

Characterization of Residuals Collected From Street Sweeping Operations

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16. Abstract: <p>Street sweeping is a routine roadway maintenance activity conducted by the Virginia Department of Transportation (VDOT). It also provides an added benefit as a non-structural stormwater best management practice implemented by VDOT to meet total maximum daily loads for the Chesapeake Bay watershed. This best management practice functions by removing pollutants from the roadway before they can enter receiving waters. Currently the material collected by VDOT during street sweeping operations is considered a solid waste and is disposed of at a lined landfill.</p> <p>Given the benefits street sweeping provides in achieving total maximum daily load requirements, it is an activity that continues to increase. As street sweeping activity increases, additional residuals will be generated, requiring management. VDOT is evaluating options to manage street sweeping residuals efficiently through reuse and recycling. Part of this evaluation requires characterization of the material to determine (1) its regulatory status; (2) whether it can be reused within the criteria established by the Virginia Department of Environmental Quality (VDEQ) Division of Land Protection and Revitalization State-wide Variance Guidance Memo No. LPR-SW-04-2012; or (3) whether the material might qualify for reuse following the VDEQ beneficial use determination (BUD) process. Potential reuse/recycling options might include using the material as traction sand, a soil amendment, beneficial fill, or other suitable application. VDEQ has a number of criteria the material must meet to qualify for a BUD, including a physical and chemical characterization of the material to demonstrate that the material does not present a hazard to human health or the environment. This study provides the needed characterization of material collected from 79 road sites of various average daily traffic loads and land cover. The material was tested for arsenic (As), barium (Br), cadmium (Cd), chromium (Cr), selenium (Se), silver (Ag), lead (Pb), copper (Cu), and zinc (Zn); the U.S. Environmental Protection Agency's 16 priority polycyclic aromatic hydrocarbons; and oil and grease.</p> <p>Based on the results of this characterization, the study found that the concentrations of these constituents cannot be reliably predicted based on average daily traffic or land cover. Rather, the findings indicate a negative correlation between the particle size of the road deposited sediment and the concentration of detected constituents. Further, the average concentration of these constituents was found to exceed the screening levels administered by VDEQ's Division of Land Protection and Revitalization State-wide Variance Guidance Memo No. LPR-SW-04-2012.</p> <p>The study recommends that VDOT's Environmental Division not pursue a BUD for this material at this time. Further, upon the request of VDOT's Environmental Division, the Virginia Transportation Research Council should conduct a survey of VDOT's districts, residencies, and area headquarters to determine the volume of this material collected by VDOT field offices during street sweeping activities. Such a survey would provide a better picture of the need for reuse of the material. Further, if the survey findings indicated a great enough need for reuse, it is recommended that additional research be conducted to determine the effectiveness and feasibility of processing methods (such as screening) to remove these constituents.</p>					
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FINAL REPORT

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ABSTRACT

Street sweeping is a routine roadway maintenance activity conducted by the Virginia Department of Transportation (VDOT). It also provides an added benefit as a non-structural stormwater best management practice implemented by VDOT to meet total maximum daily loads for the Chesapeake Bay watershed. This best management practice functions by removing pollutants from the roadway before they can enter receiving waters. Currently the material collected by VDOT during street sweeping operations is considered a solid waste and is disposed of at a lined landfill.

Given the benefits street sweeping provides in achieving total maximum daily load requirements, it is an activity that continues to increase. As street sweeping activity increases, additional residuals will be generated, requiring management. VDOT is evaluating options to manage street sweeping residuals efficiently through reuse and recycling. Part of this evaluation requires characterization of the material to determine (1) its regulatory status; (2) whether it can be reused within the criteria established by the Virginia Department of Environmental Quality (VDEQ) Division of Land Protection and Revitalization State-wide Variance Guidance Memo No. LPR-SW-04-2012; or (3) whether the material might qualify for reuse following the VDEQ beneficial use determination (BUD) process. Potential reuse/recycling options might include using the material as traction sand, a soil amendment, beneficial fill, or other suitable application. VDEQ has a number of criteria the material must meet to qualify for a BUD, including a physical and chemical characterization of the material to demonstrate that the material does not present a hazard to human health or the environment. This study provides the needed characterization of material collected from 79 road sites of various average daily traffic loads and land cover. The material was tested for arsenic (As), barium (Br), cadmium (Cd), chromium (Cr), selenium (Se), silver (Ag), lead (Pb), copper (Cu), and zinc (Zn); the U.S. Environmental Protection Agency's 16 priority polycyclic aromatic hydrocarbons; and oil and grease.

Based on the results of this characterization, the study found that the concentrations of these constituents cannot be reliably predicted based on average daily traffic or land cover. Rather, the findings indicate a negative correlation between the particle size of the road deposited sediment and the concentration of detected constituents. Further, the average concentration of these constituents was found to exceed the screening levels administered by VDEQ's Division of Land Protection and Revitalization State-wide Variance Guidance Memo No. LPR-SW-04-2012.

The study recommends that VDOT's Environmental Division not pursue a BUD for this material at this time. Further, upon the request of VDOT's Environmental Division, the Virginia Transportation Research Council should conduct a survey of VDOT's districts, residencies, and area headquarters to determine the volume of this material collected by VDOT field offices during street sweeping activities. Such a survey would provide a better picture of the need for reuse of the material. Further, if the survey findings indicated a great enough need for reuse, it is recommended that additional research be conducted to determine the effectiveness and feasibility of processing methods (such as screening) to remove these constituents.

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INTRODUCTION

The current focus and regulatory requirements associated with stormwater quality in the Chesapeake Bay watershed have led to an increasing number of stormwater best management practices being employed to meet Virginia's total maximum daily loads for nutrients and suspended solids. Street sweeping, historically used as a way to maintain aesthetic appeal, has emerged as one of the best management practices used by many municipalities and state departments of transportation as a means to improve stormwater quality before it enters receiving waters. In 2011, street sweeping was officially recognized as a stormwater best management practice after a pilot study by Law et al. in 2008 (Seattle Public Utilities and Herrera Environmental Consultants, 2009). Accordingly, the Virginia Department of Transportation (VDOT) intends to increase its street sweeping activity as one option to achieve its regulatory requirement.

Typically, municipalities will conduct their street sweeping operations two times per year: once in the fall to remove leaves and other accumulated debris, and again in the late spring or early summer to remove winter traction sand (Seattle Public Utilities and Herrera Environmental Consultants, 2009). Once this material has been collected, under the current regulations in Virginia and a number of other states, it is considered a solid waste and requires disposal at a landfill.

As street sweeping rates increase, there is merit in evaluating management options for the increased volume of residuals that will be generated. In particular, VDOT is interested in evaluating reuse and recycling options for these residuals. The evaluation process requires a

chemical and physical analysis of the material to determine what programmatic options are available for reuse of the material through the Virginia Department of Environmental Quality (VDEQ) regulations and variances or whether a specific beneficial use determination (BUD) would be required prior to reuse.

In Virginia, the Virginia Solid Waste Management Regulations and VDEQ variances prescribe the options for reuse and recycling of solid waste. The regulations provide specific exemptions for particular materials. Street sweepings do not have a specific exemption in the regulations.

Another option for reuse is provided in the VDEQ's Division of Land Protection & Revitalization State-Wide Variance Guidance Memo No. LOPR-SW-04-2012: Management and Reuse of Contaminated Media (Steers, 2012). The guidance provides a screening level (SL) framework whereby media with low-level contaminants can be reused as beneficial fill. The framework consists of three tables of SLs: Table 1 (Protection of Groundwater and Ecological Receptors), Table 2 (Soil: Residential and Other High Frequency Receptors), and Table 3 (Soil: Restricted Commercial/Industrial). The SLs in these tables are derived from the U.S. Environmental Protection Agency (EPA) regional SLs and are general in nature.

The final option is for VDOT to apply for regulatory relief by submitting a beneficial use demonstration to VDEQ for reuse of the street sweepings. In order for a material to receive a BUD in Virginia, a number of criteria must be met as outlined in Administrative Code 9VAC20-81-97 (Virginia Waste Management Board, 2015). These criteria include a physical and chemical analysis of the material. Accordingly, given these regulatory options, this study evaluated the following chemical constituents of collected street sweepings: arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), selenium (Se), silver (Ag), lead (Pb), copper (Cu), and zinc (Zn); the EPA's 16 priority polycyclic aromatic hydrocarbons (PAHs); and oil and grease (O&G).

PURPOSE AND SCOPE

The purpose of this study was to conduct an extensive characterization of road deposited sediment (RDS) collected throughout Virginia. The collection of this information is a logical and necessary first step in the BUD application process. Seventy-nine sampling locations were selected based on average daily traffic (ADT) and the National Land Cover Database (NLCD) designation of the surrounding area. All 79 sites were characterized for metals including As, Ba, Cd, Cr, Se, Ag, Pb, Cu, and Zn in addition to O&G. Of the 79 sites, 27 were tested for the EPA's 16 priority PAHs. In order to investigate the relationship between concentration and particle size, a subset of these samples was screened into five particle size categories and analyzed for the same metals and PAHs. These constituents were chosen because of their potential influence on stormwater quality and their persistence in the environment.

The scope of the study was limited to sites in Virginia and the analysis of the RDS constituents listed.

METHODS

Five tasks were performed to achieve the study objectives:

1. review of the literature
2. selection of sites
3. collection of samples
4. preparation of samples
5. analysis of samples.

Task 1: Literature Review

An extensive literature review was conducted to investigate (1) how other states and departments of transportation manage this material; (2) previous studies regarding the relationship between RDS and metals, PAHs, and O&G; and (3) the proper analytical techniques for measurement of these constituents in sediment. Journal databases such as those for *Environmental Science and Technology*, *The Journal of Environmental Engineering*, etc., were searched using the Web of Science platform. Keywords such as beneficial use determination, metals, PAHs, road deposited sediment, sediment, street sweeping, and other related search terms were used to extract relevant documents. In order to determine which states currently have BUDs (or the equivalent) for RDS collected during street sweeping, a Google search was conducted to determine which states have active street sweeping programs. Once these states were identified, a more in-depth review of each program was conducted to determine its extent and if the material was being reused. Analytical techniques were investigated in accordance with the EPA SW-846 Hazardous Waste Test Methods Compendium.

Task 2: Site Selection

Seventy-nine sampling locations were selected throughout Virginia using ArcMap 10.4.1. These locations were selected based on both ADT and the land cover of the surrounding area. Roads were sorted into six ADT groups as follows: 1-400; 401-1,500; 1,501-2,000; 2,001-4,000; 4,001-10,000; and >10,000. Land cover data for Virginia were obtained from the 2011 NLCD. This data set provides raster data with a spatial resolution of 30 m and represents land cover data as 16 classifications (Homer et al., 2015). These data commonly are used to determine various surface characteristics such as land use, percent impervious surface, and amount of tree cover. The 4 NLCD classifications used for site selection in this study were (1) developed, open space; (2) developed, low intensity; (3) developed, medium intensity; and (4) developed, high intensity. These classifications are defined in Table 1. A map of the 79 sampling sites is provided in Figure A-1 in Appendix A.

Table 1. National Land Cover Database Categories Considered in This Study and Their Descriptions

Classification	Description
Developed, Open Space	Areas with a mixture of some constructed materials but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
Developed, Low Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% of total cover. These areas most commonly include single-family housing units.
Developed, Medium Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
Developed, High Intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial/industrial uses. Impervious surfaces account for 80% to 100% of the total cover.

Classification definitions are from the National Land Cover Database (Homer et al., 2015).

Task 3: Collection of Samples

Sampling of the RDS began on Wednesday, July 6, 2016. Samples were collected after at least 2 days of an antecedent dry period. This ensured that the RDS collected was relatively dry and would not stick excessively to the inside of the Shop-Vac hose and cross contaminate subsequent samples. A 5-gal, 4.5 HP, wet dry Shop-Vac (Model No. H87S600Cr) was used to collect samples from the roadway. Similar methods of sampling were used by Duong and Lee (2011), Tian et al. (2009), and Wang et al. (2010). High-efficiency disposable Shop-Vac brand bags (Model No. 906719) were used as collection bags inside the Shop-Vac. Power was supplied to the Shop-Vac using a generator placed 6 m away from the sampling location in order to reduce possible contamination from exhaust. The vacuum head was drawn perpendicular to traffic about 2 m from the shoulder of the road outward. This was repeated until enough volume had been collected to provide a representative sample of about 1,500 g.

Samples were stored in plastic bags on ice while in transport back to the lab. The Shop-Vac hose was cleaned using an air duct brush, and the inside of the Shop-Vac tank wiped down after every three samples. This cleaning method was confirmed in the lab by passing virgin sand through the vacuum at the end of a sampling day. The results of this experiment showed no signs of significant cross contamination. Although some of the fines smaller than 75 μm are inevitably lost during sampling, this method provides particulate removal efficiencies similar to if not higher than those of regenerative air street sweepers. Samples were stored at about 3°C until extraction and digestion.

Task 4: Sample Preparation

Sample digestions and extractions were in accordance with methods in the EPA SW-846 Hazardous Waste Test Methods Compendium.

Metals Digestion

Microwave digestion was used to prepare samples for analysis on the inductively coupled plasma mass spectrometer. EPA Method 3051a was followed using a CEM Corporation MARS 6 microwave digester. The recovery efficiency of this digestion method has been verified in

other studies using SRM 2704 (Buffalo River Sediment) and has values of 98.5% for Cd, 62.7% for Cr, and 101.2% for Pb (Link et al., 1998). Further confirmation of these recovery efficiencies was achieved by spiking a blank 4-g sediment sample with 4 µg of silver as silver nitrate. The mixture was allowed to sit covered overnight in the refrigerator to allow complete sorption of the silver onto the sediment. This mixture was dried and then digested in accordance with EPA Method 3051a in the microwave along with four other method blanks containing only 70% HNO₃. The digested samples were then diluted to a 3% HNO₃ concentration, thus giving an expected silver concentration of 5 ppb. The results of this experiment are provided in Table 2.

Table 2. Recovery Efficiency of Microwave Digestion Procedure

Sample	Reported Concentration (µg/l)	SD	% Recovery
1	2.161	1.17x10 ⁻³	43.22
2	5.721	9.45x10 ⁻³	114.42
3	4.041	3.58x10 ⁻³	80.82
4	7.555	4.21x10 ⁻³	151.1

SD = standard deviation.

Extraction of EPA's 16 Priority PAHs

PAH extraction was completed using a CEM Mars 6 microwave digestion/extraction apparatus in accordance with EPA Method 3546. All reagents used were high pressure liquid chromatography grade or higher. The extraction solvent used was a mixture of 50:50 hexane and acetone. Extraction vessels were cleaned and re-extracted after each run to prevent cross contamination between batches. Twelve samples and one method blank consisting of clean solvent were extracted during each run. After extraction, samples were transferred into 7-ml borosilicate glass screw top vials and closed with a foil-lined cap. Care was taken to ensure as little headspace as possible in each vial. Samples were then refrigerated until analysis. Prior to analysis, 2 ml of each sample was filtered through 0.45-µm polytetrafluoroethylene syringe filters using glass leur lock syringes. The filtrate was collected in 2-ml crimp top amber glass auto sampler vials with a red rubber septum for analysis on the gas chromatography–mass spectrometer.

O&G Extraction

O&G extraction was conducted using Horiba Instruments S-316 solvent. From each sample, 1 g of RDS was weighed out to the nearest tenth of a gram in a 40-ml glass beaker. About 1 g of anhydrous sodium sulfate was then added to each beaker to dry the sample. With the use of a 10-ml pipette, 30 ml of S-316 solvent was added to each beaker and stirred with a metal spatula for 1 minute. The samples were then allowed to sit for 1 minute to allow the solids to settle to the bottom of the beaker. After 1 minute, approximately 1 g of 100-200 mesh chromatographic grade silica gel was added to Whatman No. 41 filter papers and the samples were gravity filtered into clean 40-ml glass beakers. The samples were then ready for analysis on the Horiba OCMA 350 oil content analyzer.

Size Fractioning

Samples from the 4,001-10,000 ADT categories (totaling 16 sites) were screened into five particle size categories. This ADT category was chosen because of the increased likelihood of PAH contamination from its increased traffic load. The particle size categories were <75 µm, 75-150 µm, 150-300 µm, 300-600 µm, and 600 µm-1.18 mm. About 500 g of sample was screened from each site. All sieves used were 6-in brass ringed stainless steel screened sieves. Samples were sieved in accordance with ASTM D6913. Between each sample, the sieves were scrubbed clean with a stainless steel brush to remove trapped particles, scrubbed again with lab soap and water, and then rinsed thoroughly with Type I water in accordance with ASTM D1193-06(2011) and dried at 100°C.

Task 5: Sample Analysis

Metals Analysis

An Agilent 7900 inductively coupled mass spectrometer was used to quantify the concentrations of the nine metals in the samples in accordance with EPA Method 6020B. Before every analysis run, the instrument was calibrated using a multi-metal certified reference material. The calibration concentrations used were 0.01 ppb, 1 ppb, 10 ppb, 100 ppb, and 1 ppm. Dilutions of the stock standard were made using trace metals grade HNO₃ and ASTM D1193-06(2011) Type I water and matched the 3% HNO₃ concentration of the sample matrix. Every 10 samples, a 1 µg/L continuing calibration verification standard was tested for quality assurance.

Analysis of EPA's 16 Priority PAHs

A Shimadzu GCMS-QP2010SE gas chromatograph–mass spectrometer with an Agilent J and W DB-EUPAH column (20 m x 0.18 mm, 0.14 µm film thickness) was used for PAH analysis. This column is specifically designed for the analysis of the 16 PAHs regulated by the European Union and the EPA. The instrument was calibrated using 10 ppb, 50 ppb, 100 ppb, 500 ppb, and 1 ppm calibration standards. These standards were prepared from a certified reference solution containing 2,000 ppm of each of the EPA's 16 priority PAHs in a solution of 50:50 benzene:dichloromethane. The certified reference solution was diluted to the required concentrations using pesticide grade dichloromethane and stored in amber glass crimp top vials in a refrigerator until calibration. The storage time of these standards was kept to a minimum to reduce concentration of the standards by volatilization.

O&G Analysis

O&G analysis was conducted using a Horiba OCMA 350 oil content analyzer. Prior to analysis, a 200-mg/l span calibration standard was prepared using Horiba Heavy B-oil standard dissolved in S-316 solvent. The instrument was calibrated using clean S-316 solvent as the zero-span solution followed by the 200 mg/L span solution. Each sample was run in duplicate, and the cuvette was rinsed using S-316 solvent between each sample. The calibration of the instrument was confirmed after every 16 samples and at the end of each run to prevent any errors in analysis.

RESULTS AND DISCUSSION

Two hypotheses were considered during this study: (1) the concentrations of metals, PAHs, and O&G are positively correlated with the ADT and land cover of the road and the surrounding area from which they are collected, and (2) the concentrations of these contaminants are negatively correlated with the particle size of the RDS. The results of this study and whether they support these hypotheses are discussed here.

Literature Review

Beneficial Use Determinations in Other States

A number of other states have successfully received BUDs (or their equivalent) for street sweeping materials including Florida (Sole, 2004), Oregon (Obrien, 2014), Minnesota (Minnesota Pollution Control Agency, 2010), Iowa (Miller et al., 2013), New Jersey (Minnicino et al., 1993), and Massachusetts (Sengupta, 2007). In 2002, Florida finalized its BUD for street sweeping debris. This decision was made after an extensive chemical characterization of both the total and leachable concentrations of metals, volatile organic compounds, semi-volatile organic compounds, and herbicides (Jang et al., 2010; Townsend et al., 2002). Prior to this, Florida had classified street sweepings as a Class I (solid waste), meaning that the material, although not hazardous, had to be disposed of in a properly lined and certified landfill (Townsend et al., 2002).

Metals in RDS

Metals in RDS come from a number of sources. Metals are released from vehicles through brake pad wear, vehicle corrosion, and exhaust emissions. Br, Cr, Cu, Pb, and Zn are some of the most prevalent metals found in RDS (Apeageyi et al., 2011; Cincotti et al., 2006; Duong and Lee, 2011; Herngren et al., 2006; Pant and Harrison, 2013; Thorpe and Harrison, 2008; Yuen et al., 2012). The degree of metal constituents associated with vehicles is dependent upon a number of variables including the volume of traffic, land use of the surrounding area, and speed of vehicles (Herngren et al., 2006; Pant and Harrison, 2013; Yuen et al., 2012). At high speeds, such as on highways, metals are released at a higher rate from increased tire wear. At slow speeds, metals such as Cu, Cd, Cr, Iron (Fe), Pb, and Zn are also released from increased brake wear typical of stop-and-go traffic (Apeageyi et al., 2011; Duong and Lee, 2011; Thorpe and Harrison, 2008). These particles can have concentrations of Cu, Cd, Cr, Fe, Zn, and Pb ranging from 70-39,400 mg/kg, 0.06-2.6 mg/kg, 135-1320 mg/kg, 1.1-53.7 mg/kg, 120-27,300 mg/kg, and 4-1,290 mg/kg, respectively (Thorpe and Harrison, 2008).

The land use of the surrounding area is another important factor that has been found to have an effect on the presence of metal constituents in RDS (Gunawardana et al., 2012; Miller et al., 2013; Yuen et al., 2012). Previous studies have found that as the land use becomes more industrialized and/or developed, the concentration of metals found in RDS also increases. In a study by Gunawardana et al. (2012) in Queensland, Australia, RDS samples were collected from a number of locations based on land use. These land uses included industrial, residential,

commercial, and mixed designations. Samples collected from these sites were analyzed for Fe, aluminum (Al), Zn, magnesium (Mn), Cu, Pb, nickel (Ni), Cr, and Cd. The results of their analysis are provided in Table 3. Again, a distinct trend can be seen with regard to the industrial and residential concentrations of these metals.

Table 3. Metal Loading (mg/m²) Across Four Land Use Categories in Queensland, Australia

Land Use	Fe	Al	Zn	Mn	Cu	Pb	Ni	Cr	Cd
Industrial	110	51	5.25	2.35	1.63	0.73	0.163	9.7x10 ⁻²	5.8x10 ⁻³
Residential	53	36.5	2	1.15	0.69	0.24	5.5x10 ⁻²	7.5x10 ⁻²	3.4x10 ⁻³
Mixed	101	55	4.85	1.7	1.18	0.97	0.122	0.211	5.2x10 ⁻³
Commercial	55	23	2.3	1.25	1.67	0.81	7.8x10 ⁻²	5.7x10 ⁻²	1.7x10 ⁻²

Fe = iron, Al = aluminum, Zn = zinc, Mn = magnesium, Cu = copper, Pb = lead, Ni = nickel, Cr = chromium, Cd = cadmium. Data from Gunawardana et al., 2012.

PAHs

PAHs are a group of semi-volatile hydrocarbons that can be found in all petroleum products and also result from the incomplete combustion of materials such as wood, oil, coal, gasoline, etc. (Abdel-Shafy and Mansour, 2015; Dickhut et al., 2000). Although many PAHs are ubiquitous throughout the environment, the EPA identified 16 as primary constituents of concern, as listed in Table 4. PAHs have been found to persist in the environment for long periods of time in the sediments of rivers and lakes (Bostrom et al., 2002). This can be attributed to their non-polar structure giving them a strong hydrophobicity and preference to sorb to particulate matter (Abdel-Shafy and Mansour, 2015).

Table 4. EPA's 16 Priority Polycyclic Aromatic Hydrocarbons (PAHs), Number of Aromatic Rings, and Possible Sources

PAH	No. of Rings	Sources
Nap	2	1,2,3
Ana	3	1,3,4
Any	3	1,2,3,
Ant	3	4
Phen	3	3,4,5,6,7
Flu	3	1,2,3,4,5
Fla	4	3,4,5,6,7
BaA	4	3,4,7
CHR	4	3,4,7
Pyr	4	3,5,6,7,8
BaP	5	3,4,7,8
BbF	5	2,3,4
BkF	5	2,3,4
DahA	6	2,3,4,8
BghiP	6	2,3,4,8
IP	6	2,3,4,8

EPA = U.S. Environmental Protection Agency, Nap = naphthalene, Ana = acenaphthene, Any = acenaphthylene, Ant = anthracene, Phen = phenanthrene, Flu = fluorene, Fla = fluoranthene, BaA = benzo(a)anthracene, CHR = chrysene, Pyr = pyrene, BaP = benzo(a)pyrene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BahA = dibenz(a,h)anthracene, BghiP = benzo(g,h,i)perylene, IP = indeno[1,2,3-cd]pyrene. 1 = Coke Oven, 2 = Oil Combustion, 3 = Gas Combustion, 4 = Diesel Combustion, 5 = Incineration, 6 = Wood Combustion, 7 = Coal Combustion, 8 = Tire Wear. Data from Liu et al., 2016.

In RDS, higher concentrations of PAHs are most commonly found during the colder winter months as the decreased ambient temperature prevents them from volatilizing (Abdel-Shafy and Mansour, 2015; Harrison et al., 1996; Liu et al., 2010). It is common for the overall concentration of PAHs in a sample to be represented as the sum of the individual PAH compound (Σ PAH) concentrations. This is done in order to make comparison of results easier and to provide quick insight into the relative level of contamination. However, it can prove to be misleading since it does not take into account the characteristics of each individual component. For instance, PAHs with a higher molecular weight like benzo(a)pyrene (BaP) are generally considered to be more concerning for human health than lighter compounds such as naphthalene (Nap) (Liu et al., 2016). Attributes like this are not accounted for in the Σ PAH value.

It has been found that the land use of an area can have a significant impact on the concentrations of PAHs present in the environment (Bucheli et al., 2004; Lau and Stenstrom, 2005; Mielke et al., 2004). For instance, in a 2005 study by Lau and Stenstrom (2005), RDS samples were taken from 18 locations in Los Angeles, California, with the following land use categories: industrial, multi-family residential, single-family residential, roads, and commercial. The study found that of the five land use categories, the commercial land use had the highest Σ PAH concentration with an average of 14.5 $\mu\text{g/g}$, followed by roads with an average of 10.2 $\mu\text{g/g}$, industrial with 9.2 $\mu\text{g/g}$, multi-family residential with 7.2 $\mu\text{g/g}$, and single-family residential with an average of 2.2 $\mu\text{g/g}$ (Lau and Stenstrom, 2005). Other studies have found similar results for soil samples taken adjacent to busy streets, residential streets, and open areas and at the foundations of buildings in both suburban and urban areas (Mielke et al., 2004). When considering the effect of ADT on PAH concentration, studies have found that some of the lowest concentrations of PAHs were in the highest ADT categories considered. Wang et al. (2010) took samples of RDS from roads across five ADT classifications ranging from 3,000 to 110,000 and a walking street with an ADT of 0. The study found that the walking street with no exposure to vehicle traffic had the second highest Σ PAH concentration (3.4 mg/kg) and the road with the 3,000 ADT classification had the highest Σ PAH concentration (3.52 mg/kg) (Wang et al., 2010). Further, the highest concentration of benzo(a)pyrene, one of the most concerning of the EPA's 16 priority PAHs, was found at the walking street location. Other studies have found similar results for material collected from the shoulder of the road (Van Dolah et al., 2005).

Effect of Particle Size on Metals and PAH Concentrations

A number of factors can affect the particle size distribution of RDS. Increased vehicular traffic can break down larger particles, increasing the amount of fines. Variations in wet and dry periods can lead to fines either washing off or building up on the roadway (Wijesiri et al., 2015). In addition, abrasives applied during the winter season for traction can increase the amount of coarse material. It is well understood that as the particle size decreases, the specific surface area increases. This greater specific surface area typically correlates with increased sorption of PAHs and metals (Azah et al., 2015; Gunawardana et al., 2014; Lau and Stenstrom, 2005; Wang et al., 2010). A number of studies have found that the majority of constituents of concern in RDS can be found in the smaller size fractions in the 0-300 μm range (Azah et al., 2015; Sutherland et al., 2012; Tian et al., 2009; Wang et al., 2010).

O&G

O&G is made up of both fatty material from plants and animals and aliphatic hydrocarbons (Boxall and Maltby, 1995; Khan et al., 2006; Rauckyte et al., 2010; Stenstrom et al., 1984). On a roadway, O&G is most commonly associated with motor oil and other lubricating oils used in passenger vehicles and trucks. Their presence can easily be identified by an iridescent sheen they give to surface waters (Khan et al., 2006; Stenstrom et al., 1984). Increased concentrations of O&G are most commonly found in parking lots and areas where vehicle traffic is slow moving (Stenstrom et al., 1984). O&G is commonly considered an important aspect of stormwater runoff and has been studied predominantly in the liquid fraction of runoff. Little is known about the interaction of RDS and O&G.

Sample Analysis

Metals

As can be seen in Table 5, the most prominent metal in all of the samples collected was Zn, with an average of 30.17 mg/kg. This result is not surprising since Zn is a primary constituent in brake components and tires (Thorpe and Harrison, 2008). Zn concentrations in tire treads can range from 5,650-9,640 mg/kg and in brake pad dust can range from 120-27,300 mg/kg (Thorpe and Harrison, 2008). Both of these sources can provide a significant amount of Zn on and around the road.

These average concentrations pass the VDEQ Table 1 beneficial fill SLs for groundwater protection but do not pass the Table 1 ecological SL or the Tables 2 and 3 SLs for residential and industrial areas. Table 6 provides an overview of how these results compare to the SLs. The average concentrations of Cd, As, and Cr specifically are very close to the Table 1, 2, and 3 SLs, respectively. The degree to which these two metals exceed the SLs is well within the standard error (SE) of these data sets (As SE = 0.08 mg/kg, Cd SE = 0.656 mg/kg, Cr SE = 1.641 mg/kg). With this taken into account, the material could pass all SLs except the Table 2 SL for Cr. It should be noted that the results of the Cr analysis represent a total Cr concentration and do not differentiate between Cr III and VI. These two species have different sets of SLs because of differences in toxicity. For the purpose of this study, the Cr VI SLs were used, as they are more stringent. If these results were compared to the Cr III SLs of 1.20×10^4 mg/kg for Table 2 and 1.50×10^5 mg/kg for Table 3, they would be well below the threshold.

Table 5. Average Concentrations of Metals in All Samples Collected

Metal	Concentration (mg/kg)
Arsenic	0.393
Lead	7.288
Selenium	0.323
Barium	13.688
Chromium	5.966
Silver	0.046
Cadmium	0.827
Copper	0.888
Zinc	30.168

Table 6. Average Concentrations of Metals Compared to Soil Screening Levels

Metal	Avg. Concentration (mg/kg)	Table 1 (Protection of Groundwater and Ecological Receptors)		Table 2 (Soil: Residential and Other High Frequency Receptors)	Table 3 (Soil: Restricted (Commercial/ Industrial))
		Beneficial Fill Ecological Screening Level (mg/kg)	Beneficial Fill Groundwater Protection Screening Level (Soil to GW) (mg/kg)	Beneficial Fill Residential Screening Level (mg/kg)	Beneficial Fill Industrial Screening Level (mg/kg)
Arsenic	0.393	18	2.91	0.390	1.6
Barium	13.688	330	822	1,500	19,000
Cadmium	0.827	0.360	3.76	7.00	80.00
Chromium	5.966	26.00	19.10	0.290	5.60
Copper	0.888	28	5,570	310	4,100
Lead	7.288	11	135	400	800
Selenium	0.323	0.519	2.55	39	510
Silver	0.046	4.2	0.596	39	510
Zinc	30.168	46	292	2,300	31,000

Screening levels From VDEQ's Division of Land Protection & Revitalization State-Wide Variance Guidance Memo No. LOPR-SW-04-2012: Management and Reuse of Contaminated Media (Steers, 2012). Values in bold indicate concentrations above the regulatory screening level.

Concentration Based on ADT

None of the metals was correlated with traffic volume when plotted against ADT. The R² values of all nine metals are provided in Table 7. These results are both in contrast and comparison to the findings of others. For instance, Irvine et al. (2009) found that the concentrations of Cd, Cu, Pb, and Zn in street sweeping material increased as ADT increased. For Cu and Pb, the concentrations about doubled with the increase in ADT (Irvine et al., 2009). Their results are provided in Table 8.

However, in another study, Liu et al. (2015) found that at higher ADT loads the volume of traffic becomes less of an influencing factor in comparison to traffic congestion. Although the study found a positive correlation between increased metal loads and traffic congestion, there was a negative correlation between traffic volume and Cu, Zn, Cd, and Ni loads. Further, the authors found a positive correlation between metal loads and roughness of the road (Liu et al., 2015). This would indicate that on higher ADT roads, the volume of traffic becomes less important than the amount of stop-and-go traffic in conjunction with the roughness of the road. These factors could cause material to be dislodged from vehicles by bumps in the road.

Table 7. R² Values of Linear Regression Plots of Metal Concentration Versus Average Daily Traffic Volume

Metal	R ²
Arsenic	1.21x10 ⁻³
Lead	2.20x10 ⁻³
Selenium	5.50x10 ⁻⁴
Barium	1.70x10 ⁻²
Chromium	4.60x10 ⁻⁵
Silver	5.10x10 ⁻⁵
Cadmium	3.64x10 ⁻²
Copper	9.21x10 ⁻²
Zinc	1.60x10 ⁻⁴

Table 8. Metal Concentrations in Road Deposited Sediment Collected From Commercial/Residential Land Use

Average Daily Traffic	Cd (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
13,560-70,137	2	164	165	544
<13,560	1.5	73.5	84.9	413

Cd = cadmium, Cu = copper, Pb = lead, Zn = zinc. Data from Irvine et al., 2009.

Concentration Based on National Land Cover Database Categories

In terms of land cover, each metal behaved differently. For example, Pb, Ba, and Ag concentrations decreased with decreasing land cover intensity. By contrast, Se concentrations increased with decreasing land cover intensity. However, the small increase of 0.05 mg/kg in the concentration of Se was most likely due to natural variances in the data. Other metals such as Cr, Cd, and As had a spike in concentration in the developed, high intensity NLCD category but remained relatively constant across the developed, medium intensity; developed, low intensity; and developed, open space categories. Figure 1 presents the results of the metals characterization with respect to NLCD category. A table of these results is provided as Table B-1 in Appendix B. This shows that although the concentration of certain metals in RDS can be

predicted by land cover, the concentration of metals in general cannot. These results are again in contrast to those in the literature. For example, a 2009 study in Seattle found a consistent trend of increased average levels of Cd, Cu, Pb, and Zn in industrial sweeper waste vs. residential sweeper waste (Miller et al., 2013). This was especially true for Cu and Pb, with an increase of 48% and 67%, respectively (Miller et al., 2013).

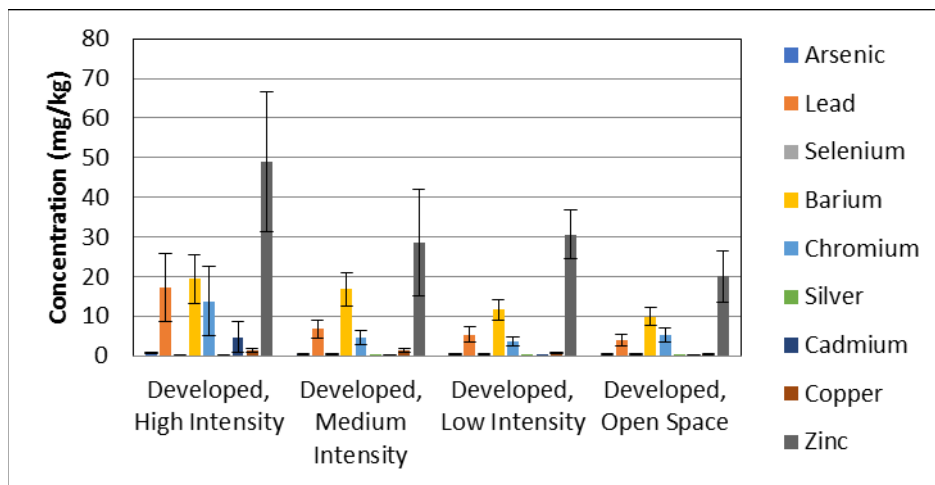


Figure 1. Average Concentrations of Arsenic, Lead, Selenium, Barium, Chromium, Silver, Cadmium, Copper, and Zinc for the Four National Land Cover Database Categories Considered in This Study. Error bars represent the standard error for each group of samples.

PAHs

A total of 27 locations were selected for PAH analysis. This allowed for at least one sample for each ADT and NLCD classification. As can be seen in Table 9, on average the PAH with the highest concentration was fluoranthene (Fla) with an average concentration of 4,065.12 $\mu\text{g}/\text{kg}$. The compound with the lowest average concentration was naphthalene (Nap) with an average concentration of 26.83 $\mu\text{g}/\text{kg}$.

When comparing these results to the screening levels provided in VDEQ’s Division of Land Protection & Revitalization State-Wide Variance Guidance Memo No. LOPR-SW-04-2012: Management and Reuse of Contaminated Media (Steers, 2012), the material does not pass the Table 1, 2, or 3 screening levels, as can be seen in Table 10. Of the eight PAHs listed in Table 10, four of them (benzo(a)anthracene [BaA], Fla, pyrene [Pyr], and Nap) are known to result from the combustion of diesel fuel or other fuel oils (Liu et al., 2016). This would indicate that vehicular activity is contributing to these increased concentrations. Further, the majority of these samples were collected during the cold month of February.

As stated previously, in RDS, increased levels of PAHs are more commonly found during the colder winter months because of their volatile nature (Abdel-Shafy and Mansour, 2015; Harrison et al., 1996; Liu et al., 2010). This trend can be seen in Figure 2 where the average ΣPAH concentration was highest in samples collected during the month of February. This could be a reason, as is evident in Table 11, that higher concentrations of PAHs were found in this study compared to other studies.

Table 9. Average Overall Concentrations of Polycyclic Aromatic Hydrocarbons (PAHs)

PAH	Concentration ($\mu\text{g}/\text{kg}$)
Nap	26.825
Any	47.612
Ana	100.931
Flu	136.419
Phen	1,797.368
Ant	241.546
Fla	4,065.118
Pyr	2,955.133
BaA	1,232.488
BbF	1,639.618
BkF	897.315
BaP	1,308.665
BghiP	1,084.499
DahA	44.429
IP	927.529
ΣPAHs	16,505.496

Nap = naphthalene, Any = acenaphthylene, Ana = acenaphthene, Flu = fluorene, Phen = phenanthrene, Ant = anthracene, Fla = fluoranthene, Pyr = pyrene, BaA = benzo(a)anthracene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BaP = benzo(a)pyrene, BghiP = benzo(g,h,i)perylene, DahA = dibenz(a,h)anthracene, IP = indeno[1,2,3-cd]pyrene, ΣPAHs = total concentration of polycyclic aromatic hydrocarbons.

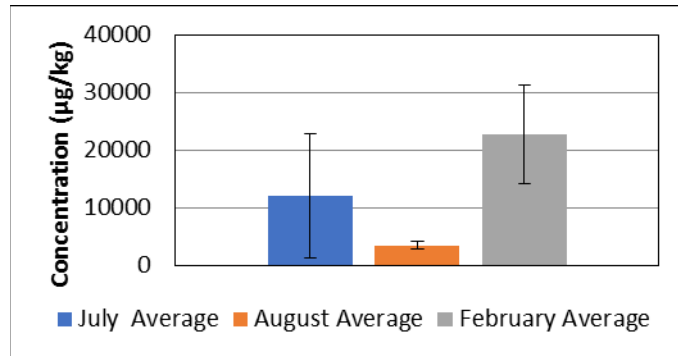


Figure 2. Average Concentration of Total Polycyclic Aromatic Hydrocarbons in Samples Collected During the Months of July, August, and February. Error bars represent the standard error for each group of samples.

Table 10. Average Concentrations of Polycyclic Aromatic Hydrocarbons (PAHs) Compared to Soil Screening Levels

PAH	Avg. Concentration (mg/kg)	Table 1 (Protection of Groundwater and Ecological Receptors)		Table 2 (Soil: Residential and Other High Frequency Receptors)	Table 3 (Soil: Restricted Commercial/Industrial)
		Beneficial Fill Ecological Screening Level (mg/kg)	Beneficial Fill Groundwater Protection Screening Level (Soil to GW) (mg/kg)	Beneficial Fill Residential Screening Level (mg/kg)	Beneficial Fill Industrial Screening Level (mg/kg)
Ana	0.101	29	17.2	340	3,300
Any	0.048	29	66.3	170	1,700
Ant	0.242	29	185	1,700	17,000
BaA	1.232	1.1	0.644	0.15	2.1
BaP	1.309	1.1	8.87	0.015	0.21
BbF	1.639	1.1	1.82	0.15	2.1
BghiP	1.084	1.1	19,400	170	1,700
BkF	0.897	1.1	18.2	1.5	21
DahA	0.044	1.1	0.427	0.015	0.21
Fla	4.065	1.1	278	230	2,200
Flu	0.136	29	17	230	2,200
IP	0.928	1.1	5.16	0.15	2.1
Nap	0.027	29	0.0149	3.6	18
Phen	1.797	29	160	170	1,700
Pyr	2.955	1.1	32.7	170	1,700

GW = groundwater, Nap = naphthalene, Any = acenaphthylene, Ana = acenaphthene, Flu = fluorene, Phen = phenanthrene, Ant = anthracene, Fla = fluoranthene, Pyr = pyrene, BaA = benzo(a)anthracene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BaP = benzo(a)pyrene, BghiP = benzo(g,h,i)perylene, DahA = dibenz(a,h)anthracene, IP = indeno[1,2,3-cd]pyrene, Σ PAHs = total concentration of polycyclic aromatic hydrocarbons. Values in bold indicate concentrations over the screening level. Screening levels from VDEQ's Division of Land Protection & Revitalization State-Wide Variance Guidance Memo No. LOPR-SW-04-2012 (Steers, 2012).

Table 11. Average Concentrations of Polycyclic Aromatic Hydrocarbons (PAHs) (μ g/kg) From Soils and Road Deposited Sediment Collected in Other Studies

PAH	Mielke et al. (2004)	Sengupta (2007)	Townsend et al. (2013)	This Study
Nap	2-10	ND	1,400	26.825
Ana	1-5	NA	1,200	100.931
Any	0-9	NA	<3	47.612
Ant	7-38	87-150	60	241.546
Phen	21-133	270-1,200	270	1,797.368
Flu	0-3	ND	<1	136.419
Fla	82-266	760-2,500	1,300	4,065.118
BaA	28-145	290-780	360	1,232.488
CHR	32-111	400-1,300	460	ND
Pyr	67-237	660-1,900	610	2,955.133
BaP	141-255	330-1,000	380	1,308.665
BbF	94-319	370-2,100	90	1,639.618
BkF	24-95	410-1,100	60	897.315
DahA	123-208	110-210	270	44.429
BghiP	122-237	350-730	1,500	1,084.499
IP	202-322	280-750	120	927.529
Σ PAH	975-2,469	4,317-13,720	8,084	16,505.496

Nap = naphthalene, Any = acenaphthylene, Ana = acenaphthene, Flu = fluorene, Phen = phenanthrene, Ant = anthracene, Fla = fluoranthene, Pyr = pyrene, BaA = benzo(a)anthracene, CHR = chrysene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BaP = benzo(a)pyrene, BghiP = benzo(g,h,i)perylene, DahA = dibenz(a,h)anthracene, IP = indeno[1,2,3-cd]pyrene, Σ PAHs = total concentration of polycyclic aromatic hydrocarbons, ND = non detect, NA = not applicable.

Concentration Based on Average Daily Traffic

The PAH with the highest R^2 value when plotted against ADT was acenaphthene (Ana) ($R^2 = 0.035$). This PAH has been identified as resulting from the combustion of gasoline and diesel fuel; therefore, a correlation between Ana concentration and ADT is expected for roadside particles (Liu et al., 2016). However, this R^2 value still inspires little confidence in the correlation of ADT and PAH concentration. The R^2 values of all PAHs are provided in Table 12. With the exception of Ana and fluorene (Flu), the highest concentrations for all other PAHs were in one site with an ADT of 4,100. This site could be contributing to some skewedness of the data. However, if this data point is removed as an outlier, the next highest Ana and Flu concentrations were at a site with an ADT of 210, indicating that PAH concentration and ADT are not correlated. As discussed previously, similar results were found in other studies (Wang et al., 2010). Although a number of PAHs have been found to result from the combustion of automotive fuels, it appears that the volume of traffic may be preventing these compounds from being deposited on the roadway. This is possibly due to the dispersion of particles from the road by passing vehicles. It has been shown that increasing the traffic volume can lead to finer particles in the RDS (Cai et al., 2007). Perhaps these finer particles are being kicked up into the air and deposited elsewhere, leading to a decrease in concentration on the roadway.

Table 12. R^2 Values for Polycyclic Aromatic Hydrocarbons (PAHs) When Plotted Against Average Daily Traffic

PAH	R^2
Nap	2.97×10^{-3}
Any	$.3 \times 10^{-5}$
Ana	3.47×10^{-2}
Flu	2.82×10^{-2}
Phen	1.04×10^{-2}
Ant	1.21×10^{-2}
Fla	6.7×10^{-4}
Pyr	3.5×10^{-4}
BaA	8.5×10^{-4}
BbF	1.7×10^{-4}
BkF	1.0×10^{-4}
BaP	3.1×10^{-4}
BghiP	3.5×10^{-4}
DahA	1.08×10^{-2}
IP	7.4×10^{-4}
$\Sigma 16$ PAHs	1.05×10^{-3}

Nap = naphthalene, Any = acenaphthylene, Ana = acenaphthene, Flu = fluorene, Phen = phenanthrene, Ant = anthracene, Fla = fluoranthene, Pyr = pyrene, BaA = benzo(a)anthracene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BaP = benzo(a)pyrene, BghiP = benzo(g,h,i)perylene, DahA = dibenz(a,h)anthracene, IP = indeno[1,2,3-cd]pyrene, Σ PAHs = total concentration of polycyclic aromatic hydrocarbons.

Concentration Based on National Land Cover Database Categorization

In terms of land cover, similar results were found. Although it was expected that the most highly developed and industrialized areas would have the highest concentrations of PAHs, as can be seen in Figure 3, this is not the case.

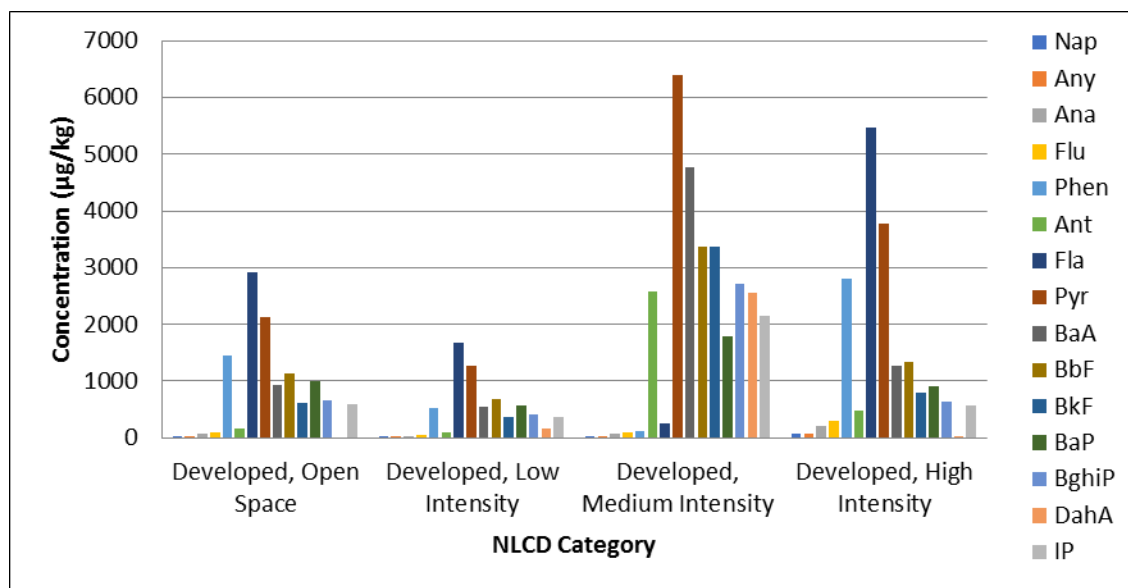


Figure 3. Concentrations of Polycyclic Aromatic Hydrocarbons for the Four National Land Cover Database (NLCD) Categories Considered in This Study. Nap = naphthalene, Any = acenaphthylene, Ana = acenaphthene, Flu = fluorene, Phen = phenanthrene, Ant = anthracene, Fla = fluoranthene, Pyr = pyrene, BaA = benzo(a)anthracene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BaP = benzo(a)pyrene, BghiP = benzo(g,h,i)perylene, DahA = dibenz(a,h)anthracene.

The highest average concentration of PAHs was in the developed, medium intensity NLCD category. Lighter PAHs such as Nap, acenaphthylene (Any), and Ana on the other hand did show a slight increasing trend with increasing intensity of land cover. For instance, the sum of two-ring and three-ring PAHs (Nap, Ana, Any, anthracene [Ant], phenanthrene [Phen], and Flu) almost doubled from about 1,800 µg/kg to 3,968 µg/kg between the developed, open space and developed, high intensity NLCD categories. Since these PAHs are naturally more volatile and short lived in the environment, this could indicate that higher intensity land covers have chronic contamination of PAHs (Cai et al., 2007; Mielke et al., 2004).

Within each NLCD category, a correlation between ADT and PAH concentration could be seen. This correlation was highest in the developed, high intensity NLCD category. In Figure 4, for benzo(a)pyrene (BaP) in the developed, high intensity NLCD category, as an example, there is a strong positive correlation between ADT and PAH concentration. However, as land cover intensity decreases, the slope of the line becomes negative. Based on the R^2 values, ADT was most strongly correlated with PAH concentration in the developed, high intensity NLCD category. The trends for all 15 PAHs detected in this study were similar to that for BaP.

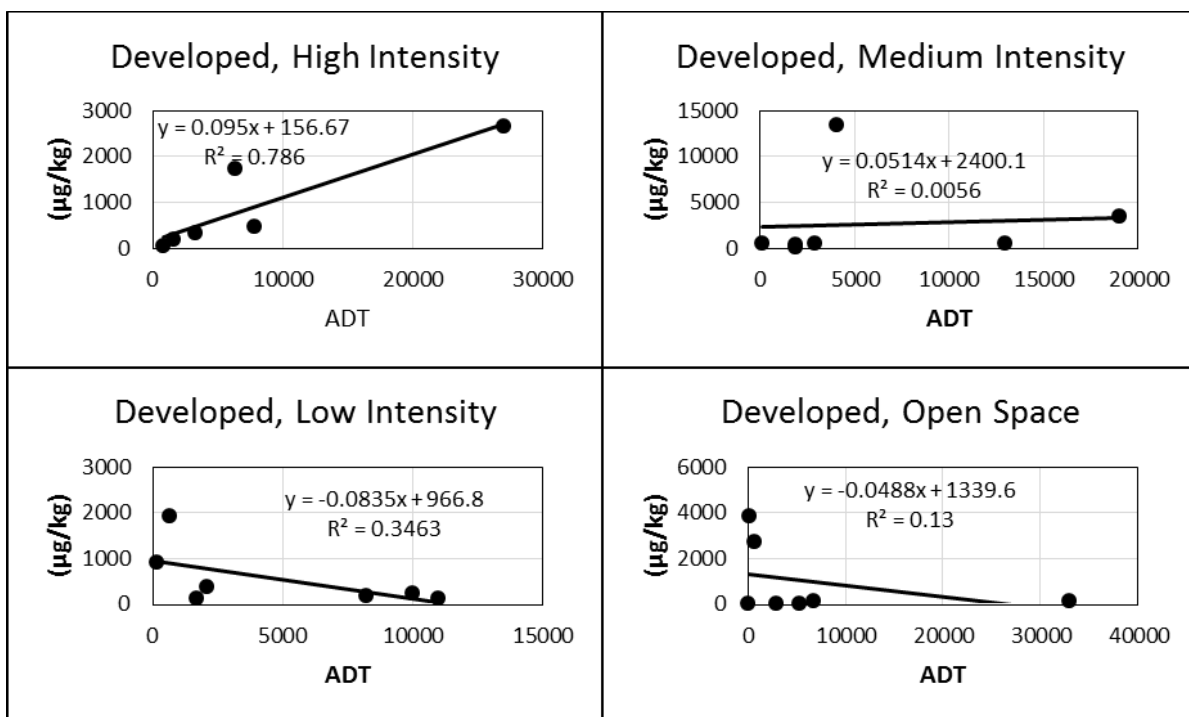


Figure 4. Concentrations of Benzo(a)pyrene as a Function of Average Daily Traffic for the Four National Land Cover Categories Considered in This Study. ADT = average daily traffic.

Effect of Particle Size on PAH and Metal Concentrations

The results of this study show that concentrations of PAHs and metals in RDS are minimally affected by ADT and land cover. The third variable considered in this study was particle size. Samples from two of the 4,001-10,000 ADT categories in each of the four NLCD classifications were used to determine the concentrations of both metals and PAHs in the ≥ 1.18 mm, 600 μm -1.18 mm, 300-600 μm , 150-300 μm , 75-150 μm , 150-75 μm , and < 75 μm screen sizes. The results of the analysis are presented in Table B-2 in Appendix B and Table C-1 in Appendix C.

All of the samples selected were screened through a stack of brass ringed sieves. Since brass is an alloy of both Cu and Zn, there was some concern that this set of samples had artificially high concentrations of these two elements because of wear-related particles originating from the sieves. In order to account for this, virgin natural sand was sampled before and after sieving to determine the relative level of contamination of the samples. There was no detectable concentration of Cu found in either the before or after sieve samples. The concentration of Zn in these samples increased from 0.24 mg/kg before sieving to 0.69 mg/kg after sieving. This increase is small in comparison to the concentrations of Zn in the actual field samples, which ranged from 16.7-289 mg/kg.

Figure 5 depicts the particle size distribution of the RDS collected in this study. More than 22% of the material collected was smaller than 300 μm . Although the material consisted primarily of larger particles, the following results indicate that the majority of the metal and PAH load resided in the finer fraction.

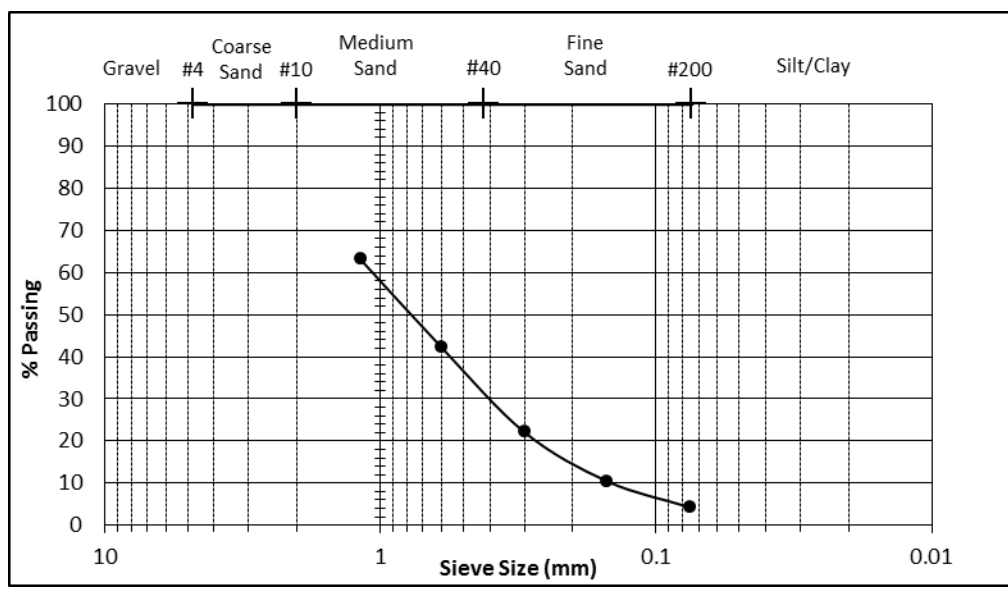


Figure 5. Particle Size Distribution of Road Deposited Sediment

Metals

The concentrations of eight of the nine metals considered in this study increased with decreasing particle size. Cd was the exception, as can be seen in Figure 6. The spike in Cd in the 300-150 µm size was due to one value in the data set that was well above the rest in the series. When this data point was removed, the trend for Cd was similar to those for the other metals.

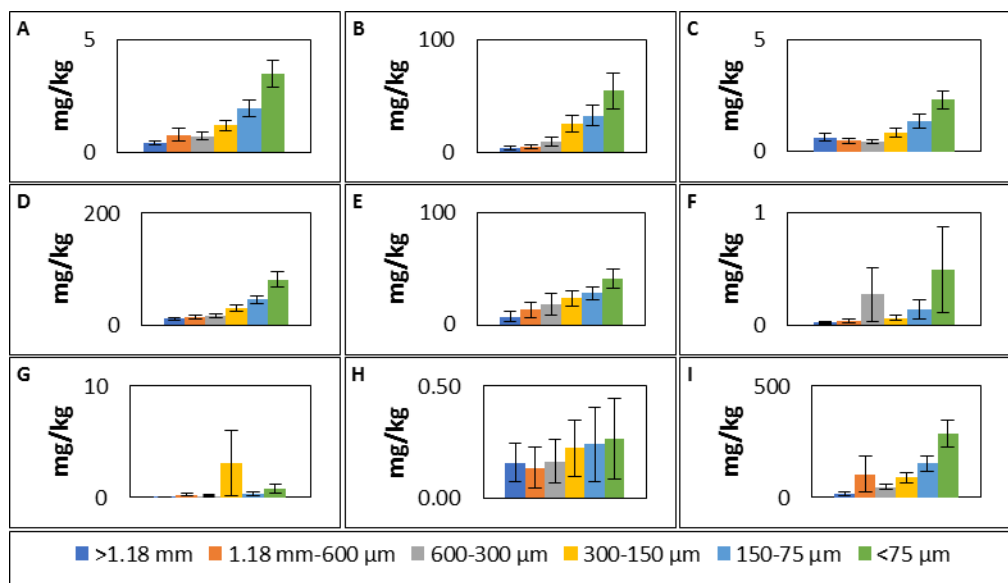


Figure 6. Concentrations of Arsenic, Lead, Selenium, Barium, Chromium, Silver, Cadmium, Copper, and Zinc for the Particle Size Categories Used in This Study. Error bars represent the standard error of the group of samples. A = arsenic, B = lead, C = selenium, D = barium, E = chromium, F = silver, G = cadmium, H = copper, I = zinc.

Between 23% and 83% (depending on the metal) of the concentration of the metal was found on particles smaller than 300 μm , a size fraction that on average makes up only 22% of the total mass. Given this, if particles smaller than 300 μm are screened and removed, significant reductions in the concentrations of metals could be made. Gunawardana et al. (2014) found similar results where 60% of the concentration of metals was sorbed onto particles smaller than 150 μm . These results confirm the hypothesis that metal concentration is negatively correlated to particle size.

PAHs

Similar to the results of the metals analysis, PAHs show a strong affinity for finer particles. For all PAHs, there was a steady rise in concentration as particle size decreased, as is evident in Figure 7. Since PAHs preferentially partition onto the soil organic matter and finer sediment particles typically have a higher percentage of soil organic matter, these results are to be expected (Abdel-Shafy and Mansour, 2015; Bucheli et al., 2004). Again, as with the metals analysis, although only about 20% of the particles were smaller than 300 μm , they contained up to 78% of the pollutant load of PAHs. This indicates that a 78% reduction in PAH concentration could be had if particles smaller than 300 μm were screened. Wang et al. (2010) found similar results across a range of particle sizes from street dust. The authors broke down their samples into five size fractions including <40 μm , 40-74 μm , 74-125 μm , 125-300 μm , and 300-500 μm . Although on average the 125-300 μm size fraction made up the majority of the sample mass at 31%, particles smaller than 40 μm had the highest concentration of $\Sigma 16\text{PAHs}$ (Wang et al., 2010).

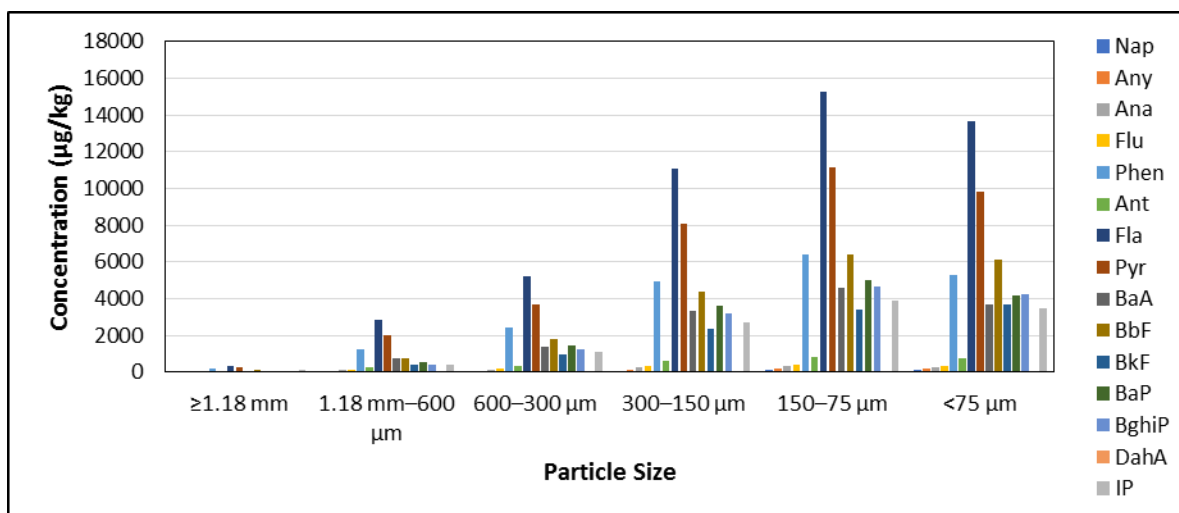


Figure 7. Concentrations of Polycyclic Aromatic Hydrocarbons for the Particle Size Categories Used in This Study. Nap = naphthalene, Any = acenaphthylene, Ana = acenaphthene, Flu = fluorene, Phen = phenanthrene, Ant = anthracene, Fla = fluranthene, Pyr = pyrene, BaA = benzo(a)anthracene, BbF = benzo(b)fluoranthene, BkF = benzo(k)fluoranthene, BaP = benzo(a)pyrene, BghiP = benzo(g,h,i)perylene, DahA = dibenz(a,h)anthracene, IP = indeno[1,2,3-cd]pyrene.

O&G

The majority of studies on O&G pertain to its concentration in stormwater runoff or the sediment of rivers, lakes, and streams. Very few studies currently exist on O&G concentrations in RDS. Because of this, the results of this study provide new insight into a constituent commonly associated with the liquid fraction of road runoff. All 79 samples were tested for O&G. The concentrations of O&G in the samples ranged from 33.6-3,440.914 mg/kg. As can be seen in Figure 8, the developed, high intensity NLCD category had the highest average O&G concentrations with an average of 1,338.08 mg/kg. In contrast, the developed, open space NLCD category had the lowest average concentration at 312.433 mg/kg. This represents an almost 77% reduction in O&G concentration between the highest and lowest intensity NLCD category. Similarly, a 54% reduction was seen between the developed, high intensity and developed, medium intensity NLCD categories. Similar to the results from the PAH and metals analysis, a small degree of correlation was shown between ADT and O&G concentrations. These results can be seen in Figure 9. These results indicate that although ADT may not be a good predictor of O&G concentrations in RDS, land cover could provide better insight.

The concentration range of O&G found in this study is comparable with that in other studies of O&G concentrations in RDS. For instance, Pulley and Baird (2010) measured the concentrations of O&G from traction sand recovered from 27 sites on the shoulder of the road and seven samples from stockpiled street sweeping material. The average concentration on the shoulder of the road was 1,959 mg/kg and from the stockpile was 1,211 mg/kg (Pulley and Baird, 2010). The authors attributed this decrease in concentration to weathering of the stockpiled material. As the material is exposed to snow and rain, O&G can be leached out of the material and washed away. Another interesting trend can be seen with regard to the maximum concentrations of O&G in road and stockpile samples. Road samples had a maximum concentration of 6,200 mg/kg, and stockpiled material had a maximum concentration of 1,700 mg/kg. This indicates that once O&G is mixed into a stockpile, the overall concentration of O&G, and for that matter any other constituent, can be diluted by other cleaner material.

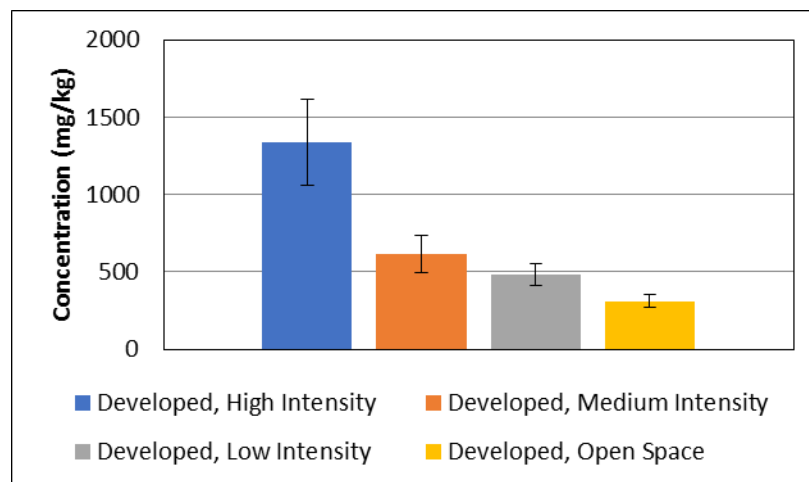


Figure 8. Concentrations of Oil and Grease for the Four National Land Cover Database Categories Considered in This Study. Error bars represent the standard error of the group of samples.

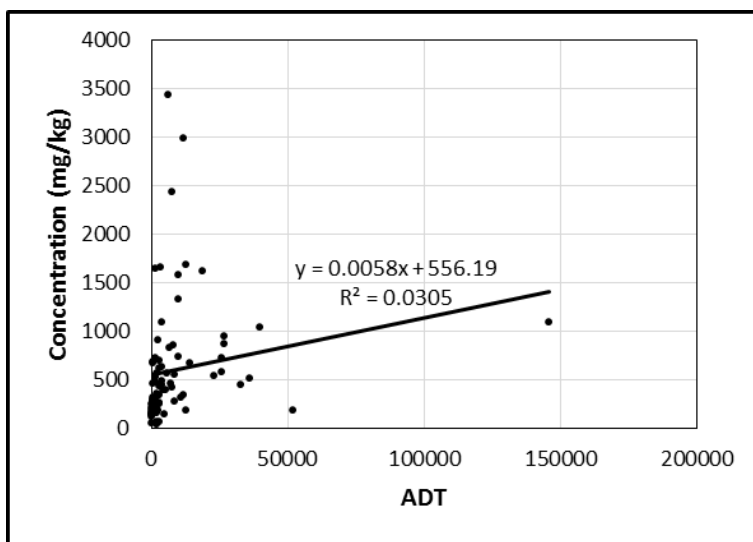


Figure 9. Concentration of Oil and Grease as a Function of Average Daily Traffic. ADT = average daily traffic.

CONCLUSIONS

- *Based on the results of the metals analysis in this study, the material collected through street sweeping is not suitable for reuse according to the SLs administered by VDEQ. However, as can be seen in Table 6, only three (As, Cd, Cr) of the nine metals considered in this study had average concentrations above one of the three SLs. In several of these cases, the average concentration was very close to the SL and well within the standard error of the sample population.*
- *Based on the results of the PAH analysis in this study, the material is not suitable for reuse according to the SLs administered by VDEQ. As can be seen in Table 10, 8 of the 15 PAHs considered had average concentrations above one or more of the SLs. These results indicate that screening or another form of processing of the material would be necessary before reuse would be possible.*
- *Based on the results of this study, ADT cannot be used to predict reliably whether or not sediment collected from a road will have elevated concentrations of metals, PAHs, or O&G.*
- *Based on the results of this study, land cover cannot be used to predict reliably whether or not sediment collected from a roadway will have elevated concentrations of metals or PAHs. However, O&G concentrations decreased with decreasing land cover intensity, indicating a correlation between these two factors.*
- *Based on the results regarding the size-fractionated samples, particle size has a strong negative correlation with the concentration of both metals and PAHs.*

- *Based on the results regarding the size-fractionated samples, the finer fraction (smaller than 300 μm) of RDS contains the majority of metal and PAH load but makes up only 20% of the total mass.*
- *Reductions in concentrations of up to 70% for ΣPAHs and from 23% to 84% for metals could be realized if particles smaller than 300 μm were screened from the collected material.*
- *Particles greater than 300 μm make up about 80% of the mass of this material. This indicates that if the material were screened, VDOT would potentially be able to reuse the large majority of the material it is collecting.*
- *Further studies could be conducted to determine the effectiveness and feasibility of processing methods such as screening of fines to reduce the concentrations of the constituents considered in this study. This should include an analysis of the costs associated with effectively screening this material at the relative scale it is collected.*

RECOMMENDATIONS

1. *VDOT should not submit for a BUD approval at this time.* The results of this study indicate that more information is needed on the possible treatment methods of the material collected by street sweepers.
2. *Upon the request of VDOT's Environmental Division, the Virginia Transportation Research Council (VTRC) should conduct a survey of VDOT's districts, residencies, and area headquarters to determine the quantities of material collected from street sweeping activities.* This survey would also include questions regarding the relative demand for reuse of this material.
3. *If the results of Recommendation 2 indicate that the volume of material being collected by street sweeping activity warrants reuse, VTRC should conduct a smaller Phase 2 study to explore the possible treatment and reuse options for this material.* The study should also include a cost-benefit analysis based on the level and type of treatment required to reuse this material.

BENEFITS AND IMPLEMENTATION

Benefits

With regard to implementing Recommendation 1, the benefits include the prevention of a potentially unsuccessful BUD application. The requirements listed under Virginia Code 9VAC20-81-97 include a number of items that were not included in the scope of this study and would limit it from acceptance. Although this study provides an extensive chemical characterization of the material, the Code also requires a demonstration of need for the material and a definition of what those needs are. Therefore, an application for a BUD at this time would be premature and potentially detrimental to future BUD efforts for this material.

With regard to implementing Recommendation 2, the benefits include the fulfillment of one of the requirements under 9VAC-81-97, Beneficial Use Demonstration. This requirement states that there must be “[a] demonstration that there is a known or reasonably probable market for the intended use of the solid waste under review” (Virginia Waste Management Board, 2015). The results of the survey would provide VDOT with more information on the extent of need for regulatory relief regarding this material within VDOT. Further, the survey would provide insight into applications such as construction and maintenance activities in need of this material.

With regard to implementing Recommendation 3, the benefits include the determination of the relative cost and feasibility of treating this material to a level that is acceptable by both VDEQ and VDOT’s Maintenance Division. The results of the study would provide information useful to VDOT to determine the feasibility of reuse of this material. Based on the treatment that is required, it may or may not be determined that it is not beneficial to reuse this material based on cost or ease of treatment.

Implementation

Recommendation 1 will be implemented by VDOT’s Hazardous Materials Compliance Program Manager. The Program Manager has reviewed the research findings and has made the decision not to submit for a BUD approval at this time.

Recommendation 2 will be implemented by members of VTRC’s environmental research staff within 1 year of a request by VDOT’s Hazardous Materials Compliance Program Manager.

Recommendation 3 will be implemented by members of VTRC’s environmental research staff based on the results of and within 1 year of the completion of the survey outlined in Recommendation 2.

ACKNOWLEDGMENTS

This work would not have been possible without the funding from VTRC and the facilities and instrumentation provided by the University of Virginia’s Department of Civil and Environmental Engineering. Further, it would not have been possible without the help of VDOT’s Environmental Division Assistant Administrator Ed Wallingford and VDOT’s Compliance Program Manager David Wilson.

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APPENDIX A

MAP OF ALL 79 SAMPLING SITES ACROSS VIRGINIA

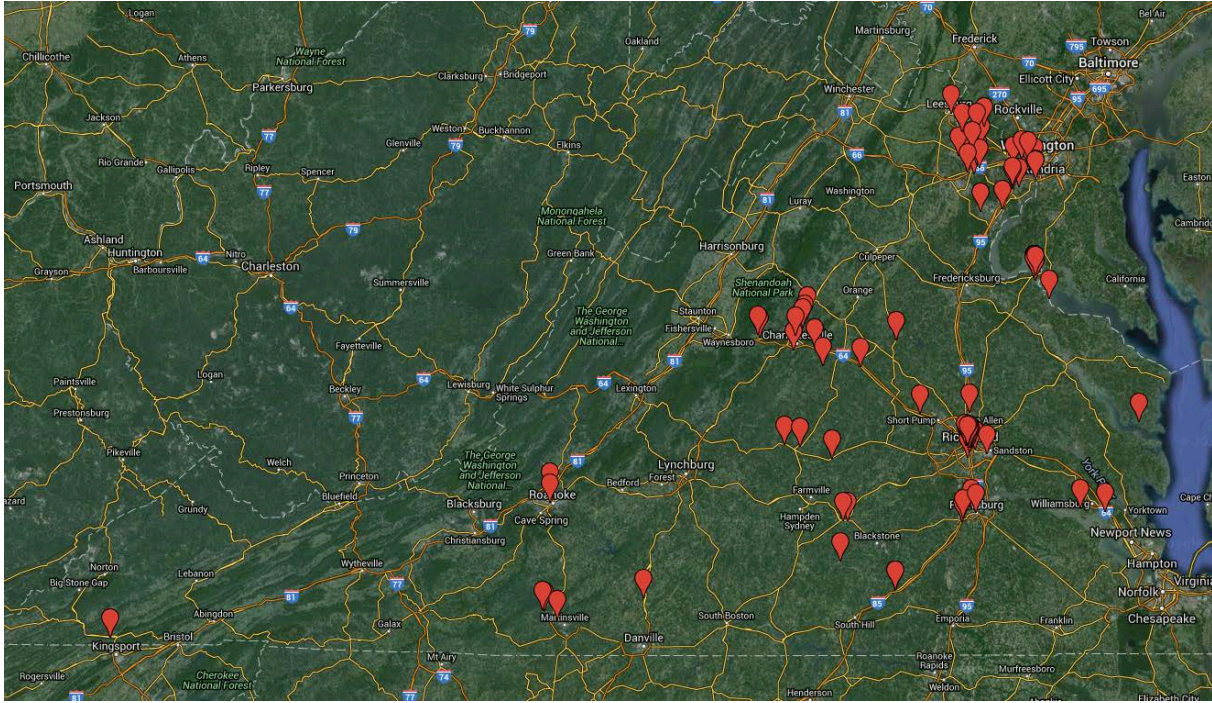


Figure A-1. Map of All 79 Sampling Sites Across Virginia. Each red icon represents one sampling location.

APPENDIX B

RESULTS OF METALS ANALYSIS

Table B-1. Average Concentrations of Arsenic, Lead, Selenium, Barium, Chromium, Silver, Cadmium, Copper, and Zinc for the Four National Land Cover Database Categories Considered in This Study

Metal	Developed, High Intensity Average Concentration (mg/kg)	Developed, Medium Intensity Average Concentration (mg/kg)	Developed, Low Intensity Average Concentration (mg/kg)	Developed, Open Space Average Concentration (mg/kg)
Arsenic	0.672	0.300	0.385	0.330
Lead	17.200	6.788	5.304	4.048
Selenium	0.220	0.300	0.350	0.401
Barium	19.355	16.817	11.560	9.820
Chromium	13.720	4.680	3.600	5.143
Silver	0.177	0.030	0.020	0.014
Cadmium	4.741	0.078	0.046	0.050
Copper	1.305	1.304	0.680	0.490
Zinc	48.920	28.611	30.600	20.050

Table B-2. Concentrations (µg/kg) of Arsenic, Lead, Selenium, Barium, Chromium, Silver, Cadmium, Copper, and Zinc for Each Particle Size Category

Metal	>1.18 mm	1.18 mm-600 µm	600-300 µm	300-150 µm	150-75 µm	<75 µm
Arsenic	0.38	0.77	0.72	1.19	1.95	3.51
Lead	3.15	4.56	9.12	25.39	32.79	55.08
Selenium	0.65	0.48	0.46	0.85	1.39	2.33
Barium	10.70	13.32	16.14	29.59	45.21	81.41
Chromium	7.45	13.40	18.68	23.84	28.41	38.13
Silver	0.02	0.03	0.27	0.06	0.14	0.50
Cadmium	0.05	0.21	0.11	3.09	0.32	0.77
Copper	0.16	0.13	0.16	0.22	0.24	0.28
Zinc	16.70	102.97	46.51	90.07	153.01	288.66

APPENDIX C

RESULTS OF POLYCYCLIC AROMATIC HYDROCARBON ANALYSIS

Table C-1. Average Concentrations ($\mu\text{g}/\text{kg}$) of Polycyclic Aromatic Hydrocarbons and Total Polycyclic Aromatic Hydrocarbons for Each Particle Size Category

PAH	>1.18 μm	1.18 μm -600 μm	600-300 μm	300-150 μm	150-75 μm	<75 μm
Nap	3.15	32.55	52.25	81.83	115.71	121.45
Any	3.98	30.96	60.36	132.03	208.55	212.83
Ana	5.65	97.29	141.28	248.10	299.11	232.43
Flu	11.05	93.17	192.49	334.08	428.80	364.73
Phen	174.46	1270.37	2454.50	4906.31	6381.20	5310.25
Ant	58.90	278.31	301.78	603.43	854.87	783.88
Fla	361.63	2828.22	5230.41	11074.39	15266.91	13641.38
Pyr	276.46	1990.51	3665.87	8064.87	11137.94	9828.56
BaA	73.67	734.84	1371.15	3312.50	4592.25	3661.29
BaF	131.18	730.91	1795.20	4354.62	6396.38	6096.73
BkF	61.01	384.29	941.07	2351.42	3387.60	3664.12
BaP	81.04	533.54	1415.25	3592.17	5036.67	4199.43
BghiP	81.28	430.44	1228.46	3172.75	4645.78	4212.67
DahA	3.59	0.66	0.00	0.00	0.00	51.37
IP	96.30	395.31	1072.89	2678.96	3892.85	3499.46
Σ PAHs	1423.34	9831.36	19922.96	44907.47	62644.63	55880.57

Nap = Naphthalene, Any = Acenaphthylene, Ana = Acenaphthene, Flu = Fluorene, Phen = Phenanthrene, Ant = Anthracene, Fla = Fluoranthene, Pyr = Pyrene, BaA = Benzo(a)anthracene, BbF = Benzo(b)fluoranthene, BkF = Benzo(k)fluoranthene, BaP = Benzo(a)pyrene, BghiP = Benzo(g,h,i)perylene, DahA = Dibenz(a,h)anthracene, IP = Indeno[1,2,3-cd]pyrene, Σ PAHs = total concentration of polycyclic aromatic hydrocarbons.