Report No. K-TRAN: KU-03-5
FINAL REPORT

TREATMENT OF CONTAMINATED ROADWAY RUNOFF USING VEGETATED FILTER STRIPS

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January 2009

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM
BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION
KANSAS STATE UNIVERSITY
UNIVERSITY OF KANSAS

KANSAS
DEPARTMENT OF TRANSPORTATION

1 Report No.	2 Government Accession No.	3 Recipient Catalog No.
K-TRAN: KU-03-5		

4 Title and Subtitle	5 Report Date
Treatment of Contaminated Roadway Runoff Using Vegetated Filter Strips	January 2009
	6 Performing Organization Code
7 Author(s) Tatsuji Ebihara, LFR Levine Fricke C. Bryan Young, Ph.D., P.E., Vibhuti Tiwari, Lisa M. Agee	8 Performing Organization Report No.
9 Performing Organization Name and Address The University of Kansas Department of Civil, Environmental and Architectural Engineering 2150 Learned Hall, 1530 W 15th Street Lawrence, Kansas 66045-7609	10 Work Unit No. (TRAIS)
	11 Contract or Grant No. C1363
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Materials and Research 700 SW Harrison Street Topeka, Kansas 66603-3745	13 Type of Report and Period Covered Final Report August 2002 - Fall 2008
	14 Sponsoring Agency Code RE-0319-01

15 Supplementary Notes
For more information write to address in block 9.

16 Abstract

The overall goal of this field study was to evaluate the potential effectiveness of vegetated highway embankments as a stormwater runoff best management practice (BMP) for retention of metals, polycyclic aromatic hydrocarbons (PAHs), and particulates. The study characterized roadway sediment particulate matter, annual pollutant mass loading, and long-term pollutant retention for three field sites in eastern Kansas. The field study indicated that pollutant retention was primarily a surficial phenomenon, limited to the top 0 to 2 inches of highway embankment soils. Effectiveness of vegetated embankments for net particle retention was found to be greater than 70% for particles of 0.020 mm or greater. The 18 ft long vegetated highway embankments evaluated in this study were effective stormwater runoff BMPs for zinc with 42 to 100% long-term pollutant mass retention. Moderate performance was observed for pyrene and chrysene with 20 to 100% mass retention. Vegetative embankments were less effective for copper and benzo(a)pyrene with 9 to 42% mass retention. The key benefits of utilizing highway embankments for runoff control include cost-effectiveness relative to other engineered systems and compatibility with roadway design and maintenance requirements. While specific pollutant mass retention was observed to be variable and dependent on metal or PAH properties in runoff, the overall result is a significant reduction in pollutant mass to the local watershed, particularly when embankments are greater than 30 to 45 ft in length.

17 Key Words	18 Distribution Statement
stormwater runoff, vegetative filter strips, embankments	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19 Security Classification (of this report)	20 Security Classification (of this page)	21 No. of pages	22 Price
Unclassified	Unclassified	52	

Form DOT F 1700.7 (8-72)

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

January 2009

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

The overall goal of this field study was to evaluate the potential effectiveness of vegetated highway embankments as a stormwater runoff best management practice (BMP) for retention of metals, polycyclic aromatic hydrocarbons (PAHs), and particulates. The study characterized roadway sediment particulate matter, annual pollutant mass loading, and long-term pollutant retention for three field sites in eastern Kansas. The field study indicated that pollutant retention was primarily a surficial phenomenon, limited to the top 0 to 2 inches of highway embankment soils. Effectiveness of vegetated embankments for net particle retention was found to be greater than 70% for particles of 0.020 mm or greater. The 18 ft long vegetated highway embankments evaluated in this study were effective stormwater runoff BMPs for zinc with 42 to 100% long-term pollutant mass retention. Moderate performance was observed for pyrene and chrysene with 20 to 100% mass retention. Vegetative embankments were less effective for copper and benzo(a)pyrene with 9 to 42% mass retention. The key benefits of utilizing highway embankments for runoff control include cost-effectiveness relative to other engineered systems and compatibility with roadway design and maintenance requirements. While specific pollutant mass retention was observed to be variable and dependent on metal or PAH properties in runoff, the overall result is a significant reduction in pollutant mass to the local watershed, particularly when embankments are greater than 30 to 45 ft in length.

ACKNOWLEDGMENT

This project was supported by the Kansas Department of Transportation through the K-TRAN Cooperative Transportation Research Program. The authors sincerely appreciate this support. Mr. Rodney D. Lacy, P.E., of KDOT deserves special thanks for this contribution as project monitor.

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CHAPTER 1 - INTRODUCTION

1.1 Background

Heavily traveled multi-lane divided highways yield stormwater runoff containing hydrocarbons, suspended solids, and heavy metals. These pollutants may impact local water bodies if runoff control measures are not implemented. Best management practices (BMPs) have been suggested for treating runoff from highways; perhaps the most feasible BMP is the use of vegetated filter strips (VFSs). Existing highway embankments and medians are often well suited for use as filter strips. Although vegetated filter strips have been suggested as a stormwater runoff best management practice (BMP), individual storm-event pollutant removal performance has been highly variable in previous documented studies. Few field studies have assessed the long-term pollutant retention capabilities of vegetated buffers that are integrated with highway design and construction.

1.2 Study Objectives

The primary objective of this study was to evaluate the long-term retention of heavy metals and polycyclic aromatic hydrocarbons (PAHs) by existing vegetated highway embankment soils in eastern Kansas. In order to meet this objective, the study sought to a) characterize highway runoff in eastern Kansas, b) characterize metals and PAH concentrations in highway sediment, c) evaluate the performance of vegetated filters for removal of suspended solids, and d) study the long-term retention of metals and PAHs by existing highway embankments. These four secondary objectives were met through a series of field experiments and laboratory analyses.

1.3 Overview

This report consists of five chapters. A review of the extant literature is presented in Chapter 2. The literature summary focuses on highway runoff characterization and removal efficiency of vegetated filter strips. Chapter 3 develops the methodology for the research, including field and laboratory procedures. Chapter 4 presents results for all phases of the research, while Chapters 5 contains discussion, recommendations, and conclusions.

CHAPTER 2 - LITERATURE REVIEW

2.1 Runoff Characterization

Highway runoff often contains a wide variety of pollutants, including some caused by vehicular traffic, highway maintenance, and pavement degradation (Pengchai et al., 2005). Prior research indicates that vegetated filter strips (VFS) may remove and retain a significant fraction of these pollutants. In assessing VFS effectiveness, it is important to understand the site-specific composition of highway runoff and to estimate pollutant mass loadings.

A number of published reports document the wide range of regional and event-based variability in the composition of highway runoff with regard to total suspended solids and heavy metals. Table 2.1 contains average heavy metals concentrations in highway runoff as found in the existing body of literature. A few of these sources are summarized here.

Barrett et al. (1998a) document concentrations and estimated annual loads for thirteen constituents, including four heavy metals. Highway runoff was collected for 98 events from three sites in the Austin, Texas, area during the period September 1993 through May 1995. Wu et al. (1998) documented fourteen constituent concentrations for 31 events at three sites in the Piedmont region of North Carolina over the period August 1995 through July 1996. Constituents monitored included five heavy metals and oil and grease. Sansalone and Tribouillard (1999) and Sansalone et al. (1998) thoroughly characterized the physical characteristics of solids in roadway runoff for thirteen events at one location in Cincinnati, Ohio. Pagotto et al. (2000) reported on highway runoff quality as a function of pavement type for a French highway.

Few papers have published results for concentrations of polycyclic aromatic hydrocarbons (PAHs) in highway runoff, therefore regional and site-specific variability in mass loading is not well understood. Pengchai et al. (2005) present analysis of 12 PAHs for 18 road dust samples collected at eight locations in Tokyo, Japan. Their analysis identified probable origins for the PAHs based on relative concentrations for 11 potential sources. Smith et al. (2000) collected and analyzed 42 samples from four sites in Virginia, including a highway off ramp, a gas station, and parking lots. Samples were analyzed for sixteen individual PAHs. Shinya et al. (2000) reported concentrations for 9 metals and fifteen 3- to 6-ring PAHs in runoff from an urban highway in Osaka, Japan.

Table 2.1a: Summary of Literature Values for Heavy Metals Concentrations in Highway Runoff.

	Barrett et al., 1998a[1]	Driscoll et al., 1990[2]	USEPA, 1983[3]	Wu et al., 1998[4]	Irish et al., 1995[5]
Cadmium (mg/L)	NR	.010-.030	NR	0.0025	NR
Chromium (mg/L)	NR	NR	NR	NR	NR
Copper (mg/L)	.007-.037	.022-.054	0.034	.0025-.015	.006-.049
Lead (mg/L)	.003-.053	.080-.400	0.144	.006-.015	.016-.123
Manganese (mg/L)	NR	NR	NR	NR	NR
Zinc (mg/L)	.024-.222	.080-.329	0.16	NR	NR

[1]Austin, Texas. Three sites on the MoPac expressway were monitored with average daily traffic (ADT) ranging from 8,780 to 58,150 vehicles per day. Values reported are the range of the median of event mean concentrations (EMCs) for the three sites.

[2]Nationwide. As cited by Wu et al. (1998). Values reported are the median of EMCs for rural (ADT < 30,000) and urban (ADT >30,000) roads.

[3]Nationwide. As cited by Barrett et al. (1998a).

[4]Charlotte, North Carolina. Three sites monitored on highways with ADT ranging from 5,500 to 25,000. Values reported are the range of the median EMCs for the three locations monitored.

[5]Austin, Texas. As cited by Wu et al. (1998). Median EMCs are reported.

Table 2.1b: (continued): Summary of Literature Values for Heavy Metals Concentrations in Highway Runoff.

	Shinya et al., 2000[6]	Pagotto et al., 2000[7]	Kayhanian et al., 2003[8]	Thomson et al., 1997[9]
Cadmium	.001-.003	.00028-.00088	0.0009	0.0017
Chromium	.002-.010	NR	0.0088	0.0131
Copper	.039-.100	.020-.030	0.0513	0.0465
Lead	.017-.039	.0087-.040	0.0796	0.207
Manganese	.056-.109	NR	NR	NR
Zinc	.427-1.19	.077-.288	0.203	0.174

[6]Osaka, Japan. An elevated highway with an ADT 75,000 was monitored during four storms. Values reported are the range of the event mean concentrations (EMCs) for the four events.

[7]Nantes, France. Runoff was monitored from an asphalt-paved bridge approach for one year and then for one year after the surface was replaced with porous pavement. The ADT for the site is 12,000. Values reported are the range of the annual mean metals concentrations for the conventional and porous pavements.

[8]California (1997-2001). Mean concentrations for the 4-year, multi-site study are presented.

[9]Minneapolis, Minnesota. Runoff was analyzed from an 21 acre site on I-94 that was 55% impervious. Mean values are reported here.

2.2 Vegetated Filter Strips for Pollutant Removal

The benefits of vegetated filter strips for treatment of stormwater pollutants were originally identified from experience with agricultural runoff (e.g., Barfield et al., 1979). The benefits of VFSs for treatment of urban and highway runoff were quickly recognized and buffer strips have been recommended as a BMP for roadway runoff for over two decades (Field, 1985; Schueler, 1987). Multiple studies are available that document event-based removal rates for total suspended solids (TSS), and in this regard examples from the agricultural literature are useful.

Dillaha et al. (1989) studied the impact of buffer length on TSS and nutrient removal for agricultural runoff. They documented TSS removal rates on the order of 70 to 84% for buffers 15 and 30 ft in length. Magette et al. (1989) documented 66%

removal of suspended sediment for buffer strips 15 ft in length. Kaighn and Yu (1996) observed an average removal of 64% for TSS over three storm events. Hook (2003) evaluated the impact of vegetation type, buffer width, stubble height, and slope using 26 plots. Hook's study concluded that buffer width strongly affects sediment retention, and that vegetation type and slope had only moderate impact. Mean retention of sediment in that study ranged from 63% to over 99%, with 18 ft buffer retention ranging from 94% to 99%. Robinson et al. (1996) studied sediment removal over two VFS plots with slopes of 7% and 12%. Mean sediment removal over the first 10 feet of VFS ranged from 70% to 80%, while a 30 ft strip removed over 85% of sediment from the runoff. The primary vegetation for both plots was brome grass. Lee et al. (2000) conducted a study to evaluate sediment and nutrient removal for a multispecies riparian buffer. Their study used simulated rainfall over bare cropland to compare runoff for plots without a VFS, with a 23 ft switchgrass VFS, and with a 53 ft switchgrass-woody plant VFS. The switchgrass buffer retained 70% of incoming sediment while the multispecies buffer removed more than 92% of sediment. Another study by Lee et al. (2003) reported higher sediment removal rates for the same VFSs (95% for the switchgrass buffer and 97% for the multispecies buffer).

Although the agricultural literature has a tremendous head start on evaluating VFS effectiveness, there are some studies that have evaluated the effectiveness of VFS for filtering highway runoff. Barrett et al. (1998b) tested the ability of vegetated embankments and swales to treat highway runoff. Their study evaluated two medians on major highways. These sites differed significantly in slope and vegetation, but behaved similarly with removal of sediment in excess of 85%. The majority of this

removal occurred on the vegetated embankments. Barrett et al. (1998b) suggested that medians with side slopes at least 24 ft in length with average slopes less than 12% are effective BMPs. Kaighn and Yu (1996) also tested the sediment removal efficiency of grassy swales. Their study found mean removal efficiencies for two grassy swales of 30% and 49% for suspended solids. Removal of total zinc was only 11% and 13% for these two swales. Kaighn and Yu (1996) also tested removal efficiency for a 9.8 ft buffer strip and found that the average removal rate for solids over three storms was 64%. Lantin and Alderete (2002) documented preliminary results for a study of the effectiveness of two existing highway embankments for pollution removal. Their study found that even steep vegetated embankments (slopes of 50% and 52%) can be effective for sediment removal. Removal efficiency was reported as 64% and 72% for the two slopes.

A few studies have focused on the long-term retention of metals and PAHs as a method for assessing BMP performance. Mikkelsen et al. (1997) studied the accumulation of metals and PAHs in two highway runoff infiltration systems. Their work indicated that such systems can be effective traps for sediment, metals, and PAHs. Mikkelsen et al. (1997) also stated that the stormwater BMPs evaluated do not appear to present risk for groundwater contamination, but attention should be given to the build-up of contaminants in the surface soils. Dierkes and Geiger (1999) evaluated soil retention of highway runoff pollutants in Germany and found that heavy metals are trapped in the surface soils of highway embankments, but reported that effluent concentrations of lead and cadmium were not detectable and that concentrations of zinc and copper were within drinking water quality limits.

CHAPTER 3 - METHODOLOGY

This study characterized roadway pollutant mass loadings, retained pollutant profiles of vegetated highway embankments, and polystyrene microsphere removal in field sites with mature vegetation growth. Methodology for each phase of the study is described below.

3.1 Pollutant Mass Loading

Eleven storm events were sampled for metals and PAHs from two interstate highway sites in Johnson County, Kansas. These sites were selected as representative locations based on highway configuration and geometry, pavement type, and embankment characteristics. Site selection also accounted for personnel safety and accessibility. Table 3.1 describes the three sites: two where runoff was sampled (R1 and R3) and a third (R2) that was targeted for runoff sampling but the collection apparatus was stolen prior to runoff characterization at this location. The embankments at all three sites listed in Table 3.1 were sampled for pollution retention analysis. Physical embankment characteristics are presented in Table 3.2. Figures 3.1 through 3.3 show aerial photographs of the field sites R1 through R3.

Table 3.1: Site Characteristics

Site	Location	Average Daily Traffic Volume (vehicles)	Drainage Area (ft^2)	Pavement Slope (ft/ft)	Lanes of Traffic
R1	I-435 E, mile 79.6	132,000	600	0.057	3
R2	I-435 W, mile 83.2	60,000	1000	0.032	5
R3	I-35 N, mile 226.1	134,000	500	0.029	3

Table 3.2: Vegetated Embankment Characteristics

Site	Embankment Properties		
	Slope (ft/ft)	Length (ft)	Vegetative Cover (%)
R1	0.11	45	70
R2	0.077	42	90
R3	0.13	45	80

Runoff at sites R1 and R3 was intercepted at the pavement edge and routed via a 24 ft long chute to a weir box using a collector constructed of polyvinyl chloride (PVC) sheet. Figure 3.4 shows a schematic of the sampling setup. Figures 3.5 and 3.6 show photographs of the collection apparatus installed at site R1. The weir box employed a Natural Resources Conservation Service (NRCS) HS flume for flow measurement. An ISCO Model 3700 automatic sampler equipped with an ultrasonic water level probe collected flow-proportional runoff composite samples from the weir box (200 mL for every cubic foot of flow through the flume). Samples were transferred to one-liter glass bottles and were acid preserved immediately at the site and stored at 39°F.

Rainfall totals for the eleven storms ranged from 0.47 to 4.14 inches as observed by adjacent ALERT-type raingages operated by Overland Park, Kansas. Runoff measured at the weir box ranged from 12 to 64 ft^3.

In addition to collecting runoff at sites R1 and R3, highway sediment traps were deployed on I-435 near mile marker 82. Traps were installed in multiple stormwater inlets that collect runoff along the highway median barrier. Traps consisted of three nested filters of differing mesh sizes (18, 50, and 200 using standard U.S. mesh size). These traps were custom designed and built to fit the stormwater inlets. Figure 3.7 shows a schematic of the sediment trap and Figure 3.8 shows a photograph of a trap fit

to a storm drain. These traps were checked periodically and removed when full. Sediment that was collected was dried at 221°F, sieved to six different particle size classes, and analyzed for metals and hydrocarbon content.

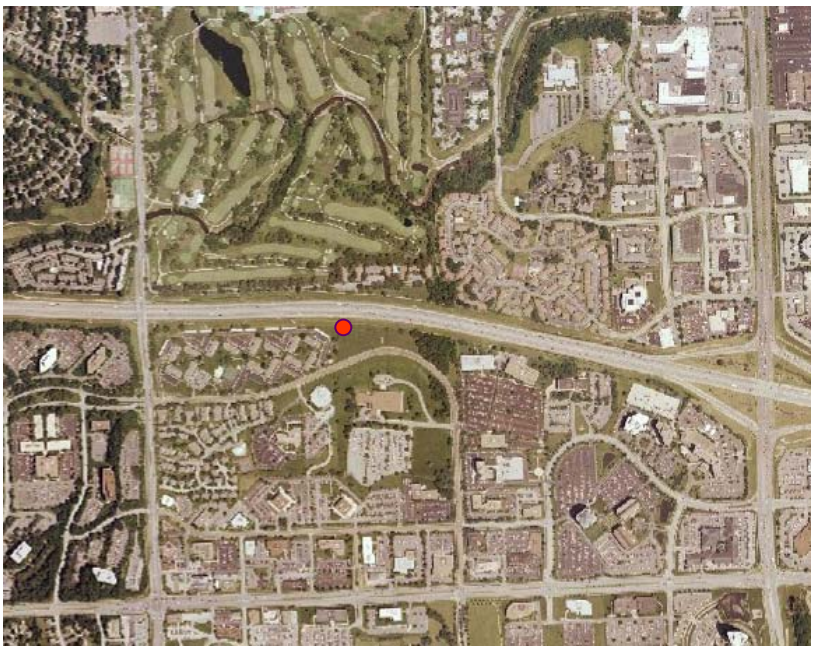

Figure 3.1: Runoff Site R1 on I-435.

Figure 3.2: Runoff Site R2 on I-35.

Figure 3.3: Runoff Site R3 on I-435.

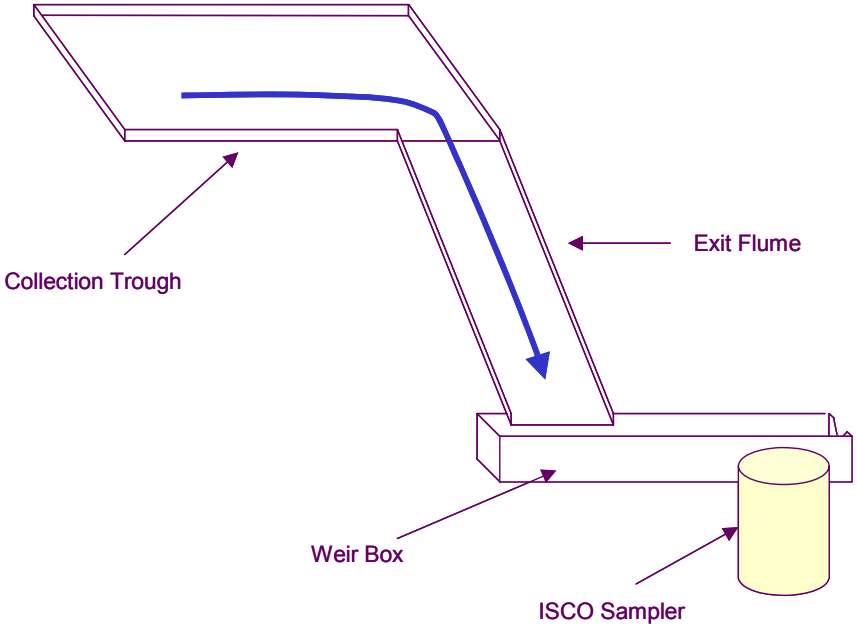

Figure 3.4: Runoff Collection Apparatus.

Figure 3.5: Collection Trough Next to Highway Shoulder.

Figure 3.6: Collection Chute, Weir Box, and ISCO Sampler.

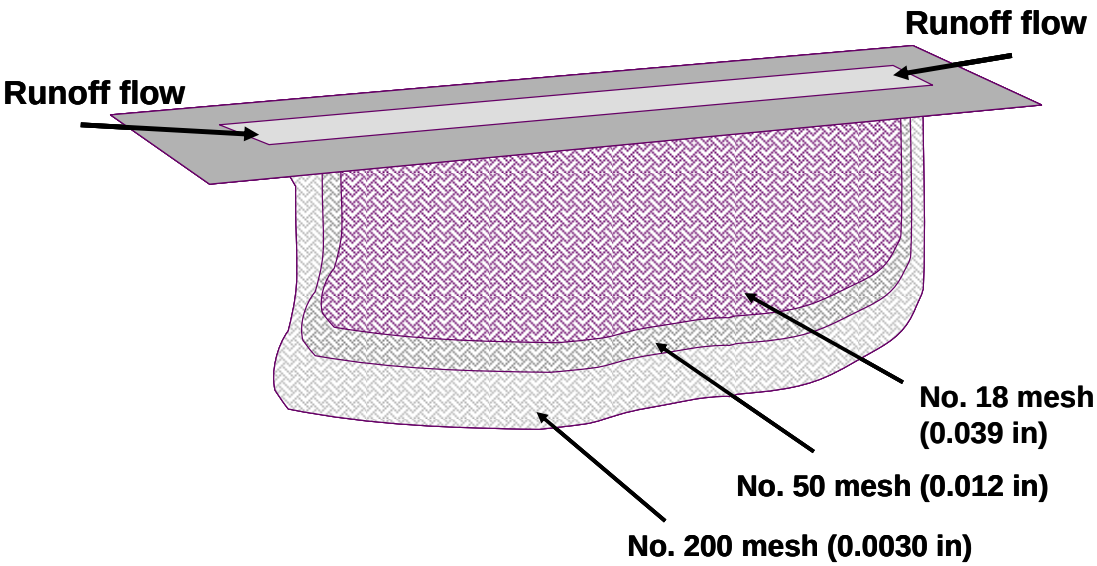

Figure 3.7: Sediment Trap Schematic.

Figure 3.8: Sediment Trap Installed in Storm Sewer Inlet Grate.

3.2 Embankment Pollutant Retention

Highway embankment soil samples and background soils were collected from the highway sites at three different soil depths (0.0 to 0.4 inches, 2.0 to 2.4 inches, and 3.9 to 4.3 inches). Soil samples were collected from a 9 ft by 18 ft area immediately adjacent to the paved highway. Samples were collected from random locations within each square yard of the sampling area at the three different depths listed above to assess distribution of pollutant concentration with depth and proximity to the paved road surface. Soil samples were taken using 2-inch diameter drive tube (Humboldt Manufacturing C., Norridge, Illinois USA). Soil samples from each depth interval, were sieved through a U.S. No. 10 sieve, and the samples were stored in 20 mL pre-cleaned glass vials and stored at 39° F. Six background samples were collected from an area near Site R1 that was not exposed to highway runoff and located at a distance of at least 45 ft from the paved highway surfaces. Sites R2 and R3 did not have areas suitable for background samples within 50 ft of the roadway surface, as all vegetated areas were exposed to highway runoff.

3.3 Controlled Field Experiments

Controlled field experiments were conducted on established vegetated embankment sites at the University of Kansas Nelson Environmental Study Area (NESA) with similar vegetation and flow channeling characteristics to field highway embankment sites. Fluorescent polystyrene latex microspheres (Polysciences Inc., Warrington, Pennsylvania, USA), 0.003, 0.020 and 0.090 mm diameter, were applied to six replicate field strips (4 ft long by 1 ft wide) with a single runoff application per strip. Figure 3.9 shows a set of replicate strips. The field strips were subjected to two

additional runoff applications without microspheres to determine net microsphere resuspension.

Runoff was applied using two Nalgene tanks in series to provide a realistic time distribution of runoff. Flow from the 30 gallon head tank to the 7 gallon lower tank was restricted with a 1/8 inch diameter orifice. Figure 3-10 displays the dual head tank arrangement. Flow from the 7 gallon tank was uniformly distributed along the top of the field strip using a T-shaped flow diffuser. The flow diffuser was constructed of ½ inch diameter CPVC pipe and had eight evenly spaced 1/8 inch diameter outlet holes. Figure 3.11 displays the T-shaped diffuser. For each application, the head tank was filled to a level of 20 gallons while the 7 gallon tank started empty. The volume was selected to represent highway runoff for a 1.39 inch rainfall depth. This depth is the 90th percentile daily rainfall for the Kansas City area (Young and McEnroe, 2002). The actual duration of flow was approximately 20 minutes, making the runoff application similar to a 5-year, 20-minute event.

Microspheres were added to water in the head tank. The water in the head tank was thoroughly mixed and a 500 mL sample was collected prior to application. Surface runoff was collected at the bottom of the vegetated strip (Figure 3.12). Grab samples were collected using 500 mL glass bottles and the volume of runoff was recorded.

Figure 3.9: Test Site for Microsphere Removal (4 ft Strips)

Figure 3.10: Dual Head Tank Configuration

Figure 3.11: Flow Diffuser at Top of VFS

Figure 3.12: Bottom Edge of a Strip

3.4 Chemical Analysis

Metal pollutant concentrations on a dry weight basis were determined following sample digestion and analysis by atomic absorption spectroscopy. Runoff samples from

highway sites were acidified and preserved at 39° F in the laboratory refrigerator. Runoff samples were acid digested with nitric acid following analytical procedures for total recoverable metals specified in SW-846, Method 3005A (U.S. EPA, 1992). Sediments and soil samples were analyzed for total metals using the laboratory standard operating procedure based on U.S. EPA Method 3050B (U.S. EPA, 1996). The prepared samples were analyzed for six metals (cadmium, chromium, copper, lead, manganese and zinc) using flame atomic absorption spectroscopy (Perkin-Elmer AAnalyst 300 series, Wellesley, Massachusetts, USA).

PAH concentrations were determined on a dry weight basis following sample preparation and extraction. Soils and sediments were extracted for 16 to 24 hours using Soxhlet extraction according to EPA Method 3540C (U.S. EPA, 1996). Runoff samples were processed using simultaneous suspended solids filtration and solid-phase extraction (SPE) to distinguish between soluble and particulate fractions. Empore™ octadecyl (C18) SPE disks (3M Corporation, St. Paul, Minnesota, USA) were conditioned for extraction according to Method 3535 (U.S. EPA, 1996). Samples were filtered through a Pall Gelman A/E glass fiber filter placed on top of a prepared Empore™ disk in the same 47 mm glass microanalysis filter holder apparatus (Fisher Scientific, Pittsburgh, Pennsylvania, USA). After filtration and rinsing with MilliQ (Millipore, Inc., Billerica, Massachusetts, USA) reagent water, the spent glass fiber filter with retained solids was stored at -4°F and processed via extraction as described above for soil and sediment samples. The SPE disk with retained analyte was then eluted as per EPA Method 3535 into pre-cleaned 60 mL glass tubes, capped with PTFE-lined caps, and stored at 39°F. Extracts were dried over sodium sulfate and concentrated

using a Kuderna-Danish apparatus. Concentrated extracts were exchanged to hexane, loaded onto silica gel cartridges, eluted with methylene chloride, and concentrated under nitrogen, then spiked with a known quantity of PHE-d10 internal standard prior to analysis. All glassware used in sample preparation, extraction, concentration and storage was thoroughly cleaned and triple rinsed with pesticide-grade methylene chloride prior to use.

Quantitation of PAHs in sample extracts was performed using gas chromatographic mass spectrometry (GC-MS), in the selected ion monitoring mode. The GC-MS analysis was performed using an Agilent Technologies Model 6890 gas chromatograph equipped with a Model 5973 mass selective detector (Wilmington, Delaware, USA). Samples were injected splitless onto a 30 meter, 0.25 mm HP5-MS capillary column with a carrier gas flow rate of 1 ml/min. PAH quantitation was accomplished by establishing a standard curve of known PAH concentrations (Supelco, Bellefonte, Pennsylvania, USA) in methylene chloride with 0.2 mg/mL phenanthrene-d10 (PHE-d10) as an internal standard. Each chromatogram peak was inspected for proper ratios of primary to secondary ions to confirm peak identification at the expected retention times. Quality control solvent blank samples and/or extraction blanks with 0.2 mg/mL PHE-d10 were analyzed with each sample batch of approximately 10 to 20 samples to ensure that the samples were not contaminated with PAH analytes during the sample preparation, extraction, and analysis. Surrogate recoveries were within expected quality control ranges for extraction and analysis.

3.5 Microsphere Counting

Microsphere counts were determined by membrane filtration and epifluorescence microscopy. A 5 mL aliquot of each head tank water sample was filtered through a 0.45 micrometer black polycarbonate filter. Microspheres on the filter were counted manually using a Zeiss UEM epifluorescence microscope. The 0.003 mm microspheres were counted for ten randomly selected fields-of-view of known area. The larger diameter spheres (0.020 and 0.090 mm) were counted over the entire filtration cross sectional area. A 200 mL aliquot of each runoff sample was centrifuged at 1200 revolutions per minute (rpm) for 12 minutes to concentrated microspheres at the base of the centrifuge tube. The top 150 mL of supernatant was removed, and the remaining 50 mL was homogenized. A 5 mL sample was filtered and enumerated using the methods described above.

CHAPTER 4 - RESULTS

4.1 Analysis of Highway Runoff and Highway Sediment

Flow-weighted composite runoff concentrations were obtained for a total of eleven storms at sites R1 and R3. Table 4.1 presents mean and 95% upper confidence limit (UCL) for concentrations of five metals (samples were also analyzed for cadmium, but cadmium was below detectable levels for all samples). Table 4.2 presents mean and 95% confidence levels, as well as percent soluble and percent particulate, for 13 PAHs.

Highway sediment collected using the sediment traps on interstate highway I-435 was analyzed for total metals associated with six different particle size groups. Figure 4.1 shows the particle size distribution for the sediment collected. Tables 4.3 and 4.4 present the mass concentration and distribution of five metals. Tables 4.5 and 4.6 present the mass concentration and distribution for four PAHs. These results indicate that 82 to 89% of particulate metal and PAH pollutants were generally associated with fine-to-medium grain size particulate matter in the 0.075 to 2.0 mm size range which should be retained by vegetated embankments.

Table 4.1: Total Metals Concentration in Highway Runoff

Pollutant	Site R1Geometric Mean(µg/L)	Site R1 95% UCL (µg/L)	Site R3 Geometric Mean (µg/L)	Site R3 95% UCL (µg/L)
Chromium	44	67	36	89
Copper	13	38	15	43
Lead	182	796	74	263
Manganese	160	242	143	262
Zinc	53	160	57	213

Table 4.2: Total PAH Concentration in Highway Runoff

PAH	Total Cocentrations, g/L			Particulate (%)	Soluble (%)
	Mean	95% LCL	95% UCL		
ACE	0.11	0.07	0.18	51	49
FLR	0.09	0.06	0.14	21	79
PHE	0.28	0.19	0.42	73	27
ANT	0.06	0.03	0.10	14	86
PYR	0.28	0.11	0.75	33	67
BAA	0.55	0.32	0.96	57	43
CHR	0.19	0.09	0.41	22	78
BBF	0.56	0.34	0.91	53	47
BKF	0.51	0.33	0.80	62	38
BAP	0.36	0.20	0.64	81	19
IPY	0.46	0.25	0.86	88	12
DBA	0.31	0.24	0.38	65	35
BPE	0.25	0.13	0.46	86	14

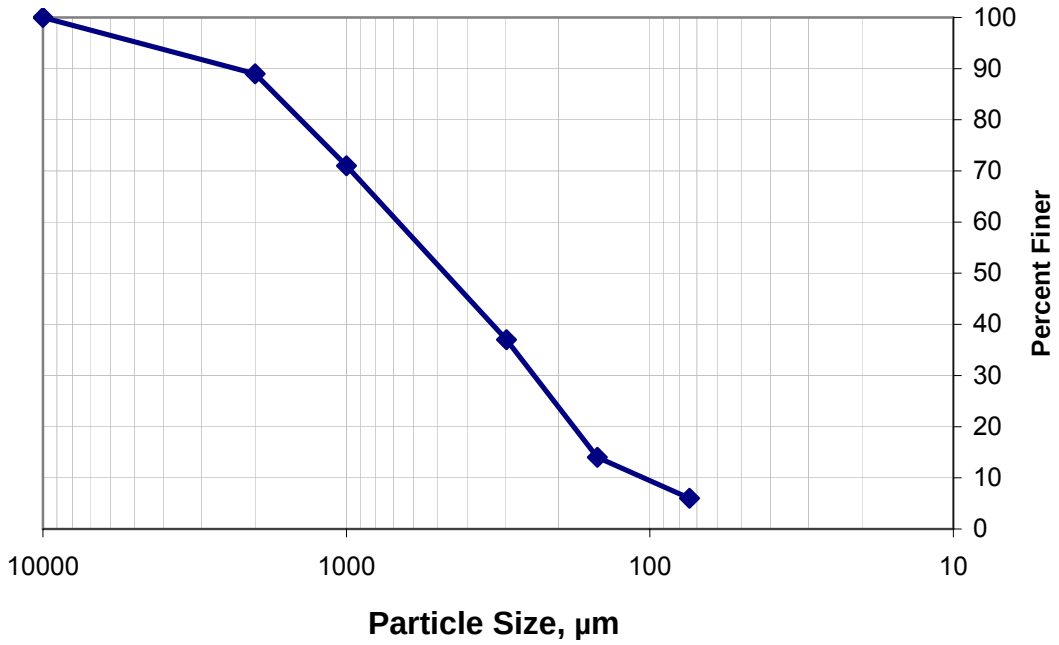

Figure 4.1: Particle Size Distribution for Highway Sediment

Table 4.3: Particulate Metal Mass Concentration for Sediment Size Classes

Particle Size (µm)	Chromium (mg/kg)	Copper (mg/kg)	Lead (mg/kg)	Manganese (mg/kg)	Zinc (mg/kg)
>2000	51.3	15.3	50.7	651	110
1000-2000	50.3	37.5	42.0	399	295
297-1000	48.8	101	39.9	372	286
149-297	67.6	85.5	50.6	354	317
74-149	122	225	85.7	512	522
<74	88.3	182	95.1	514	569

Table 4.4: Particulate Metal Mass Distribution for Sediment Size Classes

Particle Size (µm)	Chromium	Copper	Lead	Manganese	Zinc
>2000	9%	2%	11%	17%	4%
1000-2000	15%	7%	15%	17%	17%
297-1000	27%	37%	27%	30%	31%
149-297	25%	22%	23%	19%	23%
74-149	16%	20%	13%	10%	13%
<74	9%	12%	11%	7%	11%

Table 4.5: Particulate PAH Mass Concentration for Sediment Size Classes

Particle Size µm	PHE mg/kg	PYR mg/kg	CHR mg/kg	BAP mg/kg
>2000	0.88	0.94	0.56	0.90
1000-2000	1.88	2.70	0.94	1.92
297-1000	2.18	3.02	1.08	2.14
149-297	1.68	2.74	1.06	2.10
74-149	2.88	4.44	3.62	3.36
<74	3.34	3.86	2.86	1.98

Table 4.6: Particulate PAH Mass Distribution for Sediment Size Classes

Particle Size µm	PHE	PYR	CHR	BAP
>2000	5%	4%	5%	5%
1000-2000	17%	17%	13%	17%
297-1000	37%	36%	28%	36%
149-297	19%	22%	19%	24%
74-149	12%	13%	22%	13%
<74	10%	8%	13%	6%

4.2 Estimating Mass Loadings for Select Pollutants

Annual mass loading for two metals (copper and zinc) and three PAHs (pyrene, chrysene, and benzo(a)pyrene) was estimated for the three runoff sites listed in Table 3.1. The mass loadings were computed as the product of the contributing drainage area, mean annual precipitation (38 inches/year), runoff coefficient (0.95), and the geometric mean concentration for the constituent. The geometric mean was selected as representative of the statistical distribution of sample data. Although sample sizes were small (number of observations less than 12), the constituent concentrations appeared to be lognormally distributed based on Ryan-Joiner normality test and inspection of normal probability plots (Minitab Inc., version 14, State College, Pennsylvania, USA). Table 4.7 presents estimated mass loadings for copper and zinc.

4.3 Historical Deposition

Surface soil (0.0-0.4 inches) concentrations were found to be normally distributed based on sample populations of 14 to 18 observations and were compared to background concentrations. PAHs, copper, and zinc at this level were found to be

greater than area background soil concentrations at 0.0-0.4 inches based on t-test results for a level of significance (α) equal to 0.05. Concentrations of PAHs, copper, and zinc minus background concentrations are presented in Table 4.8 to represent retained pollutants in embankment soils.

Table 4.7: Mass Loading per Longitudinal Pavement Length for 25-Year Life of Embankment

Pollutant	Site R1 (g/m)	Site R2 (g/m)	Site R3 (g/m)
Copper	17	28	16
Zinc	68	110	60
Pyrene	0.36	0.60	0.30
Chrysene	0.24	0.40	0.20
Benzo(a)pyrene	0.46	0.77	0.38

Table 4.8: Highway Embankment Soils, Retained Pollutant Concentration (actual minus background concentration)

Pollutant	Site R1, 0-0.4 in Mean ± 95% CI (mg/kg)	Site R2, 0-0.4 in Mean ± 95% CI (mg/kg)	Site R3, 0-0.4 in Mean ± 95% CI (mg/kg)
Copper	7.5 ± 3.2	21.9 ± 3.7	8.0 ± 3.3
Zinc	391 ± 6.8	238 ± 30	311 ± 68
Pyrene	0.49 ± 0.087	0.86 ± 0.26	1.59 ± 0.40
Chrysene	0.25 ± 0.065	0.48 ± 0.17	1.11 ± 0.39
Benzo(a)pyrene	0.27 ± 0.055	0.42 ± 0.11	0.81 ± 0.20

Metals and PAH concentrations in soils from the 2.0-2.4 inch and 3.9-4.3 inch depth intervals were not found to be normally distributed and were compared to background concentrations. Nonparametric analysis (Mann-Whitney, α=0.05) of copper and zinc concentrations in the 2.0-2.4 inch and 3.9-4.3 inch depth intervals were not

found to exceed background metals concentrations from similar depth intervals. PAHs were not detected in 47% of samples in the 2.0-2.4 inch zone for some individual compounds, and nonparametric analysis results indicated that PAH concentrations did not exceed background concentrations for any of the field sites (R1, R2, and R3).

Long-term metal pollutant retention in embankment soils was determined for Sites R1, R2, and R3 (Table 4.9). The 95% confidence interval (CI) associated with the mean soil concentration is also presented in Table 4.9. Pollutant concentration observed from surface soil samples were assumed to apply to a depth of 0 to 0.8 inches. Pollutant concentration minus area background concentration was compared to annual mass loading rates over a 25-year period, the time period since highway construction. Results, based on this study, indicated that 18 ft long vegetated highway embankments were 8.9 to 16% effective in retention of copper and 42 to 114% effective in retention of zinc. Mass retention results for PAHs ranged from 11 to 109%. Retention rates exceeding 100% illustrate the presence of experimental error, primarily in the estimation of long-term mass loadings. The estimates of mass loadings are based on runoff samples for 11 storms in 2002. A more thorough discussion of retention rates that exceed 100% is provided in Chapter 5.

4.4 Removal Rates for Experimental Study using Microspheres

Fluorescent microsphere removal studies indicated 61 to 94% initial removal across a 4 ft vegetated buffer strip for the initial application. Results were highly variable, with a total of 5 to 15% of microspheres being resuspended from the vegetated buffer strip after two successive 90th percentile storm events. Table 4.10 presents average removal rates and resuspension rates for the six replicate buffer strips.

Table 4.9: Percent of Mean Pollutant Mass Loading Retained on Soils (actual minus background concentration)

Pollutant	Site R1, 0.0-0.8 in Mean ± 95% CI (percent)	Site R2, 0.0-0.8 in Mean ± 95% CI (percent)	Site R3, 0.0-0.8 in Mean ± 95% CI (percent)
Copper	8.9 ± 3.8	15.6 ± 2.6	10.0 ± 4.1
Zinc	114 ± 20	41.6 ± 5.3	102 ± 22.2
Pyrene	26.9 ± 4.8	28.5 ± 8.6	106 ± 26.7
Chrysene	20.2 ± 5.2	23.4 ± 8.4	109 ± 38.6
Benzo(a)pyrene	11.5 ± 2.3	10.8 ± 2.9	42.1 ± 10.5

Table 4.10: Microsphere Removal and Resuspension Rates (average for six replicate strips)

	Microsphere Diameter:		
	3 µm	**20 µm**	**90 µm**
Removed (%)	60.8	93.8	78.1
Resuspended (%)	13.8	7.4	7.2

CHAPTER 5 - DISCUSSION, RECOMMENDATIONS, AND CONCLUSION

5.1 Discussion of Results

The concentrations of copper and zinc observed in highway runoff at Sites R1 and R3 were similar to those found in other studies. Wu et al. (1998) found median event mean concentrations (EMCs) for copper at three sites to be 5, 12, and 24 μg/L. Barrett et al. (1998a) found EMCs for copper to range from 10 to 37 μg/L and EMCs for zinc to range from 46 to 213 μg/L at four locations. Concentrations of PAHs observed are similar but higher than those reported by Shinya et al. (2000) for a highway in Osaka, Japan. Shinya et al. (2000) observed EMCs for pyrene from 0.090 to 0.363 μg/L and for benzo(a)pyrene from 0.026 to 0.099 μg/L over four events. In contrast, the geometric mean concentrations observed for this study were 0.28 μg/L for pyrene and 0.36 μg/L for benzo(a)pyrene. The location studied by Shinya et al. (2000) had lower traffic volumes (75,000 vehicles per day), which is likely to reduce PAH mass in runoff.

Estimates of pollutant mass loading in highway runoff for this study were approximate and based on 11 storm events of varying intensity and duration. Factors affecting long-term pollutant mass loading include traffic volume, storm intensity, and pavement characteristics based on studies documented in the literature (Barrett et al., 1998a; Wu et al., 1998; Pagotto et al., 2000). Metals runoff data from this study indicate that Sites R1 and R3 had statistically similar concentrations of chromium, copper, lead, manganese, and zinc based on t-test results of log-transformed data (α=0.05). Based on similar runoff results and the similarity of Sites R1 and R3 in regional proximity and

average traffic volume, it was assumed that similar annual runoff mass loadings were applicable to Site R2. However, the average traffic volume for Site R2 was approximately 45% of the value for Sites R1 and R3, indicating that the mass loading estimate for Site R2 was conservatively high. Therefore, long-term pollutant retention estimates for Site R2 may be higher than the values reported in Table 4.8.

Pollutant retention in vegetated filter strips is affected by physical characteristics of the filter strip and the nature of runoff flow. Factors affecting pollutant retention include vegetative cover density, vegetation stalk height, flow channeling, and soil factors affecting infiltration (Barfield et al. 1979; Magette et al. 1989). The highest zinc, copper, and PAH concentrations in roadside soils were in the 0 to 2 inch depth range in a previous study (Dierkes and Geiger 1999). During field characterization of highway embankment sites for this study, observation of erosion channels across all three sites suggested that relatively uniform embankment slopes induced channelized flow (as opposed to sheet flow) of runoff across the embankment. In addition, during the dry soil conditions from June to August a significant amount of desiccation cracking was observed in every square yard grid cell of the embankment areas.

Metals retention varied significantly by element. Zinc retention at the three sites ranged from 41.6% to 114%. Retention rates in excess of 100% are not physically possible, but the margin of experimental uncertainty places the retention rates for zinc near 100% for Sites R1 and R3. The low zinc retention observed for Site R2 may be due overestimation of mass loading for this site as Site R2 experiences lower traffic volumes than Sites R1 and R3. Interestingly, the retention of copper was much lower than that for zinc, ranging from 8.9 to 15.6% across the three sites. Metals associated

with soluble and fine particulate matter (less than 0.075 mm) are expected to be less effectively removed compared to medium and coarse particulates (greater than 0.075 mm).

Mass retention of zinc and copper in this study was comparable to ranges observed for event-based pollutant removal across vegetated buffer strips by other investigators. Dorman et al. (1996) reported 47 to 81% removal of zinc and 14 to 65% removal for copper. Barrett et al. (1998b) reported 75 to 91% mean removal of zinc for three field sites. Kaighn and Yu (1996) reported only 18 to 84% zinc removal for grass swales and 88% zinc removal for a vegetated buffer strip.

Prior studies report similar solubility and mobility for copper and zinc in the soil column (Ellis and Revitt, 1982; Camobreco et al., 1996; McBride et al., 1997). The difference in retention found in this study may be due to differing dissolved versus particulate fractions in highway runoff at this location. The metal concentrations reported in Table 4.1 are total concentrations. The low total concentrations of runoff in this study prevented analysis of the dissolved versus particulate metal concentrations. Additional research on the variable retention of metals is warranted.

It should be noted that the metals concentrations in the soil samples collected in this study do not approach KDHE Tier 2 risk-based standards for residential environments. As such, the effective retention of metals in highway embankments does not appear to pose a human health hazard.

PAH retention in soil is likely influenced by the soluble fraction of total PAH in highway runoff. This study indicated that the average soluble fraction of PAHs in runoff was 48%. However, the soluble fraction for individual PAHs ranged from 19% for

benzo(a)pyrene to 78% for chrysene. A high potential for sorption of soluble PAH to surface soils is expected for low to moderate storm events generating low depth of runoff flow and higher soil infiltration rates. However, relatively low potential for sorption of soluble PAH to surface soils is expected during large storm events, where high depth of runoff flow limits contact with surface soils and vegetation.

A factor influencing PAH retention estimates in soil for this study is the mass removed by biodegradation. Pyrene, chrysene, and benzo(a)pyrene sorbed to embankment soils are susceptible to biodegradation by bacteria found in a range of soil types (Mueller et al., 1997; Aitken et al., 1998; Ho et. al, 2000). If significant biodegradation of PAHs retained within embankment soils had occurred over 25 years of highway life for the study sites, mass retention values reported in Tables 4.7 and 4.8 may be lower than PAH initially sorbed to soils from runoff.

Results of the microsphere removal and retention study indicate that even very short (4 ft) vegetated buffers can achieve particulate removal rates from 60 to 94%. As expected from higher sedimentation velocities and capture efficiencies, higher removal rates were observed for the larger microspheres (0.020 and 0.090 mm). Typical highway embankments are on the order of 20 to 45 ft in length and provide excellent opportunity for filtration and infiltration of contaminated runoff. Although resuspension of microspheres was found to occur, less than 10% of captured particles was released from the vegetated embankment for successive 90th percentile storm events.

Although not studied as part of this project, vegetated drainage ditches with low slopes will also provide opportunity for pollutant removal.

5.2 Recommendations

This study demonstrates that VFSs can be effective for filtration of highway runoff. However, VFS implementation and maintenance may affect the ability of the strip to remove pollutants. This section provides basic recommendations on the implementation and maintenance of VFSs for highway embankments in Kansas.

Existing guidelines for VFS implementation focus on promoting uniform sheet flow from the pavement across the vegetated embankment. If flow from the highway is permitted to concentrate at a low point, flow depth and velocity may compromise VFS effectiveness. Some degree of flow concentration is unavoidable for horizontal curves, but limiting flow concentration on straight stretches of highway is relatively easy. It is critical to maintain a proper transition from the pavement edge to embankment. Barrett et al. (1998b) observed formation of a sediment 'lip' at the pavement edge that tends to channel water parallel to the traffic flow. This has the effect of concentrating flow. This phenomenon was also observed at the R1 site in this study. Formation of the sediment lip may be avoided through maintenance. It may also be possible to direct water perpendicular to traffic using rumble strips on the pavement edge.

Locations of high flow concentration will be marked by erosion of channels on the embankments. Eroded channels should be repaired and care should be taken to identify the cause of and possible remedies for flow concentration at that location. If no remedy is feasible, additional effort may be required to stabilize the surface soil of the embankment.

Other than avoiding flow concentration, recommendations for VFS design typically list slope, length, and vegetation type as important controlling factors. Scheuler

(1987) states that filter strip performance is limited for slopes greater than 5% and that slopes greater than 15% will not function as intended. This advice is repeated in multiple BMP manuals. However, Lantin and Alderete (2002) observed effective removal of sediment for steep embankments (50% slopes) in California. The research performed for this KTRAN project indicates that the typical highway embankment slope of 1:6 (17%) can serve as an effective VFS. This is verified using both the long term retention of metals in the highway embankments and the microsphere removal study. Steeper embankments (such as 1:4 or 1:3 slopes) may provide some benefit as well.

VFS length is an important determinant in filtration capacity. Scheuler (1987) recommends VFS length in the range of 50-75 feet, with a 20 foot minimum recommended length. This study indicates that significant pollutant retention occurs in the first 18 feet of the embankment. Average microsphere removal for a very short (4 ft) VFS was over 60% for particles greater than 3 μm. Typical highway embankment slopes are sufficient to promote filtration of suspended solids in Kansas.

Vegetation density has a large effect on VFS effectiveness. Grass type should be selected such as to optimize vegetation density. Again, typical embankments sampled in this study are effective filter strips. Still, steps should be taken to promote dense vegetation in locations where vegetation is sparse. Re-seeding and regular mowing may be sufficient to promote healthy stands of vegetation. Scheuler (1987) recommends that short VFS be mowed 2-3 times per year to promote dense growth and to suppress weeds.

5.3 Conclusion

This research project indicates that typical highway embankments in Kansas can serve as effective best management practices for the removal of suspended solids and associated pollutants. This finding is substantiated both through an analysis of historical deposition on highway embankment soils and through a controlled field experiment using fluorescent microspheres.

The analysis of embankment soils indicated that pollutant retention was primarily a superficial phenomenon, limited to the top 0 to 2 inches of highway embankment soil. Sediment distribution analysis and microsphere removal studies indicate that net particulate pollutant retention within vegetated embankments should be at greater than 70% for particles of 0.020 mm diameter or larger. The 18 ft long vegetated highway embankments evaluated in this study were effective stormwater BMPs for zinc, achieving 42 to 100% long-term pollutant mass retention. Moderate performance results were observed for pyrene and chrysene, achieving 20 to 100% mass retention assuming no mass removal attributed to biodegradation. Embankments were less effective for copper and benzo(a)pyrene, with 9 to 42% retention of runoff pollutant mass loading. The key benefits of utilizing highway embankments for runoff control include cost-effectiveness relative to other engineered systems and compatibility with roadway design and maintenance requirements.

While specific pollutant mass retention was observed to be highly dependent on metal or PAH properties in runoff, the overall result is a significant reduction in runoff pollutant mass exiting the vegetated embankment, particularly when embankments are greater than 30 to 45 ft in length.

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KANSAS TRANSPORTATION RESEARCH AND NEW - DEVELOPMENTS PROGRAM

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