Nonstructural Approaches to Reduce Sediment and Pollutant Runoff from Transportation Infrastructure in Urbanized Areas

Final Report

January 2024

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Transportation Infrastructure Durability Center

Rhode Island Department of Transportation

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A report from

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Acknowledgements

Funding for this research is provided by the Transportation Infrastructure Durability Center at the University of Maine under grant 69A3551847101 from the U.S. Department of Transportation's University Transportation Centers Program. The authors would like to thank Joseph Baker, Mark Nimirowski, Ian Kirby, David Messier, and Allison Hamel at the Rhode Island Department of Transportation for their contribution in data collection and field activities.

Technical Report Documentation Page

1. Report No. 3.15	2. Government Accession No.	3. Recipient Catalog No.
4 Title and Subtitle Nonstructural Approaches to Reduce Sediment and Pollutant Runoff from Transportation Infrastructure in Urbanized Areas		5 Report Date 1/31/2024 6 Performing Organization Code
7. Author(s) Andrew Sheerin https://orcid.org/0009-0005-6164-4883 Vinka Oyanedel-Craver https://orcid.org/0000-0002-7851-2108		7 Performing Organization Report No.
9 Performing Organization Name and Address University of Rhode Island Department of Civil & Environmental Engineering 2 East Alumni Ave, Kingston, RI 02881		10 Work Unit No. (TRAIS) 11 Contract or Grant No.
12 Sponsoring Agency Name and Address Rhode Island Department of Transportation 2 Capital Hill, Providence, RI 02903		13 Type of Report and Period Covered Final Report: 07/15/2021 – 09/01/2023 14 Sponsoring Agency Code
15 Supplementary Notes		

16 Abstract

Urban stormwater runoff is a major contributor to water quality impairment in developed areas, transporting sediments, nutrients, heavy metals, and hydrocarbons from impervious surfaces into rivers and coastal waters. This study examined pollutant accumulation on state-maintained roadways in Warwick, Rhode Island, to support the development of an enhanced street sweeping program as a nonstructural stormwater management practice for the Rhode Island Department of Transportation (RIDOT). Street solids and stormwater samples were collected from roadway segments representing diverse land uses, canopy coverage, and traffic volumes across multiple seasons. Physical and chemical analyses revealed substantial spatial and seasonal variability in street solid accumulation, ranging from 1,200 to over 9,300 lb/curb-mile. Heavy metals were concentrated along high-traffic commercial and industrial corridors, while nutrients were more prevalent on residential streets with dense tree canopy. Fine particles, which carry a disproportionate share of metals, were most readily mobilized during storm events. To translate these findings into actionable strategies, a GIS-based Road Prioritization Model (RPM) was developed to rank roadway segments by sweeping priority using weighted factors such as land use, canopy coverage, and traffic volume. Seasonal configurations demonstrated that targeted sweeping combined with rain forecasting can improve pollutant removal efficiency. This framework provides RIDOT with a data-driven approach to optimize sweeping operations and enhance water quality protection.

17 Key Words		18 Distribution Statement	
Street sweeping; road prioritization; stormwater management; street solids; heavy metals; nutrients; traffic-related pollution; urban runoff; GIS-based modeling; transportation infrastructure		No restrictions. This document is available to the public through	
19 Security Classification (of this report) Unclassified	20 Security Classification (of this page) Unclassified	21 No. of pages 37 Pages	22 Price $374,133

Form DOT F 1700.7 (8-72)

Contents

List of Figures

List of Tables

List of Key Terms

Urban Stormwater Pollution, Nonstructural Best Management Practices (BMPs), Street Sweeping, Rhode Island Department of Transportation (RIDOT), Road Prioritization Model (RPM)

Abstract

Urban stormwater runoff is a major contributor to water quality impairment in developed areas, transporting sediments, nutrients, heavy metals, and hydrocarbons from impervious surfaces into rivers and coastal waters. This study examined pollutant accumulation on state-maintained roadways in Warwick, Rhode Island, to support the development of an enhanced street sweeping program as a nonstructural stormwater management practice for the Rhode Island Department of Transportation (RIDOT). Street solids and stormwater samples were collected from roadway segments representing diverse land uses, canopy coverage, and traffic volumes across multiple seasons. Physical and chemical analyses revealed substantial spatial and seasonal variability in street solid accumulation, ranging from 1,200 to over 9,300 lb/curb-mile. Heavy metals were concentrated along high-traffic commercial and industrial corridors, while nutrients were more prevalent on residential streets with dense tree canopy. Fine particles, which carry a disproportionate share of metals, were most readily mobilized during storm events. To translate these findings into actionable strategies, a GIS-based Road Prioritization Model (RPM) was developed to rank roadway segments by sweeping priority using weighted factors such as land use, canopy coverage, and traffic volume. Seasonal configurations demonstrated that targeted sweeping combined with rain forecasting can improve pollutant removal efficiency. This framework provides RIDOT with a data-driven approach to optimize sweeping operations and enhance water quality protection.

Chapter 1: Introduction

1.1 Project Motivation

Urban stormwater runoff is a leading cause of water quality impairment in developed areas. Impervious surfaces such as roads, rooftops, and parking lots prevent infiltration and create conditions for pollutants to accumulate on surfaces, which are then rapidly mobilized into receiving water bodies during rainfall events. These pollutants include sediments, nutrients, heavy metals, hydrocarbons, and microplastics, many of which originate from human activities and pose significant environmental and public health risks (Müller et al., 2020). Under the Clean Water Act (CWA), municipal separate storm sewer systems (MS4s) are regulated through the National Pollutant Discharge Elimination System (NPDES) and must implement strategies to reduce pollutant loading and comply with established Total Maximum Daily Loads (TMDLs) (EPA, 1982).

To meet these requirements, municipalities employ Best Management Practices (BMPs), which include both structural and nonstructural approaches (Shoemaker et al., 2000). Structural BMPs, such as retention ponds, rain gardens, and permeable pavements, are effective but often infeasible in highly urbanized areas due to space constraints and high implementation costs. In contrast, nonstructural BMPs are institutional or preventative measures that do not require major construction and can be implemented more flexibly (Taylor and Wong, 2002). Among these, street sweeping is widely recognized as an effective strategy for reducing pollutant loads by removing accumulated solids before storm events (Pitt et al., 2004).

For Rhode Island, these challenges are especially important. As one of the most densely populated states with limited space for structural BMPs and a high coastline-to-land ratio, impaired waterbodies are common, making stormwater management critical. The Rhode Island Department of Transportation (RIDOT) seeks to develop an enhanced street sweeping program to reduce pollutant loading from transportation infrastructure and improve water quality statewide. This program aims to leverage data-driven strategies to optimize sweeping frequency and location, ensuring compliance with water quality regulations while minimizing operational costs.

1.2 Research Objectives

Developing an enhanced street sweeping program for the Rhode Island Department of Transportation (RIDOT) requires a comprehensive understanding of pollutant accumulation on urban roadways and the factors that influence removal efficiency. While street sweeping is recognized as an effective nonstructural Best Management Practice (BMP), its success depends on strategic implementation rather than uniform schedules, which can be costly and inefficient (Shoemaker et al., 2000; Pitt et al., 2004). This study was designed to provide RIDOT with the data and tools necessary to improve its sweeping operations. Specifically, three research objectives guided the work:

Objective 1: Characterize the physical and chemical properties of street solids and evaluate their accumulation trends across different land uses and seasons.

Objective 2: Conduct a spatial analysis to identify roadway segments with the highest potential for pollutant accumulation. Factors considered include land use, canopy coverage, traffic activity, and proximity to impaired waterbodies, enabling prioritization of sweeping efforts where they will yield the greatest environmental benefit.

Objective 3: Develop a computational Road Prioritization Model (RPM) to simulate sweeping scenarios and support data-driven decision-making. The RPM integrates geographic, environmental, and transportation-related variables to rank roadway segments by sweeping priority, allowing RIDOT to allocate resources efficiently.

1.3 Report Organization

The following report is organized in the following manner. Chapter 2 presents a literature review on urban pollution, the sources of pollution, trends in street solid accumulation, and the role of street sweeping as an effective nonstructural BMP. Chapter 3 explains the methodology of sample collection and analysis, as well as the development of the RPM. Chapter 4 summarizes the results of this study and how these results can be interpreted to inform street sweeping activities. Chapter 5 provides concluding remarks and recommendations for RIDOT to implement the enhanced street sweeping program.

Chapter 2: Literature Review

This chapter reviews existing literature on pollution associated with urban transportation infrastructure, with emphasis on trends in pollutant sources, street solid accumulation, street solid physical and chemical characteristics, and the role that street sweeping can play as an effective nonstructural BMP.

2.1 Sources of Pollution

Pollutants present in roadway runoff originate from multiple sources that vary spatially and temporally. Identifying the relative contribution of these sources helps explain why certain road segments accumulate higher pollutant loads and should be prioritized for management. These sources are generally grouped into three categories: atmospheric deposition, anthropogenic activities, and urban drainage systems (Müller et al., 2020). While sweeping can remove pollutants deposited on road surfaces, sources such as atmospheric deposition or leaching from infrastructure require complementary strategies, reinforcing the need for diverse BMP implementation.

2.1.1 Atmospheric Deposition

Atmospheric deposition contributes measurable amounts of nutrients and metals to urban road surfaces through both wet (precipitation) and dry (wind and vehicle-driven turbulence) processes. While atmospheric deposition does not generate pollutants, it redistributes them across impervious surfaces and contributes to background accumulation levels that vary by region and land use (Petrucci et al., 2014). Many factors influence the transport of atmospheric particles, including the activities and weather in the surrounding area, as well as the physical state, size, density, and chemical reactivity of the particles (NRC, 1981). In general, larger particles with high reactivity and solubility experience shorter atmospheric residence times. Particles greater than 20µm may stay suspended for up to an hour and settle within a few tens of miles from their source, while particles between 2 and 20µm can have residence times of days or weeks. Particles less than 2µm can stay suspended for up to a year and can travel hundreds of miles (NRC, 1981).

Reported estimates indicate that atmospheric deposition contributes approximately 12–37% of total nitrogen (TN), 13–56% of total phosphorus (TP), 12–28% of copper, 14–33% of lead, and 5–26% of zinc observed in urban stormwater runoff (Hobbie et al., 2017; Siddiqui and Pandey, 2022; Murphy et al., 2015).

2.1.2 Anthropogenic Activities

Anthropogenic activities represent the dominant source of pollutants associated with urban roadways. These activities include vehicular transportation, road maintenance, construction, littering and illicit discharges, gardening practices, and pet and wildlife droppings. Among these, vehicular transportation is widely recognized as the most significant contributor (Müller et al., 2020).

Vehicular transportation generates pollutants through fuel combustion, tire wear, brake wear, and vehicle component degradation. Brake wear is a major source of copper, with metallic brake pads typically containing 5–10% copper by weight (Straffelini et al., 2015). Tire wear contributes substantial zinc loadings due to zinc oxide used in tire vulcanization, with reported emission rates for tires approximately 244 mg per vehicle mile traveled (VMT) (Kreider et al., 2010; Roberts et al., 2011). Although leaded gasoline has been phased out, lead continues to enter the urban environment through wheel balancing weights, vehicle components, and accidental releases from lead-acid batteries, with wheel weight abrasion alone estimated to release approximately 2 million kg of lead annually in the United States (Bleiwas, 2006). Polycyclic aromatic hydrocarbons (PAHs) are introduced through fuel combustion, oil leaks, and tire wear, with emission factors ranging from less than 1 to over 40 µg per vehicle mile traveled, depending on vehicle type and fuel (Perrone et al., 2014).

Table 2-1: *Vehicular transportation emission rates for key pollutants with originating sources and emission factors expressed per vehicle mile traveled.*

Pollutant	Originating Source	Emissions Rate	Source
Cu	Brake pad wear	25 mg/VMT	(Straffelini et al. 2015)
Pb	Wheel balancing weight, lead-acid batteries	627 mg/VMT	(Bleiwas, 2006)
Zn	Tire wear	4 mg/VMT	(Roberts et al. 2011; Kreider et al. 2010)
Rh	Catalytic converters	80 ng/VMT (new); 19 ng/VMT (>18500 miles)	(Palacios et al. 2000)
Pd		402 ng/VMT (new); 25 ng/VMT (>18500 miles)	(Palacios et al. 2000)
Pt		177 ng/VMT (new); 13 ng/VMT (>18500 miles)	(Palacios et al. 2000)
Σ16PAH	Tire wear	22 µg/VMT	(Roberts et al. 2011; Valle et al. 2007)
	Exhaust	0.5 - 8 µg/VMT (gasoline); 2 - 43 µg/VMT (diesel)	Valle et al. 2007; Perrone et al. 2014)
Microplastics	Tire wear	60 mg/VMT	(Roberts et al. 2011; Xiao et al. 2024)

Routine and seasonal road maintenance introduces pollutants through material wear and chemical applications. Winter deicing practices are particularly significant in cold regions, where road salt application rates range from 400–1,200 lb/mi per event, contributing to an estimated 18 million tons of salt applied annually in the U.S. (Corsi et al., 2010). Typical road salts contain 55% chloride and 30% sodium, along with trace metals and carbonates, which persist on roadways and elevate springtime pollutant loads (Field et al., 1974; Ramakrishna & Viraraghavan, 2005). Asphalt resurfacing also emits particulate matter (PM2.5) at concentrations up to 0.673 mg/m³, compared to background levels of 0.064 mg/m³, and coal-tar sealants contain 169–1,094 g/m³ PAHs (Chong et al., 2013; Mahler et al., 2005).

Roads adjacent to construction sites can receive up to 14 times more deposited sediment than roads influenced by traffic alone (Shaheen, 1975). Runoff from construction areas often exhibits extremely high solids concentrations, with TSS ranging from 200 to 9,700 mg/L, compared to typical urban runoff levels of 50–150 mg/L (Schueler, 2003; Sajjad et al., 2019). EPA emission factors estimate 1.2 tons of suspended particulates per acre per month during active construction (Duprey, 1975).

Gardening activities, consisting of fertilizer application and organic debris, contribute nutrients to stormwater. Nitrogen leaching rates in urban gardens range from 39–191 kg/ha/year, while phosphorus leaching ranges from 0.9–2.4 kg/ha/year, with most losses occurring during non-growing seasons (Hobbie et al., 2017; Sieczko et al., 2023). Pesticides such as Mecoprop have been detected at concentrations up to 32 µg/L in stormwater during peak gardening months (Wittmer et al., 2010).

Illicit littering adds significant pollutant loads to urban surfaces. Seasonal roadway litter has been reported at 51–88 lb/mile/day, with plastics being a major source of microplastic pollution (Shaheen, 1975). Cigarette butts are another critical contributor, with about 9.7 billion butts littered annually in the U.S., releasing trace metals and approximately 6.8 µg of PAHs per cigarette (Chevalier et al., 2018). These materials persist on streets and leach into stormwater during rainfall, increasing chemical and microplastic contamination.

Pet and wildlife waste is estimated to contribute 700 g of nitrogen and 90 g of phosphorus per dog annually, while birds contribute 40–400 g N and 3–25 g P per year, depending on species (Malmqvist, 1983; Hobbie et al., 2017). Studies suggest that 40% of dog waste is not properly removed, increasing nutrient and pathogen loads in urban runoff.

2.1.3 Urban Drainage Systems

Drainage surfaces and urban drainage systems influence pollutant accumulation through material wear, leaching, and conveyance processes. Asphalt pavements have been shown to contain average Σ16PAH concentrations of approximately 1.79 mg/kg, with leaching rates near 0.022 mg/m² per year (Birgisdottir et al., 2007). Traffic-induced abrasion generates fine pavement particles at rates ranging from 11–54 mg per vehicle mile traveled, which readily bind pollutants (Kupiainen, 2007).

Concrete pavements and infrastructure elements can increase runoff pH and leach trace metals, particularly chromium, with reported concentrations ranging from 124–641 µg/L depending on cement composition (Kayhanian et al., 2009). Stormwater drainage systems, including pipes and inlets, may further alter runoff chemistry through material interactions and sediment accumulation, particularly in older or poorly maintained systems (Wright et al., 2011). For example, elevated zinc concentrations up to 1,400 µg/L have been observed in stormwater effluent of galvanized steel pipes (Borris et al., 2017).

Building and roofing materials also contribute to pollutant loading in urban drainage systems through leaching and surface washoff. Metal roofing, asphalt shingles, gutters, and flashing have been shown to release elevated concentrations of zinc, copper, lead, and cadmium in roof runoff, with zinc concentrations commonly exceeding 1000 µg/L in runoff from galvanized materials (Steuer, 1997; Clark et al., 2008; Roberts et al., 2011). Copper roofing systems, in particular, have been reported to contribute a substantial fraction of total copper loads in urban stormwater due to the algacidal properties of copper surfaces (Tobiason, 2004; Pennington and Webster-Brown, 2008).

2.2 Trends in Street Solid Accumulation

The Nationwide Urban Runoff Program (NURP), initiated by the U.S. EPA in the late 1970s, was the first major effort to characterize urban stormwater pollution and evaluate management practices. Its findings established street sweeping as a key nonstructural BMP for reducing pollutant loads and shaped modern stormwater strategies (EPA, 1983). Since then, research has focused on trends in street solid accumulation and how pollutants mobilize between deposition and removal processes such as rainfall washoff, resuspension, and sweeping (Pitt, 1985). Accumulation rates vary widely with land use, traffic, seasonality, and sweeping frequency, as well as local environmental factors (Selbig and Bannerman, 2007; Pitt, 1985). Understanding these patterns is critical for designing street sweeping programs that prioritize high-risk areas and optimize timing for maximum pollutant removal.

2.2.1 Land Use

Land use has been shown to strongly influence both the total accumulation of street solids and the chemical composition of associated pollutants. Differences in land use reflect variations in traffic activity, anthropogenic inputs, and sweeping frequency, which together drive spatial variability in roadway pollutant accumulation.

Street solid accumulation has been quantified across residential, commercial, and industrial land uses in numerous studies throughout the United States. Early investigations conducted during the NURP studies consistently reported higher accumulation on industrial and residential streets relative to commercial streets (EPA, 1982). Subsequent studies have reinforced these findings while demonstrating substantial variability across locations and sampling methodologies (Selbig and Bannerman, 2007).

A synthesis of eighteen studies from fourteen U.S. cities indicates average street solid accumulation rates of approximately 729 lb/curb-mi for residential streets (n = 18), 387 lb/curb-mi for commercial streets (n = 12), and 2121 lb/curb-mi for industrial streets (n = 10). Industrial streets exhibited the highest accumulation in most studies, with reported increases ranging from 11% to over 1400% relative to residential streets. Residential streets showed higher accumulation than commercial streets in nine out of twelve comparative studies, with differences ranging from 29% to over 1500%, a trend often attributed to more frequent sweeping in commercial areas (Sartor and Boyd, 1972; Selbig and Bannerman, 2007). A summary of street solid accumulation by land use is provided in Table 2.2.

Table 2-2: Summary of street solid accumulation rates (lb/curb-mi) by land use across multiple U.S. cities, including summary statistics.

Source	Location	Year	Residential	Commercial	Industrial
(Sartor and Boyd, 1972)	San Jose, CA (1)	1970	743	365	1400
	San Jose, CA (2)	1971	430	680	6550
	Phoenix, AZ (1)	1971	790	425	875
	Phoenix, AZ (2)	1971	895	190	680
	Milwaukee, WI	1971	2115	235	6205
	Bucyrus, OH	1971	1403		1300
	Baltimore, MD	1971	1100	66	800
	Atlanta, GA	1971	317	245	2000
	Tulsa, OK	1971	297	180	690
	Seattle, WA	1971	353	190	710
(Pitt, 1979)	San Jose, CA	1979	310	509	
(Terstriep et al., 1982)	Champaign, IL	1982	177	1036	
(Bender et al., 1982)	Champaign, IL	1984	408		
(Pitt et al., 1984)	Bellevue, WA	1985	815		
(Selbig and Bannerman, 2007)	Madison, WI	2007	614		
(Law et al., 2008)	Baltimore, MD	2008	645		
(SPU and Herrera, 2009)	Seattle, WA	2009	970		
(Sorenson, 2013)	Cambridge, MA	2012	740	522	
Average			729	387	2121
Standard Deviation			473	271	2283
Count			18	12	10

Land use also influences the chemical composition of street solids. Studies evaluating pollutant concentrations (mg/kg) consistently report higher concentrations of heavy metals in commercial and industrial areas compared to residential areas, while residential streets tend to exhibit elevated nutrient concentrations. A synthesis of ten studies indicates that commercial streets exhibit higher average concentrations of TP, cadmium, chromium, copper, lead, and zinc, with increases ranging from approximately 11% to over 100% relative to residential streets. Industrial streets show elevated concentrations of cadmium, chromium, copper, and zinc, while residential streets exhibit higher average concentrations of total Kjeldahl nitrogen (TKN) and TN (Sartor and Boyd, 1972; Brown et al., 2004; Liu et al., 2018; Simpson et al., 2022). A summary of pollutant concentrations by land use is provided in Table 2.3.

Table 2-3: Pollutant concentrations (mg/kg) in street solids by land use type, including summary statistics.

Pollutant	Residential			Commercial			Industrial		
	μ	n	σ	μ	n	σ	μ	n	σ
TP	740	9	242	865	5	446	873	3	479
TKN	2516	8	1325	1828	4	1724	1370	3	716
TN	1429	1		789	1				
Cd	2	4	2	5	2	0	1	1	
Cr	79	7	75	139	4	93	175	3	195
Cu	173	7	169	373	4	240	275	3	179
Pb	1093	10	1066	3015	6	2399	808	3	642
Zn	425	8	343	984	4	528	685	3	452
Sources: (Sartor and Boyd, 1972; Pitt, 1985; Terstriep et al., 1982; SPU and Herrera., 2009; Trujillo-Gonzalez et al., 2016; Bender and Terstriep, 1984; Berretta et al., 2011; Pitt et al., 2005)									

2.2.2 Seasonality

Seasonal variation significantly influences street solid accumulation, particularly in regions with winter maintenance activities. Among studies that quantify seasonal accumulation, spring consistently exhibits the highest accumulation rates. Reported increases during spring range from approximately 83% to over 800% relative to summer and fall, with average increases near 300% (Sartor and Boyd, 1972; Baker et al., 2014). Elevated spring accumulation is largely attributed to residual winter maintenance materials and reduced sweeping during winter months. Fall accumulation is often elevated due to leaf litter deposition, while summer generally exhibits the lowest accumulation. Comparisons between fall and summer accumulation vary widely, ranging from decreases of approximately 50% to increases of up to 200%.

Seasonal effects are also evident in pollutant composition. Nutrient accumulation commonly peaks during spring and fall. In Minnesota, TP accumulation reached up to 0.42 lb/curb-mi during October compared to an annual average of approximately 0.22 lb/curb-mi, while TN accumulation peaked at up to 1.6 lb/curb-mi compared to an annual average near 0.75 lb/curb-mi (Baker et al., 2014).

2.2.3 Canopy Coverage

Canopy coverage adjacent to roadways has been consistently linked to increased accumulation of organic material and nutrients. Leaf litter contributes nitrogen and phosphorus through direct deposition and subsequent fragmentation, despite often representing a small fraction of total street solid mass.

Quantitative studies indicate that leaf litter may account for less than 10% of total street solid mass while contributing approximately 30% of TP loading (Waschbusch et al., 1999a). Strong relationships between canopy coverage and nutrient accumulation have been reported. In Madison, WI, phosphorus concentrations in street solids exhibited a strong correlation with overhead canopy coverage ($R^2 = 0.94$) (Waschbusch et al., 1999a). Similar relationships were observed in Minnesota, where recovered street sweeping solids showed average R^2 values of 0.83 for phosphorus and 0.89 for nitrogen when related to percent canopy coverage (Baker et al., 2014).

2.2.4 Road Characteristics

Road characteristics, including pavement material, surface roughness, and condition, influence street solid accumulation and mobilization. Deteriorated pavement with cracks and potholes retains higher quantities of street solids, which may be mobilized during high-intensity rainfall events (Pitt, 1979).

Surface roughness affects both retention and washoff. Asphalt pavements typically exhibit greater roughness than concrete pavements, with reported average depression depths of approximately 0.017 inches for asphalt and 0.008 inches for concrete (Zhao et al., 2018). Modeling studies indicate that concrete surfaces may wash off 15% to 200% more material than asphalt surfaces under comparable rainfall conditions, depending on storm intensity and surface condition (Zhao et al., 2018).

2.2.5 Traffic Activity

Traffic activity is a major driver of pollutant generation on roadways due to tire wear, brake wear, vehicle body wear, and exhaust. Tire wear rates have been estimated at approximately 135 mg per vehicle mile traveled, while brake wear rates range from 14 to 64 mg per vehicle mile traveled depending on vehicle class (Roberts et al., 2011).

Relationships between average daily traffic (ADT) and pollutant accumulation are non-linear due to competing processes of generation and resuspension. Some studies have reported 43–89% increases in metal concentrations when comparing roads with ADT of 4,000–10,000 vehicles to roads exceeding 10,000 vehicles per day (Lloyd et al., 2019), however other studies have shown that roads with ADT greater than 30,000 vehicles have exhibited 200–1000% higher concentrations of select metals and nutrients than roads <30,000 ADT (Kayhanian et al., 2003). The inconsistency in this relationship is attributed to vehicle-driven particle resuspension, where individual vehicle passes resuspend between 0.02–1% of surface particles, with resuspension rates increasing with higher speeds and for heavier vehicles (Sehmel, 1973).

2.3 Characterization of Street Solids

Street solids consist of a broad range of particle sizes that influence pollutant binding, transport, and removal. Particle size is a critical characteristic because it affects pollutant concentration, street sweeper removal efficiency, and mobilization during storm events.

Table 2.4: *Particle size classification ranges for street solids.*

0.002	**.05**	**0.10**	**0.25**	**0.5**	**1.0**	**2.0 mm**	
CLAY	**SILT**	Very Fine	Fine	Medium	Coarse	Very Coarse	**GRAVEL**
		SAND					

Although coarse particles typically dominate total mass, numerous studies have shown that finer particles contain a disproportionate share of pollutants. Across multiple investigations, approximately 50–80% of trace metals have been found in particles smaller than 250 µm, despite these particles often representing less than 40% of total street solid mass (Sartor and Boyd, 1972; Breault et al., 2005; Zhao et al., 2010; Walker et al., 2023). Lead and zinc, in particular, have been shown to be strongly associated with fine particles, with reported values exceeding 50% of total metal mass in the <250 µm fraction (Sartor and Boyd, 1972).

Similar trends have been reported for PAHs. Studies in both the United States and abroad indicate that approximately 55% of Σ16PAHs are associated with particles smaller than 250 µm, reflecting the strong affinity of PAHs for fine, organic-rich particles (Zhao et al., 2008; Hongtao et al., 2009). Nutrient distribution among particle size fractions is more variable. Some studies report higher phosphorus and nitrogen concentrations in finer particles, while others indicate greater nutrient mass associated with coarser fractions due to the presence of leaf litter and organic debris (Waschbusch et al., 1999a; Gastaldini and Silva, 2013).

Particle size also strongly influences transport in stormwater runoff. Experimental and modeling studies have shown that particles smaller than 100 µm are readily mobilized during rainfall, while particles larger than approximately 250 µm are difficult to mobilize except under high-intensity storm conditions (Hong et al., 2016; Zhao et al., 2018). These findings stress the importance of targeting fine particle fractions when evaluating pollutant removal strategies.

2.4 Street Sweeping as an Effective Nonstructural BMP

Street sweeping is widely implemented as a nonstructural BMP to reduce pollutant loading from urban roadways by removing accumulated street solids prior to mobilization during storm events. The effectiveness of street sweeping is highly dependent on spatial and temporal variability in street solid accumulation and pollutant composition, as well as on the equipment and operational strategies employed.

Several factors influence the success of street sweeping programs, including land use, seasonality, canopy coverage, traffic activity, roadway characteristics, and particle size distribution. These factors control both the quantity of material available for removal and the fraction of pollutants associated with fine particles (Sartor and Boyd, 1972; Breault et al., 2005; Zhao et al., 2010; Walker et al., 2023). As a result, sweeping effectiveness depends not only on total mass removal, but also on the ability to target fine particle fractions that are most likely to be mobilized during storm events.

Street sweeping equipment varies widely in performance. Mechanical broom sweepers are effective at removing coarse debris but exhibit low removal efficiency for fine particles, with reported removal efficiencies below 20% for particles smaller than 63 µm (Sartor and Boyd, 1972). Vacuum-assisted sweepers demonstrate substantially improved fine-particle removal, while regenerative-air sweepers further enhance performance by dislodging material embedded in pavement cracks, resulting in reported removal efficiencies exceeding 80% for particles smaller than 125 µm and greater than 90% for coarser fractions (Sutherland and Jelen, 1997; Breault et al., 2005; Sorenson, 2013). Tandem sweeping operations, which combine mechanical sweepers followed by vacuum-assisted or regenerative-air sweepers, have been shown to achieve the highest overall removal efficiencies across particle size ranges (Sutherland and Jelen, 1997). Representative removal efficiencies by sweeper type and particle size are summarized in Table 2-5.

Although increasing sweeping frequency and deploying advanced equipment can substantially improve pollutant removal, sweeping programs are constrained by cost and operational limitations. Street sweeping costs are driven primarily by equipment type, labor, fuel consumption, maintenance, and sweeping frequency. Reported operating costs for mechanical broom sweepers generally range from approximately $70–$100 per curb-mile, while vacuum-assisted and regenerative-air sweepers typically range from $120–$200 per curb-mile due to higher fuel use and maintenance demands (Sutherland and Jelen, 1997; Molloy, 2020). Tandem sweeping operations further increase costs by requiring multiple passes and additional labor, often resulting in total costs that are approximately 1.5–2 times greater than single-pass mechanical sweeping, but provide substantially higher pollutant removal efficiency, particularly for fine particles (Sutherland and Jelen, 1997; Pitt et al., 2004). Studies have shown that targeted sweeping strategies can improve material removal efficiency by 40–70% compared to uniform sweeping approaches, without proportional increases in cost (Kalinosky et al., 2014).

Developing an effective street sweeping program, therefore requires targeted strategies that prioritize roadway segments based on factors that influence accumulation and pollutant loading. Field-based characterization of street solids, combined with spatial prioritization frameworks, enables agencies to allocate sweeping resources more efficiently and apply advanced sweeping strategies where they are most likely to yield the greatest benefit. The sampling program and prioritization model developed in this study are designed to support such data-driven decision-making.

Table 2-5: *Summary of street sweeper removal efficiencies(%) by sweeper type and particle size range, compiled from multiple studies.*

Source	Sweeper Type	Particle Size Range (µm)							
		< 43	43 - 104	104 - 246	246 -840	840 - 2000	> 2000		
(Sartor and Boyd, 1972)	Mechanical	15	20	48	60	66	79		
		<63	63 - 125	125 - 250	250 - 600	600 - 1000	1000 - 2000	2000 - 6370	>6370
(Sutherland and Jelen, 1997)	Mechanical (NURP era)	44	52	47	50	55	60	78	79
	Mechanical (newer)	100	100	92	57	48	59	81	70
	Regenerative-air	32	71	94	100	100	100	94	92
	Tandem Operation	93	95	93	89	84	88	98	87
	Envirowhirl	70	77	84	88	90	91	92	96
		< 63	63 - 125	125 - 250	250 - 2000	>2000			
(Breault et al., 2005)	Mechanical	13	10	11	40	38			
	Vacuum-assisted	81	93	75	93	94			
		< 63	63 - 125	125 - 250	250 - 600	600 - 1000	1000 - 2000	> 2000	
(Sutherland, 2009)	Mechanical	78	90	91	93	93	93	96	
	Mechanical w/ water	68	69	72	84	88	91	96	
	Vacuum-assisted	94	87	90	94	96	98	99	
	Regenerative-air	89	93	96	98	98	99	99	
	Regenerative-air	91	97	98	98	98	99	99	
		< 250	< 500						
(SPU, 2012)	Regenerative-air	52	57						
		< 125	125 - 2000	> 2000					
(Sorenson, 2013)	Regenerative-air	50	83	90					
	Regenerative-air	49	79	92					
		<125	125 - 500	> 500					
(Molloy, 2020)	Mechanical	33	39	53					
	Vacuum-assisted	63	74	83					
	Regenerative-air	71	92	91					

Chapter 3: Methodology

This chapter describes the study area, field sampling program, laboratory analyses, and development of the Road Prioritization Model (RPM). Methods were designed to characterize spatial and seasonal variability in street solid accumulation and pollutant loading and to translate these observations into a practical decision-support framework for enhanced street sweeping.

3.1 Study Area

The study area is the City of Warwick, Rhode Island, a 35.7 mi^2 urban municipality located in Kent County. Warwick is bordered by Cranston, Providence, East Greenwich, and West Warwick and shares approximately 39 miles of coastline with Narragansett Bay. Due to its dense development and coastal setting, stormwater runoff represents a significant concern for local water quality (RIDEM, 2023).

Warwick contains numerous surface water features, including Gorton Pond (58 acres), Warwick Pond (85 acres), and approximately 57 miles of rivers and streams, including Buckeye Brook, Lockwood Brook, Harding Brook, and the Pawtuxet River. Many of these waterbodies are listed as impaired and subject to Total Maximum Daily Loads (TMDLs) for pollutants such as nutrients, pathogens, and metals (RIDEM, 2023). As part of its Stormwater Control Plan (SCP), the Rhode Island Department of Transportation (RIDOT) has delineated 36 SCP watersheds within Warwick. Common impairments across these watersheds include fecal coliform, dissolved oxygen, total nitrogen, total phosphorus, and metals, indicating widespread stormwater management challenges (RIDOT, 2022).

Land use within Warwick is primarily residential (approximately 43%), followed by forested land (24%), commercial land (8%), and industrial land (3%). Impervious surfaces account for approximately 35% of the total land area (RIGIS, 2020). Tree canopy coverage averages approximately 73% across the municipality, with notable variability adjacent to roadways (URI Environmental Data Center, 2020).

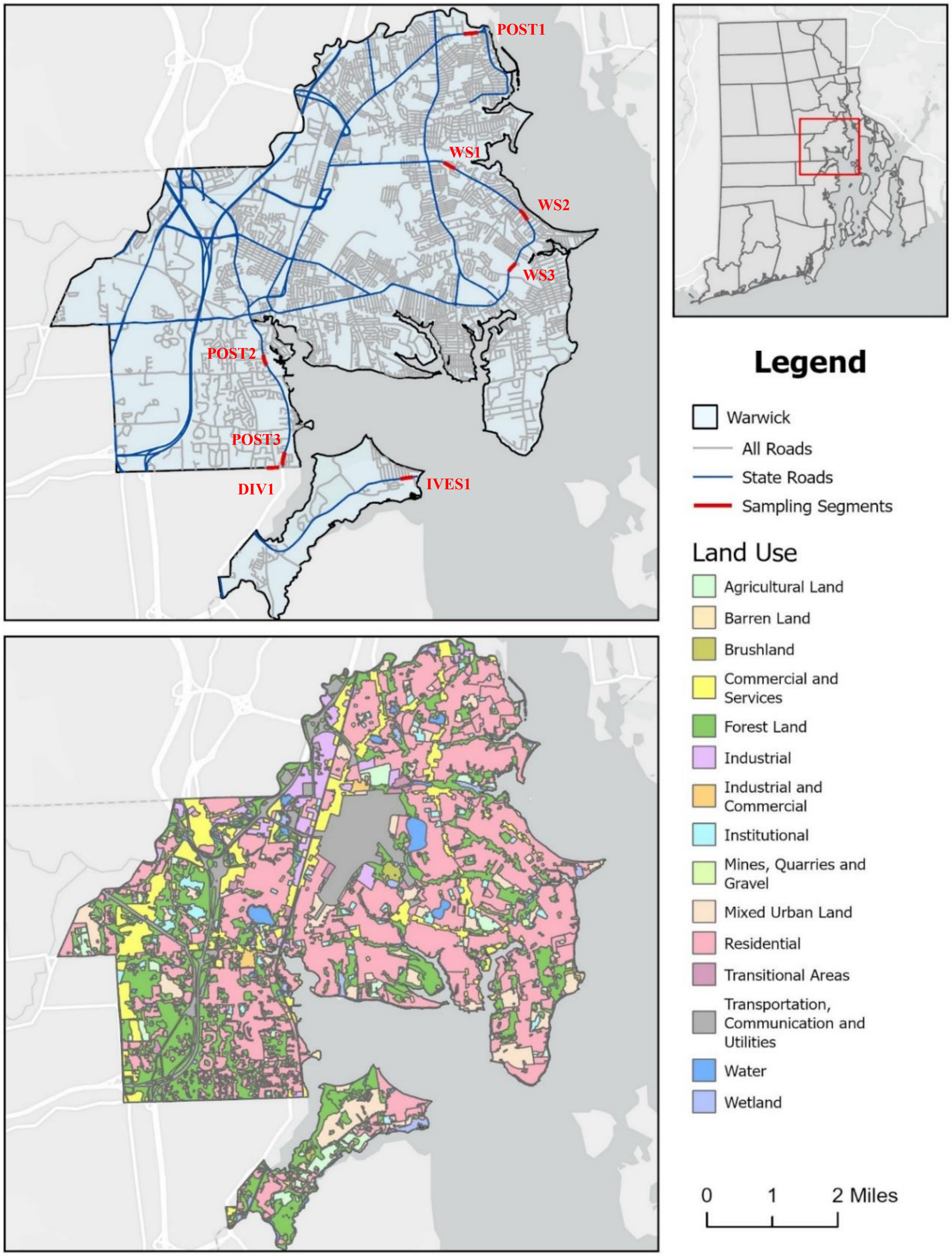

Figure 3-1: *Map of Warwick, RI, showing roadway network, selected sampling segments, and surrounding land use.*

3.2 Sample Collection

This study aims to collect, characterize, and interpret street solid and stormwater data across a range of land uses and seasonal conditions. Sampling locations were selected to capture variability in surrounding geographic characteristics, including adjacent land use and tree canopy coverage. Eight state-maintained roadway segments, each approximately 1,000 feet in length, were selected in coordination with RIDOT. These segments represent a range of residential, commercial, and forested settings, as well as varying degrees of canopy coverage. The land use and tree canopy distributions within 250-ft buffer zones surrounding each sampled segment are shown in Figure 3.2.

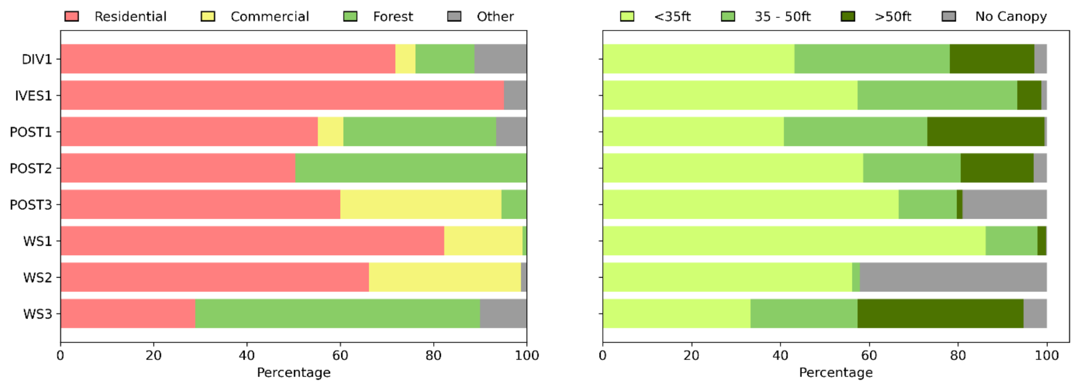

Figure 3-2: *Distribution of land use and canopy coverage within a 250-ft buffer around each sampling road segment.*

3.2.1 Street Solid Sample Collection

Street solid samples were collected from eight roadway segments three times throughout 2022, on May 13th, July 29th, and October 27th. For each road segment, eleven subsamples were collected from each road segment at 100-ft intervals marked with spray paint, using a vacuum-based collection system mounted on a RIDOT truck. The system consisted of a Vacmaster 12-gallon wet/dry vacuum (143 cfm airflow) powered by a Champion 3500W generator, as shown in Figure 3-3.

Each subsample consisted of vacuuming a strip from the curb to the roadway centerline at a constant rate of approximately 1 ft/s (Sorenson, 2013). Areas with atypical loading, such as large gravel deposits or potholes, were avoided. In cases of heavy leaf accumulation, leaves were collected separately and included in the composite sample. The eleven subsamples were composited into the sample bags and then transported to the laboratory at URI, oven-dried at 100°C for 12 hours, and weighed to determine dry mass. Street solid accumulation was calculated and expressed as pounds per curb-mile based on the measured mass, number of subsamples, and vacuum nozzle width (9-inches) (Pitt, 1985).

Particle size distribution was determined using dry sieving techniques with stainless steel sieves conforming to ASTM E11 specifications (ASTM International, 2023). Samples were separated into eight particle size fractions (>2.00, 0.85, 0.60, 0.30, 0.18, 0.125, 0.074, and <0.074 mm) using a Gilson SS-20 rotary sifter tilted at 45° and operated for 10 minutes to ensure consistent separation.

Select particle size fractions were analyzed for moisture and volatile content using thermogravimetric analysis (TGA) with a TA Instruments Q500 analyzer, which heats samples from 20°C to 950°C at 20°C/min under controlled atmosphere.

Elemental composition was determined using X-ray fluorescence (XRF) with a Shimadzu 8100 Energy Dispersive XRF analyzer. Approximately 100 grams of each fraction were placed into XRF sample cups for scanning, focusing on particles <1 mm due to instrument limitations.

Figure 3-3: *Photographs of street solid sampling using vacuum-based collection system mounted on RIDOT truck on July 29th, 2022.*

3.2.2 Stormwater Sample Collection

Stormwater runoff samples were collected during four storm events between October 2022 and May 2023 to characterize pollutant mobilization during rainfall. Sampling dates included October 14, 2022, November 30, 2022, April 23, 2023, and May 20, 2023.

Stormwater samples were collected using an ISCO 6712 autosampler installed within storm sewer systems draining selected roadway segments, shown in Figure 3-4. Flow was monitored using an ISCO 750 area-velocity flow meter, which measures water velocity using Doppler technology and water depth using a pressure transducer (Teledyne ISCO, 2019). The autosampler was programmed to collect flow-proportional samples, with sampling volumes adjusted based on forecasted rainfall intensity and upstream roadway characteristics.

Samples were preserved and transported to the laboratory at URI for analysis. Analytes included total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), and dissolved metals including aluminum, cadmium, chromium, copper, iron, manganese, nickel, lead, and zinc. Analytical methods are shown in Table 3-1.

Table 3-1: *Analytical methods and instruments used for stormwater constituent analysis, including TSS, nutrients, metals, and PAHs.*

Parameter	Analytical Method	Instrument
pH	EPA 150.2 – Electrometric monitoring	Thermo Scientific Orion Versa Star Pro
TSS	EPA 160.2 – Total suspended solids (gravimetric)	Whatman glass microfiber filter (47mm), vacuum driven filtration
TOC	Standard Methods 5310B: Total Organic Carbon by High-Temperature Combustion	Shimazu TOC-L
TN	ASTM D8083-Total Nitrogen in Water by High Temperature Catalytic Combustion	Shimadzu TNM-L
TP	EPA 365.1 – Determination of phosphorus by colorimetry	Hach DR 1900 (spectrophotometer) with TNT843 (test kit)
Heavy metals (Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn)	EPA 200.8 – Determination of trace elements in waters by inductively coupled plasma mass spectrometry	Shimadzu ICPMS – 2030
PAHs	EPA 8272 – Determination of PAHs in water by solid phase microextraction and gas chromatography and mass spectrometry	Shimadzu GC – 2030, GCMS – TQ8050 NX, AOC – 6000

Figure 3-4: *Autosampler setup for stormwater sample collection.*

3.3 Road Prioritization Model

A GIS-based Road Prioritization Model (RPM) was developed to support targeted street sweeping by ranking roadway segments based on their relative potential to accumulate pollutants of concern. The model integrates multiple spatial datasets representing geographic, environmental, and transportation-related factors that have been shown to influence pollutant accumulation, sweeping effectiveness, and public appearance. These factors, summarized in Table 3-2, include land use, tree canopy coverage, water quality indicators, and transportation characteristics.

Table 3-2: *RPM geographic, environmental, and transportation factors considered in the prioritization model.*

RPM Factors	
Land Use	Residential
	Commercial
	Industrial
	Undeveloped
Tree Coverage	Low (<35 ft)
	Medium (35-50 ft)
	Tall (>50 ft)
Water Quality	Watershed Impairment
	Waterbody Proximity
Transportation	Traffic Volume
	Bike Paths

Spatial processing and model automation were performed in ArcGIS Pro 3.4 using Python 3.9 and the ArcPy package. Key tools used in model development included buffer generation, spatial joins, Euclidean distance calculations, raster reclassification, and weighted overlay operations, allowing consistent application of scoring and weighting across the roadway network.

To increase spatial resolution, the roadway network was divided into 0.1-mile segments. Each segment was assigned a priority score using a weighted-sum approach based on user-defined factor weights. Factor scores were calculated using the inverse of the Euclidean distance between the center point of each roadway segment and the corresponding spatial features. For watershed impairment status, traffic volume, and bike path presence, roadway segments were spatially joined to the nearest feature attributes. All factor scores were normalized and assigned weights on a scale of 1 to 100, with higher values indicating greater sweeping priority (Malczewski, 1999). The resulting composite scores were then classified into three uniform priority tiers: high, medium, and low.

The RPM is designed to be configurable through user-defined inputs, allowing individual factor weights to be adjusted on a scale of 1 to 10 based on user objectives. Multiple weighting configurations were evaluated in this study; however, two representative scenarios are presented to reflect local conditions and operational priorities. A spring configuration emphasizes traffic-related factors and heavy metal accumulation, while a fall configuration emphasizes nutrient accumulation associated with canopy coverage and land use.

The RPM generates spatial heat maps of the road network that can be used to identify areas of concern, assign sweeping routes, and target roadway segments for enhanced sweeping strategies. The model is intentionally flexible, allowing users to modify factor weights, inputs, and priority thresholds to accommodate evolving regulatory requirements, operational constraints, and data availability.

Chapter 4: Results

This chapter presents the results of street solid and stormwater sampling and discusses observed trends in accumulation, particle size distribution, elemental composition, and stormwater pollutant concentrations. Results are interpreted in the context of factors identified in the literature and are used to support development and application of the Road Prioritization Model (RPM).

4.1 Sampling Schedule

Street solid samples were collected during three seasonal campaigns (spring, summer, and fall), and stormwater samples were collected during four storm events (two in fall 2022 and two in spring 2023). Sampling locations represented a range of land use and canopy coverage conditions. The results presented in this chapter focus on street solid accumulation magnitude, seasonal and land use variability, particle size distributions, elemental composition, and stormwater pollutant trends.

Table 4-1: *Schedule of data collection for street solid and stormwater sampling events*

Date	Collection Type
May 13, 2022	Street solid #1 (spring)
July 29, 2022	Street solid #2 (summer)
October 14, 2022	Stormwater #1 (POST2)
October 27, 2022	Street solid #3 (fall)
November 30, 2022	Stormwater #2 (POST2)
April 23, 2023	Stormwater #3 (POST2)
May 20, 2023	Stormwater #4 (WS3)

4.2 Street Solid Results

4.2.1 Street Solid Accumulation

Street solid accumulation varied substantially across roadway segments and seasons. Across all sampling events and locations, the average accumulation rate was 3,609 lb/curb-mile, with a standard deviation of 2,457 lb/curb-mile, indicating high spatial and temporal variability. The maximum observed accumulation was 9,320 lb/curb-mile, highlighting the presence of roadway segments with disproportionately high pollutant buildup.

Street solid accumulation by roadway segment and season is presented in Table 4-2. These results demonstrate that accumulation is not uniformly distributed across the roadway network, reinforcing the importance of targeted sweeping strategies rather than uniform schedules.

Table 4-2: *Street solid accumulation (lb/curb-mile) for each road segment across spring, summer, and fall sampling campaigns.*

Road Segment	Spring	Summer	Fall
DIV1	1172	780	1611
IVES1	3469	4465	3649
POST1	1712	1882	8057
POST2	1324	2422	3948
POST3	1949	2206	3704
WS1	8178	2118	2261
WS2	9320	3740	3672
WS3	7477	1609	N/A*
Average	**4325**	**2403**	**3843**
Standard Deviation	**3420**	**1177**	**2055**

* No sampling occurred due to an abundance of wet leaves

4.2.2 Seasonal Trends

Clear seasonal trends in street solid accumulation were observed, with accumulation generally following the pattern: Spring > Fall > Summer.

Formal statistical comparisons are limited by the small sample size. However, paired t-tests indicate that both spring and fall accumulation exceed summer accumulation, with p-values of 0.077 and 0.057, respectively. Elevated spring accumulation is attributed to residual winter maintenance materials and extended periods without street sweeping during winter months. Fall accumulation is also elevated, likely due to increased organic inputs from leaf litter. Summer accumulation was consistently lowest across all sites. For all three seasons, DIV1 recorded the lowest accumulation, likely due to its smooth pavement surface and steep grade, which reduces material retention and increases washoff during rainfall events.

4.2.3 Land Use Trends

Land use influenced street solid accumulation throughout the year. Although no road segment was exclusively surrounded by a single land use, segments were grouped based on dominant surrounding land use: WS2 and POST3 as commercial; WS3 and POST2 as forested; and WS1, POST1, IVES1, and DIV1 as residential.

When averaged across all seasons, commercial roadway segments exhibited approximately 20% greater accumulation than residential segments and 16% greater accumulation than forested segments. Seasonal differences were also observed. In spring, commercial segments accumulated 36% more material than residential segments and 22% more than forested segments. In fall, forested segments accumulated slightly more material than residential (+1%) and commercial (+7%) segments, consistent with increased leaf litter inputs. Although formal hypothesis testing was not performed due to limited sample size, the magnitude and consistency of these differences across seasons indicate that land use is a meaningful driver of street solid accumulation.

4.2.4 Particle Size Distribution

Particle size distributions were evaluated using eight size classes ranging from <74 µm to 2 mm. Across all roadway segments and seasons, particle size distributions exhibited similar overall shapes. When averaged across the spring and summer sampling events, 88.7% of street solids were less than 840 µm, 58.7% were less than 300 µm, and 10.7% were less than 125 µm by total mass. Medium sand fractions (300–600 µm) were the most abundant size class across all samples. Fine particles (<125 µm) represented a smaller fraction of total mass but are of particular interest due to their association with elevated pollutant concentrations and increased mobility during storm events. The particle size distributions for spring and summer samples are shown in Figure 4-1. The consistency in particle size distributions across sites suggests that differences in pollutant loading are driven primarily by accumulation magnitude and composition rather than by fundamental differences in physical material size.

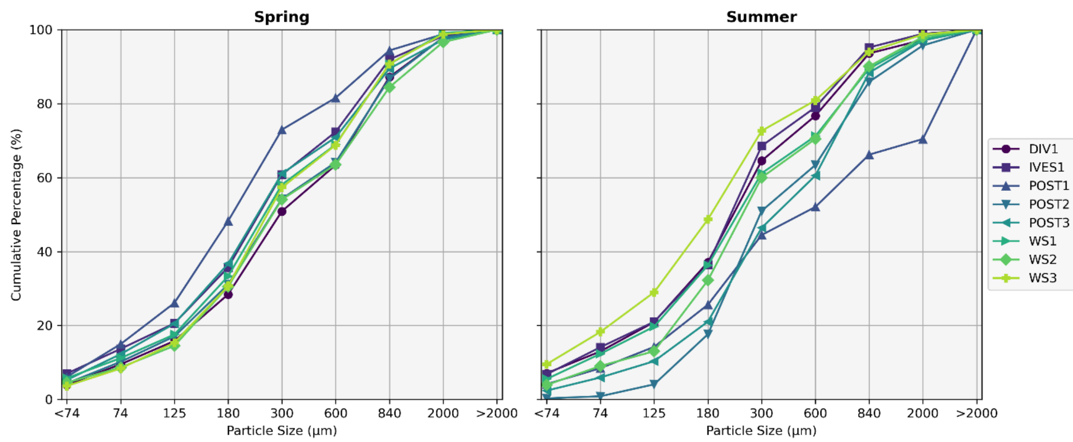

Figure 4-1: *Particle size distribution for spring and summer street solid samples, showing relative mass percentages across size classes.*

4.2.5 Elemental Composition

Elemental composition of street solids was evaluated using X-ray fluorescence (XRF) analysis on each particle size range (74–840 µm). Across all roadway segments, elemental concentrations followed the general trend:

Si > Fe > K > Ca > Al > Ti > S > P > Mn > Zn > Cu > Cr > Pb

While crustal elements dominated total mass, trace metals of regulatory concern exhibited distinct size-dependent patterns. Interestingly, zinc, copper, and lead concentrations were highest in both the smallest (<74 µm) and largest (>840 µm) particle size fractions, indicating contributions from fine particles, as well as coarse debris.

To represent the contribution of each particle size fraction to total pollutant mass, XRF-derived elemental concentrations were multiplied by the corresponding mass fraction from the particle size distribution. The resulting size-fractioned elemental concentrations are shown in Figure 4-2.

These findings are consistent with previous studies that report preferential binding of metals to fine particles while also highlighting the role of coarse material in total metal mass (Breault et al., 2005; Zhao et al., 2010).

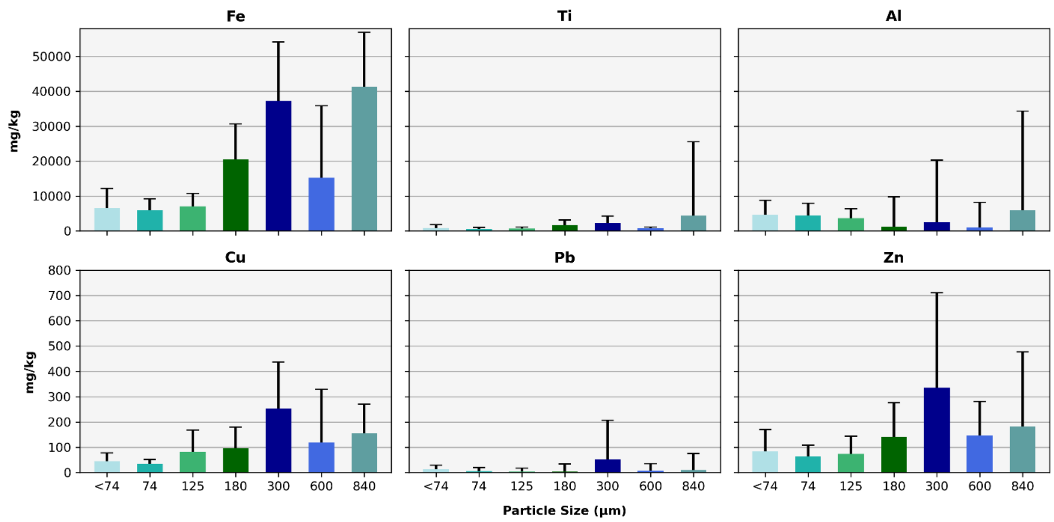

Figure 4-2: *Size-fractioned elemental concentrations of spring street solid samples, averaged across all segments.*

4.3 Stormwater Results

4.3.1 Sampling Conditions

Four stormwater sampling events were conducted, two in fall 2022 and two in spring 2023. Total rainfall during these events ranged from 0.91 to 1.91 inches, with rainfall intensities ranging from 0.07 to 0.79 inches per hour. Antecedent dry periods ranged from 3 to 23 days, as summarized in Table 4-3.

Rapid changes in flow during storm events made it difficult to maintain consistent sampling intervals using the flowmeter. As a result, the autosampler frequently triggered sample collection at short intervals (1–3 minutes). To obtain representative event-based concentrations, samples collected during each event were composited prior to laboratory analysis.

Table 4-3: *Stormwater sampling events and conditions, including rainfall depth, intensity, and antecedent dry periods.*

Event	Date	Site	Rainfall (inches)	Rainfall intensity (inches/hour)	Dry days
SW1	10/14/22	POST2	1.43	0.79	6
SW2	11/30/22	POST2	0.96	0.11	3
SW3	4/23/23	POST2	0.91	0.07	23
SW4	5/20/23	WS3	1.91	0.12	12

4.3.2 Pollutant Trends

Interesting trends were found when comparing the pollutant concentrations between each of the composite samples. Across all storm events, heavy metal concentrations followed the general trend:

$$Fe > Zn > Al > Pb > Mn > Cu > Cr > Ni$$

Seasonal differences were observed for several constituents. Average TSS concentrations were higher in spring (56.9 mg/L) than in fall (24.4 mg/L). Similarly, spring concentrations exceeded fall concentrations for TOC (9.81 vs. 2.02 mg/L) and TN (1.12 vs. 0.74 mg/L). All metals also exhibited higher concentrations in the spring than in the fall. In contrast, TP concentrations were higher in fall (1.18 mg/L) than in spring (0.83 mg/L).

These stormwater pollutant trends correspond with observed seasonal patterns in street solid accumulation and composition. Elevated spring concentrations of TSS, metals, and nitrogen support the role of street sweeping as a source-control BMP, while elevated fall phosphorus concentrations are consistent with increased organic inputs from leaf litter (Waschbusch et al., 1999a; Selbig, 2016). A complete summary of stormwater pollutant concentrations is provided in Table 4-4.

Table 4-4: *Composite stormwater sample concentrations for key pollutants (TSS, nutrients, metals, PAHs) across four storm events.*

Event	pH	TOC (mg/L)	TN (mg/L)	TP (mg/L)	TSS (mg/L)	Al (µg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	Mn (µg/L)	Ni (µg/L)	Pb (µg/L)	Zn (µg/L)
SW1	6.81	1.16	ND	2.24	30.0	8.41	8.80	2.62	12.0	0.68	0.44	2.37	37.4
SW2	6.75	2.87	0.74	0.04	18.8	14.5	1.94	4.01	16.1	5.63	0.63	2.63	54.9
SW3	6.57	4.42	1.30	0.46	40.0	30.8	1.57	5.54	238	15.4	0.16	28.1	45.0
SW4	6.39	15.2	0.94	1.20	73.8	70.7	27.2	15.6	114	21.1	0.96	28.7	87.8

4.4 Road Prioritization Model Configuration

Street solid and stormwater results, combined with trends identified in the literature, indicate that pollutant accumulation varies seasonally and is influenced by land use, canopy coverage, and transportation characteristics. Although no single prioritization configuration is universally applicable, previous studies have shown that commercial and industrial areas tend to exhibit elevated metal concentrations, while areas with dense tree canopy and residential land use are more likely to accumulate nutrients (Sartor and Boyd, 1972; Waschbusch et al., 1999a; Baker et al., 2014; Selbig, 2016).

Two example prioritization scenarios were applied to a 22-mile road network within the City of Warwick. In the spring scenario, higher weights were assigned to industrial (8) and commercial (6) land uses and traffic volume (4) to reflect conditions associated with heavy metal accumulation following winter maintenance and reduced winter sweeping. In the fall scenario, higher weights were assigned to residential land use (6) and tall canopy coverage (6), and medium canopy coverage (4) to reflect increased nutrient accumulation associated with organic debris. The selected factors and corresponding weights for each scenario are summarized in Table 4-5.

Table 4-5: Factor weights for two prioritization scenarios (spring and fall) applied in RPM, showing selected factors and corresponding weights.

Scenario	Factor 1	W_1	Factor 2	W_2	Factor 3	W_3
Spring	Industrial	8	Commercial	6	Traffic volume	4
Fall	Residential	6	Tall canopy	6	Medium canopy	4

Application of the RPM produced distinct spatial patterns between the two scenarios. Under the spring configuration, high-priority roadway segments were concentrated along corridors with higher traffic volumes and adjacent commercial or industrial land uses. Under the fall configuration, high-priority segments shifted toward residential roadways with greater tree canopy coverage. Example RPM output heat maps for the spring and fall scenarios are shown in Figures 4-3 and 4-4.

These results demonstrate that seasonal prioritization produces materially different sweeping priorities across the roadway network and that the RPM is responsive to changes in factor weighting. The model provides a flexible framework for identifying roadway segments where enhanced street sweeping may yield the greatest pollutant reduction under varying seasonal conditions.

Figure 4-3: *Spring prioritization heat map for a 22-mile roadway network in Warwick, Rhode Island. This scenario emphasizes industrial and commercial land uses and traffic volume in the calculation.*

Figure 4-4: *Fall prioritization heat map for the same roadway network. This scenario emphasizes residential areas and tree canopy coverage to reflect seasonal nutrient accumulation patterns.*

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

This study evaluated the accumulation, composition, and seasonal variability of street solids and associated stormwater pollutants on state-maintained roadways in Warwick, Rhode Island. Results show that pollutant buildup varies significantly across roadway segments and seasons, and these differences can be leveraged to improve the effectiveness of street sweeping as a nonstructural BMP.

Street solid accumulation exhibited high spatial and temporal variability, ranging from less than 1,200 to more than 9,300 lb/curb-mile. Seasonal trends followed the pattern spring > fall > summer, driven by winter maintenance residues, sweeping frequency, and organic debris inputs. These findings indicate that uniform sweeping schedules are unlikely to achieve optimal pollutant reduction.

Land use and canopy coverage were key drivers of accumulation and pollutant composition. Commercial segments exhibited higher overall accumulation and elevated metal concentrations, while residential and forested segments showed stronger nutrient signals, particularly in fall. Particle size analysis revealed that although coarse particles dominate total mass, fine particles contain a disproportionate share of metals and are more readily mobilized during storm events. These results underscore the need for sweeping strategies that target both accumulation magnitude and fine particle removal.

To translate these findings into actionable tools, a GIS-based Road Prioritization Model (RPM) was developed. The RPM integrates land use, canopy coverage, traffic activity, and water quality considerations to rank roadway segments by sweeping priority. Application of the RPM demonstrated that seasonal prioritization produces materially different sweeping priorities, highlighting the value of flexible, data-driven strategies.

5.2 Recommendations for RIDOT

Based on the results of this study, several recommendations are provided to support RIDOT's development of an enhanced street sweeping program.

1. **Adopt seasonally targeted sweeping strategies.** Spring efforts should prioritize high-traffic commercial and industrial corridors where heavy metal accumulation is greatest, while fall efforts should focus on residential streets with dense canopy coverage to address nutrient buildup.
2. **Incorporate rain forecasting into sweeping decisions.** Scheduling sweeping immediately before significant rainfall can substantially reduce pollutant washoff, improving water quality outcomes without increasing sweeping frequency.
3. **Invest in advanced sweeping technologies.** Vacuum-assisted and regenerative-air sweepers should be deployed on high-priority segments to improve fine-particle removal. Tandem operations may be warranted for corridors with heavy pollutant loads.
4. **Use the RPM as a decision-support tool.** RIDOT should adjust factor weights, integrate additional datasets, and refine prioritization criteria based on evolving regulations and operational constraints. The model's flexibility allows adaptation to other municipalities and expanded transportation assets.

5. **Continue field-based monitoring.** Periodic sampling of street solids and stormwater will help validate prioritization outcomes, track pollutant trends, and demonstrate measurable reductions to regulatory agencies.

5.3 Future Research

Future work should expand sampling across more roadway segments, additional seasons, and multiple years, while integrating sweeping performance data. Linking prioritized sweeping strategies to quantitative pollutant reduction estimates and operational costs will strengthen program optimization. Further refinement of the RPM to include additional environmental and infrastructure variables will improve its applicability and robustness. Collectively, these efforts support RIDOT's long-term goal of improving stormwater management through cost-effective, nonstructural solutions responsive to local conditions and regulatory needs.

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