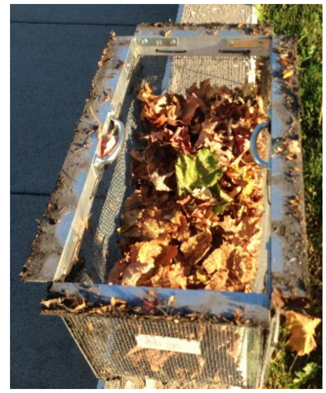
Evaluating the Particle Size Distribution and Gross Solids Contribution of Stormwater Runoff from Ohio's Roads





Prepared by:
Ryan J. Winston and Jonathan D. Witter

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16. Abstract

In order to properly size stormwater treatment systems, or best management practice (BMPs), the sediment particle size distribution (PSD) is needed to quantify the required hydraulic retention time for particle settling or to understand what other treatment processes, such as filtration, might be needed to meet a target sediment removal goal. Gross solids, or particulate matter greater than one-quarter inch in diameter, is transported by stormwater to surface waters. Gross solids include vegetation and anthropogenic sources of litter. A field monitoring study was undertaken across the state of Ohio to determine the PSD of sediment in and to quantify the mass and volume of gross solids conveyed by stormwater runoff.

At the monitoring sites, rainfall was continuously measured and weirs combined with bubbler flow meters were installed in existing catch basins to collect runoff hydrology data. These data were utilized to trigger runoff volume-proportional, composite water quality samples collected by automated samplers during rain events. A total of 176 storm event runoff samples were sent to the laboratory for analysis of TSS and PSD. Gross solids monitoring was undertaken by installing a metal mesh basket beneath the existing grate on a second catch basin near the PSD monitoring location. Gross solids samples were collected every 11 days on average and analyzed in the lab for total mass and volume. Additionally, the mass and volume of nine categories of gross solids were measured: vegetation, plastic, glass, metal, paper, cigarettes, gravel, wood, and fabric.

Observed TSS event mean concentrations at the 12 monitoring sites were on the low end of those observed in the literature, with an overall mean of 35 mg/L. Annual loading of TSS varied from 87 lb/ac/yr to 463 lb/ac/yr, with a mean value of 242 lb/ac/yr across the 11 sites. At the twelve PSD monitoring sites, a median d50 of 52.5 µm was observed, which was similar to the 44 µm median d50 from previous research studies using similar sampling techniques. The NJDEP particle size distribution, which is frequently utilized for laboratory testing of TSS removal for proprietary devices, was very similar to the mean PSD measured herein.

Gross solids volume and mass were predominated by natural vegetation (80.3% of volume and 79.7% of mass) and were seasonal in nature with significantly more gross solids contributed in the fall. During the 190-235 day monitoring periods, a total of 7.4 to 58.2 gallons of gross solids were collected by site, with a mean volumetric loading rate of 0.94 gal/ac/day. Mean gross solids weight per collection event across the eleven sites varied from 0.10 to 7.86 lb. The mean observed sample weight was 1.16 lb, resulting in a mean mass loading rate of 0.41 lb/ac/day. Similar to gross solids volume, gross solids mass was significantly higher at urban sites than at suburban or rural locations. Grass clippings from mowing of the roadside shoulder and leaf-fall during the autumn season were the principle contributors of vegetation to roadside

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Acknowledgments

We appreciate the aid of ODOT district staff in identification of research sites. Particularly, staff from districts 1, 2, 4, 6, 7, 8, and 12 contributed their local knowledge to identify sites that met the needs of this project. We appreciate the efforts of the technical panel members and staff of the Office of Hydraulic Engineering for their time spent working on this project. We appreciate the efforts made by ODOT staff in review of this document, which has substantially improved its content.

Ohio State University students and staff substantially contributed to the data collection efforts of this project. We appreciate the diligent and safe work performed in the right-of-way collecting stormwater and gross solids samples. Denin Miletto, Viktor Lillard, Haley Jenkins, Lauren Sester, and David Wituszynski all performed various field sampling and/or laboratory tasks that contributed to the success of this project. We appreciate their efforts.

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1 Executive Summary

The Ohio Department of Transportation (ODOT) is required to treat stormwater runoff from some roads because of Ohio's Construction General Permit (OHC000005), a National Pollutant Discharge Elimination System (NPDES) permit. Two pollutants of concern for ODOT are sediment and gross solids. Sediment, often quantified as total suspended solids (TSS), has undesirable impacts on receiving water bodies, including loss of habitat and loss of reservoir capacity, among others. In order to size stormwater treatment systems, or best management practice (BMPs), the sediment particle size distribution (PSD) is needed to quantify the required hydraulic retention time for particle settling or to understand what other treatment processes, such as filtration, might be needed to meet a target sediment removal goal. Gross solids, or particulate matter greater than one-quarter inch in diameter, is transported by stormwater to Ohio's surface waters. Gross solids include vegetation and anthropogenic sources of litter. Broadly, this final report describes a project undertaken to quantify the amount and size of sediment as well as the mass and volume of gross solids from Ohio's roads. These data will be used by ODOT to optimize their investments in BMPs.

A field monitoring study was undertaken across the state of Ohio to determine the PSD of sediment in and to quantify the mass and volume of gross solids conveyed by stormwater runoff. Monitoring was undertaken at roads with a variety of characteristics (pavement type, traffic load, functional class, etc.) to determine how these factors affect PSD and gross solids mass and volume. Twelve geographically-diverse sites were selected for PSD monitoring, and eleven of these were concurrently monitored for gross solids.

At the monitoring sites, a manual and a tipping bucket rain gauge were installed to measure hyetographs. Weirs and bubbler flow meters were installed in existing catch basins to collect runoff hydrology data. These data were utilized to trigger runoff volume-proportional, composite water quality samples collected by automated samplers during rain events. A total of 176 storm event runoff samples were sent to the laboratory for analysis of TSS and PSD. Gross solids monitoring was undertaken by installing a metal mesh basket beneath the existing grate on a second catch basin near the PSD monitoring location. A baffle was installed in the gutter pan to force all stormwater through this basket. The aperture of the openings in the metal mesh was 0.20 inches, and thus all gross solids larger than this were filtered out. Gross solids samples were collected every 11 days on average and analyzed in the lab for total mass and volume. Additionally, the mass and volume of nine categories of gross solids were measured: vegetation, plastic, glass, metal, paper, cigarettes, gravel, wood, and fabric.

Observed TSS event mean concentrations at the 12 monitoring sites were on the low end of those observed in the literature, with an overall mean of 35 mg/L. Maximum TSS concentrations ranged from 40 mg/L to 312 mg/L. Storm event TSS loads ranged from 0.08 to 52.8 lb/ac across the 11 sites with reliable runoff hydrology data. Annual loading of TSS varied from 87 lb/ac/yr to 463 lb/ac/yr, with a mean value of 242 lb/ac/yr across the 11 sites.

At the twelve PSD monitoring sites, d_{10} ranged from 3 to 17 μm, d_{50} from 24 to 72 μm, and d_{90} from 89 to 200 μm. A median d_{50} of 52.5 μm was observed, which was similar to the 44 μm median d_{50} from previous research studies using runoff volume-proportional sampling techniques. Significantly coarser PSD was measured during storms in the summer than in the fall or spring, with median particle diameters of 54, 42, and 45 μm, respectively. This was due to shorter duration, higher intensity storms during this season causing flashier flows and thus mobilizing larger particles. The NJDEP particle size distribution, which is frequently utilized for laboratory testing of TSS removal for proprietary devices, was very similar to the mean PSD measured herein.

Gross solids volume and mass were predominated by natural vegetation (80.3% of volume and 79.7% of mass) and were seasonal in nature with significantly more gross solids contributed in the fall. Across all gross solids samples, natural vegetation was the biggest contributor (mean 1.04 gallons per sample) to total gross solids (mean 1.23 gallons per sample). During the 190-235 day monitoring periods, a total of 7.4 to 58.2 gallons of gross solids were collected by site, with a mean volumetric loading rate of 0.94 gal/ac/day. After vegetation, the second-most common contributors to gross solids volume included cigarettes (5 sites), plastic (4 sites), and gravel (2 sites). Statistical testing showed that gross solids volume was higher for urban sites than for suburban or rural sites.

Mean gross solids weight per collection event across the eleven sites varied from 0.10 to 7.86 lb. The mean observed sample weight was 1.16 lb, resulting in a mean mass loading rate of 0.41 lb/ac/day. Vegetation was the primary contributor to total gross solids mass at 10 of the 11 sites, with gravel the primary contributor at the final site. Second-most common contributors to gross solids mass were gravel and cigarettes (3 sites apiece), paper (2 sites), and plastic, vegetation and wood (1 site apiece). Similar to gross solids volume, gross solids mass was significantly higher at urban sites than at suburban or rural locations. This is due to higher percentages of litter and debris from vehicular accidents at urban sites. Grass clippings from mowing of the roadside shoulder and leaf-fall during the autumn season were the principle contributors of vegetation to roadside catch basins, suggesting that maintenance will be optimized if scheduled to follow these events.

2 Part I: Particle Size Distribution

2.1 Introduction

Stormwater runoff from roads is a contributor to the total wet-weather pollutant load in a watershed. Highways are one source of sediment, heavy metals, nutrients, hydrocarbons, and bacteria due to anthropogenic and atmospheric deposition processes (Kayhanian et al. 2007; Davis and Birch 2011). Anthropogenic sources of pollutants include pavement wear, tire wear, and vehicular fluids (Kobriger and Geinopolis 1984; Legret and Pagotto 1999). Successful attempts have been made to tie these pollutants to factors such as annual average daily traffic (AADT), roadway classification, pavement wearing course, antecedent dry period (ADP), contributing drainage area, and rainfall depth and intensity (Kim et al. 2005; Opher et al. 2009). The size of particles entrained in stormwater runoff varies substantially, with diameters from several nanometers to several millimeters. Thus, the particle size distribution (PSD) is an important parameter to consider in determining BMP pollutant removal rates for sediment and sediment-bound pollutants, especially when relying on settling-based treatment methods.

2.1.1 *Solids in Stormwater runoff*

Particulate matter is categorized by its diameter into four principal categories: dissolved solids (<2 μm), fine solids (2-75 μm), coarse solids (75 μm – 5 mm), and gross solids (>5 mm; WERF 2008). Others separate coarse from fine solids at 63 μm (e.g., Semadeni-Davis 2013), as this is the generally-accepted border between silt and clay particle sizes. Dissolved solids are made up of fine clays, colloids, and bacteria, and are generally not able to be treated by settling-based BMPs. Coarse clays, silts, and fine organic matter make up fine solids, which require extended hydraulic retention times to settle out. Coarse solids are made up of sand, fine gravel, and organic matter, and BMPs with shorter hydraulic retention times may be utilized to sequester these particles. Finally, gross solids include gravels, trash, and large organic detritus. These largest diameter particles can be removed from stormwater using catch basin inserts, screens, trash racks, deep sumps, or structural BMPs.

Some challenges exist in attempting to quantify the entire range of particle size. Automated samplers, which are used in most current studies on solids in stormwater, typically utilize sample tubing that is 3/8 inch (9.5 mm) in diameter. This means other methods beyond automated samplers must be developed for gross solids sampling.

When quantifying runoff sediment, total suspended solids (TSS) analysis is the most commonly used gravimetric index, typically reported in mg/L. Total suspended solids (TSS), the method of solids classification typically used for NPDES permit compliance, are recommended to be analyzed by separating out gross solids using the No. 4 sieve (mesh opening of 4.76 mm) and dissolved solids using a 2 μm filter (WERF 2008).

2.1.2 Settling Theory and Measurement of Particle Sizes in Stormwater Runoff

While TSS is a general indicator of sediment in runoff, it provides no indication of the fraction of sediment that might be settleable within an BMP used to treat road runoff, such as a proprietary treatment device, swale, filter strip, or detention basin. ODOT's stormwater discharges are regulated under the NPDES program through the construction general permit (OEPA 2018). This permit requires an approved BMP per ODOT's Location and Design Manual, Volume 2 or testing of non-standard BMPs to prove they provide 80% TSS removal. However, determining the sediment trapping efficiency of BMPs is difficult unless the PSD of road runoff in Ohio is known. For example, particles larger than 100 μm in diameter are easily settled, while those less than 100 μm require lengthy (hours to days) hydraulic retention times to be settled in a BMP (Andral et al. 1999). Especially with regards to BMPs with limited hydraulic retention time, a PSD dominated by clays and silts will result in a high risk of low TSS removal.

Since sediment particles have varying diameters, they settle at differing rates. Settling velocities can substantially vary based on the diameter, density, and geometry of a particle, with measured values from 0.00275 to 15.5 ft/min in one study (Lucas-Aiguier et al. 1998). These vast differences in settling rates illustrate the need to understand the distribution of particle sizes within road runoff.

Runoff PSD substantially impacts the performance of settling-based BMPs, which are commonly employed by ODOT and DOTs nationwide (Ferreira and Stenstrom 2013). To evaluate runoff PSD, the D_{10}, the D_{50} and the D_{90} (the 10^{th}, 50^{th}, and 90^{th} percentile particle diameters, respectively) are often evaluated. The D_{10} and D_{90} give an idea of the range of the distribution and the D_{50} is often used as a measure of central tendency.

2.1.3 PSDs from Past Research

PSD has been characterized in several urban stormwater runoff studies (e.g., Characklis and Wiesner 1997; Sansalone et al. 1998; Li et al. 2005; Charters et al. 2015). Runoff PSDs exhibit a high level of variability (e.g., Figure 1 and Appendix A) due to both site characteristics and climatic/runoff conditions, which vary both temporally and spatially (Selbig and Bannerman 2007). Some researchers suggest PSD varies throughout a storm and as a function of land use in the contributing watershed (Li et al. 2006). However, research by Charters et al. (2015) found no significant differences between first flush and whole-event PSDs; thus, designing for different PSDs temporally within a storm may not be justified. Distinct PSDs by urban land use have often been suggested within a single research study (e.g., highways appeared different from urban roads in Charters et al. 2015), but accumulated data from the research literature seems to show very little pattern in PSD by land use (Figure 1). Selbig and Bannerman (2011) evaluated runoff PSD from several land uses in Wisconsin, and found “considerable” variability in median particle size and distribution. Streets and rooftops had the largest median particle diameters (both around 70-100 μm).

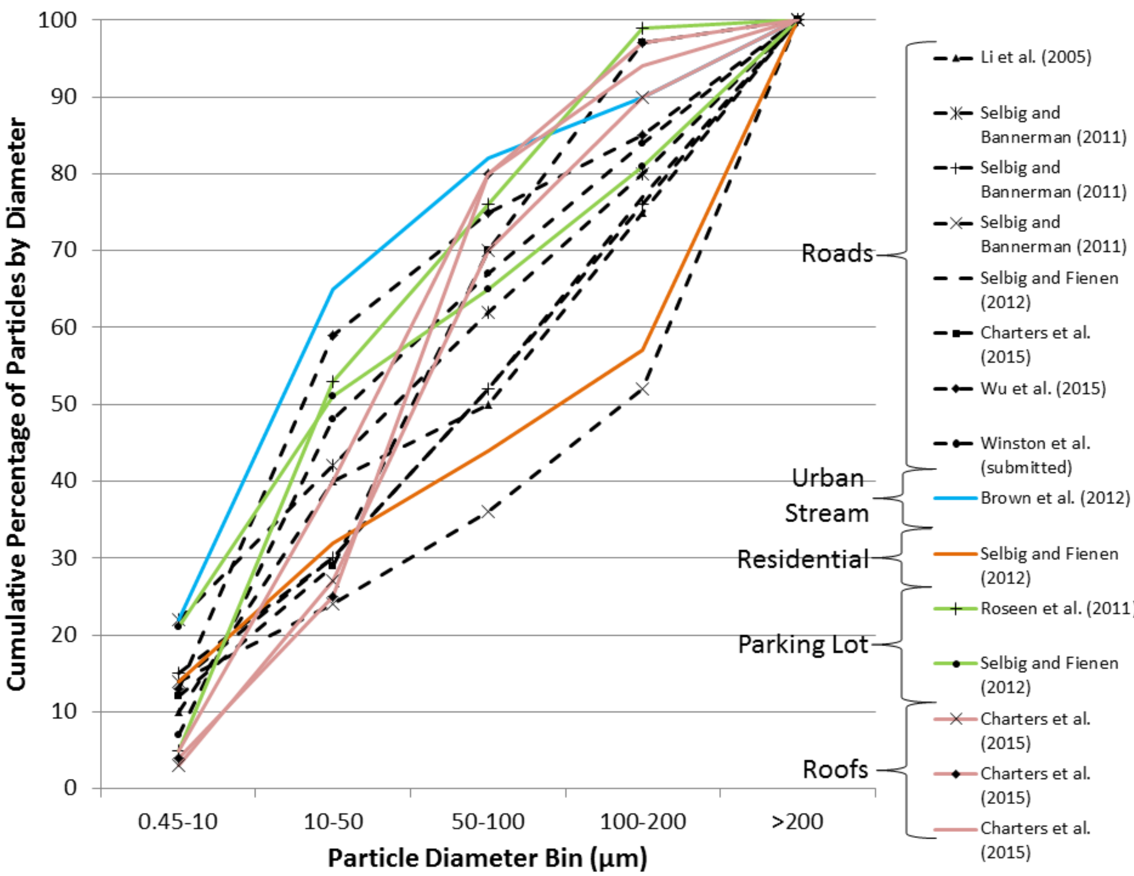

Figure 1. Particle size distribution data from selected published research. Particles were placed into 5 bins by diameter. The line color represents the land use of the monitored watershed.

Various sampling methods exist for sampling PSD, including grab sampling, flow paced composite, and vacuuming of dry sediment from road surfaces (see Appendix A for additional detail). To determine how sampling method affects PSD, d_{50} data in Table A-1 were plotted as a function of (1) the date of publication, and (2) method of sample collection (Figure 2). Sampling methods appear to have improved with time, with reduced variability in observed median particle diameters (Figure 2). Horizontal lines on the graphic are representative of the median particle diameter from previous studies (regardless of land use) by sampling method. Sediment sampling by vacuuming during dry weather produced a 250 µm median d_{50}, while grab/time paced samples resulted in an 80 µm median d_{50}. The median d_{50} for studies utilizing flow-proportional sampling was 44 µm. This illustrates the bias that can be introduced into measured PSD based on the methods used to obtain samples.

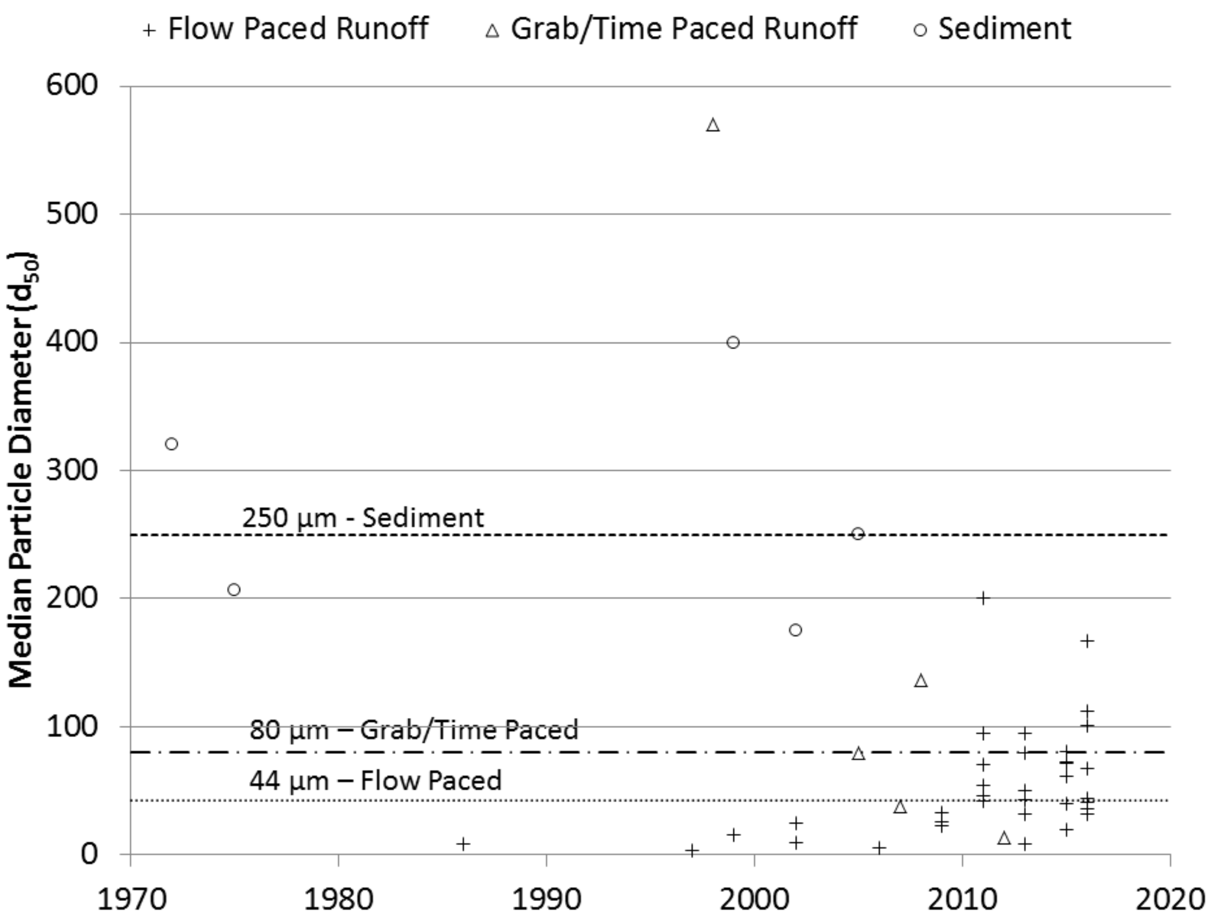

Figure 2. Urban runoff PSDs by year and sampling methodology. Median particle diameters for the three different sampling methodologies are shown as horizontal lines.

2.2 Methods

2.2.1 Description of Monitored Catchments

Twelve geographically-diverse road sites were selected for TSS and PSD monitoring in Ohio. The sites were located in Franklin, Montgomery, Delaware, Hamilton, Allen, Portage, and

Lake counties (Table 1). Monitored catchments consisted solely of road constrained by curb and gutter draining to a single catch basin. Site selection criteria developed as part of the project screened out sites where grassed shoulders were graded toward the drainage network. Other potential contributors of sediment such as construction sites, nearby mines or gravel pits, or openly eroding pervious areas were also screened out such that selected sites represented typical ODOT road conditions. Sites were selected considering an array of potential factors which might contribute to sediment build-up and wash-off: rainfall patterns, pavement type, annual average daily traffic (AADT), functional class, adjacent land use, and development density. Six sites were monitored in 2016 and an additional six in 2017.

Monitoring sites were identified by the corresponding road identifier: I-70, I-71, and I-90 were interstate highways, SR-22, SR-43, SR-48, SR-49, SR-59, and SR-81 were principal arterials, and SR-117, SR-257, and US-20 were minor arterials. Interstate highways, principal arterials, and minor arterials had AADT above 30,000, between 10,000-25,000, and less than 10,000 vehicles per day, respectively. Similarly, posted speed limits were 65-70 mph, 35-55 mph, and 35-55 mph, respectively. The wearing course at all sites was hot mix asphalt except for US-20 and I-90, which were paved with concrete.

Table 1. Characteristics of PSD monitoring sites.

Site Name	Latitude, Longitude	County	Catchment Description	ODOT Rainfall Zone	Pavement Type	Functional Class	No. of Travel Lanes	No. of Turn Lanes	No. of Shoulder Lanes	AADT (vpd)	Catchment Area (ac)	Adjacent Land Use	Development Density
I-70	39.9397,-82.9387	Franklin	Eastbound travel lanes and shoulder	C	Asphalt	Interstate	1.5	0	1	93940	0.442	Commercial	Urban
I-71	40.019,-82.995	Franklin	Northbound travel lanes, merging lane, and shoulder	C	Asphalt	Interstate	1.5	1	1	131990	0.314	Medium Density Residential	Urban
SR-257	40.1557,-83.121	Delaware	Northbound travel lane and shoulder	C	Asphalt	Minor Arterial	1	0	1	7060	0.039	Commercial	Suburban
SR-22	39.2803,-84.3185	Hamilton	Eastbound travel lanes and shoulder	C	Asphalt	Principal Arterial	2	0	0.5	24730	0.275	High Density Residential	Suburban
SR-48	39.8227,-84.24	Montgomery	Southbound travel lanes and half of center turn lane	B	Asphalt	Principal Arterial	2	0.5	0	17054	0.349	Low Density Residential	Urban
SR-49	39.8292,-84.294	Montgomery	Northbound travel lanes and shoulder	B	Asphalt	Principal Arterial	1	0	1	15630	0.147	Low Density Residential	Suburban
SR-117	40.7252,-84.0604	Allen	Eastbound lanes	B	Asphalt	Minor Arterial	2	0	0	7960	0.065	Agricultural	Rural
SR-81	40.7511,-84.1570	Allen	Westbound lanes and half of center turn lane	B	Asphalt	Principal Arterial	2	0	0.5	12070	0.118	Agricultural	Rural
SR-43	41.1230,-81.3478	Portage	Northbound lanes, half of turn lane, and 3 ft shoulder	A	Asphalt	Principal Arterial	2	0.5	0.25	16840	0.125	Low Density Residential	Urban
SR-59	41.1574,-81.3031	Portage	Eastbound lane, shoulder, and turn lane	A	Asphalt	Principal Arterial	1	1	1	14048	0.33	Commercial	Suburban
US-20	41.6887,-81.2890	Lake	Northbound lanes and half of center turn lane	A	Concrete	Minor Arterial	2	0.5	0	11950	0.225	Commercial	Urban
I-90	41.7343,-81.1052	Lake	Westbound lane and shoulder - bridge deck runoff	A	Concrete	Interstate	1	0	1	30575	0.033	Agricultural	Rural

2.2.2 Data Collection

A rain gage cluster, consisting of a tipping bucket and a manual rain gage attached to a 6-ft tall wooden post, was installed at each of the 12 monitoring sites in locations free from overhead obstructions (Figure 3). Rainfall data were collected using 0.01" resolution Davis Rain Collector tipping bucket rain gages (Davis Instruments, Hayward, California) and stored on Hobo Pendant data loggers (Onset Computer Corporation, Bourne, Massachusetts). Rainfall data were stored on a 1-minute interval and downloaded to a field laptop approximately once per month. Rainfall events were separated for hydrologic data analysis and for water quality sampling based on these criteria: (1) minimum rainfall depth of 0.1 inches and (2) minimum antecedent dry period (ADP) of 6 hrs.

To quantify runoff hydrology and obtain representative samples of stormwater quality, instrumentation was installed within a catch basin draining each catchment (Figure 3). A v-notch weir (varying angles and heights based on catchment area) was installed and all water entering the catch basin was forced behind the weir using a wooden awning. An ISCO 730 bubbler module (Teledyne Isco, Lincoln, NE), which attached to and communicated with ISCO 6712 automated samplers, measured depth of flow over the weir on a 2-minute interval. Standard weir equations were utilized to convert measured depth to flow rate (Grant and Dawson 2001). Hydrologic data were downloaded every three weeks to a field laptop.

Figure 3. Monitoring equipment utilized at the PSD monitoring sites. Manual and tipping-bucket rain gauge (left), sample intake and bubbler tubing with wooden awning in foregound in catch basin at SR-59 (second from left), weir installed at SR-49 (second from right), and automated sampler at SR-43 (right).

Runoff volume-proportional, composite stormwater samples were collected by ISCO 6712 automated samplers (Figure 3). Flow rates were integrated with time to determine stormwater volume and trigger sample aliquots. Once triggered, the automated sampler used its peristaltic pump to lift a desired quantity of water out of the catch basin through 0.375-in plastic tubing and deposit it into sample containers. Sample intake strainers (Figure 3) were located upstream of the weir where flow was well-mixed and utilized to remove gross solids. Each sampler employed a 24, 1-liter bottle configuration with a distributor arm to disperse samples into bottles. Calibration of sample aliquot volume was completed by attempting to fill 15, 1-liter bottles with samples during a 2-inch rain event. Manual rain gauges (Productive Alternatives, Fergus Falls, Minnesota) were utilized to re-calibrate sampler pacing on a weekly basis.

Site visits were made on approximately a weekly basis. Upon arrival to a site, the manual rain gauge was checked to determine total accumulated rainfall depth. The automated sampler was interrogated and the sampling report was viewed to determine whether and when samples were collected. For each qualifying event, a minimum of five and a maximum of 96, 200 mL aliquots describing greater than 80% of the pollutograph (U.S. EPA 2002) were collected. The sequence number of the first and last sample bottle for each storm event was recorded in order to separate multiple storms that may have occurred. During sample collection, each set of sample bottles from a single storm were composited in a 25L plastic carboy. Thus, laboratory reported concentrations were representative of an event mean TSS concentration or an event mean PSD.

For the sites in Franklin, Delaware, Montgomery, and Hamilton counties (Table 1), rainfall, hydrologic and water quality data were collected during the 8-month period from May 2016 to December 2016. Sites in Allen, Portage, and Lake counties were monitored from April 2017 through December 2017.

2.2.3 Laboratory Methods

Samples were composited in a 25L polypropylene carboy, vigorously mixed, and subsampled into laboratory sample bottles (Table 2). Composite samples were divided among a 1-liter plastic bottle for PSD analysis and a 200 mL plastic bottle for TSS analysis. Water quality samples were placed immediately on ice and chilled to less than 39˚F for transit to the laboratory. Total suspended solids samples were analyzed at Pace Analytical, Inc. in Englewood, Ohio, using American Public Health Association (APHA et al. 2012) methods. Particle size distribution samples were shipped on ice to the biogeochemistry laboratory at North Carolina State University (Raleigh, NC). Samples were refrigerated in the laboratory until analyzed. They were analyzed using a Beckman-Coulter 13-320 Laser Diffraction Particle Size Analyzer equipped with a Universal Liquid Module. A refractive index of 1.59 + 0.0001i was used for all PSD analysis based on standards for nondispersed samples. One-hundred seventeen divisions of particle size were evaluated across the range of 0.04-2000 μm; for each division, the volumetric percentage of the total particle volume in the sample was determined. The percentage of sand (50-2000 μm), silt (2-50 μm), and clay (<2 μm) could therefore be enumerated for each sample. All TSS and PSD samples were analyzed within a 7 day hold time.

Table 2. Sampling, preservation, laboratory testing methods, and method detection limits (MDL) for analyzed pollutants.

Parameter	Laboratory Method	Sampling Method	Container	Preservation	MDL (mg/L)
TSS	Standard Methods 2540D	Composite	Plastic	<4˚C	5
PSD	Laser Diffraction	Composite	Plastic	<4˚C	N/A

2.2.4 Data Analysis

Summary statistics for each qualifying precipitation event were developed, including rainfall depth (in), rainfall duration (hrs), average rainfall intensity (in/hr), peak rainfall intensity (maximum over any 5-minute duration, in/hr), ADP (days), and season. These data along with the start and end time of each rainfall event are tabulated in Appendix B. Summary statistics for all qualifying hydrologic events and events sampled for water quality at each site are presented in Appendix C.

Rainfall data were sometimes lost due to data logger battery failure or because of debris clogging the rain gage funnel. In these cases, rainfall data from a paired site located with 10 miles (for instance SR-48 for SR-49) were utilized to fill gaps in data. Of the 490 observed rainfall events across the 12 sites, this occurred for 20 events or 4% of the rainfall data set. Certain rainfall events were disqualified from the hydrologic data set because (1) equipment failure caused loss of data or (2) clogging of the weir with debris caused measurement error. This occurred during 24 of the 490 (5%) of the observed rainfall events.

Hydrologic measurements obtained using the bubbler flow meters were used to quantify stormwater runoff timing, volume, and rate. Runoff volume was determined by integrating under the hydrograph, while peak flow rate was determined as the instantaneous 2-minute maximum flow rate over the flow duration.

Hydrologic data collected at the I-70 site were deemed unreliable and are thus we were not able to determine TSS loads at this site. For about half of observed storms, far more runoff depth was measured than rainfall depth. This was due to a changing catchment area for this catch basin due to (1) intense periods of rainfall overwhelming upslope catch basins and (2) clogging of upslope catch basin inlets with gross solids, which both caused additional water to enter the monitored catch basin.

Summary statistics for pollutant concentrations were tabulated for TSS event mean concentrations (EMCs) from the monitored catchments. These included the range, mean, median, and standard deviation. Side-by-side boxplots were created to examine differences in water quality. TSS concentrations from roads herein were compared against those from previous studies documenting road runoff quality.

A value of one-half the detection limit was substituted for EMCs below the method detection limit (MDL; Antweiler and Taylor 2008). Sixteen of 191 measured TSS concentrations were below detection limit (BDL), or 8.3% of samples. All concentrations above the detection limit were analyzed without modification.

Total suspended solids loads at each monitoring location were determined as the product of pollutant EMC and runoff volume on a storm-by-storm basis. Pollutant loads were reported on a catchment area-normalized basis:

$$L = 2.205 \times 10^{-6} \times \frac{EMC \times V}{A_{CA}} \quad (1)$$

where L is pollutant load (lb/ac), EMC is the event mean concentration (mg/L), V is the measured runoff volume (L), A_{WS} is the catchment area (ac), and the constant converts from milligrams to pounds. Pollutant loads were tabulated and presented in boxplots for comparison between catchments. Annual loading (L_a, lb/ac/yr) was estimated by accounting for storms not sampled for water quality. The ratio of the annual average rainfall measured over 60 years at the nearest National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) rain gage (RF_{avg}) to total rainfall depth sampled for water quality (RF_{Samp}) was utilized to scale the annual loading (Equation 2); thus, the assumption is that the sampled storm events are representative of the overall population of runoff volume and pollutant concentration. The annual loading (L_a, lb/ac/yr) was also normalized by catchment area and monitoring period duration (d_{MP}, years):

$$L_a = 2.205 \times 10^{-6} \times \frac{\sum_{i=1}^{n}(EMC_i \times V_i) \times RF_{avg}}{A_{WS} \times d_{MP} \times RF_{Samp}} \qquad (2)$$

where n is the number of sampled storm events.

For PSD samples, summary statistics were developed including the 10th percentile diameter (d_{10}), median particle diameter (d_{50}), 90th percentile diameter (d_{90}), the coefficient of uniformity (C_u), and the coefficient of curvature (C_c). These data were utilized in follow-on statistical analysis to determine predictors for PSD, including rainfall characteristics, site characteristics, and TSS concentration. The coefficients of uniformity and curvature were determined using:

$$C_u = \frac{d_{60}}{d_{10}} \qquad (3)$$

$$C_c = \frac{(d_{30})^2}{d_{10} \times d_{60}} \qquad (4)$$

Among the twelve monitored catchments, comparisons between rainfall characteristics, site characteristics, TSS concentration, TSS load, and PSD characteristics (i.e., d_{10}, d_{20}, d_{50}, d_{90}, C_c, C_u) were made to determine statistically significant differences. Initial comparisons were carried out using the Kruskal-Wallis k-sample test (Kruskal and Wallis 1952). When this omnibus test was significant, paired comparisons among all possible combinations of catchments were made using Dunn's test with a Bonferroni correction (Higgins 2004). Bootstrapping was performed with n=1000 samples to determine confidence intervals for d_{10}, d_{20}, d_{50}, d_{90} for observed significant differences between road functional classes and surrounding land uses. Seasonality of rainfall and water quality data sets was tested using similar methods. Spearman's rank order correlation was done to determine correlations between PSD, TSS, and explanatory variables. All data analysis was completed using R statistical software version 3.5.2 (R Core Team, 2018). Except where noted, a criterion of 95% confidence (α=0.05) was used.

2.3 Results

2.3.1 Observed Rainfall Events

At each monitoring site, between 26 and 52 rainfall events were observed over the monitoring periods from May to December 2016 and April to December 2017. A total of 490 qualifying rainfall events were observed; of these, 176 and 190 were sampled and analyzed for PSD and TSS, respectively. A minimum of 12 and a maximum of 18 events were sampled for PSD at each monitoring site. Sampled storms represented 46.2% of the 272.63 in of rainfall observed across the 12 monitoring sites.

Median event depth for sampled storms was 0.63 in, while that for all observed storms was 0.41 inches (sampled and not sampled events). The maximum observed rainfall depth was 3.61 inches at SR-257, and this event was sampled for PSD and TSS. The median peak rainfall intensity for sampled storms (0.9 in/hr) was similar to that for observed rainfall events (0.96 in/hr). Median rainfall duration for sampled storms was 5.6 hrs, nearly the same as that for all observed storms (5.8 hrs). Median antecedent dry period (ADP) for sampled events (3.6 days) was greater than those for all observed rainfall events (2.8 days) at eight of the twelve monitoring sites. These data suggest that sampled storms generally had greater rainfall depth and longer ADP than the central tendency; sampled storms had similar rainfall intensity and duration to all observed storms.

Substantial variability in rainfall characteristics was observed across the twelve monitoring sites (Figure 4). Statistical testing showed no significant differences in rainfall depth, peak intensity, and ADP across the 12 monitored sites. Between-site significant differences were observed for rainfall duration and average intensity; follow-on paired comparisons with Dunn's test with a Bonferroni correction showed that I-71 site exhibited significantly lower rainfall duration than SR-43 ($p=0.036$) and this resulted in significantly higher average intensity at I-71 than at SR-43 ($p=0.019$). Significantly greater average intensity was also observed at I-71 than at I-90. All other combinations of sites were not significantly different for rainfall duration or average intensity; generally, these analyses suggested that rainfall characteristics were not substantially different across the geographically-varied sites monitored in this project.

Rainfall depth and antecedent dry period were not statistically different across seasons ($p>0.2$). Kruskal-Wallis tests showed significant seasonality in rainfall duration, peak intensity, and average intensity. Rainfall duration in the fall and spring were significantly greater than summer, and duration in the fall was significantly greater than spring. Peak and average rainfall intensities were significantly greater in summer than in fall and spring, which is expected given the convective summer thunderstorms that Ohio experiences (Fritsch et al. 1986).

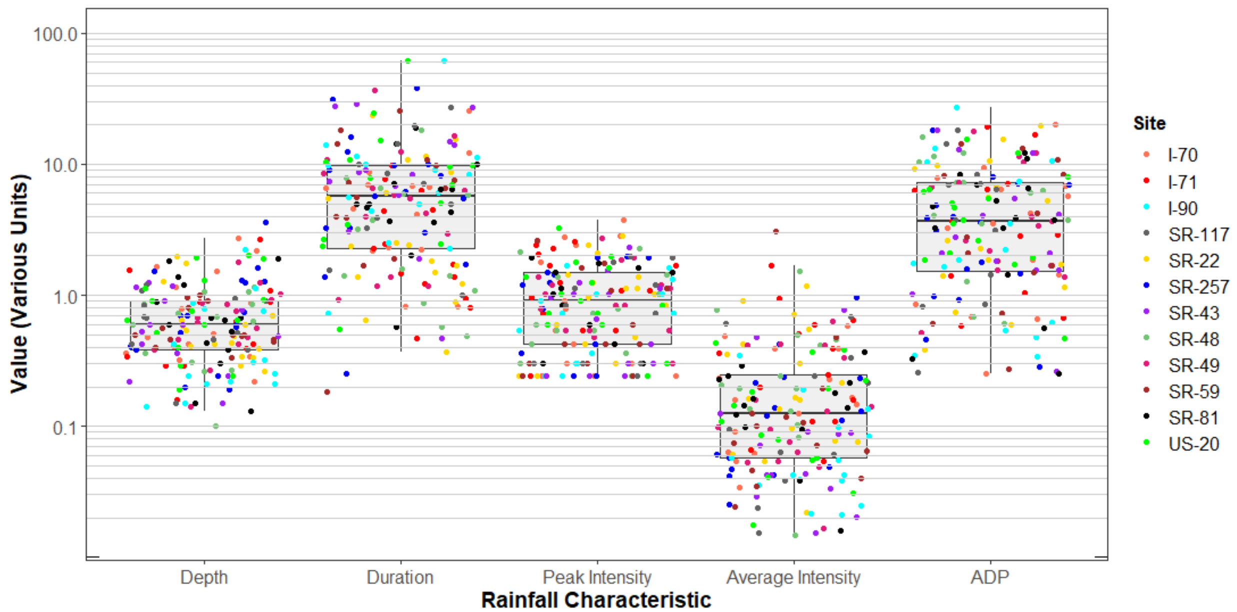

Figure 4. Rainfall characteristics for events sampled for PSD and/or TSS. Depth (in), duration (hrs), average intensity (in/hr), peak intensity (in/hr), and antecedent dry period (ADP, days) were determined for each rainfall event and plotted.

2.3.2 Water Quality

2.3.2.1 TSS Concentrations

Observed TSS EMCs at the 12 monitoring sites were relatively low, with an overall mean of 35 mg/L (Figure 5). Mean by-site concentrations ranged from 13-70 mg/L. Maximum TSS concentrations ranged from 40 mg/L to 312 mg/L (mean of the maximum concentrations observed at each of the 12 sites was 106 mg/L). Measures of central tendency for TSS concentrations from road sites studied in the literature (National Stormwater Quality Database, California, Texas, Oregon, and North Carolina) suggest a range of TSS concentrations from 19-163 mg/L. These data suggest that TSS concentrations observed in this study were on the lower end of those in the literature, but not entirely dissimilar from those in past studies.

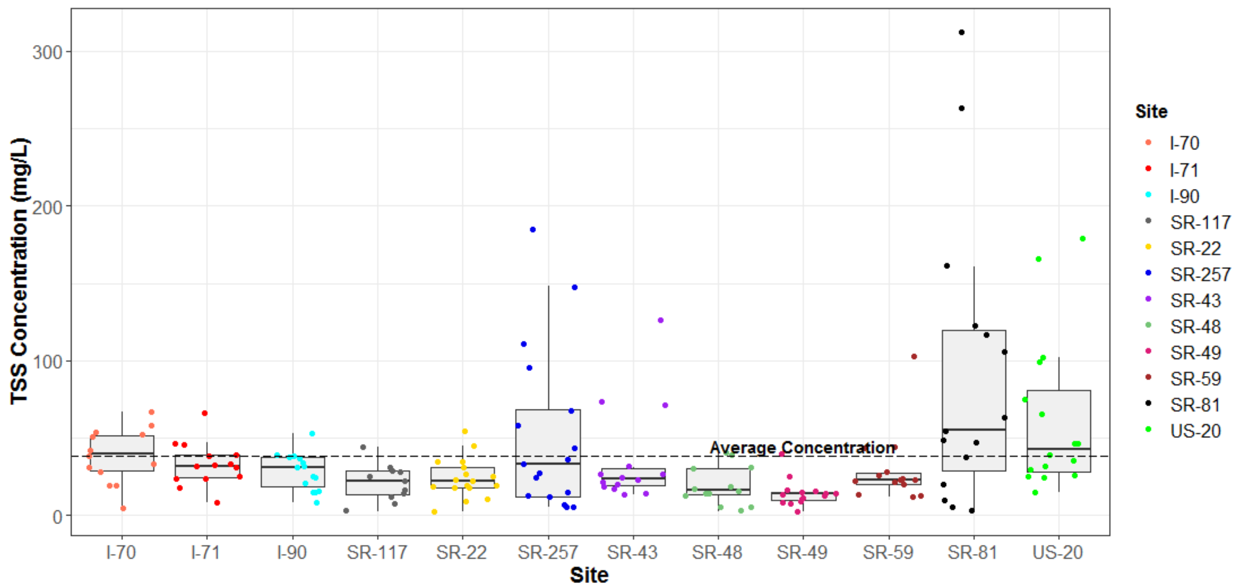

Figure 5. TSS concentrations by site. Mean TSS concentration across all sites shown as a dashed line. The line in the middle of the boxplot represents the median value for the site.

Based on a Kruskal-Wallis test, no significant seasonality was observed in TSS concentration, suggesting that road runoff TSS concentrations are consistent during fall, summer, and spring. Differences were observed in site-to-site TSS concentrations (p-value<0.001). TSS concentrations at I-70, I-71, SR-257, US-20, and SR-81 were significantly greater than those from SR-49, while US-20 and SR-81 produced significantly greater TSS concentrations than SR-48. TSS concentrations at US-20 were significantly greater (α=0.10) than SR-117. Thus, a mixture of interstate highways (I-70 and I-71) with the highest AADT and largest catchment area as well as minor arterials (SR-257) with less than 10,000 vehicles per day and a small catchment area produced comparatively higher TSS concentrations. These data suggest that other factors beyond AADT, such as ADP, rainfall intensity, and windborne dust and particulates, may contribute to TSS concentrations in stormwater runoff.

Correlations were explored between TSS concentrations and potential causative variables, including rainfall characteristics and numerical site characteristics such as AADT, speed limit, and catchment area (Figure 6). TSS concentrations were not significantly correlated to site or rainfall characteristics. Previous studies, including Winston and Hunt (2017), Kayhanian et al. (2007), Drapper et al. (2000), and Yu et al. (1994) significantly correlated various rainfall, flow, and site characteristics to TSS concentrations in road runoff. However, agreement between the studies in what are the most important causal variables is lacking.

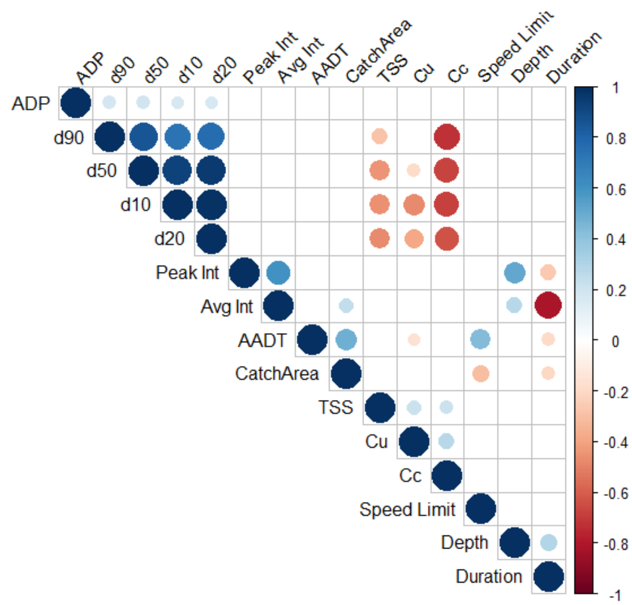

Figure 6. Correlogram between particle size statistics (d_{10}, d_{20}, d_{50}, d_{90}, C_u, and C_c) and potential predictor variables, including climatic factors and site characteristics. Positive correlations are displayed in blue and negative correlations in red. Color intensity and diameter of the circle are proportional to Spearman's correlation coefficients, with deeper colors and larger diameters signifying greater correlation. Blank cells in the correlogram were not statistically significant.

2.3.2.2 <u>TSS Loads</u>

Total suspended solid loads were determined for each sampled rainfall event and normalized by watershed area (Figure 7). TSS loads ranged from 0.08 to 52.8 lb/ac across the 177 events sampled for TSS with reliable flow data (i.e., the I-70 site was removed from this analysis). The mean TSS load across all samples collected at the 11 sites was 5.0 lb/ac per storm event, with mean by-site loads ranging from 0.8 lb/ac to 10.8 lb/ac. Irish et al. (1998) observed TSS loads of 0.9-89 lb/ac for stormwater runoff events from the MoPac Expressway in Austin, TX.

Storm event loads by site were summed and scaled by the ratio of mean annual rainfall to the total sampled rainfall event depth to determine an annual mass loading rate (Figure 7). Annual

TSS loads varied from 87 lb/ac/yr to 463 lb/ac/yr, with a mean value of 242 lb/ac/yr across the 11 sites. Previous studies on roads in North Carolina, Texas, Taiwan, and 10 sites across the U.S. observed TSS loads between 427-1754 lb/ac/yr (Chui et al. 1982; Stotz 1987; Wu et al. 1998; Barrett et al. 1998). Generally, these data suggest that annual sediment loading rates from roads in Ohio are on the low end of those observed in the literature. Perhaps this is related to the variety in road characteristics for the site studied herein, whereas many of the above studies focused solely on highway runoff.

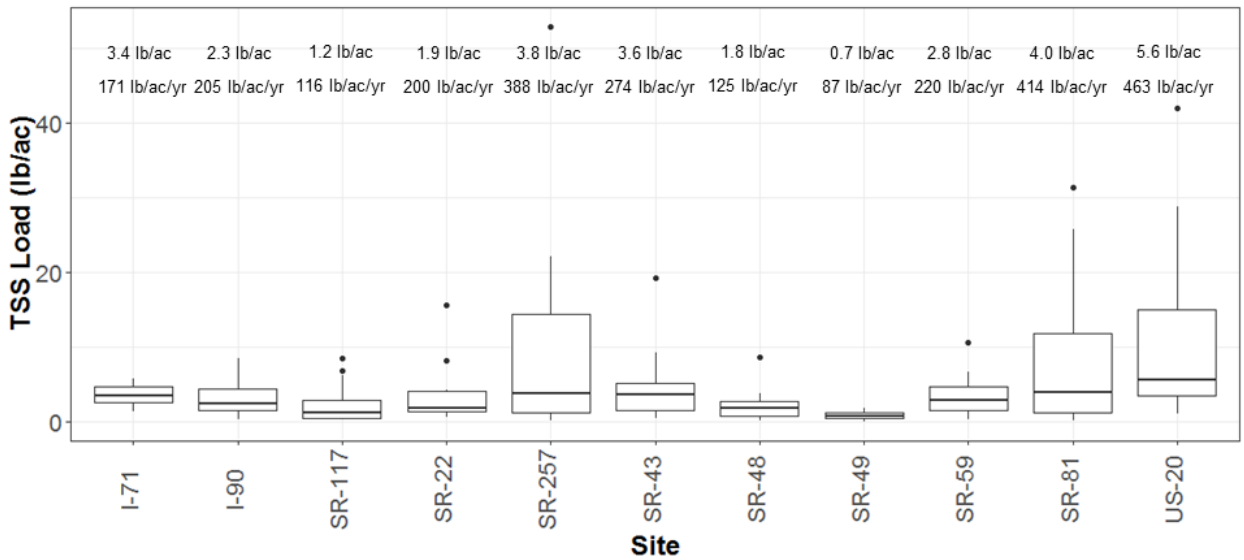

Figure 7. Boxplots of TSS load (lb/ac) by site. Median sampled storm event TSS load (lb/ac) and TSS annual loading rates (lb/ac/yr) are denoted for each site.

2.3.2.3 Particle Size Distribution

A total of 176 PSDs were collected across the twelve monitoring sites, all of which are included in the analysis that follows. Between 12-18 samples were collected at each site, with SR-117 having the least collected samples and SR-22 the most. The number of samples collected varied based on-site maintenance needs, equipment failure, rainfall patterns, and availability of staffing to collect samples, among other factors.

Median and mean PSD characteristics were determined across all samples obtained at each site (Table 3). Median d_{50} ranged from 24 µm at SR-81 to 72 µm at SR-49. Mean d_{50} particle size ranged from 29 µm at SR-81 to 102 µm at SR-48. The median d_{10} ranged from 3 µm to 17 µm, while the median d_{90} ranged from 89 µm to 200 µm. Coefficients of uniformity and curvature were in the range of 5-10 and 1.2-2.6, respectively.

Table 3. Median and mean summary statistics for particle size distributions by site.

Site	Median						Mean					
	d_{10}	d_{20}	d_{50}	d_{90}	C_u	C_c	d_{10}	d_{20}	d_{50}	d_{90}	C_u	C_c
I-70	9.5	17.8	38.4	101.4	5.56	1.40	10.1	20.6	58	225	7.67	1.55
I-71	8.7	17.4	37.9	96.3	5.35	1.47	8.71	28.3	60.5	172	7.32	2.61
I-90	16.6	29.7	63.6	176.3	5.38	1.24	16.2	29	68.9	357	5.72	1.23
SR-117	10.1	20.5	48.8	139.5	6.58	1.41	12.5	22.9	50.4	169	6.14	1.39
SR-22	13.3	26.2	59.0	155.2	5.77	1.33	13.4	25.6	60.9	178	7.3	1.43
SR-257	10.7	20.5	51.0	139.3	5.47	1.32	10.3	19.6	48.6	142	6.95	1.32
SR-43	11.4	21.2	47.6	149.0	6.34	1.30	12.1	23.6	70.5	310	6.98	1.34
SR-48	15.2	29.2	70.8	199.8	6.36	1.27	19.9	37.8	102	354	6.53	1.27
SR-49	14.8	28.7	72.4	185.9	5.99	1.28	15.1	29	71.8	203	6.09	1.28
SR-59	10.3	19.9	43.5	129.3	5.37	1.34	11.8	22.2	49.8	209	5.45	1.36
SR-81	3.0	7.8	24.5	89.6	10.15	1.70	4.1	10	29.5	94	10.4	1.71
US-20	8.8	17.6	45.0	179.2	6.65	1.45	10.7	21.1	51.9	258	6.66	1.41

Based on the United States Department of Agriculture's definition of soil texture, particles less than 2 µm are characterized as clay, those between 2 and 50 µm as silt, and those greater than 50 µm as sand (USDA 1975). Sand, silt, and clay fractions are reliable estimators of the unit processes necessary for treatment of TSS in a stormwater sample; these percentages were calculated for the 12 sites monitored herein (Table 4). Across the sites, the mean PSD was 48.7% sand, 47.4% silt, and 3.9% clay. PSDs by site varied from 27.1-66.3% sand, 31.5-64.5% silt, and 2.2-8.4% clay, suggesting that Ohio's road runoff PSD is dominated by the silt and sand fractions, similar to past studies in other states and countries (Selbig and Feinen 2012; Charters et al. 2015; Winston and Hunt 2017). The median particle size at five of the road runoff monitoring sites was characterized as sand, while for the remaining seven sites the d_{50} was silt. Based on these PSDs, stormwater control measures with short hydraulic retention time, such as roadside vegetated filter strips and swales, may provide substantial TSS removal (Lucke et al. 2014; Winston et al. 2017).

Table 4. Percentage of sand, silt, and clay particle sizes in stormwater runoff from Ohio roads. Minimum, mean, and maximum sand, silt, and clay percentages across all sites are also presented.

Statistic	I-70	I-71	SR-257	SR-22	SR-48	SR-49	I-90	SR-43	SR-59	SR-81	SR-117	US-20	Min	Median	Max
% Sand	39.6	37.1	45.4	54.2	66.3	62.9	56.7	49.2	48.0	27.1	50.5	46.9	27.1	48.6	66.3
% Silt	55.2	58.6	50.5	42.0	31.5	34.7	40.8	47.1	48.8	64.5	45.9	49.2	31.5	48	64.5
% Clay	5.2	4.3	4.1	3.9	2.2	2.3	2.5	3.7	3.1	8.4	3.5	3.9	2.2	3.8	8.4

Particle size distributions from the 176 sampled storm events are presented in Figure 8, where each of 117 particle size bins output from the laser diffraction analysis is represented by a separate boxplot. The overall median PSD is approximated by connecting the median horizontal line in each boxplot. Little inter-sample variability was observed for clay-sized and coarse sand (>500 µm) particles; the interquartile range was largest for the silt fraction. Very few particles larger than 1000 µm were observed (0.7% of the mean PSD), similar to other past studies by Selbig and Bannerman (2007), Charters et al. (2015) and Selbig et al (2016).

Across the PSDs collected, the median d_{50} was 52.5 µm, equivalent to a very fine sand particle. This was modestly smaller than those for an asphalt road in Christchurch, New Zealand (71.6 µm). Median particle size across eight road sites in NC varied from 31 to 144 µm (Winston and Hunt 2017). Selbig and Bannerman (2007) found d_{50} between 70-200 µm for road runoff in Madison, Wisconsin. Brodie and Dunn (2009), Wu et al. (2015), and Westerlund and Viklander (2006) found d_{50} values less than 50 µm for sediment in road runoff. The mean d_{10} and d_{90} measured herein (8.4 and 175.5 µm, respectively) were similar to those from an asphalt road in New Zealand (23.2 and 177.2 µm, respectively). Selbig and Bannerman (2007) found d_{10} from 2-5 µm and d_{90} from 300-400 µm for roads in Madison, Wisconsin.

In order to meet 80% TSS removal, nearly all particles greater than the d_{20} would need to be removed from runoff (assuming poor removal below this threshold). The median d_{20} in this study was 22.1 µm, suggesting that BMPs would need to be effective in treating particulate matter down to this size (Figure 8). Mean C_u and C_C values across all measured PSDs were 6.0 and 1.4, respectively. Based on the coefficients of uniformity and curvature, the mean PSD measured herein would be considered well graded. Similar results were observed for PSDs in North Carolina (Winston and Hunt 2017).

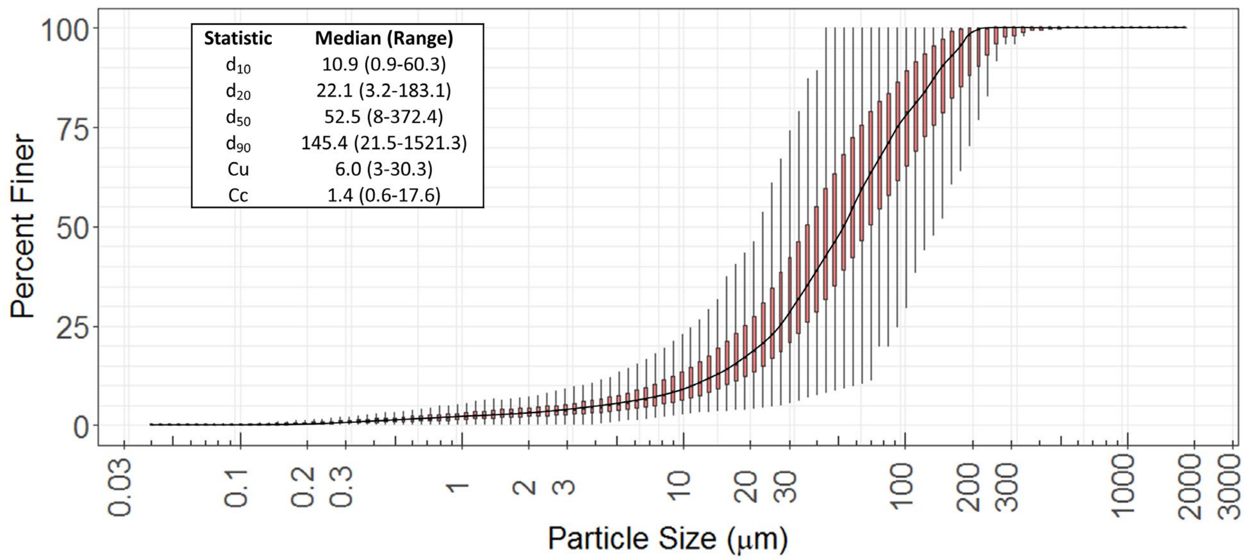

Figure 8. Aggregated particle size distributions for the 176 PSD samples across 12 road sites. Each boxplot represents the variability in particle size for that particle size class. The red boxplots are bounded by the first and third quartiles, while the upper and lower fences represent the interquartile range.

Statistical testing was undertaken to determine significant between-site differences for measured PSDs (Table 5). This testing supported the conclusion that SR-48, SR-49, and I-90 tended to have the coarsest PSDs. SR-48 and SR-49 were located 3 miles apart in the Dayton area, and the I-90 site was unique because it was paved with concrete. Perhaps local materials used to pave the Dayton sites and differences in concrete mix design vis-à-vis hot mix asphalt resulted in coarser PSDs as the pavement wears and contributes sediment. The I-70, I-71 and SR-81 sites had the finest PSDs of the monitored sites. Interestingly, the two sites with the highest AADT had statistically smaller particles entrained in runoff. Higher AADT and particularly presence of a greater number of trucks (on interstate highways, for instance), results in greater pavement wear (Ramaswamy and Ben-Akiva 1990), perhaps pulverizing pieces of asphalt and other larger particles into smaller and smaller particles during dry periods.

Table 5. Results of statistical testing for between-site differences in particle size distribution. Sites listed in the first column had significantly greater particle size than those listed in subsequent columns. Bolded parameters are significant at α=0.10 while all others are significant at α=0.05.

Site	I-71	SR-81	I-70	SR-257	I-90	SR-117	SR-22	SR-43	SR-49	SR-59	US-20	SR-48
I-90	**d10**	d10, d20, d50, d90										
SR-48	d10, d20, d50, d90	d10, d20, d50, d90	**d20**, d50, d90	**d20**								
SR-49	d10, d20, d50, d90	d10, d20, d50, d90	**d20**, d50, d90	**d20**								
SR-117	**d10**	**d20**										
SR-22	d10	d20, d50										
SR-43	d10	d20, **d90**										
SR-59	d10	**d20**										
US-20		d90										
SR-81	Cu		Cu	Cu, Cc	Cu, Cc	Cu	Cu, Cc	**Cu**, Cc	Cu, Cc	Cu, Cc	**Cu**	Cc
I-71					Cc				Cc			**Cc**

Summary statistics for d_{10}, d_{20}, d_{50}, d_{90}, C_U, and C_C were calculated across all measured PSDs for different seasons (spring, summer, and fall), wearing courses (asphalt, concrete), functional classes (interstate, principal arterial, and minor arterial), development densities (urban, suburban, rural), and surrounding land uses (commercial, low density residential, high density residential, and agricultural). Characterizing differences across these categorical variables could aid in BMP planning and implementation. Based on bootstrapped confidence intervals for d_{10}, d_{20}, d_{50}, and d_{90}, no significant differences in PSD were observed across different development densities or between concrete and asphalt wearing courses.

Surrounding land use was a significant predictive factor in road runoff PSD (Figure 9). Sites in low density residential areas had significantly larger d_{10} than high density residential and commercial sites. Low density residential sites had significantly larger d_{20}, d_{50}, and d_{90} than commercial, high density residential, and agricultural land uses. All other land use particle size comparisons were not significantly different. Previous studies have observed substantial differences in PSD by land use (Selbig and Bannerman 2011). There is the potential for surrounding land uses to contribute to runoff PSD through vehicular activities and transport of local soils onto roads by vehicles and wind (Charters et al. 2015). Generally, Kayhanian et al. (2007) found significant evidence to show that surrounding land use substantially impacts stormwater quality, which concurs with the results herein.

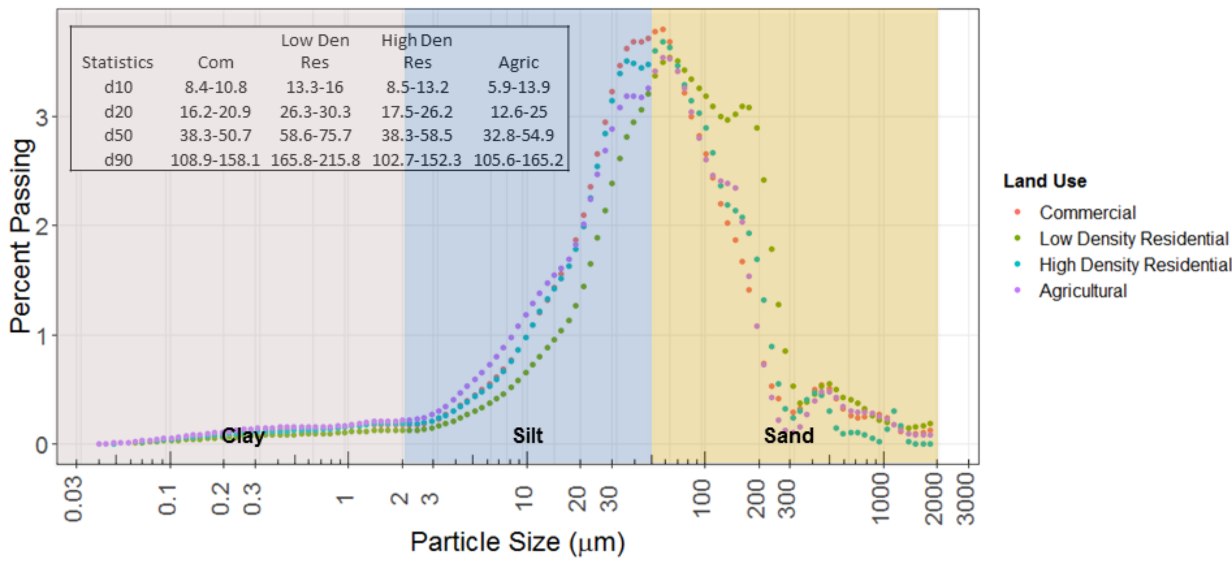

Figure 9. Particle size distributions for roads with commercial, low density residential, high density residential, and agricultural surrounding land uses. Clay, silt, and sand ranges are shown as different background colors. Bootstrapped confidence intervals (95%) for d_{10}, d_{20}, d_{50}, and d_{90} are tabulated.

Road functional class has been observed as a predictor of runoff quality, mostly through observed differences in AADT across functional classes (Opher and Friedler 2010). Bootstrapped 95% confidence intervals suggested that the largest particles in stormwater runoff (represented by the d_{90}) were significantly smaller for interstate highways than for principal arterial roads. Significant differences for the d_{10}, d_{20}, or d_{50} particle size were not observed, albeit the d_{50} confidence intervals for interstate and principal arterial roads barely overlapped. These results were observed in the aforementioned statistical testing for PSD differences by site AADT, where the sites with the highest AADT (I-70 and I-71) had significantly smaller PSDs. Winston and Hunt (2017) found no significant difference between road runoff PSD across functional classes; similarly, Selbig (2015) found no relationship between d_{50} and functional class. Taken together, results suggest that BMP design should not be modified across road functional classes.

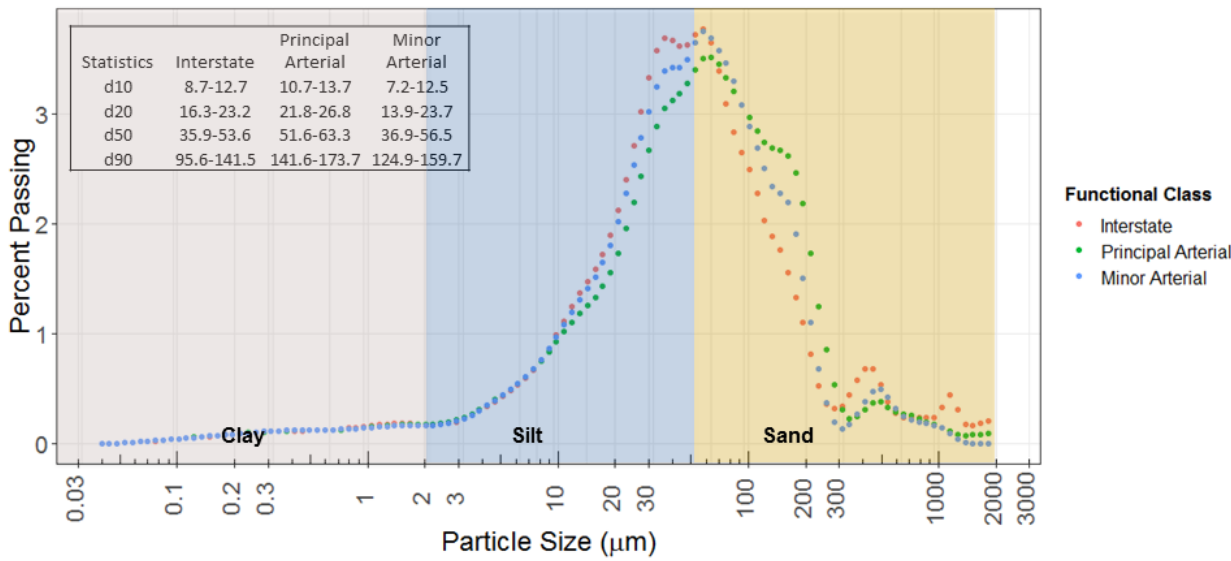

Figure 10. Particle size distributions for roads with interstate, principal arterial, and minor arterial functional classes. Clay, silt, and sand ranges are shown as different background colors. Bootstrapped confidence intervals (95%) for d_{10}, d_{20}, d_{50}, and d_{90} are tabulated.

Seasonality of particle size distribution was explored using statistical testing. The omnibus test showed that there were significant differences in d_{10}, d_{20}, d_{50}, d_{90}, C_U, and C_C. Follow-up paired comparisons showed that d_{10}, d_{20}, and d_{50} were greater in the summer than in the fall and greater in the summer than in the spring (α=0.10 for d_{10}). For the sand fraction represented by the d_{90}, fall was greater than spring (α=0.10) and summer was greater than spring. Concurrently, C_U was significantly greater in fall than in spring and summer and C_C was greater in spring than in summer. Thus, generally PSD was coarser in the summer across the 12 monitored sites than in the fall or spring (Figure 11). Since monitoring site characteristics do not change seasonally, it is hypothesized that these results are related to seasonal differences in rainfall characteristics. Since rainfall duration was significantly shorter in summer than in fall or spring and both peak and mean rainfall intensities were greater in summer than in fall or spring, resulting hydrographs during the summer were flashier and resulted in significantly higher peak flow rates. Elevated flow rates entrain larger particles in the stormwater, similar to sediment transport processes in-stream (Shields 1936), resulting in coarser PSDs during the summer than in spring or fall.

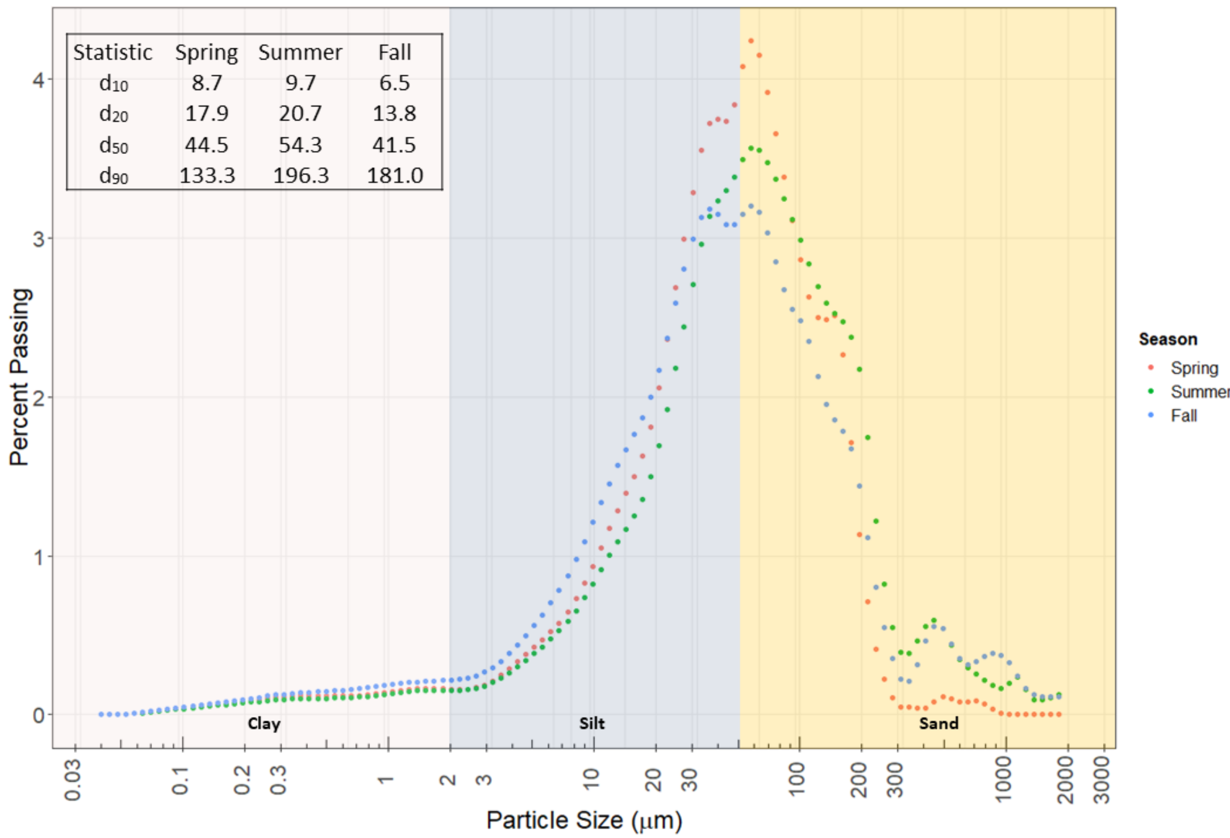

Figure 11. Mean particle size distribution by season. All PSDs collected during the project are included in the analysis. Summary statistics for d_{10}, d_{20}, d_{50}, and d_{90} are tabulated.

Correlations were explored between particle size distribution (d_{10}, d_{20}, d_{50}, d_{90}, C_U, and C_C) and potential causative variables, including rainfall characteristics and numerical site characteristics such as AADT, speed limit, and catchment area (Figure 6). These analyses were done by lumping all PSD data across all sites. Site and rainfall characteristics were not significantly correlated to any PSD statistic. TSS concentration was the only explanatory variable that was moderately negatively correlated to d_{10}, d_{20}, and d_{50} and weakly negatively correlated to d_{90}. In general, as particle size was coarser, smaller TSS concentrations were observed.

Particle size distribution in untreated runoff is particularly important for the design and function of BMPs, since it determines what unit processes are needed in the BMP to achieve a desired removal efficiency or effluent concentration. With coarser particle size, shorter hydraulic retention times and processes such as settling can be relied upon to remove particles from suspension. Processes such as filtration may be required as PSDs tend toward silt and clay particles. Standard PSDs, such as the OK110 and NJDEP distributions (Guo et al. 2008), are utilized in laboratory testing to certify the TSS removal capability of various BMPs, including proprietary stormwater treatment systems. The NJDEP distribution is of particular interest because NJDEP is the agency that other states defer to for benchmarking of proprietary device TSS removal.

The median PSD measured in stormwater runoff from the 12 roads herein was compared against the NJDEP distribution (Figure 12). The two PSDs track one another nicely, with at most a 16% difference in percent passing across the particle size distributions. Above the median particle diameter, the ODOT distribution tends to be finer than the NJDEP distribution. However, most of these larger particles are well sequestered by BMPs with very short hydraulic retention time such as hydrodynamic separators (Ferreira and Stenstrom 2013). Median particle diameters for the two distributions were somewhat similar: 75 µm for the NJDEP distribution and 52.5 µm for the distribution measured herein. Below the median particle size, the median PSD measured herein was coarser than that for NJDEP. This suggests that if designing for 80% TSS removal, BMPs designed to treat NJDEP's PSD would conservatively provide 80% TSS removal for ODOT's stormwater. Designing to trap the d_{20} particle size conservatively meets 80% TSS removal, since some particles smaller than the d_{20} will be trapped in the BMP. The d_{20} for the NJDEP distribution was 8 µm, while that for the ODOT distribution was 18 µm. This suggests that technologies certified for 80% TSS removal for the NJDEP distribution would provide slightly more than 80% TSS removal for the mean PSD measured herein.

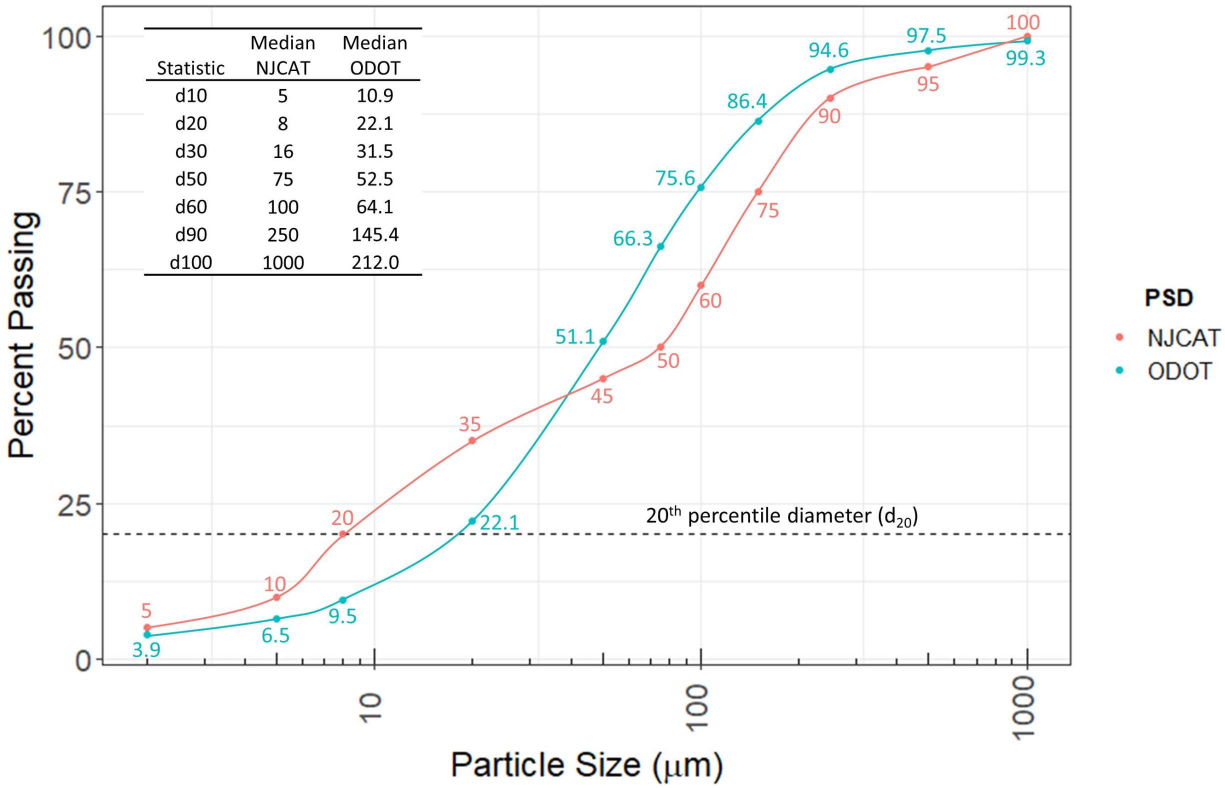

Figure 12. Comparing the mean particle size distribution measured in this study and the NJCAT particle size distribution utilized for approval of manufactured treatment systems. Numbers adjacent to symbols are percent passing values at the corresponding particle size.

2.4 Conclusions

Particle size distribution in stormwater runoff impacts the design of treatment BMPs, effectively determining what treatment processes are needed to control TSS. To understand the variability in PSD from roads and factors which affect it, PSD and TSS were monitored during at minimum 176 storm events at 12 geographically-diverse sites across Ohio. The following conclusions were drawn from this work:

1) Observed TSS event mean concentrations at the 12 monitoring sites were on the low end of those observed in the literature, with an overall mean of 35 mg/L. Maximum TSS concentrations ranged from 40 mg/L to 312 mg/L. Interstate highways with the highest AADT and largest catchment areas as well as minor arterials low AADT and small catchment areas produced the highest TSS concentrations. These data suggest that other

factors beyond AADT, such as ADP, rainfall intensity, and windborne dust and particulates, may contribute to TSS concentrations in stormwater runoff.

2) For single storm events, TSS loads ranged from 0.08 to 52.8 lb/ac across the 11 sites with reliable runoff hydrology data. The median TSS load across all samples collected at the 11 sites was 2.4 lb/ac per storm event, with median by-site loads ranging from 0.7 lb/ac to 5.6 lb/ac per storm event. Annual loading of TSS varied from 87 lb/ac/yr to 463 lb/ac/yr, with a mean value of 242 lb/ac/yr across the 11 sites. These data could be used to determine expected loading of TSS from roads to BMPs or pretreatment devices.

3) At the twelve PSD monitoring sites, d_{10} ranged from 3 to 17 μm, d_{50} from 24 to 72 μm, and d_{90} from 89 to 200 μm. The mean and median d_{50} were 48.6 μm and 52.5 μm, respectively, which was similar to the 44 μm median d_{50} observed in previous studies using runoff volume proportional sampling techniques. Very little variability existed in the percentage of clay and coarse sand-sized particles in observed samples. For the median PSD, sediment in runoff samples was comprised of 48.7% sand, 47.4% silt, and 3.9% clay. TSS concentration was moderately negatively correlated to d_{10}, d_{20}, and d_{50} and weakly negatively correlated to d_{90}, suggesting that as TSS concentration decreased, PSD was coarser.

4) Road functional class, surrounding land use, and season all significantly affected measured PSD. Interstate highways (i.e., the sites with the highest AADT) had significantly finer PSDs than other functional classes. Roads in low density residential land uses had coarser PSDs than high density residential, commercial, and agricultural roads. Significantly coarser PSD was measured during storms in the summer than in the fall or spring, with median particle diameters of 54, 42, and 45 μm, respectively. This

was due to shorter duration, higher intensity storms during this season driving flashier flows, thus mobilizing larger particles. While statistically significant differences were observed for PSD across functional classes, surrounding land uses, and seasons, the differences were small in magnitude and thus modifications to BMP design are not recommended.

5) The NJDEP particle size distribution, which is frequently utilized for laboratory testing of TSS removal for proprietary devices, was very similar to the mean PSD measured herein, with median particle diameters of 52 and 49 μm, respectively. Designing to trap the d_{20} particle size would conservatively result in 80% TSS removal since some particles below the d_{20} will also be captured. The d_{20} for the NJDEP distribution was 8 μm, while that for the mean PSD measured herein was 18 μm. When considering 80% TSS considerations, this suggests that the NJDEP testing is conservative compared to observed PSDs from field measurements in Ohio.

2.5 References

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3 Part II: Gross Solids

3.1 Introduction

Gross solids are a category of urban stormwater pollutant comprised of organic material (such as leaves, branches, and grass clippings), litter (such as plastic, metal, glass, paper, cardboard, and styrofoam), and large particulate matter (e.g., fragments of pavement and gravel). They are characterized by CALTRANS and the Water Environment Research Federation, among others, by a particle diameter greater than 0.2 inches (Allison et al. 1998a; Kim et al. 2006; Roesner et al. 2007). Gross solids are typically unaccounted for in urban stormwater studies due to the restrictive 0.375-inch diameter of the sample tubing using in conjunction with automated samplers. A portion of the gross solids load in stormwater is composed of trash, which, left unchecked, contributes to global scale pollution management issues such as ocean garbage patches (Van Sebille et al. 2012). Total maximum daily loads (TMDLs) for trash have been established in several watersheds across the U.S. (e.g., California Regional Water Quality Control Board 2007). Therefore, it is important to quantify the contribution of gross solids in road runoff. Further, knowledge of gross solids volume and mass can inform the design of pretreatment devices for stormwater control measures and catch basin inserts.

Gross solids have been characterized in urban watersheds in California, Wisconsin, Minnesota, Canada, South Africa, and Australia (Prasad et al. 1980; Dorney 1986; Allison et al. 1998b; Marais et al. 2004; Kim et al. 2006; Kalinowski et al. 2013). Most studies have focused on gross solids mass, while their volume may be particularly important for gross solids treatment system design.

Allison et al. (1998b) studied a mixed-use watershed in Coburg, Australia, and found that approximately 80% of gross solids mass was composed of vegetation with the remainder being anthropogenic refuse. Alam et al. (2017) and Crispijn (2004) found more than 90% of gross solids mass from commercial watersheds was comprised of vegetation. In a study of six highway monitoring sites in southern California, Kim et al. (2006) found 90% of gross solids volume was made up of vegetation and 10% of anthropogenic litter. This suggests, both at the site and watershed-scales, the vast majority of gross solids transported by stormwater runoff are composed of natural vegetation.

At six highway monitoring sites in southern California, Kim et al. (2006) observed total litter weights from single runoff events were 1.1-11.9 lb/ac and biodegradable litter varied from 0.36-4.0 lb/ac (Kim et al. 2006). Gross solids samples from four road sites in North Carolina were analyzed for dry weight (Winston and Hunt 2017), with observed median mass loads of 0.29, 0.38, 0.7, and 1.0 lb/ac, respectively, for approximately weekly sampling periods. The range of dry weights varied from 0.2 to 1.41 lb/ac. These values were similar to those from Allison et al. (1998b), where 0.04-1.15 lb/ac was collected (approximately weekly) from a 50 ha watershed composed of 65% residential, 30% commercial, and 5% light industrial in Melbourne, Australia. Wiackowski (2015) monitored and analyzed gross solids from four different development intensities [high density residential, older (pre 1990) and newer (post2000) low-density residential, and urban downtown areas] in North Carolina. Weekly gross solids loads between 0.2 and 6.1 lb/ac were observed, with a median load of 1.2 lb/ac. Debris loads in the study were highest for sites with greater tree abundance and larger catchment area (Waickowski 2015). The frequency of street sweeping also affected the accumulated gross solids loads collected in catch basins.

Gross solids mass was correlated to rainfall depth in separate studies by Waickowski (2015) and Winston and Hunt (2017). Peak rainfall intensity was correlated with gross solids loading (Winston and Hunt 2017), suggesting that bursts of intense rainfall mobilized a larger mass of gross solids. Waickowski (2015) found that season was significantly correlated to gross solids mass, with the autumn season contributing disproportionately high gross solids loads due to leaf fall from deciduous trees (Waickowski 2015). Leaf litter loading was also proportional to tree canopy cover in Hobbie et al. (2014), suggesting tree cover along roads may affect gross solids loading in the right-of-way.

The goal of this study was to quantify the volume and mass of gross solids contributed by stormwater runoff from roads on an annual basis to inform the design of catch basin inserts and pretreatment devices for best management practices (BMPs). Data were collected at 11 road monitoring sites in Ohio, a state with cold winters and where annual precipitation ranges from 38 to 43 inches.

3.2 Methods

3.2.1 Description of Monitored Sites

Eleven geographically-varied sites were selected for monitoring. The sites were located in the Franklin, Delaware, Hamilton, Montgomery, Allen, Portage, and Lake counties (Table 6). Monitored catchments consisted solely of road drainage constrained by curb and gutter. Sites were selected considering an array of potential gross solids contributors: rainfall patterns (i.e., rainfall zone), pavement types, number of travel lanes, annual average daily traffic (AADT), posted speed limits, adjacent land use, and development density were selected to bracket the range of mass and volume of gross solids from Ohio's roads. Data were collected at five sites in 2016 and six sites in 2017.

Monitoring sites were identified by the corresponding road identifier: I-70 and I-90 were interstate highways, SR-22, SR-43, SR-48, SR-49, SR-59, and SR-81 were principal arterials, and SR-117, SR-257, and US-20 were minor arterials. Interstate highways, principal arterials, and minor arterials in this study had AADT above 30,000, between 10,000-25,000, and less than

10,000 vehicles per day (VPD), respectively. Similarly, posted speed limits were 65-70 mph, 35-55 mph, and 35-55 mph, respectively. The wearing course at all sites was asphalt except for US-20 and I-90, which were paved with concrete.

Table 6. General characteristics of gross solids monitoring sites.

Site Name	County	Latitude, Longitude	Catchment Description	Rainfall Zone	Pavement Type	Functional Class	No. of Travel Lanes	No. of Turn Lanes	No. of Shoulder Lanes	AADT (VPD)	Catchment Area (ac)	Adjacent Land Use	Development Density
I-70	Franklin	39.9397,-82.9387	Eastbound travel lanes and shoulder	C	Asphalt	Interstate	1.5	0	1	93940	0.74	Commercial	Urban
SR-257	Delaware	40.1557,-83.121	Northbound travel lane and shoulder	C	Asphalt	Minor Arterial	1	0	1	7060	0.11	Commercial	Suburban
SR-22	Hamilton	39.2803,-84.3185	Eastbound travel lanes and shoulder	C	Asphalt	Principal Arterial	2	0	0.5	24730	0.12	High Density Residential	Suburban
SR-48	Montgomery	39.8227,-84.24	Southbound travel lanes and half of center turn lane	B	Asphalt	Principal Arterial	2	0.5	0	17054	0.1	Low Density Residential	Urban
SR-49	Montgomery	39.8292,-84.294	Northbound travel lanes and shoulder	B	Asphalt	Principal Arterial	1	0	1	15630	0.15	Low Density Residential	Suburban
SR-117	Allen	40.7252,-84.0604	Eastbound lanes	B	Asphalt	Minor Arterial	2	0	0	7960	0.07	Agricultural	Rural
SR-81	Allen	40.7511,-84.1570	Westbound lanes and half of center turn lane	B	Asphalt	Principal Arterial	2	0	0.5	12070	0.065	Agricultural	Rural
SR-43	Portage	41.1230,-81.3478	Northbound lanes, half of turn lane, and 3 ft shoulder	A	Asphalt	Principal Arterial	2	0.5	0.25	16840	0.14	Low Density Residential	Urban
SR-59	Portage	41.1574,-81.3031	Eastbound lane, shoulder, and turn lane	A	Asphalt	Principal Arterial	1	1	1	14048	0.1	Commercial	Suburban
US-20	Lake	41.6887,-81.2890	Northbound lanes and half of center turn lane	A	Concrete	Minor Arterial	2	0.5	0	11950	0.1	Commercial	Urban
I-90	Lake	41.7343,-81.1052	Westbound lane and shoulder - bridge deck runoff	A	Concrete	Interstate	1	0	1	30575	0.027	Agricultural	Rural

3.2.2 Field Data Collection and Laboratory Analysis

Each site employed curb and gutter drainage systems which discharged stormwater into catch basins. Within one catch basin along each road (locations defined in Table 6), gross solids were collected in purpose-built catch basin inserts. These inserts were built from aluminum angle iron supports which fit just inside the catch basin frame and allowed the grate to be installed so that water could enter as usual (Figure 13). Attached to the angle iron was a wire mesh netting with an aperture of 0.20 inches (5 mm) to capture all gross solids larger than this diameter. In total, the catch basin insert was 24 inches long, 12 inches wide, and 16 inches deep, providing a maximum potential storage of 2.67 ft^3 for gross solids storage. To ensure that all stormwater passed through the catch basin insert, a wooden diverter was affixed to the curb and gutter (Figure 13). This forced all stormwater through the catch basin grate instead of the inlet. Samples were collected from late May to December 2016 at I-70, SR-22, SR-257, SR-48, and SR-49 and from April to November 2017 at I-90, SR-59, SR-43, US-20, SR-81, and SR-117. Sampling period duration varied from 193 to 233 days.

Figure 13. Gross solids monitoring equipment at field sites. Gross solids accumulated in the purpose-built catch basin insert at SR-48 (left), grate placed over catch basin insert at SR-49 (center), and wooden diverter in gutter pan at SR-49 (right).

Upon arrival at each site, the catch basin insert was removed and the gross solids in it were placed in either gallon Ziploc bags or 40-gallon trash bags, depending on the total accumulated sample volume since the previous site visit. Bags were marked with marker to identify the site name, the date, and the time samples were collected. Samples were stored in a laboratory refrigerator at <39.2°F until sample analysis was performed. Gross solids were collected, on average, every 11.6 days, and so a single gross solids sample could represent debris mobilized during dry weather wind events or one or multiple rain events.

Each gross solid sample was analyzed in the laboratory to determine its content on a volume and mass basis. A sample was first categorized as either dry, moderate or wet by visual observation. Sample wet weight was determined using a laboratory scale (Intelligent Weighing Technology model PC-20001; Figure 14). The loose bulk volume was determined by measuring depth of gross solid to the nearest 1/16 inch at 6 locations in the bin and converting to volume using a known depth-volume relationship. Gross solids were separated into one of nine categories: natural vegetation (e.g., grass, leaves, twigs etc.), cigarettes, plastic, fabric, wood, glass, metal, paper and gravel. These subsamples were weighed to obtain subsample wet weights and measured for subsample volume.

Figure 14. Examples of small (left) and large (bins) used to determine gross solids volume and mass.

To understand the moisture content in typical field-collected gross solids samples, dry weights were measured on a subset of the samples collected in 2017. Samples from three visually-categorized moisture contents (7 dry, 5 moderate, and 8 wet samples) were placed in an oven for 24 hours at 105°C. The total sample mass was then measured, and sample drying was repeated until no change in total sample mass was recorded over each additional 24 hour drying window. The sample was then separated into the nine categories and weighed to understand which categories held the most water.

Instrumentation was installed at each monitoring site to quantify rainfall hyetographs and runoff hydrographs, since rainfall characteristics (intensity, depth, antecedent dry period, etc.) and runoff (total volume, peak flow, etc.) impact gross solids mobilization (Figure 3). A manual rain gauge (Productive Alternatives, Fergus Falls, MN) and a 0.01-inch resolution tipping-bucket rain gauge (Davis Instruments, Hayward, California) were located within 100 ft of the catch basin where gross solids were collected. They were mounted on a 6-ft tall wooden post away from overhead obstructions. Rainfall depth measured by the tipping bucket rain gauge on a 1-minute interval was stored on Hobo pendant loggers (Onset Computer Corporation, Bourne, MA) and downloaded monthly. Total rainfall depth since the previous site visit, as measured by the manual rain gauge, was recorded.

3.2.3 Data Analysis

Discrete storm events were identified by a minimum antecedent dry period (ADP) of 6 hr and rainfall depth of 0.1 in. For each gross solids sample collected, the following descriptive statistics were determined: season, the elapsed time since the previous sample collection, total rainfall depth, total rainfall duration, maximum peak 5-minute rainfall intensity, mean rainfall intensity, and longest dry period observed since the previous gross solids sample collection. Site characteristics, including AADT, pavement type, functional class, speed limit, surrounding land use, and development density (rural, suburban, or urban) were also tabulated. These data were utilized in Spearman's rank correlation, multiple linear regression, and multiple comparisons using Dunn's test with a Bonferroni correction to determine how climatic conditions and site characteristics were related to the transport of total and categorical gross solids volume and mass to the catch basin insert.

Cumulative mass (lb) and volume (gallons) were determined for total gross solids and all gross solids categories by summing the total previously measured mass/volume with the current sample's mass/volume. The total mass and volume were determined using this calculation across all samples. To calculate total normalized load (M_T, lb/ac/day), total mass or volume was normalized by watershed area (A_W, ac) and the total duration of the monitoring period (D_{MP}, day). The example shown in equation 1 is for total normalized mass load:

$$M_T = \frac{\sum_{i=1}^{n} M_i}{A_W \times D_{MP}} \tag{1}$$

To determine the prevalence of each gross solid category, percent by weight and volume for each gross solids category was calculated as a function of the entire weight or volume of that sample. The mean percent by mass and by volume for each category across all samples at a site was utilized to create stacked box plots to visually represent the data. Additionally, cumulative total volume and mass plots, as well as gross solids categorical cumulative mass and volume box plots were created.

For samples analyzed for dry weight, the weight of evaporated water was enumerated as a percentage of the dry weight (i.e., the moisture content). This analysis was completed for the each gross solids sample and for the nine gross solids categories. Summary statistics for water content were presented, including range, mean, and standard deviation. A statistical analysis using the Kruskal-Wallis test with follow-up multiple paired comparisons using Dunn's test with a Bonferroni correction was utilized to determine whether the dry, moderate, and wet samples were statistically different. Moisture content data were compared to levels suitable for landfilling of municipal solid waste.

All statistical analyses were performed in the statistical software R version 3.5.1 (R Core Team, 2018). Data were analyzed using a criterion of 95% confidence (α=0.05) unless otherwise noted.

3.3 Results

3.3.1 Summary Statistics for Sample Collection

Monitoring period duration, defined as the duration between the installation and removal of the catch basin insert, varied from 193 to 233 days with a mean of 213.6 days. Sites were visited to collect samples every 11.6±7.3 days (mean ± std dev.), with a minimum of 4 days and a maximum of 55 days between sample collection. Across the 11 sites monitored, a total of 202 gross solids samples were collected during 2016 and 2017. The number of gross solids samples collected by site varied from 14 to 22, with a mean of 18.3 samples. The majority of the samples were obtained during the summer months (103), with autumn (60) and spring (39) accounting for the remaining samples collected. Of the 202 total samples, 110 were visually identified as dry (54.4%), 33 as moderately wet (16.3%), and 59 as wet (29.2%).

3.3.2 Rainfall Summary Statistics

Substantial variability in rainfall characteristics was observed over the monitoring period (Figure 15). No significant between site variability was observed for rainfall depth, duration, peak intensity, average intensity, or ADP (p-values>0.50). This is supported by the lack of clustering of data points from single sites in Figure 15. Thus, statistics presented below summarize rainfall statistics between each gross solids sample collection across all sites. Rainfall depth across the sampling periods (11.6 days on average) varied from a minimum of 0.1

inches to a maximum of 7.07 inches, with a median value of 0.92 inches. For each rainfall event, rainfall duration varied from 0.5 hr to 134 hr with a median value of 9.1 hr. Peak (0.24-3.72 in/hr) and average (0.02-3.03 in/hr) storm event intensity varied over similar ranges. Median ADP per sampling event was 6.9 days and varied from 0.4 days to 28.4 days. The substantial variability in climatic variables observed among the samples collected indicated that the data set is robust and provides a reliable indication of the mass and volume of gross solids from typical roads in Ohio.

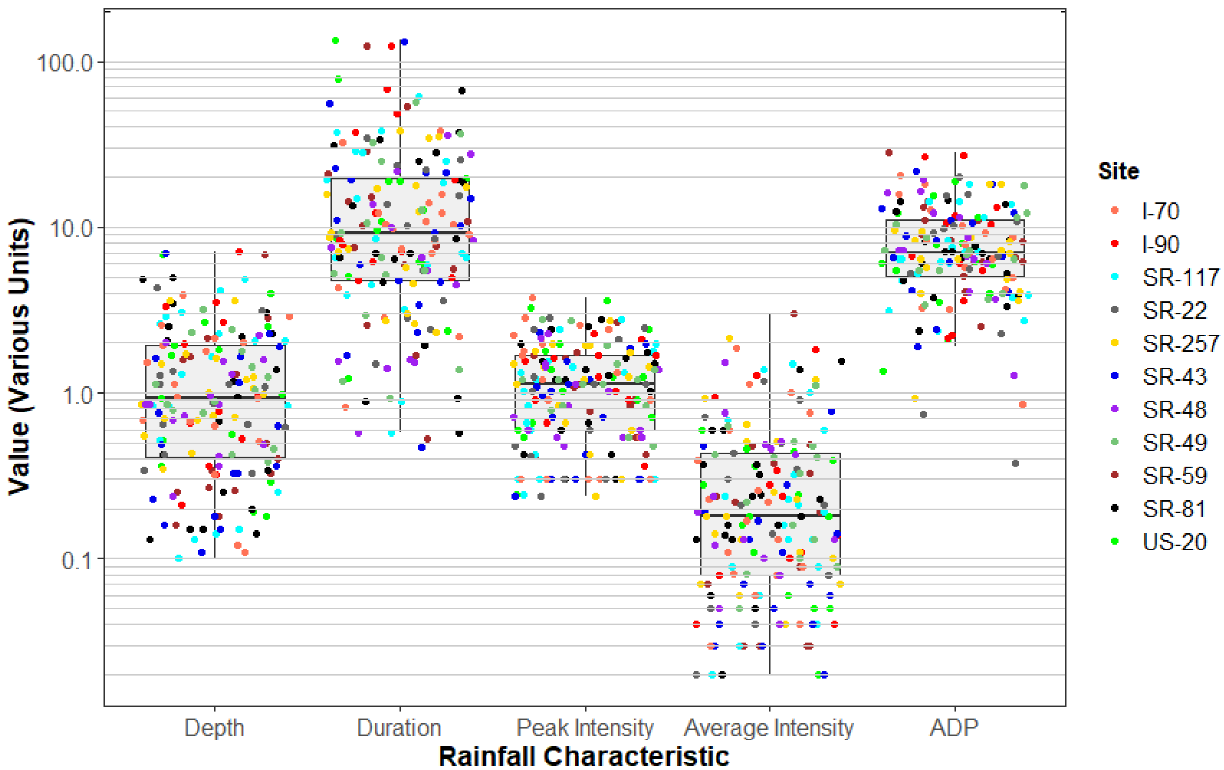

Figure 15. Rainfall characteristics for each of the collected gross solids samples. Depth (in), duration (hrs), and antecedent dry period (ADP, days) are represented as the sum of each of these characteristics over the period since the previous gross solids sample was collected. Peak intensity (in/hr), calculated as the maximum intensity over a 5-minute period, was determined as the maximum value across all storms in the sampling window. Average intensity (in/hr) was determined as the total depth across all storms divided by the total rainfall duration.

3.3.3 Volume of Gross Solids

Gross solids volume (gal) was determined for the entire sample and also for nine gross solids categories (Figure 16 and Table 7). Mean total gross solids volume for each sample (average sampling period duration was 11.6 days) varied from 0.39-2.77 gallons across the eleven sites. Maximum volume by site varied from 1.15-17.6 gal. The maximum gross solids volume observed was at SR-48 on November 8, 2016, where leaves from a nearby deciduous tree completely filled the catch basin insert, with natural vegetation representing 98% of total sample volume. The trend at SR-48 for this event held true across the broader data set, with vegetation contributing, for the average sample collection event, 1.04 gal of the 1.23 gal of total gross solids collected across all sites (i.e., 80.3% by volume). All other gross solids categories represented less than 0.1 gal per sampling period. Glass (179 samples), metal (181 samples), and fabric (174 samples) often were not observed in gross solids samples of road stormwater runoff. In contrast, vegetation was found in all 202 samples taken. Maximum volume recorded for each gross solids category was: 17.6 gal total volume, 17.3 gal vegetation, 1.14 gal gravel, 0.77 gal plastic, 0.64 gal cigarettes, 0.59 gal fabric, 0.47 gal paper, with glass, metal, and wood representing 0.3 gal or less. These maxima did not occur during a single event.

Total sampled gross solids at the 11 sites over the monitoring periods varied from 7.4-58.2 gallons. Normalizing these data by the drainage area to the catch basin and the sampling period duration, the volumetric loading rate of total gross solids varied from 0.31-2.52 gal/ac/day (mean 0.94 gal/ac/day). On average, this corresponds to 342 gallons annually of gross solids per acre of transportation imperviousness in Ohio. These data could be utilized to size and predict maintenance intervals for forebays and BMPs receiving drainage from road rights-of-way.

The primary contributor to gross solids volume was vegetation at all eleven sites (Figure 17 and Figure 18). Vegetation represented between 63.5-95.5% of total gross solids volume by site, with a mean of 80.3%. Secondary contributors to gross solids volume included cigarettes (5 sites), plastic (4 sites), and gravel (2 sites). Secondary contributors represented 1.7-12.6% of total gross solids volume (mean 7.2%). Tertiary contributors to total gross solids volume were cigarettes (4 sites), plastic (3 sites), wood (2 sites), and gravel and paper (1 site apiece). Tertiary contributors to gross solids volume represented between 1.1-9.1% (mean 5.1%).

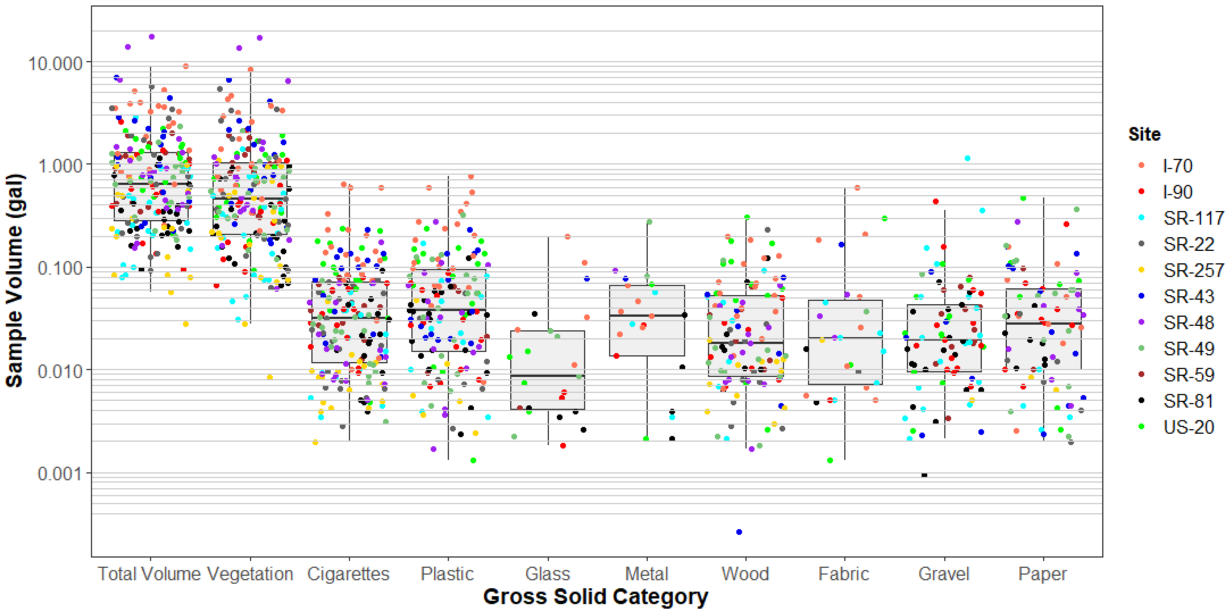

Figure 16. Total gross solids volume (gallons) and categorical characterization of gross solids volume. Colored points are indicative of different roads.

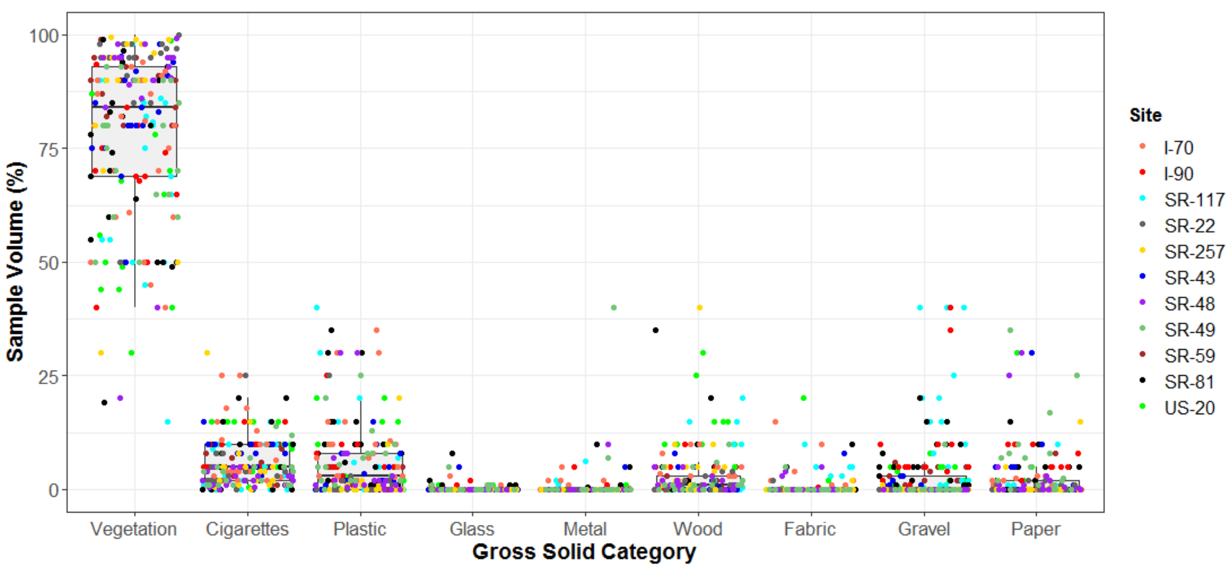

Figure 17. Categorical gross solids volume as a percent of observed total gross solids volume. Colored points are indicative of different roads.

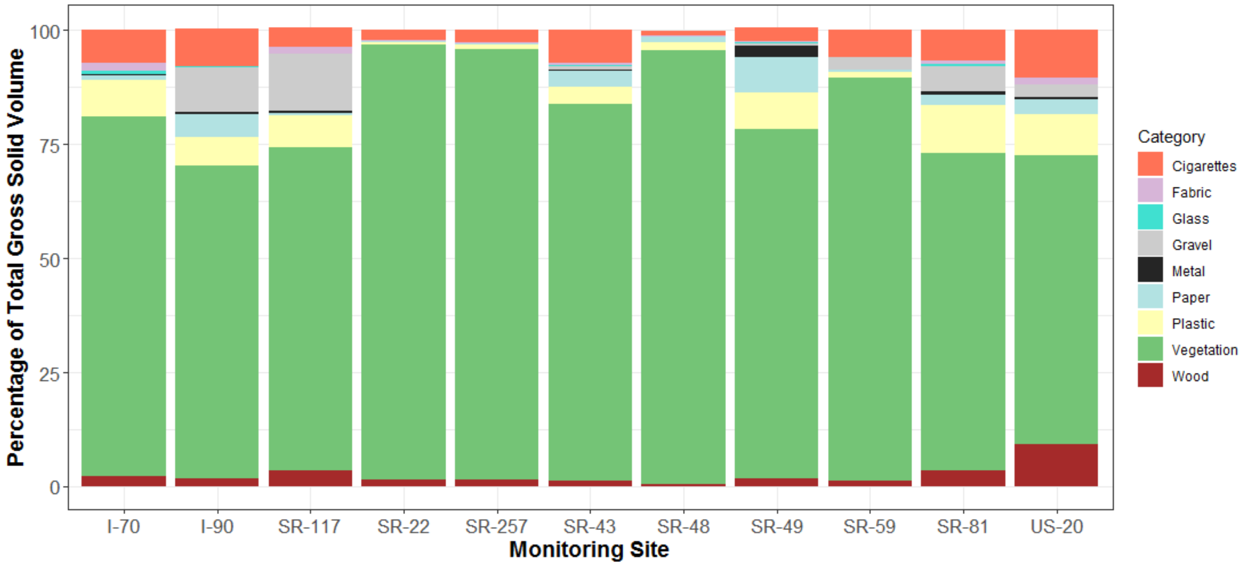

Figure 18. Stacked bar plot of percentage of total gross solids volume by category for the 11 monitoring sites.

Table 7. Summary statistics for total gross solids sample volume (i.e., considering all gross solids categories). Number of samples collected, sampling period duration, and elapsed time between sample collection are also presented.

Statistic	I-90	US-20	SR-43	SR-59	SR-81	SR-117	I-70	SR-22	SR-257	SR-48	SR-49
Number of Samples	14	16	17	15	22	21	21	20	19	19	18
Sampling Period Duration	216	217	202	203	233	219	215	193	214	212	226
Median Duration Between Samples (days)	12.0	11.0	9.5	11.5	10.0	9.5	10.2	9.7	11.3	11.2	12.6
Median Volume (gal)	0.52	1.20	1.17	36.48	0.31	0.34	2.56	0.54	0.25	0.84	0.72
Mean Volume (gal)	0.72	1.16	1.79	57.17	0.39	0.50	2.77	1.24	0.39	2.68	0.82
Maximum Volume (gal)	2.62	2.21	6.98	201.38	1.15	2.85	8.98	5.70	1.15	17.60	2.38
Volume Standard Deviation (gal)	0.67	0.61	1.76	50.71	0.27	0.61	2.09	1.52	0.34	4.84	0.55
Total Volume (gal)	10.02	18.50	30.35	15.34	8.51	10.43	58.20	24.73	7.37	50.91	14.82
Volumetric Loading Rate (gal/ac/day)	1.72	0.85	1.08	0.76	0.56	0.66	0.36	1.04	0.31	2.52	0.44
Primary Volume Contributor	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation
Primary Contributor % of Total Volume	68.4	63.5	82.4	88.4	69.6	70.8	78.8	95.5	94.5	95.1	76.6
Secondary Volume Contributor	Gravel	Cigarettes	Cigarettes	Cigarettes	Plastic	Gravel	Plastic	Cigarettes	Cigarettes	Plastic	Plastic
Secondary Contributor % of Total Volume	9.8	10.4	7.2	5.9	10.5	12.6	8.1	2.2	2.6	1.7	8.0
Tertiary Volume Contributor	Cigarettes	Plastic	Plastic	Gravel	Cigarettes	Plastic	Cigarettes	Wood	Wood	Cigarettes	Paper
Tertiary Contributor % of Total Volume	8.1	9.1	3.8	2.7	6.6	7.1	7.0	1.4	1.4	1.1	7.9

Statistical testing was utilized to determine differences in by-site volume of gross solids as a gateway to understanding how site characteristics (AADT, speed limit, pavement type, functional class, etc.) affect gross solids generation. Using the Kruskal-Wallis omnibus test, significant differences were observed among sites for total gross solids volume, vegetation, cigarettes, plastic, and wood. Additionally, glass and paper were significantly different among sites at the α=0.10 level. Follow-up paired comparisons using the Dunn's test with a Bonferroni correction highlighted a number of significant differences between sites (Table 8), but showed no differences in paper or glass volume. The I-70 site produced significantly greater total gross solids volume than I-90, SR-117, SR-22, SR-257, SR-49, and SR-81. SR-43, SR-48, SR-59, and US-20 had significantly greater total gross solids volume than SR-117, SR-257, and SR-81. Since vegetation made up between 63-96% of total volume, it is not surprising results of statistical testing for this category were similar to those for total volume (Table 8). Stormwater runoff from I-70, SR-43, and US-20 had significantly more cigarette volume than SR-117, SR-22, SR-257, SR-48, SR-49, and SR-81. I-90 and SR-49 had a greater volume of cigarettes than SR-257. For plastic and wood volume, I-70 and US-20 frequently produced greater volumes than other sites. Observed debris from vehicular accidents and plastic bottles from a nearby supermarket were the main contributors of plastic at I-70 and US-20, respectively. Wood consisted of pieces of lumber presumably from work vehicles.

Table 8. Results of statistical testing for between-site differences for gross solids volume. Sites listed in the first column had significantly greater gross solids volume than those listed in subsequent columns. Bolded parameters are significant at α=0.10 while all others are significant at α=0.05.

Site	I-90	SR-117	SR-22	SR-257	SR-49	SR-81	SR-48
I-70	TV,V,P	TV,V,C,P	TV,C,P,W	TV,V,C,P,W	**TV**,C,**P**,W	TV,V,C,P	C,P,W
SR-43		TV,V,C	C	TV,V,C	C	TV,V,C	C
SR-48		**TV**,V		TV		TV,V	
SR-59		**TV**,V		TV,V,C		TV,V	
US-20		TV,C	C,P,W	TV,C,P,W	C,**W**	TV,**V**,C	C
I-90				C			

Note: TV=total volume, V=vegetation, C=cigarettes, P=plastic, W=wood

Seasonality of gross solids volume was explored using statistical testing. The omnibus test showed there were significant differences in total volume, vegetation, cigarettes, and plastic. Follow-up paired comparisons showed total gross solids, vegetation, and cigarette volume were significantly greater in the fall than in the spring or summer ($p<0.001$). Plastic volume was greater in the fall than in the summer. Seasonality in vegetation volume was expected, especially at the five sites with nearby deciduous trees; mean daily total gross solids volume across the 11 sites in the fall was 0.16 gal/day, while for spring and summer it was 0.05 gal/day and 0.09 gal/day, respectively. Since vegetation was 63-96% of the total volume, depending on site, it was not surprising seasonal trends were also observed for total gross solids volume. For cigarettes, it seems their behavior follows that of vegetation rather than a seasonality in the incidence of smoking. Perhaps during spring and summer, passing cars may force this low weight litter off the side of the road. We observed that cigarettes often were trapped by leaf piles (perhaps cigarettes were blown there by wind) along the curb line. Alam et al. (2017) found that wind speed was the most important factor in dry weather gross solids loading. Thus, the leaves appear to "catch" the cigarettes during the autumn.

Correlations were explored between gross solids volume categories and potential causative variables, including rainfall characteristics and numerical site characteristics such as AADT, speed limit, and catchment area (Figure 19). Site characteristics were poorly correlated to gross solids volume, with speed limit not correlated to a single gross solids category. AADT was significantly, albeit weakly ($0.2<\rho<0.4$) correlated to total volume, vegetation, cigarettes, and plastic. Rainfall characteristics, such as depth and duration, were weakly correlated to total volume and plastic. Rainfall depth was also weakly correlated to gravel volume; this contrasts with results in Alam et al. (2017), where gross solids were significantly correlated to rainfall depth. Rainfall duration was weakly correlated to vegetation and cigarettes and moderately correlated to glass. Antecedent dry period was moderately correlated to glass and weakly correlated to vegetation. Average and peak rainfall intensities were not substantively predictive of gross solids volume, with only weak correlations to gravel and vegetation, respectively. Elapsed time since the previous sample was collected was weakly correlated to total volume, vegetation, gravel, cigarettes, and plastic. Elapsed time since the previous sample collection serves as a predictor of build-up processes, but this metric does not account for rainfall depth since the previous sampling event. Build-up contributes to the accumulation of gross solids in the right-of-way, but wash-off processes are needed to mobilize gross solids to the catch basin (although wind may influence this also). These generally weak correlations to site specific and weather factors suggest that other processes are at play that may be better encompassed through categorical characterization of the site, including road functional class, pavement type, surrounding land use, or surrounding development density, as described below.

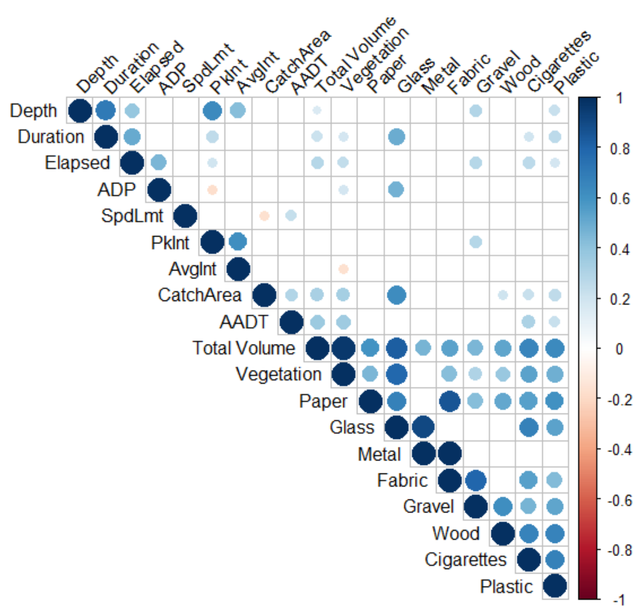

Figure 19. Correlogram depicting correlations between gross solids volume, site and rainfall characteristics, and elapsed time between gross solids sample collection. Positive correlations are displayed in blue and negative correlations in red. Color intensity and diameter of the circle are proportional to correlation coefficients, with deeper colors and larger diameters signifying greater correlation. Blank cells in the correlogram were not statistically significant.

Based on visual observation of boxplots created of total and categorical sample volume, no differences were observed between gross solids from asphalt versus concrete pavements. A similar lack of differences was observed for interstate, principal arterial, and minor arterial roads or for roads located in agricultural, commercial, high density residential, or low density residential land uses. However, trends in the data suggested rural, suburban, and urban sites may produce differences in gross solids loading. Multiple linear regression suggested that on average 4 times more total gross solids volume per sampling events was derived from urban sites (6.4 gal) than suburban (1.35 gal) or rural (1.92 gal) sites. Similar trends were observed for vegetation. Volume of cigarettes and plastic from urban sites was 2 times greater than from rural sites. No differences were observed between urban, suburban, and rural sites for glass, metal, wood, fabric, gravel, or paper.

3.3.4 Mass of Gross Solids

The wet weight of each of the nine categories and total gross solids was explored using boxplots with site signified by point colors (Figure 20). Mean total wet weight per sampling event (mean sampling period duration was 11.6 days) varied from 0.10 to 7.86 lb (mean of all samples was 1.16 lb; Table 9). Normalizing for the area of the catchment draining to the catch basin and the sampling period duration, mass loading rates varied from 0.08 to 1.03 lb/ac/day with a mean rate of 0.41 lb/ac/day. This corresponds to 150 lb/ac/yr (wet weight) of gross solids entering the average monitored catch basin in this study. This mass loading rate is considerably lower than two commercial watersheds (783, 1273, 1526, and 3280 lb/ac/yr) monitored in Australia (Chrispijn 2004; Alam et al. 2017). Waickowski observed mass loading rates of 10-320 lb/ac/yr for various densities of residential development and downtown areas in four cities in North Carolina. Nine urban catchments in Cape Town, South Africa were monitored by Marais et al. (2004) for gross solids loading. Between 1.8-55.3 lb/ac/yr (median 36 lb/ac/yr) of organic debris and 0.0-24.1 lb/ac/yr (median 8.9 lb/ac/yr) of anthropogenic refuse (cardboard and plastic) was collected at each catchment outfall. Factors such as total annual rainfall and the presence of deciduous vegetation, which vary considerably across the regions discussed above, might lead to the vast differences in annual gross solids mass loading.

Maximum gross solids weight by site collected over any sampling period varied from 0.02 lb to 61.9 lb. The sample with the largest weight was collected at I-70 following both mowing of the adjacent shoulder as well as several vehicular accidents that contributed gross solids to the catch basin. This sample had nearly 5 times greater weight than the second heaviest sample collected during the monitoring period.

Vegetation made up the vast majority of sample weight, with the remaining eight categories contributing on average less than 0.1 lb to the total weight (Figure 20). Vegetation represented 63.2-96.7% of the total wet weight at each site (mean 79.7%; Figure 21 and Figure 22), and was the primary contributor to gross solids mass at ten of the eleven sites (gravel was the primary contributor at SR-117). Alam et al. (2017) found that 93% of gross solids captured in a catch basin insert in Gosnells, Western Australia were composed of vegetation.

Mean sample weights across all sites were 1.18 lb for total mass, 1.0 lb for vegetation, 0.08 lb for plastic, 0.065 lb for gravel, 0.05 lb for fabric, 0.043 lb for cigarettes, and glass, metal, wood, and paper contributing less than 0.03 lb per sample (values represent mean for all sample events). Maximum sample weight was 61.9 lb for total gross solids, 59.7 lb for vegetation, 2.6 lb for gravel, 1.75 lb for plastic, and 1.38 lb for cigarettes, with all other categories contributing less than 0.6 lb.

Secondary contributors to gross solids mass included gravel and cigarettes (3 sites apiece), paper (2 sites), and plastic, vegetation and wood (1 site apiece). At three sites (I-90, SR-81, and SR-117), the secondary contributor represented 16.5-27.2% of total mass; at all other sites, it represented less than 7% of total mass (mean across all sites 9.2%). Tertiary contributors to total gross solids mass included plastic (4 sites), wood and cigarettes (3 sites apiece), and gravel (1 site). Tertiary contributors never represented more than 9% of total mass (mean 3.5%).

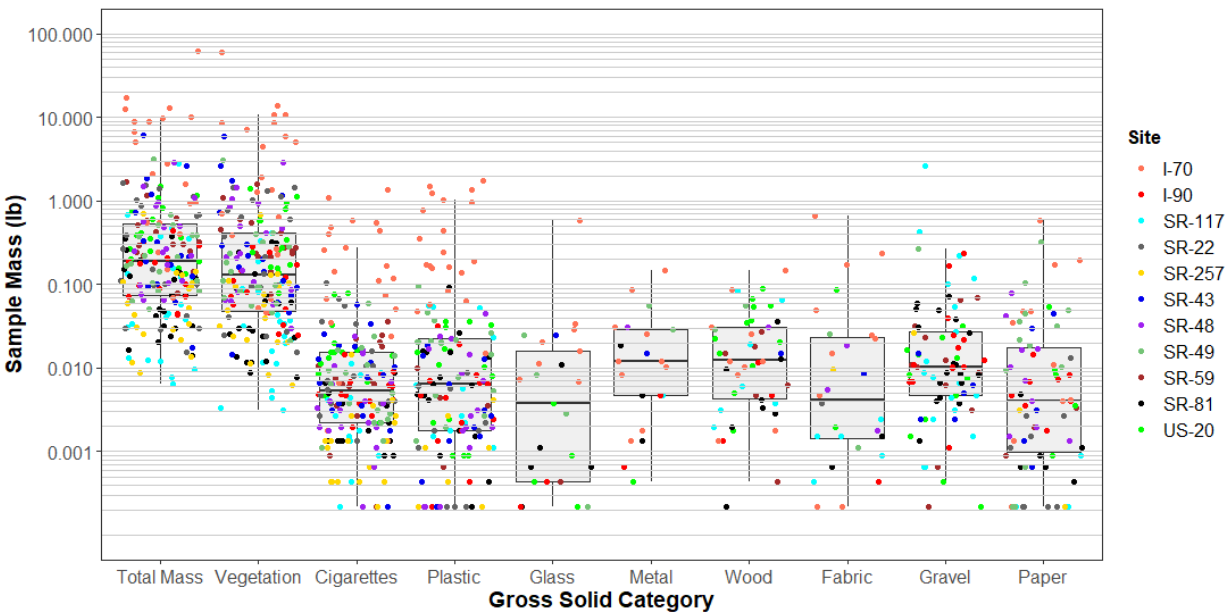

Figure 20. Total gross solids mass (lb) and categorical characterization of gross solids mass. Colored points are indicative of different roads.

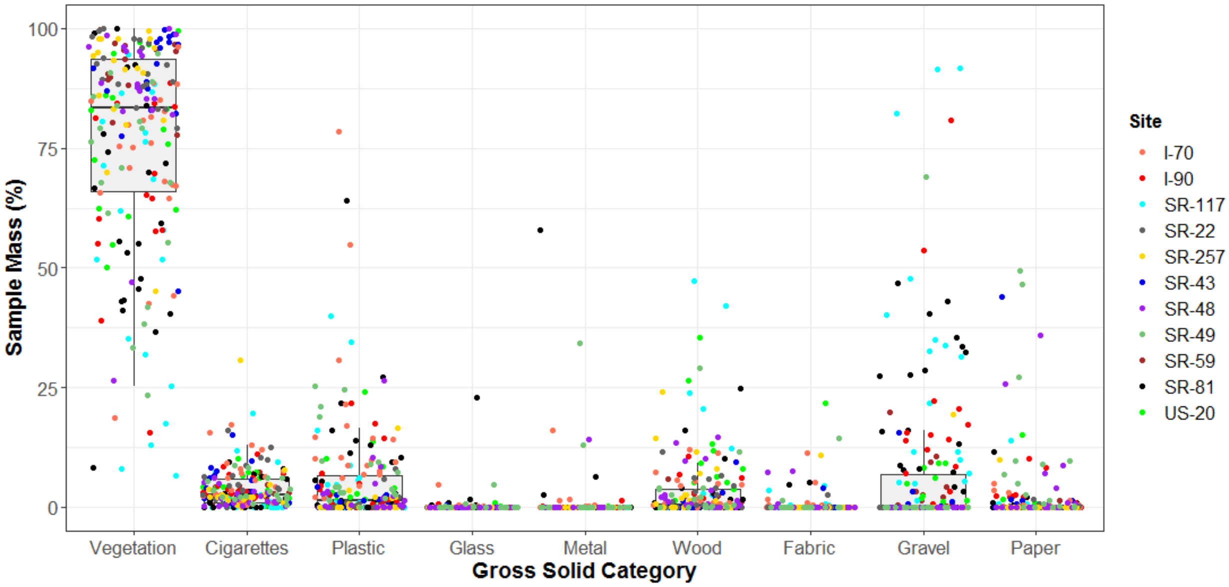

Figure 21. Categorical gross solids mass as a percent of observed total gross solids mass. Colored points are indicative of different roads.

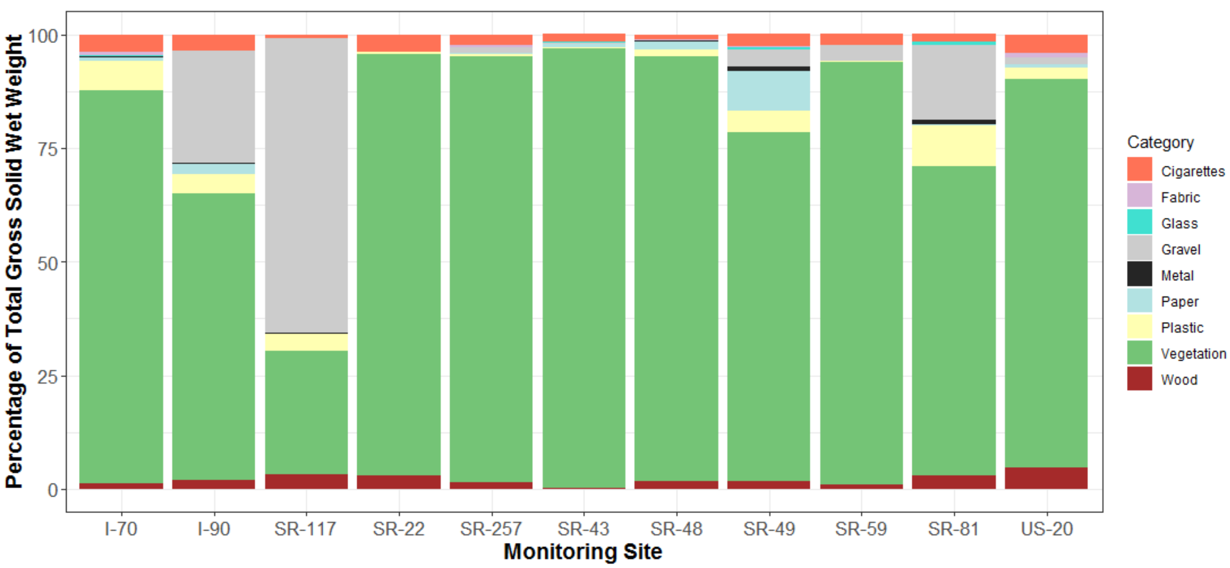

Figure 22. Stacked bar plot of percentage of total gross solids mass by category for the 11 monitoring sites.

Table 9. Summary statistics for total gross solids sample mass (i.e., considering all gross solid categories). Number of samples collected, sampling period duration, and elapsed time between sample collection are also presented.

Statistic	I-90	US-20	SR-43	SR-59	SR-81	SR-117	I-70	SR-22	SR-257	SR-48	SR-49
Number of Samples	14	16	17	15	22	21	21	20	19	19	18
Sampling Period Duration	216	217	202	203	233	219	215	193	214	212	226
Median Duration Between Samples (days)	12.0	11.0	9.5	11.5	10.0	9.5	10.2	9.7	11.3	11.2	12.6
Median Wet Weight (lb)	0.14	0.38	0.22	0.01	0.07	0.05	2.81	0.21	0.05	0.25	0.20
Mean Wet Weight (lb)	0.17	0.54	0.85	0.01	0.11	0.26	7.86	0.52	0.10	0.55	0.42
Maximum Wet Weight (lb)	0.44	1.50	6.10	0.02	0.38	2.84	61.94	1.66	0.70	2.86	3.21
Wet Weight Standard Deviation (lb)	0.12	0.41	1.54	0.00	0.10	0.62	13.45	0.57	0.15	0.69	0.72
Total Mass (lb)	2.33	8.64	14.48	7.15	2.43	5.56	165.09	10.41	1.84	10.52	7.51
Mass Loading Rate (lb/ac/day)	0.40	0.40	0.52	0.35	0.16	0.35	1.03	0.44	0.08	0.52	0.23
Primary Mass Contributor	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation	Gravel	Vegetation	Vegetation	Vegetation	Vegetation	Vegetation
Primary Contributor % of Total Mass	63.2	85.3	96.7	92.9	68.0	64.8	86.3	92.8	93.7	93.6	76.8
Secondary Mass Contributor	Gravel	Wood	Cigarettes	Gravel	Gravel	Vegetation	Plastic	Cigarettes	Cigarettes	Paper	Paper
Secondary Contributor % of Total Mass	24.8	4.8	1.6	3.4	16.5	27.2	6.6	3.7	2.1	1.7	8.6
Tertiary Mass Contributor	Plastic	Cigarettes	Gravel	Cigarettes	Plastic	Plastic	Cigarettes	Wood	Wood	Wood	Plastic
Tertiary Contributor % of Total Mass	4.2	3.9	0.6	2.4	9.0	3.7	3.8	3.0	1.5	1.7	4.9

Data were explored statistically to determine whether differences existed between sites for gross solids mass (Table 10). Using the Kruskal-Wallis test, significant differences were found in between-site total mass, vegetation, plastic, and cigarettes (all p-values < 1×10^{-11}) as well as glass and paper (p-values<0.02). Follow-up paired comparisons using Dunn's test with a Bonferroni correction showed that I-70 produced the greatest total mass of gross solids in stormwater runoff, with significantly greater total mass than 7 other sites. It also produced more vegetation, cigarettes, and plastic than at least 5 other sites. SR-117, SR-257, and SR-81 often had significantly lower total, vegetation, and cigarette mass than SR-48, SR-59, US-20, SR-22, SR-43, SR-49, and I-70. Of the eleven sites monitored, SR-117, SR-257, and SR-81 had 3 of the 4 lowest AADT counts. The site with the highest gross solids mass (I-70) had approximately 3 times greater AADT than the next site; thus, AADT may play a role in gross solids mass.

Table 10. Results of statistical testing for between-site differences for gross solids mass. Sites listed in the first column had significantly greater gross solids volume than those listed in subsequent columns. Bolded parameters are significant at α=0.10 while all others are significant at α=0.05.

Site	I-90	SR-117	SR-22	SR-257	SR-43	SR-49	SR-81	SR-48	SR-59	US-20
I-70	TM,V,C,P,**G**	TM,V,C,P,**Pa**	TM,**C**,P,Pa	TM,V,C,P	**TM**,**C**,P	TM,V,C,P	TM,V,C,P,Pa	C,P	C,P	P,**G**
SR-48		**TM**,V		TM,V			TM,V			
SR-59		TM,V		TM,V,C			TM,V			
US-20		TM,V,C		TM,V,C			TM,V,C	**C**		
SR-22		V		**TM**,C			V,C			
SR-43		V		TM,V,C			V,**C**			
SR-49			P,**Pa**	**TM**,C,P						

Note: TM=total mass, V=vegetation, C=cigarettes, P=plastic, G=glass, Pa=paper

Statistical testing was performed to determine whether seasonal differences in gross solids mass were observed. The omnibus test showed significant seasonality for total mass, vegetation, plastic, and gravel. Follow-up paired comparisons among seasons showed fall was significantly greater than summer for total mass and vegetation, while fall was not significantly greater than spring (p-values of 0.12 and 0.16, respectively). For plastic, spring was greater than fall (α=0.10) and summer. For gravel, spring was greater than fall and summer was greater than fall

(α=0.10). Seasonality for vegetation was observed mainly due to leaf-fall in the autumn. Hobbie et al. (2014) and Waickowski (2015) observed similar seasonality in vegetation mass. In our study, this was primarily observed at sites with nearby trees, including SR-48, US-20, SR-22, SR-49, and SR-59. This suggests that if catch basin inserts were utilized to capture gross solids, more frequent and onerous maintenance would be needed during the fall season. Gravel mass was greatest in the spring, which may be related to the effects of plowing and salt during winter on the structure of the wearing course of the pavement.

Correlations between causative variables, such as rainfall and site characteristics, were explored using Spearman's rank correlation analysis. Rainfall depth and duration were weakly correlated to total gross solids mass, vegetation, and cigarettes. Antecedent dry period, peak intensity, and average intensity were not good indicators of gross solids mass. ADP was weakly correlated with vegetation, peak intensity with total mass and vegetation, and average intensity with wood mass. Site characteristics, including AADT, speed limit, and catchment area, were not good predictors of gross solids mass. Speed limit and catchment area were not correlated to any gross solids mass category; lack of correlation to catchment area was probably due to the fact that variations in catchment area were small across the 11 sites (Table 6) because of the typical design of catch basins. Lack of variability in a data set substantially reduces the potential for significant correlation (Goodwin and Leech 2006). These results suggest depth and duration of rainfall were the best, albeit weak, predictors of gross solids mass. There are other factors at play, such as littering habits, wind speed and direction, vehicular accidents, etc., that are not captured in the data set and thus cannot be included in a model to predict gross solids mass. Further research is needed in this area to better quantify other factors which might predict gross solids mass.

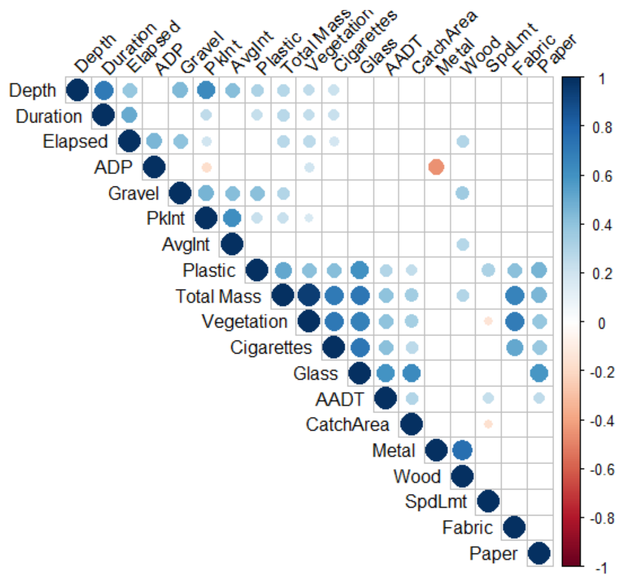

Figure 23. Correlogram depicting correlations between gross solids mass, rainfall characteristics, and elapsed time between gross solids sample collection. Positive correlations are displayed in blue and negative correlations in red. Color intensity and diameter of the circle are proportional to correlation coefficients, with deeper colors and larger diameters signifying greater correlation. Blank cells in the correlogram were not statistically significant.

Based on visual observation of boxplots created of total and categorical sample mass, no differences were observed between asphalt and concrete roads, across functional class, or by nearby land use (commercial, residential, etc.); potential differences were observed between gross solids derived from rural, suburban, and urban sites. Using multiple linear regression, it was observed that the urban sites produced a per sample mean of 2.5 lb total gross solids mass, twelve times higher than that for suburban and rural sites (0.18-0.19 lb). Runoff from urban sites conveyed 2.3 lb of vegetation per sampling event, about 10 times that of suburban sites (0.25 lb) and 30 times that of rural sites (0.08 lb). Urban sites produced on average 0.16 lb of plastic, while suburban (0 lb) and rural sites (0.01) produced very little. A similar trend was observed for cigarettes, with 0.09 lb on average for urban sites and <0.01 lb for suburban and rural sites. No significant trends were observed for glass, metal, wood, fabric, gravel, or paper. Similar results were observed by Waickowski (2015), who generally found that highly urbanized watersheds (downtown areas and high density residential) in North Carolina produced greater mass loading of gross solids than low density monitoring sites.

3.3.5 Gross Solids Water Content

Moisture content of gross solids was investigated due to its importance with respect to disposal of this waste product. If catch basin inserts were to be installed at scale, vacuum trucks would be utilized to efficiently remove accumulated debris. This debris would then presumably be landfilled.

As expected, mean moisture content was lowest for the samples visually characterized as dry (12.6%) and highest for wet samples (161.5%). Particularly for the moderate and wet samples, a high level of variability (as evidenced by the standard deviation) existed in moisture content (Table 11). Across all samples, the mean moisture content was 78.4%, with the range of moisture contents varying from 1.5% to nearly 440%. Alam et al. (2017) measured gross solid moisture content from 24-52.5% from samples collected in Western Australia. Eight of 18 gross solids samples analyzed herein exceeded the recommended maximum 70% moisture content for disposal in a landfill.

Glass, metal, fabric, and gravel contained no appreciable moisture (Figure 24). Moisture was primarily found in paper, vegetation, cigarettes, and wood. Mean moisture content for wood varied from 50-125% across the dry, moderate, and wet samples. Cigarettes in dry and moderate samples were approximately 35% moisture, while in wet samples they were 155% moisture. Similarly, paper was approximately 40% moisture in dry and moderate samples, while it was 139% moisture in wet samples. Median moisture content for vegetation was 18%, 46%, and 120%, respectively, for dry, moderate, and wet samples.

Table 11. Summary statistics for moisture content among dry, moderate, and wet gross solids samples.

	Moisture Content (%)			
Category	No. of Samples	Mean	Std. Dev.	Range
Dry	7	12.6	5.4	1.5-18.3
Moderate	5	37.2	30.5	4.2-87.2
Wet	8	161.5	120.7	39.9-439.5

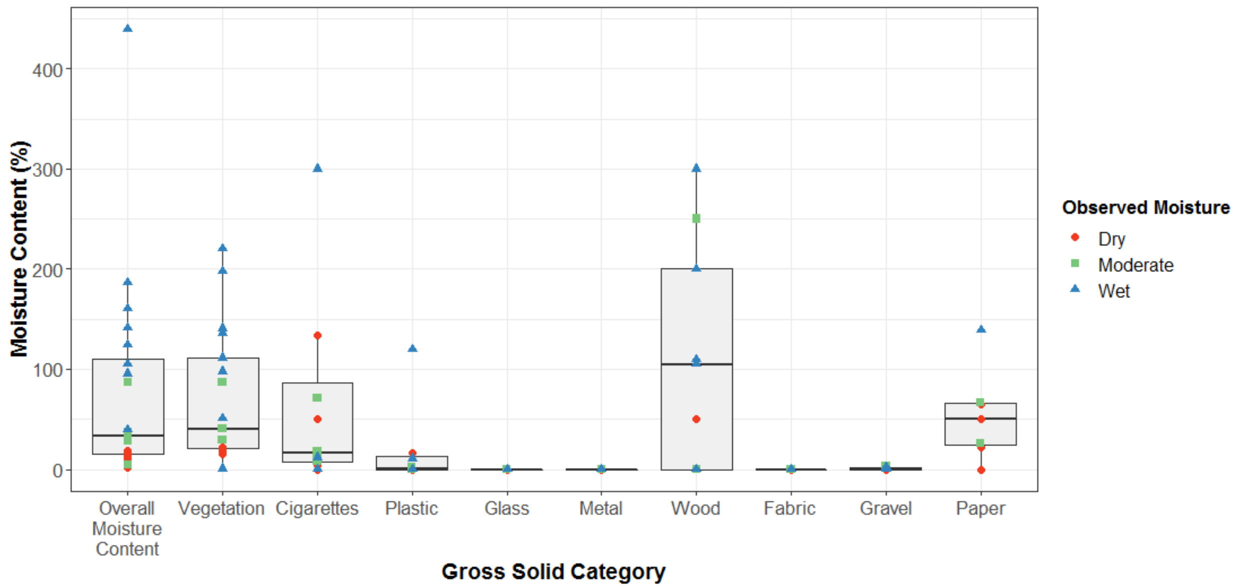

Figure 24. Boxplots of moisture content by gross solids category. Symbols show moisture content for each separate sample in a category, with symbol color and shape representative of visually dry (red circle), moderately wet (green square), and wet (blue triangle) samples.

3.4 Conclusions

Gross solids represent a class of infrequently quantified pollutants in stormwater runoff that contribute to pollution of Ohio's surface waters. As such, a monitoring study was undertaken to quantify the volume and mass of gross solids in road runoff. Mean total gross solids volume and mass for samples collected on average every 11.6 days were 1.22 gal and 1.08 lb, resulting in volumetric and mass loading rates of 0.94 gal/ac/day and 0.41 lb/ac/day, respectively. Maximum sample volume and mass were 17.6 gal and 61.9 lb, respectively. Vegetation was the primary contributor to gross solids volume and mass, averaging 80.3% and 79.7% of the total collected gross solids, respectively. Vegetation and total gross solids volume and mass were highest in the autumn season. Vegetation was primarily made up of grass clippings from mowing of the roadside shoulder and leaf-fall from trees in the autumn, suggesting that maintenance for catch basin or BMP pretreatment clean out can be scheduled around these events.

Rainfall depth, duration, elapsed time since the previous sample collection, antecedent dry period, peak rainfall intensity, catchment area, and AADT were significantly correlated to either gross solids mass or volume; correlations to gross solids mass were infrequently observed and were weaker than those for gross solids volume. Moisture content in gross solids samples was highly variable (range 1.5% to 440%), with a mean of 78.5%; in some cases, drying or solidification of gross solids may be needed prior to landfilling. The data presented herein will inform maintenance frequencies for pretreatment devices for BMPs, catch basin inserts, and hydrodynamic separators.

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Appendix A: Literature Review

Both Charters et al. (2015) and Muthukaruppan et al. (2013) found underlying soil type to be a contributing factor to PSD, presumably through atmospheric deposition on urban impervious surfaces. However, in a study of road runoff at eight sites across North Carolina, no differences in runoff PSD were found based on underlying soil type (Winston and Hunt 2017). Brodie and Dunn (2009) measured PSDs from parking lot runoff and found them to be coarser than those of roof or road runoff. Charters et al. (2015) found similar median particle diameters among road, copper roof, galvanized roof, and concrete roof monitoring sites. Wu et al. (2015) determined that particulates in roof runoff were substantially coarser than those in road runoff. So, while land use appears to affect PSD, various studies show that it affects PSD in contrary ways, suggesting there is a large amount of variability in this type of data. All of this variability in runoff PSD highlights the need for local data to be collected to refine BMP design criteria for sediment settling and trapping (Selbig and Bannerman 2011).

For roads, the maintenance practices, road characteristics, travel speed AADT, season, and rainfall characteristics may also impact runoff PSD. For example, in regions that apply sand or gravel for traction control on roads in winters, PSD will perhaps be skewed to a larger median particle diameter during this season. Selbig et al. (2016) evaluated runoff during non-winter months in Wisconsin and showed no seasonality in runoff PSD. Specific road-related stimuli, including tire and brake wear, and degradation of the pavement surface, also contribute to PSD (Zanders, 2005; Charters et al. 2015). Ferreira and Stenstrom (2013) claimed soil types and topography of a site affect how/if particles are transported in stormwater, thereby impacting the PSD. In a recent study of eight roadway sites across the three ecoregions (mountain, piedmont, and coastal plan) of North Carolina, no significant correlation was found between runoff PSD and roadway classification, ecoregion (which affects the surface slope of a site), or AADT (Winston and Hunt 2017). However, the pavement wearing course appeared to affect PSD, with significantly greater d_{50} (54 vs. 41 μm) and d_{90} (428 vs. 131 μm) for hot mix asphalt than for permeable friction course overlays (Eck et al. 2012; Winston and Hunt 2017). Charters et al. (2015) correlated road runoff PSD to average and peak rainfall intensity, rainfall depth, and event duration. Rainfall depth, peak hourly rainfall intensity, rainfall duration, and average rainfall intensity were all significantly correlated to measures of PSD (d_{10}, d_{50}, and d_{90}) from road runoff in North Carolina (Winston and Hunt, 2017).

Table A-1 presents a summary of PSD data from available published papers and government reports. Studies are sorted by monitored land use and the year of publication. Data were collected in urban areas around the world, and each study had at least 3 runoff PSDs determined using the listed sampling methodologies. Studies of untreated runoff PSD have typically focused on road runoff, with fewer studies on other types of catchments (Table A-1). The median D_{50} of all samples taken in each study is presented. It varied widely over more than 2 orders of magnitude, from 4-570 μm. This further highlights the heterogeneity inherent in runoff PSD. Wide ranges in runoff PSD may result in the need to combine various treatment technologies to achieve sediment reduction goals.

Table A-1. Description of studies characterizing urban stormwater runoff PSDs with additional information relating to location of the study, sampling methods, and median particle diameter. Sampling methods include vacuuming (dry sediment sample collection), grab (point sample collection of stormwater), and composite (sampled collected across the hydrograph).

Reference	Land Use	Location	Sample Type	Sampling Method	D_{50} (μm)
Sartor and Boyd (1972)	Road	12 U.S. urban areas	Sediment	Vacuum	320
Shaheen (1975)	Road	Washington, D.C.	Sediment	Vacuum	207
Sansalone et al. (1998)	Road	Cincinnati, Ohio	Runoff	Composite^	570
Sansalone and Tribouillard (1999)	Road	Cincinnati, Ohio	Sediment	Vacuum	400
Andral et al. (1999)	Road	Hérault, France	Runoff	Composite	16
Furumai et al. (2002)	Road	Winterthur, Switzerland	Runoff	Composite	<50

Reference	Land Use	Location	Sample Type	Sampling Method	D_{50} (µm)
Furumai et al. (2002)	Road	Winterthur, Switzerland	Sediment	Vacuum	175
Li et al. (2005)	Road	Los Angeles, California	Runoff	Grab	80
Zanders (2005)	Road	Hamilton, New Zealand	Sediment	Vacuum	250
Westerlund and Viklander (2006)	Road	Luleå, Sweden	Runoff	Composite	4-6
Kim and Sansalone (2008)	Road	Baton Rouge, Louisiana	Runoff	Composite^	136
Brodie and Dunn (2009)	Road	Toowoomba, Australia	Runoff	Composite	26
Selbig and Bannerman (2011)	Road	Madison, Wisconsin	Runoff	Composite	200
Selbig and Bannerman (2011)	Road	Madison, Wisconsin	Runoff	Composite	95
Selbig and Bannerman (2011)	Road	Madison, Wisconsin	Runoff	Composite	70
Selbig (2015)	Road	Madison, Wisconsin	Runoff	Composite	50
Selbig (2015)	Road	Madison, Wisconsin	Runoff	Composite	43
Selbig (2015)	Road	Madison, Wisconsin	Runoff	Composite	8
Charters et al. (2015)	Road	Christchurch, New Zealand	Runoff	Composite	71
Wu et al. (2015)	Road	Beijing, China	Runoff	Composite	20
Winston and Hunt (2017)	Road	Black Mountain, North Carolina	Runoff	Composite	67
Winston and Hunt (2017)	Road	Brevard, North Carolina	Runoff	Composite	112
Winston and Hunt (2017)	Road	Jack Bennett, North Carolina	Runoff	Composite	36
Winston and Hunt (2017)	Road	Hanks Chapel, North Carolina	Runoff	Composite	167
Winston and Hunt (2017)	Road	Faison, North Carolina	Runoff	Composite	101
Winston and Hunt (2017)	Road	Benson, North Carolina	Runoff	Composite	41
Winston and Hunt (2017)	Road	Wilson, North Carolina	Runoff	Composite	44
Winston and Hunt (2017)	Road	Goldsboro, North Carolina	Runoff	Composite	32
Brodie and Dunn (2009)	Roof	Toowoomba, Australia	Runoff	Composite	23
Selbig and Bannerman (2011)	Roof	Madison, Wisconsin	Runoff	Composite	95
Charters et al. (2015)	Roof	Christchurch, New Zealand	Runoff	Composite	81
Charters et al. (2015)	Roof	Christchurch, New Zealand	Runoff	Composite	61
Charters et al. (2015)	Roof	Christchurch, New Zealand	Runoff	Composite	72
Wu et al. (2015)	Roof	Beijing, China	Runoff	Composite	40
Burton and Pitt (2002)	Residential	Madison, Wisconsin	Runoff	Composite	9
Selbig (2015)	Residential	Madison, Wisconsin	Runoff	Composite	80
Brodie and Dunn (2009)	Parking Lot	Toowoomba, Australia	Runoff	Composite	33
Selbig and Bannerman (2011)	Parking Lot	Madison, Wisconsin	Runoff	Composite	54
Roseen et al. (2011)	Parking Lot	Durham, New Hampshire	Runoff	Composite	46
Selbig (2015)	Parking Lot	Madison, Wisconsin	Runoff	Composite	32
Driscoll (1986)	Mixed Use	Nat'l Urban Runoff Program (NURP)	Runoff	Composite	8
Greb and Bannerman (1997)	Mixed Use	Madison, Wisconsin	Runoff	Composite	<7
Anta et al. (2007)	Mixed Use	Galicia, Spain	Runoff	Composite^	38
Selbig and Bannerman (2011)	Mixed Use	Madison, Wisconsin	Runoff	Composite	42
Gonclaves and Van Seters (2012)	Mixed Use	Toronto, Canada	Runoff	Grab	14

Reference	Land Use	Location	Sample Type	Sampling Method	D_{50} (μm)
Selbig (2015)	Mixed Use	Madison, Wisconsin	Runoff	Composite	95

^Time-paced composite sample

Several researchers (Brodie and Dunn 2009; Charters et al. 2015; Selbig 2015) have suggested land use may impact runoff PSD. Figure A-1 presents d_{50} (data originally presented in Table A-1) by land use. To provide a valid comparison, only data collected using flow proportional, composite sampling methods were utilized, as it appears sampling method influences PSD (see discussion below). While roof runoff appears to have a slightly coarser median D_{50} than roads, the residential, parking lot, and mixed land uses all appear to produce similar D_{50} to roads. From previous studies, median D_{50} for roads, roofs, residential areas, parking lots, and mixed use urban watersheds were 44, 67, 45, 40, and 38 μm, respectively. However, a study by Selbig (2015) showed great variation among PSDs across various land uses, with d_{50} ranging from 8-95 μm (d_{50} for roads were 8, 43, and 50 μm). Selbig (2015) suggests there is not a single distribution of particle sizes that can be uniformly applied to runoff in all urban watersheds. One way to reduce variation in PSD is to increase the sample size to assure that an appropriate "middle-ground" PSD can be used for design (Burton and Pitt 2002). As suggested by Selbig et al. (2016), proper site characterization is needed to determine runoff PSD, otherwise under- or over-sized BMPs may be installed which are either ineffective or overly costly.

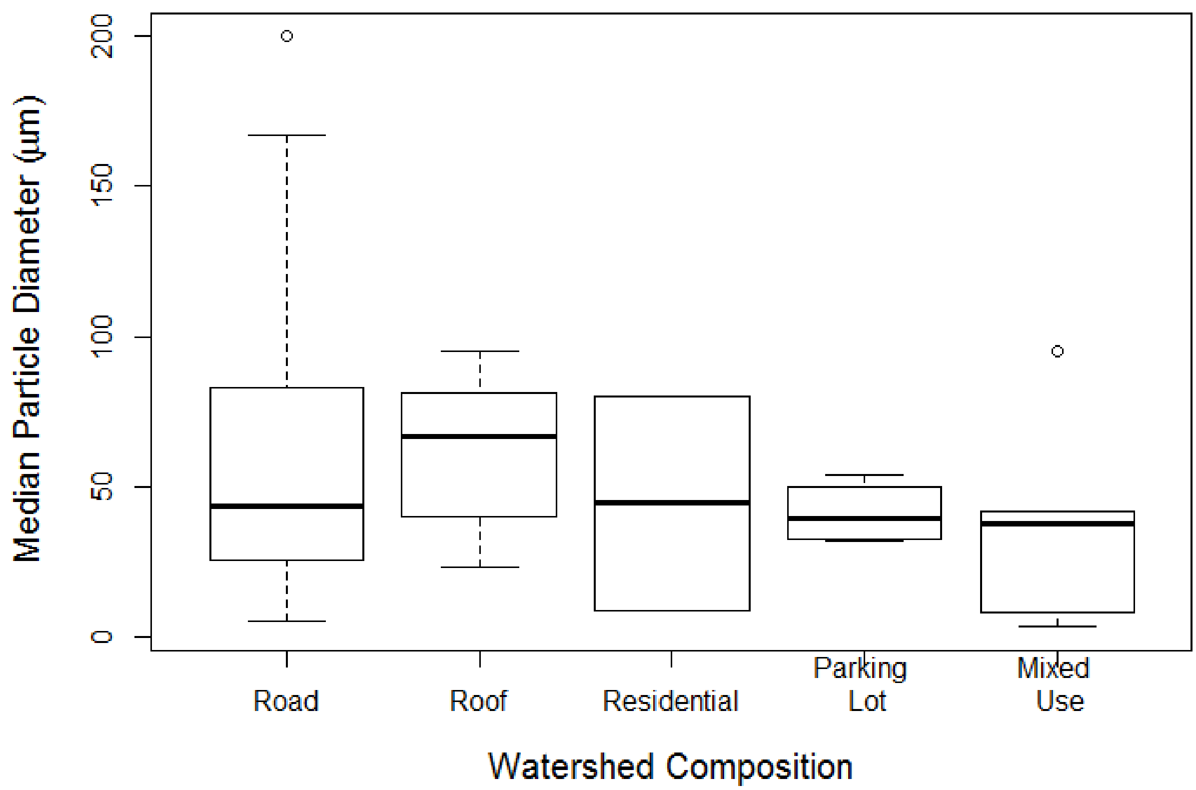

Figure A-1. Median particle diameter in previous studies by land use. Median particle diameter data informing this plot were presented in Table 1.

Previous studies on PSD have utilized three groups of methodologies to obtain particulate matter samples. The first is vacuuming of sediment from the surface of the catchment, typically a roadway (Table A-1). These samples are obtained during dry weather and the assumption made that all vacuumed particles will be mobilized during wet-weather events. In the other two methods, direct samples of stormwater are obtained during rainfall. The first involves either grab sampling (taking a single sample during the hydrograph) or time-paced, composite sampling (taking multiple grab samples during the hydrograph spaced by a chosen time interval and compositing them into one representative sample). The above methods have been infrequently applied since 2005 (Table A-1). The final method is to obtain flow-volume proportional, composite samples. In this method, an automated sampler obtains a sample each time a given amount of flow (e.g., 50 ft^3) passes the monitoring station, producing a composite sample representative of the entire hydrograph. These methods have been used in nearly every research study since 2005 (Table A-1), because it is recognized in the literature that they provide more representative samples than grab or time-paced sampling (Burton and Pitt 2001; Selbig and Fienen 2012).

Direct comparison of PSD sampling methods was provided by Furumai et al. (2002), who obtained sediment samples from a highway both through vacuuming and sampling stormwater runoff. The same PSD measurement methods were used to analyze the samples in the laboratory, but divergent PSDs were noted (Figure A-2). Stormwater runoff PSD was much finer in texture, with a median particle diameter less than 50 μm. Median particle diameter for vacuumed sediment samples was between 125-250 μm. Three processes could potentially account for this difference: (1) particle aggregation in street sediments may occur during dry periods, increasing street sediment D_{50} (Slattery and Burt, 1997), (2) turbulent runoff may break apart aggregates, decreasing D_{50} in stormwater runoff, and (3) runoff may not provide enough force to mobilize all of the sediment (the largest diameter particles may not move, especially during low-intensity rainfall); a vacuum will remove (nearly) all particles from the road surface. A recent review of literature by Semadeni-Davis (2013) confirmed samples of street dust have a higher fraction of coarse particulate matter than that commonly reported in the literature for runoff solids. This further confirms the need to measure runoff PSD, not dry street sediment PSD, to inform BMP selection and design.

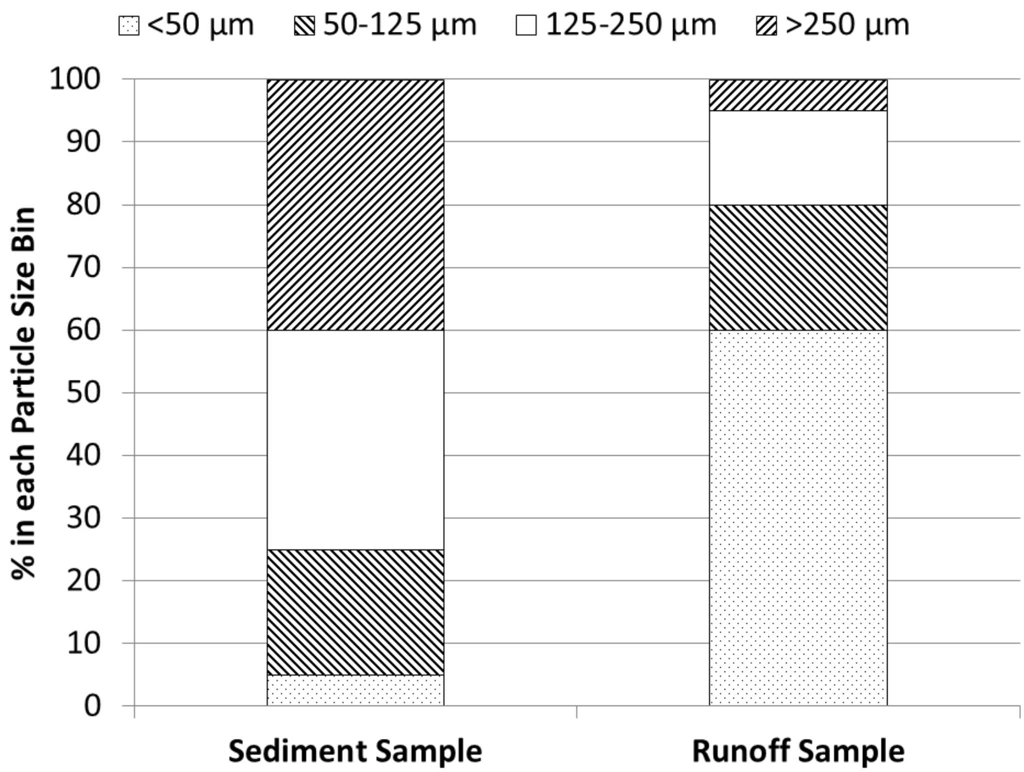

Figure A-2. Particle size distribution as affected by sampling method. Samples were obtained from a highway in Winterthur, Switzerland. Data from Furumai et al. (2002).

Appendix B: Rainfall Summary Statistics

Table B-1. Rainfall summary statistics for the I-70 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr) Median of Average	Rainfall Intensity (in/hr) Median of Peak	Median ADP (days)	Fraction of Rainfall Depth
All	<0.25	12	2.75	0.42	0.06	5.71	0.08
	0.25-0.49	15	3.93	0.78	0.08	2.78	0.22
	0.5-0.99	8	2.22	1.56	0.33	1.66	0.23
	1-1.99	5	8.53	1.80	0.16	2.89	0.28
	>2	2	5.71	2.49	0.44	5.54	0.20
Sampled	<0.25	1	4.12	0.30	0.05	5.71	0.02
	0.25-0.49	6	2.29	0.60	0.15	2.47	0.18
	0.5-0.99	2	13.88	0.39	0.13	4.05	0.10
	1-1.99	3	7.35	2.82	0.17	3.27	0.33
	>2	2	5.71	2.49	0.44	5.54	0.37

Table B-2. Rainfall summary statistics for the I-71 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr) Median of Average	Rainfall Intensity (in/hr) Median of Peak	Median ADP (days)	Fraction of Rainfall Depth
All	<0.25	15	2.38	0.42	0.08	3.93	0.11
	0.25-0.49	10	2.23	1.05	0.18	3.08	0.16
	0.5-0.99	9	2.28	1.32	0.39	4.37	0.30
	1-1.99	6	6.75	1.35	0.17	0.35	0.31
	>2	1	4.52	2.40	0.59	7.13	0.12
Sampled	<0.25	1	1.47	0.54	0.11	0.68	0.01
	0.25-0.49	5	2.47	1.08	0.16	2.88	0.14
	0.5-0.99	6	1.30	1.50	0.58	2.54	0.41
	1-1.99	2	8.08	1.41	0.18	1.82	0.22
	>2	1	4.52	2.40	0.59	7.13	0.22

Table B-3. Rainfall summary statistics for the SR-257 rain gauge for all observed event and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	18	2.21	0.54	0.08	3.94	0.14
	0.25-0.49	6	7.20	0.72	0.06	6.89	0.10
	0.5-0.99	11	3.23	1.14	0.22	4.06	0.29
	1-1.99	5	9.73	1.23	0.13	1.80	0.31
	>2	1	5.68	1.92	0.64	7.18	0.16
Sampled	<0.25	2	0.98	0.36	0.54	2.19	0.03
	0.25-0.49	2	12.17	NA	0.04	4.54	0.06
	0.5-0.99	6	4.71	1.47	0.17	3.14	0.27
	1-1.99	4	20.40	1.20	0.09	1.36	0.40
	>2	1	5.68	1.92	0.64	7.18	0.25

Table B-4. Rainfall summary statistics for the SR-22 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	2	4.98	0.27	0.08	3.64	0.02
	0.25-0.49	12	2.08	0.51	0.16	5.59	0.26
	0.5-0.99	7	2.52	1.14	0.21	1.40	0.28
	1-1.99	5	10.92	1.38	0.16	1.33	0.44
	>2	0	NA	NA	NA	NA	0.00
Sampled	<0.25	0	NA	NA	NA	NA	0.00
	0.25-0.49	9	1.82	0.84	0.17	5.44	0.28
	0.5-0.99	6	4.26	1.08	0.16	1.63	0.31
	1-1.99	3	10.92	1.38	0.16	10.72	0.42
	>2	0	NA	NA	NA	NA	0.00

Table B-5. Rainfall summary statistics for the SR-48 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	4	1.42	0.39	0.13	7.70	0.04
	0.25-0.49	10	3.85	0.54	0.10	3.64	0.23
	0.5-0.99	7	2.35	0.72	0.29	4.03	0.33
	1-1.99	5	7.85	0.84	0.14	3.73	0.39
	>2	0	NA	NA	NA	NA	0.00
Sampled	<0.25	1	0.48	0.36	0.21	10.49	0.01
	0.25-0.49	4	2.42	0.54	0.16	6.82	0.13
	0.5-0.99	6	2.40	1.05	0.33	5.04	0.49
	1-1.99	3	5.92	1.02	0.19	3.73	0.37
	>2	0	NA	NA	NA	NA	0.00

Table B-6. Rainfall summary statistics for the SR-49 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	4	2.52	0.45	0.05	3.35	0.03
	0.25-0.49	7	1.38	0.84	0.33	5.05	0.14
	0.5-0.99	12	6.02	1.11	0.14	3.01	0.44
	1-1.99	6	6.53	0.99	0.18	4.61	0.39
	>2	0	NA	NA	NA	NA	0.00
Sampled	<0.25	1	8.52	0.54	0.02	0.51	0.01
	0.25-0.49	5	1.38	0.84	0.33	5.19	0.16
	0.5-0.99	7	6.27	1.20	0.13	3.37	0.42
	1-1.99	4	9.33	0.81	0.12	5.49	0.41
	>2	0	NA	NA	NA	NA	0.00

Table B-7. Rainfall summary statistics for the I-90 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	19	4.92	0.42	0.04	1.80	0.15
	0.25-0.49	14	3.93	0.81	0.08	1.83	0.21
	0.5-0.99	11	4.65	1.32	0.12	3.56	0.35
	1-1.99	3	17.27	1.32	0.08	1.78	0.19
	>2	1	61.90	0.24	0.04	1.86	0.10
Sampled	<0.25	6	5.85	0.33	0.03	1.14	0.14
	0.25-0.49	4	6.38	0.96	0.05	1.94	0.16
	0.5-0.99	3	9.10	1.62	0.08	10.40	0.29
	1-1.99	1	11.52	1.32	0.10	0.62	0.14
	>2	1	61.90	0.24	0.04	1.86	0.27

Table B-8. Rainfall summary statistics for the SR-43 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	16	3.52	0.30	0.04	4.06	0.12
	0.25-0.49	12	7.75	0.51	0.07	1.95	0.20
	0.5-0.99	10	11.44	1.17	0.10	1.82	0.28
	1-1.99	5	13.4	1.2	0.11	2.11	0.29
	>2	0	NA	NA	NA	NA	0.00
Sampled	<0.25	3	7.35	0.30	0.03	4.06	0.07
	0.25-0.49	3	14.78	0.30	0.03	12.18	0.15
	0.5-0.99	5	6.82	1.14	0.09	1.81	0.41
	1-1.99	3	27.40	0.96	0.04	2.78	0.43
	>2	0	NA	NA	NA	NA	0.00

Table B-9. Rainfall summary statistics for the SR-59 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	11	3.63	0.30	0.05	4.07	0.08
	0.25-0.49	14	6.11	0.45	0.07	4.68	0.23
	0.5-0.99	12	8.13	1.02	0.10	1.81	0.36
	1-1.99	4	20.17	0.84	0.06	1.65	0.22
	>2	0	NA	NA	NA	NA	0.00
Sampled	<0.25	0	NA	NA	NA	NA	0.00
	0.25-0.49	6	6.11	0.36	0.07	4.84	0.31
	0.5-0.99	6	5.75	1.38	0.12	2.08	0.46
	1-1.99	1	25.42	0.24	0.04	2.80	0.12
	>2	0	NA	NA	NA	NA	0.00

Table B-10. Rainfall summary statistics for the SR-81 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	15	1.94	0.42	0.09	1.90	0.10
	0.25-0.49	15	6.67	0.30	0.06	1.90	0.24
	0.5-0.99	14	4.27	1.23	0.15	3.25	0.45
	1-1.99	6	5.74	1.68	0.27	1.94	0.38
	>2	2	31.87	0.78	0.10	2.06	0.25
Sampled	<0.25	2	0.57	0.42	0.23	5.47	0.03
	0.25-0.49	3	9.93	0.30	0.04	3.72	0.14
	0.5-0.99	5	4.35	1.14	0.14	6.52	0.41
	1-1.99	4	5.74	1.68	0.27	1.00	0.77
	>2	0	NA	NA	NA	NA	0.00

Table B-11. Rainfall summary statistics for the SR-117 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	16	1.30	0.48	0.12	1.69	0.11
	0.25-0.49	12	3.04	0.36	0.09	3.72	0.20
	0.5-0.99	14	5.48	1.17	0.15	1.84	0.48
	1-1.99	6	5.74	1.53	0.27	3.99	0.34
	>2	2	32.17	0.81	0.09	2.55	0.00
Sampled	<0.25	1	NA	NA	NA	7.04	0.02
	0.25-0.49	3	9.93	0.30	0.04	3.72	0.14
	0.5-0.99	6	5.51	1.17	0.15	2.00	0.55
	1-1.99	2	4.14	1.32	0.29	4.27	0.28
	>2	0	NA	NA	NA	NA	0.00

Table B-12. Rainfall summary statistics for the US-20 rain gauge for all observed events and events sampled for water quality.

Rainfall Events	Storm Depth (in)	Number of Storms	Median Duration (hrs)	Rainfall Intensity (in/hr)		Median ADP (days)	Fraction of Rainfall Depth
				Median of Average	Median of Peak		
All	<0.25	18	5.45	0.42	0.03	2.12	0.13
	0.25-0.49	14	4.22	0.57	0.09	1.75	0.20
	0.5-0.99	12	3.48	0.90	0.18	4.64	0.38
	1-1.99	6	16.97	0.93	0.08	1.86	0.38
	>2	1	10.35	3.24	0.19	12.12	0.09
Sampled	<0.25	2	5.71	0.48	0.23	5.73	0.05
	0.25-0.49	2	7.43	0.99	0.05	4.05	0.08
	0.5-0.99	7	3.08	0.96	0.20	5.04	0.61
	1-1.99	4	19.92	0.93	0.08	1.98	0.77
	>2	1	10.35	3.24	0.19	12.12	0.24

Appendix C: Hydrologic and TSS Data Summary

Table C-1. Hydrologic and TSS data for I-71.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1	1	1.56	6.32	2.28	0.25	Spring	No data	990	1778.1	0.66	24
2		0.19	0.55	0.96	0.35	Spring	1.07	85.5	216.6	0.185	
3	2	0.34	1.72	1.08	0.20	Spring	2.88	224.3	387.5	0.3	47
4	3	0.29	4.43	1.68	0.07	Spring	2.85	342	330.5	0.51	39
5	4	0.16	1.47	0.54	0.11	Spring	0.68	274	182.4	0.36	25
6		0.17	0.72	0.54	0.24	Spring	4.91	241.8	193.8	0.22	
7		0.14	0.17	1.02	0.84	Spring	4.87	326	159.6	0.51	
8		1.11	0.93	2.88	1.19	Spring	0.35	1134	1265.2	0.99	
9	5	2.67	4.52	2.40	0.59	Summer	7.13	3416	3043.3	1.24	8
10	6	0.9	2.28	2.04	0.39	Summer	3.69	796	1025.8	0.71	24
11		0.11	0.53	0.48	0.21	Summer	0.28	73.6	125.4	0.12	
12		0.12	3.37	0.42	0.04	Summer	3.97	44.2	136.8	0.053	
13	7	0.39	2.47	1.08	0.16	Summer	16.91	633	444.5	0.92	32
14		0.42	2.00	1.56	0.21	Summer	4.03	530.9	478.7	0.67	
15	8	0.63	1.23	1.26	0.51	Summer	6.29	835	718.1	0.6	18
16		0.57	10.02	1.92	0.06	Summer	15.82	NA		NA	
17		1.15	5.47	0.96	0.21	Summer	0.28	NA		NA	
18		0.42	2.00	0.84	0.21	Summer	0.74	NA		NA	
19		0.2	8.10	0.42	0.02	Summer	0.98	NA		NA	
20		0.14	5.85	0.24	0.02	Summer	0.38	NA		NA	
21		0.42	0.25	1.44	1.68	Summer	3.29	NA		NA	
22		0.54	3.75	1.32	0.14	Summer	4.37	NA		NA	
23		0.22	0.22	0.90	1.02	Summer	2.51	130	250.8	0.31	

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
24	9	0.78	0.47	2.58	1.67	Summer	1.04	424	889.1	0.67	31
25		1.17	8.50	0.96	0.14	Summer	11.19	2069	1333.6	0.88	
26		0.99	2.95	1.32	0.34	Summer	1.40	1272	1128.4	0.67	
27	10	0.29	0.80	0.96	0.36	Summer	6.41	345	330.5	0.35	33
28		0.17	2.70	0.36	0.06	Fall	9.17	21	193.8	0.01	
29	11	1.08	9.85	0.54	0.11	Fall	1.82	626.6	1231.0	0.14	46
30		0.31	9.40	1.02	0.03	Fall	0.86	219.4	353.3	0.36	
31		1	7.18	1.74	0.14	Fall	0.30	NA		NA	
32	12	0.88	1.37	1.68	0.64	Fall	19.28	688.3	1003.0	0.43	38
33	13	0.89	0.95	0.72	0.94	Fall	0.59	760.3	1014.4	0.1	31
34		0.2	2.42	0.42	0.08	Fall	18.32	132.9	228.0	0.147	
35		0.2	2.38	0.30	0.08	Fall	10.30	NA		NA	
36		0.44	6.85	0.30	0.06	Fall	9.45	NA		NA	
37		0.12	1.23	0.30	0.10	Fall	1.71	NA		NA	
38		0.19	4.15	0.30	0.05	Fall	3.93	98.9	216.6	0.02	
39	14	0.42	7.77	0.24	0.05	Fall	1.40	226.6	478.7	0.046	66
40		0.24	11.33	0.24	0.02	Fall	5.02	227.6	273.6	0.07	

Table C-2. Hydrologic and TSS data for SR-22.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1	1	0.42	5.50	0.48	0.08	Spring	No data	537	419.3	0.55	35
2	2	0.33	2.42	0.24	0.14	Spring	5.59	240.2	329.4	0.08	25
3	3	0.43	1.22	1.26	0.35	Spring	5.29	285.4	429.2	0.45	45
4		0.21	1.63	0.30	0.13	Summer	6.53	128.6	209.6	0.038	
5	4	0.64	1.50	2.40	0.43	Summer	0.74	599	638.9	1.24	9
6		0.28	6.82	0.24	0.04	Summer	10.11	134	279.5	0.023	11
7	5	0.34	15.52	0.30	0.02	Summer	0.38	230	339.4	0.11	11
8	6	0.26	0.37	1.14	0.71	Summer	9.26	204.5	259.5	0.48	NA
9	7	0.49	0.88	0.96	0.55	Summer	1.71	409	489.1	0.51	18
10	8	0.39	2.35	0.24	0.17	Summer	2.63	298.7	389.3	0.11	19
11	9	0.54	2.52	0.60	0.21	Summer	9.83	396.8	539.1	0.22	19
12	10	0.58	6.00	1.02	0.10	Summer	1.40	443.6	579.0	0.4	22
13	11	0.29	1.82	1.44	0.16	Summer	15.55	267.6	289.5	0.66	27
14	12	1.99	1.68	2.82	1.18	Summer	0.60	2208.9	1986.5	1.77	31
15		0.95	2.22	2.28	0.43	Summer	0.35	1164.9	948.3	1.4	
16		1.07	28.53	0.60	0.04	Summer	0.60	1085	1068.1	0.31	
17	13	0.59	0.65	1.14	0.91	Summer	2.28	519.4	589.0	0.49	34
18		0.18	8.33	0.24	0.02	Summer	0.75	104	179.7	0.06	
19	14	0.41	1.37	0.84	0.30	Summer	6.68	346.4	409.3	0.37	54
20	15	0.67	8.72	2.10	0.08	Summer	1.15	751.5	668.8	1.24	23
21	16	1.77	10.92	1.38	0.16	Summer	10.72	1995.9	1766.9	0.73	18
22		1.36	2.70	2.46	0.50	Summer	1.33	1863	1357.6	1.69	
23		0.39	1.82	0.48	0.21	Fall	15.64	226.3	389.3	0.18	
24	17	0.7	11.43	0.60	0.06	Fall	1.87	433.8	698.8	0.21	19
25		0.26	12.10	0.54	0.02	Fall	1.06	123.8	259.5	0.18	
26	18	1.27	23.40	0.42	0.05	Fall	19.91	919.4	1267.8	0.14	2.5

Table C-3. Hydrologic and TSS data for SR-48.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentrati on (mg/L)
1		0.42	5.50	0.48	0.08	Spring	No data	1267	532.1	0.3	
2	1	0.1	0.48	0.36	0.21	Spring	10.49	149	126.7	0.03	30
3	2	0.26	1.08	0.54	0.24	Summer	5.54	344.9	329.4	0.14	14
4		0.49	3.95	1.50	0.12	Summer	2.18	278.9	620.8	0.32	
5		0.47	3.57	1.14	0.13	Summer	3.64	340.1	595.4	0.18	
6	3	0.27	18.33	0.24	0.01	Summer	6.36	382.3	342.1	0.02	5
7	4	0.36	0.87	0.60	0.42	Summer	0.61	256	456.1	0.15	14
8		0.68	2.35	0.60	0.29	Summer	0.31	350.2	861.5	0.1	
9	5	0.86	0.57	2.16	1.52	Summer	1.28	542.5	1089.5	0.45	39
10	6	0.31	3.75	0.54	0.08	Summer	7.28	263.7	392.7	0.07	NA
11	7	1.07	1.40	2.28	0.76	Summer	0.68	628.6	1355.6	0.55	13
12	8	0.63	3.22	0.42	0.20	Summer	3.55	189.5	798.1	0.08	2.5
13	9	0.69	1.40	1.44	0.49	Summer	4.03	494.9	874.1	0.34	31
14	10	0.73	1.58	0.72	0.46	Summer	7.27	608	924.8	0.21	17
15	11	1.15	5.92	1.02	0.19	Summer	11.44	1037	1456.9	0.2	19
16	12	1.07	7.85	0.78	0.14	Summer	3.73	2013	1355.6	0.37	5
17		0.64	15.38	1.20	0.04	Summer	0.58	1042.6	810.8	0.19	
18		0.54	27.38	0.60	0.02	Summer	0.31	595.8	684.1	0.09	
19	13	0.85	6.58	1.38	0.13	Summer	3.37	1213.6	1076.8	0.63	40
20		0.3	0.58	1.14	0.51	Summer	5.99	400	380.1	0.35	
21		0.19	0.93	0.42	0.20	Summer	0.73	298	240.7	0.15	
22	14	0.59	5.78	0.30	0.10	Summer	12.14	752	747.5	0.19	16
23		0.27	4.23	0.54	0.06	Summer	1.56	307.2	342.1	0.14	
24		0.24	4.48	0.60	0.05	Summer	6.73	331	304.0	0.23	
25		0.11	1.90	0.30	0.06	Fall	8.67	172.6	139.4	0.18	
26		1.13	9.23	0.54	0.12	Fall	1.83	2137.8	1431.6	0.44	
27		0.34	16.23	0.30	0.02	Fall	1.36	327.44	430.7	0.21	

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28		1.56	35.43	0.84	0.04	Fall	19.15	NA	NA	NA	

Table C-4. Hydrologic and TSS data for SR-49.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1	1	0.42	5.50	0.48	0.08	Spring	No data	384.7	224.1	0.28	12
2		1.13	5.22	1.50	0.22	Spring	5.50	395	603.0	0.3	
3	2	0.46	1.38	0.84	0.33	Summer	10.31	142.4	245.5	0.12	15
4	3	0.56	3.97	1.86	0.14	Summer	2.18	189.8	298.8	0.39	10
5	4	0.48	1.17	1.92	0.41	Summer	3.64	184.9	256.1	0.39	15
6		0.31	13.13	0.24	0.02	Summer	6.46	63.2	165.4	0.004	
7	5	0.14	8.52	0.54	0.02	Summer	0.51	62.6	74.7	0.07	9
8		0.64	2.42	0.72	0.26	Summer	0.30	246.6	341.5	0.15	
9		0.34	0.67	1.14	0.51	Summer	1.28	NA	NA	NA	
10		0.56	3.90	1.32	0.14	Summer	7.28	NA	NA	NA	
11		1.05	0.95	2.76	1.11	Summer	0.68	NA	NA	NA	
12		0.73	4.28	0.84	0.17	Summer	3.57	NA	NA	NA	
13	6	0.75	1.18	2.70	0.63	Summer	3.98	339.5	400.2	0.76	14
14	7	1.24	2.93	1.14	0.42	Summer	7.27	756	661.7	0.49	11
15	8	0.92	5.77	1.02	0.16	Summer	11.41	208.4	490.9	0.16	16
16		1.07	7.85	0.78	0.14	Summer	3.72	315.3	571.0	0.11	
17		0.64	15.38	1.20	0.04	Summer	0.58	159.5	341.5	0.16	
18		0.54	27.38	0.60	0.02	Summer	0.31	132.2	288.1	0.053	
19	9	0.85	6.58	1.38	0.13	Summer	3.37	287.2	453.6	0.33	25
20	10	0.38	0.92	1.20	0.41	Summer	6.75	120.1	202.8	0.22	40
21	11	0.62	6.27	0.30	0.10	Summer	12.12	244.2	330.8	0.048	2.5
22	12	0.27	4.23	0.54	0.06	Summer	1.55	32.8	144.1	0.011	8
23		0.12	0.25	0.42	0.48	Summer	3.75	48.2	64.0	0.07	
24	13	0.67	12.37	1.20	0.05	Summer	2.64	639.7	357.5	0.28	14
25		0.12	2.98	0.24	0.04	Fall	8.70	51	64.0	0.02	
26	14	1.02	10.82	0.54	0.09	Fall	1.69	997	544.3	0.1	7
27	15	0.87	16.50	0.78	0.05	Fall	1.37	461	464.2	0.13	14

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28		0.13	2.05	0.48	0.06	Fall	1.22	37	69.4	0.04	
29	16	1.79	36.83	0.84	0.05	Fall	17.77	1415	955.2	0.16	NA

Table C-5. Hydrologic and TSS data for SR-257.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1	1	0.7	2.98	1.44	0.23	Spring	No data	74.4	99.1	0.047	185
2	2	0.74	6.18	0.78	0.12	Spring	7.00	60.7	104.8	0.01	7
3		0.14	0.15	1.14	0.93	Spring	0.68	8.5	19.8	0.008	
4		0.1	2.30	0.42	0.04	Spring	1.06	25.9	14.2	0.009	
5		0.15	0.68	0.54	0.22	Spring	3.76	21.9	21.2	0.009	
6	3	0.59	1.38	1.98	0.43	Spring	4.88	37.3	83.5	0.05	5
7		0.12	0.23	0.66	0.51	Spring	0.30	6.836	17.0	0.017	
8	4	3.61	5.68	1.92	0.64	Summer	7.18	569	511.1	0.17	58
9	5	1.25	9.12	2.70	0.14	Summer	3.63	64.8	177.0	0.069	43
10		0.32	0.15	1.80	2.13	Summer	9.34	NA	NA	NA	
11		0.23	7.27	0.54	0.03	Summer	7.27	NA	NA	NA	
12		0.68	2.72	0.84	0.25	Summer	4.09	21	96.3	0.034	
13		0.6	1.18	1.74	0.51	Summer	4.03	149.7	84.9	0.111	
14	6	0.41	16.23	No data	0.03	Summer	8.09	225.9	58.0	0.077	27
15		0.42	0.35	1.02	1.20	Summer	9.52	44.8	59.5	0.036	
16		0.17	8.87	0.30	0.02	Summer	0.40	3.2	24.1	0.004	
17	7	0.57	10.02	1.92	0.06	Summer	3.14	31.2	80.7	0.021	33
18	8	1.3	5.47	No data	0.24	Summer	0.28	136.9	184.0	0.029	12
19		0.53	2.00	No data	0.26	Summer	0.74	10.1	75.0	0.006	
20	9	0.38	8.10	No data	0.05	Summer	0.98	18.3	53.8	0.013	5
21	10	0.24	0.25	No data	0.96	Summer	3.91	61	34.0	0.12	148
22		0.22	3.38	0.54	0.07	Summer	4.35	34.9	31.1	0.015	
23		0.21	1.17	1.44	0.18	Summer	6.44	9	29.7	0.027	
24		0.5	3.80	0.54	0.13	Summer	8.32	48.9	70.8	0.009	
25	11	0.7	3.23	1.50	0.22	Summer	1.58	65.9	99.1	0.062	36
26		0.16	0.90	0.66	0.18	Summer	6.40	13.7	22.7	0.02	
27	12	0.19	1.72	0.36	0.11	Summer	0.46	23.5	26.9	0.01	15

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28		0.22	2.57	0.60	0.09	Fall	8.63	12.4	31.1	0.013	
29	13	1.27	9.73	0.42	0.13	Fall	1.80	96.3	179.8	0.015	111
30	14	1.51	31.07	1.26	0.05	Fall	0.93	79	213.8	0.033	95
31		0.22	3.38	0.54	0.07	Fall	0.72	11.8	31.1	0.011	
32	15	1.62	37.87	1.20	0.04	Fall	18.08	372.6	229.3	0.05	24
33		0.17	2.92	0.30	0.06	Fall	18.31	13.7	24.1	0.011	
34		0.16	2.12	0.24	0.08	Fall	10.30	7.2	22.7	0.002	
35		0.11	4.33	0.30	0.03	Fall	4.58	NA	NA	NA	
36		0.5	7.20	0.30	0.07	Fall	4.69	NA	NA	NA	
37		0.13	1.30	0.24	0.10	Fall	1.72	NA	NA	NA	
38	16	0.2	3.28	0.24	0.06	Fall	3.96	19.7	28.3	0.002	68
39	17	0.52	12.53	0.24	0.04	Fall	1.45	62.9	73.6	0.009	12
40		0.3	10.93	0.24	0.03	Fall	4.81	NA	NA	NA	
41		0.43	6.30	0.42	0.07	Fall	5.69	NA	NA	NA	

Table C-6. Hydrologic and TSS data for I-90.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1		0.18	0.50	0.60	0.36	Spring	N/A	28.7	21.6	0.028	
2		0.92	7.57	1.32	0.12	Spring	4.18	84.4	110.2	0.048	
3		0.17	0.13	1.14	1.28	Spring	0.40	17.6	20.4	0.044	
4		0.55	4.65	0.66	0.12	Spring	0.30	60.5	65.9	0.023	
5		0.12	5.32	0.24	0.02	Spring	4.33	15.1	14.4	0.001	
6		0.31	1.68	2.04	0.18	Spring	2.13	33.6	37.1	0.089	
7		0.23	19.13	0.24	0.01	Spring	1.08	34	27.6	0.005	
8		0.18	0.17	0.96	1.08	Spring	1.12	17.5	21.6	0.043	
9	1	1.13	11.52	1.32	0.10	Spring	0.62	112.4	135.4	0.013	38
10	2	0.15	6.12	0.30	0.02	Spring	0.54	65.3	18.0	0.013	24
11	3	2.21	61.90	0.24	0.04	Spring	1.86	279.6	264.7	0.012	16
12		0.33	0.70	2.28	0.47	Spring	11.76	57.2	39.5	0.085	
13		0.59	4.43	0.66	0.13	Spring	2.61	72.8	70.7	0.035	
14		0.11	0.40	0.66	0.28	Spring	26.34	56.4	13.2	0.035	
15	4	0.14	0.73	0.54	0.19	Spring	1.75	64.5	16.8	0.2	32
16		0.11	5.03	0.24	0.02	Spring	0.84	8.9	13.2	0.011	
17		0.39	2.65	0.96	0.15	Spring	1.09	67.1	46.7	0.031	
18		0.81	3.38	1.26	0.24	Summer	1.40	23	97.0	0.04	
19		0.31	4.75	0.72	0.07	Summer	0.74	29	37.1	0.011	
20		0.18	5.87	0.42	0.03	Summer	2.76	27.9	21.6	0.033	
21		0.22	6.13	0.60	0.04	Summer	0.43	16.3	26.4	0.008	
22	5	0.78	14.10	0.72	0.06	Summer	3.56	102	93.4	0.039	31
23		0.51	2.55	1.62	0.20	Summer	6.01	61.4	61.1	0.034	
24		0.31	3.48	0.24	0.09	Summer	3.15	21.7	37.1	0.006	
25		0.64	0.35	2.10	1.83	Summer	1.48	49.5	76.7	0.072	
26		0.38	3.35	0.60	0.11	Summer	1.04	28.3	45.5	0.023	

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
27		0.13	2.32	0.42	0.06	Summer	3.41	13.1	15.6	0.012	
28		0.22	4.25	0.30	0.05	Summer	5.50	19.3	26.4	0.009	
29		0.44	0.47	0.90	0.94	Summer	1.63	30.5	52.7	0.035	
30	6	0.76	9.10	1.68	0.08	Summer	10.40	61.9	91.0	0.087	53
31	7	0.21	9.97	0.72	0.02	Summer	0.34	16.9	25.2	0.018	25
32		0.78	7.08	1.56	0.11	Summer	6.71	67.5	93.4	0.05	
33	8	0.32	8.40	0.90	0.04	Summer	10.65	26.8	38.3	0.029	21
34	9	0.21	4.92	0.36	0.04	Summer	13.11	31.6	25.2	0.006	39
35	10	0.31	2.27	1.02	0.14	Summer	2.22	24.1	37.1	0.026	37
36	11	0.22	5.58	0.30	0.04	Summer	0.48	27.1	26.4	0.009	38
37	12	0.87	2.53	1.62	0.34	Fall	26.90	67.7	104.2	0.09	15
38		1.39	17.27	1.02	0.08	Fall	3.75	176.1	166.5	0.056	
39	13	0.42	9.88	1.02	0.04	Fall	1.66	36.3	50.3	0.059	34
40		0.12	2.63	0.66	0.05	Fall	3.94	15.1	14.4	0.032	
41	14	0.25	4.37	0.24	0.06	Fall	0.34	29.5	29.9	0.016	15
42	15	0.24	11.18	0.24	0.02	Fall	7.42	22.1	28.7	0.018	8
43		0.19	2.00	0.30	0.10	Fall	1.86	19.1	22.8	0.001	
44		0.37	9.62	0.24	0.04	Fall	2.12	36.1	44.3	0.001	
45		0.33	10.65	0.30	0.03	Fall	1.99	33.2	39.5	0.003	
46		0.62	7.73	0.36	0.08	Fall	1.87	53	74.3	0.006	
47		0.28	7.42	0.36	0.04	Fall	0.87	26.9	33.5	0.004	
48		1.75	29.75	1.68	0.06	Fall	1.78	202.2	209.6	0.037	

Table C-7. Hydrologic and TSS data for SR-43.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1		0.52	3.73	0.30	0.14	Spring	N/A	195.2	236.0	0.036	
2		0.52	8.68	0.30	0.06	Spring	0.29	175.6	236.0	0.031	
3	1	0.77	8.72	1.56	0.09	Spring	1.56	305.7	349.4	0.32	126
4	2	1.25	28.70	0.42	0.04	Spring	2.78	405	567.2	0.027	21
5	3	0.42	27.60	0.24	0.02	Spring	0.26	159.6	190.6	0.008	27
6		0.48	5.82	0.30	0.08	Spring	4.18	182.9	217.8	0.051	
7		0.13	4.87	0.30	0.03	Spring	2.48	30.8	59.0	0.028	
8	4	0.59	6.82	1.02	0.09	Spring	5.51	246.7	267.7	0.14	73
9	5	0.53	5.82	1.26	0.09	Spring	1.56	258.5	240.5	0.237	71
10		0.25	7.78	0.30	0.03	Spring	2.89	39.1	113.4	0.036	
11		0.84	15.60	0.42	0.05	Spring	0.44	364.8	381.2	0.064	
12		0.14	1.95	0.24	0.07	Spring	1.15	59.4	63.5	0.015	
13		0.49	4.50	1.86	0.11	Spring	1.65	194.9	222.3	0.29	
14		0.15	3.40	0.42	0.04	Spring	6.51	36	68.1	0.064	
15		0.27	6.92	0.90	0.04	Spring	5.25	107.4	122.5	0.16	
16		0.49	14.10	1.98	0.03	Spring	8.32	169.8	222.3	0.29	
17	6	1.15	9.12	0.96	0.13	Summer	4.12	419.6	521.8	0.16	20
18		0.26	1.52	1.14	0.17	Summer	6.62	109	118.0	0.48	
19		1.45	9.48	1.56	0.15	Summer	0.46	522.5	657.9	0.56	
20		0.27	0.97	0.60	0.28	Summer	6.16	109.4	122.5	0.098	
21		0.6	9.27	0.72	0.06	Summer	2.96	256.4	272.3	0.155	
22		0.19	0.93	0.60	0.20	Summer	0.29	56.8	86.2	0.126	
23		0.15	2.53	0.24	0.06	Summer	1.18	49.5	68.1	0.035	
24		0.45	8.83	0.24	0.05	Summer	0.85	238.5	204.2	0.049	
25		0.16	2.30	0.30	0.07	Summer	8.78	75	72.6	0.152	
26	7	0.24	8.35	0.66	0.03	Summer	12.85	73.6	108.9	0.15	14
27	8	0.9	1.88	1.14	0.48	Summer	2.08	397.2	408.4	0.125	19

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28		0.33	1.70	1.08	0.19	Summer	10.91	NA	NA	NA	
29	9	0.36	0.47	1.02	0.77	Summer	18.23	116.6	163.4	0.29	24
30		0.1	12.52	0.30	0.01	Summer	10.59	NA	NA	NA	
31		0.52	8.75	0.72	0.06	Summer	1.95	138.2	236.0	0.087	
32		0.23	4.62	0.30	0.05	Summer	2.40	71.4	104.4	0.012	
33		0.12	3.68	0.42	0.03	Fall	21.73	24.9	54.5	0.036	
34		0.24	2.33	0.60	0.10	Fall	8.24	109.7	108.9	0.158	
35		1.54	13.40	1.20	0.11	Fall	0.61	498.8	698.8	0.241	
36		0.11	4.72	0.30	0.02	Fall	1.89	31.7	49.9	0.027	
37	10	0.49	14.78	0.30	0.03	Fall	12.18	219.6	222.3	0.152	31
38	11	0.15	7.35	0.30	0.02	Fall	4.06	41.6	68.1	0.024	23
39		0.15	3.52	0.24	0.04	Fall	2.06	53.3	68.1	0.018	
40	12	0.59	14.02	0.24	0.04	Fall	1.81	235	267.7	0.098	17
41	13	0.22	3.07	0.24	0.07	Fall	1.03	130.6	99.8	0.161	13
42	14	1.17	27.40	2.34	0.04	Fall	2.11	418.9	530.9	0.375	26
43		0.18	5.93	0.24	0.03	Fall	6.45	NA	NA	NA	

Table C-8. Hydrologic and TSS data for SR-59.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1	1	0.5	3.97	0.30	0.13	Spring	N/A	865	599.0	0.17	23
2	2	0.46	7.18	0.24	0.06	Spring	0.27	924.7	551.0	0.125	23
3	3	0.81	7.53	1.74	0.11	Spring	1.68	1272	970.3	1.1	44
4	4	1.01	25.42	0.24	0.04	Spring	2.80	809.6	1209.9	0.1	21
5	5	0.44	18.27	0.24	0.02	Spring	0.73	118.9	527.1	0.016	12
6		0.32	5.08	0.24	0.06	Spring	4.26	385.6	383.3	0.095	
7	6	0.49	6.62	0.42	0.07	Spring	8.19	342.5	587.0	0.151	103
8		0.63	2.65	1.20	0.24	Spring	1.59	463	754.7	0.409	
9		1.68	38.58	0.84	0.04	Spring	3.00	2618	2012.5	0.456	
10		0.51	8.72	1.26	0.06	Spring	2.68	671	610.9	0.401	
11		0.25	7.52	0.78	0.03	Spring	6.16	283.4	299.5	0.181	
12		0.17	8.45	0.30	0.02	Spring	5.23	191.6	203.6	0.115	
13	7	0.5	10.82	1.62	0.05	Spring	8.27	518	599.0	0.83	22
14	8	0.97	9.70	0.60	0.10	Summer	4.26	1180	1162.0	0.202	28
15		0.23	0.65	1.68	0.35	Summer	6.17	343	275.5	0.81	
16		0.15	0.40	0.54	0.38	Summer	0.40	162	179.7	0.3	
17		1.22	9.80	1.32	0.12	Summer	0.51	2141	1461.4	0.87	
18		0.3	1.10	0.90	0.27	Summer	6.14	205.7	359.4	0.095	
19		0.48	8.45	0.48	0.06	Summer	2.97	355.9	575.0	0.431	
20		0.35	1.68	0.78	0.21	Summer	0.32	364	419.3	0.31	
21	9	0.56	0.18	2.64	3.05	Summer	0.60	604.4	670.8	1.199	20
22	10	0.46	3.88	0.30	0.12	Summer	1.49	465.2	551.0	0.071	14
23		0.17	2.27	0.30	0.08	Summer	8.98	68.9	203.6	0.029	
24		0.1	0.30	0.66	0.33	Summer	1.92	43.5	119.8	0.057	
25		0.25	8.25	0.96	0.03	Summer	10.92	137.8	299.5	0.275	
26	11	0.9	1.88	1.14	0.48	Summer	2.08	1008	1078.1	0.62	26
27	12	0.33	1.70	1.08	0.19	Summer	10.91	162	395.3	0.236	44

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28		0.26	0.53	0.84	0.49	Summer	5.09	123.9	311.5	0.079	
29	13	0.4	5.60	0.42	0.07	Summer	13.10	271.3	479.2	0.047	13
30		0.27	7.73	0.42	0.03	Summer	2.50	165.5	323.4	0.04	
31		0.12	4.58	0.30	0.03	Fall	28.36	71.1	143.7	0.01	
32		0.22	2.40	0.54	0.09	Fall	1.44	123	263.5	0.117	
33		0.96	13.95	0.54	0.07	Fall	0.61	1024.8	1150.0	0.31	
34	14	0.5	14.37	0.42	0.03	Fall	14.24	531	599.0	0.095	24
35		0.14	7.38	0.24	0.02	Fall	4.07	53.0	167.7	0.001	
36		0.18	3.63	0.24	0.05	Fall	2.06	66.4	215.6	0.001	
37		0.62	15.87	0.24	0.04	Fall	1.81	576.4	742.7	0.08	
38		0.61	2.72	0.90	0.22	Fall	0.93	692.3	730.7	0.291	
39		0.24	8.62	0.54	0.03	Fall	1.91	114.6	287.5	0.098	
40		1.02	14.92	0.84	0.07	Fall	0.28	1002.6	1221.9	0.515	
41		0.16	5.92	0.30	0.03	Fall	6.55	92.7	191.7	0.001	

Table C-9. Hydrologic and TSS data for SR-81.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1		0.34	0.92	1.38	0.37	Spring	N/A	27.4	145.6	0.12	
2		0.45	7.45	0.24	0.06	Spring	7.69	175	192.8	0.031	
3		0.67	9.32	0.60	0.07	Spring	0.31	229	287.0	0.095	
4		0.33	0.72	0.84	0.46	Spring	0.43	116	141.4	0.146	
5		0.26	0.17	1.20	1.56	Spring	0.65	96.6	111.4	0.23	
6		0.35	6.67	0.30	0.05	Spring	1.31	138.5	149.9	0.051	
7		2.86	41.58	0.30	0.07	Spring	1.75	1107	1225.1	0.046	
8		0.7	2.33	0.72	0.30	Spring	5.22	222	299.8	0.092	
9	1	0.67	7.10	1.14	0.09	Spring	8.29	419.6	287.0	0.23	47
10		0.2	1.00	1.98	0.68	Spring	0.86	102.3	85.7	0.243	
11		0.15	8.25	0.24	0.02	Spring	0.37	20	64.3	0.019	
12	2	0.38	9.93	0.30	0.04	Spring	3.68	168	162.8	0.141	20
13	3	1.2	5.00	1.92	0.24	Spring	1.45	561	514.0	0.276	6
14		0.71	4.18	2.40	0.17	Spring	1.64	372	304.1	0.227	
15	4	0.15	NA	NA	NA	Spring	7.12	90	64.3	0.553	49
16		0.1	2.42	0.30	0.04	Spring	8.60	3	42.8	0.004	
17		0.11	0.93	0.24	0.12	Spring	0.45	24.2	47.1	0.023	
18		0.11	0.18	0.66	0.60	Spring	0.63	36	47.1	0.091	
19		0.37	1.10	1.20	0.34	Spring	1.82	112.5	158.5	0.23	
20		0.25	6.87	0.24	0.04	Spring	1.16	72.5	107.1	0.014	
21	5	0.43	2.00	0.84	0.22	Spring	0.32	146	184.2	0.154	55
22		0.16	8.25	0.24	0.02	Spring	0.91	25	68.5	0.033	
23		0.11	1.53	0.30	0.07	Spring	0.98	28.8	47.1	0.049	
24		0.99	12.73	0.96	0.08	Summer	2.20	545	424.1	0.201	
25		0.24	2.35	0.42	0.10	Summer	6.04	123	102.8	0.056	
26		0.16	1.48	0.54	0.11	Summer	0.32	80.5	68.5	0.035	
27	6	1.82	4.95	1.50	0.37	Summer	0.56	702	779.6	0.311	37

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28	7	0.89	6.48	1.62	0.14	Summer	6.52	197	381.2	0.108	2.5
29		1.09	9.48	2.76	0.11	Summer	2.43	509	466.9	0.378	
30		0.98	3.82	1.32	0.26	Summer	0.32	399	419.8	0.252	
31		0.8	6.65	1.74	0.12	Summer	1.99	272	342.7	0.41	
32		1.07	1.78	1.32	0.60	Summer	3.45	142	458.3	0.284	
33	8	1.89	6.48	1.74	0.29	Summer	5.28	703	809.6	0.351	10
34		0.16	0.12	0.84	1.37	Summer	1.37	6.5	68.5	0.016	
35	9	0.13	0.57	0.42	0.23	Summer	3.90	67	55.7	0.21	312
36		0.14	0.88	0.66	0.16	Summer	7.16	31	60.0	0.052	
37		0.64	2.02	2.52	0.32	Summer	13.63	220	274.1	0.388	
38	10	0.53	4.35	0.60	0.12	Summer	11.12	338.2	227.0	0.199	122
39		0.25	1.93	1.56	0.13	Summer	6.93	50.5	107.1	0.231	
40		0.15	7.02	0.60	0.02	Summer	14.41	24.1	64.3	0.101	
41		0.14	4.88	0.30	0.03	Fall	14.70	31.9	60.0	0.027	
42	11	0.6	3.68	1.02	0.16	Fall	3.23	225.5	257.0	0.189	263
43		0.48	9.65	0.30	0.05	Fall	0.83	175.2	205.6	0.08	
44		0.16	4.98	0.42	0.03	Fall	1.90	46.9	68.5	0.106	
45	12	0.3	18.87	0.30	0.02	Fall	12.30	108.8	128.5	0.032	106
46		0.42	6.93	0.30	0.06	Fall	3.34	139.9	179.9	0.01	
47	13	0.67	4.67	0.30	0.14	Fall	4.79	265.1	287.0	0.047	63
48	14	0.64	3.58	1.50	0.18	Fall	3.28	243.7	274.1	0.226	161
49	15	1.39	14.23	1.62	0.10	Fall	0.25	416	595.4	0.311	117
50		0.46	19.53	0.24	0.02	Fall	6.47	102.4	197.0	0.013	
51		0.27	2.77	0.24	0.10	Fall	1.99	57.6	115.7	0.013	
52		2.79	22.15	1.26	0.13	Fall	2.37	878.4	1195.1	0.196	

Table C-10. Hydrologic and TSS data for SR-117.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1		0.39	5.68	0.24	0.07	Spring	N/A	90.3	92.0	0.019	
2		0.58	6.87	0.42	0.08	Spring	0.35	154.9	136.9	0.055	
3		0.16	2.33	0.42	0.07	Spring	0.52	33	37.8	0.057	
4		0.19	2.13	1.32	0.09	Spring	0.59	47.5	44.8	0.171	
5		0.15	2.25	0.42	0.07	Spring	0.43	28.1	35.4	0.037	
6		2.66	41.85	0.30	0.06	Spring	2.73	547	627.6	0.028	
7		0.54	2.33	0.54	0.23	Spring	5.21	112.5	127.4	0.058	
8	1	0.67	7.10	1.14	0.09	Spring	8.31	150.7	158.1	0.141	22
9	2	0.68	1.00	1.98	0.68	Spring	0.86	174	160.4	0.41	2.5
10		0.15	8.25	0.24	0.02	Spring	0.37	33.5	35.4	0.003	
11	3	0.38	9.93	0.30	0.04	Spring	3.72	80	89.7	0.039	12
12	4	1.2	5.00	1.92	0.24	Spring	1.45	274	283.1	0.195	8
13		0.71	4.18	2.40	0.17	Spring	1.65	133.8	167.5	0.189	
14	5	0.15	NA	NA	NA	Spring	7.14	37.5	35.4	0.071	31
15		0.15	0.15	0.72	1.00	Spring	7.54	21.6	35.4	0.05	
16		0.25	1.87	0.96	0.13	Spring	0.71	39.9	59.0	0.086	
17		0.15	0.47	0.48	0.32	Spring	1.10	21.2	35.4	0.025	
18		0.11	0.40	0.30	0.28	Spring	0.28	13.5	26.0	0.013	
19		0.27	2.62	0.24	0.10	Spring	2.89	43.3	63.7	0.013	
20		0.37	0.48	1.02	0.77	Spring	0.33	68.7	87.3	0.105	
21		1.36	14.75	0.72	0.09	Summer	4.53	256.5	320.9	0.077	
22		0.49	1.52	1.44	0.32	Summer	6.01	91.5	115.6	0.173	
23		0.15	1.30	0.54	0.12	Summer	0.31	26	35.4	0.029	
24		0.88	10.92	0.54	0.08	Summer	0.38	175.5	207.6	0.057	
25		0.89	6.48	1.62	0.14	Summer	6.46	149.8	210.0	0.159	
26		1.09	9.48	2.76	0.11	Summer	2.43	230.7	257.2	0.417	
27		0.98	3.82	1.32	0.26	Summer	0.32	177.8	231.2	0.142	

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28		0.8	6.65	1.74	0.12	Summer	2.03	147.9	188.8	0.191	
29		1.07	1.78	1.32	0.60	Summer	3.45	212.7	252.5	0.148	
30		1.89	6.48	1.74	0.29	Summer	5.28	367.2	445.9	0.203	
31		0.16	0.12	0.84	1.37	Summer	1.37	32	37.8	0.1	
32		0.13	0.57	0.42	0.23	Summer	3.90	NA	NA	NA	
33		0.14	0.88	0.66	0.16	Summer	7.16	19.4	33.0	0.04	
34		0.44	1.62	1.68	0.27	Summer	13.63	99.2	103.8	0.209	
35		0.15	0.10	0.72	1.50	Summer	4.00	22.6	35.4	0.092	
36	6	1.09	3.28	0.72	0.33	Summer	7.09	244.9	257.2	0.081	29
37	7	0.94	1.55	1.80	0.61	Summer	0.82	230.7	221.8	0.206	28
38		0.25	1.93	1.56	0.13	Summer	6.13	NA	NA	NA	
39		0.15	7.02	0.60	0.02	Summer	14.41	NA	NA	NA	
40	8	0.84	3.92	0.84	0.21	Fall	18.13	139.4	198.2	0.088	25
41		0.42	10.90	0.24	0.04	Fall	0.81	50	99.1	0.017	
42		0.42	27.27	0.30	0.02	Fall	14.20	37.6	99.1	0.009	
43	9	0.52	8.50	0.30	0.06	Fall	3.15	85.6	122.7	0.013	NA
44		0.83	4.48	0.30	0.19	Fall	4.73	156.3	195.8	0.024	
44	10	0.3	3.47	0.42	0.09	Fall	3.29	62.2	70.8	0.032	16
45	11	0.9	14.28	1.20	0.06	Fall	0.26	200	212.4	0.148	44
47	12	0.46	19.53	0.24	0.02	Fall	6.47	99.2	108.5	0.023	14
48		0.24	2.67	0.24	0.09	Fall	2.00	42.4	56.6	0.008	
49		2.84	22.48	1.32	0.13	Fall	2.37	493.7	670.1	0.467	
50		0.11	3.18	0.24	0.03	Fall	11.47	16.8	26.0	0.005	

Table C-11. Hydrologic and TSS data for US-20.

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
1		1.14	5.90	2.40	0.19	Spring	N/A	921	931.1	0.86	
2		0.11	0.18	0.78	0.60	Spring	0.41	63.6	89.8	0.152	
3		0.44	3.68	0.66	0.12	Spring	0.34	263	359.4	0.15	
4		0.18	8.82	0.24	0.02	Spring	7.84	120.7	147.0	0.03	
5		0.57	6.78	0.84	0.08	Spring	2.15	480.3	465.5	0.349	
6		0.1	6.20	0.24	0.02	Spring	0.74	79.2	81.7	0.028	
7	1	1.9	61.23	0.30	0.03	Spring	1.86	1073.8	1551.8	0.066	25
8		0.1	2.43	0.24	0.04	Spring	6.82	75.1	81.7	0.033	
9		0.11	0.68	0.42	0.16	Spring	2.47	64.6	89.8	0.083	
10	2	0.6	2.67	1.62	0.23	Spring	5.04	409.2	490.1	0.572	179
11		0.12	3.07	0.24	0.04	Spring	3.25	47.1	98.0	0.014	
12		1.15	18.68	0.24	0.06	Spring	0.31	566	939.3	0.037	
13		0.33	13.75	0.30	0.02	Spring	2.55	227	269.5	0.076	
14		0.11	0.40	0.66	0.28	Spring	18.79	66.0	89.8	0.23	
15		0.14	0.73	0.54	0.19	Spring	1.75	94.9	114.3	0.152	
16		0.11	5.03	0.24	0.02	Spring	0.84	63.5	89.8	0.031	
17		0.39	2.65	0.96	0.15	Spring	1.09	294	318.5	0.349	
18		0.81	3.38	1.26	0.24	Summer	1.40	539.0	661.6	0.45	
19		0.31	4.75	0.72	0.07	Summer	0.74	207.6	253.2	0.207	
20		0.18	5.87	0.42	0.03	Summer	2.76	125.2	147.0	0.127	
21		0.22	6.13	0.60	0.04	Summer	0.43	146.3	179.7	0.184	
22		0.78	14.10	0.72	0.06	Summer	3.56	596.0	637.1	0.273	
23		0.28	0.95	1.32	0.29	Summer	6.01	217.2	228.7	0.476	
24		0.4	1.95	0.30	0.21	Summer	3.21	279.7	326.7	0.087	
25	3	0.9	2.47	1.98	0.36	Summer	2.59	769	735.1	0.843	102
26	4	0.24	0.55	0.72	0.44	Summer	3.52	152.6	196.0	0.233	46
27	5	0.92	2.38	0.90	0.39	Summer	5.51	723	751.4	0.38	75

Event Number	Water Quality Event Number	Rainfall Depth (in)	Rainfall Duration (hrs)	Peak 5-Minute Rainfall Intensity (in/hr)	Average Rainfall Intensity (in/hr)	Season	Antecedent Dry Period (days)	Runoff Volume (cf)	Rainfall Volume (cf)	PSD Peak Flow Rate (cfs)	TSS Concentration (mg/L)
28	6	2	10.35	3.24	0.19	Summer	12.12	1598.0	1633.5	3.4	65
29		0.24	8.48	0.42	0.03	Summer	0.28	273.2	196.0	0.141	
30		0.26	0.72	0.54	0.36	Summer	2.16	288.4	212.4	0.266	
31		0.72	7.00	3.60	0.10	Summer	4.58	644.4	588.1	2.55	
32		0.26	1.43	1.08	0.18	Summer	5.89	216	212.4	0.416	
33	7	0.52	9.53	0.72	0.05	Summer	4.71	436	424.7	0.441	46
34	8	0.64	NA	NA	NA	Summer	6.52	503	522.7	0.088	25
35	9	0.29	5.03	0.60	0.06	Summer	6.37	173.6	236.9	0.181	29
36		0.24	8.93	0.42	0.03	Summer	1.34	147	196.0	0.121	
37		0.3	1.87	0.54	0.16	Summer	0.49	175	245.0	0.125	
38	10	1.14	7.90	1.26	0.14	Summer	0.47	875	931.1	0.499	26
39		0.56	1.22	0.54	0.46	Summer	11.42	603	457.4	0.254	
40	11	0.64	3.48	1.02	0.18	Fall	15.38	505.8	522.7	0.42	39
41	12	1.3	15.25	0.60	0.09	Fall	3.71	1101	1061.8	0.202	15
42	13	0.4	9.83	1.38	0.04	Fall	1.73	260	326.7	0.504	166
43		0.14	2.72	0.66	0.05	Fall	3.95	88.6	114.3	0.152	
44	14	0.19	10.87	0.24	0.02	Fall	7.95	116	155.2	0.09	32
45		0.15	11.37	0.30	0.01	Fall	1.77	78.1	122.5	0.033	
46		0.32	9.32	0.24	0.03	Fall	1.78	265.5	261.4	0.016	
47		0.22	8.15	0.24	0.03	Fall	0.76	127.6	179.7	0.016	
48		0.28	9.43	0.30	0.03	Fall	0.94	216.7	228.7	0.119	
49	15	0.76	6.97	0.84	0.11	Fall	1.94	448.8	620.7	0.239	36
50		0.32	8.65	0.42	0.04	Fall	0.73	304.2	261.4	0.107	
51	16	1.95	24.58	1.80	0.08	Fall	2.10	1530	1592.7	1.248	99