil was added in the second influent vessel containing the tap water which was applied during the tailing portion of the event at a lower flow rate of 1.11 gpm (4.20 lpm). Actual concentrations measured in the influent flow as it sprayed onto the distributor plate for the low concentration portion of the tests varied from the target concentration on more than one occasion; however, the average influent concentrations for a few tests were relatively close to the target concentration of 9 mg/L.

For the four low concentration tests, influent concentrations averaged 8 mg/L, 15 mg/L, 11 mg/L, and 8 mg/L. Influent suspended solids concentrations decreased during the lower flow rate for the tailing 51 min for the first three tests and 24 min for the last test, and averaged 1 mg/L, 3 mg/L, 0.7 mg/L, and 2 mg/L.

For the first three medium flow tests, surface runoff was only generated during the first 9 min of the test. Once the concentration and flow decreased for the tailing 51 min, all the water delivered to the bed infiltrated and no surface samples could be collected. Sediment concentrations in the surface runoff exhibited varying trends for each test. For each of the tests except the 4:1 medium flow test, a few of the surface sediment concentrations were higher than the influent sediment concentrations. For example, the 8:1 medium flow test had a single surface sediment concentration of 20 mg/L, which was well above the average influent concentration of 8 mg/L for the water quality event portion of the test. The 2:1 medium flow test had a very large spike in sediment concentration at around 5 min. The surface samples collected around 6 and 7 min also had sediment concentrations above the influent sediment concentrations. The 4:1 medium flow test was unlike the other two, and each of the 3 surface sediment samples had decreasing concentrations that were below the influent. The 2:1 high flow run did not generate more surface runoff than the other three tests, which was not consistent with the other Bed 1 and Bed 2. The first collected sample had a sediment concentration of 11 mg/L, slightly above the influent average of 8 mg/L. The other four collected samples had sediment concentrations slightly below the influent average. Baseline suspended solids concentrations averaged 7 mg/L, which was slightly below the average surface suspended solids concentration for each slope and test. When accumulated over the entire storm, the percent removals of the event mean concentration were 50.4% for the 8:1 test, 26.9% for the 4:1 test, and 16.7% for the 2:1 high flow test. The percent removals for the 2:1 medium flow test could not be computed because influent suspended solids concentrations were much lower than the surface concentrations, and percent removals were negative.

For the 8:1 medium flow test, the first two underdrain sediment samples were above the average first portion influent concentration of 8 mg/L at 12 mg/L and 17 mg/L. The third sediment sample was below the average influent concentration at 2 mg/L. For the tail end portion of the test, the sediment sample collected at 20 min had an unusually large spike in sediment concentration at 90 mg/L, but the other collected samples had low sediment concentrations that were around the influent average of 1 mg/L. The other three tests had similar sediment concentration trends. For example, the sample collected at 5 min had a large spike in sediment concentration for all three tests at 25 mg/L, 71 mg/L, and 104 mg/L. As the slopes increased, this spike in concentration also increased. It is possible that an increase in slope causes more sediment to be released from the underdrain. The other sediment samples gradually decreased in concentration, and were slightly above the tail end average influent concentrations, except the tail end portion of the 4:1 medium flow test, which had sediment concentrations that were slightly below the average influent concentration of 3 mg/L. Baseline underdrain suspended solids concentrations averaged 11 mg/L, which is only slightly lower for the 8:1 test and 2:1 medium and high flow tests; however, this concentration is higher than the 4:1 medium flow test when compared with average underdrain concentrations for each test.

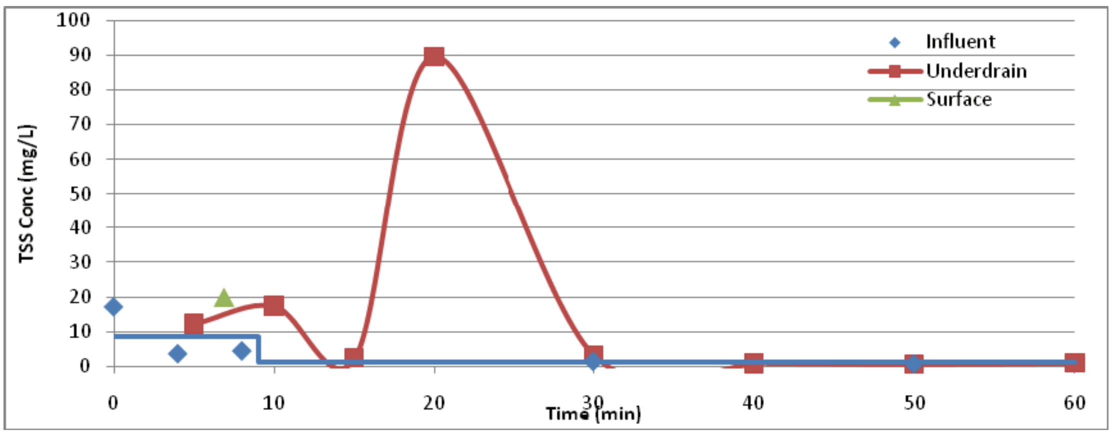


Figure 204. Concentration of suspended solids in 8:1 slope, medium flow rate.

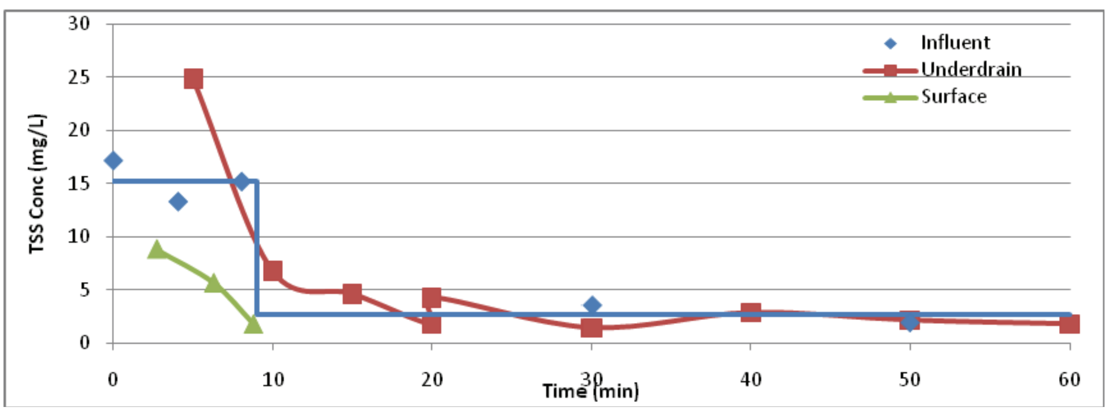


Figure 205. Concentration of suspended solids in 4:1 slope, medium flow rate.

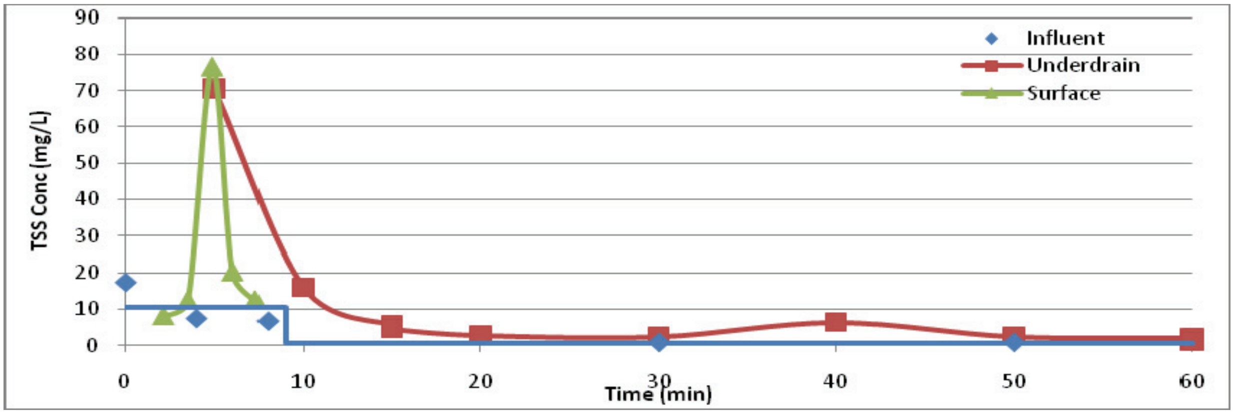


Figure 206. Concentration of suspended solids in 2:1 slope, medium flow rate.

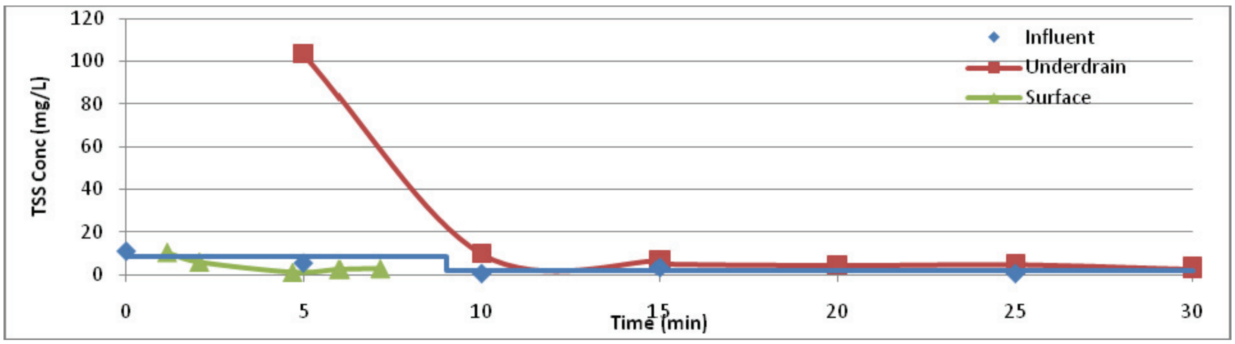


Figure 207. Concentration of suspended solids in 2:1 slope, high flow rate.

12.3.1 Particle Size Analysis

One particle size analysis of sediment in the influent water and in the surface runoff was performed for each test and results are shown in Figure 208 and Figure 209. Influent samples varied considerably with two of them being dominated by small particles (mean diameters of 12.5 µm (0.49 mil) and 14.5 µm (0.57 mil)) and the other two having both small and large particles (mean diameters of 238 µm (9.37 mil) and 852 µm (33.5 mil). The larger particles were inconsistent with the soil added to the influent that was sieved to be smaller than 841 µm (33.1 mil) and the baseline sediment distributions (see Figure 61). It is likely that the clay particles agglomerated in the influent mixing tank forming larger particle aggregations that entered the bed. Surface runoff distributions were fairly uniform and consistent from sample to sample being dominated by small particles (mean diameter of 5.1 µm (0.20 mil) to 14.4 µm (0.57 mil)) and consistent with baseline tests.

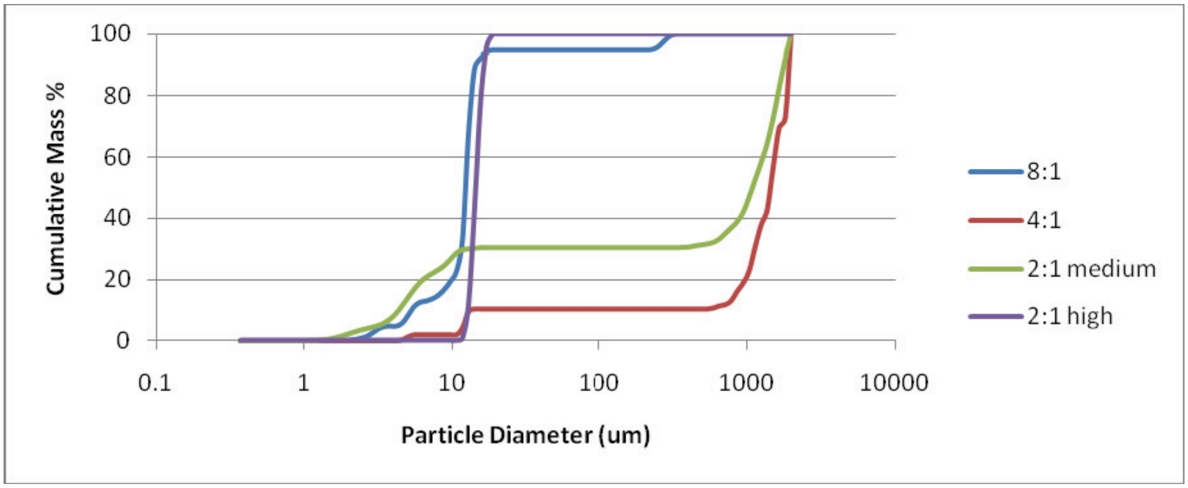


Figure 208. Particle size distribution of influent samples from Bed 1.

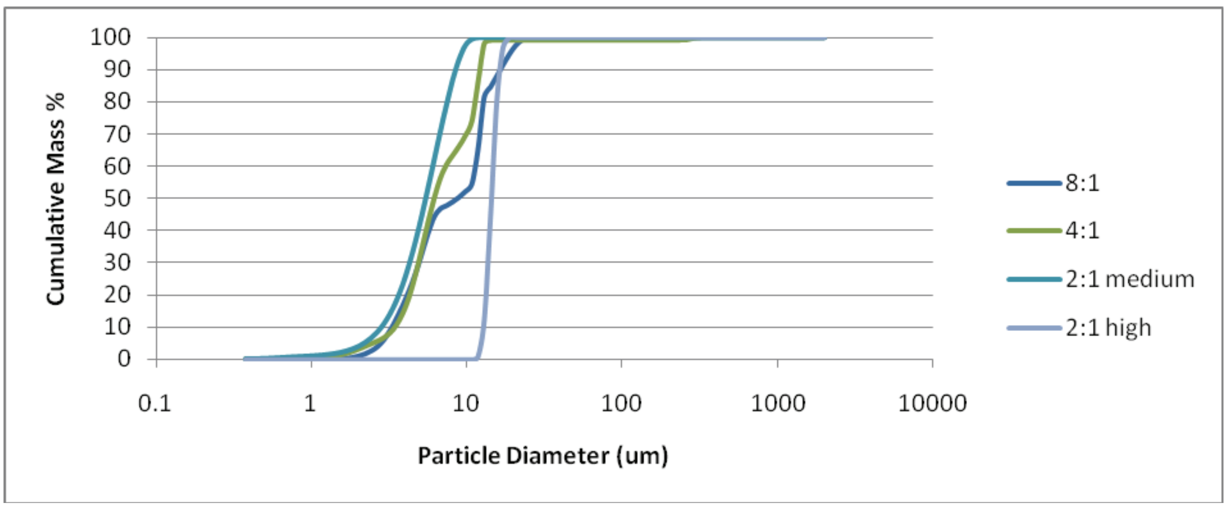


Figure 209. Particle size analysis for surface runoff from Bed 3.

12.4 Total Metals Results

Table 11 displays the low target contaminant concentrations and Table 12 displays tap water contaminant concentrations. For the medium flow rate test with an 8:1 slope, total metals concentrations are displayed in Figure 210 through Figure 216. Measured influent concentrations for Cd, Cr, Ni, and Pb were somewhat lower than the target concentrations for the water quality event portion of the test. For example, the low target concentration for Cd was 20 µg/L, and the average measured influent concentration was 9 µg/L. Cu, Fe, and Zn had higher measured influent concentrations than the target concentrations. For example, the low target concentration for Cu was 35 µg/L, and the average measured influent concentration was 84 µg/L. For the remaining 51 minutes of the test, measured influent concentrations were not detected for Cd, Cr, Ni, and Pb, but were for Cu, Fe, and Zn. Zn exhibited very high influent concentrations throughout the duration of the test, and most likely arose from high concentrations of Zn in the tap water. Cr, Ni, and Pb were within a 40% margin of the target values, while Cd was within a

60% margin of the target values. Overall, the influent concentrations remained fairly constant over time for every metal despite their differences from the target concentrations.

Collected surface runoff was only generated during the initial higher flow rate period of the 8:1 medium flow test. Each of the metals except Fe and Zn were not detected in the surface runoff sample, with the following detection limits for Cd, Cr, Cu, Ni, and Pb: 8 µg/L, 6 µg/L, 12 µg/L, 18 µg/L, and 77 µg/L. Fe remained below 200 µg/L, while Zn remained below 50 µg/L. In the surface baseline samples, none of the metals were detected except Fe and Zn, with concentrations below 135 µg/L and 40 µg/L, respectively. Both of these concentrations were below the experimental surface concentrations. EMC percent removals for Cd, Cr, Cu, Fe, Ni, Pb, and Zn are as follows: 66.3%, 85.4%, 94.7%, 40.4%, 87.3%, 77.8%, and 69.8%. In the 8:1 slope test, Cu, Ni, and Cr had the highest percent removals out of the metals. For underdrain samples all metals were nondetects, except Fe and Zn; detection limits were the same as for the surface samples. Fe remained below 420 µg/L, while Zn remained below 90 µg/L. Figure 213 shows an initial spike in Fe concentration, with all the other samples above the influent concentrations. Erratic Zn concentrations are depicted in Figure 216 for the underdrain samples, and are both above and below influent concentrations. In the underdrain baseline samples, Fe and Zn had concentrations below 500 µg/L and 35 µg/L. Zn baseline concentrations remained below the experimental underdrain concentrations, but Fe had higher baseline concentrations, which means that Fe occurs in naturally high concentrations in the tap water or soil.

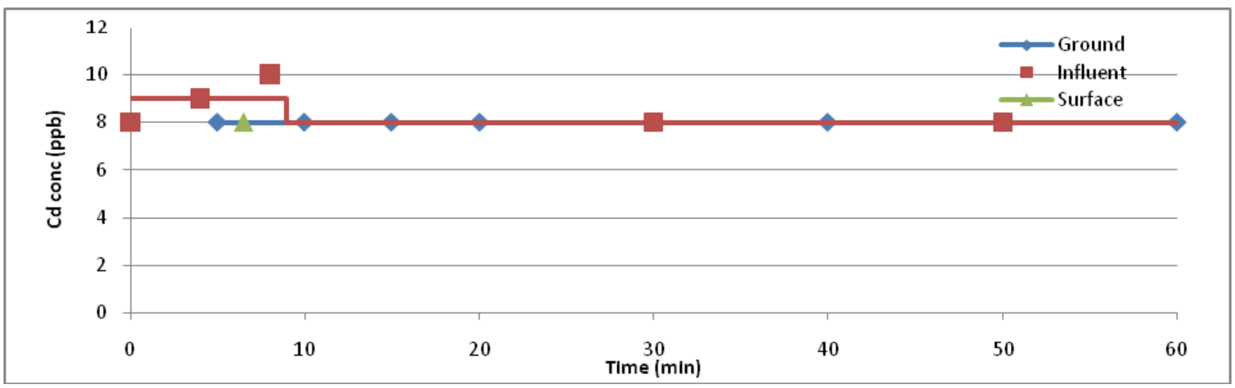


Figure 210. Total concentration of cadmium in 8:1 slope, medium flow rate.

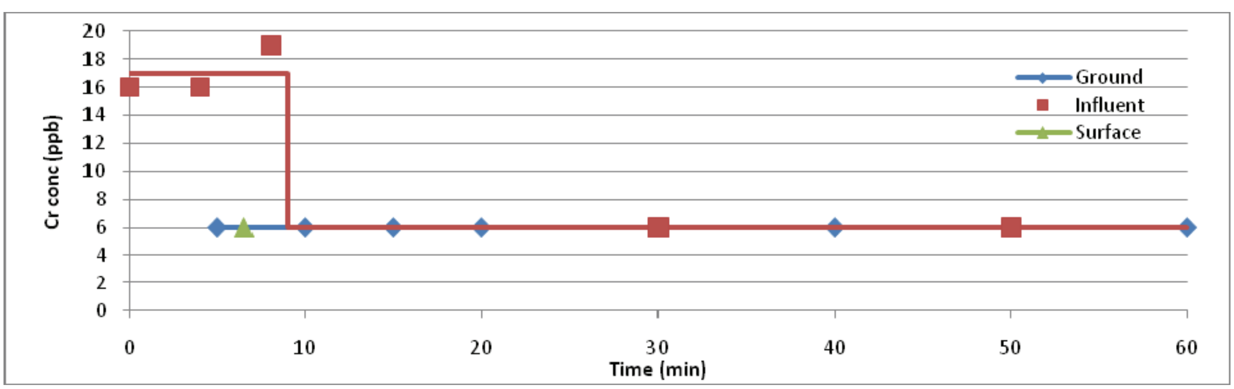


Figure 211. Total concentration of chromium in 8:1 slope, medium flow rate.

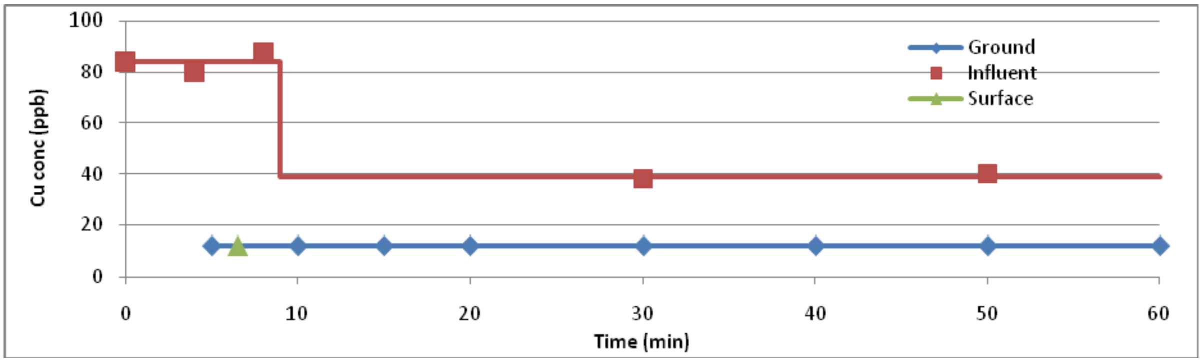


Figure 212. Total concentration of copper in 8:1 slope, medium flow rate.

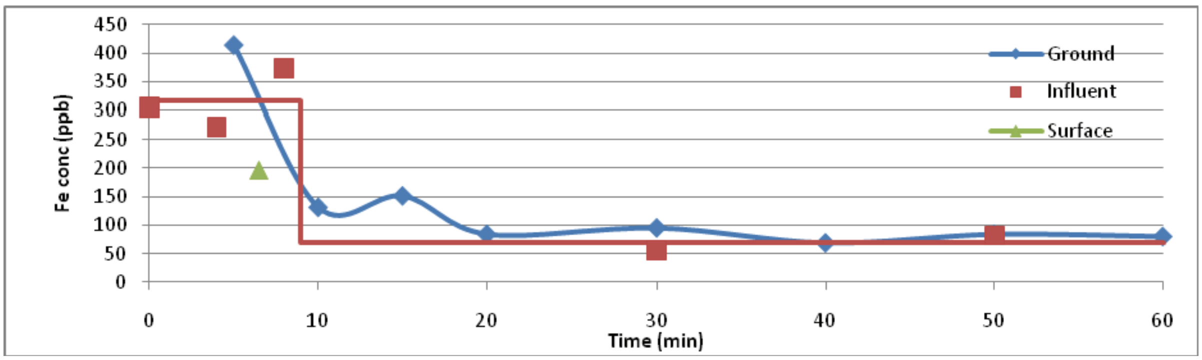


Figure 213. Total concentration of iron in 8:1 slope, medium flow rate.

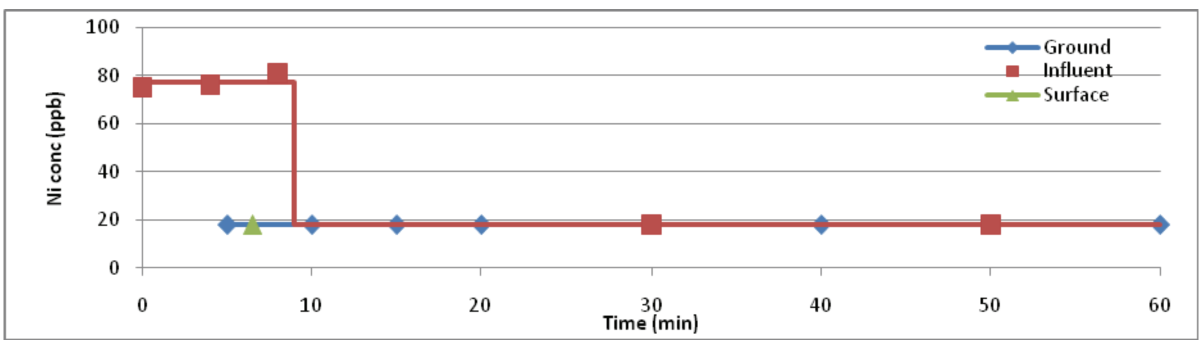


Figure 214. Total concentration of nickel in 8:1 slope, medium flow rate.

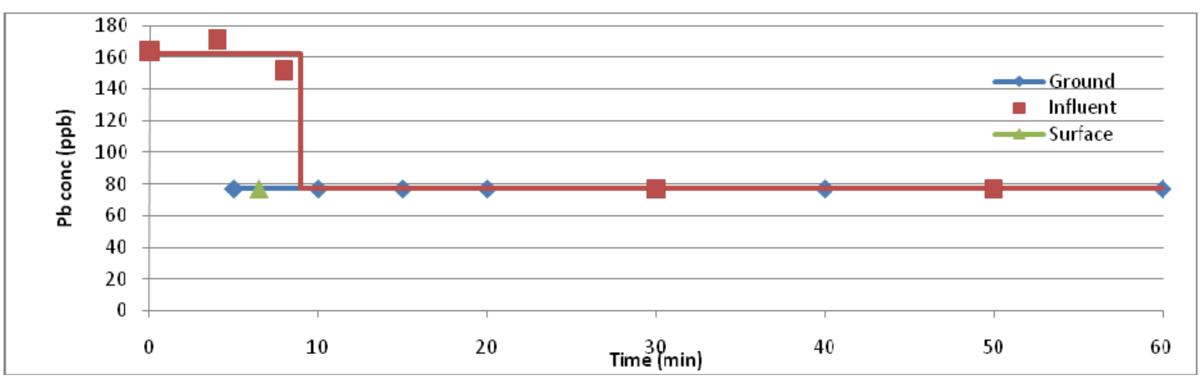


Figure 215. Total concentration of lead in 8:1 slope, medium flow rate.

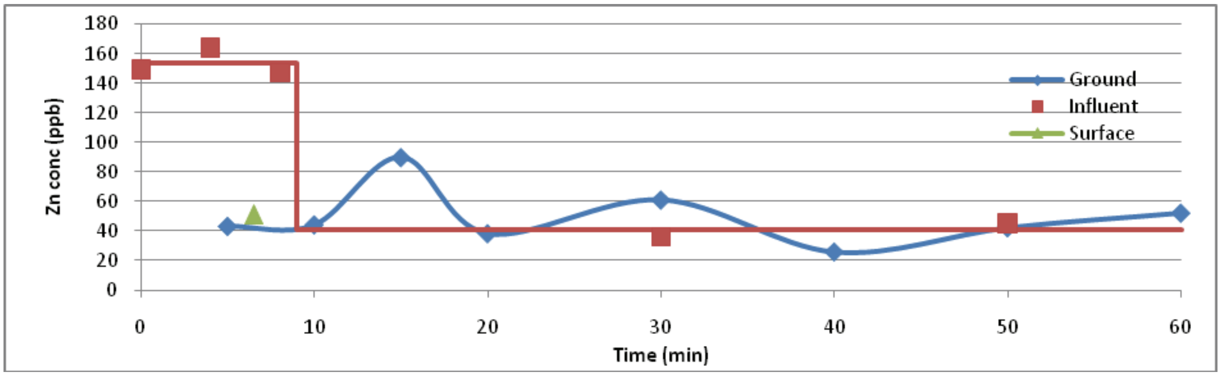


Figure 216. Total concentration of zinc in 8:1 slope, medium flow rate.

For the medium flow rate test with a 4:1 slope, total metals concentrations are displayed in Figure 217 through Figure 223. When compared with the 8:1 slope test, the influent metal concentrations vary slightly. Unlike for the 8:1 slope, Cr was below detection limits in the influent for the entire duration of the test with an average detection limit of 17 µg/L. Similar to the 8:1 slope, Cd and Pb had initial influent concentrations that were slightly lower than the low target concentrations, except for this slope Ni had influent concentrations higher than low target concentrations. Cu, Fe, and Zn also had higher influent concentrations than the low target concentrations. For the water quality event portion of the test, the influent concentrations were erratic and not consistent, particularly for Cu, Ni, Pb, and Zn. Cd and Pb, which had slightly lower average influent concentrations than the low target concentrations, were within a 27% and 16% margin of the low target concentrations. The tailing portion of the test had very consistent influent metal concentrations, where Cd, Cr, and Ni were not detected with average detection limits of 9 µg/L, 11 µg/L, and 27 µg/L respectively.

The surface and underdrain samples at the 4:1 slope exhibited slightly different trends than the 8:1 slope test, but the surface runoff was still only generated during the water quality event period of the test. In the surface runoff, Cd, Cr, and Cu were not detected throughout the test with average detection limits of 9 µg/L, 13 µg/L, and 8 µg/L, respectively. Ni and Pb were not detected for the first 6 min of the test, with average detection limits of 27 µg/L and 79 µg/L. Zn was not detected at around 2 min with a detection limit of 6 µg/L. At around 8 min, Ni was detected below 65 µg/L, while Pb was detected below 140 µg/L. From 6 to 9 min when the surface runoff stopped, Zn was detected below 50 µg/L. Fe was the only metal detected throughout the duration of the surface runoff. Percent removals for Cd, Cu, Fe, Ni, Pb, and Zn were as follows: 53.5, 91.3, 57.6, 62.8, 55.2, and 75.1. Cr was not included in the percent removals because influent concentrations were not detected. Cu and Zn had the highest percent removals out of all the metals. When comparing the 8:1 and 4:1 slope tests, Ni and Pb had a significant drop in percent removals, but the rest of the metals remained about the same.

In the underdrain, Cd, Cr, Cu, and Pb were the only metals that were not detected throughout the entire test with average detection limits 9 µg/L, 14 µg/L, 5 µg/L, and 79 µg/L, respectively. Ni was not detected throughout the entire test with an average detection limit of 32 µg/L, except at 20 min when it was detected at 57 µg/L. Zn was mostly detected throughout the entire test below 95 µg/L, but was not detected from 15 to 20 min with a detection limit of 6 µg/L. Similar to the 8:1 test, the results in Figure 213 show an initial spike in Fe concentration occurred followed by gradually decreasing concentrations mostly above influent levels. Zn had tail end underdrain concentrations below influent concentrations.

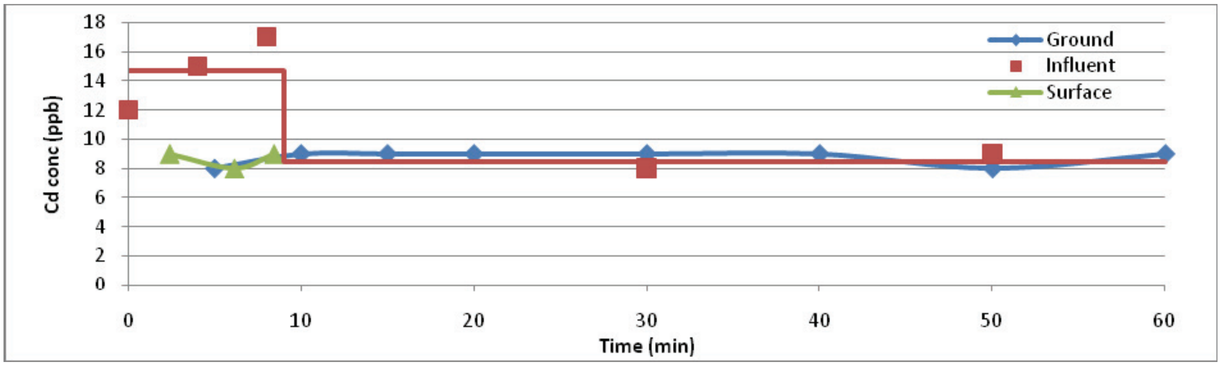


Figure 217. Total concentration of cadmium in 4:1 slope, medium flow rate.

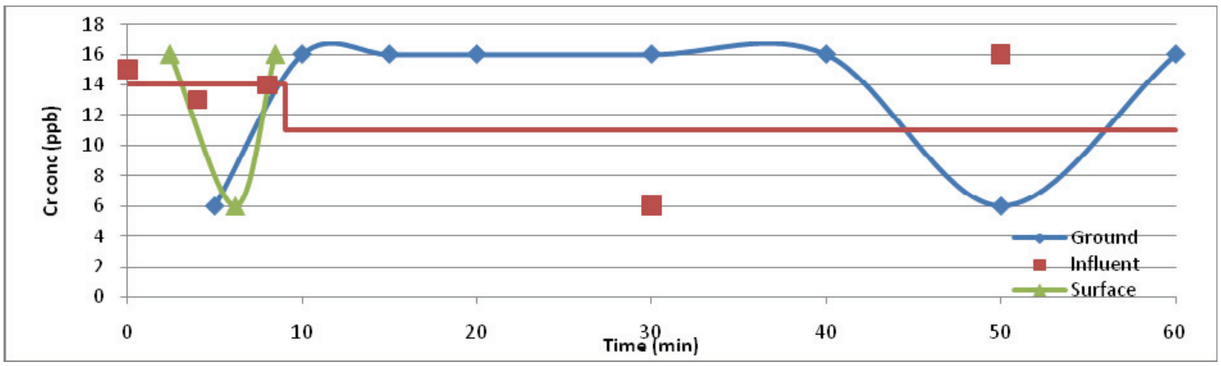


Figure 218. Total concentration of chromium in 4:1 slope, medium flow rate.

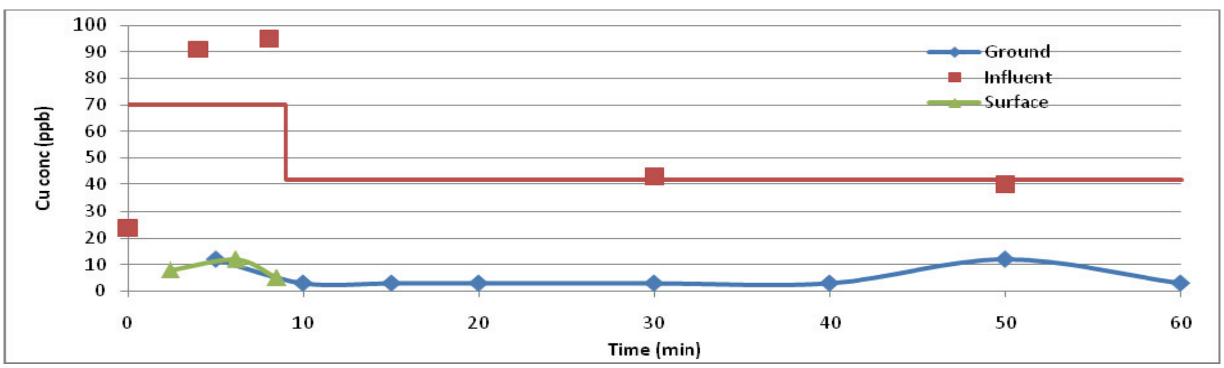


Figure 219. Total concentration of copper in 4:1 slope, medium flow rate.

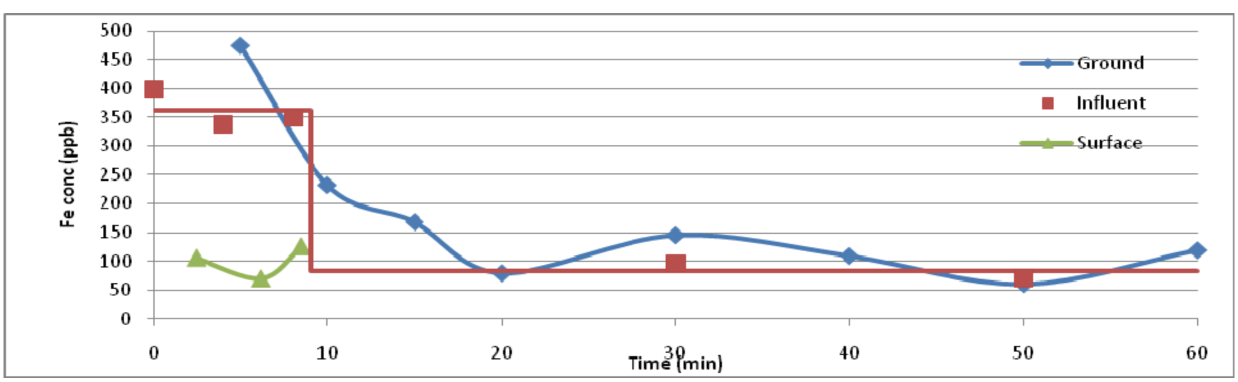


Figure 220. Total concentration of iron in 4:1 slope, medium flow rate.

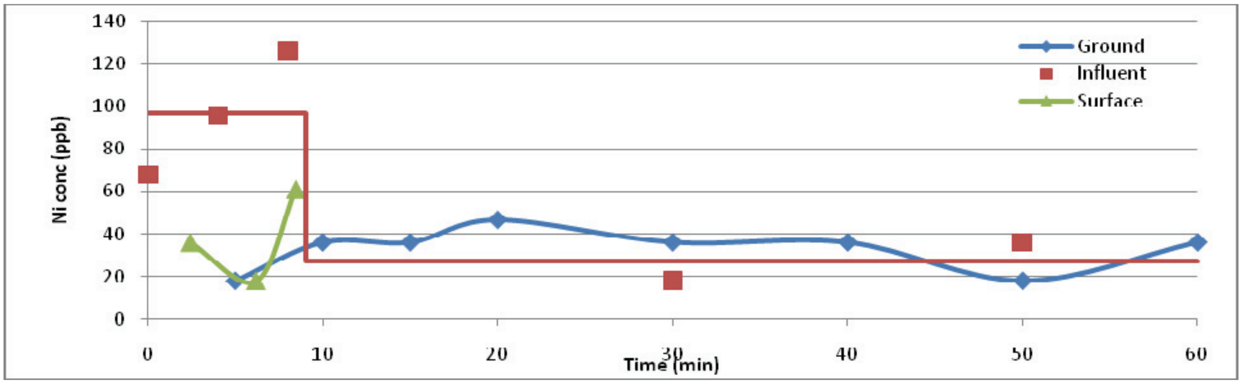


Figure 221. Total concentration of nickel in 4:1 slope, medium flow rate.

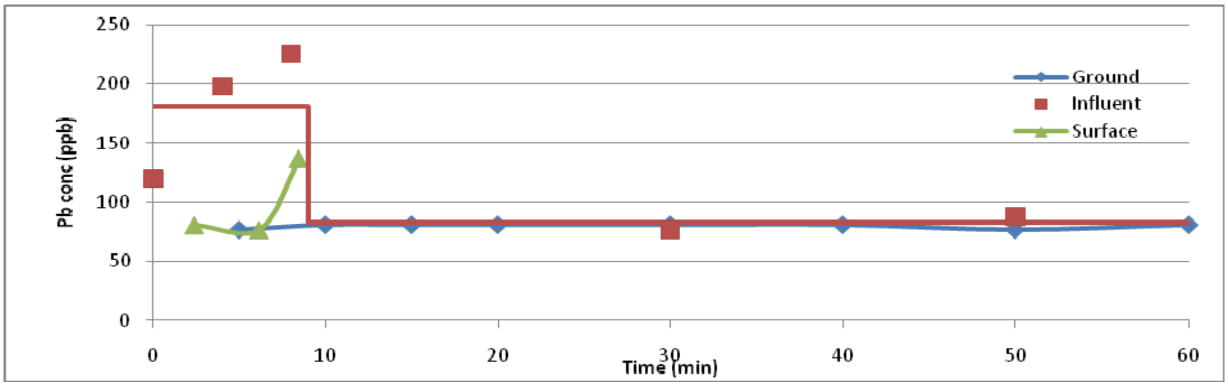


Figure 222. Total concentration of lead in 4:1 slope, medium flow rate.

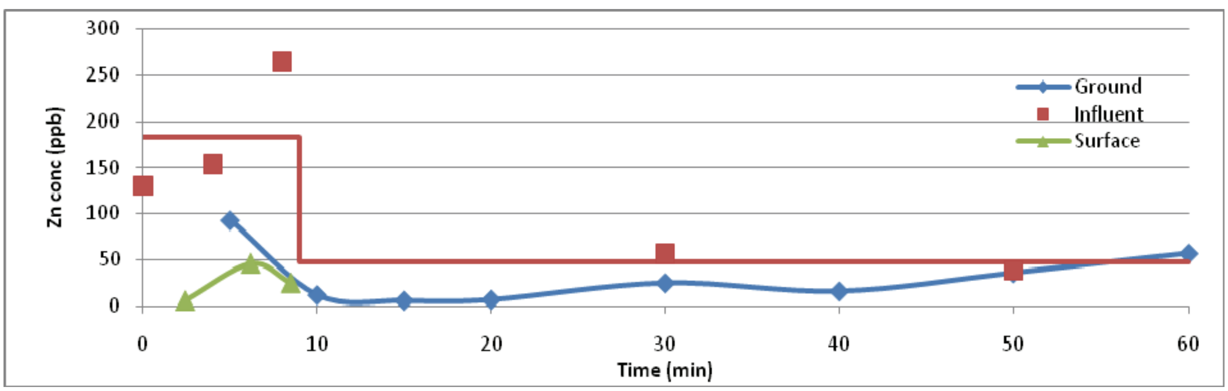


Figure 223. Total concentration of zinc in 4:1 slope, medium flow rate.

Figure 224 through Figure 230 portray the 2:1 slope test with a medium flow rate. Similar to the 8:1 medium flow rate test, Cd, Cr, Ni, and Pb had initial average influent concentrations slightly lower than the low target concentrations. Cd and Cr were the furthest away from their target concentrations, each within a 60% and 44% margin, respectively. Ni was within a 24% margin of its low target concentration, while Pb was the closest to its low target concentration within a 1% margin. Cu, Fe and Zn had initial average influent concentrations slightly higher than the low target concentrations. Cd was the only metal that was not detected in the influent for the entire test, with a detection limit of 8 µg/L. In the tailing end of the test, Cr and Pb were not detected with average limits of 11 µg/L and 79 µg/L respectively. The rest of the metals were detected and consistent, except Cr and Ni, which had concentrations below and above the influent average.

Even with the 2:1 slope, surface runoff virtually ceased to be generated after the water quality event of the storm. In the surface samples, Cd, Cr, and Pb were not detected throughout the entire test with detection limits of 8-12 µg/L, 6-16 µg/L, and 77-81 µg/L, respectively. Ni was not detected throughout the entire test at detection limits of 18-36 µg/L, except one sample at 10 min of 66 µg/L, which can be seen from the spike in concentration in Figure 221. Cu was not detected throughout most of the test with an average detection limit of 3-12 µg/L, except at 2 min and 4 min, detected below 20 µg/L. Fe and Zn were detected throughout the entire test below 590 µg/L and 60 µg/L, respectively. Figure 227 shows a spike in Fe concentration at 4 min and 10 min which was above the average influent concentration, with increasing concentrations from 6 min to 10 min in the surface runoff. Zn had surface concentrations well below the average influent concentration. Overall, the surface runoff percent removals for Cr, Cu, Ni, Pb, and Zn were as follows: 42.9, 92.3, 70.8, 68, and 74.8. Cd was not included in the percent removals because it was not detected in the influent. Fe was detected at lower concentrations in the influent than in the surface runoff. Soil released from the bed could contain high concentrations of Fe, which would also explain the suspended solids concentrations above influent concentrations. For the 2:1 medium flow test, Cu, followed by Zn and Ni, had the highest percent removals. When compared to the other slopes, these percent removals are similar, and an increase in slope did not appear to influence percent removals very much.

In the underdrain samples, Cd, Cr, and Cu concentrations remained below their detection limits, which averaged 9 µg/L, 13 µg/L, and 6 µg/L, respectively. Pb concentrations remained below detection limits throughout the entire test, except at 15 minutes at 158 µg/L; the average detection limit was 80 µg/L. Ni concentrations remained below detection limits throughout the entire test, except at 15 min and 60 min Ni was detected at concentrations below 50 µg/L; the average Ni detection limit was 28 µg/L. Fe and Zn were the only metals detected throughout the entire run, and their concentrations remained below 830 µg/L and 30 µg/L, respectively. Similar to the other two tests, Fe has an initial high spike in concentration and then decreases over time, as seen in Figure 227, and Zn had consistently low underdrain concentrations, as seen in Figure 230.

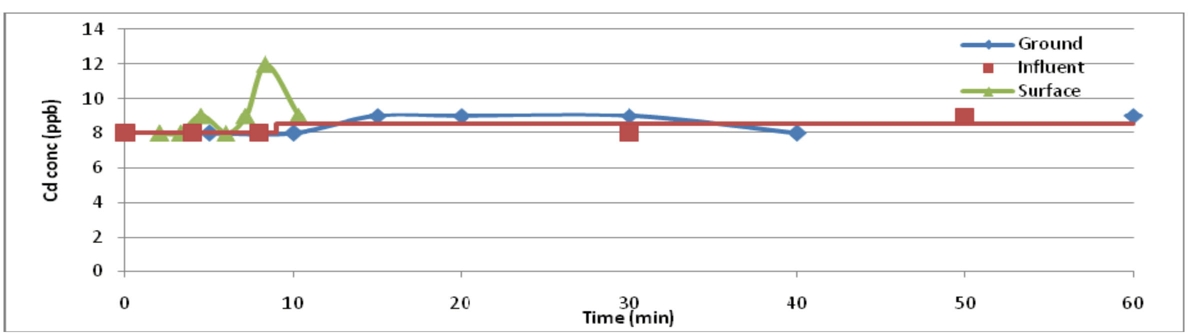


Figure 224. Total concentration of cadmium in 2:1 slope, medium flow rate.

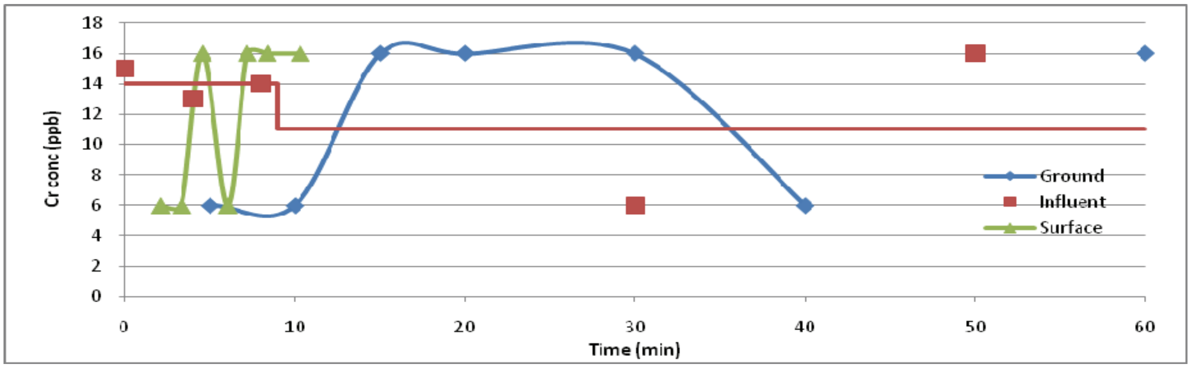


Figure 225. Total concentration of chromium in 2:1 slope, medium flow rate.

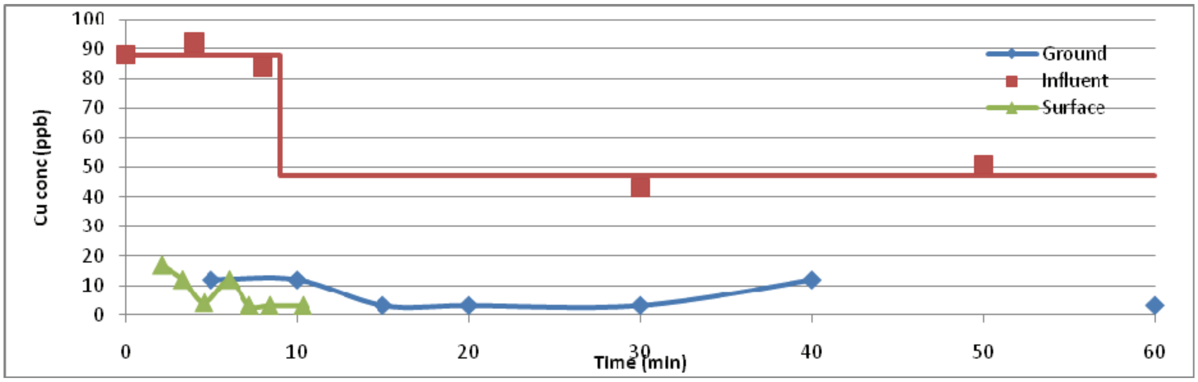


Figure 226. Total concentration of copper in 2:1 slope, medium flow rate.

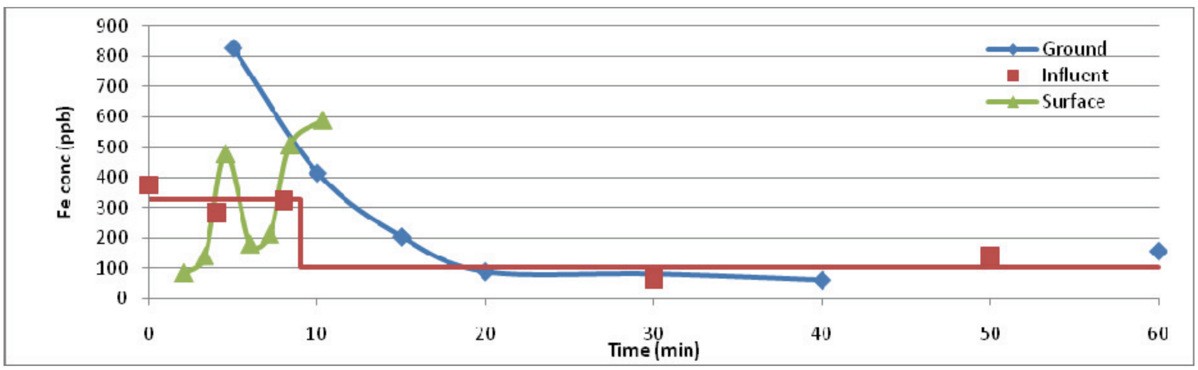


Figure 227. Total concentration of iron in 2:1 slope, medium flow rate.

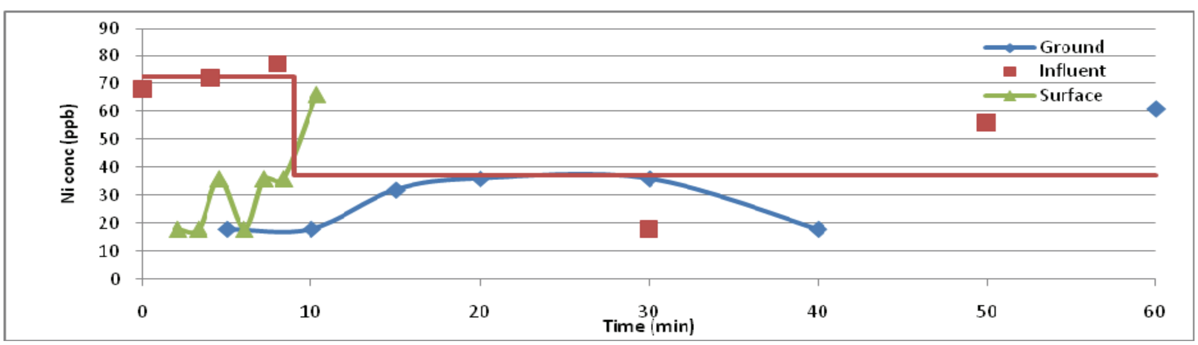


Figure 228. Total concentration of nickel in 2:1 slope, medium flow rate.

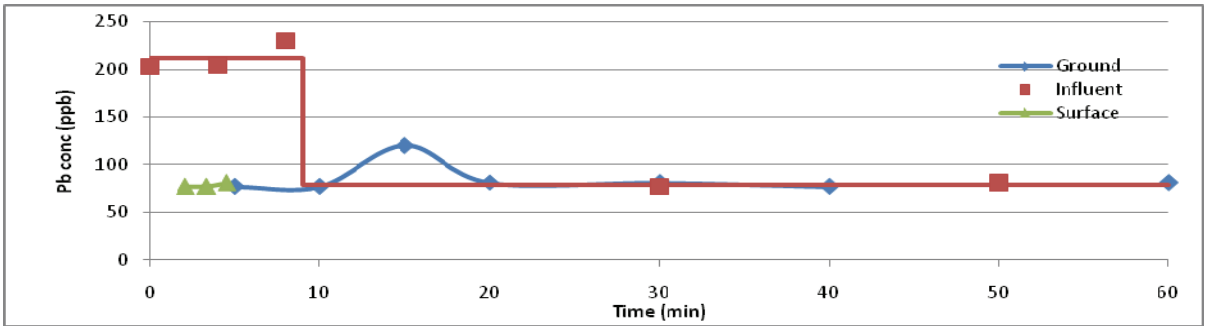


Figure 229. Total concentration of lead in 2:1 slope, medium flow rate.

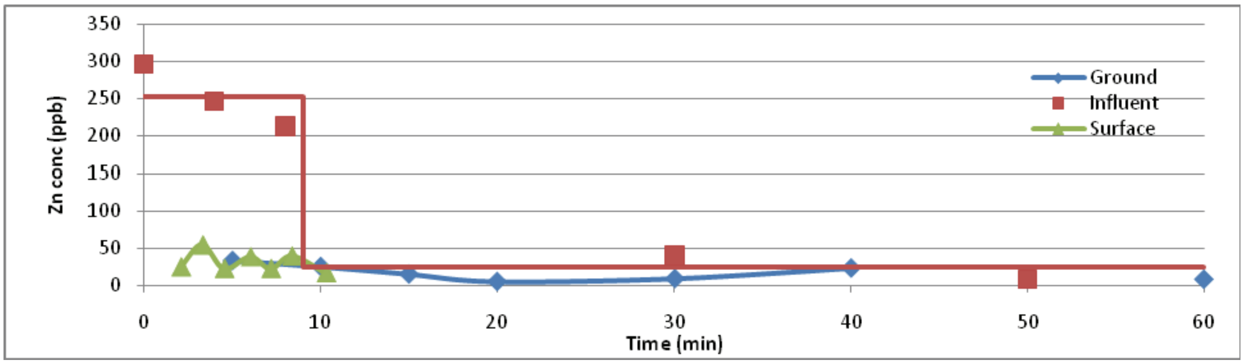


Figure 230. Total concentration of zinc in 2:1 slope, medium flow rate.

Figure 231 through Figure 237 portray the fourth test, which consisted of a 2:1 slope with a high flow rate. For the high flow simulation, an initial flow rate of 5.43 gpm (20.55 lpm) was maintained for 6 min and then followed by a flow rate of 1.18 gpm (4.47 lpm) for 24 min. Similar to the 2:1 medium flow rate test, Cd, Cr, Ni, and Pb had influent concentrations that were below the low target concentrations for the water quality event portion of the test. Cd was within a 43% margin, Ni and Pb were within a 20% margin, and Cr was within a 4% margin of the target concentrations. Cu, Fe, and Zn had influent concentrations that were above the low target concentrations. In the tail end portion of the test, Cd, Cr, Ni, and Pb were not detected with detection limits of 8 µg/L, 6 µg/L, 18 µg/L, and 77 µg/L, respectively. Cu, Fe, and Zn were detected throughout the entire test, and were detected below 90 µg/L, 580 µg/L, and 250 µg/L respectively. At 25 min there was a large spike in Fe concentration for the tail end portion of the test at 575 µg/L (see Figure 234).

Surface runoff was only generated during the first portion of the storm event. Cd, Cr, and Pb were not detected throughout the duration of the test, similar to the 2:1 medium flow rate test. Cu and Ni were only detected within the first minute at 15 µg/L and 37 µg/L, respectively. Beyond the first minute, Cu and Ni were not detected with limits of 12 µg/L and 18 µg/L, respectively. Similar to the other tests, Fe and Zn were detected throughout the entire test, and were below 165 µg/L and 80 µg/L. Both Fe and Zn surface concentrations remained below average influent concentrations. EMC percent removals for Cd, Cr, Cu, Fe, Ni, Pb, and Zn are as follows: 60.5%, 76.9%, 88.6%, 76.4%, 76.7%, 66.8%, and 71.3%. For the 2:1 high flow test, Cu had the highest percent removal. Once again, these percentages remained similar to the other slopes.

In the underdrain samples, Cd, Cr, Cu, Ni and Pb were not detected throughout the duration of the test, somewhat similar to the 2:1 medium flow rate test, with detection limits of 8 µg/L, 6 µg/L, 12 µg/L, 18 µg/L, and 77 µg/L, respectively. Fe and Zn were detected throughout the entire test, with concentrations below 2000 µg/L and 105 µg/L, respectively. As with the other tests, Fe had a large spike in concentration at 5 min, and then decreased past this time below average influent concentrations (See Figure 234). Zn concentrations consistently remained below average influent concentrations (See Figure 237).

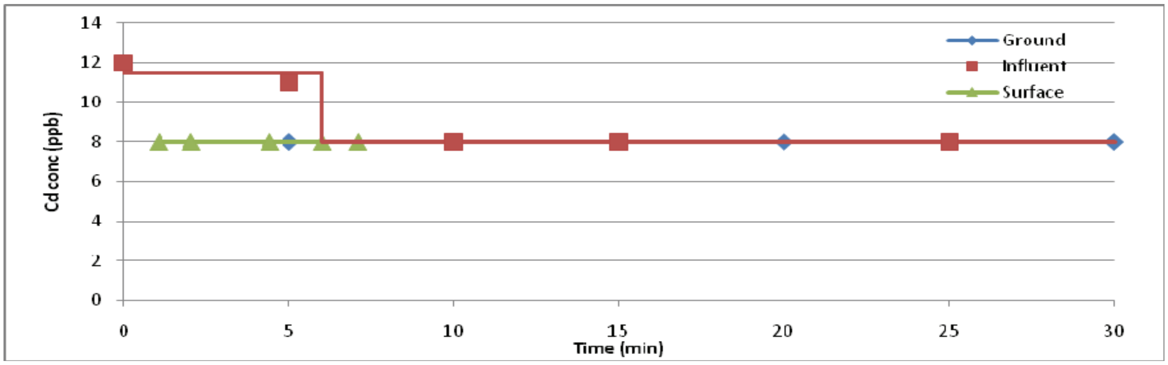


Figure 231. Total concentration of cadmium in 2:1 slope, high flow rate.

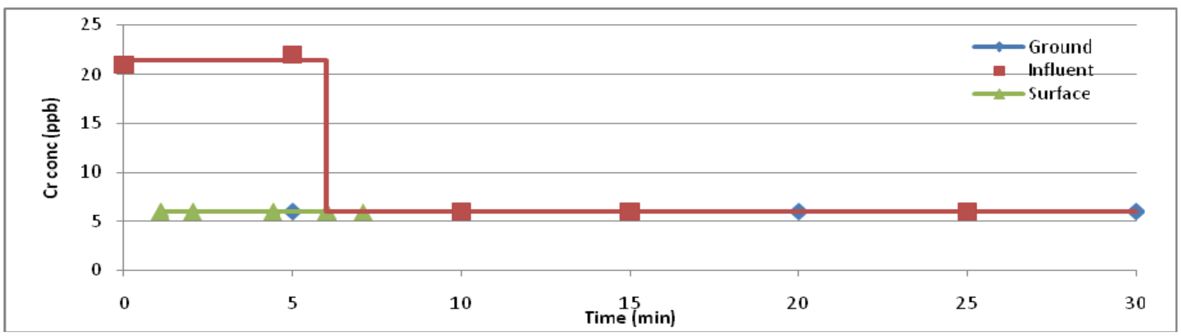


Figure 232. Total concentration of chromium in 2:1 slope, high flow rate.

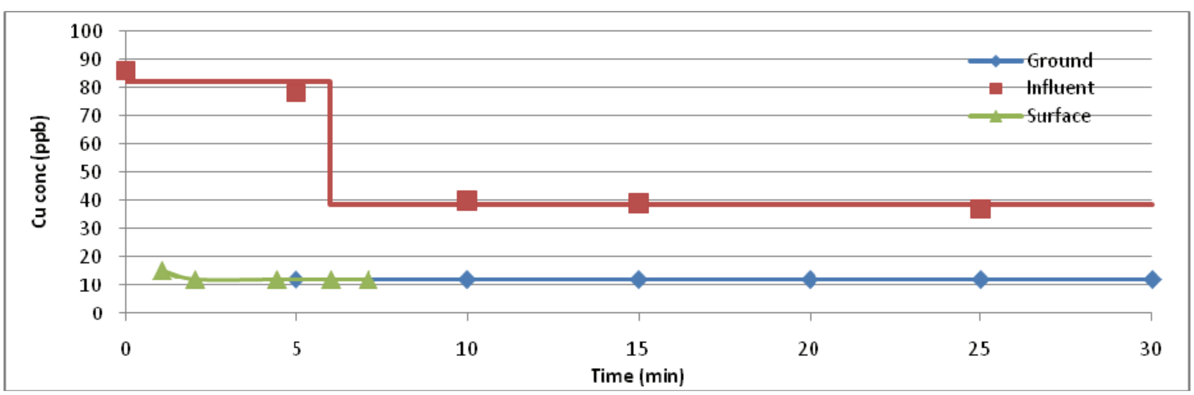


Figure 233. Total concentration of copper in 2:1 slope, high flow rate.

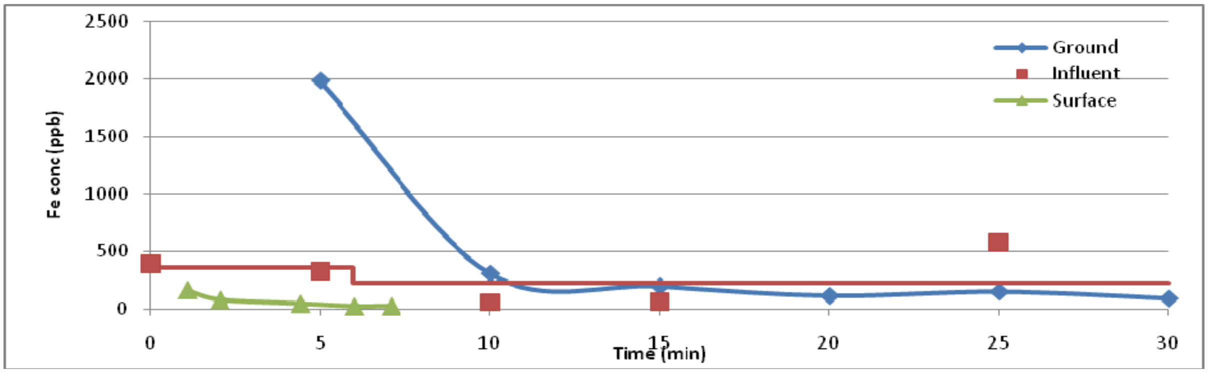


Figure 234. Total concentration of iron in 2:1 slope, high flow rate.

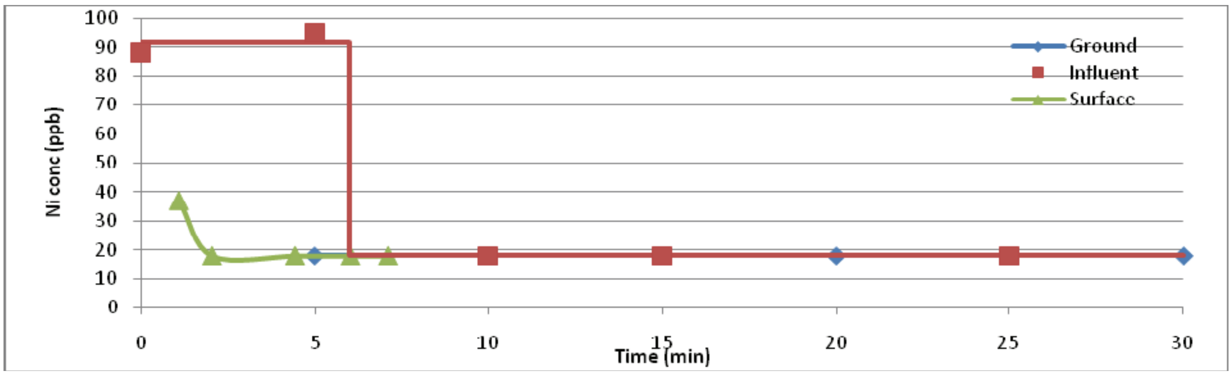


Figure 235. Total concentration of nickel in 2:1 slope, high flow rate.

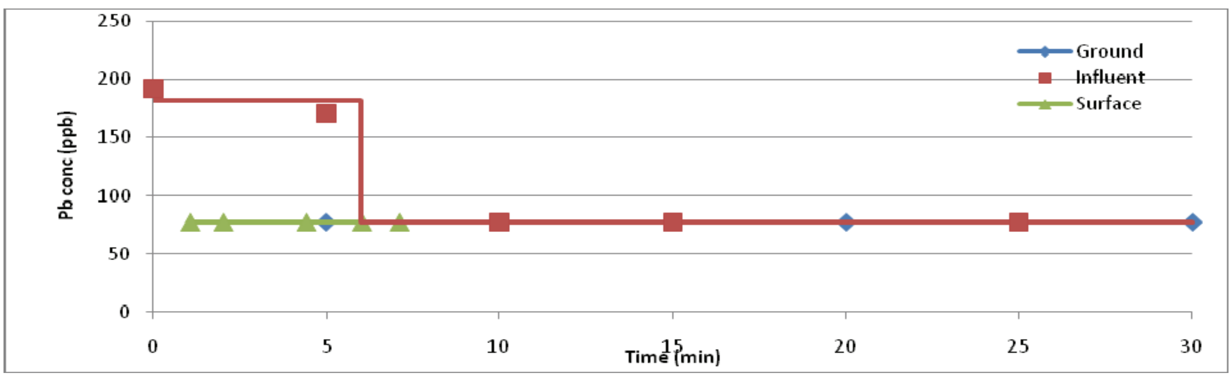


Figure 236. Total concentration of lead in 2:1 slope, high flow rate.

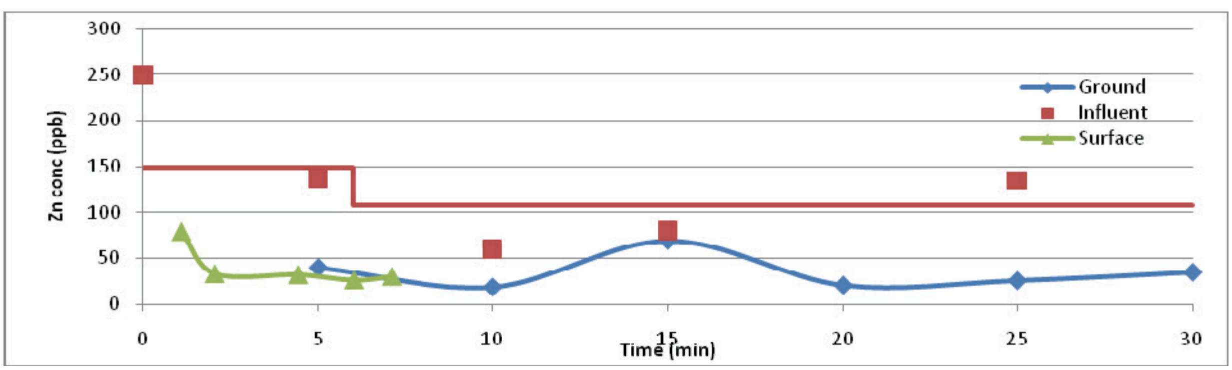


Figure 237. Total concentration of zinc in 2:1 slope, high flow rate.

12.5 Dissolved Metals Results

Figure 238 through Figure 240 exhibit a few of the dissolved metals for the 8:1 medium flow test, and Figure 241 through Figure 243 show the same metals in the 4:1 medium flow test. For the water quality event portion of the 8:1 medium flow test, influent Cr and Fe concentrations exhibited similar trends, where they were detected as soon as the test started, but were not detected for the remaining 15 min, with detection limits of 6 µg/L and 4 µg/L, respectively; however, Cr was not detected in the tail end portion of the test, and Fe was with concentrations below 25 µg/L, which was similar to Fe in the 4:1 test. In the 4:1 medium flow test, Cr was not detected throughout, with a detection limit of 6 µg/L. Also in the 4:1 medium flow test, the first collected influent sample spilled; therefore no metal concentrations are available. In both the 8:1 and 4:1 medium flow tests, Cd, Ni, and Zn were detected during the water quality event portion of the test in the influent, with concentrations below 20 µg/L, 90 µg/L, and 75 µg/L, but were not detected in the tail end of the test, with detection limits of 3 µg/L, 25 µg/L, and 4 µg/L, respectively. Cu was the only metal detected throughout the entire test with concentrations below 55 µg/L in both the 8:1 and 4:1 tests. However, Cu and Fe were unlike the other metals because the influent concentrations in the tail end portion of the test were higher than the water quality event portion, which was similar to Zn in Bed 1. In the tail end portion of the test, Cu and Fe were consistently below average influent concentrations.

In the surface samples, Cu was the only detected metal in both the 8:1 and 4:1 medium flow tests, with a concentration of 8 µg/L for the 8:1 test and an average concentration of 10 µg/L for the 4:1 test, although these values were far below dissolved influent concentrations of 35 µg/L to 55 µg/L. In the underdrain, Fe was the only detected metal for both the 8:1 and 4:1 tests, with concentrations below 55 µg/L, and was above influent concentrations in both tests, indicating leaching out of the soil.

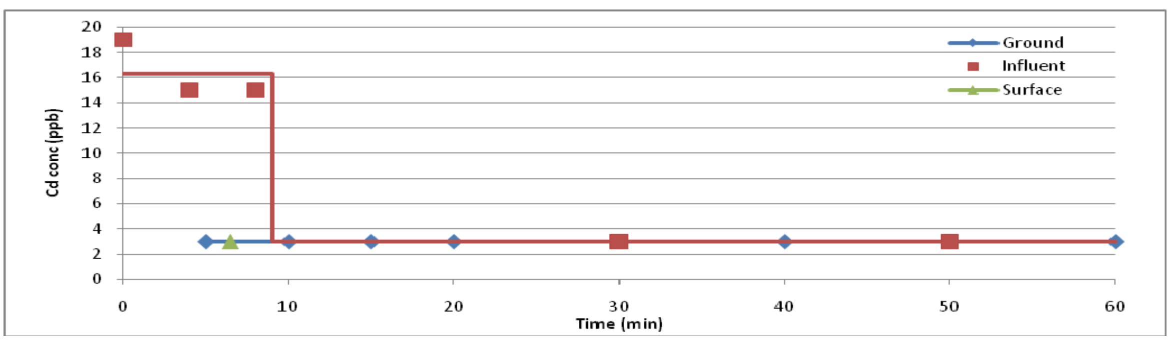


Figure 238. Dissolved concentration of cadmium in 8:1 slope, medium flow rate.

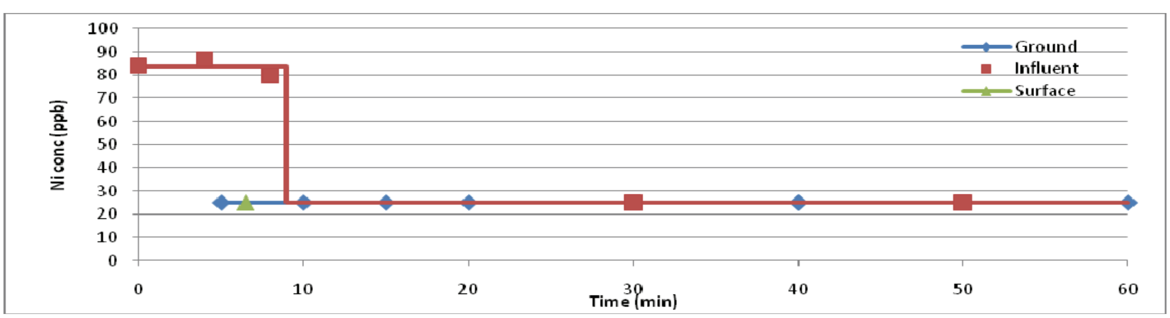


Figure 239. Dissolved concentration of nickel in 8:1 slope, medium flow rate.

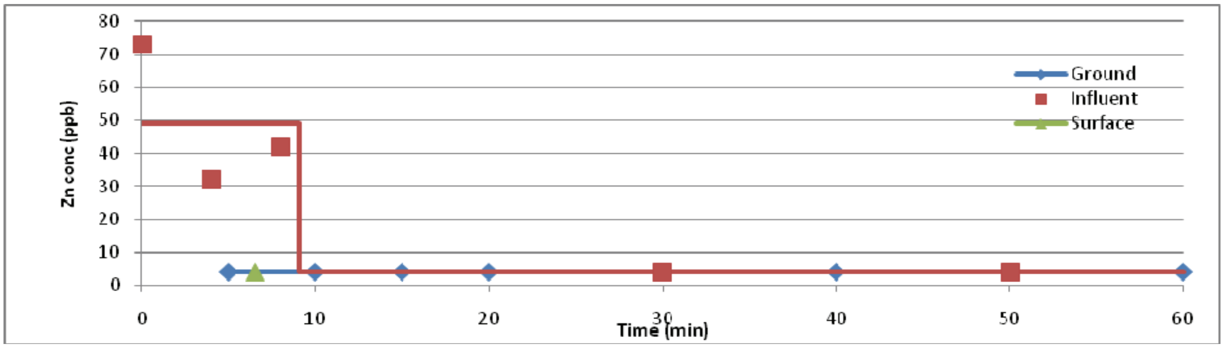


Figure 240. Dissolved concentration of zinc in 8:1 slope, medium flow rate.

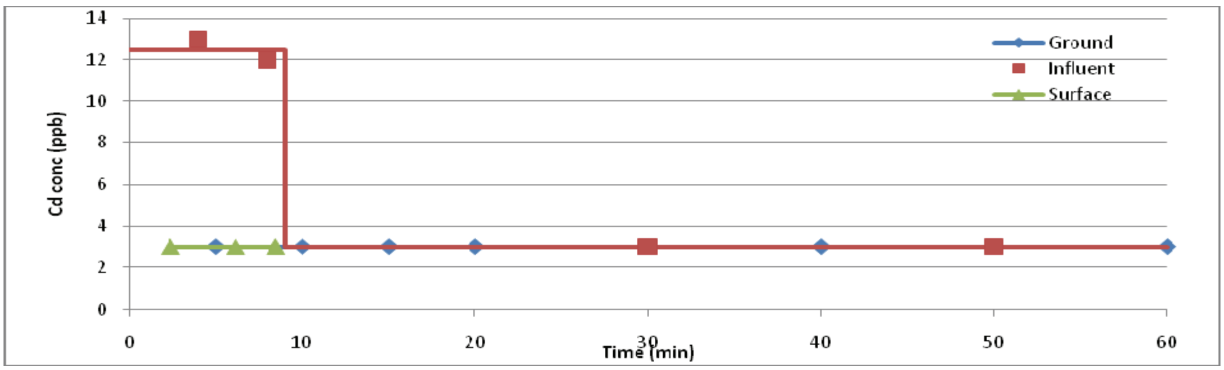


Figure 241. Dissolved concentration of cadmium in 4:1 slope, medium flow rate.

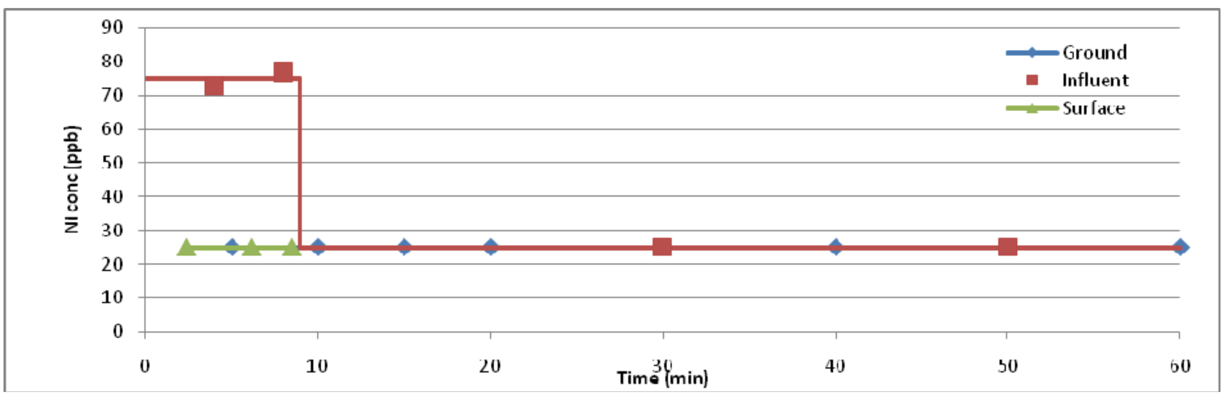


Figure 242. Dissolved concentration of nickel in 4:1 slope, medium flow rate.

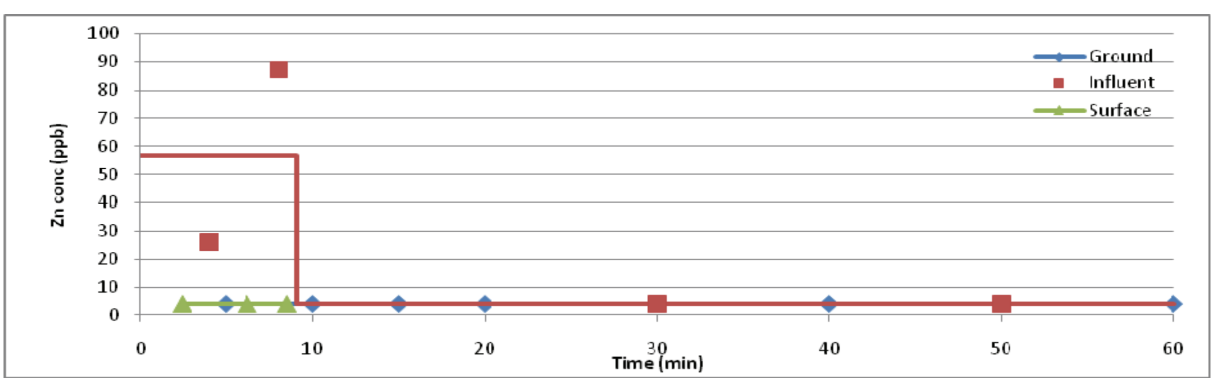


Figure 243. Dissolved concentration of zinc in 4:1 slope, medium flow rate.

The 2:1 medium flow test metals results were similar to the 2:1 high flow test results, where a few of the dissolved metals are displayed in Figure 244 through Figure 246 for the 2:1 slope with medium flow rate and in Figure 247 through Figure 249 for the 2:1 slope with high flow rate. Similar to the 8:1 and 4:1 medium flow tests, both the 2:1 medium and high flow tests exhibit detectable influent, surface, and underdrain concentrations only with Cu throughout the entire test. In the 2:1 high flow test, Cd is detected throughout the entire test with influent concentrations below 20 µg/L. In the 2:1 medium flow test, Cd is detected throughout the entire test with concentrations below 30 µg/L, except at 50 min with a detection limit of 2 µg/L. Ni, Cr, and Zn exhibit similar trends for both tests, and were detected in the water quality event portion of the test with concentrations below 95 µg/L, 10 µg/L, and 185 µg/L, but were not detected or were close to detection limits in the tail end portion of the test, with detection limits of 15 µg/L, 2 µg/L, and 3 µg/L, respectively. Once again, Cu and Fe had an unusual trend with the tail end concentrations higher than the water quality event concentrations.

In the surface samples for both the 2:1 medium and high flow tests, Cd and Cr were detected, but were close to detection limits. Ni, Pb, and Zn were not detected in the surface and underdrain samples, with detection limits of 15 µg/L, 20 µg/L, and 3 µg/L. Fe was not detected in the surface samples, except for a few samples close to the detection limit, but was detected in the underdrain samples with concentrations below 60 µg/L. These concentrations were above influent concentrations, indicating leaching out of the soil, similar to the 8:1 and 4:1 medium slope tests.

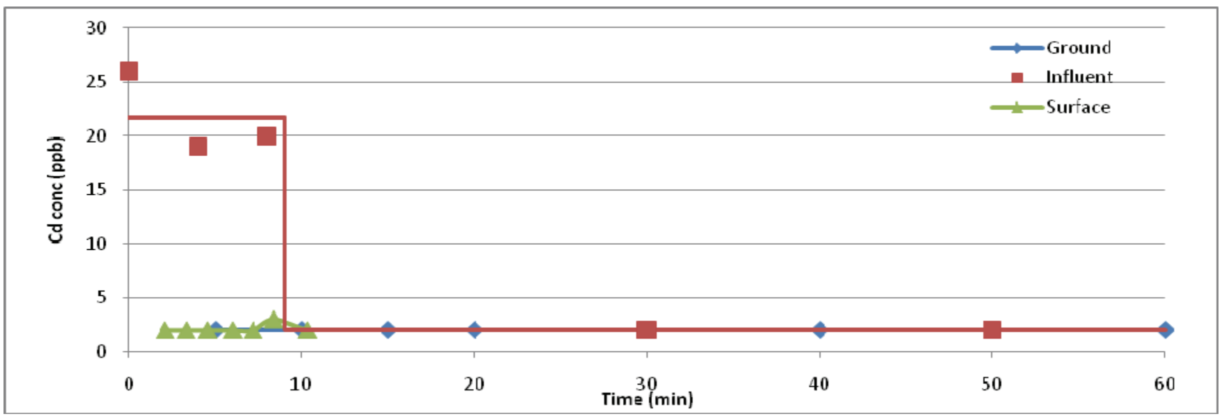


Figure 244. Dissolved concentration of cadmium in 2:1 slope, medium flow rate.

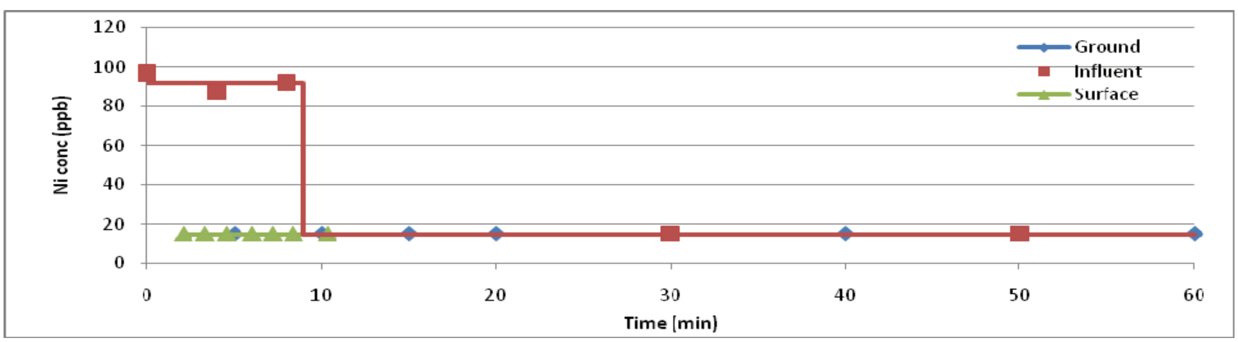


Figure 245. Dissolved concentration of nickel in 2:1 slope, medium flow rate.

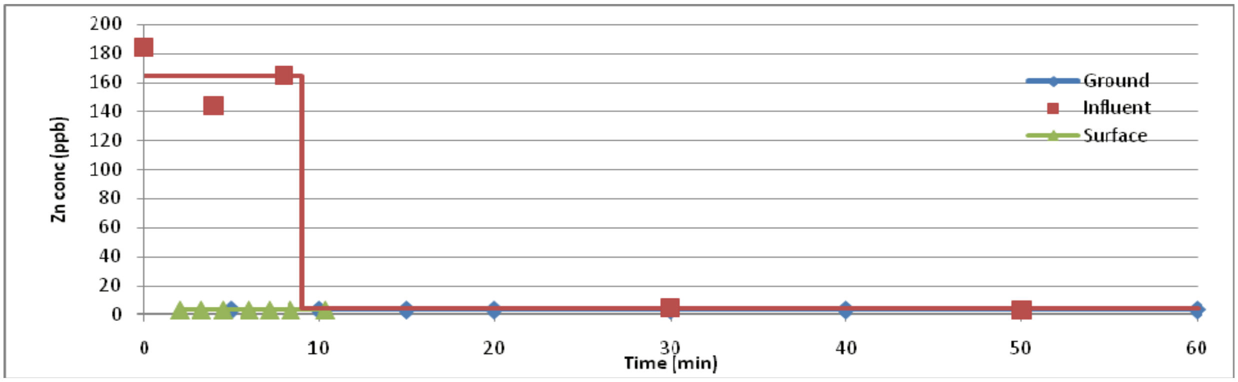


Figure 246. Dissolved concentration of zinc in 2:1 slope, medium flow rate.

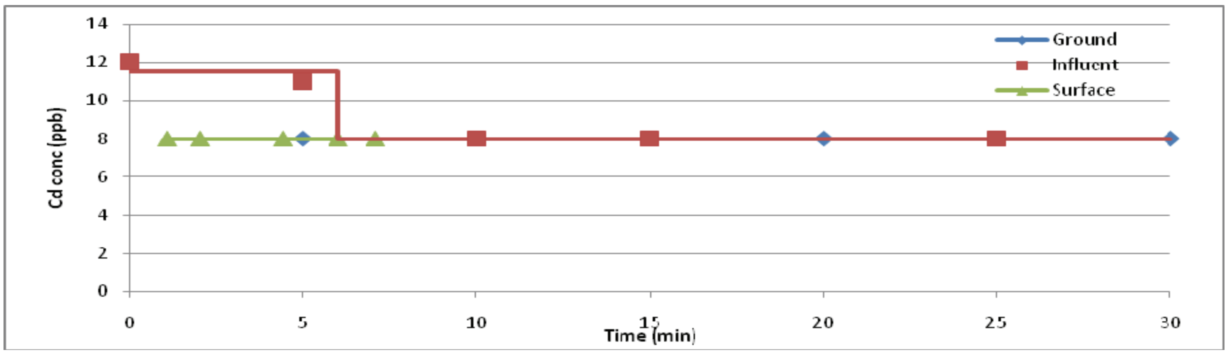


Figure 247. Dissolved concentration of cadmium in 2:1 slope, high flow rate.

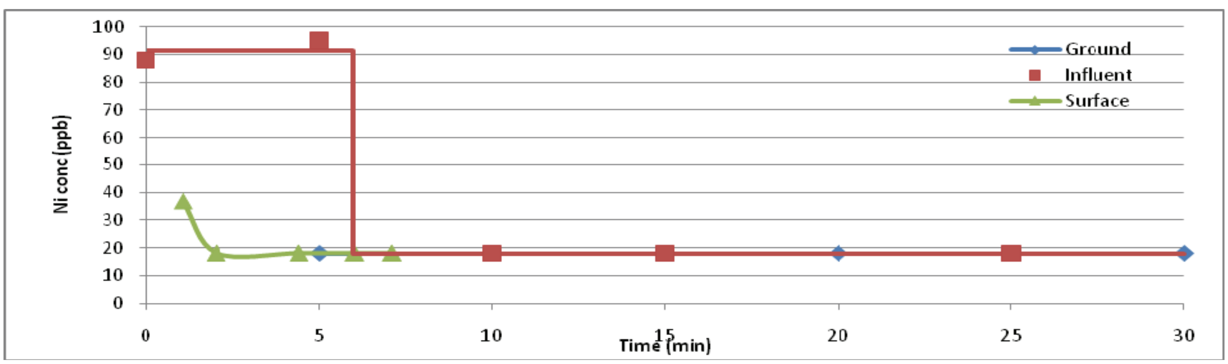


Figure 248. Dissolved concentration of nickel in 2:1 slope, high flow rate.

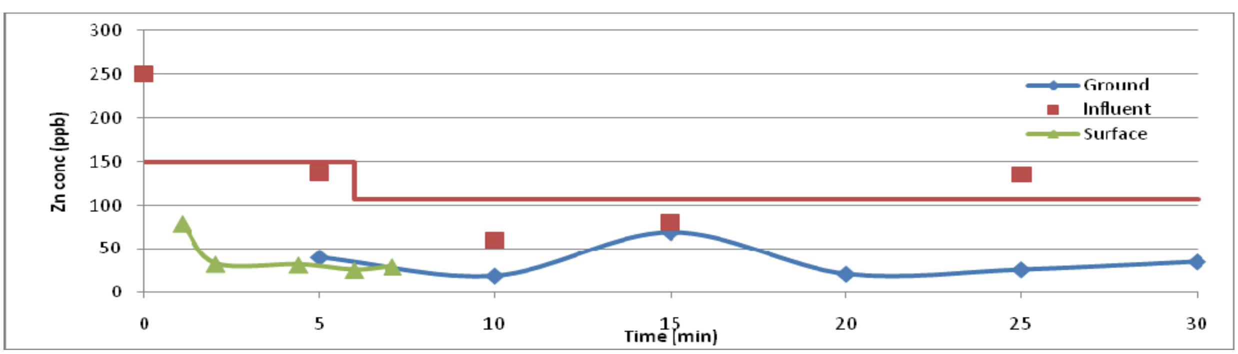


Figure 249. Dissolved concentration of zinc in 2:1 slope, high flow rate.

12.6 Oil and Grease Results

In the low concentration tests for Bed 3, motor oil was added directly to the distributor plate as a pure phase with target concentrations after mixing with the influent water at a target concentrations of 100 mg/L for the first portion of the simulated storm event followed by 20 mg/L during the second portion of the event. Results for the 8:1, 4:1, 2:1 medium flow, and 2:1 high flow tests are shown in Figure 250 through Figure 253. 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. Because motor oil floats on water, it is transported chaotically across the bed and is difficult to capture a representative sample in a bottle, and results tend to be erratic. Surface runoff concentrations were at or near the detection limit of 0.4 mg/L for all four tests except for two high detects at approximately half the influent concentration in the 2:1 slope, high flow test. Bed 2 behaved similarly with the only surface runoff detects occurring in the high flow event. Percent removals from event mean concentrations were 95%, 100%, 97%, and 80% for the 8:1, 4:1, 2:1 medium flow, and 2:1 high flow tests. Concentrations of oil and grease were similarly low in the underdrain except for several moderately high spikes.

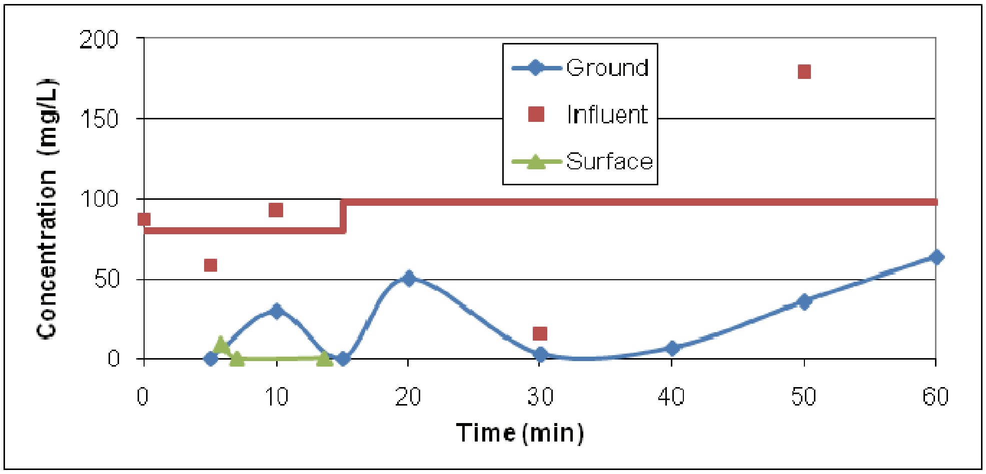


Figure 250. Concentration of oil and grease at 8:1 slope.

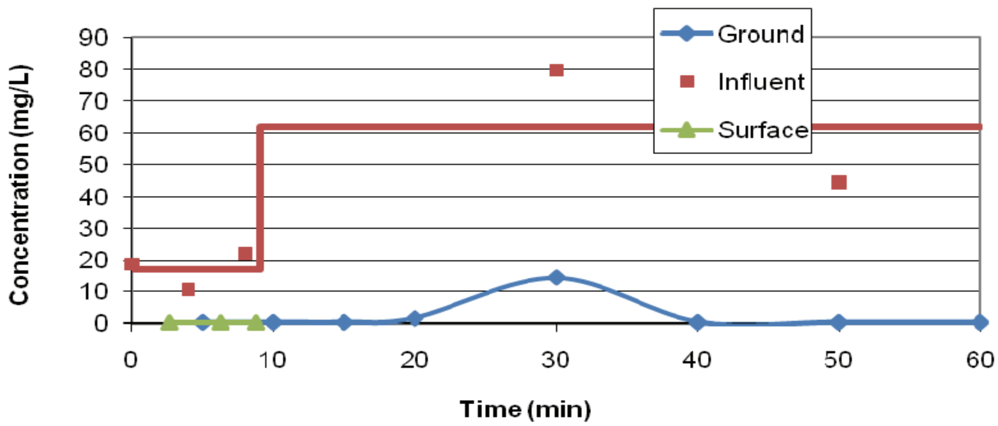


Figure 251. Concentration of oil and grease at 4:1 slope.

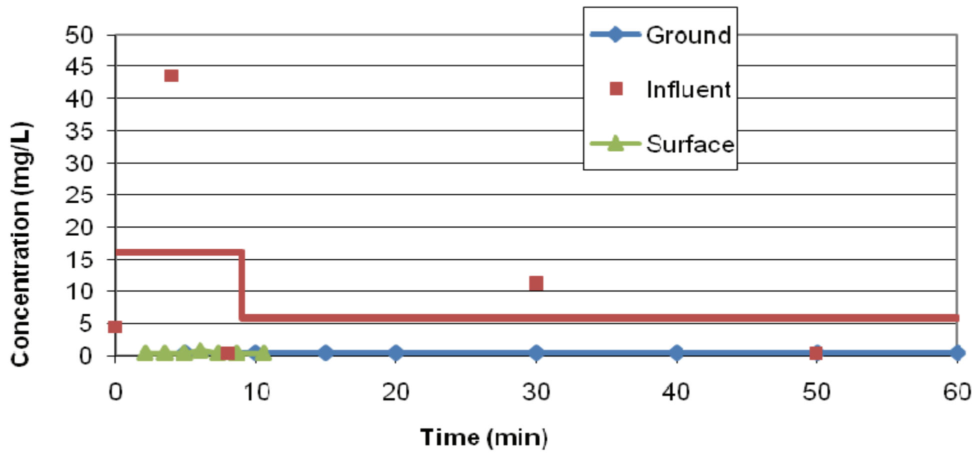


Figure 252. Concentration of oil and grease at 2:1 slope, medium flow.

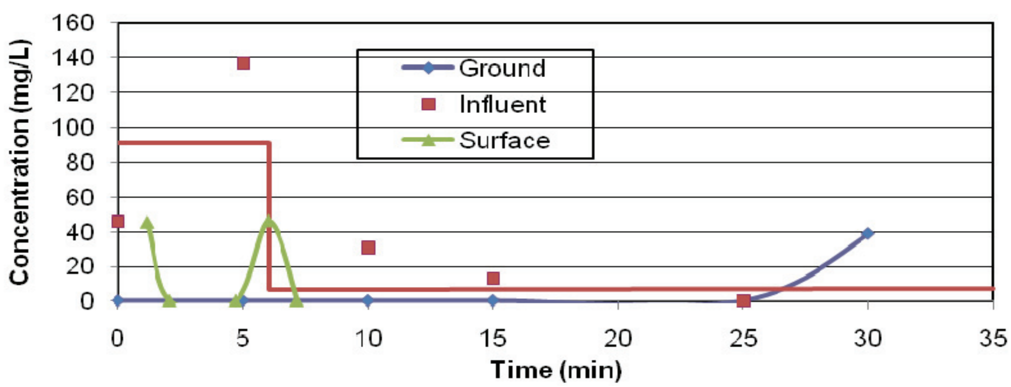


Figure 253. Concentration of oil and grease at 2:1 slope, high flow.

12.7 Deuterated Alkane Results

Three different n-alkanes typically found in motor oil with deuterium atoms substituted for the hydrogen atoms were added to the motor oil before it was directly added to the distributer plate on Bed 3. Results for the deuterated alkanes analyses are shown in Figure 254 through Figure 257. In these graphs, the total concentration of the three deuterated alkanes was summed and plotted. Influent concentrations were much higher than in both Bed 2 and Bed 3 performance tests to improve the accuracy of the analysis. However, deuterated alkanes influent concentrations were still erratic varying widely in the water quality event portion of the storm. This behavior again illustrates the chaotic nature of oil transport. Surface runoff concentrations were uniformly low for all four tests being near the detection limit of 5 µg/L, except in the 4:1 test where two of the three samples had elevated concentrations, though still well below influent concentrations. Deuterated alkanes were detected in underdrain samples several times in the 8:1 test at high concentrations and in the 2:1 medium flow test at low levels.

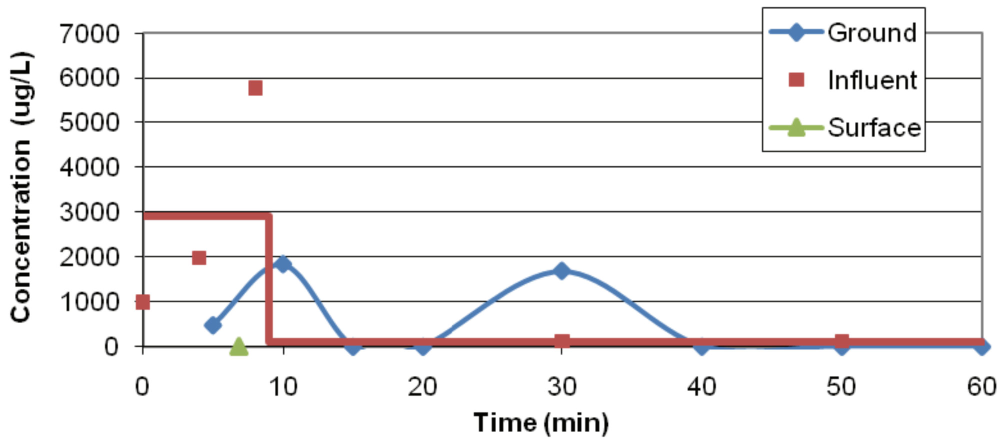


Figure 254. Total concentration of deuterated alkanes at 8:1 slope.

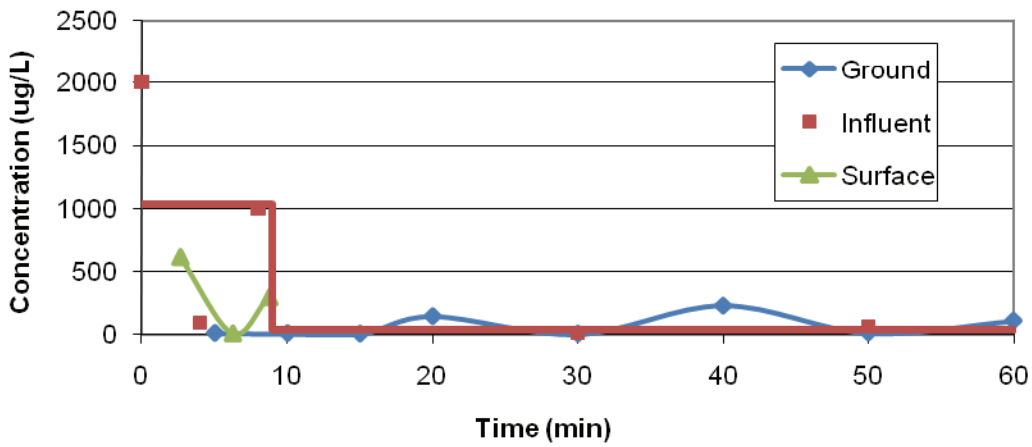


Figure 255. Total concentration of deuterated alkanes at 4:1 slope.

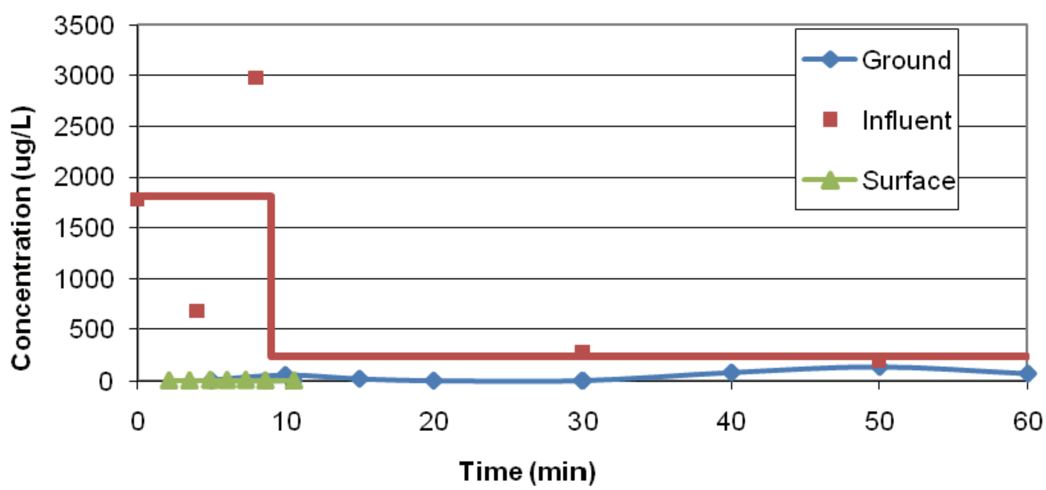


Figure 256. Total concentration of deuterated alkanes at 2:1 slope, medium flow.

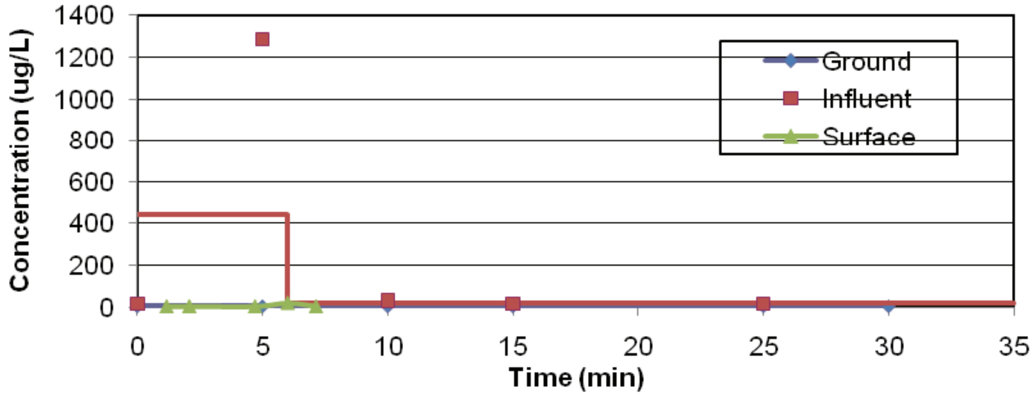


Figure 257. Total concentration of deuterated alkanes at 2:1 slope, high flow.

12.8 Removals

Figure 258 displays the average event mean concentration percent removal for each metal, total suspended solids, and oil and grease for each slope for Bed 3. For a number of the analytes, a percent removal could not be determined, because the event mean concentration of the surface runoff was higher than the event mean concentration of the influent. It can be seen from this figure that average percent removals were fairly low for each metal, except Cu, which had the highest percent removals for each test, above 85%. Ni, Pb, and Zn were the only metals besides Cu removed in all four tests; their removal rates were generally 55% to 85%. Suspended solids removals ranged from a negative value at 2:1 medium flow to 50% at 8:1 medium flow.

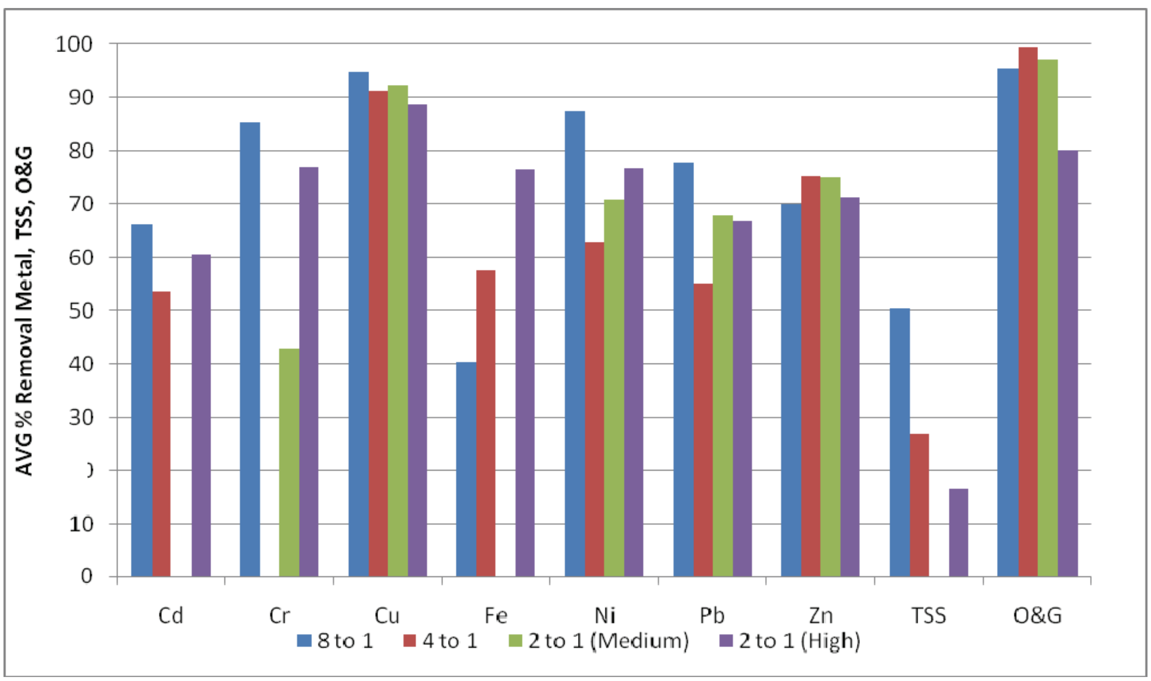


Figure 258. Percent removals of event mean concentration for total metals, TSS, and oil and grease from low concentration influent tests on Bed 3.

Percent removals of contaminants from storm water was 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 are shown in Figure 259. Percent removals were significantly higher for all except one point when considering only the water quality event portion, because the event mean concentration of the storm water influent was higher, because it did not include the tailing portion of the storm that has lower concentrations. For Bed 3, differences between using the complete storm and only the water quality event portion were 11.5% to 17.6% higher for Cd, 5.8% to 18.5% higher for Cr, 1.7% to 2.6% higher for Cu, 2.6% to 28.5% higher for Fe, 6.9% to 17.0% higher for Ni, 10.3% to 15.5% higher for Pb, 2.9% to 13.6% higher for Zn, 26.6% to 31.9% higher for TSS, and -0.7% to 9.6% higher for oil and grease.

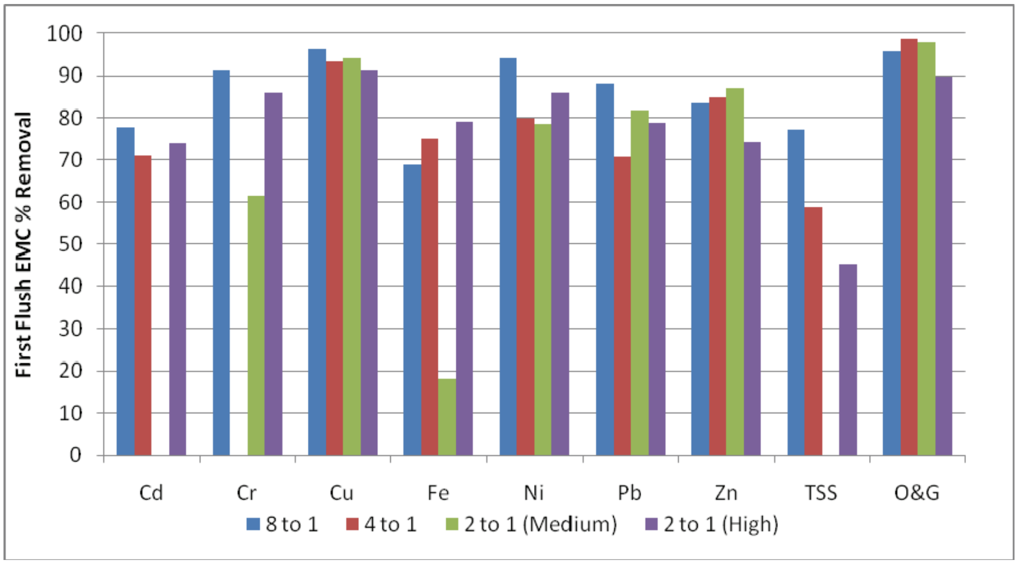


Figure 259. Percent removals of event mean concentration during the water quality event portion of the storm event for total metals, TSS, and oil and grease for Bed 3.

12.9 Resuspension Results

After the four tests were completed on the bed, resuspension tests were conducted to determine the amount of tagged suspended solids that could become remobilized. Four resuspension tests were conducted that represented each slope and flow rate used for the initial testing. For the initial 8:1 slope performance test, target concentrations of La tagged suspended solids were added to the influent; 9 mg/L for the water quality event portion and none 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 260, the first three collected influent samples exhibited tagged suspended solids concentrations that were slightly lower than the target concentration for the water quality event, with an average tagged suspended solids concentration of 6 mg/L, and an average La concentration of 372 µg/L. The last two collected influent samples exhibited tagged suspended solids concentrations much lower than the first three samples, with an average tagged suspended solids concentration of 0.03 mg/L, and an average La concentration of 2 µg/L for the tail end of the test.

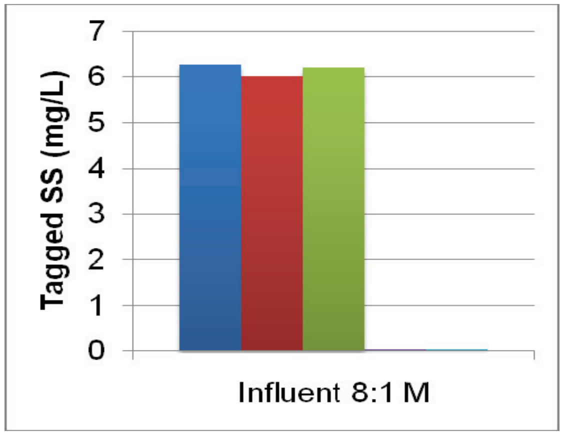


Figure 260. Influent tagged suspended solids concentration in 8:1 slope, medium flow rate for Bed 3. From left to right, the bars represent influent samples collected at times of 0 min, 4 min, 8 min, 30 min, and 50 min during the simulated storm event. Note that at 30 min and 50 min the influent was tap water.

Figure 261 displays the tagged suspended solids concentrations in the surface runoff samples for each test on Bed 3, four performance tests and four resuspension tests. As seen from this figure, the tagged suspended solids concentrations were highest for the 8:1 medium flow test, with a tagged suspended solids concentration of 0.65 mg/L and La concentration of 39 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 tagged suspended solids concentration of 4 mg/L and average La concentration of 224 µg/L. The fraction of La tagged soil in the samples greatly decreased from around 0.70 in the influent to 0.03 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 5 mg/L for this run, see Figure 204) 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 1.8 mg/L with only tap water as the influent. The other three performance tests resulted in very low concentrations of tagged suspended solids in surface runoff, averaging 0.04 mg/L for the 4:1 medium flow test, 0.04 for the 2:1 medium flow test, and 0.03 mg/L for the 2:1 high flow test. La was not detected for any of the tests, at any slope or flow rate.

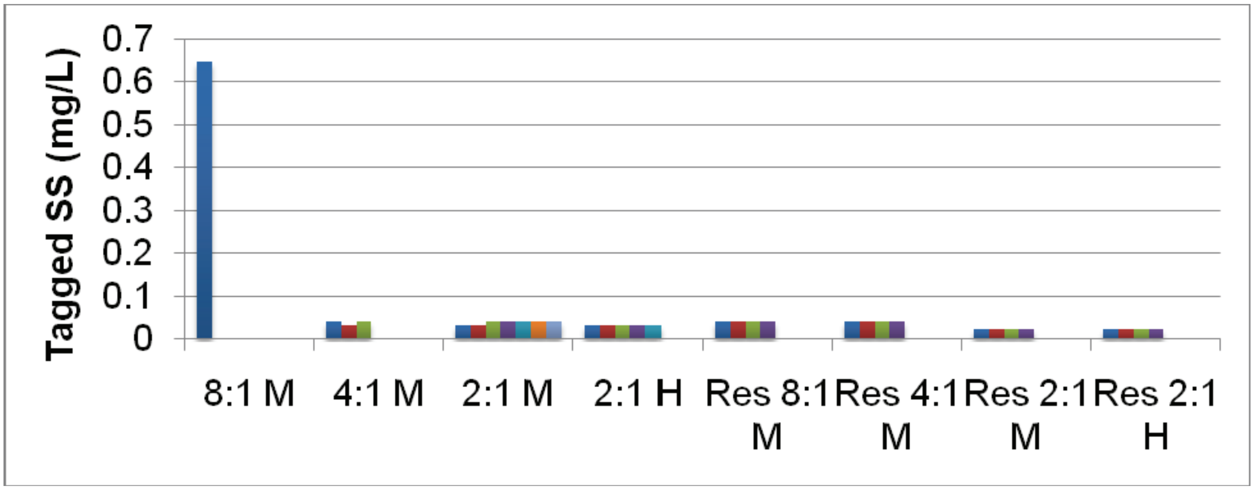


Figure 261. Tagged suspended solids concentrations for experimental and resuspension tests for Bed 3. Each bar represents a collected surface sample.

Each of the resuspension tests also had very low concentrations of tagged suspended solids, with average concentrations of 0.04 mg/L for the 8:1 and 4:1 medium flow tests and 0.02 mg/L for the 2:1 medium flow and 2:1 high flow tests. La concentrations were not detected for any of the tests. Based on this data, it appears that the tagged suspended solids initially added to the 8:1 medium flow influent did not become resuspended for any slope or flow rate.

12.10 Metals Accumulation in Grass, Soil, and Roots

Five soil cores were initially collected from the bed from random locations to determine the baseline metal concentrations. After completion of all performance and resuspension tests, twenty-five cores were collected throughout the bed, five replicates at five different locations down the length of the bed. As described previously, the cores were separated into grass, roots, and soil fractions, and each fraction was digested and analyzed for metal concentrations. The metals added to the influent included Cd, Cr, Cu, Fe, Ni, Pb, and Zn. Figure 262 through Figure 268 display the concentrations (mg of metal/kg of dry matter) of each metal 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 solid horizontal lines on each graph represent the average background concentrations of the grass, soil, and roots before polluted water was introduced.

In terms of highest concentrations of metals accumulating within the media, each metal exhibited different trends. Cd, Cu, Pb, and Zn exhibited the highest concentrations detected in the roots, next highest in grass for Cu, Pb, and Zn, and in soil for Cd, and low concentrations detected in soil for Cu, Pb, and Zn, and in grass for Cd. Soil concentrations of Cu were below baseline concentrations. Cr and Fe had the highest concentrations detected in the soil, next highest in roots, and low concentrations were detected in the grass. Ni was unusual and had the highest concentration detected in the grass, next highest in the roots, and lowest in the soil. In terms of the spatial distribution of metals, concentrations typically decreased along the length of the bed with highest concentrations detected at a distance of 1 ft (0.305 m) from the beginning of the bed, the location of the drip line where the polluted water was delivered to the bed. Distances in the following discussion are relative to the origin of the bed at 1 ft (0.305 m), 3 ft (0.91 m), 6 ft (1.83 m), 9 ft (2.74 m), and 12 ft (3.66 m); relative to the drip line, these positions are 0 ft (0.0 m), 2 ft (0.61 m), 5 ft (1.52 m), 8 ft (2.44 m), and 11 ft (3.35 m).

Out of all these metals, Zn was the only metal that had a statistically significant amount of accumulation throughout the bed in the grass, soil, and root media (see Figure 268). Highest concentrations were found in the roots and grass. Even though the standard deviations were large for some of the root samples, the differences were statistically significant. Cu was also detected at elevated concentrations throughout the bed in the roots and grass, with highest concentrations at a distance of 1 ft (0.305 m) (see Figure 264). Cu was found above background in roots along the entire length of the bed, and in grass at 1 ft (0.305 m), 3 ft (0.61 m), 6 ft (1.83 m), and 9 ft (2.74 m), and accumulation was significant in the grass and roots along the entire length of the bed. Cd similarly had elevated concentrations in roots along the length of the bed (see Figure 262). Except at a distance of 1 ft (0.305 m), all concentrations of Cd in grass were indistinguishable from background. Ni had elevated concentrations in the grass at 1 ft (0.305 m) and 3 ft (0.91 m) above background, but there was only a significant difference at 1 ft (0.305 m). In the roots, Ni was above background concentrations along the length of the bed, but the difference was only significant at 1 ft (0.305 m), 3 ft (0.91 m), and 12 ft (3.66 m). Even though above background concentrations along the length of the bed, Ni accumulation in the soil was not statistically significant (see Figure 266). Cr had elevated concentrations in the soil, with concentrations above background along the entire length of the bed, and accumulated at a significant level throughout the length of the bed as well. Even though Cr had lower concentrations in the grass, there was a statistically significant amount of accumulation at 1 ft (0.305 m) and 6 ft (1.83 m) along the bed (see Figure 263). Fe also had elevated concentrations in the soil, with concentrations above background at 1 ft (0.305 m), 6 ft (1.83 m), 9 ft (2.74 m), and 12 ft (3.66 m), but was only significant at 1 ft (0.305 m) and 9 ft (2.74 m). Fe did not have a significant amount of accumulation in any of the grass or root samples (see Figure 265). Pb showed root, grass, and soil concentrations above the background concentrations, but differences were only statistically significant in the grass at 1 ft (0.305 m) (see Figure 267).

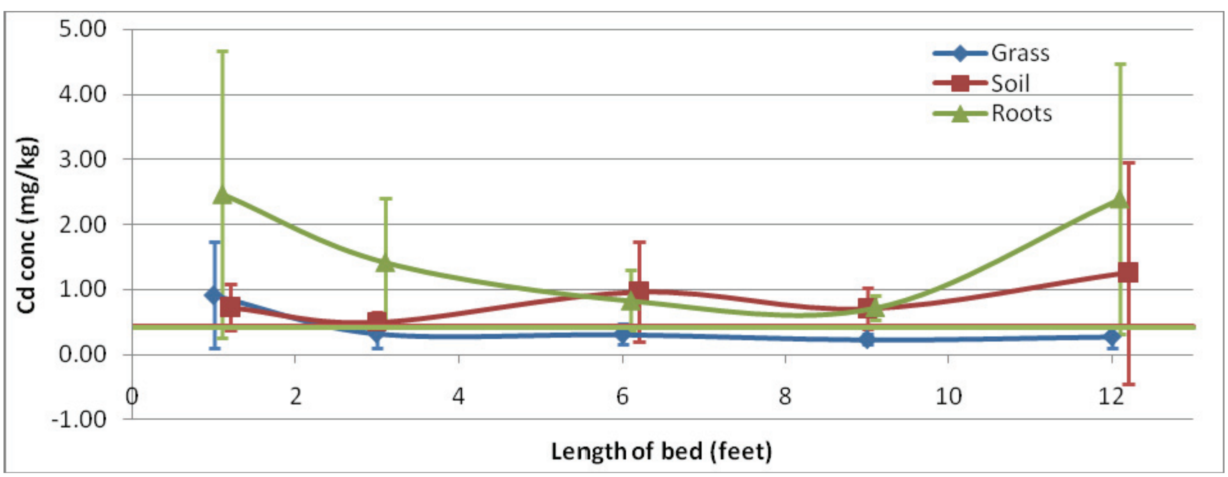


Figure 262. Concentration of Cd throughout length of Bed 3.

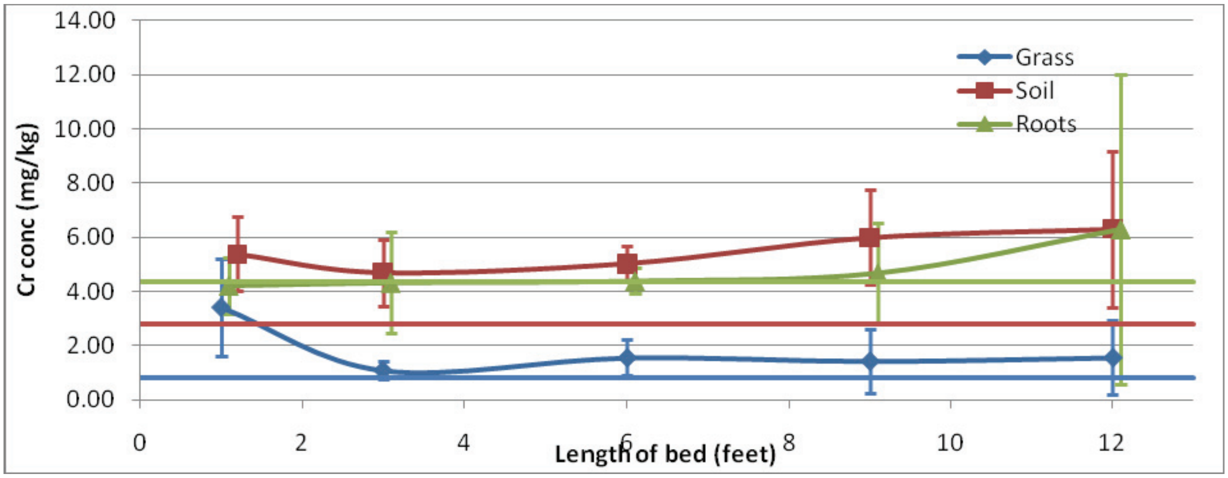


Figure 263. Concentration of Cr throughout length of Bed 3.

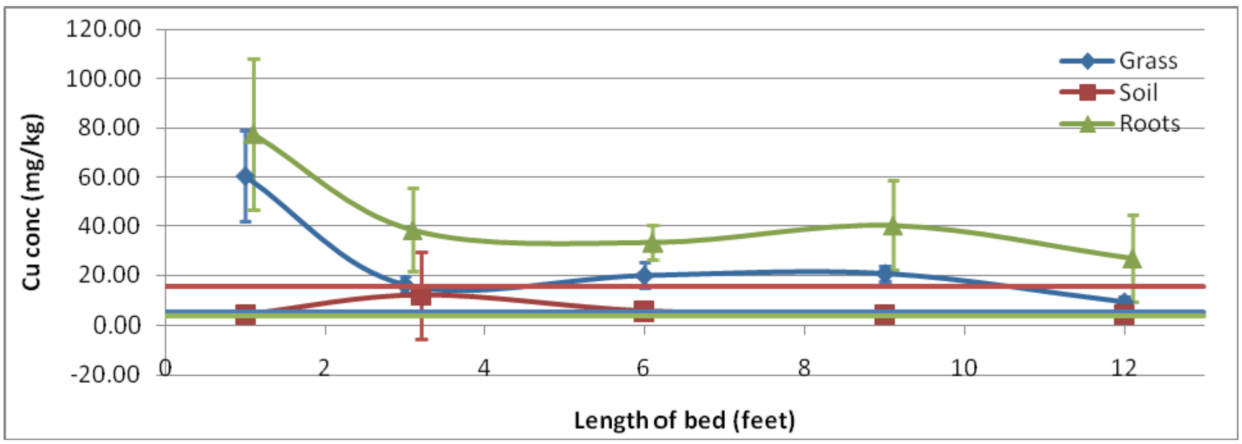


Figure 264. Concentration of Cu throughout length of Bed 3.

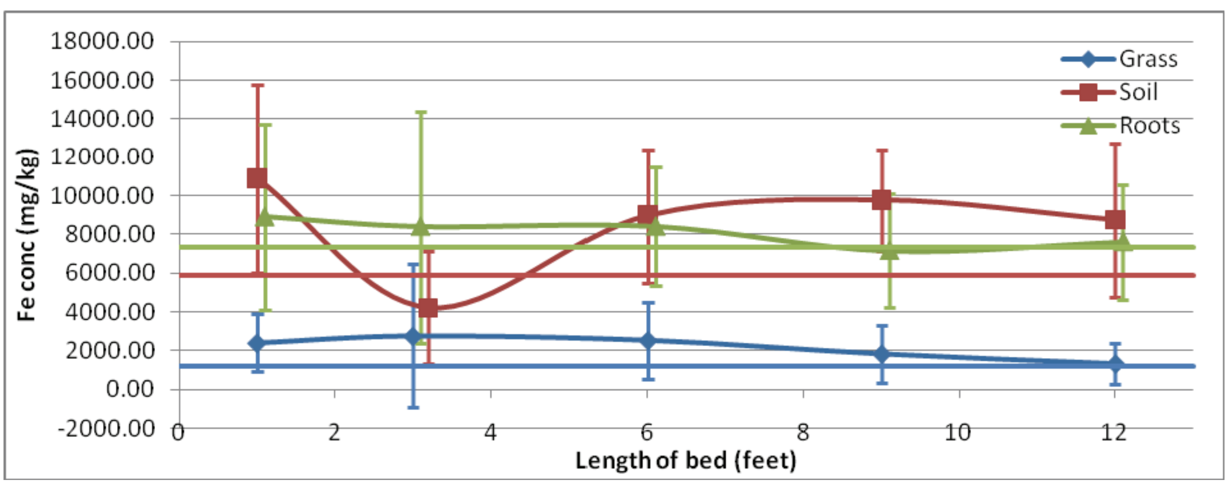


Figure 265. Concentration of Fe throughout length of Bed 3.

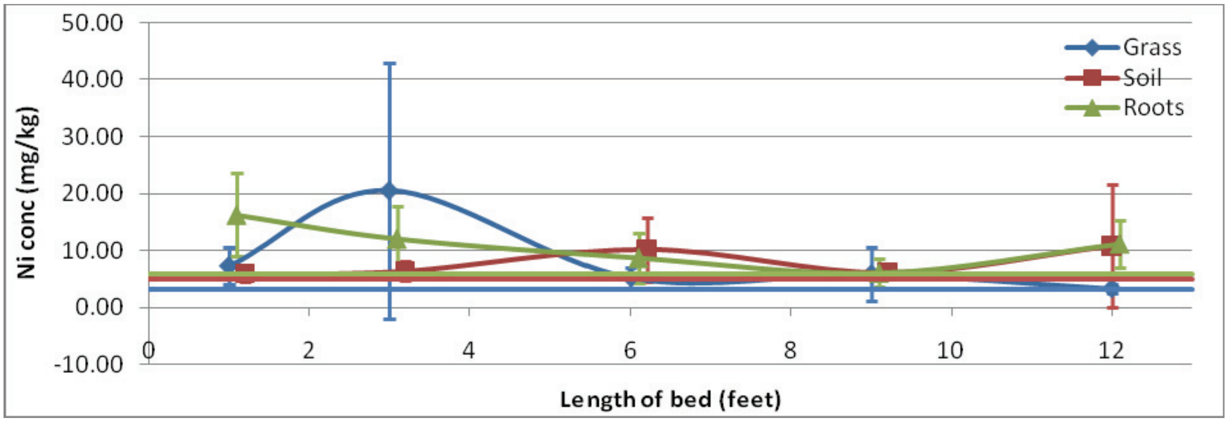


Figure 266. Concentration of Ni throughout length of Bed 3.

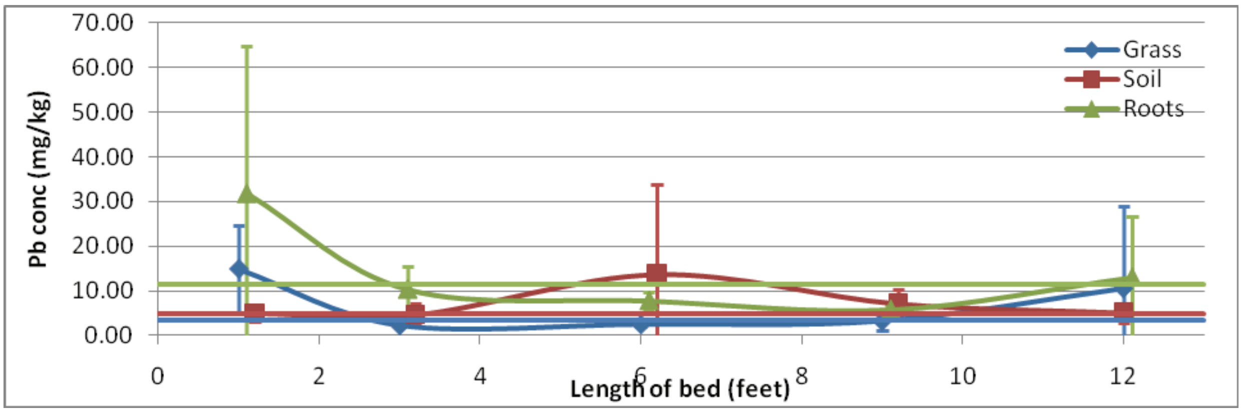


Figure 267. Concentration of Pb throughout length of Bed 3.

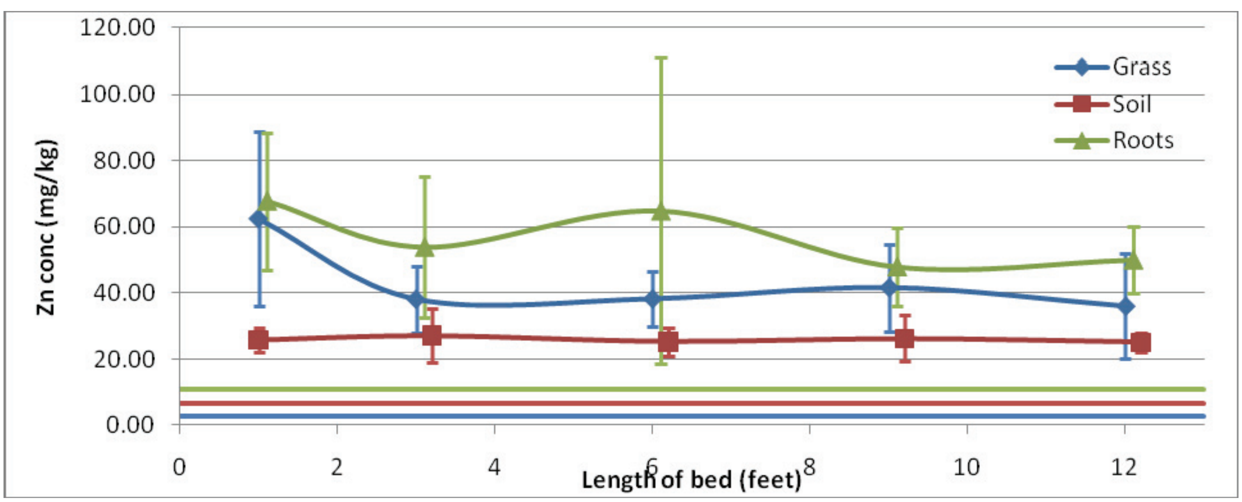


Figure 268. Concentration of Zn throughout length of Bed 3.

In the roots, every metal except Cr, Fe, and Pb showed a statistically significant amount of accumulation along the length of the bed. Cu and Zn accumulated significantly down the entire length of the bed. Cd and Ni only accumulated significantly at the 1 ft (0.305 m), 3 ft (0.91 m), and 12 ft (3.66 m) locations, and Cd also accumulated at the 6 ft (1.83 m) location. Highest concentrations for Cu and Zn were found in the roots. Cu accumulated to the highest concentration in roots at 77 mg/kg. In the grass, all of the metals except Cd and Fe accumulated significantly in the tissues, where Cu and Zn accumulated significantly down the entire length of the bed. Cr, Ni, and Pb accumulated significantly at 1 foot, and Cr also accumulated significantly at 6 ft (1.83 m); however, these concentrations were not much higher than the soil, and were actually lower for Cr. Highest concentrations for Pb were found in the roots, with a concentration of 31 mg/kg.

In the soil, Cr and Zn accumulated significantly at maximum concentrations of 6 mg/kg and 27 mg/kg, respectively, which are slightly higher than observed concentrations in vegetation for Cr, but slightly lower in Zn. Further these metals were not the highest present in the influent. As a fraction of the concentration in the roots to the concentration in the influent, Zn and Cu dominate with the proportions at 6.79 and 2.21, respectively, in the roots. Other metals range from 0.12 to 0.25. As in Beds 1 and 2, Cd, Cu, Pb, and Zn accumulated at much higher concentrations in the grass tissues and roots than in the soil. However, this is exaggerated by reporting concentrations in terms of dry mass, which can be seen in Table 29. On average the moisture content of the root, grass, and soil samples from Bed 2 were 66.8%, 70.0%, and 23.5%, respectively. This was used to convert concentrations of mg/kg dry mass to mg/kg wet mass for the highest concentrations found in the bed (see Table 29). After correcting for this distortion, concentrations in the three media were similar. Only Cu had a wet root concentration that was statistically significantly higher than the wet soil concentration. Therefore it is unclear if the vegetation preferentially took up any of the metals, Cu being the most likely candidate. Cu also had the greatest uptake in Bed 1 and Bed 2.

Table 29. Maximum metal concentrations in Bed 3 per dry and wet mass.

mg/kg (ppm) dry mass						
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Grass	0.91	3.41	60.34	20.51	14.85	62.58
Roots	2.46	6.28	77.42	16.25	31.89	67.85
Soil	1.26	6.31	11.95	10.79	13.65	27.23
mg/kg (ppm) wet mass						
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Grass	0.3	1.0	18.1	6.2	4.5	18.8
Roots	0.8	2.1	25.7	5.4	10.6	22.5
Soil	1.0	4.8	9.1	8.3	10.4	20.8

Because the total mass of grass, roots and soil in the bed could not be directly measured without destruction of the bed, and the variability of metals concentration with depth was not determined, a precise mass balance could not be performed. Nevertheless, extrapolating the relative mass of soil, roots, and grass from the cores over the extent of the bed, and assuming that the metals did not penetrate any deeper than the 2 in (5 cm) depth of the cores, the mass of contaminants collected by each media fraction was computed (see Table 30). These accumulations were higher than both Bed 1 and Bed 2, which is inconsistent because concentrations in the media were lowest for bed. However, this calculation was highly sensitive to the background concentrations which were very low for Bed 3 compared to Beds 1 and 2. The majority of the metal mass was concentrated in the soil for all metals except Cu which accumulated significantly in grass and roots. Zn accumulated to the greatest extent.

Table 30. Estimated mass of metal accumulated in different media of top 2 in (5 cm) over the entire area of Bed 3.

	Total dry mass in top 5 cm (2 in) of Bed 3 (kg)	Cd (g)	Cr (g)	Cu (g)	Ni (g)	Pb (g)	Zn (g)
Grass	65.7	0	0.05	1	0.33	0.14	2.49
Roots	41.4	0.04	0.02	1.43	0.17	0	1.84
Soil	983	0.41	2.69	0	3.28	2.66	18.96
	(lb)	**(oz)**	**(oz)**	**(oz)**	**(oz)**	**(oz)**	**(oz)**
Grass	144.8	0.0000	0.0018	0.0353	0.0116	0.0049	0.0878
Roots	91.3	0.0014	0.0007	0.0504	0.0060	0.0000	0.0649
Soil	2167.1	0.0145	0.0000	0.0000	0.1157	0.0938	0.6688
		(ppm)	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**
Grass		0.00	0.76	15.22	5.02	2.13	37.90
Roots		0.97	0.48	34.54	4.11	0.00	44.44
Soil		0.42	2.74	0.00	3.34	2.71	19.29
	(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
Grass	6.0%	0.0%	71.4%	41.2%	8.7%	5.0%	10.7%
Roots	3.8%	8.9%	28.6%	58.8%	4.5%	0.0%	7.9%
Soil	90.2%	91.1%	0.0%	0.0%	86.8%	95.0%	81.4%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

13 General comparisons of performance at different concentrations

13.1 Comparison of percent removal computations

Each of the methods of computing percent removals discussed in Section 8.8 yields different values. Determinations of percent removal of TSS, using the three methods, are provided in Table 31 and Figure 269 for comparison for the four tests for each of the three vegetated beds. As illustrated in Figure 269, in comparing the high concentration Bed 1 to the results of the medium concentration Bed 2, the percent removals were comparable for the three slopes (8:1, 4:1 and 2:1) at the medium flow rate, but greater divergence is seen at the 2:1 high flow rate. Reviewing the data for the low concentration Bed 3, very large variations in removals are noted among the three methods, for example ranging from 17% to 88% at the 2:1 slope, high flow rate.

Evaluating the efficiency using concentration percent removal yielded erratic results, because of the method's sensitivity to outliers. If a single surface runoff sample had high concentration, the average percent removal for the test could be very low, or even negative. In the 2:1 slope, high flow test on Bed 2, one surface sample had a higher concentration than the influent average during the tailing portion of the simulated storm event, leading to a negative concentration percent removal. Use of mass loadings also seemed inappropriate since for many of the tests the majority of the inflow infiltrated, resulting in extremely high percent removals. In light of these observations and considering that the use of EMC is well established to assess stormwater pollutants, the evaluation of the efficiency of the biofilters in this project was based on the EMC percent removal.

EMC removals based on water quality event data only were computed in addition to the overall removals. Influent data for the water quality event portion which occurred within the first 15, 6, or 9 minutes of applied flow were compared to the surface runoff data during this period and an additional five minutes to capture the water quality event portion effluent flow. Compare Figure 121, Figure 190, and Figure 259.

Table 31. Percent removals of TSS for each pollutant removal test using each computational method.

Concentration	Slope/ Flow	Computation method		
		Concentration	EMC	Mass Loading
High (Bed 1)	8:1 M	93%	92%	99%
	4:1 M	92%	88%	98%
	2:1 M	96%	97%	99%
	2:1 H	90%	88%	95%
Medium (Bed 2)	8:1 M	97%	98%	100%
	4:1 M	94%	96%	100%
	2:1 M	95%	97%	99%
	2:1 H	-8%	93%	99%
Low (Bed 3)	8:1 M	54%	50%	100%
	4:1 M	65%	27%	94%
	2:1 M	-96%	-377%	0%
	2:1 H	46%	17%	88%

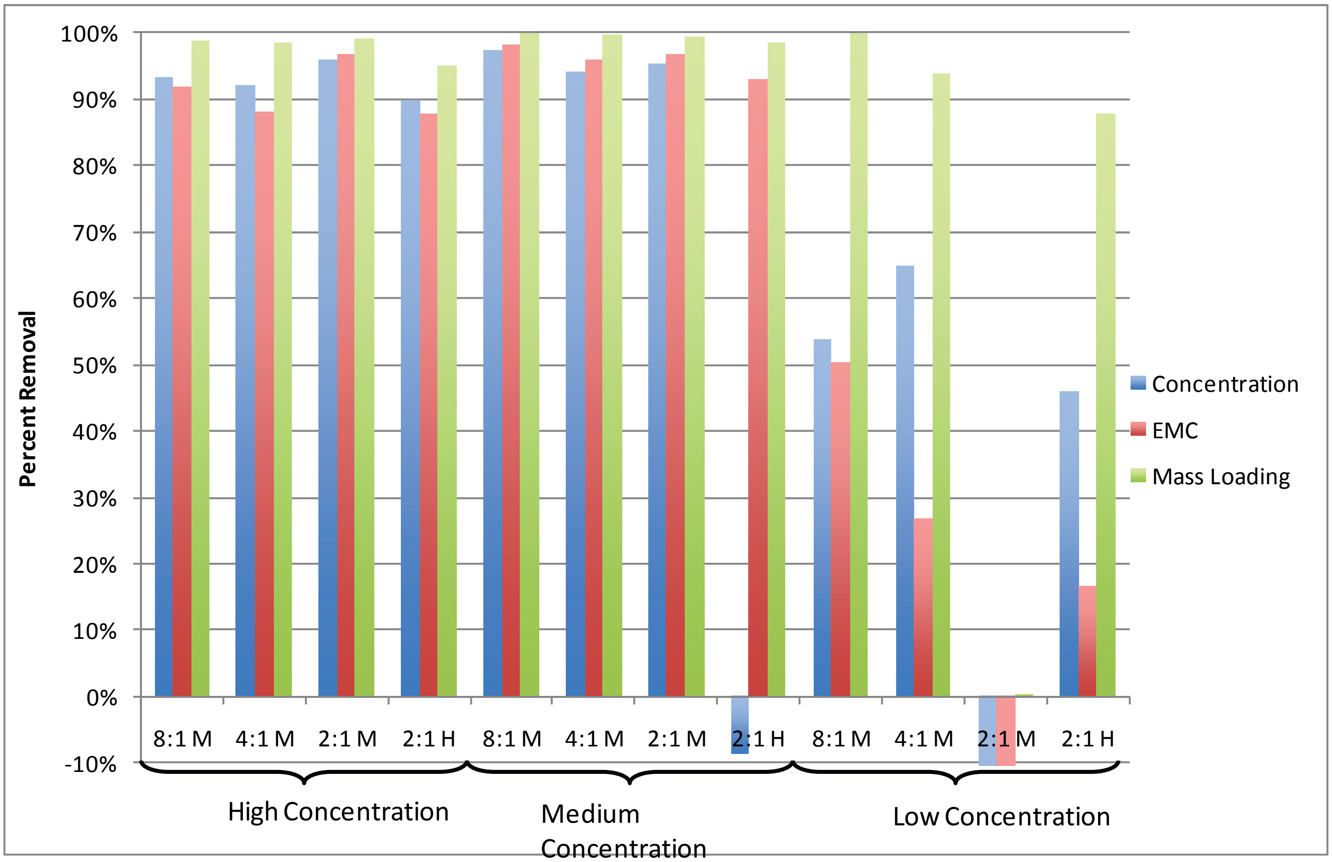


Figure 269. Percent removals of TSS for each pollutant removal test using each computational method.

13.2 Summary of tracer study results

Table 32 summarizes the results from the tracer studies on all three beds. The percent runoff column indicates the amount of influent that resulted in surface flow. The variability observed in the three beds may be partly attributable to the variations in coverage, soil density, and other attributes. The grass coverage for the high, medium, and low concentration beds during the time of the tests was 83%-85%, 76%-97%, and 94%, respectively. The wet density of the soil in the three beds was measured at 99.1 pcf (1590 kg/m^3), 90.8 pcf (1455 kg/m^3), and 78.1 pcf (1251 kg/m^3), respectively.

Table 32. Summary of tracer study results for all performance tests.

Concentration	Slope	Flow	Surface Residence Time (min)	Underdrain Residence Time (min)	Percent Runoff	Percent Recovery
High (Bed 1)	8:1	M	6	6	15%	94%
	4:1	M	4	5	36%	99%
	2:1	M	3	5	41%	95%
	2:1	H	1.5	2	70%	91%
Medium (Bed 2)	8:1	M	5.5	6	13%	92%
	4:1	M	4.5	5	24%	80%
	2:1	M	3.9	3	27%	74%
	2:1	H	1.0	4	58%	74%
Low (Bed 3)	8:1	M2	3.5	6	5.3%	71%
	4:1	M2	3.0	4	7.4%	74%
	2:1	M2	2.2	4	15%	67%
	2:1	H	1.7	4	29%	69%

14 Analysis and documentation of performance issues

Note: This chapter was written by Mark McCabe of CDM and Jay Mosley of URS, Inc. and edited and revised by Kevin White of E.L. Robinson.

14.1 Introduction

Successful stormwater management programs require more than just the use of runoff control techniques. Meeting the regulatory requirements developed to protect, enhance and restore the waters of the United States to a level that meets their beneficial and designated use are the objectives of a comprehensive stormwater program. Stormwater management requires establishing a strong institutional foundation which can be built on and that will establish effective mechanisms that will ensure stormwater systems are properly designed, constructed, operated, inspected and maintained properly.

ODOT defines a Vegetated Biofilter as a best management practice that filters storm water through the vegetated portion of the graded shoulder, vegetated slope, and the vegetated ditch. This section references sources from other states that describe swales or ditches that provide a similar function that are defined as “swales”, “biofilters”, “enhanced water quality swales”, “enhanced swales”, “dry extended detention swales”, or “vegetated swales” in those other sources. This section addresses specific areas associated with the analysis and performance of the vegetated biofilter. These performance areas are:

- *General Information* – This section provides information on the vegetated biofilter inspections completed and the inspection forms.
- *Life Cycle Costs* – This performance area deals with the range of costs associated with designing, constructing, operating, maintaining and replacing a vegetated biofilter.
- *Operation and Maintenance Issues* – This performance area deals with operating and maintaining the vegetated biofilter to ensure that it functions, operates and performs as designed. The area addresses performance issues and maintenance of different vegetated biofilter elements (i.e., foreslope, swale bottom, side slopes, outlet, etc.), type and frequency of maintenance, and inspection protocols.

14.2 General Information

14.2.1 Roadside Vegetated Buffer

The United States Environmental Protection Agency (USEPA) defines vegetated buffers as “areas of natural or established vegetation maintained to protect the water quality of neighboring areas…. Vegetated buffers can be used in any areas able to support vegetation. They are most effective and beneficial on floodplains, near wetlands, along stream banks and on unstable slopes” [USEPA, 2000]. Based on the description above, a vegetated buffer performs as a broad low sloped filter strip usually located between a construction site or transportation facility and a riparian area. Filter strips and grass swales are also considered vegetated buffers and are most often associated with and used adjacent to urban and rural roadways [Storey, et al., 2009]. Figure 270 illustrates a roadside vegetated buffer [Storey, et al., 2009].

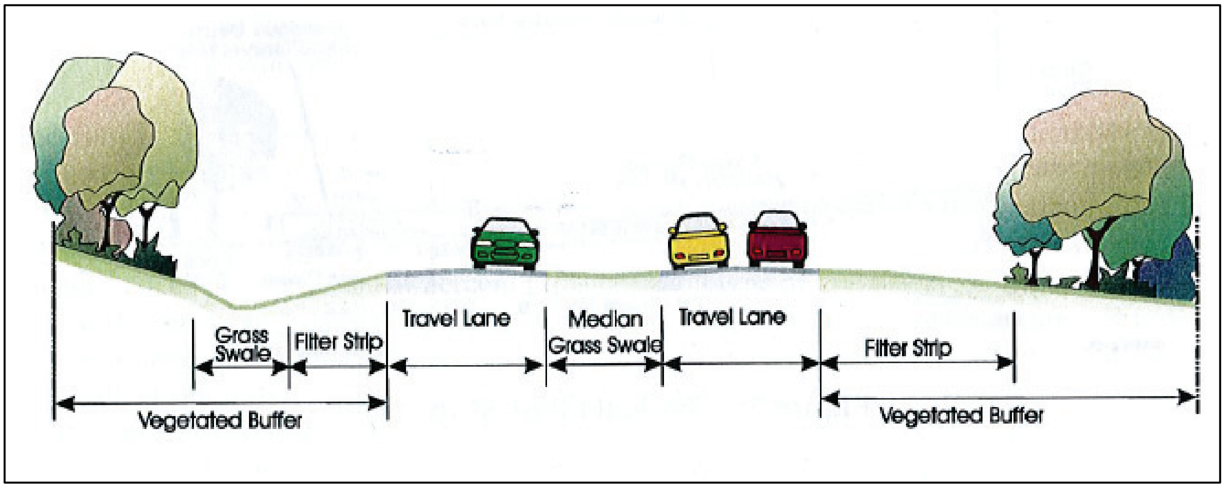


Figure 270. Vegetated buffers in median and on roadside [Storey, et al., 2009].

As stated in the CGP [OEPA, 2008], the post-construction stormwater management requirements are intended to protect the receiving stream's physical, chemical, and biological characteristics, and stream functions are maintained through post-construction stormwater practice that shall provide perpetual management of runoff quality and quantity. These post-construction stormwater practices have performance thresholds [CWP, 2007] which limit the pollutant removal rates and efficiencies of the practice. "These performance thresholds are affected greatly by performing or not performing maintenance".

The current research project has shown, within the limited scope of the research, that the foreslope can be an effective water quality BMP without considering the vegetative swale. It is important to consider the various design and maintenance practices and how they impact the pollutant removal efficiency for the vegetated biofilter.

14.2.1.1 Soil Requirements

The literature suggests that vegetated swales should not be constructed in gravelly and coarse sandy soils that cannot easily support dense vegetation. If available, alkaline soils and subsoils should be used to promote the removal and retention of metals. Soil infiltration rates should be greater than one-half inch per hour; therefore, care must be taken to avoid compacting the soil during construction [USEPA, 1999b].

The *Wisconsin Storm Water Manual* [Donovan et al., 2000] suggests that swale infiltration rate should be between 0.5 in (0.012 m) and 5.0 in (0.127 m) per hour, and that suitable soil types are sand, loamy sand, sandy loam, loam, and silty loam. The coarser soils provide little treatment capability because of the high permeability and soils with very low permeability do not provide adequate infiltration.

However, the current research project utilized beds constructed of very fine clay soils typical in Ohio. Using this AASHTO A-6 soil, lightly compacted, the vegetated slopes were effective in removing pollutants, particularly suspended solids.

14.2.1.2 Vegetation

A fine, close-growing, water-resistant grass should be selected for use in vegetated swales, because increasing the surface area of the vegetation exposed to the runoff improves the effectiveness of the swale system. In addition, care should be taken to choose plants that will be able to thrive at the site [USEPA 1999b].

Several current ODOT seed mixtures used for roadside vegetation seem to be well suited for vegetated biofilters. However, the Crown Vetch Mixture is not suitable. Current ODOT specifications would either require or allow for this mixture to be used on slopes greater than 3:1. Recommendations from this research indicate that all 4:1 slopes of sufficient length are potential vegetated biofilter locations even without considering benefits from the swale/ditch portion of the BMP. The ODOT CMS Item 659 Class 3A seed mixture identified as Slope Mixture is permitted for slopes flatter than 3:1 and allows for the use of the Crown Vetch Mixture. This mixture should not be permitted for use in Vegetative Biofilters. Coverage with the crown vetch is insufficient.

There is a trade-off between vegetation length and vegetation density. Vegetation that is mowed regularly and kept at a lower height typically results in more dense vegetation coverage. However, the lower height has less retardance to water flow. Without further research it is not possible to recommend changes to current ODOT practices. The literature is varied on the subject with some sources indicating that a low vegetation height is preferable and other sources indicating that vegetation height has little impact on pollutant removal [Claytor and Schueler, 1996] [California Stormwater Quality Association, 2003].

14.2.1.3 Swale Slope

Schueler [1987] recommends a vegetated swale slope as close to zero as drainage permits. The Minnesota Pollution Control Agency [Minnesota Stormwater Steering Committee, 2008] recommends that the slope be less than 2 percent. The *Storm Water Management Manual for the Puget Sound Basin* [WDEC, 1992] specifies channel slopes between 2 and 4 percent. This Manual indicates that slopes of less than 2 percent can be used if drain tile is incorporated into the design, while slopes greater than 4 percent can be used if check dams are placed in the channel to reduce flow velocity.

The *Wisconsin Storm Water Manual* [Donovan et al., 2000] states that grassed swales encourage deposition of sediment if the velocity of flow across the swale is less than 1.5 ft per second (0.457 m/s). High velocities in excess of 5 to 8 feet per second (1.5 to 2.4 m/s) may reduce the treatment effectiveness and may induce erosion.

The current research did not include the incorporation of swale slope. The current research suggests that the swale portion of the vegetative biofilter may be unnecessary froma pollutant removal standpoint. Additional research or site monitoring/testing is necessary to determine a maintenance interval that would allow the slope to continue to function adequately throughout its pollutant removal life cycle. In terms of the vegetative swale, it will be necessary to determine if concentrated flow acts any different than the sheet flow utilized in this project.

14.2.2 Integrating other Practices with the Vegetated Biofilter

Biofilters consist primarily of vegetated swales and filter strips. The swales are shallow channels with flow depths below the height of the vegetation that grows within them. The filter strips are vegetated flat surfaces over which water flows in a thin sheet. Roadside ditches can be designed as biofilters and as landscaping amenities [AASHTO, 1998].

As described in the *Statement of the Problem* for this research project the vegetated biofilter incorporates several types of stormwater controls that are integrated into a comprehensive stormwater management system.

The different components associated with the vegetated biofilter, depicted in Figure 271, are:

- Vegetated foreslope
- Vegetated backslope
- Vegetated swale

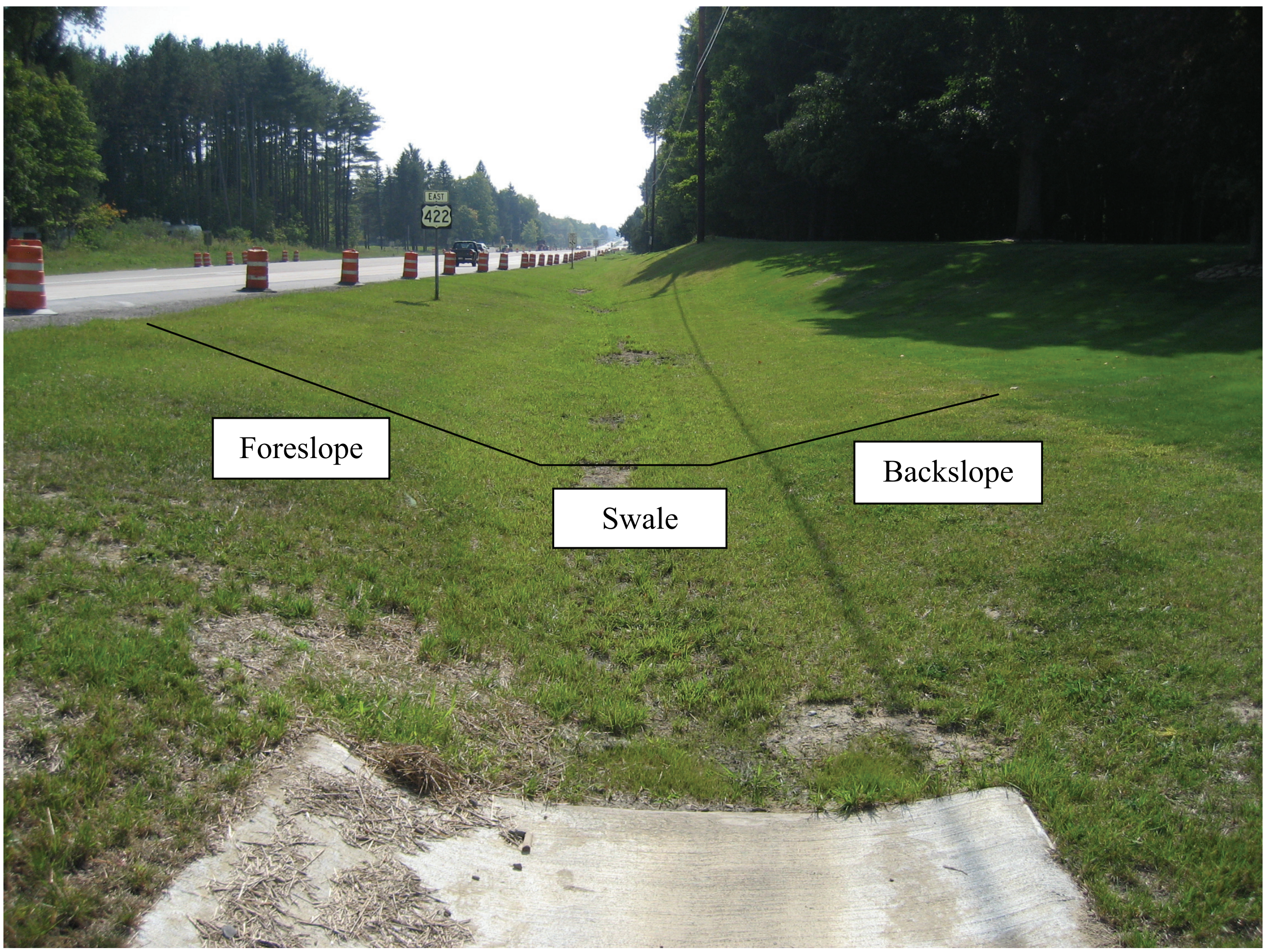


Figure 271. Components associated with the vegetated biofilter.

During development of design information for this practice one of the critical areas that needs to be addressed is the transition between the foreslope and the ditch in the vegetated biofilter. As the runoff moves down the foreslope, the flow will enter the vegetated biofilter swale; a design consideration needs to address the potential for erosive forces associated with flow exiting the foreslope and entering the vegetated biofilter swale. The design information needs to account for this directional change. Current ODOT design methodology, which considers the shear forces in the swale bottom, appears to adequately address this concern. However, maintenance of ditch bottoms, to include installation of erosion control mats should be incorporated into ODOT maintenance efforts. This will ensure the vegetative swale remains fully vegetated.

14.2.3 Vegetated Stormwater Treatment and Safety

Historically, the design of the roadside has been from a safety and drainage perspective, Designs for channels, ditches, swales and roadside slopes emphasize the conveyance of stormwater runoff. Stormwater treatment has not been a significant consideration when determining the design of the roadside vegetated areas. AASHTO's *A Policy on Geometric Design of Highways and Streets* (aka the "Green Book") [AASHTO, 2004], recommends slopes flatter than 25 percent to meet safety requirements; many rural roadsides can and do accommodate flatter slopes. A number of DOTs design guidelines for roadside channel side slopes set the maximum of 33 percent for side slopes. Figure 272 shows a typical rural roadway section [Storey, et al., 2009]. Roadside vegetated areas designed for water quality treatment must meet the safety clear zone and recoverable slope requirements of the specific roadway types [Storey, et al., 2009]. The key point is that most standard roadside designs can accommodate the use of vegetated buffers, filter strips and grass swales as stormwater quality BMP.

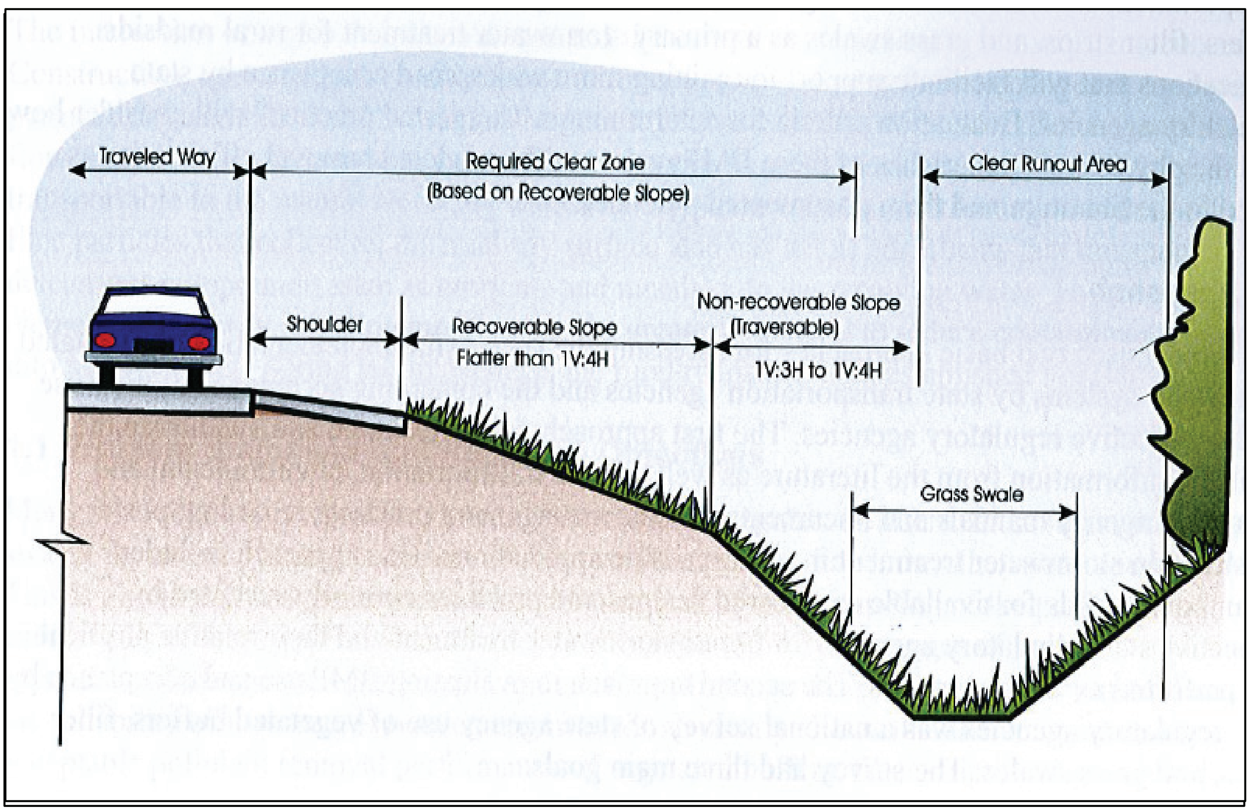


Figure 272. Roadside safety elements for a vegetated BMP [from Storey, et al., 2009].

14.2.4 Vegetated Biofilter Field Inspection Sheets

This section provides information on the layout and functionality of the vegetated biofilter inspection sheets. A blank inspection sheet is reproduced in Appendix D. The sheets are limited to two sides of one sheet of paper and are divided into three sections as follows:

- Site Characterization – This section covers general location information, weather conditions, traffic, and general notes on the project sites conditions relevant to the vegetated biofilter.

- BMP Characterization – Foreslope and ditch information associated with cross sections size, slope, ground cover, condition of slopes, maintenance issues, presence of trash.

- Facility Sketch – Place to include a sketch with notes, size information, and condition information.

The inspection sheets have proven to be well designed and easy to complete in the field. It is recommended that ODOT personnel develop and utilize a similar inspection form to document inspection and monitoring observations. If a similar inspection form is adopted by ODOT, the following comments on the format and content of the inspection forms may be helpful:

- Field inspectors may not know the contributing drainage area, the USGS basin development factor, or the AADT without additional office work before or after the site inspection. If this additional office work is unrealistic, then these fields could be removed from the inspection sheets.

- The "Date of Last Maintenance (garage)" field may be difficult to complete if the field inspector is not involved with the maintenance of the BMPs or does not have ready access to BMP maintenance logs.

- The area for additional comments has proven to be very necessary to note observed items that do not fall within one of the inspection sheet fields.

14.3 Life Cycle Costs

The costs associated with the vegetated biofilter can be divided into three categories: 1. planning and design costs, 2. construction costs, and 3. operation and maintenance costs. Each of these is discussed separately below.

14.3.1 Planning and Design Costs

According to Section 1117 of the ODOT Location and Design Manual [ODOT, 2009], a vegetated biofilter is a BMP that filters stormwater through vegetation that consists of the vegetated portion of the graded shoulder, vegetated slope, and vegetated ditch or swale. These BMPs are appropriate for use in narrow areas along roads and medians where insufficient space exists to accommodate the additional storage depth and width of other BMPs. These BMPs are relatively inexpensive, and the total cost is principally related to earth moving construction costs.

Because grassed channels are commonly installed in roadway right-of-way areas to provide essential drainage even without the requirement to install Post-Construction BMPs, implementing a wider swale design typically results in a relatively small additional design cost with the supplemental benefit of providing significantly better water quality management [USFHWA, 2006b].

14.3.2 Construction costs

The base capital costs referred to in this section consist of only the cost to construct the BMP including any costs for erosion and sediment control during construction. The costs of design, geotechnical testing, legal fees, land costs, and other unexpected or additional costs are not included in these estimates unless noted. The costs presented herein represent average costs since the cost to construct any BMP can be quite variable depending upon the site conditions and drainage area [USEPA, 1999b].

Swales are considered relatively inexpensive BMPs. Schueler, Kumble, and Heraty [1992] estimated that conceptual construction costs are typically around $1,500 ($2312 in 2009 dollars) per acre (0.4 ha) served based on a nearly flat dry swale with 10 feet (3.05 meters) bottom width, 3:1 side slopes, and a ponding depth of 1 foot (0.304 m). It was also suggested that the cost of a swale could also be inferred from the cost of a traditional grass swale, which typically ranges between $5 and $15 ($7.70 and $23.13 in 2009 dollars) per linear foot (0.305 m) depending on local conditions, swale dimensions, and the degree of internal storage (i.e., check dams) provided. Schueler [1987] reported that costs may vary from $4.90 to $9.00 ($9.33 and $14.14 in 2009 dollars) per linear foot (0.305 m) for a 15-foot (4.57 m) wide (top width) channel.

Hathaway and Hunt [2007] present a cost estimate of $0.95 ($1.73 in 2009 dollars) per square foot (0.305 m) of swale based on a width of roughly 6 to 8 feet (1.83 to 2.44 m), side slopes between 3:1 and 4:1, and a depth of 1 foot (0.305 m). They suggest that turf reinforcement matting will be needed if high velocities (greater than 4.0 ft/s (1.22 m/s)) are experienced and that this reinforcement would add to their estimated construction.

The USEPA [1999b] estimated from various planning level studies that typical grass swale unit costs are $0.5 ($0.65 in 2009 dollars) per square ft (0.093 m^2) assuming 6 in (15 cm) depth of storage in the filter.

Lakesuperiorstreams [2009] suggested that swale construction costs have not been well studied since costs will differ regionally and with site condition. A best estimate of $0.50 per ft^2 (0.093 m^2) (in 2002 dollars) ($0.60 in 2009 dollars) or a value of $5.50 ($6.61 in 2009 dollars) per ft^3 (0.028 m^3) of storage were provided.

The Southeastern Wisconsin Regional Planning Commission [SEWRPC, 1991] researched the costs to construct vegetated swales and reported that costs may vary from $8.50 to $50.00 ($13.50 to $79.42 in 2009 dollars) per linear foot (0.305 m) depending upon swale depth and bottom width. Some of these cost estimates are higher than other published estimates because they include the cost of activities (such as clearing, grubbing, leveling, filling, and sodding) that may not be included in other published estimates. Table 33, adapted from SEWRPC [1991], presents the range of estimated capital costs for a 1.5-foot (0.45 m) deep, 10-foot (3.05 m) wide grassed swale as determined by their research. The costs in Table 33 were multiplied from the original source by a factor of 1.59 to inflate the 1991 costs to 2009 dollars.

Table 33. Estimated capital cost of a 1.5 ft (0.475m) deep, 10 ft (3.05 m) wide grassed swale. Adapted from [SEWRPC, 1991].

Component	English unit	Extent	Metric unit	Extent	Unit Cost Low	Unit Cost Med.	Unit Cost High	Total Cost Low	Total Cost Med.	Total Cost High
Mobilization/ Demobilization - Light	Swale[a]	1	Swale[a']	1	$170	$436	$701	$170	$436	$701
Site Preparation:										
Clearing[b]	ac	0.5	ha	0.202	$3,498	$6,042	$8,586	$1,749	$3,021	$4,293
Grubbing[c]	ac	0.25	ha	0.101	$6,042	$8,268	$10,494	$1,511	$2,067	$2,624
Geenral Excavation[d]	yd^3	372	m^3	284	$3.34	$5.88	$8.43	$1,242	$2,188	$3,135
Level and Till[e]	yd^2	1210	m^2	1012	$0.32	$0.56	$0.80	$385	$673	$962
Site Development:										
Salvaged Topsoil, Seed, and Mulch[f]	yd^2	1210	m^2	1012	$0.64	$1.59	$2.54	$770	$1,924	$3,078
Sod[g]	yd^2	1210	m^2	1012	$1.91	$3.82	$5.72	$2,309	$4,617	$6,926
Subtotal	-	-	-	-	-	-	-	$8,135	$14,927	$21,719
Contingencies	Swale	1	Swale	1	25%	25%	25%	$2,034	$3,732	$5,430
Total	-	-	-	-	-	-	-	$10,168	$18,658	$27,148

Adapted from [SWERPC, 1991], with costs inflated by 59% to update cost estimate to 2009

Note: Mobilization/demobilization refers to organization and planning involved in establishing a vegetative swale

[a] Swale has a bottom width of 1.0 ft, a top width of 10 ft, 1:3 side slopes, and a 1,000 ft length

[a'] Swale has a bottom width of 0.305 m, a top width of 3.05 m, 1:3 side slopes, and a 305 m length

[b] Area cleared = (2 × top width) × swale length

[c] Area grubbed = top width × swale length

[d] Volume excavated = (0.67 × top width × swale depth) × swale length (parabolic cross-section)

[e] Area tilled = (top width + (8 × (swale depth)^2)/(3 × top width)) × swale length (parabolic cross-section)

[f] Area seeded = area cleared/2

[g] Area sodded = area cleared/2

Table 34 presents a summary of the estimated construction costs as described by the references in this section exclusive of the costs presented in Table 33 above.

Table 34. Summary of vegetated biofilter construction costs.

Source	Estimates of Construction Cost
USFHWA, 2006b	$1,500 ($1609 in 2009 dollars) per acre served based on a nearly flat dry swale with 10 ft (3.05 m) bottom width, 3:1 side slopes, and a ponding depth of 1 ft (0.3 m)
Schueler, 1992	$5 and $15 ($7.71 to $ 23.13 in 2009 dollars) per linear foot (0.3 m) depending on local conditions, swale dimensions, and the degree of internal storage (i.e., check dams)
Hathaway, Jon and William F. Hunt, 2007	Total = $0.95 ($0.99 in 2009 dollars) per ft^2 (0.093 m^2) (including excavation @ $0.09 ($0.09 in 2009 dollars) per ft^2 (0.093 m^2); hauling @ $0.21 ($0.22 in 2009 dollars) per ft^2 (0.093 m^2); grading @ $0.36 ($0.38 in 2009 dollars) per ft^2 (0.093 m^2); and grass @ $0.29 ($0.30 in 2009 dollars) per ft^2 (0.093 m^2)). Assuming 6 ft (1.82 m) to 8 ft (2.43 m) width; a depth of 1 ft (0.30 m); and side slopes between 3:1 and 4:1
USEPA, 1999b	$0.50 ($0.60 in 2009 dollars) per ft^3 (0.028 m^3) assuming 6 in (0.15 m) of storage in the filter.
Duluth Streams, Lake Superior, 2009	$0.50 per ft^2 (0.093 m^2) (2002 dollars) ($0.60 in 2009 dollars) or a value of $5.50 ($6.61 in 2009 dollars) per ft^3 (0.028 m^3) of storage provided.
Schueler, 1987	$4.90 to $9.00 ($9.93 to $17.14 in 2009 dollars) per linear foot (0.3 m) for a 15-ft (4.57 m) wide channel (top width).

14.3.3 Operation and Maintenance Costs

Annual costs for maintaining vegetated swales are approximately $0.58 ($0.92 in 2009 dollars) per linear foot for a 1.5-foot (0.457 m) deep swale and $0.75 ($1.19 in 2009 dollars) for a 3.0 foot (0.91 m) deep swale according to SEWRPC [1991]. If the $25 per inspection cost is factored in (4 inspections per year, total $100) and divided by an assumed 1000 ft (300 m) length, these costs go up by $0.10 ($0.16 in 2009 dollars). These average annual operating and maintenance costs of the vegetated swales were broken out by SWERPC as shown in Table 35. The costs in Table 35 were multiplied by a factor of 1.59 to inflate the 1991 costs to 2009 dollars. The mowing frequency was also reduced from eight times per year to two times per year to reflect current ODOT practice.

Table 35. Estimated operation and maintenance costs for vegetated biofilter. Adapted from [SWERPC, 1991].

Component	English unit	Unit Cost	Annual recurrence	Annual cost per linear ft	
				Small swale[a]	Large swale[b]
Lawn mowing[c]	1000 ft^2	$1.35	2	$0.055	$0.0825
General lawn care[c]	1000 ft^2	$14.31	1	$0.29	$0.45
Debris and litter removal	ft	$0.16	1	$0.16	$0.16
Grass reseeding with mulch and fertilizer[d]	yd^2	$0.48	1%	$0.02	$0.03
Program administration[e]	ft	$0.24	1	$0.24	$0.24
Swale inspection[f]	-	$39.75	4	$0.16	$0.16
Total				**$0.92**	**$1.12**

Source: Adapted from [SWERPC, 1991] with inflation of 59% to 2009 costs

Notes:

[a]Small swale cross-section dimensions: 1.5 ft depth, 1 ft bottom width, 10 ft top width

[b]Large swale cross-section dimensions: 3 ft depth, 3 ft bottom width, 21 ft top width

[c]Lawn maintenance area = (top width + 10 ft) × length; Recurrence in original table was given as 8 times per year, but 2 is ODOT standard, and costs have been reduced proportionally.

[d]Original table had reseeding costs the same for both small and large swales despite factor of two difference in cross-section

[e]Program administration and Swale inspection were combined in original table

[f]Swale inspection and Program administration were combined in original table; 1000 ft length assumed

Component	Metric unit	Unit Cost	Annual recurrence	Annual cost per linear m	
				Small swale[a]	Large swale[b]
Lawn mowing[c]	100 m^2	$1.45	2	$0.1825	$0.275
General lawn care[c]	100 m^2	$15.40	1	$0.94	$1.46
Debris and litter removal	m	$0.52	1	$0.52	$0.52
Grass reseeding with mulch and fertilizer[d]	m^2	$0.57	1%	$0.05	$0.10
Program administration[e]	m	$0.78	1	$0.78	$0.78
Swale inspection[f]	-	$39.75	4	$0.53	$0.53
Total				**$3.01**	**$3.68**

Source: Adapted from [SWERPC, 1991] with inflation of 59% to 2009 costs and metric units

Notes:

[a]Small swale cross-section dimensions: 0.46 m depth, 0.3 m bottom width, 3 m top width

[b]Large swale cross-section dimensions: 1 m depth, 1 m bottom width, 6.4 m top width

[c]Lawn maintenance area = (top width + 3 m) × length; Recurrence in original table was given as 8 times per year, but 2 is ODOT standard, and costs have been reduced proportionally.

[d]Original table had reseeding costs the same for both small and large swales despite factor of two difference in cross-section

[e]Program administration and Swale inspection were combined in original table

[f]Swale inspection and Program administration were combined in original table; 300 m length assumed

14.4 Operation and Maintenance Issues

Maintenance can be broken down into two primary categories: functional maintenance and aesthetic or routine maintenance. Functional maintenance is required to ensure the performance and safety of the BMP, while aesthetic maintenance is important primarily for the public appearance of the BMP; however, it may also reduce the need for functional maintenance at a later date.

Vegetated swales require routine inspection and maintenance to prevent problems with odor, insects, weeds, turbidity, trash, and sediment. Sediment that has built-up within the bottom of the swale should be removed when it has accumulated to the point where it occupies approximately 25 percent of the original design volume or when the depth of sediment exceeds 4 in (0.10 m) [Claytor and Schueler, 1996]. Urbonas, et al. [1992] suggests that the owners of publicly maintained swales should anticipate removing sediment from 3 to 10 percent of the total swale length for each year of operation.

Maintenance of swales should include measures to ensure vigorous and healthy grass growth including periodic mowing to keep grasses at acceptable levels and to minimize the growth of unwanted invasive vegetation. In swales with a minimal slope, wetland plant species may colonize the area of the swale below the waterline; however, it is unclear whether wetland vegetation will interfere with the basic function of the swale [Urbonas et al., 1992].

Regular and thorough maintenance is necessary for stormwater management measures to perform effectively and reliably. Failure to perform such maintenance can lead to diminished performance, deterioration, failure, and even health and safety problems. The potential for such problems to develop is accentuated by many of the very features and characteristics that allow stormwater management measures to do their job, including standing or slowing moving water, dense vegetation, check dams, and the need to continually function in all types of weather [New Jersey, 2009].

The summary of the DOT responses to the survey questions associated with BMP operation and maintenance issues described in Chapter 3 showed that a majority of the DOTs (56%) said that no special maintenance was required. The most common maintenance step reported was periodic inspections, selected by five respondents (25%).

14.4.1 Operational and Performance Issues

Important construction items to minimize maintenance issues [Lakesuperiorstreams, 2009]:

- Provide accurate grading to ensure a properly functioning swale.
- Minimize machinery use in swale to minimize compaction of soil.
- Protect swale from erosion and sedimentation during construction.
- Perform final grading and planting after the adjoining areas draining into the swale are stabilized.
- Remove any accumulation of sediments during the final stages of grading.
- Install erosion control matting or blanketing to stabilize soil during establishment of vegetation.

- Desired level of establishment of vegetation may take two to three growing seasons.

The USEPA in Storm Water Technology Fact Sheet 832-F-99-006 [USEPA, 1999b] listed the following limitations for vegetated swales:

- Very flat grades, steep topography, or wet or poorly drained soils can make vegetated swales impractical.
- Erosion may be a problem when flow volumes and/or velocities are high.
- Land may not be available for them.
- They are impractical in areas with erosive soils or where a dense vegetative cover is difficult to maintain.
- Leaching from swale vegetation may increase the presence of trace metals and nutrients in the runoff.
- Infiltration through the swale may carry pollutants into local groundwater.
- Standing water in vegetated swales can result in potential safety, odor, and mosquito problems. [USEPA, 1999b].

The California Stormwater Quality Association [2003] listed the following limitations for vegetated swales:

- Can be difficult to avoid channelization.
- Grassed swales cannot treat a very large drainage area.
- A thick vegetative cover is needed for these practices to function properly.
- They are impractical in areas with steep topography.
- They are not effective and may even erode when flow velocities are high, if the grass cover is not properly maintained.
- Swales are susceptible to failure if not properly maintained.

14.4.2 Types and Frequencies of Maintenance Activities

BMPs will not perform as designed if they are not regularly maintained. A regular maintenance program is the best way to ensure that a BMP will consistently perform its water quality improvement functions. The useful life of a vegetated swale system is directly proportional to its maintenance frequency. If properly designed and regularly maintained, vegetated swales can last indefinitely.

The application of fertilizers and pesticides should be minimal. Another aspect of a good maintenance plan is repairing damaged areas within a channel. For example, if the channel develops ruts or holes, it should be repaired utilizing a suitable soil that is properly tamped and seeded. The grass cover should be thick; if it is not, reseed as necessary. Any standing water removed during the maintenance operation must be disposed to a sanitary sewer at an approved discharge location. Residuals (e.g., silt, grass cuttings) must be disposed of in accordance with local or State requirements [USEPA, 1999b].

Table 36 summarizes appropriate maintenance activities for vegetated swales. This table is based on our understanding of routine ODOT maintenance procedures, along with best practices from Alameda County [2007], and Lakesuperiorstreams [2009].

Table 36. Maintenance activities for vegetated swales [derived from Alameda County, 2007 and Lakesuperiorstreams, 2009 with additional material by the authors].

Defect	Conditions when Maintenance is Needed	Frequency	Results Expected when Maintenance is Performed
Sediment Accumulation on Vegetation	Sediment accumulating in channels builds up to 3 in (7.6 cm) at any spot, or it covers vegetation	As needed. In cold climates inspection should be once per year. Typically in spring, to assess winter debris.	When finished, swale should be level from side to side and drain freely toward outlet. There should be no areas of standing water once inflow has ceased and sediment is disposed of properly
Standing Water	When water stands in the swale between storms	Complete during other routine inspections	There should be no areas of standing water once inflow has ceased. Any of the following may apply: sediment or trash blockages removed, improved grade from head to foot of swale, removed clogged check dams
Trash and Debris Accumulation	Trash and debris accumulated in the swale	Prior to mowing operations	Trash and debris removed from swale.
Inlet/Outlet	Inlet/outlet areas clogged with sediment and/or debris	Once per year	Material removed so that there is no clogging or blockage in the inlet and outlet areas.
Poor Vegetation Coverage	When planted vegetation is sparse or bare or eroded patches occur in more than 10% of the swale bottom.	Once per year. Typically in spring.	Vegetation coverage in more than 90% of the swale bottom . Determine why growth of planted vegetation is poor and correct that condition. Replant with plugs of vegetation from the upper slope: plant in the swale bottom at 8-inch (20.3 cm) intervals, or re-seed into loosened, fertile soil.
Vegetation Height	Vegetation height is excessive	Twice per year. Typically early summer and early fall.	Vegetation height reduced to desirable level

15 Summary and Conclusions

15.1 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 study examined the slope portion of vegetated biofilters to evaluate 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].

First, a review and synthesis of the literature relative to characteristics of highway runoff and application of BMPs utilizing vegetation were conducted. Literature derived data were used to formulate an artificial storm water runoff for subsequent application to a prototype vegetated biofilter. Also, literature derived data were integrated to develop relational graphs for percent reduction in total suspended solids versus vegetated slope and length. Second, a two-part survey instrument was developed to query state DOTs on post construction BMPs for managing highway runoff; the first part of the survey addressed all types of BMPs and the second part focused specifically on roadside vegetation. Results from this survey were entered into spreadsheets and analyzed.

The major portion of the effort was directed toward the design, development and testing of a biofilter foreslope prototype to determine: the ability to capture and treat the water quality volume, performance of the biofilter in removing typical roadway runoff contaminants, impact of slope, accumulation and retention of contaminants in the foreslope soil and vegetation, and suitability of foreslope designs to accommodate varying concentrations of runoff and/or intensity of storms.

A final component of the project included developing a field inspection sheet for vegetated biofilters and utilizing the inspection sheet at two field sites. Results from the field inspection, literature, survey and prototype testing were utilized to address performance and maintenance issues and to guide planning for subsequent field studies.

Survey responses were garnered from 39 states and one Canadian province. Slightly over half of the states reported having a design manual that addresses post-construction stormwater BMPs. As pointed out by Storey et al. [2009], several states adopt or adapt other states guidelines for BMPs and in some cases may thus perpetuate dated information and criteria. Respondents were asked to list factors used in designing BMPs; responses from highest to lowest were: first flush volume (7 responses), drainage area (6 responses), urban location (6 responses), and rainfall/runoff amounts, event rainfall, and rural location, each cited by 4 respondents; only 1 or 2 respondents listed a variety of nine other factors. Relative to specific vegetated type BMPs, 29 responded that their states were permitted to use or were considering using vegetated surfaces as a post-construction BMP with 24 indicating their use without incorporating other BMPs. Responses regarding acceptable foreslope lengths were too varied to classify; however, 6 specified a minimum length, 1 a maximum, and 8 both a minimum and a maximum. Others indicated the length depended on slope, drainage area or site conditions. Responses for slope angles were: 8 responses for < 10%, 4 responses each for 10% to 20% and 25% to 33%, and 3 selected 50% maximum. Questions on grade and width of ditch receiving the flow from the slope noted unspecified grade by 8 respondents, followed by 5 with maximum and minimum (plurality cited < 0.5% and maximum of 4%) and 5 indicating it was site specific.

Three similar prototype vegetated biofilter foreslopes were studied, each 4 ft (1.22 m) wide by 14 ft (4.27 m) long (direction of flow). Two vegetated foreslopes ("beds"), one receiving a "high" and the other a "medium" concentration storm water runoff, performed well at all slopes (8:1, 4:1, 2:1) and flows (medium and high flow storm event simulation) tested. Based on EMC calculated data, removals of TSS and the total metals (Cd, Cr, Cu, Fe, Ni, Pb and Zn) monitored in the influent flow were at or above 80%, except for Cd (75%) and Cr (78%) in the 8:1 slope, medium flow, medium concentration test. For the high and medium concentration influent Ni, and to a somewhat lesser extent Cd, tended to predominate in the dissolved form. For the high concentration test influent Zn was primarily in the suspended form but for the medium concentration Zn ranged from about a third dissolved to predominately dissolved. In the surface samples, dissolved metal concentrations were generally below influent concentrations and also often at or below detection limits.

Oil and grease removal ranged from 30% to nearly 70% for the high concentration bed and 50% to above 90% for the medium concentration bed. For the high concentration bed, deuterated alkanes, used to track the oil concentration, were removed by about 67% at the 8:1 slope and 85% at the 4:1 slope. For the medium concentration bed, removal of deuterated alkanes ranged from about 46% to 94% with the higher removal at higher influent concentrations. The high concentration bed data were influenced by difficulty in delivering the oil and deuterated alkanes to the bed; the oil and grease delivery method was improved for the medium and low concentration beds.

Results for the bed receiving low concentration flow were mixed. This was not surprising since the low influent concentrations were close to detection limits of the constituents and near surface runoff concentrations measured in baseline runs with tap water. In addition this bed had a greater infiltration rate than the other two beds, which limited the volume and number of surface samples available for analysis in the effluent. Using EMC, removals of TSS ranged from negligible to about 50%. With the exception of iron and zinc the best removal of total metals occurred at the 8:1 slope. Zinc removal was near 70 % for all slopes. Removal of Cu was about 90% at all slopes and flow. Ni removal ranged from 62% to 88% removal and Pb 55% to 78%. Cd, Cr, and Fe had negligible to up to 65%, 85%, and 75% removal, respectively, at various slopes and flow. All dissolved metals were reduced to detection limits or were removed by at least 50%. In order to be able to differentiate influent from effluent values, oil was added at a concentration of 100 mg/l followed by 20 mg/l in the second portion of the flow; removals of 70% to 90% were achieved. Deuterated alkanes in surface samples were near detection limits for all four tests with the exception of two of three samples with elevated concentrations at the 4:1 slope but half the concentration of the influent.

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, are greater than those computed for the entire runoff event.

For the high concentration bed, the particle size distribution was primarily about 1 mm (39 mil) or greater in both the influent and surface flow for the three slopes receiving medium flow; samples were not taken for the 2:1 high flow. For the medium concentration 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. For the low concentration bed, influent particle size ranged between about 1 μm (0.039 mil) to 50 μm (19 mil) for the 8:1 medium flow and 2:1 high flow tests, while the 4:1 and 2:1 medium flow tests received particle sizes from 1μm (0.039 mil) to 1000 μm (39 mil). The effluent surface particle sizes were consistently between about 1μm (0.039 mil) and 10μm (0.39 mil) for the four tests. Although there is scatter in the data, the suspended sediment in the surface runoff was comprised of larger particles in the high concentration tests than in the lower concentration tests.

EMC removals of TSS achieved with this study were compared to results integrated from the literature. From Figure 5 for natural events and from Figure 6 for simulated events, removal at the 14 ft (4.27 m) distance along the slope was 70%-75% and 75%, respectively. In this study TSS removals over the 14 ft (4.27 m) length at four slopes and two simulated storm events ranged from 88% to 97% for the high concentration tests, 93% to 98% for the medium concentration tests, and negative to 50% for the low concentration tests.

Subsequent resuspension tests at the slopes and flow rates studied indicated that for over seven runoff events following tagged suspended sediment deposition, negligible amounts of that original sediment were resuspended from the bed and released in the surface runoff. This was consistently observed for all three beds.

Data indicate that the majority of uptake of metals occurred in the vegetated root structure for the beds receiving high and medium concentration influent. For the high concentration bed, the majority of metal pollutant uptake occurred within the first 6.6 ft (2.01 m) from the inlet, and the majority of the metal mass was concentrated in the roots of the grass for all metals except lead which accumulated in the soil. Based on the core sampling locations relative to the drip line, metal concentrations, excepting Fe, peaked at about 2.2 ft (0.67 m) longitudinally. For the medium concentration flow 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. As a fraction of dry mass, Cd, Cu, Ni, and Pb exhibited the highest concentration in the roots, next highest in the grass and low concentrations in the soil, whereas concentrations of Cr and Zn were highest in grass, followed by roots (although concentrations in roots and grass were not statistically different) and then soil. On a wet mass basis, Cd, Cu, and Ni had higher accumulation in the roots, Pb and Zn had higher accumulation in the grass foliage, and Cr had about the same amount of accumulation in the grass and soil. More Fe was detected in the soil, then the roots and lowest in the grass. None of the metals had a statistically significant accumulation in grass, roots, or soil.

For the bed receiving the low concentration influent, and based on dry mass, Cd, Cu, Pb, and Zn had the highest concentration in the roots. Cr and Fe were highest in soil, followed by roots and then lowest in grass. Ni was highest in grass, then roots and lowest in soil. On a wet mass basis, Cu and Zn accumulations were highest in the roots, Pb had similar accumulation in roots and soil, and Cd and Cr accumulations were higher in the soil. Similar to the medium concentration the highest accumulation of metals was where the influent entered the bed and then generally decreased along the length of the bed with some exceptions. Results were more mixed at this lower concentration, and data were largely not statistically significant.

Preferential adsorption of some metals over others can occur depending on a number of factors such as concentration, pH, valence, ionic size, etc. Each of the components of the bed, i.e. grass, roots and soil, would have an upper maximum adsorptive capacity. More repetitive experiments would need to be conducted to arrive at more definitive adsorptive capacity for each metal.

In summary, the three prototype vegetated biofilter foreslopes provided excellent performance in removal of pollutants (seven metals and suspended material) from a high and medium concentration simulated storm water runoff. Removals of oil were more sporadic. Results of treating a low concentration runoff were mixed, which is consistent with other studies. All BMPs will have a performance threshold for treatment, and if a relatively "clean" influent enters the BMP, minimal or no treatment will be provided. Results from various tests at slopes of 8:1, 4:1, and 2:1 did not indicate declining performance with increasing slope. Integration of data from the literature showed poor correlation on removal of TSS as function of slope. During the testing period, vegetative coverage on all three biofilters was above 80% for all tests except for the 8:1 slope, medium concentration flow at 76% coverage. Data reported in the literature noted the importance of density or coverage of vegetation in removal of pollutants, e.g. Barrett et al. [2004, 2006], and Han et al. [2005]. Hence, for vegetated biofilters with more sparse vegetation it may be expected that slope would be more significant; steeper slopes would experience higher velocity of runoff flow and constituents in the flow would have less opportunity to be captured in the biofilter. This also indicates the importance of maintaining good vegetative coverage for appropriate performance of the vegetated biofilter. Assessment of accumulation of seven metals in the grass, roots and soil showed uptake of all seven metals with the roots dominating in removal of most metals for the high and medium concentration tests. The accumulation predominately occurred within seven feet of introduction of flow. Studies using soil tagged with La indicated that resuspension was insignificant. Again, the coverage of vegetation probably played a major role in this outcome. Overall within the parameters of this study, findings indicated that the foreslope portion of the vegetated biofilter plays a significant role in reducing the quantity of pollutants in the runoff.

15.2 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.

The current study needs to be expanded to include tests under dormant conditions since for Ohio the biofilter will be expected to perform during the winter. Preliminary assessment of the effects of chlorides present in winter maintenance materials could also be performed. In addition, the results from this study need to be validated with a field study.

16 Implementation

ODOT can use the information in this 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 this 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.
- Exclusion of the use of crown vetch.
- Establishment of a standard inspection schedule using a form similar to the field inspection record in Appendix D.
- 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 to implementation could include the efficacy of the biofilter during the winter season. Appropriate construction and maintenance will be important to the success of the BMP.

As discussed in Section 14.3 and Section 14.4, 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.

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Appendix A: Survey form as sent to state DOTs

OHIO UNIVERSITY

Russ College of Engineering and Technology

STATE OF OHIO DEPARTMENT OF TRANSPORTATION

Ohio Research Institute for Transportation and the Environment

Use of Vegetation as a Best Management Practice for Treatment of Pollutants in Stormwater Runoff from Roadways - Survey of State DOTs

This survey is about post-construction Best Management Practices (BMPs) used to reduce pollutant loads in stormwater runoff from linear transportation infrastructure, such as highways and roads whether in urban or rural settings. "Post-construction" means that these devices are designed to treat stormwater pollutants (e.g. metals, petroleum residue, etc.) washed off the roads in the course of regular traffic and other designed uses, such as anti-icing and ordinary maintenance, as opposed to treating and preventing the loss of soil during construction work.

This survey is being conducted as part of an Ohio Department of Transportation (ODOT) sponsored research project regarding the suitability of vegetated surfaces to meet current and near-future stormwater remediation requirements.

The following questions include items pertaining to general stormwater management practices your agency uses to meet environmental water quality requirements and questions specifically about the use of vegetated surfaces as post-construction BMPs, including both foreslopes and ditches.

Please fill in the name and contact information below for the person completing this survey.

Name: ______________________________

Title: ______________________________

Agency: ______________________________

Address: ______________________________

City: ________________ State: __________ ZIP Code: __________

Email address: ____________________ Telephone: ______________

General questions:

1. If available, please supply a copy or web link of the **design manual** that addresses **post-construction stormwater BMPs**.
   ____

2. Is pollutant load determined and used as a factor in designing BMPs? ___Yes ____No
   a. If yes, which of the following are considered as factors (check all that apply):
   _____ Typical first flush volumes. (i.e. Water Quality Volume)
   Specify: ______________________
   _____ Annual average daily traffic,
   _____ Other traffic measures (e.g. % trucks) List:___________________
   _____ Drainage area.
   _____ Cumulative annual rainfall. Specify: ______________________
   _____ Rainfall/runoff amounts. Specify: ______________________
   _____ Event rainfall. Specify: ______________________
   _____ Urban location
   _____ Rural location
   _____ Amount of anti-icing or other winter maintenance treatment
   _____ Other factors. List:____________________________________
   ____

3. If available, please supply a copy or web link of the **post-construction** stormwater BMP **maintenance manual and/or guidelines**.
   ____

The following questions specifically concern the use of vegetated surfaces as BMPs to control stormwater pollution. Vegetated surfaces may include the foreslope and backslope of a ditch and the ditch bottom.

1. Does your state's environmental resource agency permit or is it considering the use of vegetated surfaces as a post-construction BMP to provide treatment of storm water runoff?
   ____ Yes ____ No ___ No, but it is considering
   a. If yes, is it acceptable to use vegetated surfaces without incorporating other storm water post-construction BMPs? ____ Yes ____ No
   b. Are vegetated surfaces under consideration as a **stand-alone** BMP (i.e. not part of a treatment train)? ____ Yes ____ No

If vegetated surfaces are permitted for use or under consideration as a stormwater treatment BMP, please answer the following questions:

2. What foreslope/backslope slope and length ranges are considered acceptable for pollutant removal? ____

3. What ditch grade and ditch width ranges are considered acceptable for pollutant removal? ____

4. Do vegetated BMPs require the use of a roadside vegetation mix unique for BMP purposes? ____ Yes ____ No
   a. If yes, what type of vegetation is used for vegetated BMPs? __________ ____

5. Do vegetated BMPs require the use of soil type(s) that are unique for BMP purposes? ____ Yes ____ No
   a. If yes, what type of soil(s) are specified for vegetated BMPs design? ____

6. Are upkeep or maintenance activities performed after construction on vegetated surface BMPs different than routine roadside maintenance (including winter maintenance)? ____ Yes ____ No
   a. If yes, please describe: ____

7. Are there any criteria to establish a pollutant saturation level for vegetated surface BMPs? ____ Yes ____ No
   a. If yes, what are these criteria? ________________________________
   b. What steps are taken to remedy the saturation condition (e.g. replacement of the vegetation)? _________________________________
   c. How is the recovered contaminated material disposed of? ______________

8. Do you document vegetated BMP effectiveness? ____ Yes ____ No
   a. If yes, how is effectiveness documented? ____

9. Would you like to see a copy of the survey results? ____ Yes ____ No

Thank you for completing this survey.
Please return the survey by February 15, 2008 by emailing to orite@bobcat.ent.ohiou.edu

If you have any questions, please contact
Dr. Gayle Mitchell, Ph.D., P.E.
Director of the Ohio Research Institute for Transportation and the Environment
141 Stocker Center, Ohio University
Athens OH 45701
mitchelg@ohio.edu
740-593-1470

Appendix B: Survey respondents, titles, affiliations, and contact information

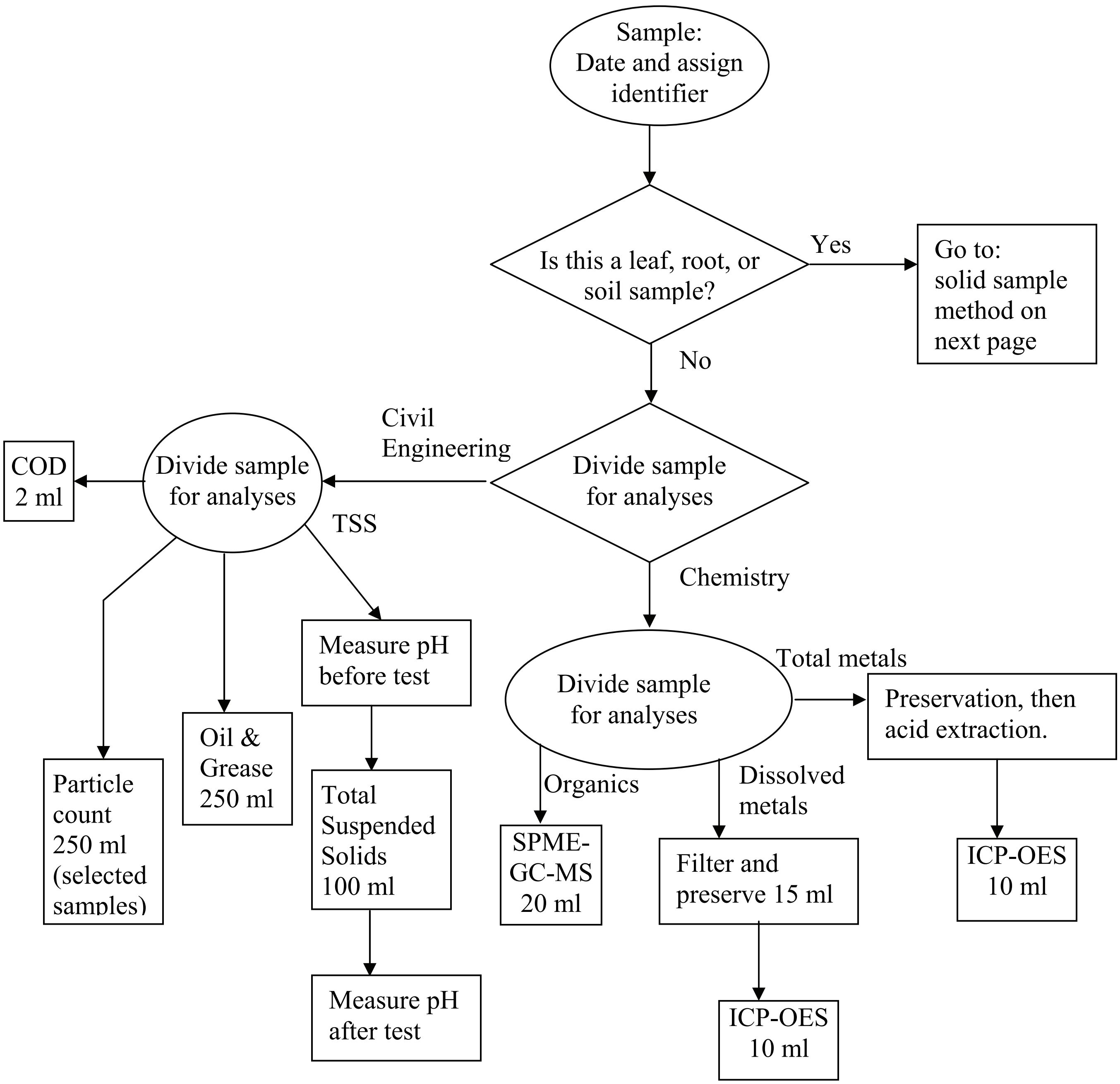
Note: states with blank entries did not respond to the survey.

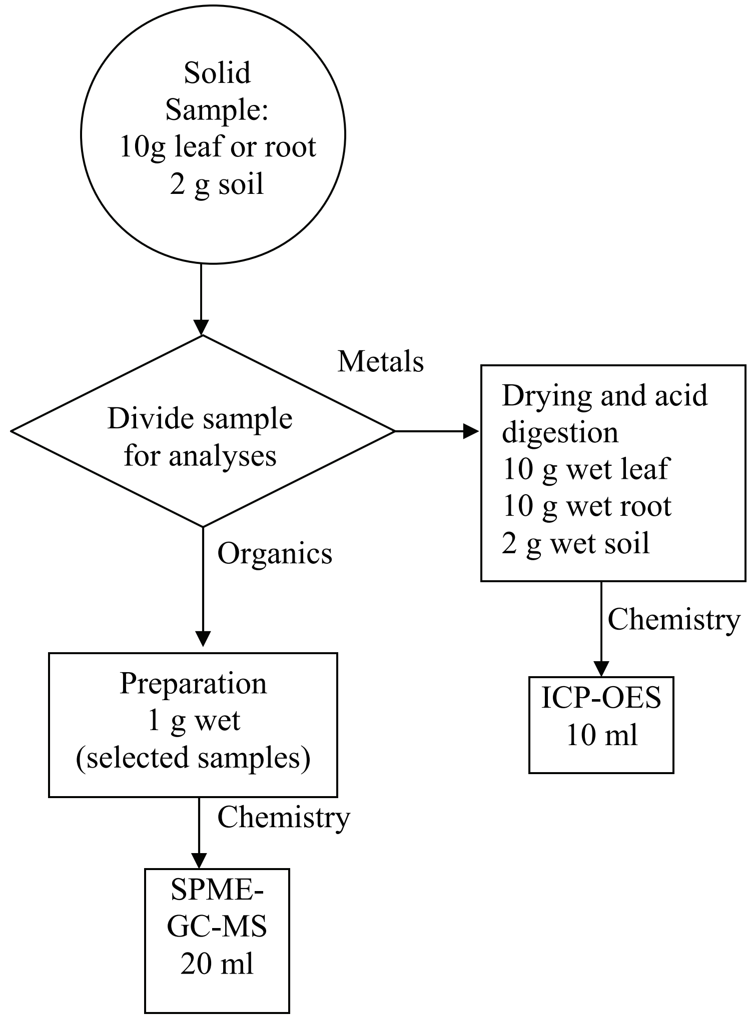
State	Name(s)	Title	Affiliation	Telephone	E-mail
AL	John Ammons	storm water permit co-ordinator	Alabama DOT (design bureau)	334-242-6105	ammonsj@dot.state.al.us
AK	Sam Lamont	Environmental Liaison Construction Section	AK-DOT&PF	907-451-5066	sam.lamont@alaska.gov
AZ	Wendy Terlizzi	Water Quality Manager	Arizona Department of Transportation	602-712-8353	wterlizzi@azdot.gov
AR	Gary Williamson	Environmental Analyst	Arkansas State Highway and Transportation Dept.	(501) 569-2230	gary.williamson@arkansashighways.com
CA	Harold Hunt	Sr. Environmental Planner	California Department of Transportation	(916) 324-2903	harold_hunt@dot.ca.gov
CO	Rick Willard	Water Quality Program Mgr	Colorado DOT	303-757-9343	richard.willard@dot.state.co.us
CT					
DE	Vincent W. Davis	Stormwater Engineer	Delaware Department of Transportation	(302) 760-2180	vince.davis@state.de.us
FL	Larry Ritchie	Environmental specialist	Florida DOT	850-414-4168	larry.ritchie@dot.state.fl.us
GA					
HI					
ID					
IL	Craig Mitckes	Roadside Maintenance Manager	Illinois Department of Transportation	217-782-2984	craig.mitckes@illinois.gov
IN					
IA	Mark Masteller	Chief Landscape Architect	Iowa DOT	515-239-1424	mark.masteller@dot.iowa.gov
KS	Scott Vogel	(no reply)	Kansas DOT	785-296-3726	vogel@ksdot.org
KY	A	Research co-ordinator	Kentucky Transportation Cabinet	502-564-3730	Jamie.Bewleybyrd@ky.gov
LA	Joubert Harris	Environmental Program Manager	LA DOTD	225-248-4141	joubertharris@dotd.la.gov
MD	Peter Newkirk	Senior Environmental Engineer	MaineDOT	207-624-3002	peter.newkirk@maine.gov
ME	Karuna Pujara	Chief, Highway Hydraulics Division	Maryland State Highway Administration	410-545-8390	kpujara@sha.state.md.us
MA					
MI	Judy Ruszkowski	Operations Environmental Engineer / Stormwater Program Manager	Michigan DOT	517-322-5698	ruszkowskij@michigan.gov
MN					
MS	Randy Beatty	vice chair Mississippi DOT		601-359-7650	randyb@mdot.state.ms.us
MO	Randy Morris	Field Materials Engineer	MoDOT	573-526-5381	Randy.morris@modot.mo.gov
MT	Eric Mason	Erosion Control, Maintenance & Construction Permitting Supervisor	Montana Department of Transportation	406-444-0802	emason@mt.gov
NE	Ronald Poe	Highway Environmental Program Manager	Nebraska Department of Roads	402-479-4499	rpoe@dor.state.ne.us

NV	Paul Frost	Chief Hydraulic Engineer	Nevada Department of Transportation	775-888-7797	pfrost@dot.state.nv.us
NH	Mark Hemmerlein	Water Quality Program Manager	New Hampshire Department of Transportation	603) 271-1550	mhemmerlein@dot.state.nh.us
NJ	Robert W. Lane	Section Chief	NJDOT	609-530-2973	robert.lane@dot.state.nj.us
NM	Reza Afaghpour	Drainage Development Engineer	New Mexico Department of Transportation	505-256-9079	reza.afaghpour@state.nm.us
NY	David R. Graves	Environmental Specialist 2	New York State Department of Transportation	518-457-9608	_dgraves@dot.state.ny.us
NC	Ms. Richardson	Environmental Consultant (URS Corporation)	North Carolina Department of Transportation.	919-461-1449	aimee_richardson@urscorp.com
ND	Tom Huncovsky	Environmental Scientist	North Dakota Department of Transportation	701-328-4824	thuncovsky@nd.gov
OH					
OK	Michele Dolan	Storm Water Coordinator	OK Dept. of Transportation	405-521-6771	mdolan@odot.org
OR	Jeff Moore	Environmental Program Coordinator	Oregon Dept. of Transportation	(503) 731-8289	Jeffrey.T.Moore@ODOT.state.or.us
PA					
PR					
RI					
SC	Ray Vaughan	Storm Water Manager	SCDOT	803-737-6378	vaughanrh@scdot.org
SD	Dave Graves	Environmental Engineer	SDDOT	605-773-5727	dave.graves@state.sd.us
TN	Ali R. Hangul	C. E. Manager I	TDOT, Design Division	(615)741-0840	ali.hangul@state.tn.us
TX	Amy Foster	Environmental Specialist	TxDOT	512-416-2649	afoster@dot.state.tx.us
UT	Jerry Chaney	Environmental Engineer	Utah Dept. of Transportation	(801) 965-4317	jchaney@utah.gov
VT	Jonathan Armstrong	Stormwater Management Engineer	Vermont Agency of Transportation	802-828-1332	jon.armstrong@state.vt.us
VA	Roy T. Mills	State Hydraulics Engineer	VDOT	804-786-9013	roy.mills@vdot.virginia.gov
WA					
WV	Laura A. Conley-Rinehart & Charles R. Riling, Jr	Assist. to the State Hwy Engr & Special Proj Environmental Coord, respectively	WVDOT	304-558-2804	criling@dot.state.wv.us, lconley-rinehart@dot.state.wv.us
WI					
WY	John F. Samson	Agronomist	WYDOT	307-777-4416	john.samson@dot.state.wy.us
AB - CD	Darren Carter		Alberta Infrastructure and Transportation	780.644.4499	darren.carter@gov.ab.ca

Notes:
IA sent an email stated that “I did not feel we have enough experience for me to competently complete your survey”.
AB-CD = Alberta, Canada

Appendix C: Sample analysis protocol





Note: Civil Engineering will conduct acid digestion of samples prior to delivery to Chemistry.

Appendix D: Field Inspection Record

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

Vegetated Biofilter site inspection record

Site characterization

Inspector(s): ________________

Site location (road, city): ______________________________________ Date: ____________

Mile Marker: ____________ GPS coordinates: ____________________elevation: _________ft

Type of road (# lanes, lane width, etc): _______________ Surface: AC / PCC / other_________

Date of last resurfacing/paving: _______________ Surface condition: _____________________

Drainage system notes (in addition to BMP): ____

Rural / urban / suburban area. Contributing drainage area: ___________________________ ft^2

Land use in area: _____________________________ USGS basin development factor: ______

ADT (from Tech services web site): _________ Traffic conditions during visit: _____________

Weather conditions during visit: ________________ Antecedent dry days: ________________

Slope instabilities in area? ____

Other site features of note: ____

____

BMP characterization

Age since construction or construction date: ____

Date of last maintenance (garage): ______________ Appearance of site: __________________

Foreslope average/typical dimensions: Width (|| road): _________ft Length (⊥ road): _______ft

Slope: _______% Grass coverage: __________% Grass height: _________in

Grass species: _____________________________ Other species/weeds: ___________________

Ditch average/typical dimensions: Length (|| road): ________ft Width (⊥ road): __________ft

Slope: ______________% Grass coverage: __________% Grass height: _________in

Grass species: _____________________________ Other species/weeds: ___________________

Where does ditch drain (if observable): _______________ __________________________

Depth of water (if standing water): _________________in Sludge/sediment: _____________

Description of **adjacent drainage area** (may include visual estimate of slope and area, use of land, type of vegetation (if any): ____

____

Use of adjacent land: ____

Describe off-road potential sources of runoff: ____

____

1/2

Vegetated Biofilter site inspection record

Sketch of BMP:

Sampling

Samples collected (list number gathered, if any, and location notes):

Sampling date: ________________________________Sampling personnel _______________

Cores from foreslope __________________________ Locations ______________________

Cores from ditch _________________________ Locations ___________________________

Loose vegetation _________________ Locations ___________________________________

If raining, grab water samples:

pavement ____________________ Locations ______________________________

foreslope ____________________ Locations ______________________________

ditch ________________________ Locations ______________________________

Additional notes and sketches:

Appendix E: Details on preparation of artificial stormwater runoff.

Equation 1 (liquid standards; Cd, Cr, Cu, Ni, Pb, and deuterated standards):

(Initial Concentration)(Initial Volume) = (Final Concentration)(Final Volume)
--or--
(C1)(V1)=(C2)(V2)

Equation 2 (solid standards; Zn and Fe):
example of Fe for high concentration (16.5 ppm) in 45 gal (170.3 L)
Pt.1-

$$16.5\frac{mg}{L} * 1\frac{g}{1000mg} * 170.3\ L = 2.81\ g\ Fe$$

Pt. 2-

$$2.81\ g\ Fe * \frac{1mol\ Fe}{55.845\ g\ Fe} * \frac{1\ mol\ FeN_3O9 * H_2O}{1\ mol\ Fe} * \frac{404\ g\ FeN_3O9 * 9H_2O}{1\ mol\ FeN_3O9 * 9H_2O} = 20.3\ g\ FeN_3O9 * 9H_2O$$

Please refer to the table below to see the actual amounts of each metal added in the stock solution. On site, the 50 gal (189 L) container was filled with ~20 L (~5 gal) of domestic tap water from a hose and the suspended solids. The 3 L (0.79 gal) stock solution was then added to the 50 gal (189 L) container. The container with the stock solution was rinsed out a few times with the tap water, and those rinses were also added to the 50 gallon (189 L) container. The 50 gallon (189 L) container was then filled up with the water from the hose to the appropriate volume for each experiment. The artificial stormwater runoff was then mixed for about three hours before conducting the experiment.

It is important to note that the final concentrations of the high and medium artificial runoff solutions remained the same for all of the experiments except for the nickel. For all of the runs, the medium concentration stayed the same at 0.475 ppm of Nickel in the water solution. For the high concentration runs of 8:1 medium flow, 4:1 medium flow, and 2:1 high flow the final concentration in solution was as expected at 2.375 ppm. However, for the 2:1 medium flow run, the standard was running low, and only 29 mL (0.98 fl oz.) of Ni standard was added to the high concentration solution. Thus giving a final concentration for the Ni in the 2:1 medium flow experiment to be 1.7 ppm.

Table: Values used in calculating the volumes of standards needed to make the artificial road runoff at medium and high concentrations. A) High concentrations in 45 gal (170.3 L) of water used for all tests, B) Medium concentrations in 30 gal (113.6 L) of water used for 8:1, 4:1. And 2:1 medium flows, C) Medium concentrations in 40 gal (151.4 L) of water used for 2:1 high flow.

A. High Concentration (8:1 medium flow, 4:1 medium flow, 2:1 medium flow, and 2:1 high flow)

	Initial Conc. (ppm)	Units of Std. Added	Initial Volume (L)	Final Conc. (ppm)	Final Volume (L)
Cadmium (Cd)	10,000	L	*0.0085*	0.5	170.3
Chromium (Cr)	10,000	L	*0.0106*	0.625	170.3
Copper (Cu)	10,000	L	*0.0150*	0.875	170.3
Iron (Fe)	N/A	g	*20.3*	16.50	170.3
Nickel (Ni)	10,000	L	*0.0404*	2.375	170.3
Lead (Pb)	10,000	L	*0.0915*	5.375	170.3
Zinc (Zn)	N/A	g	*1.32*	1.700	170.3
N-Eicosane ($C_{20}D_{42}$)	10,000	L	*0.0017*	0.100	170.3
N-Tetracosane ($C_{24}D_{50}$)	10,000	L	*0.0017*	0.100	170.3
N-Triacontane ($C_{30}D_{62}$)	10,000	L	*0.0017*	0.100	170.3

B. Medium Concentration (8:1 medium flow, 4:1 medium flow, 2:1 medium flow)

	Initial Conc. (ppm)	Units of Std. Added	Initial Volume (L)	Final Conc. (ppm)	Final Volume (L)
Cadmium (Cd)	10,000	L	*0.0011*	0.1	113.6
Chromium (Cr)	10,000	L	*0.0014*	0.125	113.6
Copper (Cu)	10,000	L	*0.0020*	0.175	113.6
Iron (Fe)	N/A	g	*6.3*	7.70	113.6
Nickel (Ni)	10,000	L	*0.0054*	0.475	113.6
Lead (Pb)	10,000	L	*0.0122*	1.075	113.6
Zinc (Zn)	N/A	g	*0.22*	0.425	113.6
N-Eicosane ($C_{20}D_{42}$)	10,000	L	*0.000568*	0.050	113.6
N-Tetracosane ($C_{24}D_{50}$)	10,000	L	*0.000568*	0.050	113.6
N-Triacontane ($C_{30}D_{62}$)	10,000	L	*0.000568*	0.050	113.6

C. Medium Concentration (2:1 high flow)

	Initial Conc. (ppm)	Units of Std. Added	Initial Volume (L)	Final Conc. (ppm)	Final Volume (L)
Cadmium (Cd)	10,000	L	*0.0015*	0.1	151.4
Chromium (Cr)	10,000	L	*0.0019*	0.125	151.4
Copper (Cu)	10,000	L	*0.0026*	0.175	151.4
Iron (Fe)	N/A	g	*8.4*	7.70	151.4
Nickel (Ni)	10,000	L	*0.0072*	0.475	151.4
Lead (Pb)	10,000	L	*0.0163*	1.075	151.4
Zinc (Zn)	N/A	g	*0.29*	0.425	151.4
N-Eicosane ($C_{20}D_{42}$)	10,000	L	*0.000757*	0.050	151.4
N-Tetracosane ($C_{24}D_{50}$)	10,000	L	*0.000757*	0.050	151.4
N-Triacontane ($C_{30}D_{62}$)	10,000	L	*0.000757*	0.050	151.4

Appendix F: 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: Monique Evans
Sponsor(s): ODOT
Study Start Date: October 15, 2007
Study Completion Date: May 15, 2010
Study Duration: 31 Months
Study Cost: $391,826.31
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

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

RESEARCH DELIVERABLES:
Final Report, Executive Summary

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.

The current study needs to be expanded to include tests under dormant conditions since for Ohio the biofilter will be expected to perform during the winter. Preliminary assessment of the effects of chlorides present in winter maintenance materials could also be performed. In addition, the results from this study need to be validated with a field study. It is possible that a field study may lead to significant changes in biofilter design which could include elimination of the need for a wide bottom swale.

PROJECT PANEL COMMENTS:

IMPLEMENTATION STEPS & TIME FRAME:
ODOT can use the information in this 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 this 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.
- Exclusion of the use of crown vetch.
- Establishment of a standard inspection schedule using a form similar to the field inspection record in Appendix D of the project report.
- 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 to implementation could include the efficacy of the biofilter during the winter season. Appropriate construction and maintenance will be important to the success of the BMP.

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.

If it is determined that further research phases, such as a field study, are needed before full implementation of vegetated biofilters in the field, the implementation plan for this phase will be limited accordingly.

EXPECTED BENEFITS:

This phase of the research project is anticipated to provide the following benefits:

- Guidance on how to maintain vegetated biofilters, based primarily on the literature search and survey results.
- A form and method for inspecting vegetated biofilters in place in the field.

The recommended validation phase studying both the foreslope and ditch in the field is anticipated to provide the following additional benefits:

- The basis for a standardized design of vegetated filter foreslopes to mitigate costly retrofits and bring pollutant removal levels up to standards
- Facilitate OEPA evaluation of vegetated biofilters as a best management practice
- Minimize or eliminate the need for costly right-of-way land purchases and reduce the need for constructing basins for runoff treatment.
- Provide design recommendations and revisions to the ODOT *Location and Design Manual, Volume 2*.
- Provide a methodology for identifying existing roadside vegetation that with little or no modification can be counted as instances of best management practice for vegetated biofilters for stormwater runoff.

Verified design criteria, such as slopes, will be identified. The processed water quality from the foreslopes of vegetated biofilters will be determined.

EXPECTED RISKS, OBSTACLES, & STRATEGIES TO OVERCOME THEM:

There are no immediate impediments to implementation of the first set of items. The second set will require a second phase of the research to be conducted.

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: ________________

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