Stormwater Particle Size Distribution & Implications for BMP Effectiveness

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EVERGREEN
STORMH2O

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LEAD ENTITY

Erika Schaffer, Department of Natural Resources (DNR)

AUTHORS

Aimee Navickis-Brasch, PhD, PE, Evergreen StormH2O

Taylor Hoffman-Ballard, PE, Evergreen StormH2O

Mark Maurer, PE, PLA, Evergreen StormH2O

TECHNICAL ADVISORY COMMITTEE

Dana DeLeon, PE, City of Tacoma

Michael Henao, City of Pasco

Ani Jayakaran, PhD, PE, Washington State University

Carla Milesi, University of Washington

STORMWATER ACTION MONITORING COORDINATOR

Brandi Lubliner, Washington State Department of Ecology

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Chapter 1 Project Overview & Summary of Findings

1.1 Chapter Purpose

This chapter is intended to be an expanded executive summary that could be a standalone document providing a concise overview of the study and summary of the findings.

1.2 Project Background

Selecting a suitable stormwater best management practice (BMP) for a specific site is typically based on site constraints, receiving water body conditions, pollution-generating surfaces, approved BMP functions, and regulatory requirements for runoff treatment and flow control. However, not all pollutant sources are the same with respect to pollutant types and loads, and not all BMPs are as effective across a range of conditions. Specifically, particle size distribution (PSD) may vary depending on the basin characteristics, affecting the chemistry of stormwater runoff and, subsequently, the necessary treatment mechanisms to reduce and/or control the total pollutant load. In addition, BMP effectiveness as a function of PSD is typically not reported or even been tested for some BMPs, which makes selecting a BMP to target specific particle sizes challenging.

PSD is a required screening parameter for BMPs going through the Technology Assessment Protocol Ecology (TAPE) evaluation and has been required for stormwater studies and monitoring conducted per the Washington State Municipal Separate Storm Sewer System (MS4) Permits. The 2018 *TAPE Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies* (TAPE Manual) indicates that the reason PSD analysis is conducted is to determine whether the influent PSD to BMPs consists primarily of silt-sized particles (i.e., 3.9 to 62.5 μm), which are believed to be the highest concentration of particles in Washington State stormwater runoff (Ecology, 2018). As such, evaluating whether a BMP is effective at reducing silt-sized particles is critical to understanding whether this particle size can be reduced using available BMP options. However, a challenge in evaluating BMPs is that it can be difficult to find laboratories that can test for PSD using the methods defined in the TAPE Manual.

In the built environment, particle sizes transported in stormwater systems can range from a few micrometers to a few feet. Particle size refers to the effective particle diameter and PSD is the portion of particles in a specific size range. This document narrowly focuses on the particle sizes and PSD that are sampleable in stormwater runoff, which are classified as clay (<0.4 μm) to medium and coarse gravel (>1000 μm) as defined by the Wentworth scale (USGS, A scale of grade and class terms for clastic sediments, 1922). Considering the narrow focus on a small particle size range, most of the total mass of particles in stormwater are excluded. It is also important to note that the PSD data included in this document provides information about the physical size of particles and how particle size may influence stormwater chemistry; the composition of the particles in stormwater runoff is not discussed (e.g., mineral, plastic, organics, twigs, solid metals, etc.).

1.3 Study Goals and Objectives

The goal of this study was to evaluate how pollutant types and loads vary with particle size and summarize the pollutant removal mechanisms and effectiveness of a range of BMP types to develop guidance that could assist Permittees in selecting the most effective BMP for their site based on the anticipated PSD. The objectives that were completed to achieve this goal are as follows:

- Conduct a systematic review of available literature, databases, and regional reports on PSD and suspended sediment.
- Evaluate the different methods for measuring PSD to determine whether there are other methods that could achieve similar results to the method defined in the TAPE Manual.
- Synthesize, analyze, and evaluate available data to determine whether there are patterns or relationships that could be used to understand PSD influences that could inform BMP selection.
- Provide recommendations for incorporating the study findings into the current BMP selection process outlined in the Ecology Stormwater Manuals considering the respective PSD, contributing basin area, and discharge location.
- Identify data gaps and provide recommendations for future research.

1.4 Study Overview and Results

The information reviewed and data collected for this study were from journal articles, government reports, and databases that contain water quality data. These sources were identified by the research team, through online libraries, and Technical Advisory Committee (TAC). Journal articles were sought out for topics covered by each chapter (described below) and used to provide a synthesis of literature and PSD data. Government reports included documents and sources of data such as the National Urban Runoff Program (NURP) report, Phase I BMP and outfall monitoring reports, and TAPE study PSD water quality sample results. Databases from which PSD data were extracted include the International BMP Database and Highway Runoff Database. The PSD data collected from these sources were analyzed using basic statistics and summarized into tables and figures, which were used to assess whether any relationships or trends existed in the data.

The data and information collected from the literature review and synthesized in this document focused on the specific topics noted below. Also summarized are the reasons for including this information, and a summary of the findings, which are described in this section and organized by the chapter in which they appear in this document.

Chapter 2. Identify Methods for Measuring PSD

The purpose of the work described in this chapter was to review, compare, and summarize the common sampling practices and testing methods found in the literature for determining PSD, suspended sediment concentrations, and total suspended solids (TSS) were reviewed and compared. The results were used to assess the comparability and transferability of the data collected in the subsequent chapters before deciding whether to include the data in this study and to recommend testing methods that may be more readily available and result in similar measurements to the method defined in the TAPE Manual. This method is ASTM D3977-97, which is a modified version of ASTM 3977-97 Method B and Method C. The only differences between the TAPE method and ASTM D3977-97 Method B and Method C are the sieve sizes used in each test.

Findings: Using ASTM 3977-97 Method B with laser diffraction would likely result in comparable results to using the method defined in the TAPE Manual. In addition, there are laboratories accredited by

Ecology for testing both methods which would increase the number of options for getting PSD samples tested.

Chapter 3 – Characterize Sources of Particulates to Stormwater

The purpose of the work in this chapter was to identify how site-specific conditions (land use, zoning, etc.) could influence PSD and to use this information to guide the estimation of the pollutant loads and the selection of BMPs.

Findings: Insufficient basin condition data were reported in the literature to characterize PSD and sources in terms of basin conditions. Based on the literature review, sources of PSD to stormwater that were identified include automotive, local soil erosion products, and atmospheric deposition. The most transported sizes of particulates regardless of land use appear to be clay and silt sizes.

Chapter 4 – Identify the Influence of PSD on Stormwater Chemistry

The purpose of the work in this chapter was to identify what is known about the influence of PSD on stormwater chemistry to aid in understanding pollutant transport. The information collected for **Chapter 4** (and **Chapter 3**) was intended to be used to determine the effects of PSD on land-based pollutant loads and then develop weight factors for different basin conditions. The loads and weight factor would then be used to predict pollutant loading and select appropriate BMPs for a site.

Findings: It was not possible to estimate the effects of PSD on land-based pollutant loads because insufficient data were located for different land use types or other basin conditions. The literature reviewed generally focused on heavy metals, nutrients, and PAHs attached to particles, and indicated that pollutant concentrations are generally higher for finer (clay- and silt-sized) particles, but that the particle size associated with most pollutant loads may differ between monitoring sites, depending on basin conditions upstream of the site.

Chapter 5 – Identify Impacts of Particle Sizes on Receiving Waters.

The purpose of the work in this was to identify detrimental impacts of different particle sizes to receiving water bodies and identify what is known about the stormwater-related impacts on receiving water bodies based on specific ranges of particle sizes. This information would then have been used to guide the selection of BMPs based on discharge locations (e.g., infiltration vs. surface water bodies) and assess whether a threshold or categories of impact can be determined for surface waters.

Findings: No studies were located that focused on the specific impacts of PSD ranges on receiving water bodies; therefore, the intent of this chapter was not able to be met. Instead, the chapter provides a summary of the information that was located: a few studies reported PSD ranges in stormwater that were transported to and reached water bodies. Based on the data from these studies, targeting clay- and silt-sized particles may remove the highest amounts of metals, nutrients, and bacteria. As these particle sizes are already the target, it appears the current approach best benefits water bodies. Additional research is needed to confirm the findings from these studies.

Chapter 6 – Determine BMP Effectiveness as a Function of PSD

The purpose of the work in this chapter was to identify and report on structural, operational, and source control BMP effectiveness based on the range of particle sizes. This information was intended to be used to identify BMPs that are more effective at removing specific ranges of particles.

Findings: BMP studies with PSD data were located for nineteen structural BMPs and one operational BMP. Based on this data, most BMPs have the highest removal in the silt and fine sand sizes. The BMPs that removed the highest overall percentage of particles across the size ranges were proprietary BMPs (StormGarden Biofilter System and Kraken). Non-proprietary BMPs, which achieved greater than 50% removal for clay- and silt-sized particles included bioinfiltration swales and ponds, bioretention, and wet vaults. As some of the findings are based on only a few data points and there are other Ecology-approved BMPs for which data were not located, additional research is needed to confirm the findings and understand the performance of other BMPs in the Stormwater Management Manual for Western Washington (SWMMWW), especially operational and source control BMPs.

1.5 Conclusion and Recommendations for Future Research

Based on the information available, PSD concentration in stormwater runoff generally appears to be highest for the clay and silt size range. In addition, the other pollutants identified in this study generally appear to have the highest concentration in the clay to silt size range and in general are more likely to partition to particles this size. As such, using BMPs, such as those identified in **Chapter 6**, that can effectively remove this particle size could reduce higher concentrations of these pollutants. In addition, using ASTM 3977-97 Method B with laser diffraction is recommended as an alternative to the method defined in the TAPE Manual which would increase the number of options for getting PSD samples tested.

Chapter 7 was intended to provide recommendations for applying the study results. However, because insufficient data was found during this study, it was not possible to provide the planned recommendations. Instead **Table 7-1** was developed which provides a summary of the intended applications of the study findings organized by chapter along with the data gaps that need to be addressed to provide recommendations for applying the study results. In addition, several factors were identified during the study that could bias the PSD data and analysis presented in this study such as sample collection methods and locations (**Sections 3.4.3** and **3.4.4)** as well as the limited amount of data available in some size ranges. Recommendations for additional research needed to address the data gaps and potential data bias identified in this study which could provide the information necessary to make recommendations for applying the study results are as follows:

- **Testing Methods** – Using consistent PSD testing methods or methods that provide comparable measurements reported in consistent units would provide a more accurate analysis. In addition, further research is needed to determine whether the laser diffraction method can be correlated with the TAPE Method. If a correlation exists or could be established, then the laser diffraction method could be substituted for the TAPE Method or replace it. This could provide another option for measuring PSD.
- **Data needed to characterize PSD using common basin characteristics and to develop land-based pollutant loadings** – Collecting more data about the basin conditions such as average annual daily traffic (AADT), land use, and basin area when doing research or monitoring related

to PSD. This information could be used to determine where treatment for specific PSD ranges may be needed. Additionally, staff managing databases and conducting monitoring should be encouraged to request or collect more pollutant data in terms of particle size, and to study contaminants of emerging concern or pollutants besides metals and nutrients.

- **Research needed to develop thresholds of impact to water bodies** – Research is needed to understand how different particle sizes impact receiving waters. In addition, data are needed regarding concentrations of pollutants attached to specific particle sizes that reach water bodies, especially while suspended in the water column.
- **Data needed to select BMPs** – PSD data (influent and effluent) on Ecology-approved BMPs not included in the report, especially source and operational BMPs, need to be collected. Additional testing for BMPs that were identified in the report at different sites with different basin characteristics may provide a better understanding of the effectiveness of these BMPs.
- **Potential bias in PSD data reported –** Factors such as the type of automated samplers and diameter of the tubing used to collect samples as well as the site selected for testing may bias the PSD results, indicating higher concentrations in the smaller (clay and silt) particle size ranges than are actually occurring. More research should be done evaluating whether these factors bias the data and whether the bias matters.

Chapter 2 Identify Methods for Measuring PSD

2.1 Chapter Purpose

The purpose of the work described in this chapter was to review, compare, and summarize the common sampling practices and testing methods found in the literature for PSD and suspended sediment of total suspended solids (TSS). The information was used to assess the comparability and transferability of the data before deciding whether to include the data in this study and to recommend testing methods that may be more readily available than methods defined in the 2018 *TAPE Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies* (TAPE Manual) (Ecology, 2018).This included:

- Compare and contrast the methods reported in the literature to the PSD method referenced in the TAPE Manual: a modified Suspended Sediment Concentration Method following the American Society for Testing and Materials (ASTM) Method D3977-97 using wet sieve filtration (Method C) and glass fiber filtration (Method B).
- Develop a ranking system and rank the test methods compared to the TAPE testing method.
- Use ranking results to develop recommendations for future testing methods.

2.2 Particle Size Distribution Test Methods

A literature search was performed to identify articles that mentioned particle size distribution testing methods. Once the methods were identified, an additional literature search was conducted to collect information about each testing method. The testing methods identified are summarized in this section.

2.2.1 Modified SSC Method (TAPE Method)

The TAPE Manual specifies a modified version of ASTM Method D3977-97 to determine Suspended Sediment Concentration (SSC) using Methods B and C to determine the sand, silt, and clay concentrations of a sample. The modification is the inclusion of sieve sizes to determine the TSS concentration between 3.9 and 250 microns. The required PSD size fractions and their associated sieve sizes are summarized in Table 12 in the Tape Manual (and replicated in **Table 2-1**). Hereafter in this document, this method is referred to as the “TAPE Method”.

Table 2-1. Required PSD Size Categories for the Modified Suspended Sediment Concentration Method

Size Category[a,b] (µm)	Particle Description	Analysis Method [c]
>250	Medium sand and larger	Retained on a No. 60 sieve
62.5-250	Very fine to fine sand	Passing No. 60 sieve and retained on No. 230 sieve
3.9-62.5	Silt	Passing No. 230 sieve and retained on 4-5 µm glass fiber filter
<3.9	Clay	Passing 4-5 µm glass fiber filter and retained on 1 µm glass fiber filter

[a] Size categories are based on the Wentworth (1922) grade scale.

[b] Additional size categories may be added to the analysis if the proponent would like to acquire additional particle size distribution data.

[c] Sieve sizes are based on ASTM standard sieve sizes.

µm – microns

The TAPE Manual allows for some flexibility in the sizes that are analyzed. Specifically, the manual states, *"Further modification of the SSC method is allowed if additional size fractions are desired by the proponent for evaluating effects of particle size on pollutant removal. Analysis of additional sand fractions may be conducted by using two additional sieves (No. 125 and 500 microns) in the wet sieve filtration to differentiate between very fine and fine sand (125 microns, No. 120 sieve) and between medium and coarse sand (500 microns, No. 35 sieve). The analysis of the silt and clay fractions may also be conducted by laser diffraction to determine the percentages of coarse silt (62.5-31.25 microns), medium silt (31.25-15.6 microns), fine silt (15.6-7.8 microns), very fine silt (7.8-3.9 microns), and clay (<3.9 microns). These size categories are based on the Wentworth (1922) grade scale"* (Ecology, 2018).

2.2.2 Other Sieve Methods

In addition to the ASTM method, Clark reported that other sieve methods are widely used in the United States to measure solids concentrations in stormwater. These are: U.S. EPA TSS (160.2)/ISO (11923) and the SM TSS (2540D) method (Clark & Siu, 2008). These methods use a sub-sample of the original sample as opposed to the ASTM method. USGS reports that these testing methods can result in *"errors of load concentrations to several orders of magnitude"* (Goosens, 2008). However, these methods can be correlated with the ASTM results for a specific location if there are enough concurrent tests done using the two methods (Gray, 2006).

2.2.3 Sedimentation (Hydrometer Analysis)

The sedimentation method has long been the most common method used by soil scientists to determine particle size distribution. It uses sieving to remove the particles greater than 65 µm (sand-sized) and sedimentation for the fraction less than 65 µm (silt- and clay-sized). The sedimentation portion of the test employs Stokes Law and the density of water—as measured by the hydrometer—to calculate the percentage of silt and clay particles. The method breaks down the PSD in terms of mass for the sand, silt, and clay categories. This allows soil scientists to categorize the sample in the corresponding spot on the soil triangle.

An alternative sedimentation method uses a pipette instead of a hydrometer to determine particle sizes. The pipette is used to remove a sample of water from a predetermined depth of the water column, at specific times determined by Stokes Law, to target clay-sized particles. The sample is then dried and weighed to determine clay fractions.

2.2.4 Laser Diffraction

Laser diffraction (LD) shoots laser light through a sample and measures how the light is scattered to determine PSD.[1] It provides grain size data as a volume percentage (Goosens, 2008). LD is used extensively in manufacturing to check the particle sizes of powders or granular materials. It is very accurate at measuring spherical particles but is less accurate with irregularly shaped particles. LD uses cross-sectional averages to assign the particle size and tends to report larger particle sizes than other methods; thus, LD shifts the results to coarser fractions (Eshel, Levy, U., & SInger, 2004). (as compared to other methods). The TAPE Manual does allow LD to be used to determine silt and clay fractions.

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[1] See Goossens 2008 for a more in-depth explanation of how laser diffraction measures particle sizes.

2.2.5 Optical Method

There are two optical methods used to determine PSD: static and dynamic. The *static* method takes a photo of a sample and then a computer analyzes the particles to determine the size. The *dynamic* method uses a video camera to analyze particles moving by it in a stream of water or air (Goosens, 2008). These methods are generally fast and can analyze millions of particles quickly.

2.2.6 Electron Resistance (Impedance) Method

The electron resistance method, such as the Coulter Counter, measures the change in conductivity in a fluid as it passes through an aperture. Particle size is determined by running the test with different-sized apertures, much like the sieve method uses different-sized sieves. Aperture sizes are determined by the target particle size ranges specified by the client. As a nonconducting particle passes through the aperture, it changes the conductivity of the solution. These changes are read as pulses by the instrument, and the pulses determine the particle count.

2.3 Discussion

Each method of determining PSD has strengths and weaknesses, which can result in different measurements on the same sample. However, some results can be calibrated to other test methods to show similar results through a correction factor. The following is a discussion of the differences and similarities between the methods and the information is organized into categories that were also used to rank and compare the different testing methods. These categories include common quality assurance measures, such as detection limits and reproducibility, as well as other important considerations when selecting a testing method, such as time to perform the analysis, cost per test, and availability of the testing method. The information in this section is also summarized in **Table 2-2**.

2.3.1 Reproducibility

Reproducibility is the consistency and sensitivity between repeated measurements and an important criterion used in ranking test methods. According to Goossens (Goosens, 2008), LD instruments showed very high reproducibility, moderate reproducibility for the sedimentation techniques, and much lower reproducibility for the optical and impedance methods (Goosens, 2008). Goossens (2008) also looked at reproducibility as a function of grain size. The LD instruments had the best reproducibility in this respect. The reproducibility of wet sieve tests, such as ASTM D3977-97, was not discussed in the literature. However, the test method is assumed to be highly reproducible if done in an accredited laboratory.[2]

2.3.2 Time to Perform Analysis

Time to perform analysis is a factor discussed in the literature; however, it is not used in ranking the test methods in this analysis. The sedimentation method takes the longest time to perform. Since it relies on the settling time of very small particles, it can take from 6 to 24 hours or more to perform the test. A technician must read the hydrometer frequently at first, but the times between readings increase quickly to hours. The sieve method also can take a day or more, but the time to prepare the sample and perform the wet sieve tests is relatively short. The samples collected on the sieves must be

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[2] Sieve tests are done using defined sieve sizes and with clear instructions concerning the handling of the sieves, samples, and methods for performing the tests. Accredited labs undergo testing and certification by third party organizations to assure they are following the correct procedures for performing the test.

dried and weighed after that. Drying the samples is the time-consuming aspect of the test. LD, optical image, and electron resistance methods are the fastest. These tests can be performed in minutes. This, in combination with the small sample size needed, means that many runs can be done on a sample quickly. The results can be averaged to get the PSD for the entire sample.

2.3.3 Detection Limits

Detection limits vary by test methods and are an important consideration used in ranking them.

- **Sieve Method:** The sieve method relies on different-sized sieves to determine PSD. The detection limits for this method span a large range. This method separates particles into groups based on sieve sizes. The sieves are then dried and weighed to determine PSD.
- **Sedimentation Method:** The sedimentation method detection limits are wide and limited by the number of readings taken and the time allowed for settling. Since this method relies on sedimentation, the larger particles fall out quickly and the smallest particles fall out much more slowly. Also, the shape, orientation of the particle in the water, and density of the particle play a role in how fast it settles out. This affects the PSD curve and results in much coarser results than other methods.
- **LD Method:** TAPE allows the use of LD to determine the PSD of stormwater if the project proponent desires a finer breakdown in PSD than that provided by the TAPE Method. LD does an excellent job of analyzing particles ≤106 µm and produces a smoother PSD curve line than the sieve method because the user can set smaller virtual “buckets.” LD machines can have over 200 buckets as opposed to 8 with the sieve method.
- **Optical Method:** The optical method detection limits are similar to the LD method. As discussed below, repeatability between samples is the main difference between the optical method and LD.
- **Impedance Method:** The impedance method is similar to the sieve method in that different apertures are used to measure different-sized particles. Like the LD and optical methods, it is better at analyzing the fine fraction.

2.3.4 Cost Per Test

Cost per test is not used in the ranking table because we do not have enough information about real costs per test. There were no exact costs listed in the literature for these tests, just relative costs, and those costs usually pertain to the equipment needed to run the test. Sedimentation techniques have the least expensive equipment costs. All that is required for these tests is a mixing vessel for stirring the sample; a cylinder for settling; a hydrometer or pipette depending on the method; a stopwatch or other timer; and a logbook. Sieve methods are the next least expensive. They require the sieves, a drying oven, high precision lab scales, and logbook. The LD, optical, and electron impedance methods are the most expensive in terms of equipment costs. What is unclear in the literature is how much labor cost is needed to perform these tests. Since the sedimentation and sieve methods can take hours versus minutes for the other methods, the labor costs might offset the cost per test.

2.3.5 Availability of Testing

Availability of testing (accredited labs) was not used as a criterion for ranking the methods. To our knowledge, there are no labs accredited by the Washington State Department of Ecology (Ecology), or any other third-party certification entity, that perform ASTM Method D3977-97 Method D. However, Ecology does allow results from labs that can perform the test according to the methodology outlined in the TAPE Manual as long as the lab is accredited for soil and sediment analysis. Since there are labs accredited to perform ASTM Method D3977-97 Method B, TSS, and laser diffraction.

2.3.6 *Comparison of Sieve Methods*

A comparison of sieve methods is included here to clarify the differences between them. The U.S. EPA TSS (160.2) and ISO (11923) and the SM TSS (2540D) methods use a sub-sample of the original sample. Because they use a sub-sample, the United States Geological Survey (USGS), and others, argue that these methods may not capture the larger particle sizes in the original sample because they settle out while taking the sub-sample (Gray, 2006). Others argue that the smaller particle sizes are likely to be carried the farthest in stormwater flows and are therefore more important to categorize (Clark & Siu, 2008). Clark's research shows that the U.S. EPA TSS method and the SM TSS method report less TSS compared to methods that use the whole sample. However, Clark also points out that this may not be a problem if the interest is in TSS as opposed to SSC (Clark & Siu, 2008). The USGS says, *"The biased TSS data can result in errors in load computations of several orders of magnitude"* (Gray, 2006). The ASTM SSC method was statistically indistinguishable from the known concentrations in the control samples (Clark & Siu, 2008).

2.4 Recommendations

A summary of the comparison and ranking between the different methods is summarized in **Table 2-3**, with the scores defined in **Table 2-4**. As noted, the TAPE method had the highest ranking because it is the method approved by Ecology for determining SSC. ASTM D3977-97 Method B combined with the laser diffraction methods had the second highest ranking because Method B is the method used by TAPE, except with different sieve sizes, and laser diffraction methods are highly precise in the particle size ranges defined by TAPE. In addition, there are laboratories accredited by Ecology to perform both these tests making it easier to find labs that can perform the needed testing.

USGS uses ASTM Method D3977-97 Method B to determine SSC in water samples. Guo indicated that this method is the most accurate way to measure SSC because it uses a whole sample rather than a sub-sample like other methods (Guo, 2006). TAPE uses ASTM Method D3977-97 Methods B and C to determine the sand, silt, and clay concentrations of a sample. The modification to the standard is the inclusion of certain sieve sizes to determine the TSS concentration between 3.9 and 62.5 microns. This method is the preferred method for determining SSC because it has been used in a regulatory environment and is relatively inexpensive to perform (Gray, 2006). The SSC method is good at determining the total amount of sediment in a water sample but is limited in determining the PSD by the number of sieves used in the test. LD can group the particle size into more buckets and thus produce a smoother distribution. Using the ASTM method with the LD is likely to produce the best results for analyzing PSD in a given water sample. ASTM's SSC Method D3977-97 Method B used with LD would produce the most precise results because the larger particles would be accounted for with the ASTM sieve test and the LD would give a smoother representation of the fine fraction particles than using ASTM Method D3977-97 methods B and C alone. Using these two methods in combination would give results as good as, or better than, the TAPE method used alone.

USGS does report that SSC and TSS can be correlated at a given location; however, they estimate that it will take at least 30 concurrent samples to obtain the proper correlation (Gray, 2006). TSS testing is widely used and relatively inexpensive, so it might make sense to establish this correlation if the site is going to be tested frequently or over a long period of time.

As discussed at the start of the chapter, the information collected for each testing method was intended to be used to assess the usability of the data collected for the study. Many of the sources did not report the method used to analyze PSD; as such, the breakdown of the particle size ranges was used to assume which method was used. Sources that used or appeared to use (based on particle size ranges reported) ASTM D3977-97 were included for analysis. Other sources appeared to use a modified SSC method with an optical method, based on the higher number of particle size ranges reported; these data points were included and results in the particle size ranges were summed to match the particle size ranges for ASTM D3977-97 (unless they were the only study identified for a particular topic, pollutant, etc.). Sources that reported a particle size distribution based on one or two ranges were evaluated on a case-by-case basis, and they were included if one of the ranges fit or could be adjusted to fit into a particle size range defined by the ASTM D3977-97 method (e.g., concentration of particles smaller than 63 µm would have been included; concentration of particles greater than 63 µm would have been excluded, as it could not be broken down into particle size ranges that match the ranges in ASTM D3977-97).

2.5 Recommendations for Future Research

There were comparisons in the literature between sedimentation methods and optical methods, but none was found that compared sieve methods with LD or other optical methods. LD has advantages that include *“short time analysis (5–10 minutes per sample), high repeatability, small size sample needed (≤ 1 gram), and a wide range of size fractions into which the entire range of particle sizes can be divided”* . Further research is needed to determine whether LD PSD results correlate, or can be correlated with, the ASTM Method D3977-97 methods B and C. If a correlation exists or could be established, then the LD method could be substituted for ASTM Method D3977-97 methods B and C or replace it.

Table 2-2. PSD Test Method Comparison[1]

Method	Method Overview	Pros	Cons
Modified SSC Method – ASTM D3977-97 Methods B and C (Sieve Method)	Uses various sieves to determine the particle size distribution.	> Simple to perform > Sieve sizes are known and the particles on that sieve are in the size range between that sieve size and the one above it > Uses whole sample, not a sub-sample	> No known accredited labs > Time-consuming > Sieves used to measure very fine particles are very fragile > Fragile particles can be reduced to smaller particles during the sieving process, thus skewing results
Sedimentation (Hydrometer) Analysis	Uses a column of water and a hydrometer to measure change of water density over time. Stokes Law is used to determine the particle size settlement over time.	> Long history of use > Relatively inexpensive > Lab equipment is easy to obtain and inexpensive	> Uses sub-sample > Good for only fine-grained soils > Time consuming (observations can take over 24 hours) > Overestimates silt and clay fractions
Laser Diffraction	Uses the scatter pattern of laser light shot through a sample to determine particle sizes.	> Quick (5–10 minutes/sample) > Uses small samples > Repeatable > Wide range of fractions gives a smooth PSD curve	> High cost of LD equipment > Insufficient confidence in results due to relatively low number of LD analyses vs the hydrometer method
Optical Method	Uses a camera to record particles and a computer to analyze the image to determine particle sizes.	> Fast > Highly accurate for particles sizes greater than 1 µm	> High cost of equipment
Electron Resistance (Impedance)	Uses the changes in conductivity of a solution to measure the number of particles suspended in the solution. Particle size range is determined by using different aperture sizes.	> Fast > Highly accurate for particles sizes greater than 1 µm > Uses small sample aliquots	> Size is determined partially by the orientation of the particle as it passes through the aperture (i.e., size may not be truly represented if the particle is elongated)

1. The purpose of Table 2-2 is to determine whether the method is equivalent to TAPE guidance or, if it is not, how it compares. The goal is to analyze and recommend other methods that might be more readily available.

Table 2-3. Test Method Ranking

Test Method	Process Synopsis	Overall Score[1,2]	Repeatable Results	Detection Levels
Sieve Method Modified SSC Method (based on ASTM Method D3977-97) (TAPE method)	Modified to measure the concentration of four size categories: clay less than 3.9 microns; silt between 3.9 to 62.5 microns; very fine to fine sand between 62.5 and 250 microns; and medium to coarse sand greater than 250 microns (No. 60 sieve).	★★★	★★	★★★
Sieve Method ASTM SSC Method D3977-97B	Uses whole water sampling. Most accurate according to Guo (2006). Does not measure specifically 3.9 to 62.5 microns like the TAPE method; however, it is the method that TAPE modified.	★★	★★	★★
Sieve Method EPA's TSS Method 160.2	Sub-sample taken by pouring from the original bottle, though sub-sampling method not specified. Does not capture coarse particles as well. Correlates well with ASTM SSC Method for the 0–106 micron range.	★★	★★	★★
Sieve Method Standard TSS Method (a.k.a., APHA's TSS Method 2540 D)	Sub-sample taken using a pipette. Does not capture coarse particles as well. Correlates well with ASTM SSC Method for the 0–106 micron range.	★★	★★	★★
Laser Diffraction	Uses the scatter pattern of laser light shot through a sample to determine particle sizes.	★★	★★★	★★
Optical	Uses a camera to record particles and a computer to analyze the image to determine particle sizes.	★	★	★★
Sedimentation – Hydrometer	Uses a column of water and a hydrometer to measure change of water density over time. Stokes Law is used to determine the particle size settlement over time.	★	★	★
Electron Resistance (Impedance) Method	Uses the changes in conductivity of a solution to measure the number of particles suspended in the solution. Particle size range is determined by using different aperture sizes.	★	★	★

1. Table 2-3 shows the symbols and scoring criteria for Table 2-2. Not all criteria shown in Table 2-4 were used to score the test methods. The criteria were included here because the information might be useful for a project proponent to use in analyzing methods for a particular project.
2. Highlighted cells indicate the method is recommended based on the ranking results.

Table 2-4. Scoring Criteria Defined for Table 2-3

Criteria	Score	Rationale
Detection levels equivalent to ASTM Method D3977-97) (TAPE method)	★★★	TAPE Method
Detection levels between 3.9 to 62.5 microns	★★	Identified by TAPE as the range representative of Pacific Northwest stormwater
Detection levels 0–100 Microns	★	Captures the target range specified in TAPE, but not as finely
Repeatable results	★★★	High
	★★	Medium
	★	Low
The following criteria were not used to analyze the test method's validity, but could be used as criteria for determining which method(s) to use on a specific project.		
Cost	★★★	High
	★★	Medium
	★	Low
Accredited labs	Y/N	Yes, No
Lab Location	★★★	Within 100 miles
Lab Location	★	Greater than 100 miles
Shipping Costs	★★★	High
	★★	Medium
	★	Low

Chapter 3 Characterize Sources of Particulates to Stormwater

3.1 Chapter Purpose

The purpose of the work described in this chapter was to identify how site-specific conditions (e.g., land use, zoning) could influence PSD and use this information to guide the estimation of the pollutant loads and the selection of BMPs. Specifically:

- Identify what is known about the sources of suspended sediment particles that can become part of stormwater (atmospheric, windblown, erosion, land use, etc.), including the particle size range and common land uses where these sources are expected.
- Based on the information collected, characterize PSD using common Washington basin conditions (i.e., land use, basin area).

3.2 Literature Review Summary

3.2.1 Source Summary

Literature was reviewed related to sources of PSD and characterization of particle size range based on common Washington basin conditions. The specific data and information sought out in literature included typical PSD ranges present in the built environment (what is present before rainfall) and typical PSD ranges present in stormwater, as well as data that reported PSD with sources or contributing basin conditions (i.e., area, land use). Relevant sources that were identified were used either to develop the synthesis of literature (**Section 3.2.2**) and/or for data analysis (**Section 3.3**).

The identified literature included the following sources:

- **Journal articles** – Eighteen journal articles were initially identified. Of those identified, data were extracted from eleven and the synthesis of literature was developed from three of the articles. The other articles were eliminated because information related to PSD were not included in the article or data related to PSD in the built environment or stormwater could not be extracted from the sources.
- **Government reports** were collected and reviewed; they included TAPE studies, Phase I BMP monitoring and outfall studies, and effectiveness studies. Data were extracted for analysis from ten TAPE studies, two Phase I Permittee BMP monitoring studies, eight Phase I outfall studies, and two eastern Washington (EWA) effectiveness studies.
- **Databases** – Five databases were identified prior to starting the study that might contain PSD data: the National Urban Runoff Program (NURP), Federal Highway Administration Highway Runoff Database, the International BMP Database, National Stormwater Quality Database, and the P8 Model database. Of those, two were used in the study: the International BMP Database and the Federal Highway Administration Highway Runoff Database. The others were eliminated because they had either been previously incorporated into another database used for the study (e.g., the NURP data was incorporated into the National Stormwater Quality Database), they did not include PSD data, or they only included PSD data in terms of points on the distribution curve below which 10% (D10), 50% (D50), and 90% (D90) fall.

Data were extracted from a total of 48 studies to characterize sources of particles in stormwater to particle size. As the intent of the chapter was to identify how site-specific conditions could influence PSD, data reporting PSD concentrations existing due to a certain source or site-specific condition were desired. Data that could be extracted from journal articles for analysis were primarily PSD data associated with a specific land use or location (e.g., roadway, car park), instead of a specific source (e.g., atmospheric deposition). Databases and government reports reported land use, but not source, as its own category. As a result, determining the influence of site specific-conditions was limited. An overview of the studies and the data located is as follows:

- We had intended to look for common jurisdictional conditions identified in the Structural Stormwater Controls Science Review and Synthesis White Paper (Navickis-Brasch, et al., 2021); however, there were such limited data, we instead focused on what was available.
- Study locations were primarily in Washington State as well as Oregon, Alabama, California, Florida, Massachusetts, North Carolina, Texas, South Korea, Spain, Australia, and France.
- The journal articles all described field studies, with the majority of them focused on roadways in urban locations. Furthermore, four articles examined residential areas, three examined mixed-use areas, and two examined parking lots and industrial or commercial land uses.
- Results were reported using five different unit types, with the two most common units being mg/L and percent (%) PSD. Since the two most common unit types had the most data, only data with these units were included in the study.
- For some sources, the particle size ranges measured did not “line up” with most of the data; as such, they were not included in the study.

3.2.2 Synthesis of Literature

The literature identified in **Section 3.2.1** was also reviewed to understand sources of PSD to stormwater and characterize PSD using common basin conditions. Some of the literature that could not be used for data analysis was included in the synthesis because the content was relevant to this section. The following provides a synthesis of what was found.

The most studied sources of PSD in the literature were automotive, local soil erosion products, and atmospheric deposition (Pitt, B, Clark, & Williamson, 2005). The street surface dust and materials by weight are primarily composed of soil from erosion as well as motor vehicle emissions and wear. Aryal et al. (2010) reported that vehicle-related street dust is from pavement wear (37%), tire wear (37%), and abrasion of vehicle parts such as brakes and engines (18.5%), with the remaining attributed to settleable exhaust particles. Atmospheric deposition was reported to primarily consist of dust fall and precipitation (Pitt, B, Clark, & Williamson, 2005). Most of the dust fall in urban areas is due to resuspended particulate matter from roadways or wind erosion from vacant lots and, depending on land use, it likely contributes little of the load to stormwater discharges. The amount of sediment deposited by atmospheric deposition can be difficult to quantify because the transfer of particles between the source and the transport of particles downstream occurs constantly.

The distribution of sediment that was measured and reported in the studies was either in dry deposited road pavement particles or in stormwater runoff. Of the studies that researched sediment in dry deposited road pavement particles, two looked at ranges of particle sizes and found somewhat even distribution between sizes from <75 µm to >2,000 µm (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010). NURP and other studies summarized by Aryal et al. (2010), however, found most of particles were smaller than 100 µm (very fine sand), and that the median diameter of particulates was within the silt size range (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010). One study attempted to relate PSD to roadway classification, AADT, and underlying soil type; however, a significant difference was not observed in the D10, D50, and D90 sizes (Winston & Hunt, 2017). The one exception noted was for the presence of a permeable friction course (PFC) overlay, which reduced the D90 particle size. In stormwater runoff, finer particles were reported to make up most of the PSD. This was supported by Anta et al. (2006), who indicated particles in stormwater are typically transported in suspension and 90% of the particles are <100 µm on average. Most of the studies that researched PSD in stormwater appeared to focus on roadways, and they reported that the majority of particles transported by stormwater are silt-sized or smaller (Kayhanian, et al., 2012; Yun, Park, Kim, & Ko, 2010). However, several studies indicated that medium-to-coarse sand sizes and larger particles could comprise a significant portion of the total particulate load by mass from a (test) basin, even if the majority of the particle load by mass is composed of finer particles, and as such should be accounted for during sampling and analytical procedures (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010).

3.3 Data Analysis

Data collected from the sources identified in **Section 3.2** were summarized into tables and figures and analyzed using basic statistics. The intent was to collect data for particle size ranges and information about the basin conditions where the data was collected. However, there were only two consistently reported basin conditions, land use and basin areas, so only data associated with those studies are used in this report. The following provides an overview of the data analysis and presentation of data included in this section.

The particle size data available were compiled and grouped by land use and basin area in **Table 3-1** and **Table 3-2**. **Table 3-1** lists the arithmetic mean, geometric mean, and median concentrations of each specific particle size range (clay, silt, very fine to fine sand, medium to coarse sand, and very coarse sand and larger) for the land use types reported in the literature. All three were included because they provide a measure of the central value of the data. Median provides a measure of the central value even if a high number of non-detects are present in the dataset (Clary, Leisenring, Hobson, & Strecker, 2020) and the geometric mean provides a central value that is less sensitive to a few high concentrations (Hobbs, Lubliner, Kale, & Newell, 2015). Because datasets were combined to characterize sources of PSD and the resulting dataset per basin characteristic varies in the number of non-detects and skew, all three are included. **Table 3-1** also includes the sample size of each land use and units of measure for the particle size range to show the power of results.

Table 3-2 provides information about the basin areas reported for each land use type, broken down by the unit of measure for particle size ranges. Also included in the table is the overall sample size representing a land use that reported basin area, as well as minimum, maximum, and mean/median basin area for each land use. The minimum and maximum basin areas, along with the sample size for each area, are also reported to describe the spread/distribution of the available data.

Figure 3-1 and **Figure 3-2** are scatter plots of the basin areas compared to the concentrations of each particle size. The intent of including the scatter plots was to assess whether trends existed for PSD data relative to basin area.

Figure 3-3 through **Figure 3-12** plot the cumulative distribution function (CDF) curves for each particle size range. CDF curves illustrate the likelihood of any given sample concentration to occur in the population of a dataset by percentiles. The data reflected in the CDF curves were categorized by location of the study to compare trends in Washington to other locations. The TAC suggested that Washington data be separated from other states to see whether any differences in the results were found. This provides a comparison to assess whether there are differences in PSD ranges, particularly for silt-sized particles, which are believed to be the highest concentration of particles in Washington State stormwater runoff. As such, CDF curves were generated for each PSD range that include curves for all the data, Washington-only data, and other states' data.

3.4 Discussion

The following provides an overview of the results, which are organized by topic.

3.4.1 Basin Conditions

Characterizing PSD using basin conditions was limited due to a lack of data for basin conditions. Specifically, for land use data, only the following classifications were reported: commercial, roadway, residential, industrial, and mixed use. In addition, data reported in mg/L (**Figure 3-1**) did not include industrial and mixed use, which further limited the amount of available data. Almost all the studies were performed in urban areas so a comparison between urban and rural or developed and undeveloped could not be performed. Finally, AADT for roadway data was rarely reported, and no literature was found that reported infiltration, land availability, climate condition (with respect to PSD), receiving water body conditions (also with respect to PSD, see **Chapter 5**), or other basin characteristics.

3.4.2 Basin Areas

Basin area was reported for approximately 50% of the studies and land use was reported for approximately 95% of the studies. However, as shown in **Table 3-2**, there were only a few basin areas reported: for commercial land use, six basin areas were reported from seven studies, and for residential land use, six basin areas were reported from six studies. Furthermore, while about 60% of the data was from roadway land use, most of these studies did not report a basin area. Because of the limited basin area data, all the basin areas were combined for all land uses (as opposed to evaluating the basin area by land use). As shown in **Figure 3-1** and **Figure 3-2**, even with the data combined, no pattern was observed between basin area and PSD ranges.

3.4.3 Silt-Sized Particles

The highest concentration of PSD was measured for silt-sized particles (**Table 3-1**), which is consistent with the synthesis of literature in **Section 3.2.2**. However, when this information was shared with the TAC during a meeting, they suggested that the results could be skewed or an artifact of the sampling method. Specifically, samples collected using automated samplers, which have a fixed point for sample collection through a tube and the tube diameter could limit the size of particles that can be collected. Based on the TAC's comment, the research team did the following to assess this theory:

- All the sources were reviewed to determine how the samples were collected. It was found that while data from some of the sources were reported to have been collected using automated samplers ((Charters, Cochrane, & O'Sullivan, 2015)[referenced in **Chapter 6**]; (Anta, Peña, & Cagiao, 2006; Roger, Montrejaud-Vignoles, Andral, Herremans, & Fortune, 1997); PSD data from the TAPE program (Ecology, Varies); PSD data from Washington Phase I Permittee's Outfall Monitoring and BMP Monitoring (Hobbs, Lubliner, Kale, & Newell, 2015); and PSD data from Eastern Washington Phase II effectiveness studies (Spokane County, 2021; Spokane County, 2021)), for the other sources it was not reported.

- Other possible reasons for the higher concentration of silt-sized particles were considered and the following were identified:
    - There are a higher number of data points analyzed for the silt particle size range, particularly for roadway land use types, which may have skewed the central tendency (arithmetic mean, median, geometric mean) of silt concentrations.
    - Organizations conducting testing through the TAPE program want a site where the PSD predominantly falls between 3.9-62.5 µm. As such, the data from the TAPE program may skew concentrations in this range.
    - A manufacturer of automated samplers, that are commonly used to collect stormwater samples, was contacted, and asked if they knew of the maximum size of particles that could be collected using their sampler. They indicated that they were unaware of testing that had been conducted to determine the maximum size but in their professional opinion they did not think particles larger than medium sand size could be pumped through the sampler tubing and make it to the sample jar.
- As shown in **Figure 3-3** through **Figure 3-12**, CDF curves were generated for Washington-only data and data from other states. In comparing the curves, similar concentrations were observed for particle sizes <4 (clay), 62-250 (very fine to fine sand), and >1000 µm (coarse sand and larger). It is worth noting that the amount of data in the <4 and >1000 µm ranges was lower than the amount of data found for other ranges, which could skew the results. **Figure 3-3** through **Figure 3-12** also indicate that Washington data appears to have lower concentrations of silt-sized (8-62 µm) particles and higher concentrations of medium to coarse sand (250-1000 µm) particles. These results may be due to the high number of data points collected for roadway sites outside of Washington, especially for silt-sized particles (which comprise 40% of all the silt size data collected for the study). Additionally, Washington data comprises most of the data in the medium to coarse sand size range (greater than 60% of the data collected for medium to coarse sand for the study).

3.4.4 Sampler Bias

A literature review was conducted to find articles that addressed the issue of sampler bias. Horowitz (Horowitz, 2013) looked at water quality monitoring in rivers and streams and reported that sediment was vertically and horizontally distributed differently, with larger particles closer to the bottom of the water column and finer particles more uniformly distributed throughout the column. In response to the concerns about TSS and SSC, the United States Geological Survey developed a fully automated depth-integrated sampler arm (DISA) designed to collect water quality samples from multiple points in the water column (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010). This study shows that the DISA more accurately represents the SSC in a water column than a fixed-point sampler (such as the automated samplers previously mentioned). However, Roseen et al. (Roseen, Ballestero, Fowler, Guo, & Houlse, 2011) conducted a study comparing PSD measurements collected using a fixed-point sampler to large volume (total storm capture) sampling collected from 18 storm events over two years. No significant difference was observed between the D50 and midrange particle sizes (25-75 µm, silt size). However, the fixed-point sampler appears to overrepresent particles <25 µm (smaller silt size to clays) and underrepresent particles >75 µm (very fine sand and larger) from the total storm capture, which suggests that the measurements collected with the fixed-point sampler maybe biased for these particle size ranges (Roseen, Ballestero, Fowler, Guo, & Houlse, 2011). It appears that using the DISA system developed by the USGS may provide a more accurate representation of particle size distribution compared to fixed-point samplers. However, if the main concern is determining the D50 of a sample of water, then the fixed-point sampler appears sufficient.

3.5 Conclusion

Insufficient basin condition data were reported to characterize PSD in terms of typical Washington basin conditions. Based on the literature review, sources of PSD to stormwater that were identified include automotive, local soil erosion products, and atmospheric deposition. These sources were generally reported in studies focused on roadway surfaces, and PSD related to a land use-specific source (such as industrial or commercial) was less frequently reported. The PSD of dry sediment reported in the literature was well graded from clay to gravel sizes, with silt and clay being the most transported sizes in stormwater. For the data analysis, some land use and basin size data were reported with the PSD dataset, and a few sources reported AADT, but no other basin conditions were identified. The results of the data analysis indicated that the highest particle size distribution was observed in the silt size range for most land uses. This finding is consistent with the synthesis of literature in **Section 3.2.2**. However, when comparing the data collected in Washington to data collected from other states, Washington had smaller concentrations in the silt size range and higher concentrations of medium to coarse sand. These results may have been influenced by how samples were collected and the sample size, which was not the same for all PSD ranges. In addition, it is not known whether all the samples were collected using the same methods, which may have affected the results.

3.6 Recommendations and Future Research

Recommendations for future research identified during the literature review and data analysis include:

- **Sources of PSD** – Information related to sources of PSD was primarily reported in the form of a narrative and did not include data. Further, the only sources reported were from vehicle-related particles and atmospheric deposition. Additional research on the sources of dry particles on roadways and suspended in stormwater may provide insight for prioritization of where to locate BMPs.
- **Characterization of PSD** – It was not possible to characterize PSD based on basin conditions because of lack of data reported about basin conditions. Researchers should be encouraged to report more details about the basin conditions such as AADT, land use, and basin area. Additionally, larger range/wider distribution of basin areas are needed to assess whether trends exist between basin area and PSD.
- **Potential bias in PSD data reported** – Factors such as the type of automated samplers and diameter of the tubing used to collect samples as well as the site selected for testing may bias the PSD results, indicating higher concentrations in the smaller (clay and silt) particle size ranges. More research should be done evaluating whether these factors bias the data and whether the bias matters. For example, depth-integrated sampler arms that take samples from various locations in the water column could be evaluated and compared to fixed point automated samplers.

Table 3-1. Summary of Contributing Basin Conditions and Particle Size Distribution

Land Use	Units	Sample Size	<4 µm Clay n = 358			4-62 µm Silt n = 624			62-250 µm Very Fine to Fine Sand n = 519			250-1000 mm Medium to Coarse Sand n = 354			>1000 mm Very Coarse Sand and Larger n = 288		
		n	AM[1]	Median	GM[2]	AM[1]	Median	GM[2]	AM[1]	Median	GM[2]	AM[1]	Median	GM[2]	AM[1]	Median	GM[2]
Commercial	%	72	4.63	2.01	2.03	22.73	17.60	17.71	14.18	12.60	10.23	40.75	43.00	38.38	13.04	10.00	10.46
Commercial	mg/L	84	3.70	0.93	1.14	13.54	7.16	1.66	8.71	1.66	0.68	12.33	3.92	3.15	6.93	0.80	0.88
Residential	%	20	4.16	2.62	2.40	36.94	33.35	26.76	19.54	18.60	15.53	18.71	15.60	13.29	9.23	6.00	5.34
Residential	mg/L	61	13.91	6.94	6.44	12.24	2.11	0.43	0.55	0.02	0.03	3.61	2.47	1.38	3.18	1.73	1.06
Roadway	%	246	22.66	16.90	16.59	36.67	29.88	21.75	14.90	13.75	12.06	5.78	4.20	4.81	14.25	10.70	9.00
Roadway	mg/L	132	18.26	9.35	8.92	50.41	21.65	35.04	29.62	0.29	12.51	53.02	4.40	15.89	4.34	2.00	2.83
Industrial	%	2	10.40	10.40	9.93	73.85	73.85	73.60	4.40	4.40	4.38	4.40	4.40	4.37	1.95	1.95	1.95
Industrial	mg/L	0	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3
Mixed Use	%	2	Note 3	Note 3	Note 3	52.65	52.65	49.60	33.15	33.15	31.65	7.95	7.95	7.68	12.00	12.00	Note 3
Mixed Use	mg/L	0	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3
Overall	%	371	10.84	5.73	7.74	35.26	28.76	37.88	14.70	13.00	14.77	21.20	14.60	13.71	12.35	10.00	6.69
Overall	mg/L	277	12.69	5.50	5.50	30.96	11.02	12.38	16.05	0.02	4.41	28.38	3.30	6.80	4.38	1.72	1.59

1. Arithmetic mean (AM) or average is a commonly used measure of central tendency, and it is based on adding all the values and dividing by the number of samples.
2. Geometric mean (Hobbs, Lubliner, Kale, & Newell, 2015) takes the product of and finds the root of values. Geometric mean is anticipated to be a more accurate measure of mean for positively skewed data (when there are more values close to the average on the left side of the distribution, and/or more outliers are present on the right side of the distribution; an example is distribution of income).
3. Insufficient data were collected to calculate the means or median.

Table 3-2. Summary of Basin Area Values in Dataset

Land Use	Basin Areas Reported for % Units				Basin Areas Reported for mg/L Units			
	Overall n[2]	Min	Mean/Median	Max	Overall n[2]	Min	Mean/Median	Max
Commercial	32	1.30 n=24	10.01 / 1.30	152.00 n=1	84	0.20 n=11	0.29 / 0.20	0.41 n=19
Roadway	25	0.12 n=2	22.29 / 32.00	32.00 n=17	72	0.06 n=24	13.86 / 0.41	32.00 n=31
Residential	13	0.12 n=1	77.51 / 68.00	239.00 n=2	61	0.61 n=27	4.84 / 8.20	8.20 n=34
Industrial	2	137.00 n=2	137.00 / 137.00	137.00 n=2	0	Note 1	Note 1	Note 1
Mixed Use	2	2.27 n=1	69.09 / 69.09	135.9 n=1	0	Note 1	Note 1	Note 1
Undefined	29	0.41 n=2	0.45 / 0.45	0.45 n=27	0	Note 1	Note 1	Note 1

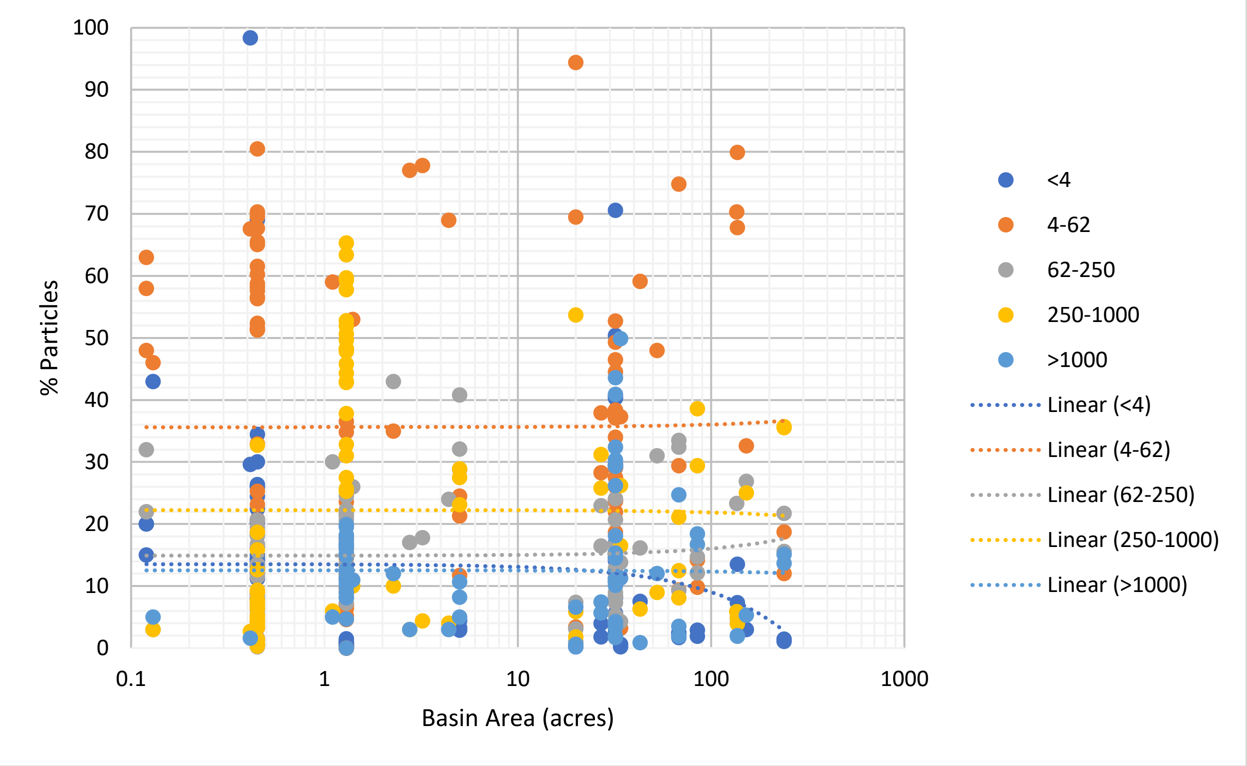


Figure 3-1. All Basin Area vs. PSD %

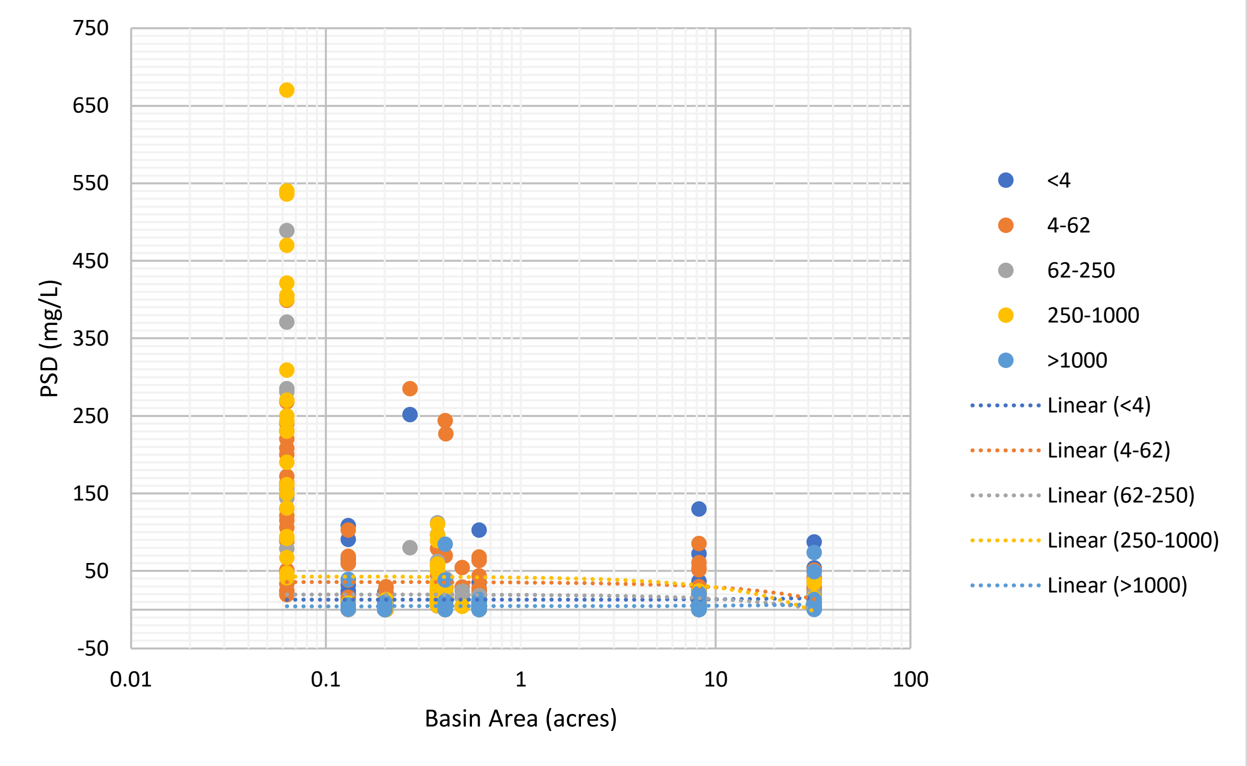


Figure 3-2. All Basin Area vs PSD (mg/L)

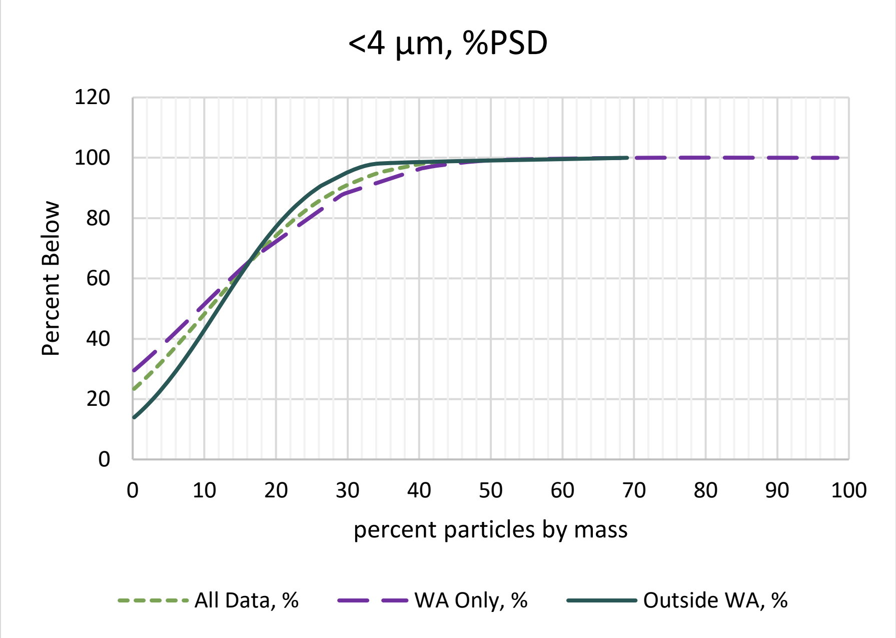


Figure 3-3. PSD % Cumulative Distribution Curves, <4 µm

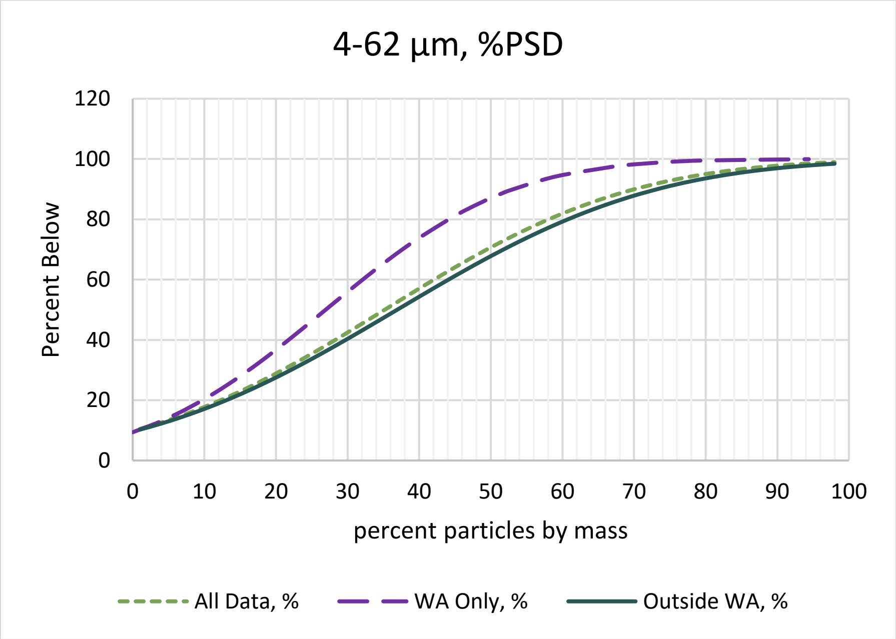


Figure 3-4. PSD % Cumulative Distribution Curves, <4-62 µm

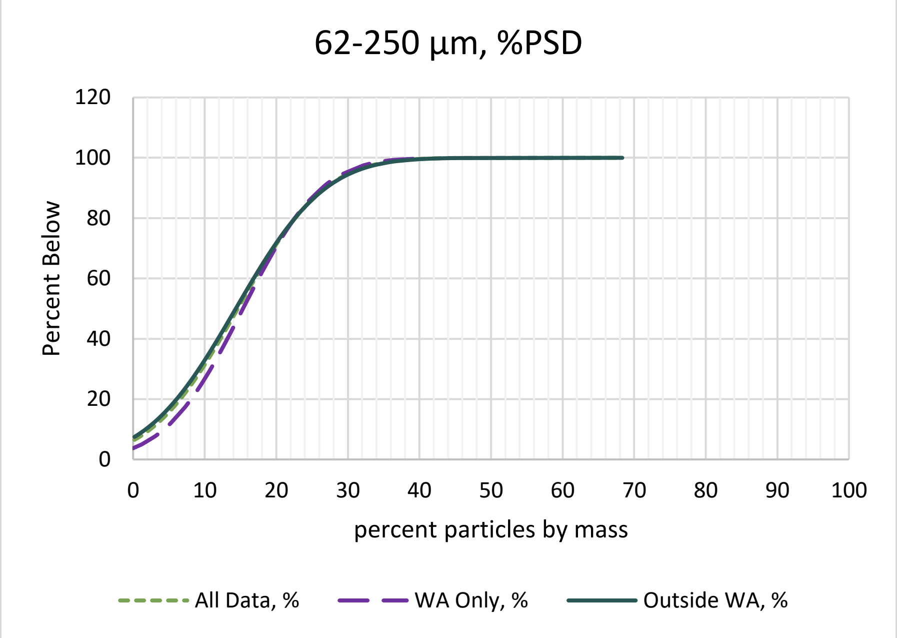


Figure 3-5. PSD % Cumulative Distribution Curves, <62-250 µm

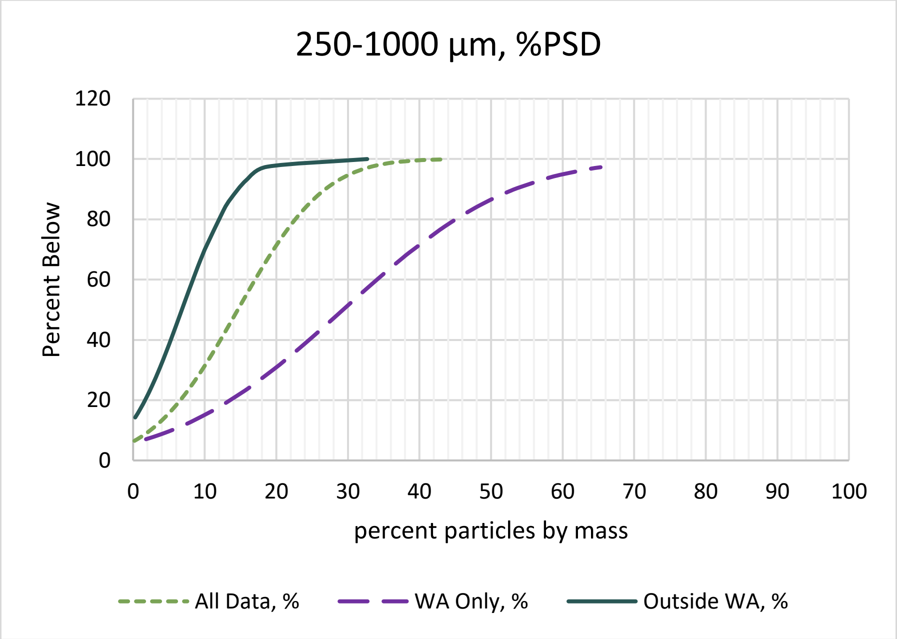


Figure 3-6. PSD % Cumulative Distribution Curves, <250-1000 µm

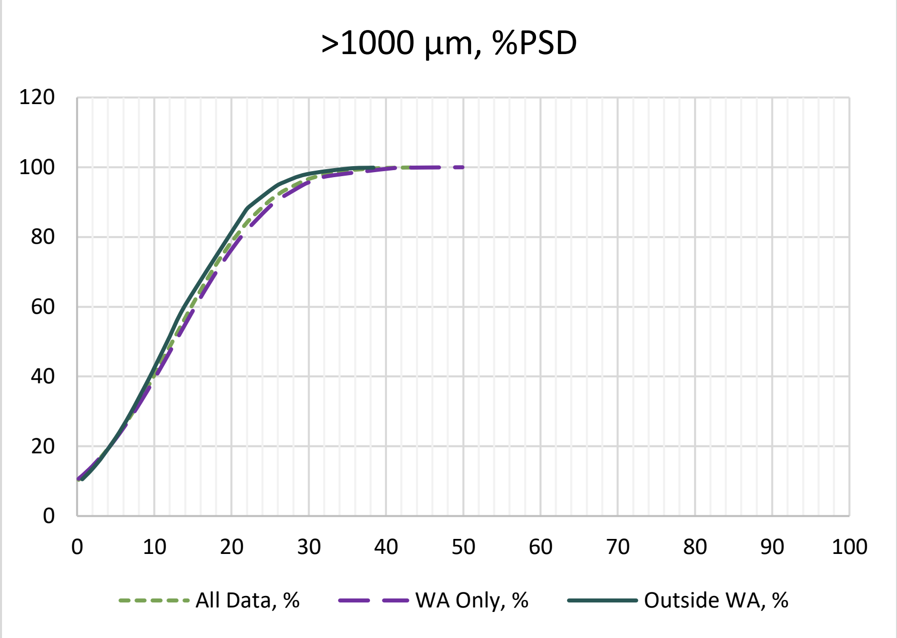


Figure 3-7. PSD % Cumulative Distribution Curves, <1000 µm

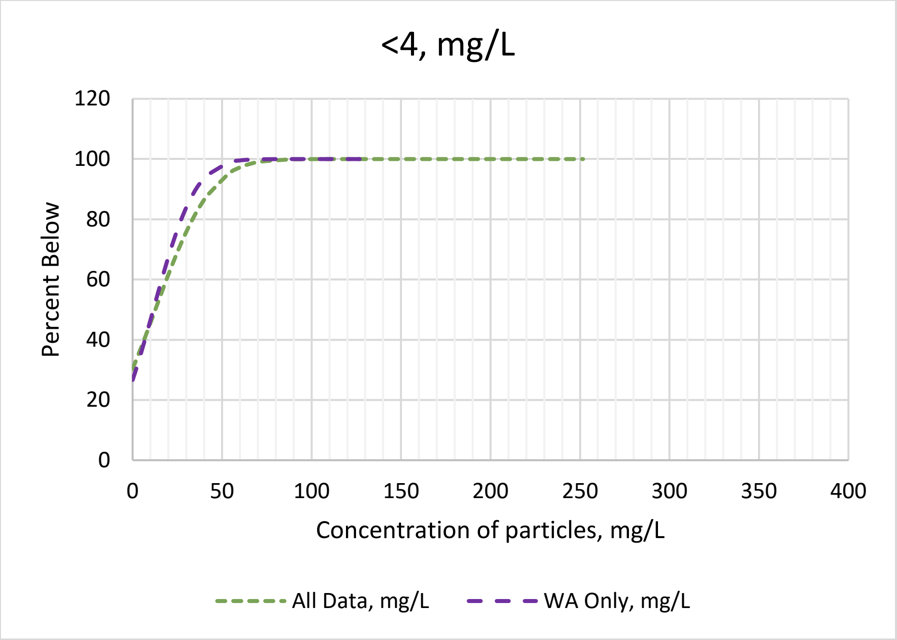


Figure 3-8. PSD mg/L Cumulative Distribution Curves, <4 µm

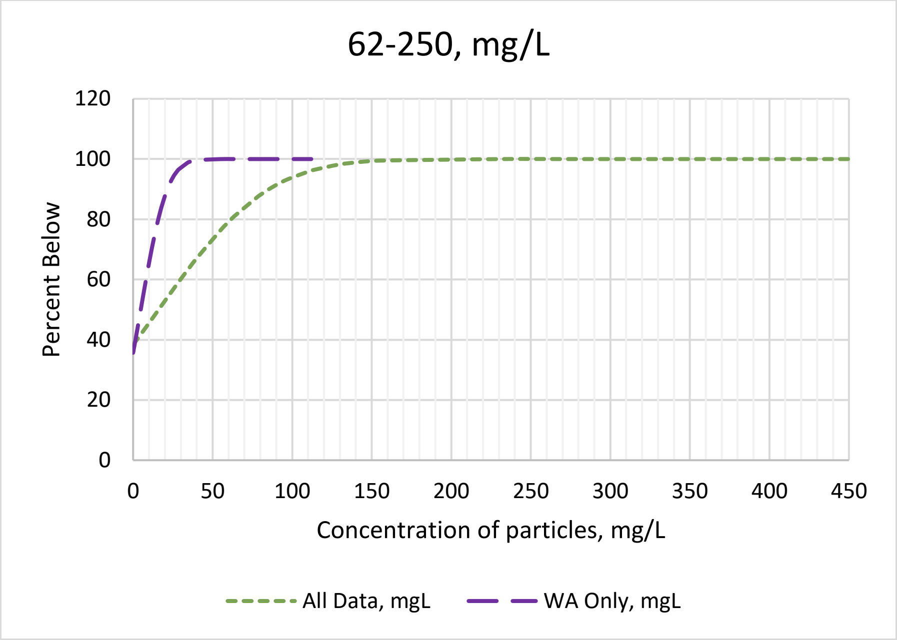


Figure 3-10. PSD mg/L Cumulative Distribution Curves, <62-250 µm

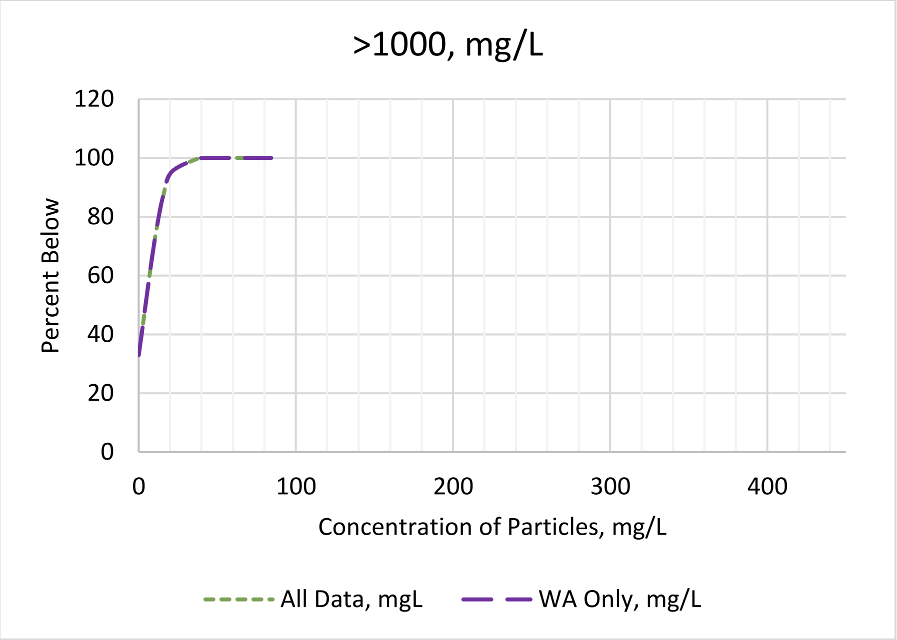


Figure 3-12. PSD mg/L Cumulative Distribution Curves, <1000 µm

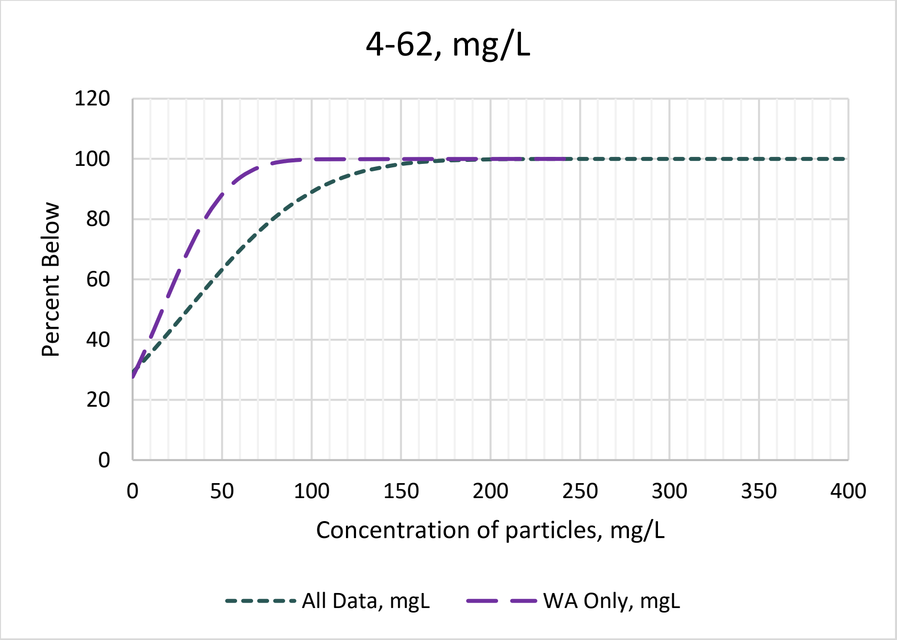


Figure 3-9. PSD mg/L Cumulative Distribution Curves, <4-62 µm

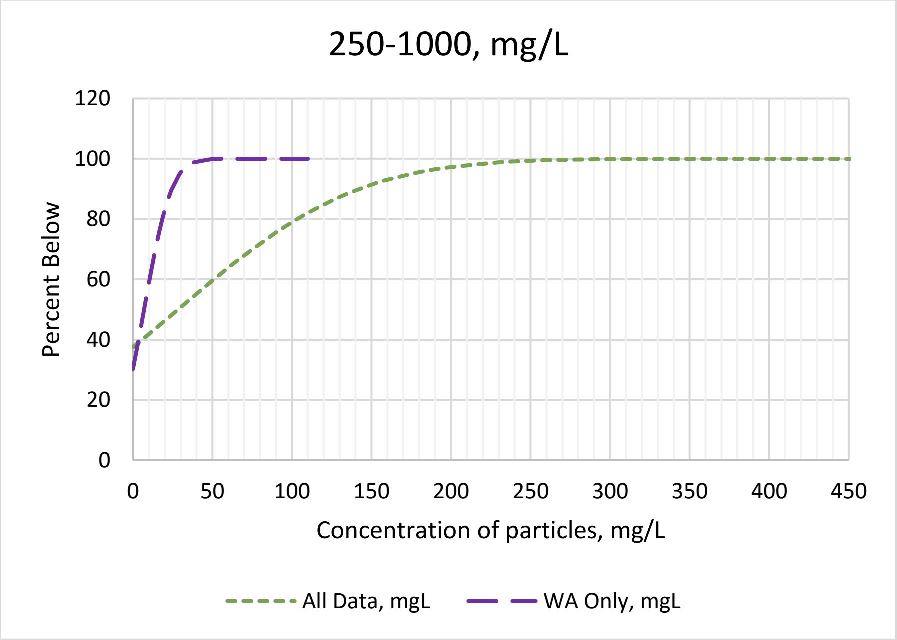


Figure 3-11. PSD mg/L Cumulative Distribution Curves, <250-1000 µm

Chapter 4 Identify Influence of PSD on Stormwater Chemistry

4.1 Chapter Purpose

The purpose of the work described in this chapter was to identify what is known about the influence of PSD on stormwater chemistry to aid in understanding pollutant transport. Specifically:

- Identify what is known about the influence of PSD on the speciation and mass of stormwater pollutants of concern and identify the treatment mechanism needed to remove the respective pollutants.
- Use the information collected, along with the information from **Chapter 3** (characterization of PSD to sources), to determine the effects of PSD on land-based pollutant loads. Based on the information and data collected, weight factors for different basin conditions may be developed to predict pollutant loading and select an appropriate BMP for a site.
- Provide guidance regarding how this information could be used in watershed plans and total daily maximum load (TMDL) studies, and for estimating BMP credits.

4.2 Literature Review Summary

4.2.1 Source Summary

A literature review was performed related to the influence of PSD on stormwater chemistry. Within the literature, what had been reported on this topic was reviewed (synthesis of literature) as well as data that could be analyzed to meet the purpose of the chapter. Sources were used for this report if they included either a synthesis of literature on the topic or data that could be extracted for analysis.

The literature review identified a total of 21 sources, which fell into the following categories:

- **Literature** – 20 journal articles were identified that appeared to provide relevant information. Of those identified, data were extracted from ten. The other articles were eliminated because data or syntheses of information related to the impact of PSD on stormwater chemistry were not able to be extracted, or because data were already presented in another article that was identified.
- **Government reports** – During a TAC Meeting, the TAC recommended reviewing the National Urban Runoff Program (NURP) reports. The NURP was established in 1978 to address uncertainties around the significance of urban runoff as a contributor to receiving water quality problems. The NURP report included information about stormwater chemistry and the performance and effectiveness of BMPs for reducing stormwater pollutants. However, the report did not contain PSD data and as such was not used for this report.
- **Stormwater databases** – No databases were identified that provided pollutant concentrations in terms of particle size (e.g., for particles in the silt size range, the zinc concentration was 720 µg/g). The only databases identified for the study that contained PSD data are listed in **Sections 3.2** and **6.2**.

An overview of the studies and the extracted data is as follows:

- Sources used were limited to journal articles.

- Study locations included Washington, Alabama, California, Wisconsin, Nevada, Illinois, Massachusetts, Colorado, New Hampshire, New York, Ohio, Texas, Canada, the Netherlands, Korea, Sweden, Norway, Australia, and China.
- Studies were mostly conducted on roadway surfaces. Other land use categories studied in the sources were industrial, commercial, residential, and mixed land use.
- Three different unit types were reported in the articles. As described in **Section 3.2.1**, data with the two most common units were included in this study: mg/L and percent (%) PSD.

4.2.2 Synthesis of Literature

The literature review was performed to understand the influence of PSD on stormwater chemistry. The pollutants studied in the sources identified were heavy metals, nutrients, and PAHs. The highest concentrations of all pollutants were generally partitioned in clay- and silt-sized particles. The following summarizes the data available in the literature related to the intent of this chapter.

Most of these studies focused on heavy metals, specifically, total metals. Most heavy metals are associated with clay- and silt-sized particles during pollutant buildup (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010; Boogaard, van de Ven, Langeveld, & van de Giesen, 2014; Ferreira & Stenstrom, 2013; German & Svensson, 2002; Pitt, B, Clark, & Williamson, 2005; Sansalone & Buchberger, 1997; Smith, Sorenson, & Granato, 2018); as well as during rain events (Pitt, Clark, Eppakayala, & Sileshi, 2017; Wang, et al., 2018; Wijesiri, Egodawatta, McGree, & Goonetilleke, 2016). There were a few exceptions to this noted in the literature. In industrial land uses, metals may be associated with larger particle sizes due to types of source material present (Pitt, Clark, Eppakayala, & Sileshi, 2017). Heavy metals attached to a particle can be replaced by other metals due to competitive adsorption (Wijesiri, Egodawatta, McGree, & Goonetilleke, 2016). As such, metals with lower relative mobility have a stronger affinity for particles (lowest to highest mobility: Cd, Zn, Pb, Mn, Ni, Cu, Cr). Other metals released into solution may bind to particle size fractions larger than 150 µm. Additionally, while the highest concentrations of metals were found in the finest particles, the proportion of fine and coarse particles varies. One study reported a higher load in coarse particles (Smith, Sorenson, & Granato, 2018), another study reported a higher load in smaller particles (Kayhanian, McKenzie, Leatherbarrow, & Young, 2012) and two studies acknowledged that different results have been reported regarding particle size (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010; Yun, Park, Kim, & Ko, 2010). The differences in the study results may be due to the type of impervious surface (i.e., roadway material) and adjacent land use (Winston & Hunt, 2017; Pitt, B, Clark, & Williamson, 2005).

Additional pollutants studied in the literature included nutrients and polyaromatic hydrocarbons (PAHs). High nutrient concentrations tended to be associated with silt or smaller-sized particles (Cha, Lee, Park, & Kim, 2013; Pitt, Clark, Eppakayala, & Sileshi, 2017; Smith, Sorenson, & Granato, 2018), though larger particles can have greater pollutant strengths for nutrients, since large particles (e.g., leaves) can contain more organic matter (Pitt, Clark, Eppakayala, & Sileshi, 2017). Variability in concentrations of nutrients and particle sizes between sites may be explained by time of concentration and the slope of pipes in the basin. Specifically, a shorter time of concentration means particles are less likely to be broken into smaller particles, and low-gradient drain pipes allow dense, larger particles to settle out instead of travelling downstream (Khan, Edward Beighley, VanHoven, & Watkins, 2021). PAHs appeared to be associated with fine and coarse particles (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010; Pitt, Clark, Eppakayala, & Sileshi, 2017). PAHs with high molecular weights attached to sediment more readily. Moreover, PAHs have high organic soil coefficients, which means they preferentially adsorb to organic matter. As a result, PAHs can attach to a range of particle sizes depending on the organic content of the particle.

4.3 Data Analysis

Data analysis was intended to be conducted to understand stormwater chemistry as a function of PSD. However, this analysis was not performed due to the small number of studies and corresponding data points. As mentioned in **Section 4.2.1**, data were extracted from only ten studies, which corresponded to roughly the same number of data points (n=11). The extracted data were organized into **Table 4-1** through **Table 4-3**. **Table 4-1** summarizes the available data related to metals, **Table 4-2** summarizes the data related to nutrients, and **Table 4-3** summarizes the data related to PAHs. The data are organized to show the average concentration of each parameter attached to different sediment particle sizes, for different land uses. However, because of the distribution of data among different land use and unit types, most of the land use types are only represented by 1–2 sources/data points. This especially applies to land use types other than roadway.

4.4 Discussion

An overview of the data and observations in the results is summarized below.

- Based on the limited data summarized in **Table 4-1**, the concentrations of copper, zinc, phosphorus, and nitrogen appear to be higher for smaller particle sizes (clay and silt sizes), regardless of land use. This could suggest that targeting removal of smaller solids could reduce higher concentrations of these pollutants.
- Nutrients were only reported for three land uses and limited particle size ranges. Data obtained indicates similar concentrations between residential, commercial, and industrial land use for phosphorus. For nitrogen, concentrations observed in residential land use are similar to those observed in commercial land use. However, this is only based upon one data point.
- PAHs were reported for roadway residential, commercial, and industrial land uses. The data shown reflect one study, which reported that the highest concentrations occur for silt- and very fine sand-sized particles (Herngren, Goonetilleke, Ayoko, & Mostert, 2010).

4.5 Conclusions

The effects of PSD on land-based pollutant loads were not able to be estimated, as insufficient data were in the literature located for different land use types or other basin conditions. The literature reviewed generally focused on heavy metals, nutrients, and PAHs attached to particles. It indicated that pollutant concentrations are generally higher for finer (clay- and silt-sized) particles, but that the particle size associated with the majority of pollutant loads may differ between monitoring sites, depending on basin conditions upstream of the site. For example, metals can attach to larger particles because of competitive adsorption between the metals occurring in the built environment. Larger organic particles could also contain high amounts of nutrients and PAHs due to the pollutants’ affinity for organic matter.

4.6 Recommendations for Future Research

Recommendations for future research identified during the literature review and data analysis include:

- **Limited data available for analysis** – Databases containing pollutant concentrations are readily available; however, pollutant concentration reported for a certain particle size was not. Limited data in this format were available from Washington State. If more data points reporting particle size distribution of pollutants were available, determining land-based pollutant loads might be more feasible.
- **Few commonly studied pollutants** – The literature appears to focus on only a few specific groups of pollutants when discussing pollutants adhered to particles. Additional studies related to pollutants of emerging concern may inform strategies for treatment of those pollutants.

Table 4-1. Summary of PSD and Metals Stormwater Chemistry

Land Use	Units	Total Copper						Total Zinc					
		<4 µm Clay	4-62 µm Silt	62-125 µm Very Fine Sand	125-250 µm Fine Sand	>250 µm Medium Sand & Larger	Number of Sources	<4 µm Clay	4-62 µm Silt	62-125 µm Very Fine Sand	125-250 µm Fine Sand	>250 µm Medium Sand & Larger	Number of Sources
Roadway	µg/g	-	720	250	218	508	4	-	1890	963	749	416	4
Residential	µg/g	420	110	162	-	-	1	680	293	460	-	-	1
Commercial	µg/g	220	130	-	-	-	1	1200	750	-	-	-	1
Industrial	µg/g	150	138	288	85	-	2	550	578	496	284	-	2
Roadway	µg/L	9	-	-	-	-	1	27	-	-	-	-	1
Residential	µg/L	-	-	-	-	-	0	-	-	-	-	-	0
Commercial	µg/L	-	-	-	-	-	0	-	-	-	-	-	0
Industrial	µg/L	-	-	-	-	-	0	-	-	-	-	-	0

Table 4-2. Summary of PSD and Nutrients Stormwater Chemistry

Land Use	Units	Phosphorus						Nitrogen					
		<4 µm Clay	4-62 µm Silt	62-125 µm Very Fine Sand	125-250 µm Fine Sand	>250 µm Medium Sand & Larger	Number of Sources	<4 µm Clay	4-62 µm Silt	62-125 µm Very Fine Sand	125-250 µm Fine Sand	>250 µm Medium Sand & Larger	Number of Sources
Roadway	ug/g	-	-	-	-	-	0	-	-	-	-	-	0
Residential	ug/g	710	817	620	-	-	1	3000	1645	1030	-	-	1
Commercial	ug/g	910	950	-	-	-	1	4300	720	-	-	-	1
Industrial	ug/g	-	-	670	-	-	1	-	-	560	-	-	1
Roadway	ug/L	-	-	-	-	-	0	-	-	-	-	-	0
Residential	ug/L	-	-	-	-	-	0	-	-	-	-	-	0
Commercial	ug/L	-	-	-	-	-	0	-	-	-	-	-	0
Industrial	ug/L	-	-	-	-	-	0	-	-	-	-	-	0

Table 4-3. Summary of PSD and PAHs (mg/kg) Stormwater Chemistry

PAH	<0.45			0.45-75			75-150			>150		
	Residential	Industrial	Commercial	Residential	Industrial	Commercial	Residential	Industrial	Commercial	Residential	Industrial	Commercial
Napthalene, NAP	0.05	0.07	0.13	0.94	1.91	5.18	1.01	1.77	1.58	0.93	0.71	0.99
Acenaphthylene, ACY	0.01	0.02	0.04	0.12	0.19	0.55	0.12	0.2	0.37	0.12	0.11	0.22
Acenaphthene, ACE	<0.01	0.02	0.02	0.07	0.28	0.21	0.13	0.22	0.11	0.07	0.05	0.08
Fluorene, FLU	<0.01	0.01	0.01	0.08	0.08	0.3	0.11	0.05	0.09	<0.01	0.03	0.07
Phenanthrene, PHE	<0.01	<0.01	0.02	0.12	0.12	0.55	0.16	0.06	0.23	<0.01	0.01	0.05
Anthracene, ANT	<0.01	<0.01	0.02	0.09	0.05	0.11	0.15	0.06	0.03	<0.01	<0.01	0.05
Fluoranthene, FLA	<0.01	0.01	0.03	0.18	0.17	0.36	0.2	0.09	0.16	0.18	0.08	0.11
Pyrene, PYR	<0.01	<0.01	0.01	0.14	0.2	0.32	0.17	0.07	0.07	0.15	0.07	0.14
Benzo[a]anthracene, BaA	<0.01	0.01	0.02	0.13	0.12	0.38	0.18	0.09	0.18	0.06	0.06	0.08
Chrysene, CHR	<0.01	<0.01	0.01	0.1	0.24	0.2	0.16	0.1	0.14	<0.01	0.07	0.1
Benzo[b]fluoranthene, BbF	<0.01	<0.01	0.01	0.12	0.07	0.39	<0.01	0.04	0.14	0.12	0.02	0.09
Benzo[a]pyrene, BaP	0.01	0.04	0.06	0.11	0.11	0.26	0.17	0.07	0.13	0.13	0.08	0.09
Indeno[1,2,3-cd]pyrene, IND	<0.01	<0.01	0.01	<0.01	0.02	0.09	<0.01	<0.01	0.03	<0.01	<0.01	0.07
Dibenzo[a,h]anthracene, DbA	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
Benzo[ghi]perylene, BgP	<0.01	0.01	0.01	<0.01	0.02	0.04	<0.01	0.02	0.03	<0.01	<0.01	<0.01

Note: Table 4-3 represents findings from one study. Cells highlighted gray indicate the highest concentration.

Chapter 5 Identify Impacts of Particle Sizes on Receiving Waters

5.1 Chapter Purpose

The purpose of the work described in this chapter was to identify detrimental impacts of different particle sizes to receiving water bodies and identify what is known about the stormwater-related impacts on receiving water bodies based on specific ranges of particle sizes. This information is intended to be used to guide the selection of BMPs based on discharge locations (e.g., infiltration vs. surface water bodies). Specifically:

- Use what is known about the stormwater-related impacts of PSD on receiving water bodies related to specific ranges of particle sizes to guide the selection of BMPs based on discharge locations.
- Use the information collected to assess whether a threshold or categories of impact can be determined for if/when there is a benefit to receiving waters for targeting removal of different PSDs and selecting BMPs based on PSD effectiveness. Based on the information available, qualitative categories of impact will be developed that identify species and/or conditions that are more sensitive (i.e., high, medium, low).
- Use the results to develop guidance (**Chapter 7**) regarding how this information could be used to identify receiving water bodies that need to be protected and when/where to locate BMPs that are more effective for reducing specific PSD ranges upstream of these water bodies.

5.2 Literature Review Summary

5.2.1 Source Summary

A literature review was performed on the impact of PSD on water bodies. Within the literature, what had been reported on this topic was reviewed (synthesis of literature) as well as data that could be analyzed to meet the purpose of the chapter. Sources were used for this chapter if they included either a synthesis of literature on the topic or data that could be extracted for analysis.

The literature review identified a total of six sources, which fell into the following categories:

- **Literature** – No journal articles were identified that provided information about the detrimental impacts of PSD ranges on receiving waters. Six journal articles were identified that appeared to provide relevant information regarding PSD ranges in stormwater that reaches water bodies. Of the articles identified, data were extracted from four. Of those four articles, one article described flow sampled in a creek known to be heavily influenced by runoff during storm events. The remaining three articles included data that were less relevant to the topic covered in this chapter and reflected either PSD in deposited sediment in the water body or at locations in the storm system immediately upstream of a water body, or described pollutants attached to sediment without noting particle sizes. Of the original six articles identified, two articles were eliminated because data were either too coarse to be extracted or were reported too far upstream in the storm system to be related to potential impacts to water bodies.
- **Government reports** – No reports containing information related to the topic covered in this chapter were identified during the study.

- **Databases** – No databases containing information related to the topic covered in this chapter were identified during the study.

An overview of the studies and the extracted data is as follows:

- Study locations included Louisiana, California, Canada, and China.
- PSD data and pollutant data in terms of particle size were all reported in PSD % units.
- Pollutant data not related to PSD were reported in mg/kg units.
- The parameters studied in the sources identified included metals, bacteria, PAHs, and the PSD of sediment.
- Water bodies represented in the studies included lakes, streams, and rivers.

5.2.2 Synthesis of Literature

The literature review was performed to understand the impact of PSD ranges on water bodies; however, no literature was located on this topic. Instead, what was found is included in this section; specifically, information about the transport of PSD, pollutants, and other related particulate matter to water bodies. The following summarizes the data available in the literature related to the intent of this chapter.

The PSD of sediment during storm events was reported by Ma et al. (Ma, Hao, Zhao, Zhao, & Li, 2018) and Brown et al. (Brown, Stein Ed Fau-Ackerman, Fau-Dorsey, Lyon, & Carter, 2012). Ma et al. (2018) studied the PSD of sediment specifically in sewer pipes during storm events, and they found that road runoff contributed 69.24% and roof runoff contributed 5.35% of the particles to urban receiving waters. The particle range with the highest mobility through the sewer system was found to be particles <20 µm. Additionally, the study found that particles become finer grained as they move through the combined sewer system. Brown et al. (2012) sampled metals directly from a stream during storm events and found that an increase in the clay and silt particle sizes in the stream as stormwater began to enter the channel, followed by a peak in concentration before the peak of the storm. The proportion of coarser particles increased as the storm continued.

The studies that reported pollutants adhered to particles in or adjacent to water bodies focused on metals (Cu, Ni, Zn, Pb), E. Coli, Fecal Coliform, and PAHs concentrations. Ma et al. (2018) and Brown et al. (2012) reported metals in terms of particle size. Ma et al. (2018) indicated that road runoff was the highest contributor of metals to urban receiving water. Brown et al. (2012) found that most of the metals were associated with the smallest particle sizes (<6 µm) in the stream sampled. However, the study found that the <6 µm particle size fraction (clays) represented a significantly lower proportion of the total mass of stormwater particles entering the stream.

Jeng et al. (Jeng, Englande, Bakeer, & Bradford, 2005) and Brown et al. (2012) reported fecal coliform and E. coli concentrations with particle size. Jeng et al. (2005) reported concentrations in a lake with an urban contributing basin area. The study reported a significant increase in bacterial concentrations in the lake water column during and following observed storm events. Concentrations of bacteria returned to background levels three to seven days after the storm event. The study also reported that sedimentation contributed to the reduction in E. coli concentrations, as the bacteria adhered to the suspended particles in the water column. Both Jeng et al. (2005) and Brown et al. (2012) reported that bacteria tended to adhere to clay-sized particles in the water column.

Pitt et al. (Pitt, Clark, Eppakayala, & Sileshi, 2017) reported PAH concentrations for urban creek sediment by particle size. The study found that PAH concentrations were strongly associated with particulate matter. Large variations in the measured concentrations were observed, and PAHs appeared to be attached to either the smallest or largest particles instead of the very fine to medium sand-sized particles.

5.3 Data Analysis

Data were extracted from only four studies which were organized into **Table 5-1** to **Table 5-5**. **Table 5-1** summarizes the PSD that reaches a water body. **Table 5-2** summarizes metals that reach a water body attached to particles in different size ranges. **Table 5-3** summarizes bacteria that reach a water body attached to particles in different size ranges. **Table 5-4** includes concentration of metals attached to particles (size of particles not reported) that reach a water body. **Table 5-5** includes concentrations of PAHs that reached a water body attached to particles in different size ranges. As only 1–3 sources were located for each table, no averaging or other statistical calculations were made. A discussion of the data that was compiled is included in the following section.

5.4 Discussion

An overview of the data located through the literature search is as follows:

- Based on the limited data available, the majority of E. coli and fecal coliform in stormwater attach to the smallest particle size (clay size). This could suggest that targeting removal of smaller solids could reduce higher concentrations of these pollutants. However, this is based upon only two data points; Brown et al. (2012) also mentioned that event mean concentrations (EMCs) varied widely for bacteria.
- Of the metals, the highest concentrations of Copper, Zinc, and Nickel occurred for particle sizes below 6 µm, followed by 6-35 µm sizes. Lead was higher for particle sizes >35 µm, followed by coarse silt size.
- The particle size comprising the largest fraction (%) of sediment that reached a water body are similar between the two studies that reported PSD independent of pollutants. According to Ma et al. (2018), the predominant size appears to be the same size as what most of the metals and bacteria are attached to (clay size). Particle sizes larger than silt comprised less than 10% of sediment reaching a water body. Brown et al. (2012) found that the clay-sized particles comprised a small portion of stormwater particles (less than 25%). The study found that 6-35 µm size made up 39%, and >35 µm sizes made up the remainder of the particles. That said, 35 µm is still in the silt size range.

It is worth noting that the topic covered in this chapter was included in the study because of TAPE requirements to test PSD and to assess whether a reason it was included was to protect receiving water bodies from a particular particle size range that was more detrimental. However, based on discussion with staff involved in TAPE, the reason why PSD testing is required is because most particles in Washington State stormwater runoff are believed to be silt sized. Thus, the reason PSD testing is conducted as part of TAPE is to better understand the BMP performance related to specific particle size ranges rather than how they affect the receiving waters. It is worth noting that the types of samplers used to collected data for TAPE studies (automated samplers) could skew the data because samples are collected at a fixed point in the water column and the size of particles that can be collected is limited to the diameter of the tube that is used to pump the sample to the sampler. **Sections 3.4.3** and **3.4.4** provide additional discussion on this topic.

5.5 Conclusions

A threshold or category of impact related to PSD in water bodies could not be determined and subsequently the application of the information, because no studies were located that focus on the specific impacts of PSD ranges on receiving water bodies. Further, only a few studies were located that reported PSD ranges in stormwater that reaches water bodies. Based on data from a few studies in this chapter and **Chapter 6**, targeting clay- and silt-sized particles may remove the highest amounts of metals, nutrients, and bacteria. As this is already the target, it appears it may be approaching removal in a way that best benefits water bodies. However, more research/data is needed to confirm this hypothesis. This and other research gaps are discussed in the subsequent section.

5.6 Recommendations for Future Research

Recommendations for future research identified during the literature review and data analysis include:

- **Stormwater-related impacts of PSD on receiving water bodies** – Research is needed to understand how different particle sizes impact receiving waters. In addition, data are needed regarding concentrations of pollutants attached to specific particle sizes that reach water bodies, especially while suspended in the water column. This data would help in the understanding of whether certain sizes should be targeted to remove certain pollutants.
- **Assess potential for a threshold or categories of impact** – If additional research is conducted on the stormwater-related impacts of PSD on receiving waters, that information could be used to identify the categories of impact (i.e., high, medium, low) where receiving waters need to be protected and subsequently when to located BMPs that are more effective for reducing specific PSD ranges.

Table 5-1. Quantitative PSD Data Retrieved from Literature

Author	Water Body Type	Basin Area (ac)	Primary Land Use		PSD					
					Clay	**Silt**	**Fine Sand**	**Coarse Sand**	**Fine Gravel**	**Units**
					<4	**4-62**	**62-125**	**125-250**	**250-1000**	
Ma, 2018	NA; Study summarizes concentrations in sewer pipe sediment	12.4	Residential	**Actual Particle Size Range**	**<20**	**20-63**	**63-125**	**125-250**	**>250**	**µm**
				Amount (mg/L, %, etc.)	72%	20%	6%	2%	1%	%
Brown, 2012	Ballona Creek Watershed, samples taken directly from the creek		Urbanized watershed	**Actual Particle Size Range**	**<6**	**6-35**	**>35**	**-**	**-**	**µm**
				Amount (mg/L, %, etc.)	<25%	39%	~50%	-	-	%

Table 5-2. Quantitative PSD and Total Metals Chemistry Data Retrieved from Literature

Author	Water Body Type	Basin Area (ac)	Primary Land Use		Total Copper			Units	Total Lead			Units
Brown, 2012	Ballona Creek Watershed, samples taken directly from the creek	56,835	Urbanized watershed	**Actual Particle Size Range**	**<6**	**6-35**	**>35**	µm	**<6**	**6-35**	**>35**	µm
				Amount (mg/L, %, etc.)	51%	16%	33%	%	33%	23%	44%	%

Table 5-3. Quantitative PSD and Bacteria Chemistry Data Retrieved from Literature

Author	Water Body Type	Basin Area (ac)	Primary Land Use		Fecal Coliform		Units	E. Coli		Units
Jeng, 2004	Lake	3,187,659	Various; Urban Watershed	**Actual Particle Size Range**	**0.45-30**	**>30**	**µm**	**0.45-30**	**>30**	**µm**
				Amount (mg/L, %, etc.)	95.2%	4.8%	%	96.8%	3.2%	%
Brown, 2012	Ballona Creek Watershed, samples taken directly from the creek		Urbanized watershed	**Actual Particle Size Range**	**-**	**-**	**-**	**<6**	**-**	**µm**
				Amount (mg/L, %, etc.)	-	-	-	63%	-	%

Table 5-4. Source Summary for Quantitative Data Retrieved from Literature, Without PSD Data

Author	Water Body Type	Basin Area (ac)	Primary Land Use	Pollutant Concentration		
				Copper	**Zinc**	**Units**
Hall, 1999	River	17,792	Various; Urban Watershed	164	557	mg/kg

Table 5-5. Quantitative PSD and PAH (ug/kg) Data

PAH	Mean Concentration								
	<45 µm	45 µm-90 µm	90 µm-180 µm	180 µm-355 µm	355 µm-710 µm	710 µm-1400 µm	1400 µm-2800 µm	>2800 µm (w/o LOM)	>2800 µm (with LOM)
Napthalene	255	177	163	94	124	790	891	124	2637
Florene	257	189	225	125	139	196	293	216	1771
Phenanthrene	264	205	140	92	110	130	197	188	2007
Anthracene	354	288	261	152	182	366	491	218	2255
Fluoranthene	650	624	345	202	247	259	237	191	1520
Pyrene	653	519	412	175	240	207	192	172	2054
Benzo(a)aanthracene	501	408	258	169	224	167	271	278	2164
Chrysene	591	602	363	202	273	190	296	171	1810
Benzo(b)fluoranthene	597	517	358	402	227	316	375	329	2179
Benzo(a)pyrene	1474	1524	662	434	351	502	1119	392	2330
Indeno (1,2,3,-cd) pyrene	787	657	942	258	332	576	706	357	1774
Dibenz(a,h) anthracene	1267	787	675	276	355	687	835	286	1492
Benzo(a,g) perylene	706	465	591	199	174	551	396	348	2236

Note: Table 5-5 represents findings from one study.

Chapter 6 Determine BMP Effectiveness as a Function of PSD

6.1 Chapter Purpose

The purpose of the work described in this chapter was to identify and report on structural, operational, and source control BMP effectiveness based on the range of particle sizes and considerations for maintenance. This information was intended to be used to identify BMPs that are more effective at removing specific ranges of particles. Specifically:

- Identify the specific types of BMPs that will be included in this chapter.
- For each BMP identified, develop a permit-related definition that includes the physical characteristics, treatment mechanisms, and stormwater-related functions.
- Collect and analyze BMP effectiveness data for a range of particle sizes.

6.2 Synthesis of Literature

Literature was collected and reviewed that contained information about BMP effectiveness related to particle size range. The literature review identified the following sources:

- **Literature** – Seventeen journal articles were initially identified. Of those identified, data were extracted from seven. Ten articles were not used in the data analysis as they either did not report PSD data; only reported PSD in terms of D10, D50, and D90 sizes; data were repeated from another source collected; or the data represented PSD concentrations at a single point and could not be used to determine BMP effectiveness.
- **Government reports** – Data from eighteen TAPE studies were initially identified. Of those identified, data were extracted from ten of the studies for analysis, and eight of the studies did not report PSD data. Three BMP monitoring studies from Phase I Permittees were also collected and data were extracted from two of the studies. Two effectiveness studies were collected, and data were used in the analysis from both studies.
- **Databases** – One database, which was previously identified for use in **Chapter 3**, was the International BMP Database. Where influent and effluent PSD data were provided, they were used in the analysis.

Including the individual studies reported in databases, data were extracted from a total of forty-one studies to help understand BMP effectiveness with respect to PSD. An overview of the studies and the extracted data is as follows (also see **Table 6-10)**:

- Sources included: journal articles, TAPE study results, effectiveness study results, Phase I BMP Monitoring, and the International BMP Database.
- Study locations were primarily in Washington State as well as Oregon, Alabama, Massachusetts, Texas, and New Zealand.
- All the journal articles described field studies on roadways in urban locations.
- Three different unit types were used to measure data, with the two most common units being mg/L and percent PSD. Since the two most common unit types had the most data, only data with these units were included in the study.

- Data was located for twenty BMPs: nineteen flow control and treatment BMPs and one street sweeping BMP. No data were located that could be extracted for other operational or source control BMPs; as such, they were not included in the analysis.

6.3 Data Analysis

Data from the sources identified in **Section 6.2** were summarized using basic statistics in tables, bar charts, and box and whisker plots. **Table 6-1** shows the BMPs that were identified in the literature and for which data was able to be extracted and analyzed. The name of each BMP, the definition of the BMP, the source of the definition, treatment mechanisms provided by the BMP, and stormwater functions (such as flow control, specific treatment types) are included in the table. Following **Table 6-1** is a series of tables containing results from the analysis. The tables also list the number of sources and data points in the dataset for each BMP. The purpose of the tables is to show the typical influent and effluent and range of concentrations for each BMP dataset. Following is a list of the tables as well as what specific data is featured:

- **Table 6-2** (mg/L) and **Table 6-3** (PSD %) list the average influent and effluent concentrations by BMP for the two most common unit types. The average percent removal is also reported in these tables.
- **Table 6-4** (PSD %) and **Table 6-5** (mg/L) list the minimum and maximum influent and effluent concentrations by BMP for the two most common unit types. This information was provided to show a range of the data reported from the studies.
- **Table 6-6** and **Table 6-7** list the average, minimum, and maximum influent and effluent concentrations for the data with units of mg/L finer, which represents the concentration of particles below the particle size range.
- **Table 6-8** shows the average percent removal for street sweepers.
- **Table 6-9** summarizes the average percent removal for each particle size range for each BMP. The data presented here is the average of all the data reported (both mg/L and PSD % combined).
- **Table 6-10** summarizes what sources were identified and used to gather the data.

The following is a list of the figures included as well as what specific data are featured:

- **Figure 6-1** and **Figure 6-2** display the average percent removal for each particle size range for each BMP. **Figure 6-1** shows the percent removal for non-proprietary BMPs, while **Figure 6-2** shows the percent removal for proprietary BMPs. These figures were meant to provide a summary of BMP effectiveness in removing different particle size ranges.
- The box plots in **Figure 6-3** through **Figure 6-12** were also intended to provide a summary of BMP effectiveness and compare influent and effluent concentration ranges for each BMP.

6.4 Discussion

An overview of the data and results is as follows:

- Overall, structural BMPs removed the highest percentage of particles in the silt (4-62 μm) and very fine to fine sand-sized (62-250 μm) ranges as shown in **Table 6-9**, **Figure 6-1**, and **Figure 6-2**.

- BMPs on average removed the least amount of clay-sized (<4 µm) and medium sand (250-500 µm) particles, as shown in **Table 6-9**. It is important to note data were not always reported for this size range.
- The BMPs with the highest overall removal of particles in any size range appear to be the proprietary StormGarden Biofilter System and Kraken, as shown in **Table 6-9**.
- Non-proprietary BMPs with greater than 50% removal for clay- and silt-sized particles included bioinfiltration swales and ponds, bioretention, and wet vaults. BMPs with greater than 50% removal for any PSD range are highlighted in gray in **Table 6-9**. It is worth noting that results for most of the non-proprietary BMPs are based on only one to two studies and/or data points (samples). In addition, many of the studies were conducted on BMPs outside of Washington and while they had the same or similar names, they may not be the exact same BMPs as those defined in the Stormwater Management Manual for Western Washington (SWMMWW) or Stormwater Management Manual for Eastern Washington (SWMMEW). Both the small number of data points and potential differences in the BMPs included in the analysis could affect the accuracy of the results presented in this chapter.
- Street sweeping was the only operational BMP for which data were extracted. Mechanical and vacuum sweepers tended to perform well (approximately 50% or higher removal) for silt and larger particles, as shown in **Table 6-8**, though it is important to note that the percent removal is based on only a few data points. Additionally, less data was available for the clay- and silt-sized particle ranges. Additional data is needed to confirm the efficiencies calculated.

6.5 Conclusions

Of the structural, operational, and source control BMPs in the SWMMEW and the SWMMWW, as well as from TAPE studies, 19 structural BMPs and one operational BMP (street sweeping) were identified and defined for this chapter. Effectiveness data for each BMP was summarized by particle size. Based on the data that were available, the BMPs generally appeared to achieve the highest removal in the silt and very fine to fine sand sizes. The BMPs that removed the highest overall percentage of particles across the size ranges were proprietary BMPs (StormGarden Biofilter System and Kraken).

6.6 Recommendations for Future Research

Recommendations for future research identified during the literature review and data analysis include:

- **Small datasets for certain BMPs** – While some of the effectiveness data for BMPs were based on a larger number of data points (sample size), most of the BMP performance estimations were represented by only one data point. Additional testing for these BMPs at different sites may provide a better understanding of the effectiveness of these BMPs.
- **Missing data for Ecology-approved BMPs** – While data were located for 20 structural BMPs (including proprietary), there are other structural BMPs in the Ecology SWMMEW and SWMMWW for which no data were located. Additionally, street sweeping was the only operational BMP for which data were located, and no data were located for source control BMPs. Data on other Ecology-approved source and operational BMPs will further inform BMP effectiveness for PSD.

Table 6-1. Definition of BMPs Analyzed

BMP Name	Source for Definition	Definition	Treatment Mechanisms	Stormwater-Related Functions
Biofiltration Swale	(WSDOT, 2019)	Vegetation-lined channels designed to remove suspended solids using filtration as stormwater travels in shallow concentrated flow through the swale.	Filtration, Biological uptake, Sorption, Ion exchange	Treatment: Basic
Bioinfiltration Swale	(WSDOT, 2019)	Grass-lined swales that remove stormwater pollutants by percolation into the ground.	Filtration, Infiltration, Biological uptake, Sorption, Ion exchange	Treatment: Basic, Enhanced, Oil Control
Bioinfiltration Pond	(WSDOT, 2019)	Grass-lined shallow ponds that remove stormwater pollutants through percolation into the ground. Designed to contain runoff treatment below the first 6” of pond depth, then overflow into higher permeability infiltration BMP.	Infiltration, Biological uptake, Sorption, Ion exchange	Flow Control Treatment: Basic, Enhanced, Oil Control
Bioretention	(Ecology, 2019)	Bioretention areas are shallow landscaped depressions, with a designed soil mix (the bioretention soil mix) and plants adapted to the local climate and soil moisture conditions that infiltrate stormwater.	Infiltration, Filtration, Adsorption, Biological Action	Flow Control Treatment: Basic, Enhanced, Oil Control
Dry detention basin	(WSDOT, 2019; Ferreira & Stenstrom, 2013)	This type of detention basin does not have a permanent pool, and the accumulated runoff usually is discharged up to 72 hours after collection. Also described as open basins that provide live storage to enable the reduction of stormwater runoff flow rates and matching of predeveloped flow durations discharge.	Sedimentation, Infiltration	Flow Control
Extended Detention Basin	(Karamalegos, Barrett, Lawler, & Malina, Jr., 2005)	Open basins (detention pond) that provide live storage to enable the reduction of stormwater runoff flow rates and matching of predeveloped flow durations.	Sedimentation, Infiltration	Flow Control

BMP Name	Source for Definition	Definition	Treatment Mechanisms	Stormwater-Related Functions
Filterra	(Ecology, Varies)	Filterra is an engineered biofiltration device with components similar to bioretention in pollutant removal and application, but that provides treatment of high volume/flows.	Proprietary product; not specified	Treatment: Basic, Enhanced, Phosphorus, Oil Control
High Rate Media Filtration	International BMP Database: 2020 Summary Statistics	Manufactured devices with high rate filtration media consisting of a variety of inert and sorptive media types and configurations.	Not specified	Varies
Jellyfish	(Ecology, Varies)	The Jellyfish Filter is a stormwater quality treatment technology that provides high flow pretreatment and membrane filtration in a single unit.	Proprietary product; not specified	Treatment: Basic, Phosphorus
Media Filter Drain	(WSDOT, 2019)	Linear flow-through stormwater runoff treatment device along highway side slopes and medians. The four components include: a gravel no-vegetation zone, a grass strip, a media filter drain (MFD) mix bed, and a conveyance system for flows leaving the MFD mix. The conveyance system typically consists of a gravel-filled underdrain trench.	Infiltration, Ion exchange, Carbonate precipitation, and Biofiltration	Treatment: Basic, Enhanced, Phosphorus
MWS-Linear Modular Wetland	(Ecology, Varies)	A biofiltration system that uses horizontal flow to provide treatment in a small footprint.	Proprietary product; not specified	Treatment: Basic, Enhanced, Phosphorus
Oil/Grit Separator	(International Stormwater BMP Database, 2022): 2020 Summary Statistics	Manufactured devices, including oil/water separators and baffle chambers designed for removing floatables and coarse solids.	Gravitational settling, Trapping	Oil Control
Porous Pavement – Modular Blocks	(International Stormwater BMP Database, 2022): 2020 Summary Statistics	Full-depth pervious concrete, porous asphalt, paving stone or bricks, reinforced turf rings, and other permeable surface designed to replace traditional pavement.	Sedimentation, Infiltration, Filtration, Adsorption, Biodegradation	Flow Control

BMP Name	Source for Definition	Definition	Treatment Mechanisms	Stormwater-Related Functions
Sand Filter	(Ecology, 2019)	A basic sand filter basin is constructed so that its surface is at grade and open to the elements. Instead of infiltrating to native soils, stormwater filters through a constructed sand bed with an underdrain system.	Filtration	Treatment: Basic
Wet Vault	(City of Tacoma, 2021)	A wet vault is an underground structure similar in appearance to a detention vault, except that a wet vault has a permanent pool of water (wetpool), which dissipates energy and improves the settling of particulate pollutants. Being underground, the wet vault lacks the biological pollutant removal mechanisms, such as algae uptake, present in surface wetponds.	Sedimentation	Flow Control
StormGarden Biofilter System	(Ecology, Varies)	StormGarden is a micro-bioretention system engineered for high-flow treatment and pollutant removal. Stormgarden has a "Runoff Reduction Infiltration Panel" that allows some runoff to infiltrate into the ground.	Proprietary product; not specified	Treatment: Basic, Phosphorus, Treatment
The BioPod BioFilter	(Ecology, Varies)	BioPod uses biofiltration design for filtration, sorption, and biological uptake. It uses a high-flow media. It comes in a single-piece unit composed of precast concrete.	Proprietary product; not specified	Treatment: Basic, Enhanced, Phosphorus
The Kraken	(Ecology, Varies)	The Kraken Filter utilizes pretreatment and membrane filtration in vault and manhole configurations. The device uses reusable filter inserts, which require low maintenance.	Proprietary product; not specified	Treatment: Basic, Phosphorus

Table 6-2. Structural BMP Effectiveness Summary; Average Influent and Effluent Concentrations, mg/L

BMP	Units	Sources	Average Influent						Average Effluent						% Removal				
			Data Points	<4	4-62	62-250	250-500	>500	Data Points	<4	4-62	62-250	250-500	>500	<4 µm	4-62 µm	62-250 µm	250-500 µm	>500 µm
Bioinfiltration Swale	mg/L	1	27	12.5	10.9	0.7	3.9	3.3	20	6.2	0.1	0.0	2.5	1.9	51%	100%	97%	37%	41%
Biofiltration Swale	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Bioretention	mg/L	1	1	19.5	14.4	0.1	2.2	2.1	1	5.0	1.2	ND	1.8	1.6	74%	92%	-	15%	22%
Dry Detention Basin	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Extended Detention Basin	mg/L	2	1	ND	20.5	ND	27.6	10.1	1	ND	8.2	ND	18.3	8.3	-	60%	-	34%	18%
Bioinfiltration Pond	mg/L	1	34	15.0	13.3	0.4	3.4	3.1	35	3.7	0.5	0.02	2.1	1.6	75%	96%	96%	37%	49%
Wet Vault	mg/L	1	30	7.4	13.7	0.02	6.2	6.9	46	3.6	1.2	0.05	3.0	3.0	52%	92%	0%	51%	56%
Sand Filter	mg/L	1	4	ND	75.2	23.6	10.3	ND	4	ND	92.1	9.9	2.9	ND	-	-22%	58%	72%	-
Bioretention Plus Jellyfish[1,2]	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
High Rate Media Filtration[2]	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Porous Pavement – Modular Blocks	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Oil/Grit Separator	mg/L	3	1	4.4	2.3	0.01	4.9	3.9	1	2.8	1.2	0.13	2.4	2.3	36%	46%	0%	51%	41%
MWS-Linear Modular Wetland[2]	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Porous Pavement – Modular Blocks	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Filterra[2]	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
The BioPod BioFilter[2]	mg/L	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Media Filter Drain	mg/L	1	48	10.4	16.4	1.6	2.7	2.1	0	ND	ND	ND	ND	ND	-	-	-	-	-
StormGarden Biofilter System[2]	mg/L	1	17	9.1	15.7	4.0	4.0	3.0	17	1.5	1.8	0.9	0.7	0.4	83%	89%	77%	83%	85%
The Kraken[2]	mg/L	1	14	21.5	22.7	7.9	10.4	12.6	14	3.0	2.8	0.9	0.8	0.3	86%	88%	88%	93%	97%

[1] A study was conducted on a treatment train that included bioretention and a Jellyfish (proprietary BMP).

[2] Indicates a proprietary BMP.

Table 6-3. Structural BMP Effectiveness Summary, Average Influent and Effluent Concentrations, %

BMP	Units	Sources	Average Influent						Average Effluent						% Removal				
			Data Points	<4	4-62	62-250	250-500	>500	Data Points	<4	4-62	62-250	250-500	>500	<4 µm	4-62 µm	62-250 µm	250-500 µm	>500 µm
Bioinfiltration Swale	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Biofiltration Swale	%	1	1	43.0	46.0	3.0	3.0	5.0	1	71.0	12.0	0.0	10.0	7.0	-65%	74%	100%	-233%	-40%
Bioretention	%	1	1	98.4	0.0	0.0	0.0	1.6	8	79.0	6.6	0.8	1.6	13.9	20%	-	-	-	-771%
Dry Detention Basin	%	1	1	9.0	12.0	52.0	27.0	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Extended Detention Basin	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Bioinfiltration Pond	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Wet Vault	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Sand Filter	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
Bioretention Plus Jellyfish[1,2]	%	1	0	ND	ND	ND	ND	ND	1	99.9	0.1	ND	ND	ND	-	-	-	-	-
High Rate Media Filtration[2]	%	1	1	0.6	32.5	20.3	ND	10.0	1	0.5	5.4	2.0	ND	0.0	11%	83%	90%	-	100%
Porous Pavement – Modular Blocks	%	1	0	ND	ND	ND	ND	ND	1	85.7	14.3	ND	ND	ND	-	-	-	-	-
Oil/Grit Separator	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
MWS-Linear Modular Wetland[2]	%	1	27	30.0	61.6	10.0	6.4	ND	27	23.2	41.3	7.5	4.2	ND	23%	33%	25%	35%	-
Porous Pavement – Modular Blocks	%	1	0	ND	ND	ND	ND	ND	1	85.7	14.3	ND	ND	ND	-	-	-	-	-
Filterra[2]	%	1	4	4.1	10.7	4.9	5.6	ND	4	4.8	0.0	0.2	2.2	ND	-17%	100%	96%	61%	-
The BioPod BioFilter[2]	%	1	17	23.2	32.4	12.4	ND	17.5	17	39.8	34.8	9.7	ND	6.6	-72%	-8%	22%	-	62%
Media Filter Drain	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
StormGarden Biofilter System[2]	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-
The Kraken[2]	%	0	0	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND	-	-	-	-	-

[1] A study was conducted on a treatment train that included bioretention and a Jellyfish (proprietary BMP).

[2] Indicates a proprietary BMP.

Table 6-4. Structural BMP Influent and Effluent Summary Statistics, %

BMP	Units	Sources	Minimum Influent					Minimum Effluent					Maximum Influent					Maximum Effluent				
			<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500
Bioinfiltration Swale	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Biofiltration Swale	%	1	43.0	46.0	3.0	3.0	5.0	71	12	ND	10	7	43	46	3	3	5	71	12	ND	10	7
Bioretention	%	1	98.4	ND	ND	ND	1.6	ND	ND	ND	ND	ND	98.4	ND	ND	ND	1.6	100	46.3	6.67	5	93.8
Dry Detention Basin	%	1	9.0	12.0	52.0	27.0	ND	ND	ND	ND	ND	ND	9	12	52	27	ND	ND	ND	ND	ND	ND
Extended Detention Basin	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bioinfiltration Pond	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Wet Vault	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sand Filter	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bioretention Plus Jellyfish[1,2]	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
High Rate Media Filtration[2]	%	1	ND	ND	ND	ND	ND	99.9	0.1	ND	ND	ND	ND	ND	ND	ND	ND	99.9	0.1	ND	ND	ND
Porous Pavement – Modular Blocks	%	1	0.6	32.5	20.3	ND	10.0	0.49	5.4	2.04	ND	ND	0.55	32.5	20.3	ND	10	0.49	5.4	2.04	ND	ND
Oil/Grit Separator	%	1	ND	ND	ND	ND	ND	85.7	14.3	ND	ND	ND	ND	ND	ND	ND	ND	85.7	14.3	ND	ND	ND
MWS-Linear Modular Wetland[2]	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Porous Pavement – Modular Blocks	%	1	0.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	171.01	201.59	20.66	32.7	ND	85.4	70.29	22.4	23.7	ND
Filterra[2]	%	1	ND	ND	ND	ND	ND	85.7	14.3	ND	ND	ND	ND	ND	ND	ND	ND	85.7	14.3	ND	ND	ND
The BioPod BioFilter[2]	%	1	2.4	ND	ND	2.0	ND	1.32	ND	ND	ND	ND	5.96	25.07	15.04	11.21	ND	7.44	ND	0.51	8.47	ND
Media Filter Drain	%	1	2.5	12.3	4.3	ND	1.7	12.95	ND	ND	ND	ND	70.6	52.7	24.1	ND	43.6	100	77.5	38.5	ND	28.5
StormGarden Biofilter System[2]	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
The Kraken[2]	%	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[1] A study was conducted on a treatment train that included bioretention and a Jellyfish (proprietary BMP).

[2] Indicates a proprietary BMP.

Table 6-5. Structural BMP Influent and Effluent Summary Statistics, mg/L

			Minimum Influent					Minimum Effluent					Maximum Influent					Maximum Effluent				
BMP	Units	Sources	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500
Bioinfiltration Swale	mg/L	1	ND	0.0	ND	0.0	0.0	ND	0.01	ND	0.01	0.01	102.39	67.97	18.01	12.29	12.83	34.49	0.82	0.02	8.92	6.27
Biofiltration Swale	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bioretention	mg/L	1	19.5	14.4	0.1	2.2	2.1	4.98	1.21	ND	1.82	1.64	19.5	14.4	0.11	2.15	2.09	4.98	1.21	ND	1.82	1.64
Dry Detention Basin	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Extended Detention Basin	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bioinfiltration Pond	mg/L	2	ND	20.5	ND	27.6	10.1	ND	8.2	ND	18.3	8.3	ND	20.5	ND	27.6	10.1	ND	8.2	ND	18.3	8.3
Wet Vault	mg/L	1	ND	0.0	ND	0.0	0.0	ND	0.01	ND	0.01	0.01	129.96	85.2	9.4	24.28	21	31.2	15.57	0.02	11.41	6.59
Sand Filter	mg/L	1	1.5	0.0	0.0	0.0	0.0	0.02	0.01	0.02	0.01	0.01	34.88	243.59	0.05	37.44	84.31	12.64	24.66	1.25	9.12	9.36
Bioretention Plus Jellyfish [1,2]	mg/L	1	ND	17.6	10.5	4.8	ND	ND	13.59	4.79	1.6	ND	ND	226.67	39.97	21.47	ND	ND	286.84	16.65	4.4	ND
High Rate Media Filtration[2]	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Porous Pavement – Modular Blocks	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Oil/Grit Separator	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MWS-Linear Modular Wetland[2]	mg/L	3	4.4	2.3	0.0	4.9	3.9	2.84	1.22	0.13	2.37	2.32	4.44	2.25	0.01	4.86	3.9	2.84	1.22	0.13	2.37	2.32
Porous Pavement – Modular Blocks	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Filterra[2]	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
The BioPod BioFilter[2]	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Media Filter Drain	mg/L	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
StormGarden Biofilter System[2]	mg/L	1	0.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	41.3	90.1	63.5	10.3	7.5	ND	ND	ND	ND	ND
The Kraken[2]	mg/L	1	1.2	1.1	0.5	0.5	0.2	ND	ND	ND	ND	ND	41.4	39.7	17.5	15	8.5	3.5	5.9	3.5	2.5	3.5

[1] A study was conducted on a treatment train that included bioretention and a Jellyfish (proprietary BMP).

[2] Indicates a proprietary BMP.

Table 6-6. Structural BMP Effectiveness Summary, mg/L Finer

BMP	Units	Sources	Average Influent						Average Effluent						% Removal				
			Data Points	<4	4-62	62-250	250-500	>500	Data Points	<4	4-62.5	62-250	250-500	>500	<4	4-62	62-250	250-500	>500
High Rate Media Filtration[1]	mg/L Finer	3	1	ND	209.2	287.3	275.5	547.5	1	ND	29.2	34.6	24.2	25.9	-	86%	88%	91%	95%

[1] Indicates a proprietary BMP.

Table 6-7. Structural BMP Influent and Effluent Summary Statistics, mg/L Finer

BMP	Units	Sources	Minimum Influent					Minimum Effluent					Maximum Influent					Maximum Effluent				
			<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500	<4	4-62	62-250	250-500	>500
High Rate Media Filtration[1]	mg/L Finer	3	ND	209.2	287.3	275.5	547.5	ND	29.2	34.6	24.2	25.9	ND	209.2	287.3	275.5	547.5	ND	29.2	34.6	24.2	25.9

[1] Indicates a proprietary BMP.

Table 6-8. Operational BMP Effectiveness Summary, Street Sweeping

BMP	Units	Sources	% Removal				
			<4	4-62	62-250	250-500	>500
Mechanical Street Sweeper	%	2	-	56.5	52.9	44.4	61
Vacuum Street Sweeper	%	2	-	65.0	69.9	85.9	87.7
Regenerative Air Street Sweeper	%	3	-133	-73.5	41.8	80.0	79.0

Table 6-9. Structural BMP Effectiveness Summary by BMP and Particle Size

BMP	Units	Sources	Data Points (n)	% Removal[1]				
				<4 µm	4-62 µm	62-250 µm	250-500 µm	>500 µm
Biofiltration Swale	%	1	1	-65%	74%	100%	-233%	-40%
Bioinfiltration Swale	mg/L	1	27	51%	100%	97%	37%	41%
Bioinfiltration Pond	mg/L	1	34	75%	96%	96%	37%	49%
Vegetated Filter Strip	mg/L	0	0	-	-	-	-	-
Bioretention	mg/L	1	1	74%	92%	-	15%	22%
Bioretention Plus Jellyfish [4,5]	mg/L	0	0	-	-	-	-	-
Dry Detention Basin	mg/L	0	0	-	-	-	-	-
Extended Detention Basin	mg/L	2	1	-	60%	-	34%	18%
Filterra[5]	%	1	4	-17%	100%	95%	61%	-
High Rate Media Filtration[5]	%	1	1	11%	83%	90%	-	100%
Media Filter Drain[2]	mg/L	1	48	-	-	-	-	-
Oil/Grit Separator	mg/L	3	1	36%	46%	0%[3]	51%	41%
Porous Pavement – Modular Blocks[2]	%	1	1	-	-	-	-	-
Sand Filter	mg/L	1	4	-	-22%	58%	72%	-
Wet Vault	mg/L	1	30	52%	92%	0%[3]	51%	56%
MWS-Linear Modular Wetland[5]	%	1	27	23%	33%	25%	35%	-
The BioPod BioFilter[5]	%	1	17	-72%	-8%	22%	-	62%
StormGarden Biofilter System[5]	mg/L	1	17	83%	89%	77%	83%	85%
The Kraken[5]	mg/L	1	14	86%	88%	88%	93%	97%

[1] Text is color-coded according to ranges of values. Black text includes values less than zero up to 50%. Blue text includes values between 50-75%. Red text includes values greater than 75%.

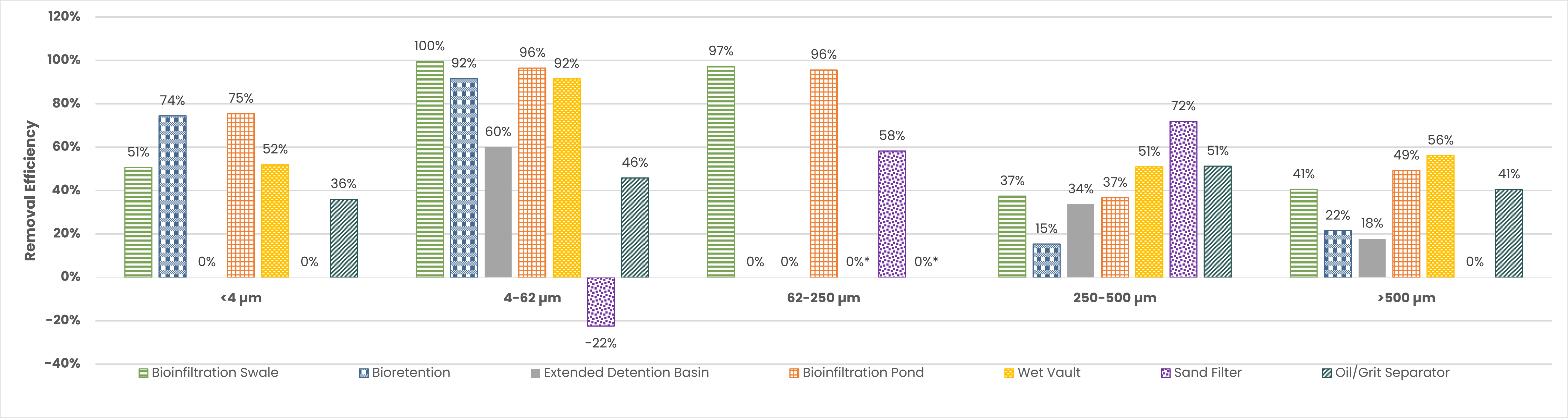
[2] Only influent data or only effluent data was available for the BMP. As such, % removal could not be calculated.

[3] Removal efficiency was estimated from very low values for influent and effluent (<0.2%). As such, removal efficiency is approximated to be 0% for the associated particle size range.

[4] A study was conducted on a treatment train that included bioretention and a Jellyfish (proprietary BMP).

[5] Indicates a proprietary BMP.

Note: Shaded cells indicate 50% or higher removal.



*Removal efficiency was estimated from very low values for influent and effluent (<0.2%). As such, removal efficiency is approximated to be 0% for the associated particle size range.

Figure 6-1. Percent Removal by Structural Non-Proprietary BMP Type and Particle Size

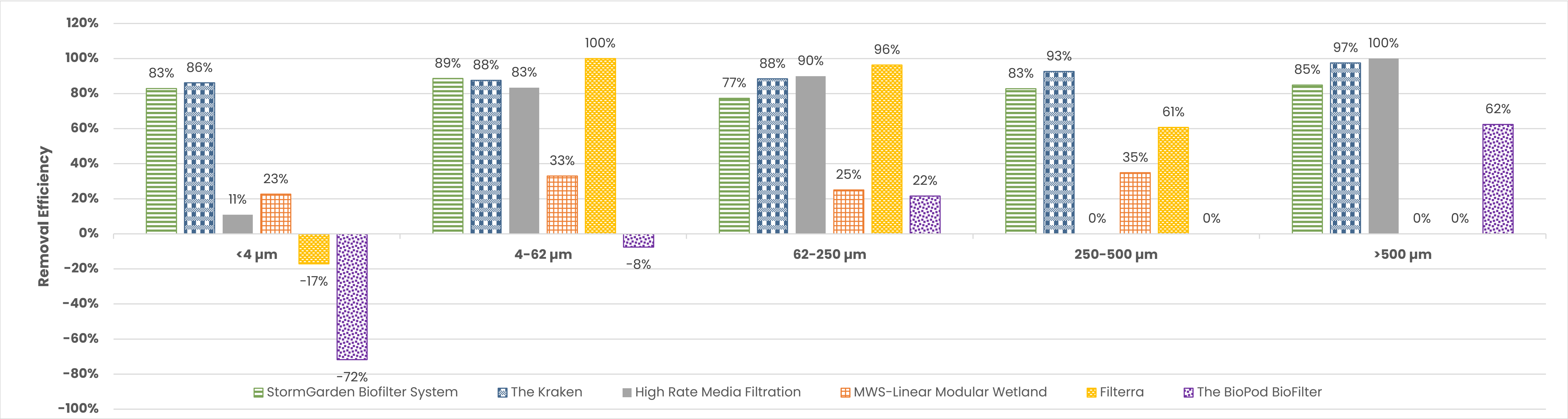


Figure 6-2. Percent Removal by Structural Proprietary BMP Type and Particle Size

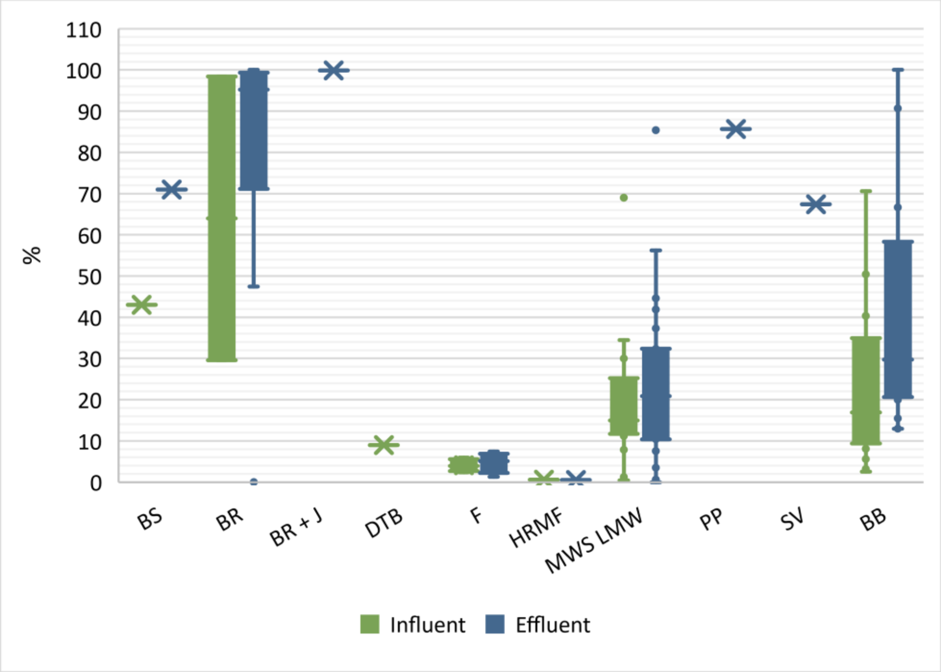


Figure 6-3. Influent and Effluent Concentrations by Structural BMP, <4 µm Particle Size

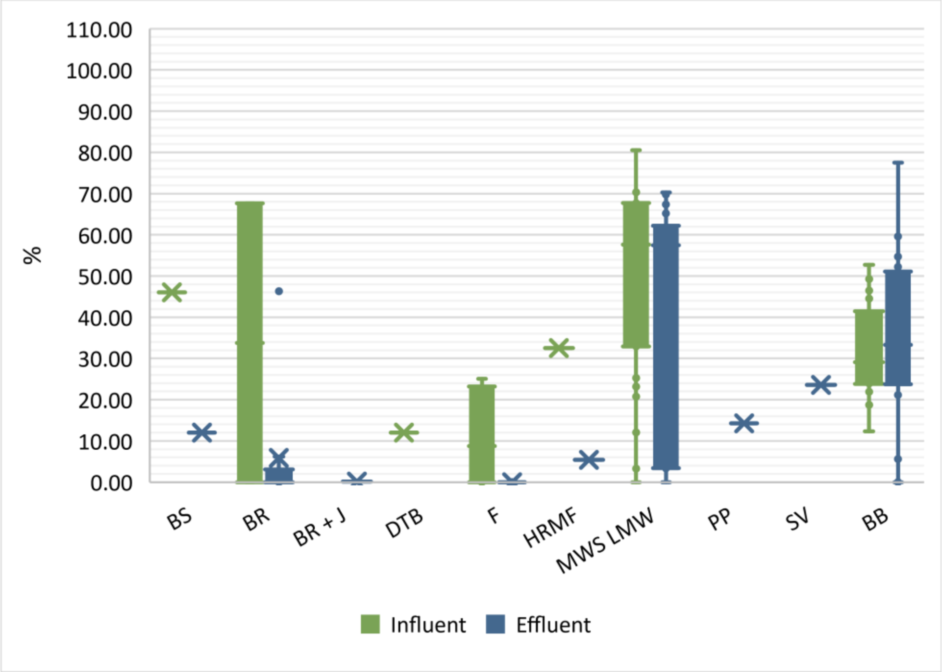


Figure 6-5. Influent and Effluent Concentrations by Structural BMP, 4-62 µm Particle Size

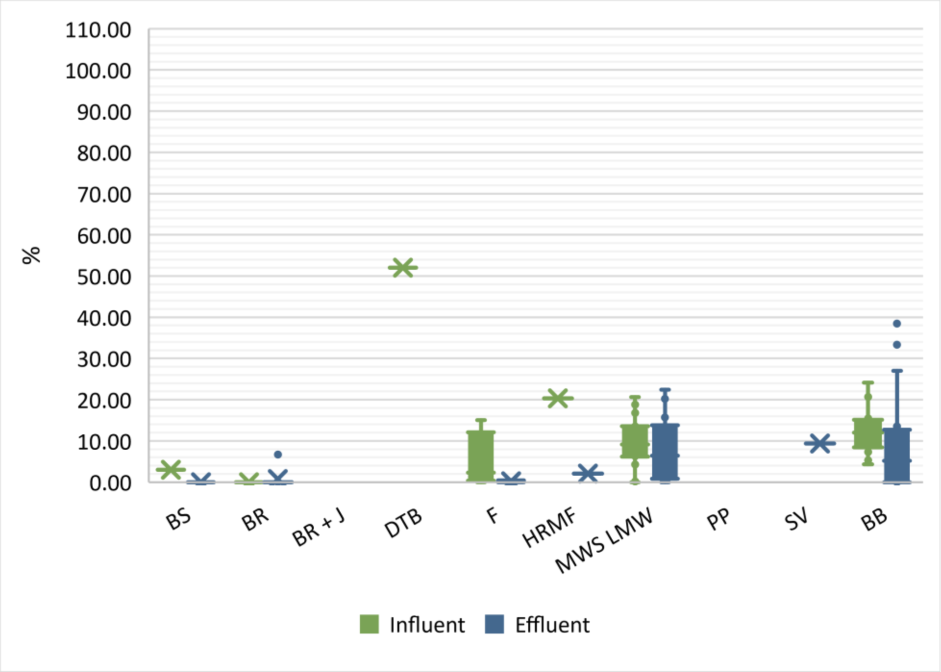


Figure 6-7. Influent and Effluent Concentrations by Structural BMP, 62-250 µm Particle Size

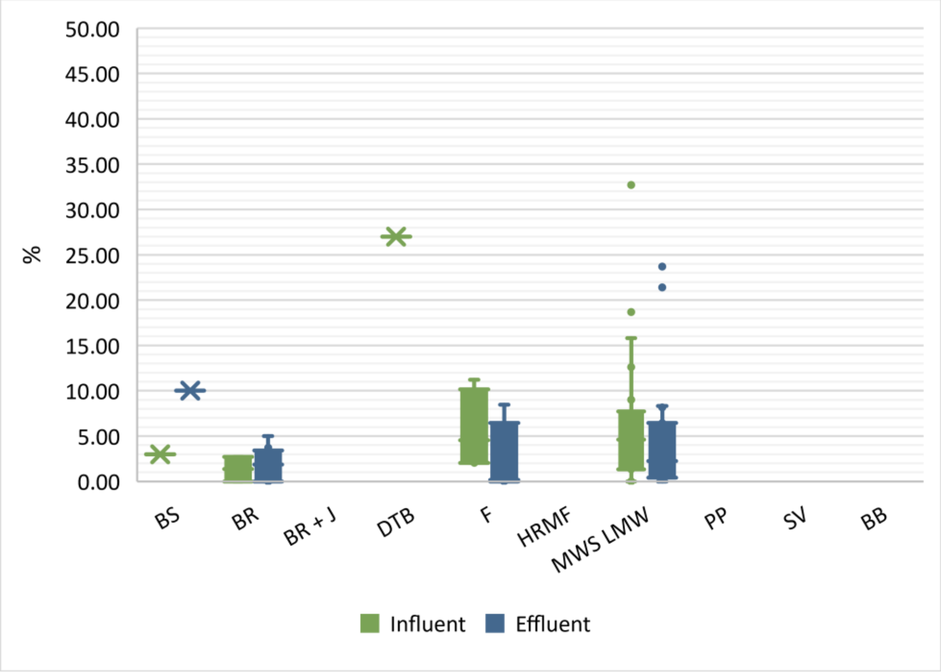


Figure 6-4. Influent and Effluent Concentrations by Structural BMP, 250-500 µm Particle Size

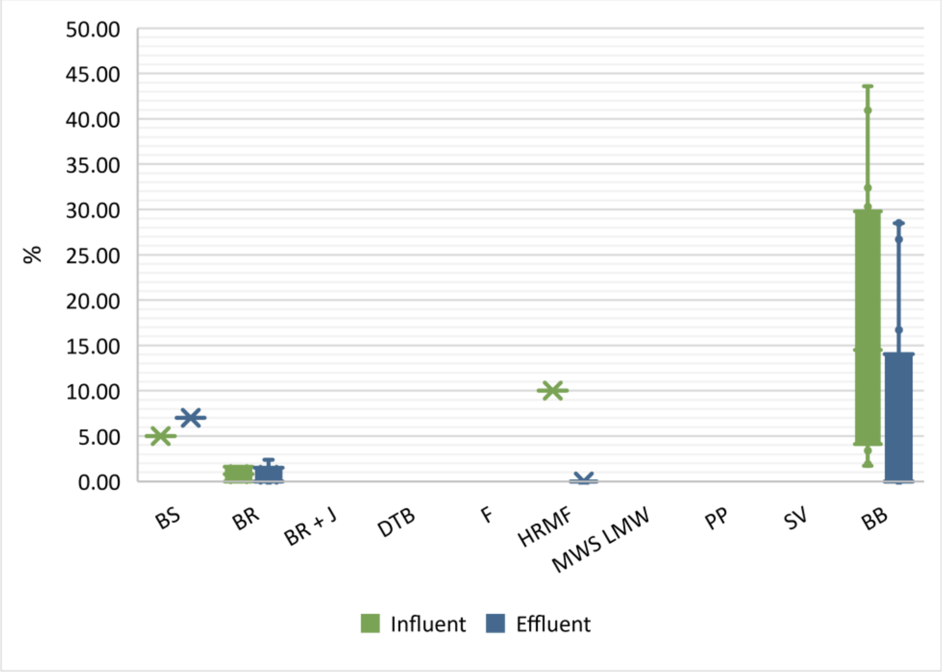


Figure 6-6. Influent and Effluent Concentration by Structural BMP, >500 µm Particle Size

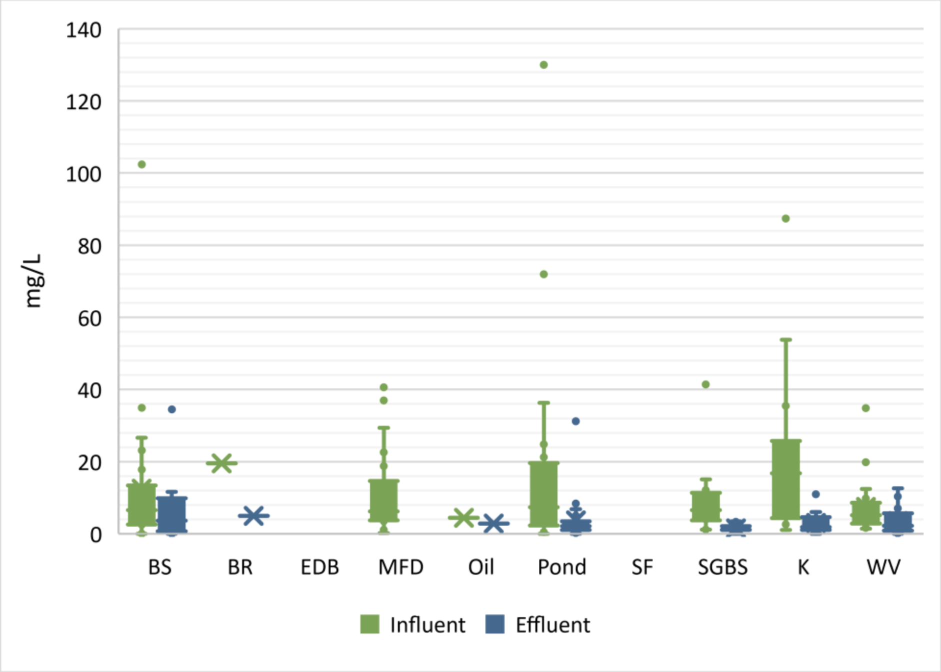


Figure 6-8. Influent and Effluent Concentration by Structural BMP, <4 µm Particle Size

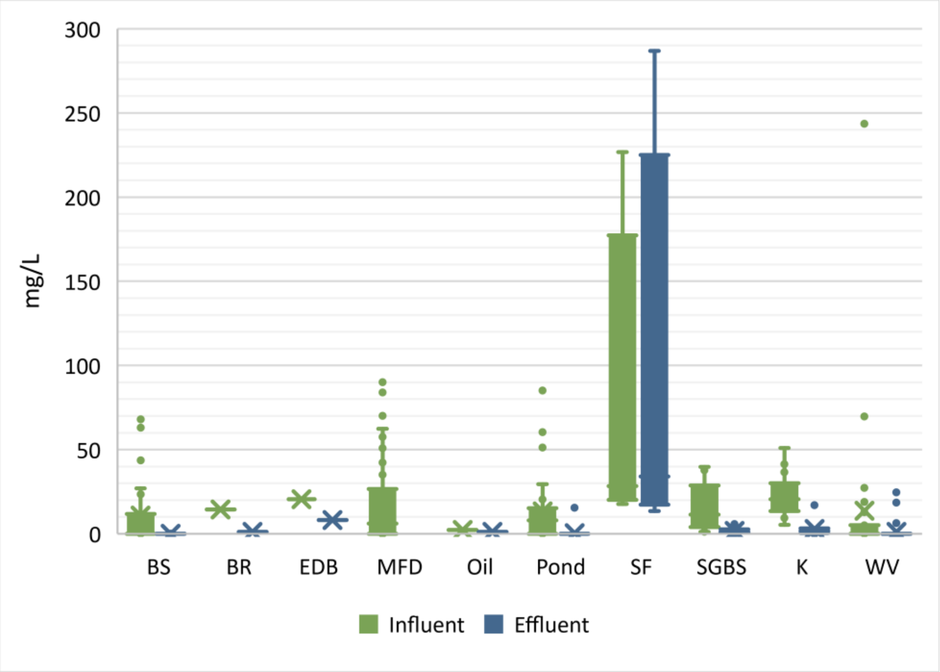


Figure 6-10. Influent and Effluent Concentration by Structural BMP, 4-62 µm Particle Size

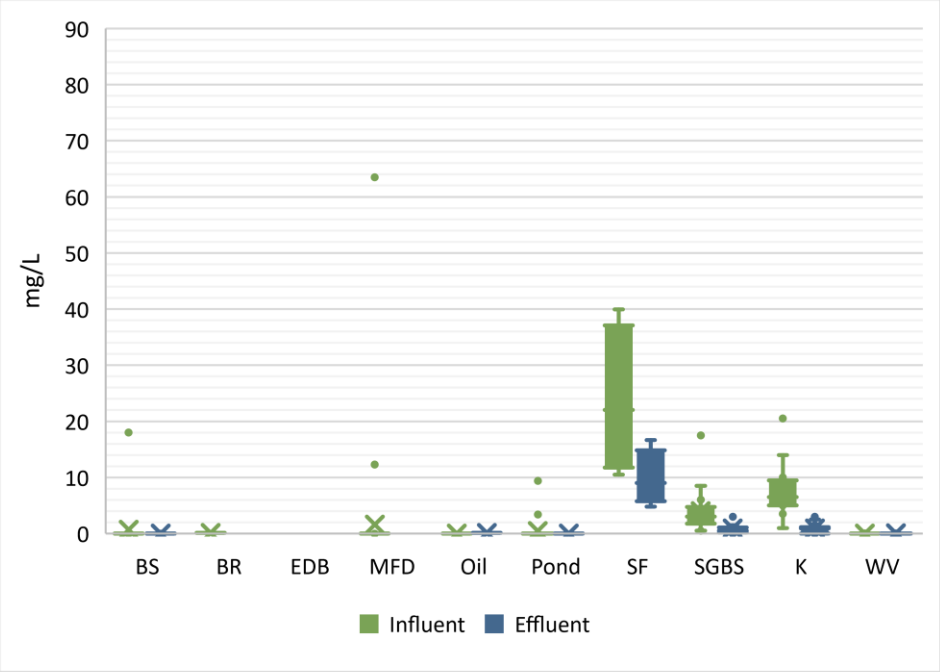


Figure 6-12. Influent and Effluent Concentration by Structural BMP, 62-250 µm Particle Size

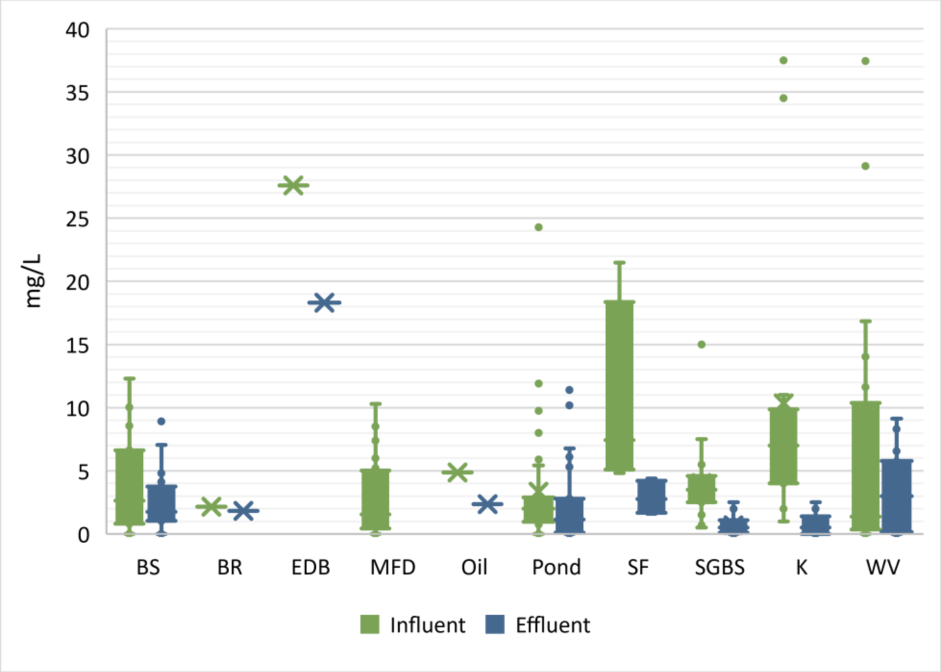


Figure 6-9. Influent and Effluent Concentration by Structural BMP, 250-500 µm Particle Size

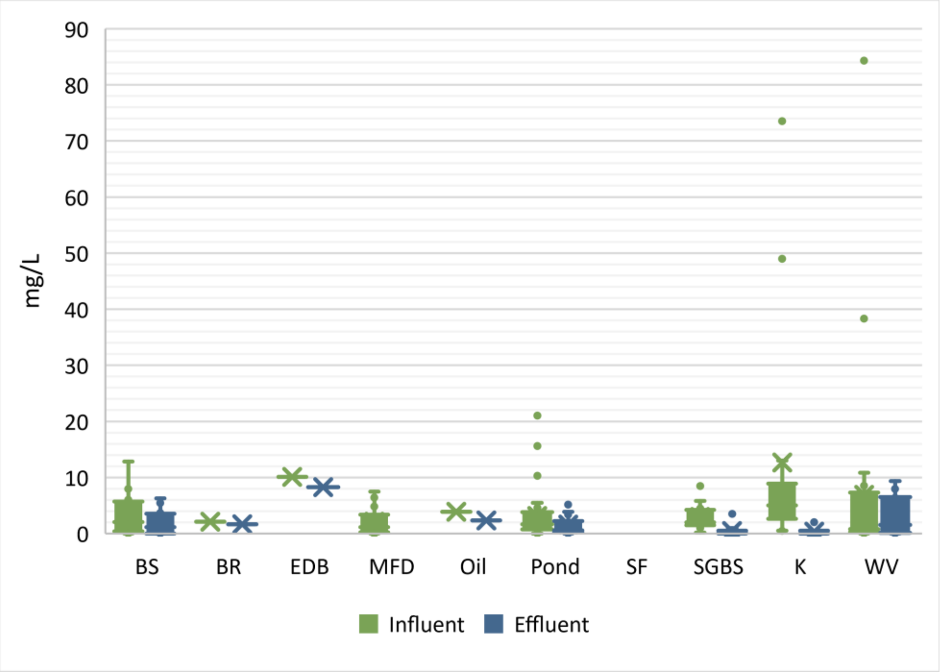


Figure 6-11. Influent and Effluent Concentration by Structural BMP, >500 µm Particle Size

Table 6-10. Inventory of BMP Data Reviewed

Source	Identifier	Source Type	BMP Type[1]	Solids Parameter	Effluent Data	PSD info included[2]	Particle Range (µm)	Comments
TAPE	GULD22 Database	Database	Compost Amended Biofiltration Swale; Standard Biofiltration Swale	PSD (mg/L)	Yes	Yes	Coarse Sand (>500 µm), Medium Sand (250-500 µm), Fine Sand (125-250 µm), Very fine Sand (62.5-125 µm), Silt (3.9-62.5 µm), Clay (1.0-3.9 µm), Colloid (<1 µm)	
TAPE	GULD23 Database	Database	Media Filter Drain	PSD (mg/L)	No	Yes	>500 µm, 250-500 µm, 125-250 µm, 62.5-125 µm, 3.9-62.5 µm, 1.0-3.9 µm, <1 µm	
TAPE	GULD02 Database	Database	Canister Filter	TSS	NO	No	-	No particle size distribution
TAPE	GULD03 Database	Database	Canister Filter	TSS	Yes	No	-	No particle size distribution
TAPE	GULD05 Database	Database	Media Filter	PSD (mg/L)	Yes	Yes	>1,>5,>16,>32,>74,>420	
TAPE	GULD06 Database	Database	Media Filter	PSD (% finer)	Yes	YES	<3.9, 3.9-62.5, 62.5-250, >250	
TAPE	GULD07 Database	Database	Canister Filter	TSS	Yes	No	-	No particle size distribution
TAPE	GULD14 Database	Database	Media Filter	TSS	Yes	No	-	No particle size distribution
TAPE	GULD17 Database	Database	Canister Filter	SSC	Yes	No	-	No particle size distribution
TAPE	GULD18 Database	Database	Media Filter	TSS, PSD (% finer)	Yes	YES	<4, <63, <125, <500	
TAPE	GULD19 Database	Database	Canister Filter	TSS, PSD (%)	Yes	YES	<2, 2-4, 4-8, 8-16, 16-31, 31-63, 63-128	Omitted data with percentage over 100%
TAPE	GULD24 Database	Database	Hydrodynamic Separator	SSC	Yes	No	-	No particle size distribution
TAPE	GULD26 Database	Database	Swale	TSS	Yes	No	-	No particle size distribution
TAPE	GULD29 Database	Database	Media Filter	TSS, PSD (%)	Yes	YES	1-2, 2-5, 5-15, 15-25, 25-50, 50-100, >100	
TAPE	GULD30 Database	Database	Media Filter	TSS	Yes	No	-	No particle size distribution
TAPE	GULD31 Database	Database	Media Filter	PSD (mg/L)	Yes	YES	<62.5, <100, <250, <500	
TAPE	GULD32 Database	Database	Membrane Filter	PSD (mg/L)	Yes	YES	1-3.9, 3.9-62.5, 62.5-125, 125-500, >500	
TAPE	GULD36 Database	Database	Media Filter	TSS, PSD (mg/L)	Yes	YES	1-3.9, 3.9-62.5, 62.5-125, 125-500, >501	

Source	Identifier	Source Type	BMP Type[1]	Solids Parameter	Effluent Data	PSD info included[2]	Particle Range (μm)	Comments
Phase 1 Monitoring Reports	Attachment C- Seattle 2012	Database	Mesocosm Treatment	PSD (%)	Yes	Yes	>500, 500-250, 250-125, 125-62.5, 62.5-3.9, 3.9-1, <1	
Phase 1 Monitoring Reports	King County 2012 BMP effective	Database	Sand Filter, Detention Basin	PSD	Yes	No	-	PSD data for individual storms not available
Phase 1 Monitoring Reports	King County 2010 BMP effective	Database	Sand Filter	TSS, PSD (mean + median)	No	No	-	No particle size distribution
Phase 1 Monitoring Reports	Attachment C- Seattle 2011	Database	Mesocosm Treatment	PSD	Yes	No	>500, 500-250, 250-125, 125-62.5, 62.5-3.9, 3.9-1, <2	Data reported in Seattle 2012
Phase 1 Monitoring Reports	BMP Evaluation - Tacoma 2015	Database	Biofiltration, wet vaults	TSS, PSD (mg/L)	Yes	Yes	<1, 1-3.9, 3.9-62.5, 62.5-125, 125-250, 250-500, >500	
Literature Search	Carbone, 2014	Literature	Sand-Zelbrite Filter Media	TSS	No	No	-	In graph form, No Table
Literature Search	Charters, 2015	Literature	Hydrodynamic separator, dry detention pond, pond and wetland	TSS, PSD (%)	No	Yes	<2 ,2-63, 63-2000, >2000 ; <8, 8-20, 20-100, >100; <70, 70 - 150, 150-250 , 250-425, >425	
Literature Search	Deletic, 1999	Literature	Grass Filter Strip	SS	No	No	-	In old graph
Literature Search	German, 2002	Literature	Street Sweeping	% Finer	No	No	<2 mm, <.25 mm	No useful PSD
Literature Search	Gharabaghim, 2006	Literature	Vegetative Filter Strips	Sediment Load	No	No	.5-2.9, 2.9-6.4, 6.4-12, 12-39, 39-68, 68-151	Ranges too varied from standard
Literature Search	Karamalegos, 2005	Literature	Vegetated filter strips, detention basin	SSC, PSD (%)	No	Yes		
Literature Search	Li, 2007	Literature	Constructed wetland	-	No	No	-	No tables with particle size distribution
Literature Search	Marsalek, 1997	Literature	Pond	None	No	No	-	No TSS or SSC reported
Literature Search	Nara, 2005	Literature	Swales	D10, D50, D90	No	No	-	Data has D10, D50, D90 but no particle size ranges
Literature Search	NAS, 2006	Literature	Various	TSS	No	No	-	No particle size distribution
Literature Search	Stagge, 2012	Literature	Swales	TSS	No	No	-	No particle size distribution
Literature Search	Vietz, 2014	Literature	Various	TSS	No	No	-	No particle size distribution
International BMP Database	InternationalBMPDatabase FilteredtoPSD	Database	Various	PSD (mg/L and %)	Yes	Yes	Various	Includes large dataset

Source	Identifier	Source Type	BMP Type[1]	Solids Parameter	Effluent Data	PSD info included[2]	Particle Range (µm)	Comments
Literature Search	Sand Filter Sidewalk Vault Effectiveness Study Technical Evaluation Report	Study	Sand Filter	TSS, PSD (mg/L)	Yes	Yes	<62.5, 62.5-250, >250	
Literature Search	Gonzaga Bioretention Soil Media Thickness Effectiveness Study	Study	Bioretention	TSS, PSD (mg/L)	Yes	Yes	<62.5, 62.5-250, >250	
Literature Search	Breault, Smith, and Sorenson, 2003-04	Study	Street Sweeping	PSD (% Removal Efficiency)	No	Yes	> 2.00 mm, 250 µm-2 mm, 125 µm-250 µm, 63 µm-125 µm, <63 µm	
Literature Search	CWP, 2006	Literature review	Street Sweeping	PSD (% Removal Efficiency)	N/A	Yes	Various >2000 µm, 840-200 µm, 246-840 µm, 104-246 µm, 43-104 µm, <43 µm; <43 µm,43-246 µm, >246 µm; >2000 µm, 1000-2000 µm, 600-1000 µm, 250-600 µm, 125-250 µm, 63-125 µm, <63 µm	
Literature Search	USGS, 2009-11	Study	Street Sweeping	PSD (% Removal Efficiency)	N/A	Yes	<0.125 mm,0.125-2.00 mm, >2.00 mm	
Literature Search	Sartor, Boyd, and Agardy, 1974	Literature	Street Sweeping	PSD (% Removal Efficiency)	N/A	Yes	<43 µm,43-104 µm, 104-246 µm, 246-840 µm, 840-2000 µm, >2000 µm	
Literature Search	SPU, 2018	Study	Street Sweeping	PSD (% Removal Efficiency)	N/A	Yes	>500 µm, 250-500 µm, 62.5-250 µm, 3.9-62.5 µm, <3.9 µm	

[1] The BMP Type listed for TAPE sources in the table above reflects the general type of BMP reported to the program instead of the proprietary name of the BMP.

[2] Yellow highlighted cells indicate no particle size data was included in source.

Chapter 7 Applying Study Results

7.1 Chapter Purpose

The purpose of this chapter was to discuss the application of the study findings from **Chapter 2** through **Chapter 6** as well as the next steps.

7.2 Recommendations for Applying Study Results

Because insufficient data was a common issue when fulfilling the intent of each chapter, providing guidance for applying the results from each chapter is limited. **Table 7-1** summarizes the desired outcome or application of each chapter, what was able to be determined in each chapter, and what data gaps, if addressed, could allow future research teams to meet the desired outcome of each chapter and provide recommendations for applying the results.

Table 7-1. Summary of Intended Application of Chapter Findings

Chapter	Intended Application of Chapter Findings	Existing Application of Chapter Findings	Data Gaps to Address to Achieve Intended Application
2	Use ranked test methods to develop recommendations for future testing methods.	Using the TAPE Method with the laser diffraction (LD) is likely to produce the best results for analyzing PSD in a given water sample. ASTM's SSC Method D3977-97B used with LD would produce the most precise results because the larger particles would be accounted for with the ASTM sieve test, and the LD would give a smoother representation of the fine fraction particles.	Further research is needed to determine whether LD PSD results correlate, or can be correlated with, the ASTM Method D3977-97 methods B and C.
3	Characterize PSD using common Washington basin conditions (e.g., land use, basin area).	Insufficient basin condition data was reported to characterize PSD in terms of typical Washington basin conditions. The particle size with the highest concentration was silt, regardless of land use. It is likely that most basins can expect to find high quantities of silt-sized particles on impervious surfaces, specifically roadways.	Encouraged researchers to report more details about the basin conditions such as AADT, land use, basin area, etc. Additionally, larger range/wider distribution of basin areas are needed to assess whether trends exist between basin area and PSD.
4	Using the intended application from **Chapter 3**, develop weight factors for different basin conditions to predict pollutant loading and select an appropriate BMP for a site. Provide guidance regarding how this information could be used in watershed plans, total daily maximum load (TMDL) studies, and for estimating BMP credits.	Basin condition-based pollutant loads were not able to be estimated as insufficient data were located in the literature for different land use types or other basin conditions. Pollutant concentrations are generally higher for finer (clay- and silt-sized) particles, but the size associated with the majority of the particle load to surface waters was not consistent in the literature. Continuing to target these particle sizes is anticipated to remove pollutants before they reach water bodies.	If more data points reporting particle size distribution of pollutants were available, determining land-based pollutant loads might be more feasible. Additional studies related to pollutants of emerging concern may inform strategies for treatment of those pollutants.
5	Assess whether a threshold or qualitative categories of impact can be determined for if/when there is a benefit to receiving waters for targeting removal of different PSDs and selecting BMPs based on PSD effectiveness. Use the results to develop guidance regarding how this information could be used to identify receiving water bodies that need to be protected and when/where to locate BMPs that are more effective for reducing specific PSD ranges upstream of these water bodies.	A threshold or category of impact related to PSD in water bodies could not be determined and subsequently the application of the information, because no studies were located that focus on the specific impacts of PSD ranges on receiving water bodies. The size ranges of particles most commonly transported to water bodies include clay- and silt-sized particles. Continuing to target these particle sizes is anticipated to remove pollutants before they reach water bodies.	Research is needed to understand how different particles sizes impact receiving waters. In addition, more data are needed regarding particle sizes and concentrations of pollutants attached to specific particle sizes that reach water bodies, especially while suspended in the water column. These data would help to determine whether certain sizes should be targeted to remove certain pollutants.
6	Identify BMPs that are more effective at removing specific ranges of particles.	Of the 20 identified, BMPs generally appeared to achieve the highest removal in the silt and fine sand sizes. Because these particles appear to contain high amounts of pollutants and have the highest concentrations in the built environment, BMPs are targeting an appropriate particle size. BMPs that removed over 50% of each particle size range include: proprietary BMPs (StormGarden Biofilter System and Kraken), bioinfiltration swales and ponds, bioretention, and wet vaults.	Additional data for some of the BMPs that were identified in the chapter are needed to better understand their performance related to specific particle sizes. There are structural, operational, and source control BMPs in the Ecology SWMMEW and SWMMWW for which no data were located. Data for these BMPs will further inform BMP effectiveness for PSD.

Chapter 8 References

Anta, J., Peña, E. S., & Cagiao, J. (2006). A BMP selection process based on the granulometry of runoff solids in a separate urban catchment. *Water SA, 32*(3), 419-428.

Aryal, R., Vigneswaran, S., Kandasamy, J., & Naidu, R. (2010). Urban Stormwater Quality snf Treatment. *Korean Journal of Chemical Engineering*, 1343-1359. doi:https://doi.org/10.1007/s11814-010-0387-0

Boogaard, F. C., van de Ven, F., Langeveld, J. G., & van de Giesen, N. (2014). Stormwater quality characteristics in (Dutch) urban areas and performance of settlement basins. *Challenges, 5*, 112-122.

Breault, R. F., Smith, K. P., & Sorenson, J. R. (2005). *Residential street-dirt accumulation rates and chemical composition, and removal efficiencies by mechanical-and vacuum-type sweepers.* New Bedford: U.S. Geological Survey.

Brodie, I. M., & Dunn, P. K. (2009). Suspended particle characteristics in storm runoff from urban impervious surfaces in Toowoomba, Australia. *Urban Water Journal, 6*(2), 137-146.

Brown, J. S., Stein Ed Fau-Ackerman, D., Fau-Dorsey, J. H., Lyon, J., & Carter, P. M. (2012). Metals and Bacteria Partitioning to Various Size Particles in Ballona Creek Storm Water Runoff. 1552-8618.

Brown, R. A., & Line, D. H. (2012). LID Treatment Train: Pervious Concrete with Subsurface Storage in Series with Bioretention and Care with Seasonal High Water Tables. *Journal of Environmental Engineering*, 689-697.

Center for Watershed Protection. (2006). *Technical Memorandum 1 - Literature Review: Research in Support of an Interim Pollutant Removal Rate for Street Sweeping and Storm Drain Cleanout Activities.* Fulton: Center for Watershed Protection.

Cha, S. M., Lee, S. W., Park, Y., & Kim, J. H. (2013). Characterizing particle size distribution of nonpoint source pollutants in an agricultural area. *Desalination and water treatment, 51*(19-21), 4138-4145. doi:https://doi.org/10.1080/19443994.2013.781110

Charters, F. J., Cochrane, T. A., & O'Sullivan, A. D. (2015). Particle size distribution variance in untreated urban runoff and its implication on treatment selection. *Water Research*, 337-345.

Chen, G., Zeng, G., Du, C., Huang, D., Tang, L., Wang, L., & Shen, G. (2008). Transfer of heavy metals from compost to red soil and groundwater under simulated rainfall conditions. *Journal of Hazardous Materials, 181*(1), 211-216. doi:https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.04.118

City of Seattle, City of Tacoma, Clark County, King County, Pierce County, Port of Seattle, Port of Tacoma. (2012). S8.D Stormwater Outfall Monitoring Data. Washington State Department of Ecology.

City of Tacoma. (2015). *Section S8.F Best Management Practice Evaluation Final Report.* Tacoma: City of Tacoma.

City of Tacoma. (2021). *Stormwater Management Manual.* Tacoma, WA: City of Tacoma Environmental Services.

Clark, S. E., & Siu, C. Y. (2008). Measuring Solids Concentration in Stormwater Runoff: Comparison of Analytical Methods. *Environmental Science and Technology, 42*(2), 511-516. doi:https://doi.org/10.1021/es070371g

Clary, J., Leisenring, M., Hobson, P., & Strecker, E. (2020). *International Stormwater BMP Database: 2020 Summary Statistics.* The Water Research Foundation. Retrieved from https://www.waterrf.org/system/files/resource/2020-11/DRPT-4968_0.pdf

Ecology. (2018, September). *Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies: Technology Assessment Protocol - Ecology (TAPE).* Retrieved from State fo Washington Department of Ecology: https://apps.ecology.wa.gov/publications/SummaryPages/1810038.html

Ecology. (2019). *Stormwater Management Manual for Western Washington.* Olympia: Washington State Department of Ecology.

Ecology. (Varies). TAPE Program Particle Size Distribution Data for GULD BMPs. Lacey: Washington State Department of Ecology.

Eshel, G., Levy, G. J., U., M., & SInger, M. J. (2004). Critical Evaluation of the Use of Laser Diffraction for Particle-Size Distribution Analysis. *Soil Science Society of America Journal, 68*(3), 736-743. doi:https://doi.org/https://doi.org/10.2136/sssaj2004.7360

Evergreen StormH2O. (2023). *Particle Size Distribution Analysis Memorandum.* Spokane, WA.

Ferreira, M., & Stenstrom, M. K. (2013). The importance of particle characterization in stormwater runoff. *Water Environment Research, 85*(9), 833-842.

German, J., & Svensson, G. (2002). Metal content and particle size distribution of street sediments and street sweeping waste. *Water Science and Technology, 46*(6-7), 191-198.

Goosens, D. (. (2008). Techniques to measure grain-size distributions of loamy sediments: a comparative study of ten instruments for wet analysis. *Sedimentology, 55*(1), 65-96. doi:https://doi.org/https://doi.org/10.1111/j.1365-3091.2007.00893.x

Granato, G. E. (2019). Highway-Runoff Database (HRDB) Version 1.1.0. U.S. Geological Survey data release. doi:https://doi.org/10.5066/P94VL32J.

Gray, J. R. (2006). *Collection and Use of Total Suspended Solids Data.* Federal Interagency Sedimentation Project (FISP), Technical Committee Memorandum 2007.01 .

Guo, Q. (2006). Correlation of Total Suspended Solids (TSS) and Suspended Sediment Concentration: Final Report. doi: https://doi.org/https://doi.org/doi:10.7282/T3M32TZZ

Hall, K. J., Kiffney, P., Macdonald, R., McCallum, D., Larkin, G., Richardson, J., . . . Thomson, B. (1998). *Non-point Source Contamination in the Urban Environment of Greater Vancouver: A Case Study of the Brunette River Watershed.* Vancouver: Environmental Conservation Branch, Aquatic and Atmospheric Sciences Division.

Herngren, L., Goonetilleke, A., Ayoko, G. A., & Mostert, M. M. (2010). Distribution of polycyclic aromatic hydrocarbons in urban stormwater in Queensland, Australia. *Environmental Pollution, 158*(9), 2848-2856. doi:https://doi.org/10.1016/j.envpol.2010.06.015

Hobbs, W., Lubliner, B., Kale, N., & Newell, E. (2015). *Western Washington NPDES Phase 1 Stormwater Permit: Final Data Characterization 2009-2013.* Olympia: Washington State Department of Ecology.

Hong, Y., Bonhomme, C., Le, M.-H., & Chebbo, G. (2016). A new approach of monitoring and physically-based modelling to investigate urban wash-off process on a road catchment near Paris. *Water Research, 102*, 96-108.

Hongtao, Z., Chengqing, Y., Meixue, C., Weidong, W., Chris, J., & Baoqing, S. (2009). Size distribution and diffuse pollution impacts of PAHs in street dust in urban streams. *Journal of Environmental Sciences, 21*(2), 162-167.

Horowitz, A. J. (2013). A review of selected inorganic surface quality-monitoring practices: Are we really measuring what we think, and if so, are we doing it right? *Environmental Science & Technology*, 2471-2486. doi:https://doi.org/10.1021/es304058q

International Stormwater BMP Database. (2022, November). Urban Stormwater BMP Database. Water Research Foundation.

International, A. (2019). ASTM D3977-97 Standard Test Methods for Determining Sediment Concentration in Water Samples. doi:https://doi.org/10.1520/D3977-97R19

Jeng, H. A., Englande, A. J., Bakeer, R. M., & Bradford, H. B. (2005). Impact of Urban Stormwater Runoff on Estuarine Environmental Quality. *Estuarine Coastal and Shelf Science, 63*(4), 513-526. doi:https://doi.org/10.1016/j.ecss.2004.11.024

Karamalegos, A. M., Barrett, M. E., Lawler, D. F., & Malina, Jr., J. F. (2005). *Particle Size Distribution of Highway Runoff an Modification through Stormwater Treatment.* Austin: Center for Research in Water Resources.

Kayhanian, M., Fruchtman, B. D., Gulliver, J. S., Montanaro, C., Ranieri, E., & Wuertz, S. (2012). Review of highway runoff characteristics: Comparative analysis and universal implications. *Water research, 46*(20), 6609-6624. doi:https://doi.org/https://doi.org/10.1016/j.scitotenv.2012.08.077

Kayhanian, M., McKenzie, E. R., Leatherbarrow, J. E., & Young, T. M. (2012). Characteristics of road sediment fractionated particles captured from paved surfaces, surface run-off and detention basins. *Science of the Total Environment, 439*, 172-186.

Khan, S. T., Edward Beighley, R., VanHoven, D., & Watkins, K. (2021). Dynamic stormwater management to mitigate phosphorous export. *Science of the Total Environment*, 120-124.

Kim, M. H., Sung, C. Y.-H., & Chu, K.-H. (2012). Bioretention for stormwater quality improvement in Texas: Removal effectiveness of Escherichia coli. *Separation and Purification Technology, 84*, 120-124.

Li, Y., Lau, S.-L., Kayhanian, M., & Stenstrom, M. K. (2006). Dynamic characteristics of particle size distribution in highway runoff: implications for settling tank design. *Journal of Environmental Engineering*, 852-861.

Ma, Y. K., Hao, S. N., Zhao, H. T., Zhao, J., & Li, X. Y. (2018). Pollutant Transport Analysis and Source Appointment of the Entire Non-Point Source Pollution Process in Separate Sewer Systems. *Chemosphere, 211*, 557-565.

Monrabal-Martinez, C., Muthanna, T., & Meyn, T. (2016). Seasonal variation in pollutant concentrations and particle size distribution in urban stormwater - design implications for BMPs. *9th International Conference on planning and technologies for sustainable management of Water in the City.* Lyon: Novatech.

Navickis-Brasch, A. S., Peraki, M., Packman, J., Fendt, P., Nilsen, C., Hoffman-Ballard, T., & Maurer, M. (2021). Structural Stormwater Controls (SSC) Science Review and Synthesis White Paper.

Novak, J. M., Cantrell, K. B., Watts, D. W., Bussvher, W. J., & Johnson, M. G. (2014). Designing relevant biochars as soil amendments using lignocellulosic-based and manure-based feedstocks. *Journal of Soils and Sediments, 14*(2), 330-343.

Pitt, R. E., B, R., Clark, S., & Williamson, D. (2005). Sources of Pollutants in Urban Areas (Part 1) - Older Monitoring Projects. *Journal of Water Management Modeling*.

Pitt, R., Clark, S. E., Eppakayala, V. K., & Sileshi, R. (2017). Don't Throw the Baby Out with the Bathwater - Sample Collection and Processing Issues Associated with Particulate Solids in Stormwater. *Journal of Water Management Modeling*.

Revitt, D. M., Lundy, L., Coulon, F., & Fairley, M. (2014). The sources, impact, and management of car park runoff pollution: a review. *Journal of Environmental Management, 146*, 552-567.

Roger, S., Montrejaud-Vignoles, M., Andral, M., Herremans, L., & Fortune, J. (1997). The solid matter carried by motorway runoff water. *Water Research, 32*(4), 1119-1125.

Roseen, R. M., Ballestero, T. P., Fowler, G. D., Guo, Q., & Houlse, J. (2011). Sediment Monitoring Bias by Automatic Sampler in Comparison with Large Volume Sampling for Parking Lot Runoff. *Journal of Irrigation and Drainage Engineering, 137*(4), 251-257.

Sansalone, J. J., & Buchberger, S. G. (1997). Characterization of solid and metal element distributions in urban highway stormwater. *Water Science and Technology, 36*(8-9), 155-160.

Seattle Public Utilities. (2013). *Attachment C - WY2012 Stormwater Monitoring Report.* Seattle: City of Seattle.

Seattle Public Utilities and Herrera Environmental Consultants. (2009). *Seattle Street Sweeping Pilot Study Monitoring Report.* Seattle: Seattle Public Utilities.

Selbig, W. R. (2015). Characterizing the distribution of particles in urban stormwater: advancements through improved sampling technology. *Urban Water Journal, 12*(2), 111-119.

Selbig, W. R., Cox, A., & Bannerman, R. T. (2012). Verification of a depth-integrated sample arm as a means to reduce solids stratification bias in urban stormwater sampling. *Journal of Environmental Monitoring, 14*(4), 1137-1143.

Smith, K. P., Sorenson, J. R., & Granato, G. E. (2018). *Characterization of stormwater runoff from bridge decks in eastern Massachusetts.* Scientific Investigations Report, Issue U. S. G. Survey.

Sorenson, J. R. (2013). *Potential reductions of street solids and phosphorus in urban watersheds from street cleaning.* Cambridge: U.S. Geological Survey.

Spokane County. (2021). *Bioretention Soil Media Thickness Effectiveness Study Technical Evaluation Report.* Spokane: Spokane County.

Spokane County. (2021). *Sand Filter Sidewalk Vault Effectiveness Study Technical Evaluation Report.* Spokane: Spokane County.

USGS. (1922). A scale of grade and class terms for clastic sediments. *Journal of Geology*, 377-392. Retrieved from https://pubs.usgs.gov/of/2003/of03-001/htmldocs/nomenclature.htm

USGS. (2011). Biochar for Soil Fertility and Natural Carbon Sequestration.

Wang, Q., Zhang, Q., Dzakpasu, M., Lian, B., Wu, Y., & Wang, X. C. (2018). Development of an indicator for characterizing particle size distribution and quality stormwater runoff. *Environmental Science and Pollution Research, 25*, 7991-8001.

Wentworth, C. K. (1922). A Scale of Grade and Class Terms for Clastic Sediments. *The Journal of Geology, 30*(5), 377-392.

Wijesiri, B., Egodawatta, P., McGree, J., & Goonetilleke, A. (2016). Influence of uncertainty inherent to heavy metal build-up and wash-off on stormwater quality. *Water Research, 91*, 264-276.

Winston, R., & Hunt, W. (2017). Characterizing Runoff from Roads: Particle Size Distributions, Nutrients, and Gross Solids. *Journal of Environmental Engineering*.

WSDOT. (2019). *Highway Runoff Manual.* Olympia, WA: Washington State Department of Transportation.

Ying., G., & Sansalone, J. (2008). Granulometric relationships for urban source area runoff as a function of hydrologic event classification and sedimentation. *Water Air Soil Pollution, 193*, 229-246.

Yun, Y., Park, H., Kim, L.-H., & Ko, S. (2010). Size Distributions and Settling Velocities of Suspended Particles from Road and Highway. *KSCE Journal of Civil Engineering*, 481-488.