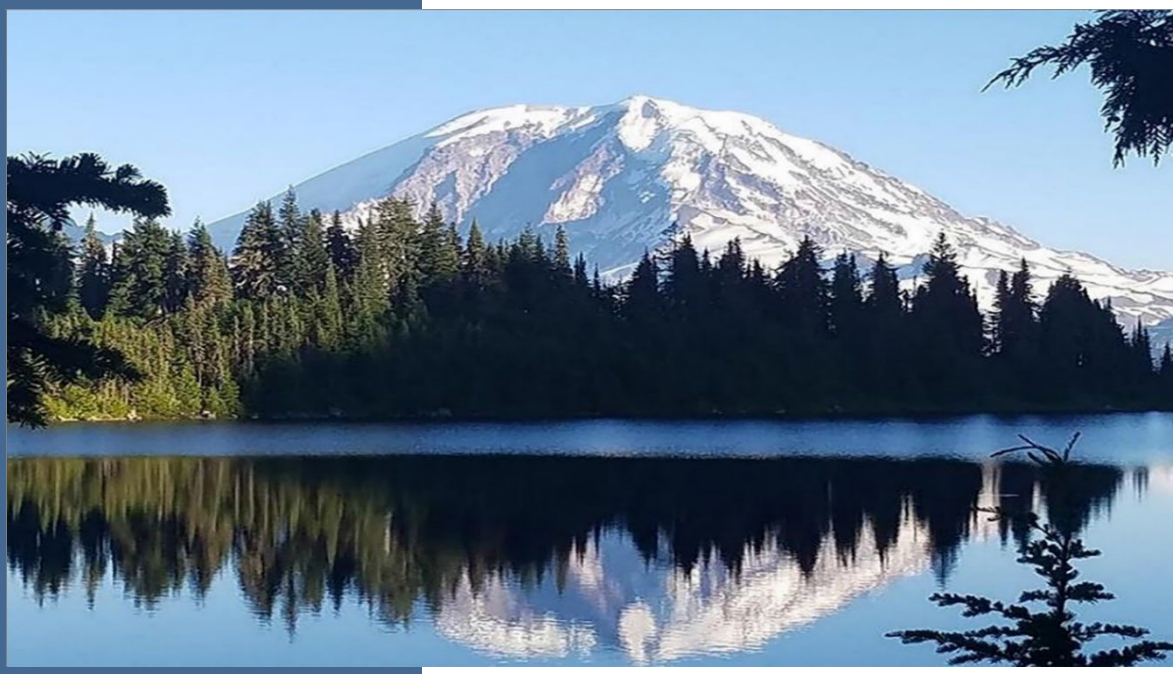


Investigating the Use of Unamended Soils for Treatment Of 6PPDQ in Stormwater

Interim Progress Report

By

EA Engineering, Science, and Technology Inc., PBC.

For the

Water Quality Program

Washington State Department of Ecology

Olympia, Washington

September 2026, Publication 26-10-060

DEPARTMENT OF ECOLOGY
State of Washington

Publication Information

This document is available on the Department of Ecology's website at:
https://apps.ecology.wa.gov/publications/summarypages/2610060.html

Cover photo credit

- Standard Ecology image, 2019

Contact Information

Water Quality Program

Headquarters Office
P.O. Box 47600
Olympia, WA 98504-7600
Phone: 564-669-4582
Website[1]**:** Washington State Department of Ecology

ADA Accessibility

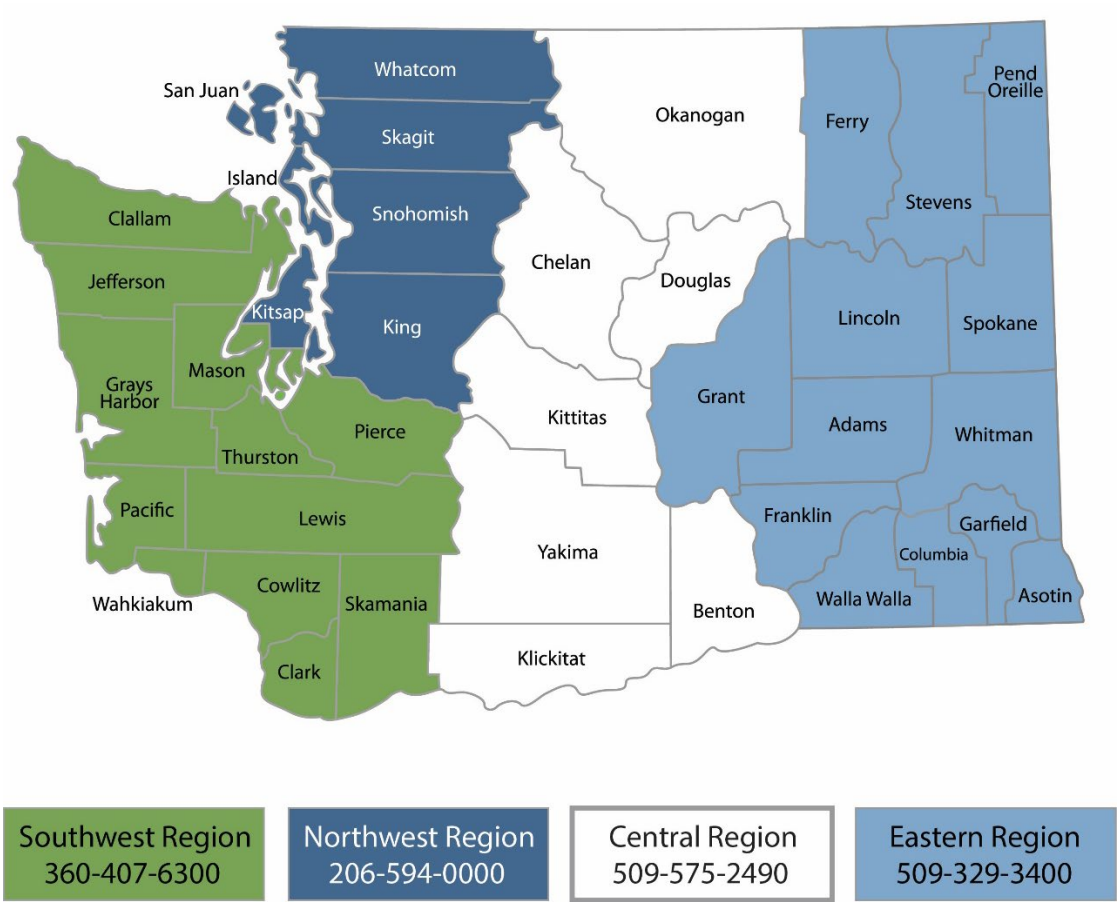
The Department of Ecology is committed to providing people with disabilities access to our information and services by meeting or exceeding the requirements of state and federal laws.

To request an ADA accommodation, email sgil461@ecy.wa.gov, call (360) 746-9182, or call Ecology through the Washington Telecommunication Relay for services including text telephone (TTY) at 711 or through your preferred relay service provider. Visit ecology.wa.gov/ADA for more accessibility information.

[1] www.ecology.wa.gov/contact

Department of Ecology's Region Offices

Map of Counties Served



Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	PO Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	PO Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	PO Box 47600 Olympia, WA 98504	360-407-6000

Investigating the Use of Unamended Soils for Treatment of 6PPDQ in Stormwater

Interim Progress Report

Water Quality Program
Washington State Department of Ecology
Olympia, WA

September 2026| Publication 26-10-060



Table of Contents

List of Figures and Tables **2**

Figures 2

Tables 2

Executive Summary **3**

Introduction **4**

Background 4

Study goals 5

Experimental Design and Methodology **6**

Experimental design 6

Bioretention system construction and flushing 2

Soil collection and analysis 3

Stormwater collections 7

Data treatment and analysis 8

Results **9**

Soil characteristics and background concentrations 9

Soil persistence study 26

Discussion **30**

Influent and effluent 6PPDQ concentrations 30

Summary **34**

References **36**

List of Figures and Tables

Figures

Figure 1. Schematic of the experimental design 1
Figure 2. Schematic of the bioretention column. 2
Figure 3. Bioretention system during the experiment. 3
Figure 4. Map of soil sampling locations. 6
Figure 5. Location of the stormwater sampling site. 8
Figure 6. Grain size for the unamended soils and the bioretention soil mix. 12
Figure 7. Average concentrations of 6PPDQ in soil over the persistence study. 27
Figure 8. Concentrations of 6PPDQ in influent (red bars) and effluent (blue bars) in three unamended soils and one bioretention soil mix. 31
Figure 9. Percent removal of 6PPDQ by three unamended soils and one bioretention soil mix. 32

Tables

Table 1. Properties of target soils for collection from the USDA web soil survey..... 4
Table 2. Soil Analyses and Methods 5
Table 3. Precipitation Amounts and Stormwater Sampling Dates 7
Table 4. Concentrations of metals and 6PPDQ in unamended soils and a bioretention soil mix.. 9
Table 5. Measured soil characteristics in the unamended soils and bioretention soil mix. 11
Table 6. Metal and 6PPDQ concentrations in effluent following a deionized water flush. 13
Table 7. Metal and 6PPDQ concentrations in stormwater collected on 10 January, 2025..... 14
Table 8. PAH concentrations in stormwater collected on 10 January, 2025..... 15
Table 9. Metal and 6PPDQ concentrations in influent and final effluent following the first stormwater application. 17
Table 10. Metal and 6PPDQ concentrations in the initial influent and final effluent following the second stormwater application. 19
Table 11. Metal and 6PPDQ concentrations in untreated stormwater collected on 31 January 2025. 20
Table 12. Metal and 6PPDQ concentrations in initial influent and final effluent following the third stormwater application..... 21
Table 13. Metal and 6PPDQ concentrations in untreated stormwater collected on 16 February. 22
Table 14. Metal and 6PPDQ concentrations in initial influent and final effluent following the fourth stormwater application. 23
Table 15. Metal, polycyclic aromatic hydrocarbon, and 6PPDQ concentrations in stormwater collected February 25. 24
Table 16. Metal and 6PPDQ concentrations in the initial and final effluent following the fifth stormwater application. 25
Table 17. Timepoints and sampling dates for the soil persistence study. 26
Table 18. Metal concentrations in soil over the persistence study..... 29

Executive Summary

A recent review of stormwater best management practices identified bioretention as a potentially effective method for reducing concentrations of the tire particle derived contaminant, N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone (6PPDQ). Typically, bioretention systems utilize engineered soil mixes comprising a mineral aggregate and an organic fraction, such as compost. However, incorporating unamended soils into bioretention systems represents a potential low impact development best management practice that is more sustainable and preserves natural landscapes. Consequently, this interim report describes a study to determine the efficacy of three unamended soils for removal of 6PPDQ from stormwater. A total of three unamended soil types were collected from Capitol State Forest (Olympia, Washington) and tested for soil characteristics including organic matter, cation exchange capacity, pH, moisture content, and grain size as well as background concentrations of 6PPDQ, metals (cadmium, copper, lead, mercury, and zinc), and 13 polycyclic aromatic hydrocarbons. A 60:40 sand: compost BSM was sourced and tested for the same parameters as unamended soils.

To determine the capacity of unamended soils to remove 6PPDQ under storm conditions, runoff from four storm events were collected from the Lake Union Ship Canal Test Facility and collected stormwater was passed through a total of 12 columns containing three replicates of each of the four soil types at a flow rate representative of storm conditions. Concentrations of 6PPDQ in untreated stormwater ranged from near detection limits (0.003 micrograms per liter [µg/L]) to 0.680 µg/L. Overall, three of the tested unamended soil types showed good removal of 6PPDQ (greater than or less than 94 percent), with one of the three unamended soils showing significantly lower removal (87 percent) relative to the other soil types (94 to 95 percent, Dunn's Test, p less than 0.05). The tested BSM removed 94 percent of the measured 6PPDQ. Following five applications of the collected stormwater, potential persistence of 6PPDQ in soil was determined by repeated sampling at days 0, 7, 15, 30, 60, and 90 following the last stormwater application. Persistence of 6PPDQ was variable across the tested soils, with 6PPDQ not measured above reporting limits after 30 days in the Centralia Loam and Olympic Clay soils but still detected up to 60 days later in the BSM. Overall, these findings will be used to develop sustainable, low-impact solutions for managing priority stormwater contaminants such as 6PPDQ.

Introduction

This interim progress report describes the results of a study conducted by EA Engineering, Science, and Technology, Inc., PBC (EA) to determine the efficacy of unamended soils in mitigating levels of N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone (6PPDQ) in stormwater. This study was conducted as part of a larger project focused on the potential use of unamended soils as best management practices (BMPs) for stormwater 6PPDQ mitigation. This project is funded by the Washington Department of Ecology (Ecology) through the Environmental Consulting Services statewide contract.

Background

Tire wear particles (TWP) generate pollutants such as microplastics and N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), which may be transported to aquatic environments through stormwater runoff. Impacts to coho salmon from 6PPD, a tire anti-degradant, and its metabolite 6PPDQ in Washington State were first observed in the 1980s when monitoring surveys reported abnormal swimming behaviors and increased pre-spawning die-offs associated with more urbanized waterbodies (Scholz et al. 2011). Further studies elucidated a suite of organic contaminants in TWP leachates associated with salmon die-offs in urban streams (Peter et al. 2018), with 6PPDQ, ultimately identified as the primary driver of coho salmon mortality (Tian et al. 2021). Since these studies, 6PPD and 6PPDQ have been detected in a range of matrices globally, including roadside dust, terrestrial soils, atmospheric fine particles, and stormwater (Chen et al. 2023). Given that 6PPDQ has been shown to induce toxicity to salmonids at concentrations below those recorded in the environment (Tian et al. 2022), developing approaches to mitigate stormwater contamination is a priority.

In a literature review conducted in 2022, Ecology evaluated a suite of stormwater BMPs for their potential efficacy in mitigating 6PPDQ concentrations and identified data gaps (Ecology 2022). A suite of BMPs were identified as having high potential to remove 6PPD and 6PPDQ, including street sweeping, bioretention, infiltration basins, and soil mixes consisting of sand and organic matter, with additional BMPs including vegetation, modular wetlands, and vegetation identified as having medium potential effectiveness. One approach to address management of roadway-related contaminants such as 6PPD and 6PPDQ is to invest in low impact development (LID) BMPs. This approach employs designs that incorporate aspects of nature-based solutions, such as preservation of natural landscapes and utilization of plants for retention of pollutants. LID approaches offer the advantage of using on-site natural features to manage stormwater, including the use of unamended soil, tree retention, vegetated roofs, and rainwater harvesting. Due to their use of on-site natural features, LID approaches may be implemented more easily and may be more cost efficient compared to specifically designed retention cells and other approaches. However, implementation of these approaches is limited by a lack of information regarding their efficacy in removal of 6PPD and 6PPDQ. For example, no studies to date have quantified the removal of 6PPD and 6PPDQ by unamended soils, with most research implementing modified soils such as high performance bioretention soil mixes (BSM) (McIntyre et al. 2015, 2023).

Study goals

The goals of this study were as follows:

- To quantify the reduction of 6PPDQ by three unamended soils with different characteristics (e.g., cation exchange capacity [CEC], percent organic carbon, grain size) relative to a standard BSM
- To determine the longevity of 6PPDQ in unamended soils and BSM following use for stormwater mitigation

Experimental Design and Methodology

This section describes the experimental design and methodology, including construction of the bioretention system, identifying and collecting appropriate soils, collection and application of stormwater, and analysis of stormwater contaminants. These components are discussed in further detail in the following subsections.

Experimental design

An overview of the experimental design for the study is shown on Figure 1. Overall, the study intended to test the efficacy of three different soil types for removal of 6PPDQ from stormwater compared to a standard BSM. Three replicates of each of the 4 soil types was targeted, totaling 12 individual bioretention columns. Overall, 5 individual stormwater applications were planned with a target frequency of one stormwater application per week. The Lake Union Ship Canal Test Facility (SCTF), Seattle, Washington, which is commonly used for BMP testing and stormwater analysis, was the target collection site for stormwater.

For each stormwater sampling event, a total collection volume of at least 61.2 liters (L) was targeted to allow for sufficient stormwater to pass through each column at a rate of 10.6 milliliters per minute (mL/min) for 8 hours. This rate was chosen based on previous studies adopting a similar design and is equivalent to a heavy rain event based on Canadian and European classification systems (Environment Canada 2013; United Kingdom Met Office 2012). Simulated storm rates are greater than those commonly observed on the US West Coast and are intended to be a worst-case scenario. For example, our tested storm rates equate to approximately 35 mm/hr, with average maximum storm intensities on the US West Coast ranging from 1.5 – 3 mm/hr (Lamjiri et al. 2017). Upon each stormwater collection, untreated stormwater samples were submitted to Texas Tech University and Alliance Technical Group (Fremont, Washington) for analysis of 6PPDQ and metals/ polycyclic aromatic hydrocarbons, respectively. Though 6PPDQ was the primary focus of this project, metals and PAHs were incorporated primarily to understand the correlation between concentrations of 6PPDQ and other common stormwater contaminants. To determine the potential influence of shipping and temporary storage on concentrations of stormwater contaminants, resampling of stormwater following receipt at the EA Ecotoxicology Laboratory and immediately prior to applications to soil was targeted. Following the application of stormwater to columns, EA intended to collect treated effluent for analysis of the same suite of contaminants (6PPDQ, metals, and PAHs) to determine the removal efficiency relative to initial concentrations. Finally, to determine the persistence of 6PPDQ in soil after use in bioretention systems, EA intended to sample the soil on days 0, 7, 15, 30, 60, 90, and 120 after the final stormwater application for 6PPDQ, metal, and PAH analysis.

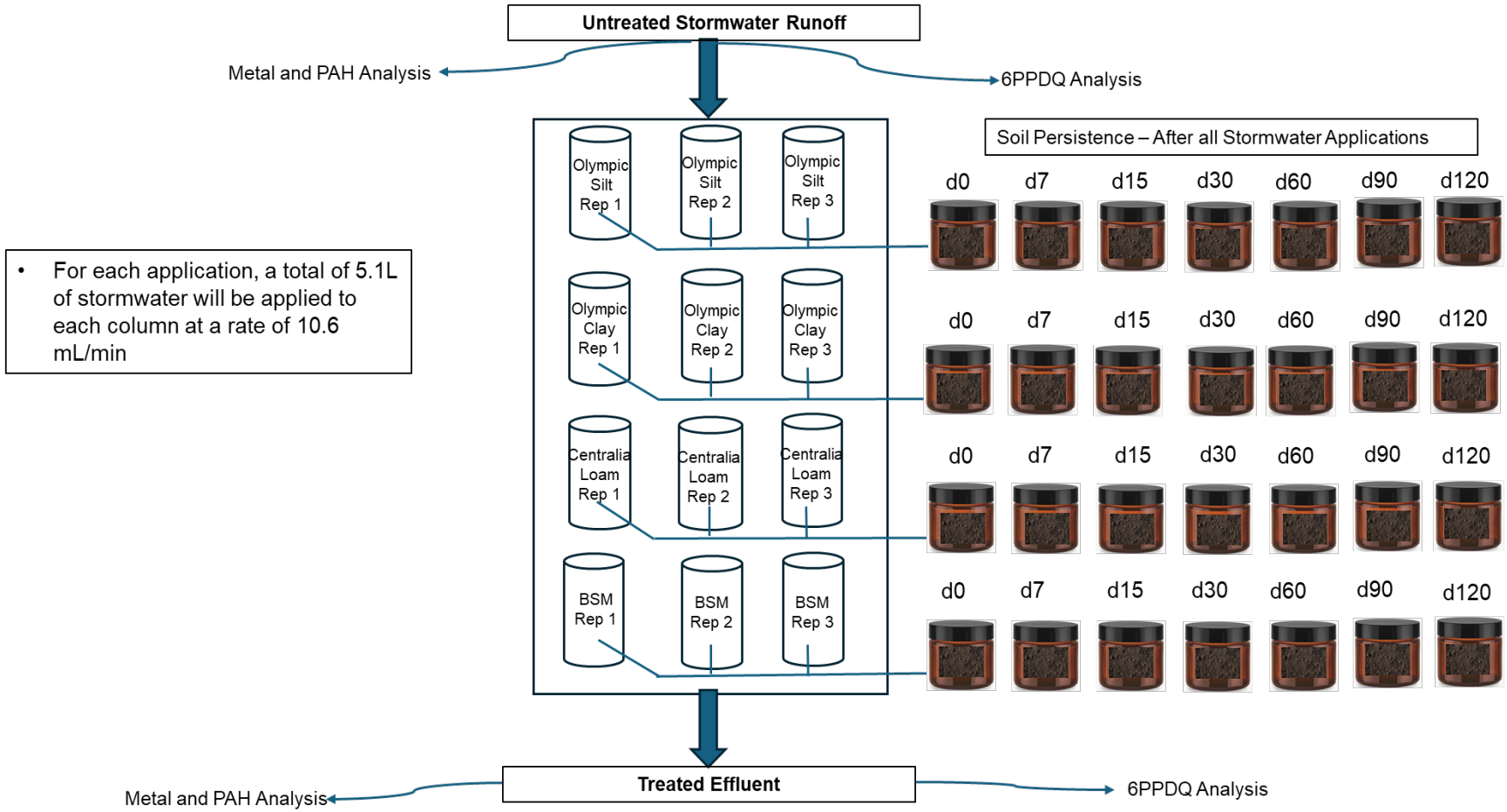


Figure 1. Schematic of the experimental design

Bioretention system construction and flushing

As described in the Experimental design section above, twelve bioretention columns were constructed for the initial experiment. Each column consisted of a polyvinyl chloride pipe with a diameter of 15.2 centimeters (cm) (equivalent to 6 inches) and a height of 60 cm (23.6 inches) as shown on Figure 2. Each column was fitted with Nitex nylon mesh (50 micrometers) at the bottom to allow applied stormwater to drain into the collection vessel.

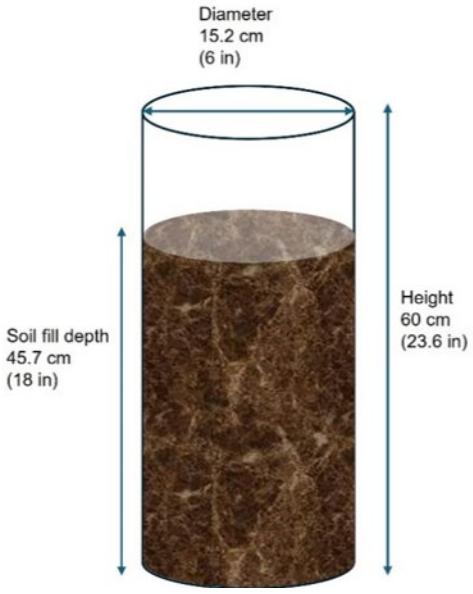


Figure 2. Schematic of the bioretention column.

Each of the columns was placed on a wooden shelving unit with peristaltic pumps located above to introduce stormwater to the columns at a predetermined rate (Figure 3). A 75.7 L header tank (equivalent to 20 gallons) was placed behind the columns from which stormwater was pumped. A polyethylene funnel was fitted underneath each column to minimize loss of treated stormwater, with a glass 9.5 L tank (equivalent to 2.5 gallons) underneath each funnel to collect treated stormwater. The bioretention system was housed within a climate-controlled laboratory with a 16:8 L:D light cycle.

To test for background contamination prior to initiating the experiment, an initial flush of the system using deionized water (DI) was performed in December 2024 after soils were transferred to columns and placed on the system. A total of 5.1 L of DI sourced from EA's Ecotoxicology Laboratory in Hunt Valley, Maryland, was added to each individual column at a rate of 10.6 mL/min. For the initial DI flush only, effluent was composited across each soil type (i.e., samples from each of the three replicates per soil type was combined) and shipped for analysis of 6PPDQ, metals, and PAHs. For all subsequent testing with collected stormwater, effluent from each individual column was analyzed separately.



Figure 3. Bioretention system during the experiment.

Soil collection and analysis

As highlighted in the Experimental design section, three unamended soil types were targeted for this study, with a goal to identify soils differing in primary characteristics such as particle size and CEC to determine the influence of these parameters on 6PPDQ removal efficiency. In addition, identifying a collection location in an area of low urban development and imperviousness was an important consideration to avoid background 6PPDQ contamination. Based on a desktop evaluation using ArcGIS, the Washington soils map from the Washington Geospatial Open Data Portal (Washington State Department of Natural Resources 2025), and the U.S Department of Agriculture's (USDA) Web Soil Survey (USDA 2025), Capitol State Forest was identified as a candidate location for soil collection. Additionally, soils were targeted to meet the physical and chemical suitability (SSC-6) for infiltration BMPs as described in Ecology's Stormwater Management Manual for Western Washington (SWMMWW, Ecology 2024). This criterion includes the following:

- CEC value of ≥ 5 milliequivalents CEC/100g dry soil.
- Soil depth minimum of 18 inches

- Minimum of 1% organic content.
- No waste fill materials

This location was chosen due to the associated land use, which was predominantly forested with a low degree of impervious surface, as well as the presence of several different soil types in close proximity (Figure 2). Prior to initiating fieldwork, a general land use license was obtained on 1 November 2024, from the Washington State Department of Natural Resources to allow field staff to access and collect soil from the site. The following soil types were targeted: Centralia Loam, Olympic Clay, and Olympic Silt. Further details on these soils from the USDA's Web Soil Survey are provided in Table 1.

Table 1. Properties of target soils for collection from the USDA web soil survey.

Soil Type	K_{Sat} inches per hour)	Typical Profile	Drainage Class	Hydrologic Soil Group
Olympic Silt	Moderately high, 0.20 – 0.57	0 – 12 inches: silt loam 12 – 24 inches: silty clay loam 24 – 60 inches: clay	Well drained	C
Olympic Clay	Moderately high, 0.20 – 0.57	0 to 7 inches: clay loam 7 to 22 inches: silty clay loam 22 to 60 inches: silty clay	Well drained	C
Centralia Loam	Moderately high to high, 0.57 – 1.98	0 to 16 inches: loam 16 to 50 inches: clay loam 50 to 60 inches: loam	Well drained	B

Notes:
KSat = saturated hydraulic conductivity.

Soil sampling was conducted on 8 November 2024. Soils were collected using a stainless-steel hand trowel, with one individual trowel used for each soil type to minimize cross-contamination. For each soil type, two samples were added to a 500 mL amber glass jar, with headspace, and shipped on ice to Texas Tech University for subsequent 6PPDQ analysis. Soil samples for 6PPDQ analysis were stored at 4 degrees Celsius (°C) prior to shipping on 11 November 2024 and received at the laboratory on 12 November 2024. An additional single 118 mL polypropylene jar was collected for each soil type for analysis of PAHs, metals, CEC, organic content, and sample moisture. Finally, a single 473 mL polypropylene jar was filled for each individual soil type for grain size analysis. Samples for PAH, metal, and soil characteristics were stored on ice after collection and delivered by field staff to Alliance Technical Group on the day of collection. Analysis methods followed either U.S. Environmental Protection Agency (EPA) or ASTM International (ASTM) standard protocols with further details provided in Table 2.

The remaining soil was transferred to two individual 18.9L- (5-gallon) high-density polyethylene buckets, taped closed, and shipped to EA's Ecotoxicology Laboratory. Bulk soil samples were shipped on 9 November 2024, a day after collection and received on 18 November 2024. The BSM was procured from Pacific Top Soil in Everett, Washington, on 19 November 2024. The BSM was a 60/40 bioretention and rain garden soil meeting state and local requirements for

bioretention (https://pacifictopsoils.com/products/60-40-bio-retention-rain-garden-soil/ provides additional details). Upon collecting, samples were distributed to sample vessels and shipped for the analyses described previously, with the remaining bulk soil shipped to EA's Ecotoxicology Laboratory and received on 25 November 2024. Soils were stored at 4°C in the dark until bioretention experiments were initiated. Prior to stormwater collections, soil was transferred to individual pre-labelled columns using individual stainless-steel trowels for each soil type to minimize potential cross-contamination. Three columns were included for each soil type, with the columns organized randomly on the bioretention system to minimize bias associated with sample placement.

Table 2. Soil Analyses and Methods

Parameter	Method	Values Measured
6PPDQ	EPA 1634 (EPA 2023)	6PPDQ
PAHs	EPA 8270ESIM (EPA 2018)	1-Methylnaphthalene, 2-Methlynapthalene, Acenaphthene, Acenaphthylene, Benz[a]anthracene, Benzo[a]pyrene, Benzo(b)fluoranthene, Benzo(ghi)perylene, Benzo(k)fluoranthene, Chrysene, Dibenzo(ah)anthracene, Fluoranthene, Fluorene, Indeno(1,2,3-cd)pyrene, Naphthalene, Phenanthrene, and Pyrene
Metals	EPA 6020B (EPA 2014)	Cadmium, Copper, Lead, Mercury, and Zinc
pH	EPA 9045 (EPA 2004)	pH value
Organic Content	ASTM D2974 (ASTM 2025)	Percent Organic Matter
Cation Exchange Capacity	EPA 9081 (EPA 2014)	CEC in milliequivalents per 100 grams (meq/100g)
Sample Moisture	NA	Percent Moisture
Grain Size	ASTM D422 (ASTM 2007)	Percentage of Individual Grain Size Fractions

Notes:
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
ASTM = ASTM International
EPA = U.S. Environmental Protection Agency
meq/100g = milliequivalents per 100 grams
NA = not analyzed
PAH = polycyclic aromatic hydrocarbons

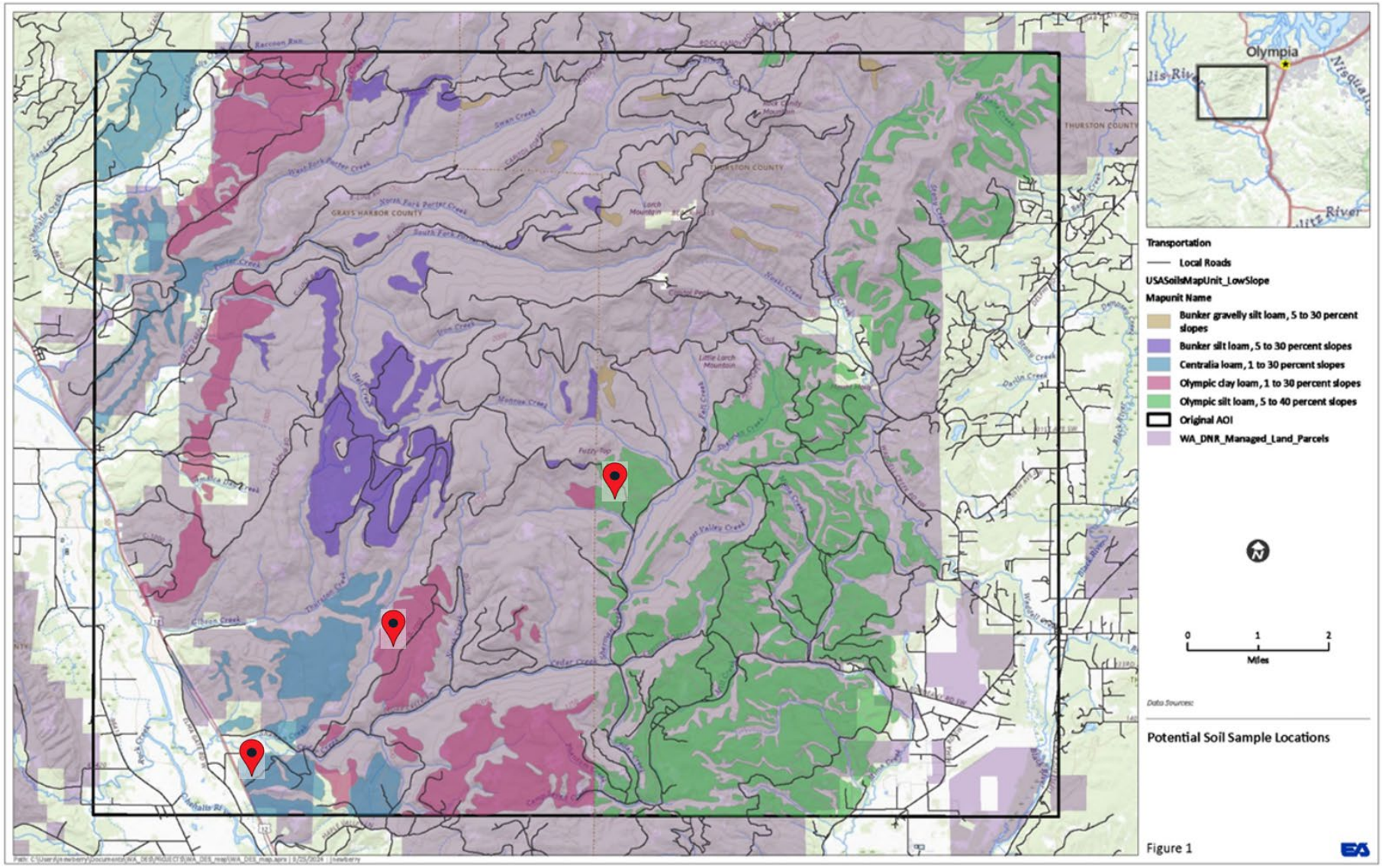


Figure 4. Map of soil sampling locations.

Stormwater collections

Four stormwater collections were conducted on 10 and 31 January 2025 and 16 and 25 February 2025 Though EA initially targeted five stormwater collections, sustained periods of dry weather throughout the winter sampling period necessitated collection of double the target amount of stormwater (61.2 L, doubled to 122.4 L) during the first collection event on 10 January 2025. Details on each collection event including precipitation amounts and antecedent precipitation (amount of rain on the day immediately prior to collection) are provided below in Table 3.

Table 3. Precipitation Amounts and Stormwater Sampling Dates

Collection Date	Average Temperature (°C)	Amount of Precipitation (cm)	Antecedent Precipitation (cm)
10 January 2025[(a)]	6.7	0.97	0
31 January 2025	7.2	1.2	0.25
16 February 2025	7.2	0.48	0.05
25 February 2025	8.6	1.2	0.94

Notes:
(a) The amount of stormwater collected was doubled for this sampling event.
°C = degrees Celsius
cm = centimeter(s)
Antecedent precipitation refers to the amount of rain on the day immediately prior.

Collections were conducted at the Lake Union SCTF (Figure 5), where stormwater draining a major highway travels through a network of polyvinyl-chloride pipes with various access locations. Stormwater samples were collected by opening a supply valve with dedicated tubing leading to an 9.5 L-high-density polyethylene carboy (equivalent to 2.5 gallons). Seven 2.5-gallon carboys were targeted for each stormwater collection, with carboys placed within coolers packed with ice for shipping to EA's Ecotoxicology Laboratory in Hunt Valley, Maryland.

At each sampling event, stormwater samples were added directly to two 250-mL amber glass jars for 6PPDQ analysis. In addition, a single 500-mL amber glass jar and a 250-mL high-density polyethylene bottle were filled with stormwater during each sampling event for PAH and metal analysis, respectively. Finally, a field blank consisting of DI water that was treated in the same manner as the stormwater was submitted for 6PPDQ analysis at each sampling event.

Samples for 6PPDQ analysis were either shipped to the analytical laboratory the following day or within 3 days following storage in the dark at 4°C. For example, untreated stormwater samples collected on 10 and 31 January 2025 for 6PPDQ analysis were held for 3 days in the dark at 4°C prior to shipping to avoid samples arriving outside of analytical laboratory hours.

The holding time for 6PPDQ extraction under EPA Method 1634 is 14 days following collection (EPA 2024), with 6PPDQ concentrations known to be stable for up to 150 days when stored at 5°C within glass jars (Lane et al. 2024). Samples for metal and PAH analysis were delivered to the laboratory on the same day as stormwater collections.

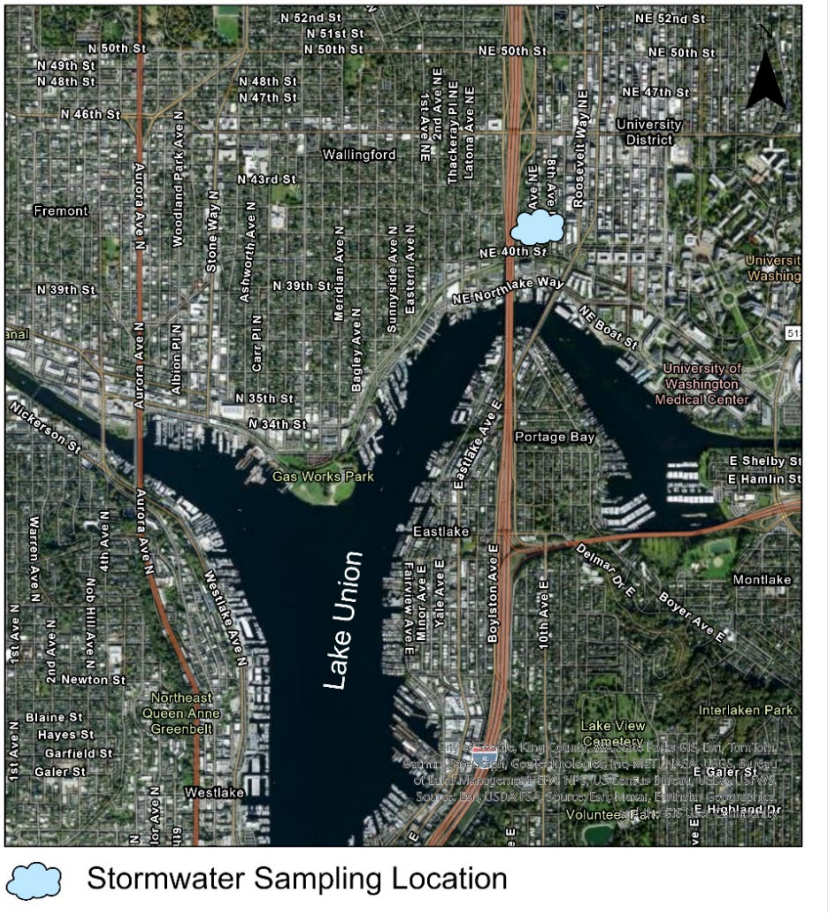


Figure 5. Location of the stormwater sampling site.

Data treatment and analysis

To compare the efficacy of different soil types for mitigating 6PPDQ, percent removal of 6PPDQ was calculated using the following equation:

$$\frac{Influent\ Concentration - Effluent\ Concentration}{Influent\ Concetration}$$

Measured concentrations in stormwater following shipment and receipt to the EA Ecotoxicology Laboratory were used as the influent concentration. Concentrations below the limit of detection (LoD) were replaced with a value of 0.5*LoD, with values below the limit of reporting (LoR) replaced with 0.5*LoR. To compare the percent removal of 6PPDQ across soil types, a nonparametric Kruskal-Wallis H-test with a post hoc Dunn's Test was used, with alpha α set at 0.05.

Results

Soil characteristics and background concentrations

Metal, polycyclic aromatic hydrocarbon, and 6PPDQ concentrations

Metal concentrations in each of the collected soil types are given below in Table 4. For the unamended soils, values are shown compared to mean statewide concentrations taken from Ecology's Toxics Cleanup Program (Ecology 1994). The value for mercury represents a mean concentration for western Washington due to a lack of statewide data. Overall, concentrations of zinc and mercury exceeded Washington background concentration in all three unamended soil types, with two of the three soil types exceeding background for lead (Centralia Loam and Olympic Clay) and copper (Olympic Clay and Olympic Silt). However, geochemical and mineralogical maps of Western Washington indicate that elevated concentrations of copper and zinc up to 325 mg/kg and 104 mg/kg may be present in the Capitol State Forest area (U.S. Geological Survey [USGS] 2017). Furthermore, soil concentrations of mercury are known to be elevated in forested areas of the Pacific due to the high amounts of precipitation and binding to vegetation and forest soils (USGS 2016).

PAHs were not detected in any of the analyzed unamended soils with detection limits ranging from 0.003 to 0.1 mg/kg. Three PAHs were detected in the BSM sample, with concentrations of 0.0351 mg/kg, 0.0428 mg/kg, and 0.0249 mg/kg for fluoranthene, phenanthrene, and pyrene, respectively. 6PPDQ was not detected in the unamended soils, with concentrations below detection limits (0.05 nanograms per gram [ng/g]) in all three collected soil types. A single sample of the BSM contained trace concentrations of 6PPDQ at 0.75 micrograms per kilogram (µg/kg) dry weight. The source of the trace 6PPDQ in the BSM is unclear; however, the presence of compost within the BSM may have contributed to 6PPDQ occurrence due to the potential for sequestration of urban runoff within this media. Furthermore, the BSM was stored in an urban location prior to procurement for this study and may have been exposed to roadway dust.

Table 4. Concentrations of metals and 6PPDQ in unamended soils and a bioretention soil mix.

Soil Type	Copper (mg/kg)	Cadmium (mg/kg)	Lead (mg/kg)	Mercury (mg/kg)	Zinc (mg/kg)	6PPDQ (µg/kg)
Centralia Loam	19.5 (20.5)	0.0859 (0.63)	10.2 (10.1)	0.0859 (0.04)	77.9 (55.5)	
Olympic Clay	48.4 (20.5)	0.146 (0.63)	13.7 (10.1)	0.18 (0.04)	98.1 (55.5)	<LoD
Olympic Silt	147 (20.5)	0.247 (0.63)	4.7 (10.1)	0.0588 (0.04)	81.2 (55.5)	<LoD
BSM	18	0.115	4.14	0.0467	45.3	0.75

Notes:
Values in parentheses represent statewide mean concentrations for all metals excluding mercury, which represents the mean for western Washington. All values are from Ecology (1994).
µg/kg = microgram(s) per kilogram
<LoD = below limit of detection

6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
BSM = bioretention soil mix
LoD = limit of detection (0.15 ng/g)
mg/kg = milligram(s) per kilogram

Soil characteristics

Characteristics of each of the analyzed soils are provided in Table 5. Three of the unamended soils had CEC values below the 5.0 meq/100g threshold suggested in the Stormwater Management Manual for Western Washington (SWMMWW) (Ecology 2024a) for siting infiltration BMPs. The low CEC values were discussed with both the analytical laboratory and Ecology staff including stormwater engineers in December 2024, and the soils were approved for use in our experiments. The SWMMWW indicates that lower CEC values may be considered dependent on the soil loading capacity, target pollutant, and local jurisdiction (Ecology 2024a). All soils had organic matter content exceeding the target 1 percent from the SWMMWW using method ASTM D2974 as specified in the SWMMWW (Ecology 2024a). The unamended soils had notably higher organic matter and moisture content compared to the BSM (Table 5), with organic matter ranging from 13.2 to 16.4 percent and 8.72 percent in the unamended soils and the BSM, respectively. Unamended soils were more acidic compared to the BSM, with pH values ranging from 5.51 to 5.93 and 7.5 in the unamended soils and the BSM, respectively.

Grain size analysis for each individual soil type is shown below on Figure 6. Overall, grain size was comparable among the three unamended soils, with the percentage of clay ranging from 15 percent (Centralia Loam) to 16.2 percent (Olympic Clay). The Olympic Silt soil had a higher proportion of fine and medium sands (8 and 16 percent, respectively) compared to the other unamended soils (range: 4.1 to 5 percent for fine sands and 5 to 8.7 percent for medium sands), with the Centralia Loam soil having the highest proportion of coarse sand (30 percent, compared to 25.8 percent and 19 percent in the Olympic Clay and Olympic Silt soils, respectively). Finally, the BSM was found to consist predominantly of medium sand (50.9 percent), with a much lower proportion of clay (3.8 percent) and silt (2.7 percent) relative to the unamended soils.

Grain size data was used to calculate K_{Sat} values for each soil type based on the equation below from Table V-5.3 of the SWMMWW (2024):

$$log_{10}K_{Sat} = -1.57 + 1.90 * d_{10} + 0.015 * d_{60} - 0.013 * d_{90} - 2.08 * f_{fines}$$

Where:

K_{Sat} = saturated hydraulic conductivity (centimeters per second [cm/sec])
d_{10} = grain size for which 10 percent of the sample is finer (millimeters [mm])
d_{60} = grain size for which 60 percent of the sample is finer (mm)
d_{90} = grain size for which 90 percent of the sample is finer (mm)
f_{fines} = fraction of the soil (by weight) that passes a No. 200 sieve

The K_{Sat} value calculated using this method for the BSM exceeded 0.01 cm/sec. In this instance, the SWMMWW recommends recalculating the value using the below equation and using the greater of the two values for K_{Sat}.

$$log_{10}K_{Sat} = -1.32 + 1.225 * d_{10} - 0.376 * f_{fines}$$

It is important to note that the grain size equation is currently under revision in the forthcoming edition of SWMMWW due to a lack of conservatism in the approach as the soil gradation becomes finer. As such, there is some uncertainty in the calculated K_{Sat} values calculated within this report.

Table 5. Measured soil characteristics in the unamended soils and bioretention soil mix.

Soil Type	CEC (meq/100g)	pH	Moisture Content (%)	Organic Matter (%)	K_{Sat} (cm/sec)	K_{Sat} (inches per hour)
Centralia Loam	1.12	5.93	29.0	14.0	2.10E-03	2.97
Olympic Clay	3.11	5.97	25.7	16.4	1.91E-03	2.70
Olympic Silt	3.11	5.51	35.6	13.2	2.98E-03	4.22
BSM	1.09	7.5	19.6	8.72	9.39E-02	133

Notes:
% = percentage
BSM = bioretention soil mix
CEC = cation exchange capacity
cm/sec = centimeter(s) per second
K_{Sat} = Saturated hydraulic conductivity
meq/100g = milliequivalents per hundred grams

The high K_{Sat} value calculated for the BSM of 0.094 cm/sec (equivalent to 5.63 centimeters per minute [cm/min]) is consistent with infiltration rate values calculated for different BSMs by Jay et al. (2019). The single-ring falling head procedure was used by Jay et.al (2019) to determine infiltration rate for 13 different BSMs, with values ranging from 0.03 to 3.3 cm/min, compared with 5.63 cm/min for the 60:40 BSM in the present study. It is important to consider that the methods used to determine infiltration rate and the specific endpoint measured (i.e., infiltration rate versus K_{Sat}) are variable among studies, with the grain size method known to have lower precision than in situ field measurements such as pilot infiltration tests (Ecology 2024a).

For the unamended soils, values were slightly higher than published global geometric mean K_{Sat} values based on field measurements by Gupta et al. (2020). Values for loam, clay loam, and silt loam from Gupta et al. (2020) were 4.0E-04, 7.0E-04, and 5.2E-04 cm/sec, respectively, though these values were calculated using different methods to the present study.

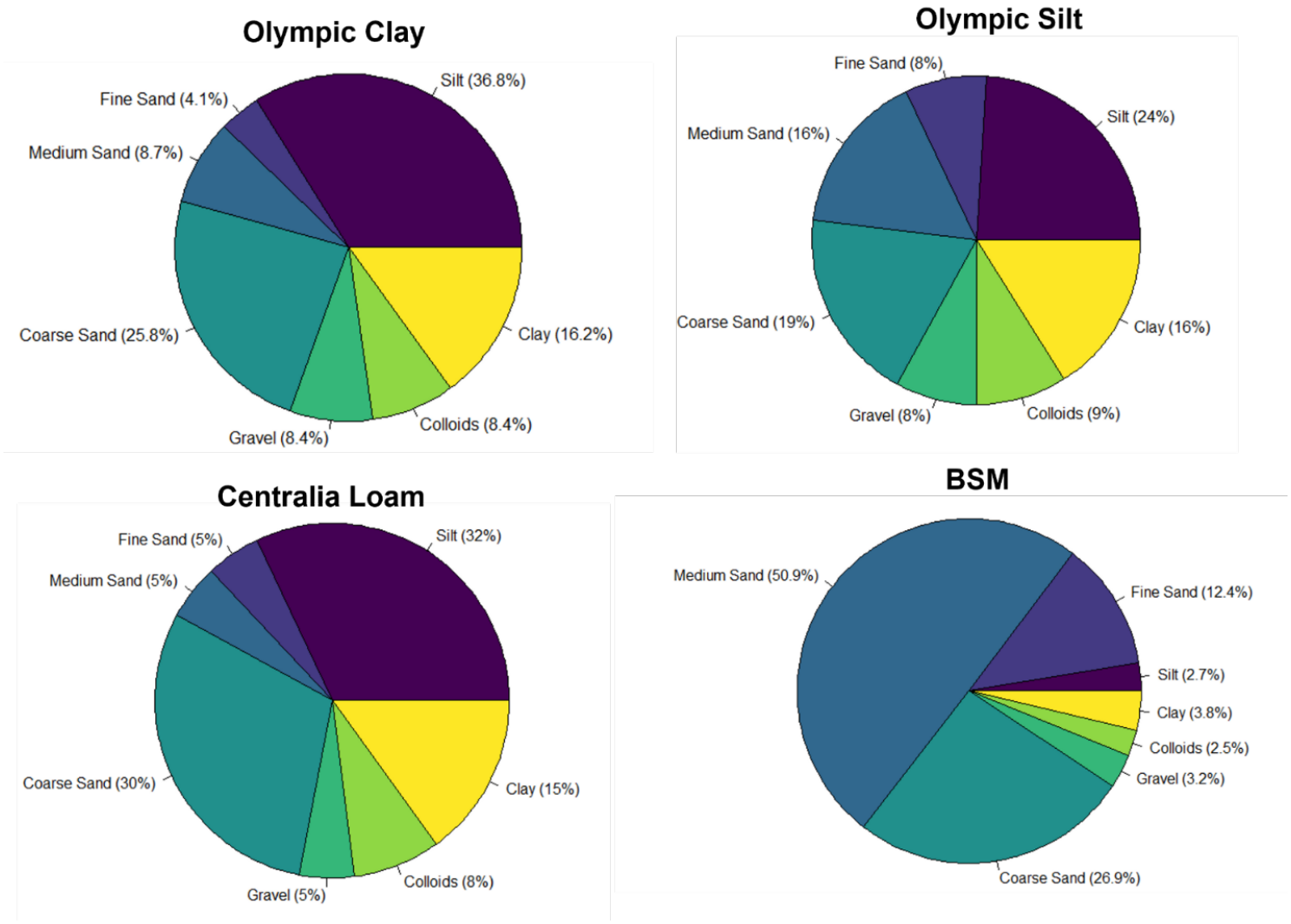


Figure 6. Grain size for the unamended soils and the bioretention soil mix.

Initial deionized water flush

As described in the Bioretention system construction and flushing section, an initial flush of the bioretention system was performed using DI water only prior to initiating stormwater testing. A total of 5.1 L of DI water was pumped from the glass 76 L header tank through each of the individual soil columns at a rate of 10.6 mL/min. The effluent was collected and shipped for analysis of 6PPDQ, select metals (cadmium, copper, mercury, lead, and zinc) and PAHs, with water from each of the three replicate soil columns per soil type composited for a single sample for each type. PAHs were not detected at concentration above the detection limits in any sample and are not shown in Table 6. Overall, the highest metal concentrations were observed in the BSM effluent, with zinc the highest measured metal at 127 micrograms per liter (µg/L). Previous studies have found that bioretention soil mixes can act as a source of metals, with Jay et al. (2019) finding higher concentrations of dissolved copper and lead in select soil mixes relative to stormwater. Measured concentrations 6PPDQ in DI water effluent were either below detection limits of 0.001 µg/L (unamended soils) or below reporting limits of 0.003 µg/L (BSM).

Table 6. Metal and 6PPDQ concentrations in effluent following a deionized water flush.

Soil Type	Lead (µg/L)	Copper (µg/L)	Zinc (µg/L)	Cadmium (µg/L)	Mercury (µg/L)	6PPDQ (µg/L)
Centralia Loam	3.63	6.85	15.4	0.107	<LoD	<LoD
Olympic Clay	1.26	6.53	5.72	0.065	<LoD	<LoD
Olympic Silt	0.942	26.4	6.78	ND	<LoD	<LoD
BSM	25.5	58	127	0.83	<LoD	<LoR

Notes:
Values in parentheses represent detection or reporting limits.
µg/L = microgram(s) per liter
<LoD = below limit of detection
<LoR = below limit of reporting

First stormwater application

As described above, the first stormwater collection was conducted on 10 January 2025 and was received at the EA Ecotoxicology Laboratory on 13 January 2025, following a shipping delay due to weather conditions. All sample vessels received were below 0.6°C upon receipt, indicating that samples were well preserved in transit and storage. Half of the received stormwater was added to the 76 L glass header tank on 13 January 2025 with the remaining half stored in a walk-in refrigerator at 4°C in the dark until use the following week. The stormwater added to the header tank was allowed to equilibrate to room temperature overnight, and the peristaltic pumps started on the morning of 14 January 2024. Immediately prior to starting the pumps, two additional water samples were taken from the header tank for 6PPDQ analysis with a single sample taken for metal and PAH analysis to monitor changes in concentrations from initial collection to use in the bioretention experiment. In Tables 3-4 and 3-5 and throughout, samples taken immediately from the stormwater collection site and shipped for analysis are labelled as 'Untreated', with samples taken after shipping and temporary storage labelled as 'Initial'.

For the metals and PAHs, concentrations declined from initial collection of stormwater to use in bioretention systems, with PAHs detected only in the untreated samples collected on 10 January 2025 and not following shipping and temporary storage on 14 January 2025 (Tables 7 and 8), likely due to volatilization during shipping. Furthermore, PAHs bind to suspended solids and particles owing to their high hydrophobicity; as such, settling of particles following shipping and temporary storage may have reduced measured aqueous concentrations from initial collection to subsequent use. Similarly, measured total metal concentrations declined by 80 to 87 percent from initial collection to use in bioretention systems, with cadmium initially detected at concentrations of 0.242 µg/L but not recorded above detection limits of 0.0301 µg/L in samples following shipping and temporary storage (Table 8). Reductions in 6PPDQ concentrations with shipping and storage were less marked, with concentrations of 0.68 and 0.60 µg/L measured in untreated samples collected on 10 January and concentrations of 0.33 and 0.40 µg/L measured prior to initiating experiments on 14 January indicating a 42 percent decrease. 6PPDQ was not detected in the field blank sample.

Table 7. Metal and 6PPDQ concentrations in stormwater collected on 10 January, 2025.

Sample ID	Collection Date	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Mercury (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Untreated	10 January 2025	0.242	48.8	20.5	<LoD	264	0.68
Untreated Duplicate	10 January 2025	NA	NA	NA	NA	NA	0.60
Initial	14 January 2025	<LoD	9.11	2.6	<LoD	48.2	0.33
Initial Duplicate	14 January 2025	NA	NA	NA	NA	NA	0.40

Notes:
µg/L = microgram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
ID = identification
NA = not analyzed
Untreated samples represent stormwater taken directly from the Ship Canal Test Facility and shipped for analysis.
Initial samples represent stormwater resampled after shipment and receipt at EA.

Table 8. PAH concentrations in stormwater collected on 10 January, 2025.

Sample ID	Benzo(b)fluoranthene (µg/L)	Benzo(ghi)perylene (µg/L)	Chrysene (µg/L)	Fluoranthene (µg/L)	Phenanthrene (µg/L)	Pyrene (µg/L)
Untreated	0.108	0.181	0.099	0.2	0.12	0.344
Initial	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD

Notes:
µg/L = microgram(s) per liter
<LoD = below limit of detection
ID = identification
Untreated samples represent stormwater taken directly from the Ship Canal Test Facility and shipped for analysis
Initial samples represent stormwater resampled after shipment and receipt at EA.

Average effluent concentrations across the three replicate columns are shown in Table 9, along with percent reductions in concentration relative to the initial. Overall, tested soils demonstrated removal of 6PPDQ, with effluent concentrations ranging from 0.019 ± 0.012 µg/L in the Centralia Loam effluent (average ± one standard deviation) to below reporting limits of 0.003 µg/L in the Olympic Silt effluent. Calculated percent removal for 6PPDQ ranged from 97 to 99.6 percent. For the metals, concentrations of copper and lead were higher in effluent of the BSM relative to the influent, with values of 17.9 and 4.71 µg/L for copper and lead in effluent, respectively, compared to concentrations of 9.11 and 2.60 µg/L for copper and lead in influent (Table 9). A reduction in metals was observed for all other soil types and test compounds, ranging from 43 to 83.2 percent.

Table 9. Metal and 6PPDQ concentrations in influent and final effluent following the first stormwater application.

Sample	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Initial Influent	<LoD	9.11	2.6	48.2	0.365
Centralia Loam Effluent	<LoD	3.48 ± 0.236 (61.8%)	1.10 ± 0.106 (57.7%)	8.97 ± 0.732 (81.4%)	0.019 ± 0.012 (97%)
Olympic Clay Effluent	<LoD	2.74 ± 0.314 (69.9%)	0.510 ± 0.105 (80.4%)	9.71 ± 2.31 (79.9%)	0.0048 ± 0.0045 (99.3%)
Olympic Silt Effluent	<LoD	11.3 ± 1.56 (-24%)	0.438 ± 0.224 (83.2%)	8.11 ± 6.36 83.2%)	< LoR (99.6%)
BSM Effluent	0.387 ± 0.149 (NA)	17.9 ± 4.27 (-96%)	4.71 ± 0.886 (-81%)	33.7 ± 8.55 (43.0%)	0.005 ± 0 (99.2%)

Notes:
µg/L = milligram(s) per liter
<LoD = below limit of detection
<LoD = below limit of reporting
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
Values in parentheses represent percent reduction relative to the influent.
Bolded values represent where concentrations in effluent were higher than influent.
NA = not applicable
6PPDQ influent concentration represents the average of the two initial samples.

Second stormwater application

On 20 January 2025, the remaining stormwater collected on 10 January 2025 was added to the 76 L glass header tank for equilibration. Prior to initiating the peristaltic pumps on 21 January 2025, duplicate water samples were taken for 6PPDQ analysis and a single sample taken for metal and PAH analysis as described previously. PAHs were not detected in any of the measured influent and effluent samples and are not shown in Table 10 below. Results were comparable with the first application, with effluent concentrations of 6PPDQ highest in the Centralia Loam soil type (average of 0.012 ± 0.006) and concentrations below reporting limits in the Olympic Silt soil (Table 10). Percent removal of 6PPDQ ranged from 97.1 percent in the Centralia Loam soil to 99.6 percent in Olympic Silt. For metals, effluent concentrations of copper, lead, and cadmium were higher in the effluent of the BSM relative to the influent, suggesting that the BSM acted as a source of these compounds. In addition, elevated concentrations of lead were observed in the effluent of the Olympic Silt soil, with average concentrations of 17.9 ± 30.3 µg/L. However, this was driven by concentrations of 52.9 µg/L in one of the three replicate effluent samples, with concentrations below detection limits and 0.395 µg/L in the other two replicates, indicating high variability.

Table 10. Metal and 6PPDQ concentrations in the initial influent and final effluent following the second stormwater application.

Sample ID	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Mercury (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Initial Influent	<LoD	6.79	1.35	<LoD	49.9	0.405
Centralia Loam Effluent	<LoD	2.95 ± 0.32 (62.3%)	0.689 ± 0.129 (49.0%)	<LoD	6.86 ± 0.977 (86.3%)	0.012 ± 0.006 (97.1%)
Olympic Clay Effluent	<LoD	2.52 ± 0.243 (62.8%)	0.317 ± 0.017 (76.5%)	<LoD	6.20 ± 1.79 (88.0%)	0.003 ± 0.004a (99.3%)
Olympic Silt Effluent	<LoD	9.23 ± 1.09	17.9 ± 30.3	<LoD	6.64 ± 1.99 (87%)	<LoD (99.6%)
BSM Effluent	0.271 ± 0.019	14.0 ± 3.48	2.85 ± 0.731	<LoD	34.1 ± 15.2 (31.7%)	0.004 ± 0.001 (99%)

Notes:
(a) One of the three replicates was <LoR and replaced with 0.5*LoR.
% = percent
µg/L = milligram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
Values in parentheses represent percent reduction relative to the influent.
Bolded values represent where concentrations in effluent were higher than influent.
6PPDQ influent concentration represents the average of the two initial samples.

Third stormwater application

Another stormwater collection was performed on 31 January 2025, for the third application to bioretention columns. Collected bulk stormwater was received at EA's Ecotoxicology Laboratory on 1 February 2025, added to the header tank on the same day and peristaltic pumps initiated 2 February 2025. Samples were taken for 6PPDQ and metal/PAH analysis immediately prior to initiating the pumps. PAHs were not detected in the collected stormwater samples. Overall, concentrations of both metals and 6PPDQ were lower in the second collection event compared to the first (Second stormwater application, Tables 10 and 11), with an average concentration of 0.31 ± 0.021 µg/L 6PPDQ compared to 0.64 ± 0.057 µg/L, respectively. Across all analyzed compounds, a smaller decline in concentrations was observed between stormwater collection and use in bioretention systems, likely due to the shorter hold time. For example, concentrations of 6PPDQ in two duplicate samples collected immediately from the SCTF site on 31 January 2025 were 0.29 and 0.32 µg/L, with similar concentrations of 0.29 and 0.35 µg/L measured 2 days later following shipping and temporary storage.

Table 11. Metal and 6PPDQ concentrations in untreated stormwater collected on 31 January 2025.

Sample	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Mercury (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Untreated 1/31	0.128	17	4.27	<LoD	104	0.29
Untreated 1/31 Duplicate	NA	NA	NA	NA	NA	0.32
Initial 2/2	0.082	13.7	2.12	<LoD	75.5	0.29
Initial 2/2 Duplicate	NA	NA	NA	NA	NA	0.35

Notes:
µg/L = milligram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
NA = not analyzed

Effluent concentrations relative to influent are shown below in Table 12. Overall, results were consistent with previous applications with all tested soils showing great than 90 percent removal of 6PPDQ. The Centralia loam soil was the least effective, with average measured effluent concentrations of 0.023 µg/L and a 6PPDQ percent reduction of 92.8 percent. Metal concentrations were lower in effluent samples compared to influent for this application, except for copper in the Olympic Silt soil, which had almost twofold higher average concentrations in effluent (25.7 ± 4.49 µg/L) compared to influent (13.7 µg/L).

Table 12. Metal and 6PPDQ concentrations in initial influent and final effluent following the third stormwater application.

Sample ID	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Initial 2/2	0.082	13.7	2.12	75.5	0.29
Initial 2/2 Duplicate	NA	NA	NA	NA	0.35
Centralia Loam Effluent	<LoD	3.99 ± 1.27 (71%)	0.983 ± 0.340 (54%)	12.2 ± 4.26 (84%)	0.023 ± 0.028 (92.8%)
Olympic Clay Effluent	<LoD	<LoD	<LoD	5.17 ± 0.65 (93%)	0.004 ± 0.004 (98.8%)
Olympic Silt Effluent	<LoD(a)	25.7 ± 4.49	<LoD	12.4 ± 2.06 (84%)	<LoD (99.8%)
BSM Effluent	0.075 ± 0.0164	9.82 ± 0.946 (28%)	1.74 ± 0.071 (17.9%)	16.2 ± 0.55 (79%)	0.008 ± 0.001 (97.5%)

Notes:
(a) Two of three effluent samples were less than LoD.
% = percent
µg/L = milligram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
BSM = bioretention soil mix
NA = not analyzed
Bolded values represent where concentrations in effluent were higher than influent.
6PPDQ influent concentration represents the average of the two initial samples.

Fourth stormwater application

Another stormwater collection was performed on 16 February 2025, with samples shipped to analytical laboratories and EA the following day. Bulk stormwater was received at EA on 18 February 2025, with the sample transferred to the 76 L header tank the same day and stormwater applied to columns on 19 February 2026. Consistent with previous application, a duplicate water sample was taken from the header tank immediately prior to initiating the application for analysis of 6PPDQ, with a single water sample taken for metal and PAH analysis. Concentrations of all compounds excluding cadmium were lower in stormwater collected on 16 February 2025 compared to previous rain events (Table 13). For example, measured concentrations of 6PPDQ ranged from 0.003 to 0.008 µg/L, compared with 0.29 to 0.68 µg/L in previous rain events. This was likely due to smaller rainfall on this day (0.48 cm) relative to other rain events sampled (0.97 to 1.2 cm, Stormwater collections).

Table 13. Metal and 6PPDQ concentrations in untreated stormwater collected on 16 February.

Sample	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Mercury (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Untreated 2/16	0.381	4.94	0.698	<LoD	90.3	0.004
Untreated 2/16 Duplicate	NA	NA	NA	<LoD	NA	0.003
Initial 2/19	0.378	5.18	1.00	<LoD	95.4	0.008
Initial 2/19 Duplicate	NA	NA	NA	<LoD	NA	0.005

Notes:
µg/L = milligram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
NA = not analyzed

Effluent concentrations relative to influent, as well as percent removal, are shown in Table 14. Concentrations of 6PPDQ were below reporting or detection limits in all soil types, excluding one replicate of the Centralia Loam soil that had concentrations of 0.004 µg/L. Percent removal of 6PPDQ was lower compared to previous applications; however, this was likely due to the use of half of the detection limit values for non-detects, which likely biased calculated removal values low. Similar to the previous application, high concentrations of copper were observed in the effluent of the Olympic Silt soil (399 ± 17.3 µg/L), with concentrations over an order of magnitude higher than influent (5.18 µg/L). Similarly, concentrations of zinc in the effluent of the Olympic Silt soil (170 ± 13.7 µg/L) exceeded the influent concentrations (95.4 µg/L).

Table 14. Metal and 6PPDQ concentrations in initial influent and final effluent following the fourth stormwater application.

Sample ID	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Initial Influent	0.378	5.18	1.00	95.4	0.0065
Centralia Loam Effluent	0.12 ± 0.029 (68%)	1.42 ± 0.727* (73%)	0.332 ± 0.051* (67%)	7.35 ± 1.16 (92%)	< LoR[(c)] (64%)
Olympic Clay Effluent	<LoD	<LoD	<LoD	17.2 ± 1.63 (82%)	<LoR[(a)] (82%)
Olympic Silt Effluent	0.055* (85%)	399 ± 17.3	0.360 ± 0.084 (64%)	170 ± 13.7	<LoD[b] (85%)
BSM Effluent	0.073 ± 0.020 (81%)	3.99 ± 1.27 (23%)	0.758 ± 0.150 (24%)	11.1 ± 1.57 (88%)	<LoR[a] (82%)

Notes:
(a) Two samples were <LoR, one was <LoD.
(b) Two samples were <LoD, one was <LoR.
(c) Two samples were <LoR, one was detected at 0.004 µg/L.
% = percent
µg/L = milligram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
BSM = bioretention soil mix
NA = not analyzed
Bolded values represent where concentrations in effluent were higher than influent.
6PPDQ influent concentration represents the average of the two initial samples.

Fifth stormwater application

The final stormwater collection was conducted on 25 February 2025, with bulk stormwater received at the EA Ecotoxicology Laboratory and added to the 76 L header tank on 26 February 2025. Initial water samples (two for 6PPDQ, one for metals and PAHs) were taken on 27 February 2025, immediately prior to initiating the peristaltic pumps. A single PAH, pyrene, was detected in the collected untreated stormwater sample at a concentration of 0.097 µg/L (Table 15) with this compound not recorded in any of the other analyzed samples, or in the sample taken after shipping and temporary storage.

Table 15. Metal, polycyclic aromatic hydrocarbon, and 6PPDQ concentrations in stormwater collected February 25.

Sample	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Mercury (µg/L)	Zinc (µg/L)	Pyrene (µg/L)	6PPDQ (µg/L)
Untreated 2/25	0.138	20.2	7.83	<LoD	109	0.097	0.196
Untreated 2/25 Duplicate	NA	NA	NA	NA	NA	NA	0.160
Initial 2/27	0.1	13.8	3.95	<LoD	77	<LoD	0.144
Initial 2/27 Duplicate	NA	NA	NA	NA	NA	NA	0.104

Notes:
µg/L = milligram(s) per liter
<LoD = below limit of detection
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
NA = not analyzed

Concentrations of metals and 6PPDQ in influent and effluent as well as percent removal are shown in Table 16. 6PPDQ showed high percent removal across all soil types, ranging from 90 to 99 percent, with the Centralia Loam having the lowest removal efficiency consistent with all other applications. Both cadmium and copper were recorded at higher concentrations in the effluent of the Olympic Silt soil (1.03 ± 0.537 and 301 ± 144 µg/L) compared to the influent (0.1 and 13.8 µg/L, respectively).

Table 16. Metal and 6PPDQ concentrations in the initial and final effluent following the fifth stormwater application.

Sample	Cadmium (µg/L)	Copper (µg/L)	Lead (µg/L)	Zinc (µg/L)	6PPDQ (µg/L)
Initial	0.1	13.8	3.95	77	0.124
Centralia Loam Effluent	0.063 ± 0.015 (37.3%)	4.42 ± 1.39 (68%)	1.37 ± 0.426 (65.3%)	11.6 ± 2.06 (84.9%)	0.012 ± 0.011 (90%)
Olympic Clay Effluent	0.279 ± 0.0331	2.25 ± 0.286 (83.7%)	0.457 ± 0.103 (88.4%)	11.7 ± 1.78 (84.8%)	<LoR[(a)] (99%)
Olympic Silt Effluent	1.03 ± 0.537	301 ± 144	0.241 ± 0.158 (93.9%)	2.5 ± 0 (96.8%)	0.006 ± 0.008 (95%)
BSM Effluent	0.114 ± 0.0582	10.4 ± 2.27 (24.6%)	1.53 ± 0.280 (61.3%)	15.4 ± 1.70 (80%)	<LoR[(a)] (98%)

Notes:
(a) <LoD in one replicate.
% = percent
µg/L = microgram(s) per liter
<LoR in one replicate, and above reporting limit in other replicate
<LoR = below limit of reporting
6PPDQ = N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine-quinone
BSM = bioretention soil mix
Bolded values represent where concentrations in effluent were higher than influent.
6PPDQ influent concentration represents the average of the two initial samples

Soil persistence study

Immediately following the final stormwater application, soil samples (25 grams per sample for 6PPDQ, 10 grams for metals and PAHs) from each individual column were collected for analysis of all stormwater contaminants. This collection timepoint was considered d0, with samples taken at the following intervals: d7, d15, d30, d60, d90, and d120. Since the primary goal was to determine the persistence of 6PPDQ, once data indicated 6PPDQ was below reporting or detection limits in all three replicates, further sampling at additional timepoints was not conducted. A summary of samples taken is provided in Table 17.

Table 17. Timepoints and sampling dates for the soil persistence study.

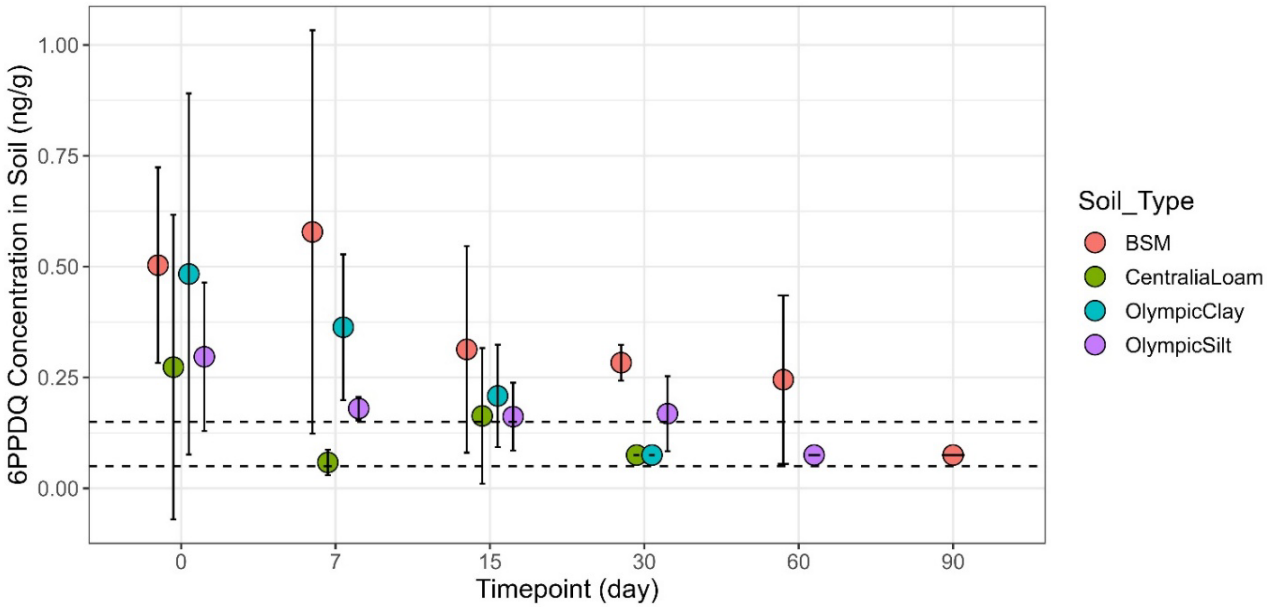
Timepoint	Date	Samples Taken
d0	2/27/2025	BSM, Olympic Clay, Olympic Silt, Centralia Loam
d7	3/6/2025	BSM, Olympic Clay, Olympic Silt, Centralia Loam
d15	3/14/2025	BSM, Olympic Clay, Olympic Silt, Centralia Loam
d30	3/29/2025	BSM, Olympic Clay, Olympic Silt, Centralia Loam
d60	4/28/2025	BSM and Olympic Silt
d90	5/28/2025	BSM Only

Notes:
BSM = bioretention soil mix
d refers to sampling timepoint relative to last stormwater application.

6PPDQ persistence

Average 6PPDQ concentrations in all soil types across the persistence study are shown on Figure 3-2. At the initial d0 timepoint, the highest 6PPDQ concentrations were observed in the BSM, with an average concentration of 0.503 ± 0.221 ng/g, followed by the Olympic Clay (0.483 ± 0.407 ng/g), Olympic Silt (0.297 ± 0.167 ng/g), and Centralia Loam (0.273 ± 0.344 ng/g). For the Centralia Loam soil, two of the three replicates at the d0 timepoint were below the reporting limit of 0.15 ng/g, with no concentrations recorded above the reporting limit in this soil type at the d7 sampling timepoint. At the d7 sampling timepoint, the BSM similarly had the highest soil 6PPDQ concentration of 0.578 ± 0.455 ng/g, followed by Olympic Clay (0.363 ± 0.164 ng/g), and Olympic Silt (0.180 ± 0.0265 ng/g). At d15, one replicate of the Olympic Silt and Olympic Clay soils had 6PPDQ concentrations below the reporting limit of 0.15 ng/g, with average concentrations of 0.161 ± 0.0765 ng/g and 0.208 ± 0.116 ng/g. Consistently with previous sampling timepoints, the BSM had the highest average soil concentration of 0.313 ± 0.233 ng/g at the d15 sampling timepoint. At d30, all replicates of the Olympic Clay and Centralia Loam soil types were below the reporting limit, and no further sampling was conducted. For the Olympic Silt, two of three replicates were above the reporting limit, with an average concentration of 0.168 ± 0.0846 ng/g. Average concentrations of 0.283 ± 0.0404 ng/g were recorded in the BSM at d30. For the d60 timepoint, three replicates of the Olympic Silt

were below the reporting limit of 0.15 ng/g, with average concentrations of 0.245 ± 0.190 ng/g recorded in the BSM and one of the three replicates below the reporting limit. Finally, three replicates of the BSM had 6PPDQ concentrations below the reporting limit at the d90 timepoint.



Notes: Error bars represent ± standard deviation. The upper dashed line is the reporting limit of 0.15 ng/g, with the lower dashed line the detection limit of 0.05 ng/g.

Figure 7. Average concentrations of 6PPDQ in soil over the persistence study.

Few studies to date have considered the persistence of 6PPDQ in soil. A recent study by Weyrauch et al. (2025) considered the biodegradation of tire and road wear particles in water and soil over a 2-year period. The authors used both cryo-milled tire tread and untreated tire and road wear particles with an artificial soil according to standardized methods (i.e., International Organization for Standardization [ISO] Method 17556:2019-09) (ISO 2019). Weyrauch et al. (2025) determined a first-phase half-life of 108 days for 6PPDQ from tire and road wear particles in artificial soil. The methods used by Weyrauch et al. (2025) involved starting concentrations of 6PPDQ that were orders of magnitude higher than in the present study (8 micrograms per gram compared to less than 1 ng/g in the present study), with studies performed in the dark to minimize photochemical oxidation. Conversely, Xu et al. (2023) found a 50 percent loss of 6PPDQ from tire tread within 7 days in natural aerated soils exposed to light, with a 90 percent loss occurring within 60 days. Another study conducted by Mumford et al. (2024) recorded half-lives of radiolabeled (C14) 6PPDQ of 22.3 and 62.4 days in two different natural soil types collected from the United Kingdom. While our study used different methods to focus on persistence under more environmentally relevant conditions for bioretention, 6PPDQ concentrations declined by 50 percent after 60 days, 7 days, 15 days, and 15 days for the BSM, Centralia Loam, Olympic Clay, and Olympic Silt, respectively, which is broadly consistent with other studies of 6PPDQ degradation.

Our findings suggest that 6PPDQ was more persistent in the BSM compared to the unamended soils tested, with measurable concentrations up to 60 days following application of 6PPDQ-contaminated stormwater. The greater persistence in the engineered BSM is likely due to the addition of compost and the subsequent higher organic carbon content within this soil type. In a previous study, Hildebrandt et al. (2024) evaluated the sorption of 6PPDQ to a suite of treatment media and engineered soil mixes, including the 60:40 bioretention mix used within the present study, granulated activated carbon, zeolite, perlite, and several natural soils. The authors calculated higher solid-water partitioning coefficient (Kd) values for bioretention mixes containing compost compared to natural soils (Hildebrandt et al. 2024), indicating that 6PPDQ shows stronger sorption and lower mobility within bioretention mixes and is subsequently anticipated to be more persistent. It is important to note that the BSM was the only soil type used within this study that had measurable 6PPDQ concentrations prior to beginning stormwater applications (Metal, polycyclic aromatic hydrocarbon, and 6PPDQ concentrations Section), which may have influenced the mass balance of 6PPDQ within this soil type and overall persistence.

Metals and PAHs

The primary goal for measuring metals and PAHs within this study was to determine potential relationships among common stormwater contaminants and 6PPDQ, as opposed to demonstrating a reduction in effluent compared to influent concentrations. Excluding benzo(a)pyrene, benzo(b)fluoranthene, fluoranthene, and pyrene that were detected sporadically in the BSM only, no PAHs were detected. Concentrations of metals in soil over the persistence study are provided in Table 18. For the BSM, Olympic Silt, and Centralia Loam soil types, no significant effect of time on any of the measured metal concentrations were observed (ANOVA, $p > 0.05$). For the Olympic Clay soil, significantly higher copper concentrations were observed at d15 (66.9 ± 5.21 mg/kg) relative to d0 (45.1 ± 3.40 mg/kg) and d15 (47.7 ± 4.92 mg/kg, ANOVA, Post-hoc Tukey's HSD, $p < 0.05$). Similarly, significantly higher lead concentrations were observed in the Olympic Clay soil sampled at d15 (11.5 ± 0.513 mg/kg) and d30 (11.7 ± 0.361 mg/kg) relative to d0 (9.81 ± 0.920 mg/kg, ANOVA, Post-hoc Tukey's HSD). The increase in copper and lead concentrations observed over time may be related to heterogeneity in metal distribution with depth and insufficient mixing following repeated resampling. No significant differences in mercury and zinc concentrations over time were recorded for the Olympic Clay soil (ANOVA, $p > 0.05$).

Table 18. Metal concentrations in soil over the persistence study.

Soil Type	Timepoint	Cadmium (mg/kg)	Copper (mg/kg)	Lead (mg/kg)	Mercury (mg/kg)	Zinc (mg/kg)
BSM	d0	0.112 ± 0.0181	17.0 ± 4.03	4.32 ± 1.04	0.0689 ± 0.0297 UU	40.8 ± 9.26
Centralia Loam	d0	0.0877 ± 0.004	18.4 ± 0.757	8.57 ± 0.295	0.0646 ± 0.003 UU	72.7 ± 0.819
Olympic Clay	d0	0.165 ± 0.003	45.1 ± 3.40	9.81 ± 0.920	0.138 ± 0.011	82.4 ± 8.10
Olympic Silt	d0	0.373 ± 0.042	148 ± 11.6	3.41 ± 0.351	< LoD	85.7 ± 8.98
BSM	d7	0.125 ± 0.036	17.8 ± 6.21	4.7 ± 0.503	< LoD	41.9 ± 7.48
Centralia Loam	d7	0.104 ± 0.015	18.6 ± 1.01	9.22 ± 0.612	0.0558 ± 0.002 UU	74.4 ± 3.68
Olympic Clay	d7	0.205 ± 0.019	47.7 ± 4.92	11.0 ± 0.231	0.139 ± 0.002	89.9 ± 8.49
Olympic Silt	d7	0.342 ± 0.050	145 ± 16.4	2.92 ± 0.472	< LoD	90.5 ± 22.5
BSM	d15	0.113 ± 0.026	17.8 ± 2.60	4.23 ± 0.765	0.0477 ± 0.002 UU	39.6 ± 6.12
Centralia Loam	d15	0.104 ± 0.018	27.5 ± 0.520	8.81 ± 0.411	0.0654 ± 0.005	66.7 ± 9.66
Olympic Clay	d15	0.176 ± 0.024	66.9 ± 5.21	11.5 ± 0.513	0.129 ± 0.177	81.0 ± 5.14
Olympic Silt	d15	0.330 ± 0.0527	391 ± 75.1	3.56 ± 0.516	< LoD	80.7 ± 18.3
BSM	d30	0.128 ± 0.008	20.3 ± 1.79	4.53 ± 0.786	< LoD	41.7 ± 4.15
Centralia Loam	d30	0.0838 ± 0.005	16.4 ± 0.814	8.77 ± 0.539	0.0675 ± 0.002	64.2 ± 3.13
Olympic Clay	d30	0.160 ± 0.016	51.2 ± 11.7	11.8 ± 0.361	0.159 ± 0.012	84.5 ± 1.80
Olympic Silt	d30	0.332 ± 0.0359	160 ± 6.93	3.12 ± 0.385	< LoD	88.8 ± 3.48
BSM	d60	0.117 ± 0.029	17.7 ± 2.04	4.37 ± 0.791	0.0464 ± 0.007 UU	41.0 ± 3.45
Centralia Loam	d60	NA	NA	NA	NA	NA
Olympic Clay	d60	NA	NA	NA	NA	NA
Olympic Silt	d60	0.412 ± 0.0162	135 ± 23.1	3.54 ± 0.329	< LoD	82.7 ± 3.82
BSM	d90	0.135 ± 0.018	19.4 ± 1.66	5.20 ± 0.907	0.0451 ± 0.002 UU	46.8 ± 5.89
Centralia Loam	d90	NA	NA	NA	NA	NA
Olympic Clay	d90	NA	NA	NA	NA	NA
Olympic Silt	d90	NA	NA	NA	NA	NA

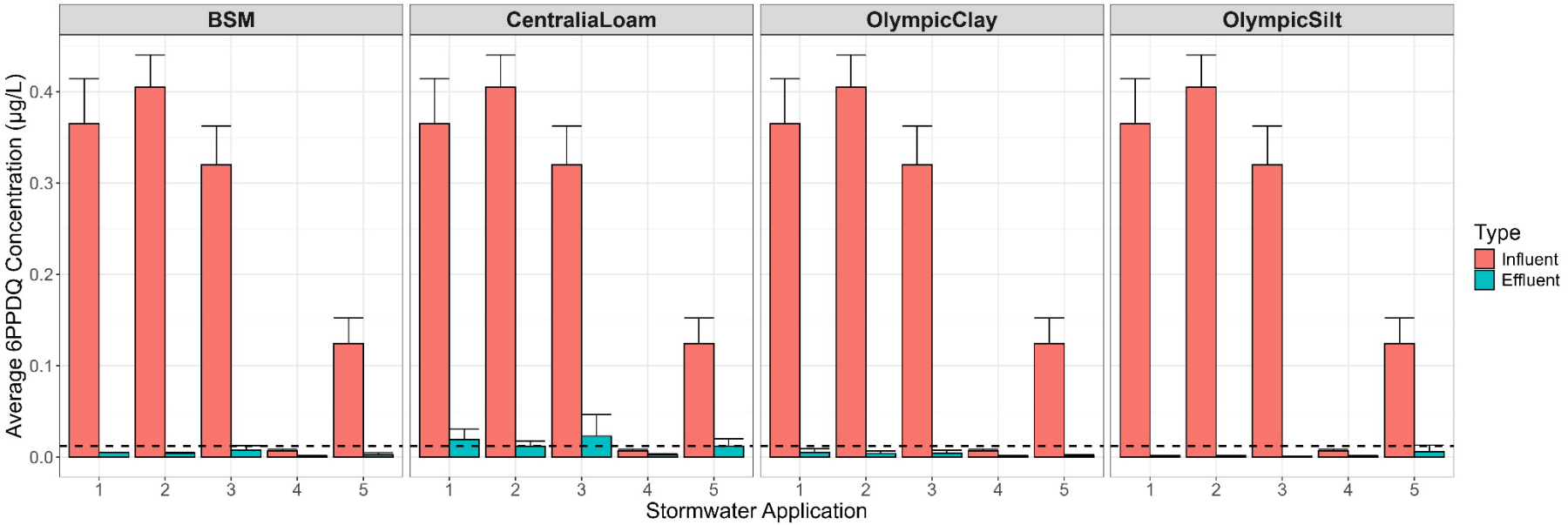
Notes:
< LoD = <LoD = below limit of detection
BSM = bioretention soil mix
mg/kg = milligram(s) per kilogram
NA = not analyzed
d refers to sampling timepoint relative to last stormwater application.

Discussion

Influent and effluent 6PPDQ concentrations

The concentrations of 6PPDQ in both influent and effluent across all soil types and stormwater applications are summarized on Figure 4-1. Influent concentrations shown below are based on the analysis of stormwater samples following shipment and temporary storage of collected stormwater. Average concentrations of 6PPDQ in influent ranged from 0.005 to 0.400 µg/L, with concentrations ranging from 0.003 to 0.680 µg/L in stormwater collected and shipped for analysis immediately following collection. These concentrations are slightly lower than those previously measured in stormwater samples collected from the Lake Union Ship Canal Test Facility, with a study by Herrera (2024) finding concentrations ranging from 0.421 to 1.04 µg/L based on 11 separate storm events. However, the Herrera (2024) study sampled larger storm events than the present work, with total storm depths ranging from 0.56 to 3.7 cm, compared with 0.48 to 1.2 cm within the study (Stormwater collections section). The concentrations of 6PPDQ in untreated stormwater measured during this study are consistent with urban areas around the world (Interstate Technology and Regulatory Council [ITRC] 2024). As summarized in ITRC (2024), concentrations of 6PPDQ from urban areas of Canada, the United States, Hong Kong, China, and Norway range from 0.00003 to 5.6 µg/L. A previous study by Zhao et al. (2023) measured 6PPDQ concentrations in roadway runoff from Seattle, Washington, finding an average concentration of 0.140 µg/L.

Effluent concentrations are shown on Figure 4-2 relative to the aquatic life criteria of 0.012 µg/L for 6PPDQ in the State of Washington (Ecology 2024b). For the Centralia Loam soil, average effluent concentrations for all applications excluding application 4 exceeded both the Ecology and EPA aquatic life criteria of 0.012 µg/L and 0.011 µg/L, respectively, with average values of 0.019 ± 0.012 µg/L, 0.012 ± 0.006 µg/L, 0.023 ± 0.023 µg/L, and 0.012 ± 0.008 µg/L for applications 1, 2, 3, and 5, respectively. Average effluent concentrations across all other soil types were below both aquatic life criteria in all applications.



Error bars are ± standard deviation. The black dashed line represents the Ecology Aquatic Life Criteria of 0.012 µg/L.

Figure 8. Concentrations of 6PPDQ in influent (red bars) and effluent (blue bars) in three unamended soils and one bioretention soil mix.

Percent removal of 6PPDQ

To compare the efficacy of the different soil types for mitigating 6PPDQ, percent removal was calculated for each of the five stormwater applications (Figure 4-2). Across all stormwater applications, average percent removal was 94.4 ± 8.03 percent, 87.8 ± 15.6 percent, 95.4 ± 7.14 percent, and 95.2 ± 7.55 percent for the BSM, Centralia Loam, Olympic Clay, and Olympic Silt, respectively. Percent removal of 6PPDQ in the Centralia Loam soil type was significantly lower than all other tested soil types (Dunn's Test, $p < 0.05$). No significant differences between any of the other tested soil types were observed (Dunn's Test, $p > 0.05$), indicating comparable 6PPDQ mitigation capacity between amended and two of the three tested unamended soil types. The lower percent removal for application 4 is likely an artifact of the low concentrations of 6PPDQ measured in the stormwater used for this application (average of 0.0065 µg/L) and use of half the detection limit values for 6PPDQ concentrations in effluent that were below detection limits.

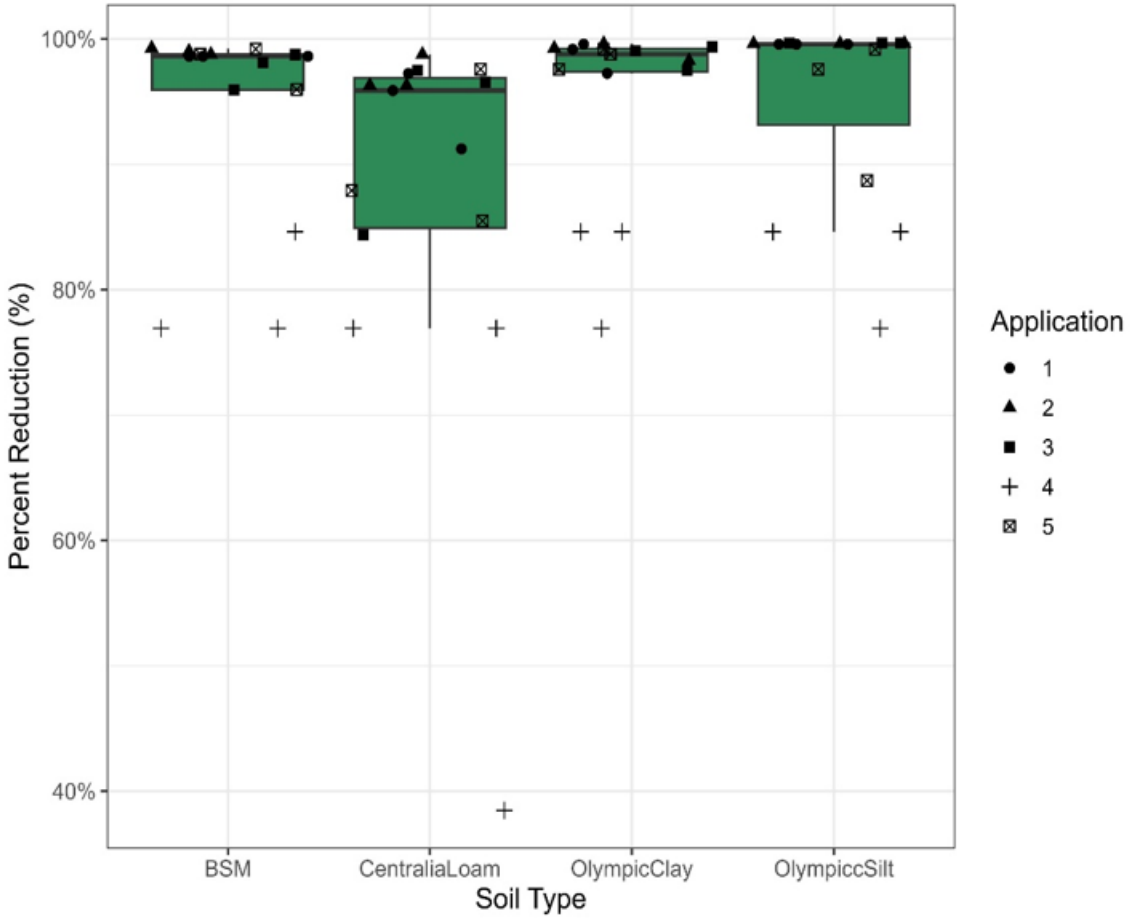


Figure 9. Percent removal of 6PPDQ by three unamended soils and one bioretention soil mix.

Given that the measured soil characteristics were broadly similar among the collected unamended soils (Soil characteristics and background concentrations section), the poorer performance of the Centralia Loam soil relative to the Olympic Clay and Olympic Silt soils for 6PPDQ removal are unclear. The Centralia Loam had the lowest measured CEC value of the

unamended soils (1.12 meq/100g), with CEC known to be positively correlated to the binding and subsequent bioavailability of metals and pesticides (Dollinger et al. 2015; Vega et al. 2010). The higher CEC values (3.11 meq/100g) in the Olympic Clay and Olympic Silt soils may have promoted greater binding of 6PPDQ from stormwater, leading to increased percent removal relative to the Centralia Loam. However, the measured CEC for the BSM, which showed high 6PPDQ percent reduction was 1.09 meq/100g, indicating that CEC may not have been the sole driver of the differences in 6PPDQ removal. Other soil parameters that are known to influence the binding of contaminants including microbial activity, organic matter content, and percent clay (ITRC 2017). The Centralia Loam soil had the lowest percent clay of the tested unamended soils (15 percent); thus, a lower clay percentage could have been a driver of the poorer performance, though clay percentages in the other two soils was not markedly different (16 and 16.2% for the Olympic Silt and Olympic Clay, respectively). Overall, further testing of soils with a broader range of characteristics including grain size, organic matter and clay content, and microbial activity would be required to determine underlying drivers of 6PPDQ removal in unamended soils.

Relationship among stormwater contaminants

Metals and PAHs were measured within this study with the primary goal of relating concentrations of common stormwater contaminants to 6PPDQ. Given that metals and 6PPDQ are likely to degrade at different rates during shipping and temporary storage, correlations were performed using only data derived from the initial collections from the SCTF and using all influent data that includes resampled stormwater after receipt at the EA Ecotoxicology Laboratory. Using only initial SCTF data, significant positive correlations were recorded between 6PPDQ concentrations and copper, lead, and zinc (Spearman's rho, $p < 0.05$), with no significant relationship recorded between 6PPDQ and cadmium concentrations (Spearman's rho, $p > 0.05$). These tests were based on only four data points due to metals being analyzed in a single stormwater sample from each of the four stormwater collections. As such, these findings are highly uncertain due to the low sample size and associated low statistical power. When including metal and 6PPDQ data from stormwater resampled after shipment, no significant relationships were observed between 6PPDQ concentration and any of the measured metals, which may reflect different degradation of metals and 6PPDQ in stormwater following temporary storage. Overall, these findings suggest that 6PPDQ may be positive correlated with other common stormwater contaminants; however, incorporation of a greater number of stormwater collections is required to increase statistical power.

Summary

This study aimed to determine the efficacy of unamended soils in removing 6PPDQ from stormwater and determine the persistence of 6PPDQ in soils following their use in bioretention columns. A total of three unamended soils were collected from Capitol State Forest (Olympia, WA), including Centralia Loam, Olympic Clay, and Olympic Silt. These soils were selected based on differing primary characteristics including grain size and clay content based on a desktop analysis, as well as the surrounding land use indicating low potential for background concentrations of 6PPDQ. A standard BSM, consisting of 60:40 sand: compost, used widely in bioretention systems was procured to compare findings. Prior to initiating column experiments, all soils were analyzed for pH, CEC, organic matter, grain size, metals, PAHs, and 6PPDQ. 6PPDQ was not recorded above the LoD in any of the unamended soils, with trace concentrations recorded in the BSM (0.75 µg/kg). The unamended soils had broadly similar characteristics including pH, organic matter, and CEC, with some differences observed in grain size and calculated K_{Sat}.

The bioretention system used for the study include three replicate polyvinyl chloride columns for each soil type filled to a depth of 18 inches (45.7 cm) following the SWMMWW guidelines for bioretention cells (Ecology 2024a). Stormwater was collected from the SCTF (Lake Union, Seattle, Washington) for testing, with a total of four stormwater collections and five applications to soil columns. For the first stormwater collection, the amount of stormwater collected was double in anticipation of a dry spell of insufficient rain. For each stormwater application, stormwater was resampled for analysis of 6PPDQ, metals, and PAHs following receipt of the stormwater at EA's Toxicology Laboratory to track any changes following temporary shipment and storage. For each soil column, a total of 5.1 L of stormwater was applied at a rate of 10.6 mL/min, and the effluent collected for analysis of metals, PAHs, and 6PPDQ. Measured concentrations of 6PPDQ in stormwater collected from the SCTF ranged from 0.003 to 0.68 µg/L and were consistent with previous 6PPDQ analyses from this site and urban areas in north America. PAHs were detected infrequently in collected stormwater, with zinc detected at the highest concentrations of the tested metals (range: 90.3 to 264 µg/L).

Overall, all three unamended soil types showed effective removal of 6PPDQ, with average percent removal of 87.8 percent, 95.4 percent, and 95.2 percent for the Centralia Loam, Olympic Clay, and Olympic Silt, respectively, relative to 94.4 percent removal in the BSM. The Centralia Loam soil type had significantly lower 6PPDQ removal relative to all other tested soil types, with effluent from four of the five applications exceeding proposed aquatic life criteria for 6PPDQ of 0.012 µg/L. In terms of soil persistence, 6PPDQ was recorded at low concentrations in all soil types following use in bioretention experiments (range: 273 to 0.503 ng/g). 6PPDQ was most persistent in the BSM, with concentrations still detectable 60 days following the final stormwater application, which may have been due to the increased binding capacity of the amended soil mix. For the unamended soils, 6PPDQ was not detected either 30 or 60 days after the final stormwater application. These findings will be used to develop effective, low impact mitigation strategies for 6PPDQ in urban stormwater.

A phase 2 study will be conducted to address several of the key questions arising from this study, including the soil characteristics driving the differences in 6PPDQ removal across unamended soils, the influence of adjacent land use and urbanization on unamended soil efficacy, and the incorporation of vegetation in bioretention soil mixes. This study will involve the collection of additional unamended soils from areas of high imperviousness that are expected to contain 6PPDQ, as well as soils with elevated levels of organic matter, a pure sand soil, and a pure silt soil to ascertain the underlying drivers impacting 6PPDQ removal. The final study will incorporate commonly used bioretention vegetation mixes along with unamended soils to determine the influence on 6PPDQ removal and potential bioaccumulation in plant tissue.

References

ASTM International. 2007. Standard Test Method for Particle-Size Analysis of Soils. ASTM D422-63(2007). February.

ASTM International. 2025. Standard Test Methods for Determining the Water (Moisture) Content, Ash Content, and Organic Material of Peat and Other Organic Soils. ASTM D2974-20e1. April.

Chen, X., He, T., Yang, X., Gan, Y., Qing, X., Wang, J., and Huang, Y. 2023. Analysis, environmental occurrence, fate and potential toxicity of tire wear compounds, 6PPD, and 6PPDQuinone. *Journal of Hazardous Materials*, *452*, 131245.

Dollinger, J., Dagès, C., and Voltz, M. 2015. Glyphosate sorption to soils and sediments predicted by pedotransfer functions. *Environmental Chemistry Letters*, *13*(3), 293-307.

Environment Canada. 2013. MANOBS. Manual of Surface Weather Observations. Seventh Edition Amendment 18. January.

Gupta, S., Hengl, T., Lehmann, P., Bonetti, S., and Or, D. 2020. SoilKsatDB: global soil saturated hydraulic conductivity measurements for geoscience applications. *Earth System Science Data Discussions*, *2020*, 1-26.

Herrera Environmental Consultants. 2024. *2023–2024 Summary Report. 6PPDQ in Highway Runoff and BMP Effectiveness Seattle, Washington and Portland, Oregon*. Prepared for Washington State Department of Ecology.

Hildebrant, A., Hu, X., Germeau, H., Gonzalez, M., Yih, F., Rideout, C. 2024. *Evaluation of 6PPD-Quinone Sorption to Treatment Media and Engineered Soil Mixes.* Final Report for Washington Ecology.

International Organization for Standardization (ISO). 2019. ISO 17556:2019. Plastics – Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved. Edition 3.

Interstate Technology and Regulatory Council (ITRC). 2017. Bioavailability of Contaminants in Soil: Considerations for Human Health Risk Assessment (ITRC BCS-1). November.

———. 2024. 6PPD and 6PPD-Quinone. Chapter 4. Occurrence, Fate, Transport, and Exposure Pathways.

Jay, J. G., Tyler-Plog, M., Brown, S. L., and Grothkopp, F. 2019. Nutrient, metal, and organics removal from stormwater using a range of bioretention soil mixtures. *Journal of Environmental Quality*, *48*(2), 493-501.

Lamjiri, M. A., Dettinger, M. D., Ralph, F. M., & Guan, B. (2017). Hourly storm characteristics along the US West Coast: Role of atmospheric rivers in extreme precipitation. *Geophysical Research Letters*, *44*(13), 7020-7028.

Lane, R. F., Smalling, K. L., Bradley, P. M., Greer, J. B., Gordon, S. E., Hansen, J. D., and Masoner, J. R. 2024. Tire-derived contaminants 6PPD and 6PPD-Q: Analysis, sample handling, and reconnaissance of United States stream exposures. *Chemosphere*, *363*, 142830.

McIntyre, J. K., Davis, J. W., Hinman, C., Macneale, K. H., Anulacion, B. F., Scholz, N. L., and Stark, J. D. 2015. Soil bioretention protects juvenile salmon and their prey from the toxic impacts of urban stormwater runoff. *Chemosphere*, *132*, 213-219.

McIntyre, J. K., Spromberg, J., Cameron, J., Incardona, J. P., Davis, J. W., and Scholz, N. L. 2023. Bioretention filtration prevents acute mortality and reduces chronic toxicity for early life stage coho salmon (Oncorhynchus kisutch) episodically exposed to urban stormwater runoff. *Science of the Total Environment*, *902*, 165759.

Mumford, I. Evans, D., Yeomans, P., Mumford, J. & Swales, S. 2024. The Fate of 6PPDQ-Quinone in Soil and Water-Sediment Systems Using a ^{14}C Radiotracer. Presentation at SETAC 45th Annual North American Meeting, Fort Worth, Texas.

Peter, K. T., Tian, Z., Wu, C., Lin, P., White, S., Du, B., and Kolodziej, E. P. 2018. Using high-resolution mass spectrometry to identify organic contaminants linked to urban stormwater mortality syndrome in coho salmon. *Environmental Science and Technology*, *52*(18), 10317-10327.

Scholz, N. L., Myers, M. S., McCarthy, S. G., Labenia, J. S., McIntyre, J. K., Ylitalo, G. M., and Collier, T. K. 2011. Recurrent die-offs of adult coho salmon returning to spawn in Puget Sound lowland urban streams. *PloS one*, *6*(12), e28013.

Tian, Z., Zhao, H., Peter, K. T., Gonzalez, M., Wetzel, J., Wu, C., and Kolodziej, E. P. 2021. An ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. *Science, 371*(6525), 185-189.

Tian, Z., Gonzalez, M., Rideout, C. A., Zhao, H. N., Hu, X., Wetzel, J., ... & Kolodziej, E. P. 2022. 6PPD-quinone: Revised toxicity assessment and quantification with a commercial standard. *Environmental Science & Technology Letters*, *9*(2), 140-146.

United Kingdom Met Office. 2012. Water National Meteorological Library and Archive. Fact Sheet 3 – Water in the Atmosphere.

U.S. Department of Agriculture. (2025). Web Soil Survey. Available here: https://websoilsurvey.nrcs.usda.gov/app/

U.S. Environmental Protection Agency (EPA). 1986. Method 9081: Cation-Exchange Capacity of Soils (Sodium Acetate). Revision 0. September.

———. 2004. Method 9045D: Soil and Waste pH. Revision 4. November.

———. 2014. Method 6020B: Inductively Coupled Plasma-Mass Spectrometry. SW-846 Update V. July.

———. 2018. Method 8270E: Semivolatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC-MS). SW-846 Update VI. July.

U.S. Environmental Protection Agency (EPA). 2023. Draft Method 1634: Determination of 6PPDQuinone in Aqueous Matrices Using Liquid Chromatography with Tandem Mass Spectrometry (LC/MS/MS). EPA 821-D-24-001. December.

———. 2024. Acute Aquatic Life Screening Values for 6PPD and 6PPD-Quinone in Freshwater. EPA 821-D-24-001. December. Office of Water. May.

U.S. Geological Survey (USGS). 2016. Widespread Mercury Contamination Across Western North America. September. Available at: https://www.usgs.gov/news/featured-story/comprehensive-study-finds-widespread-mercury-contamination-across-western-north

———. 2017. Geochemical and Mineralogical Maps, with Interpretation, for Soils of the Conterminous United States. Scientific Investigations Report 2017-5118.

Vega, F. A., Andrade, M. L., and Covelo, E. F. 2010. Influence of soil properties on the sorption and retention of cadmium, copper and lead, separately and together, by 20 soil horizons: comparison of linear regression and tree regression analyses. *Journal of Hazardous Materials*, *174*(1-3), 522-533.

Washington State Department of Ecology (Ecology). 1994. Natural Background Soil Metals Concentrations in Washington State. Toxics Cleanup Program. October. Publication #94-115.

———. 2022. Stormwater Treatment of Tire Contaminants Best Management Practices (BMP) Effectiveness. Final Report. Prepared by Evergreen StormH20, Geoengineers, and Tetra Tech. June.

———. 2024a. Stormwater Management Manual for Western Washington. Publication Number 24-10-013. July.

———. 2024b. Chapter 173-201A WAC (Aquatic Life Toxics Criteria).

Washington State Department of Natural Resources. 2025. WA Soils. Washington Spatial Data. Available at: https://geo.wa.gov/datasets/bfade7c2303541108fa543ff96aaa536_0/about

Weyrauch, S., Seiwert, B., Voll, M., & Reemtsma, T. 2025). Long term biodegradation study on tire and road wear particles and chemicals thereof. *Science of The Total Environment*, *975*, 179240. https://doi.org/10.1016/j.scitotenv.2025.179240

Xu, Q., Li, G., Fang, L., Sun, Q., Han, R., Zhu, Z., & Zhu, Y. G. (2023). Enhanced formation of 6PPD-Q during the aging of tire wear particles in anaerobic flooded soils: the role of iron reduction and environmentally persistent free radicals. *Environmental science & technology*, *57*(14), 5978-5987.

Zhao, H. N., Hu, X., Tian, Z., Gonzalez, M., Rideout, C. A., Peter, K. T., Dodd, M. C., and Kolodziej, E. P. 2023. Transformation Products of Tire Rubber Antioxidant 6PPD in Heterogeneous Gas-Phase Ozonation: Identification and Environmental Occurrence. *Environmental Science & Technology*, *57*(14), 5621–5632. https://doi.org/10.1021/acs.est.2c08690