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Quality Assurance Project Plan

Screening Model for 6PPD-q Delivery to the Stormwater Network

Prepared for
King County Water and Land Resources Division
King County Wastewater Treatment Division
King County Road Services Division

Prepared by
Herrera Environmental Consultants, Inc.

HERRERA
Science + Planning + Design

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Public Information

The EPA requires an approved Quality Assurance Project Plan (QAPP) for all EPA-funded projects that generate or use environmental information, including modeling efforts, before the projects begin. The plan describes the objectives of the study and the procedures to be followed to achieve those objectives This QAPP describes a project selected by the EPA's National Estuary Program (NEP)

Results from this project will be available on request from the authors or Ecology. Relevant data will be uploaded to Ecology's Environmental Information Management (EIM) database (www.ecy.wa.gov/eim/index.htm) and/or EPA's Water Quality Exchange (WQX) portal (https://www.epa.gov/waterdata/water-quality-data-wqx)

The QAPP is valid until August 2029. All QAPPs for programs or projects exceeding one year in duration shall be reviewed and recertified annually.

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1. Abstract

Tire-derived pollutants, such as 6PPD(N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine) and its oxidation product 6PPD-quinone (6PPD-q), are conveyed through roadway runoff to streams, causing coho salmon pre-spawn mortality and adverse effects to other salmonids and aquatic organisms. There are hundreds of stormwater outfalls within 100 feet of coho bearing streams in King County, Washington. King County roads vary in their potential to generate tire-derived toxic chemicals, and King County is looking to develop a method to prioritize the placement of stormwater treatment facilities.

This Quality Assurance Project Plan (QAPP) was prepared in support of the *Multi-Criterion Decision Tool to Address 6PPD-Q Tire Wear Particles project (Multi-Criterion Decision Tool* project hereafter*)*. More specifically, this QAPP addresses development of a 6PPD-q Screening Model (Screening Model) that predicts the relative delivery of 6PPD-q to the stormwater network via runoff from roadways. Under the *Multi-Criterion Decision Tool* project, the output from the Screening Model will be integrated into a King County stormwater prioritization tool (tool), which is a decision guidance tool being separately developed to support retrofit planning efforts. The tool will identify and prioritize drainage subbasins and roadway segments where improvements to existing stormwater management infrastructure would yield multi-benefit outcomes. The tool will compare subbasins and/or roadway segments. The tool allows the user to consider multiple decision criteria, such as presence of fish-bearing streams, hotspots of other stormwater pollutants, and metrics for human health equity, among others, when evaluating the selection and siting of stormwater retrofits.

The next phase of this project will include field sampling for 6PPD-q, which is outside of the scope of this QAPP and for which a separate QAPP will be developed. The purpose of the field sampling will be to characterize 6PPD-q export from roadways across a gradient of road use and road drainage characteristics. The 6PPD-q Screening Model, developed under this QAPP, will be used to support site selection across a gradient of output scores. This work will be funded mainly through a Puget Sound National Estuary Program (NEP) grant and an Interagency Agreement (IAA) with the Washington State Department of Ecology (Ecology), as well as through in-kind support from the Washington State Department of Transportation (WSDOT) and King County.

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2. Background

The *Project Overview* presents how this Modeling QAPP fits into the greater context of the overall project. The *Problem Statement* serves as the literature review that supported the project team's development of the conceptual model, with assistance from the subject matter experts (SMEs). The *Conceptual Model for 6PPD-q Delivery to Surface Waters* presents the conceptual model, which serves as the foundation for the Screening Model and Stormwater Prioritization Tool for this project by identifying the key factors that influence the delivery of 6PPD-q to surface water.

Tire-derived pollutants, such as 6PPD(N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine) and its oxidation product 6PPD-quinone (6PPD-q), are conveyed through roadway runoff to streams, causing coho salmon pre-spawn mortality and adverse effects to other salmonids and aquatic organisms. There are hundreds of stormwater outfalls within 100 feet of coho bearing streams in King County, Washington. King County roads vary in their potential to generate tire-derived toxic chemicals, and King County is looking to develop a method to prioritize the placement of stormwater treatment facilities.

This Quality Assurance Project Plan (QAPP) was prepared in support of the *Multi-Criterion Decision Tool to Address 6PPD-Q Tire Wear Particles project (Multi-Criterion Decision Tool* project hereafter*)*. More specifically, this QAPP addresses development of a 6PPD-q Screening Model (Screening Model) that predicts the relative delivery of 6PPD-q to the stormwater network via runoff from roadways. Under the *Multi-Criterion Decision Tool* project, the output from the Screening Model will be integrated into a King County stormwater prioritization tool (tool), which is a decision guidance tool being separately developed to support retrofit planning efforts. The tool will identify and prioritize drainage subbasins and roadway segments where improvements to existing stormwater management infrastructure would yield multi-benefit outcomes. The tool will compare subbasins and/or roadway segments. The tool allows the user to consider multiple decision criteria, such as presence of fish-bearing streams, hotspots of other stormwater pollutants, and metrics for human health equity, among others, when evaluating the selection and siting of stormwater retrofits.

This Screening Model seeks to identify and quantify the influential factors contributing to the delivery of 6PPD-q from roadways to surface waters, including sources, deposition, fate and transport, and treatment. This model will be an expert-knowledge-based spatial model that classifies roadways by the relative expected amount of 6PPD-q delivery to the stormwater drainage network, using available spatial data for model inputs. Model output will be a cumulative score based on high-influence factors. The next phase of this project will include field sampling for 6PPD-q. The purpose of the field sampling will be to characterize 6PPD-Q export from roadways across a gradient of road use and road drainage characteristics. The 6PPD-q Screening Model, developed under this QAPP, will be used to inform site selection across a gradient of road use and road drainage characteristics. This work will be funded mainly through a Puget Sound National Estuary Program (NEP) grant and an Interagency Agreement (IAA) with the Washington State Department of Ecology (Ecology), as well as through in-kind support from the Washington State Department of Transportation (WSDOT) and King County.

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The QAPP is being submitted to Washington State Department of Ecology (Ecology) in accordance with Agreement No. WQNEPSW-2023-KiCoRD-00003. The project includes U.S. Environmental Protection Agency (EPA) funding from the Puget Sound National Estuary Program (NEP) Stormwater Initiative Lead (SWSIL). Hence, this submission also aligns with EPA's sub-award terms and conditions that pertain to projects involving the collection, production, evaluation, or use of environmental information.[1]

2.1. Project Overview

This section provides an overview of the modeling project deliverables within the greater context of King County's Statement of Work for the *Multi-Criterion Decision Tool* project. The *Multi-Criterion Decision Tool* project includes development of a model to qualitatively estimate 6PPD-q export form roadways (Screening Model), field sampling to characterize of 6PPD-q in roadway runoff, validation of the model based on the results of the runoff study, and integration of model outputs into a decision-support tool for prioritizing roadway retrofit planning efforts. This Model QAPP focuses on the development of the qualitative Screening Model.

2.1.1. Modeling

This Modeling QAPP has been created to accompany the development of a Screening Model, which will provide qualitative estimates of 6PPD-q delivery to the stormwater drainage network (e.g., high, medium, and low). Table 1 summarizes the project deliverables. The "Quality Assurance Project Plan: Screening Model for 6PPD q Delivery to the Stormwater Network ("Modeling QAPP")" is satisfied by this document.

This Modeling QAPP describes the work needed to develop the Screening Model for the project. The Screening Model will use a combination of existing and emerging traffic and road data to create a GIS spatial data layer linking concentrations of roadway-derived contaminants in roadway runoff with road segment attributes.

The Screening Model will be developed through a multistep process further detailed in Section 6.2. Broadly, a conceptual model will be developed based on literature review and elicitation from subject matter experts (SMEs). Under advisement of SMEs, the conceptual model will be further refined and specified into an initial draft Screening Model based on the most influential factors affecting 6PPD-q export and availability of suitable spatial proxies for those factors. The initial draft Screening Model will be further reviewed by SMEs. This review will inform further refinement of the Screening Model and its

[1] The development of this QAPP and early modeling work were funded and managed through an existing project called the Water Quality Benefits Evaluation (WQBE) Toolkit. The WQBE Toolkit is a King County-funded effort to use modeling to provide consistent, science-based methods for assessing how actions improve water quality outcomes, which is one consideration for King County planning and prioritization processes. Work was already underway to model 6PPD-q as part of the WQBE Toolkit and so that work was leveraged to feed into the larger goals of the *Multi-Criterion Decision Tool to Address 6PPD-q Tire Wear Particles* project.

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underlying geospatial analysis. The resulting 6PPD-q spatial layer, model development process, and recommendations for improvements will be documented in a technical memorandum.

Table 1. Modeling Deliverables Summary

Deliverable	Purpose	Timeline
Quality Assurance Project Plan: Screening Model for 6PPD q Delivery to the Stormwater Network ("Modeling QAPP")	The Modeling QAPP will describe how traffic and road data will be used to create a GIS 6PPD-Q spatial data layer linking relative amounts of 6PPD-q in roadway runoff with road segment attributes	Q2–Q3 2024
Screening Model Technical Memorandum	Document how the 6PPD-Q spatial data layer was developed and identify data gaps that could be filled to further refine the map	Q3 2024

2.1.2. Sampling

The next phase of this project will include field sampling for 6PPD-q. The purpose of the field sampling will be to characterize 6PPD-Q export from roadways across a gradient of road use and road drainage characteristics. The 6PPD-q Screening Model, developed under this QAPP, will be used to inform site selection across a gradient of road use and road drainage characteristics. This work will be funded mainly through a Puget Sound National Estuary Program (NEP) grant and an Interagency Agreement (IAA) with the Washington State Department of Ecology (Ecology), as well as through in-kind support from the Washington State Department of Transportation (WSDOT).

Ten to twenty candidate sites will be selected based on the feasibility and safety of collecting samples of roadway runoff, while ensuring a gradient of Screening Model outputs are represented across the sites. After conducting field reconnaissance, up to 12 sites will be selected for the monitoring study. Site selection will be documented in a Site Screening Technical Memorandum (see Table 2). Monitoring data will include rainfall, discharge, total suspended solids, 6PPD-q, and particle size distribution. Collected 6PPD-q data will be used to ground truth and validate the Screening Model. The final report from that study may include recommendations for adjustments of the Screening Model to improve performance.

Separate from the Modeling QAPP and therefore not detailed herein, a Sampling QAPP describing the methods to be used (see Table 2) will be developed. The Sampling QAPP will describe methods used to collect stormwater samples from King County roads, including goals and objectives of sampling, types of data to be collected, sampling locations, data collection procedures, data collection frequency, duration of sampling period, data quality objectives, and data quality assurance review procedures.

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Table 2. Sampling Deliverables Summary

Deliverable	Purpose	Timeline
Site Screening Technical Memorandum	This memorandum will summarize observations at each candidate site and provide a list of recommended sites for stormwater sampling to be conducted. It will also include a summary of sampling methods expected to be potentially feasible at each stormwater sampling site and the pros and cons of each method. Some sampling methods will likely only be possible at sites with certain characteristics. Examples of sampling methods that may be considered include flow-weighted sampling of sheet flow with installation of curbs or weirs, flow-weighted sampling from stormwater pipes or ditches, manual time-weighted sampling with grabs, passive sampling technologies, and more.	Early 2025
QAPP: 6PPD-q Road Runoff Characterization Study (*Sampling QAPP*)	The *Sampling QAPP* will describe methods used to collect stormwater samples from King County roads, including goals and objectives of sampling, types of data to be collected, sampling locations, data collection procedures, data collection frequency, duration of sampling period, data quality objectives, and data quality assurance review procedures.	Early 2025
Stormwater Sampling Data Report	This document will develop a report including tabular and graphical summaries of the data collected under the *Sampling QAPP* and an evaluation of differences in field-collected 6PPD-q concentrations and those estimated by the 6PPD-q spatial data layer (i.e., field validation of the Screening Model). Recommendations for model improvements will be included.	Late 2026

2.1.3. Roadway Prioritization

Under the *Multi-Criterion Decision Tool* project, the output from the Screening Model will be integrated into a King County stormwater prioritization tool (tool), which is a decision guidance tool being separately developed to support retrofit planning efforts. The tool will identify and prioritize drainage subbasins and roadway segments where improvements to existing stormwater management infrastructure would yield multi-benefit outcomes. The tool will compare subbasins and/or roadway segments. The tool allows the user to consider multiple decision criteria, such as presence of fish-bearing streams, hotspots of other stormwater pollutants, metrics for human health equity, and principles of social justice, among others, when evaluating the selection and siting of stormwater retrofits.

King County will develop a final Road Segment Prioritization report that will summarize methods, results, lessons learned, and recommendations for future work.

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2.2. Problem Statement

For the past two decades, researchers in the Pacific Northwest of the United States (U.S.) have been studying urban runoff mortality syndrome (URMS) in coho salmon. Decades of investigations have sought to identify the chemical(s) causing the mortality in coho salmon (Tian et al. 2020, Tian et al. 2021). In 2020, researchers identified a chemical in stormwater. The chemical, 6PPD-quinone (6PPD-q), forms from an antioxidant, 6PPD, which is used in tires to extend their lifespan. This chemical is acutely toxic to coho and, to a lesser degree, toxic to several other aquatic species (Tian et al. 2021, 2022; Brinkmann et al. 2022; Hiki et al. 2021).

The following subsections provide more detail on the chemical and toxicological properties of 6PPD-q, its sources and deposition, fate and transport, and treatment. The authors acknowledge much of the information in these subsections was taken directly from the 2022 report "6PPD in Road Runoff Assessment and Mitigation Strategies"[2] prepared by Ecology. Where relevant, we have included additional information, particularly around tire wear particle (TWP) generation and deposition.

This section serves as the literature review to inform the development of the conceptual model. The conceptual model and, thereby, the Screening Model do not include all aspects of the information obtained through the literature review. During the expert elicitation process (see Section 6.2), some elements identified during the literature review were determined to be outside of the scope and scale of the model. The information is included here to document the results of the research.

2.2.1. What are 6PPD and 6PPD-q?

6PPD is a rubber antioxidant/antiozonant that is used in automobile tires to extend their lifespan (Tian et al. 2021, 2022; Brinkmann et al. 2022; Hiki et al. 2021). When 6PPD is exposed to air, it reacts with ozone or oxygen to create a degradation product called 6PPD-q. It is still unclear how long it takes for all the 6PPD to fully migrate out of a tire or its wear particles, but, eventually, the 6PPD will react with oxygen gas or ozone and will be released to the environment in various forms, called transformation products. Recent studies suggest that, upon exposure to the atmosphere and oxidation, about 10 percent of 6PPD in tires transforms to 6PPD-q and that the remaining 90 percent is transformed into other chemical byproducts with unknown fates and toxicity (Hu et al. 2022, Seiwert 2022). Several studies have been conducted related to the transformation of 6PPD to 6PPD-q in the presence of ozone under various conditions (Hu et al. 2022, Zhao et al. 2023, Seiwert et al. 2022); however, more research is needed to understand whether ozone concentrations as an environmental variable impacts the transformation of 6PPD to 6PPD-q.

[2] https://apps.ecology.wa.gov/publications/summarypages/2203020.html

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2.2.1.1. Chemical Structure

6PPD stands for the chemical N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine. The chemical formula for 6PPD is $C_{18}H_{22}N_2$ and the chemical formula for 6PPD-q is $C_{18}H_{22}N_2O_2$.

2.2.1.2. Toxicity

6PPD-q has been found to be highly toxic to juvenile coho salmon and other aquatic organisms (Table 3). Estimates of 6PPD-q toxicity closely matched estimates derived from bulk roadway runoff and tire wear particle (TWP) leachate exposures, indicating that 6PPD-q was contributing most of the observed mixture toxicity (Zhenyu, et al. 2021).

In tire leachate, 6PPD-q is likely not the only contaminant that is hazardous to aquatic life (Challis, et al., 2021; Rauert, et al., 2022). However, it appears that, in TWP leachate, 6PPD-q is the most toxic chemical to coho salmon adults (McIntyre & Kolodziej, 2021) and juveniles (Tian Z., et al., 2020). Brinkmann et al. (2022) investigated the acute toxicity of 6PPD-q to rainbow trout, brook trout, arctic char, and white sturgeon and reported 96-hour acute toxicity thresholds (LC_{50}) of 1.0 ug/L or less for the two trout species. Tian et al (2022) reported a revised juvenile coho salmon LC_{50} of 0.095 ug/L, indicating substantial sensitivity to 6PPD-q (Ecology 2022), and Lo et al. (2023) found even lower toxicity thresholds for newly feeding juvenile coho (~3 weeks post swim-up) at an LC_{50} of 0.041 ug/L.

Table 3. Summary of Toxicity Thresholds from Peer-Reviewed Literature.

Species	LC_{50} (ug/L)	Source
Brook Trout (*Salvelinus fontinalis*)	0.59 (24 hr)	Brinkmann et al. 2022
Rainbow Trout (*Oncorhynchus mykiss*)	1.00 (72 hr)	Brinkmann et al. 2022
Coho (juvenile) (*Oncorhynchus kisutch*)	0.095 (24 hr)	Tian, 2022
Coho (juvenile) (*Oncorhynchus kisutch*)	0.041 (24 hr)	Lo et al. 2023
Arctic Char (*Salvelinus alpinus*)	>14.2 (96 hr)	Brinkmann et al. 2022
White sturgeon (*Acipenser transmontanus*)	>12.7 (96 hr)	Brinkmann et al. 2022
Zebrafish larvae (*Danio rerio*)	>70 (96 hr)	Hiki et al. 2021
Japanese medaka (*Oryzias latipes*)	>40 (96 hr)	Hiki et al. 2021
Daphnia magna	>60 (40 hr)	Hiki et al. 2021
Hyalella azteca	>90 (96 hr)	Hiki et al. 2021

2.2.2. Sources and Deposition of 6PPD-q

2.2.2.1. Where does 6PPD-q come from?

The parent compound, 6PPD, from which 6PPDq is derived, is recommended for use as an antioxidant and antiozonant in the tread, sidewall, and rim strip of tires, as well as in the rubber cover of conveyor belts (Sheridan 2010). All tires produced by the 12 member companies of the U.S. Tire Manufacturers Association use 6PPD as the primary antiozonant (https://www.ustires.org/6ppd-and-tire-manufacturing). Tires that are stored uncovered and outdoors, as well as products with re-used tires, such as crumb

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rubber infills of synthetic turf, playgrounds, and materials that incorporate tire rubber (i.e., rubberized asphalt), may continue to contribute 6PPDq to the environment; however, direct investigation is required for confirmation.

Currently, the suspected primary pathway of 6PPD-q transport is via runoff carrying TWP from roads and parking areas to surface waters. 6PPD will continue to migrate from within a tire rubber matrix (including a TWP) to the surface of the TWP, until there is no more 6PPD remaining in the rubber matrix. Additionally, as long as 6PPD is in the presence of ozone or oxygen, it will form a variety of transformation products, including 6PPD-q.

TWPs on roadways come in all sizes. Some are large parts of tires generated when delamination or blowouts occur. Others are very small particles, between 5 and 300 µm, with an abundance reported between 70–80 µm (Kreider et al. 2010; Wagner, et al., 2018). These TWPs are caused by wear between the tire and road surface. During typical tire wear, small (<10 µm; clay to fine silt size) TWPs are emitted into the air. The smaller coarse and larger fine particles, particularly those between 1 and 10 µm, can become entrained in the atmosphere through mechanical processes, such as the intense turbulence in the wakes of vehicles (Brahney et al., 2021). These particles have atmospheric residence times of 8 days (PM 10[3]) to 28 days (PM 2.5[4]) (Evangeliou et al., 2020). Larger TWPs (>10 µm), which make up the majority of TWPs by weight, are deposited onto road surfaces (Wagner, et al., 2018). Most of the mass of emitted TWPs appear to deposit within about 6 meters of roads (Blok, 2005; Cadle & Williams, 1978; Saito, 1989; Spies et al., 1987; Wik & Dave, 2009). Typically, in urban areas, roadside areas have relatively high imperviousness; they often drain directly to storm drains and surface waters (Moran, et al. 2023). Exponentially decreasing levels of deposition occur up to about 30 meters from the pavement edge (Blok, 2005; Saito, 1989; Wik & Dave, 2009). A study performed by Gao et al (2022) showed a substantial decrease in putative[5] TWP particles as the distance from a highway increased. The TWP deposition rate at 5 m away from the highway was 340 ± 145 particles/cm^2/day. At 15 m, the rate decreased by 47 percent to 180 ± 88 particles/cm^2/day. At 30 m, the rate decreased by 71 percent to 99 ± 54 particles/cm^2/day (Gao et al. 2022).

The smallest of the deposited TWPs may become trapped in asphalt pavement or transported by stormwater runoff into soils, storm sewers, and surface waters, where they can continue to leach their chemical constituents into the surrounding environment (Kole, et al. 2017; Saifur and Gardner, 2021). Larger particles can remain on the roadside for long periods. Larger particles will likely keep exuding 6PPD and 6PPD-q bound to smaller TWP or other sediments until they are removed from the environment or until the 6PPD in the rubber compound is exhausted (Ecology 2022). Rainfall and runoff can wash off large mass fractions (up to 50 percent) of tiny particles like TWP from impervious surfaces (Bannerman et al., 1983; Pitt, 1985, 1987; Pitt et al., 2005).

[3] PM 10 – particulate matter with a diameter of 10 microns (µm) or less.

[4] PM 2.5 – particulate matter with a diameter of 2.5 microns (µm) or less.

[5] Criteria of putative TWPs were based on their dark/black color, cylindrical/elongated fragment shape, and rough surface texture, as well as a lack of any obvious cellular or biological structures (Gao et al. 2022).

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Particles that are not washed off into creeks have multiple fates, including resuspension/re-deposition onto pervious surfaces (where most particles end up being sequestered), removal by street sweeping, accumulation in pavement texture/cracks, and deposition in the drainage system. Due to variations in storm intensity and duration, antecedent dry period, surface smoothness, roadway and drainage system maintenance practices, and other factors, real-world particle wash-off from impervious surfaces is typically lower than the theoretical wash-off. According to a review by Pitt et al. (2005), around 9 percent of the mass of particles that initially deposits on impervious surfaces should be expected to wash off the impervious surfaces and into surface waters. The remaining 91 percent of particles that are initially deposited on impervious surfaces, which are typically<1,000 µm, are ultimately sequestered (e.g., trapped in pavement or resuspended and deposited in nearby landscaping or other nearby pervious areas) or removed (e.g., street sweeping or catch basin cleaning). TWP wash-off from impervious surfaces may be slightly higher than this 9 percent average. However, since TWP are primarily <100 µm (Kreider et al., 2010), some particles will initially deposit on pervious surfaces where wash-off potential is very small; therefore, overall total wash-off of TWP is anticipated to be less than 9 percent (Pitt et al., 2005). The retention of some amount tire wear/6PPD-q on the roadway surface is expected to be considered implicitly in the model.

Dust (diameter <100 µm) generated from electronic waste recycling, specifically from wires, cables, and plastics, is a potentially important source of 6PPD-q, with concentrations of 87 to 2,850 ng/g (Liang *et al.* 2022). For comparison, 6PPD-q in various other dusts (25–250 µm) was reported at up to 0.4 ng/g for households, 88 ng/g for roads, 146 ng/g for vehicles, and 277 ng/g for parking lots (Huang *et al.* 2021). 6PPD-q in roadside soils (<250 µm), was reported to be 9.5 to 936 ng/g (Cao *et al.* 2022).

Limited research suggests that discharges from wastewater treatment plants that are treating wastewater from combined sewer systems are a minor source of either 6PPD or 6PPD-q (Seiwert et al. 2022). Urbanized or urbanizing areas are particularly prone to wet weather runoff of TWPs and associated chemicals, due to the relatively high percentage of untreated impervious surface area and high vehicle traffic and associated TWPs (Wagner, et al., 2018; Challis, et al., 2021; Baensch-Baltruschat et al., 2020). This Screening Model focuses on stormwater runoff from roadways. Wastewater inputs are outside the scope.

2.2.2.2. What causes tire wear?

Motor vehicle tires emit pieces of rubber debris as large as visible chunks or as small as microscopic-size particles, as vehicles turn, stop, start, and drive on the road. Smaller TWPs are sometimes called "dust," "microplastic," or "microrubber." Tire wear debris and dust are believed to continually release 6PPD and 6PPD-q into the environment.

Tire wear particles have a relatively unique size distribution, spanning a range that includes tiny particles (<2.5 µm in diameter) that transport long distances in air and larger particles (>10 µm) that typically deposit close to their near-ground point of emission. Tire wear particles have a higher density than many other types of microplastics detected in the environment. Sample collection and microplastic separation methods have likely underestimated the presence of tire particles in aquatic environments, due to their small (<100 µm) size distribution and density (SFEI 2021).

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At a watershed scale, when averaging over many thousands of vehicles, one of the most impactful factors to TWP generation is vehicle miles traveled (SFEI 2021). Using estimated wear rates and vehicle miles traveled (VMT), several publications have estimated US tire wear. All of the estimates have used wear data from non-United States (US) vehicles. These estimates range from 3.0 to 5.5 kilograms per year (kg/y) per capita (Councell et al., 2004; Kole et al., 2017; Wagner et al., 2018). In October 2021, the US Tire Manufacturers Association (USTMA) estimated annual California statewide tire emissions based specifically on the characteristics of US tires. USTMA estimated tire tread loss (material worn off) of about 2.1 kg/y per capita (USTMA, 2021). In 2023, San Francisco Estuary Institute (SFEI) developed San Francisco Bay Area tire wear emissions estimates, using two methods: one based on tire wear rates and vehicle distance traveled, and the other based on tire sales and the amount of tread material worn off of tires at the time of replacement. The two methods generated similar annual emissions estimates of about 2 to 3 kg per capita each year (SFEI 2023). These emissions estimates do not include the relatively minor emissions from airplanes, bicycles, and non-road (non-licensed) vehicles like construction equipment, recreational off-road vehicles, and forklifts (SFEI 2021).

Generation of TWPs depends on a variety of features, including the number of vehicles and tires on the road, tire characteristics, road surface properties, environmental characteristics, vehicle characteristics, and vehicle operations. The following subsections detail several of the factors contributing to tire wear rates.

Number of Vehicles (Average Daily Traffic)

At a watershed scale, averaging over many thousands of vehicles, one of the most impactful factors to TWP generation is vehicle miles traveled (SFEI 2021). The literature suggests that highly urbanized areas are the most likely areas to generate TWP and thus 6PPD and 6PPD-q toxic concentrations. Other suspected hot spots include parking lots, mass transit hubs, ferry terminals, bridges, industrial transportation facilities, and other hubs of vehicular traffic.

A roadway with a high average daily traffic (ADT) likely has higher concentrations of TWP, 6PPD, and 6PPD-q than roads with lower ADTs. Gao et al. (2022) found that higher vehicle speeds and traffic volumes increased the number of TWPs present at the tested locations. Further research and monitoring are needed to determine which ADT levels cause 6PPD and 6PPD-q levels to reach levels of concern in roadway runoff.

Tire Materials and Design

Sakai (1996) found that tire wear rates are highest during a "breaking-in" distance of approximately 300 km, based on road simulation tests with all new tires. This was attributed to lubricants and other substances used in the manufacturing process wearing off. After the initial "breaking-in" distance, the tire wear became almost constant at 75 percent of the initial wear rate. Furthermore, when not having used the tires for 3 months, the tire wear rate reverted to its initial wear rate. Extremely rapid wear during the first few hundred kilometers of a tire's life has also been observed (Stalnaker et al. 1996). High wear rates may also occur because of steering system misalignment and incorrect tire pressure. Other tire wear factors include worn or damaged suspension parts, overloading, incorrect steering geometry and track setting, and the improper matching of rims and tires (Luhana et al. 2004).

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Wear rates of winter and summer tire types may also differ. In order to give them proper grip on cold pavement, the treads of winter friction tires have a softer rubber mix than the treads of summer tires. Hence, late exchange of winter tires, exposing them to prolonged periods with warmer asphalt, will significantly impact tire wear (Vogelsang et al., 2019).

The use of studded tires, particularly PM10, significantly increases road dust production as well. However, all this increase in road particles seems to originate from the asphalt and not from tire treads (Gustafsson et al. 2008).

Road Conditions (Material/Roughness)

Road types affect friction and abrasion of tires, resulting in TWPs. Since the micro-texture of the road surface directly influences the frictional forces on the tire tread, it also has a huge impact on the overall tire wear. Lowne (1970) observed a large variation in the degree of tire wear as a result of different road surfaces, where the wear on rough, harsh surfaces was approximately three times as severe as that on smooth, polished surfaces. However, this has proven difficult to study, since both controlled laboratory simulation studies and on-road studies have their inherent limitations—the influence from other factors are difficult to suppress (Luhana et al. 2004, Boulter 2006, Grigoratos and Martini 2014).

Additionally, road surfaces may contain tire crumb, either as a component of asphalt pavement ("rubberized asphalt") or as a component of a surface coating ("chip seal" or "slurry seal"). While rubberized asphalt only partially wears away during its lifetime, in contrast, the majority of pavement sealant materials wear away due to mechanical abrasion and weathering because the sealant is entirely on the pavement surface. Rubberized asphalt, chip seal, and other pavement sealcoats could release tire-related chemicals into the environment as they wear (pavement surface) or when exposed to water (surfaces and interlayers). Again, this potential is greatest for surface coatings, as wear processes will disperse the coating material into the environment (SFEI 2021).

Environmental Conditions

Roads tend to have smaller microtexture and friction due to polishing during the summer months (Veith 1992). LeMaitre et al. (1998) found that tire wear during winter was found to be 40 percent higher than tire wear during summer. During development of this Modeling QAPP, a brief literature search was conducted for studies that evaluated the impact of wintertime traction enhancement methods (e.g., salting and sanding), but no studies were found that directly related these methods to tire wear rates. Pirelli (2000) reported 90 percent longer tire life when the outside temperature decreased from 15°C to 0°C. LeMaitre et al. (1998) also observed 50 percent higher tire wear during dry conditions, compared to when the road was wet.

Acceleration, Braking, and Cornering

Most of the tire wear happens at road sections where changes of direction occur, such as during cornering. Cornering sections of roads are most likely to accumulate high quantities of TWPs (Pohrt 2019). Additionally, low speed turning movements, like those in parking lots, likely produce more TWP residue than higher speed movements around curves. Similarly, intersections controlled by stop lights

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might have more TWP residue than similar intersections where the main route is free-moving and where the side routes are controlled by stop signs. The roadway speeds and ADT likely play a role at intersections as well.

Urban driving that involves frequent acceleration and braking, with more corners and bends, has been shown to result in higher tread wear per kilometer than does driving within rural areas or on highways (Dannis 1974, Stalnaker et al. 1996, LeMaitre et al. 1998, Luhana et al. 2004). Broeke et al. (2008) have suggested that urban driving is expected to produce twice the amount of tire wear as driving elsewhere. Similarly, an aggressive driving style will tend to result in more rapid and uneven tire wear than a 'smooth' driving style (Luhana et al. 2004, Boulter 2006, Councell et al. 2004). Areas where drivers were prone to braking have a significantly higher concentration of TWPs, demonstrating that driver behavior plays a role in TWP generation (Gao et al. 2022).

More studies are needed to substantiate these findings, as older tire wear simulation studies[6] may be outdated due to advances in technology and improved properties of tires (such as wear resistance and grip).

Vehicle Speed

Some studies have indicated that there is increased tread wear with increasing vehicle speed[7] (e.g. Dannis 1974 and Sakai 1996). Based on the findings of a study conducted by Pohrt in 2019, reduction of vehicle speeds is the local measure best suited to counteract high local or global tire wear emissions. Additionally, there seems to be a strong correlation between vehicle speed and wear when using studded tires (Gustafsson et al. 2008, Snilsberg 2008).

Vehicle Type and Weight

Automobile types and weights produce variable amounts of tire and road dust. Greater traffic and heavier vehicles lead to increased 6PPD-q pollutant loading on roadways and (presumably) streams (Tian et al. 2020). Due to their high weights and large tires, buses and trucks are suspected to have the highest TWP generation rates among all vehicle classes (Baensch-Baltruschat et al., 2020; Councell et al., 2004; Kole et al., 2017; Wagner et al., 2018). Additionally, electric vehicles are predicted to wear down conventional tires more quickly than non-electric vehicles of a similar size. This is predicted due to the electric vehicles' higher weights from the batteries and higher torques, compared to internal-combustion engine vehicles.

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[6]In tests simulating both 'city' and 'motorway' driving conditions, Stalnaker et al. (1996) found that city driving, which included large numbers of turns, accounted for 63% of the tire wear, even though it represented only 5% of the distance driven or 32 times greater than that of motorway driving. Dannis (1974) measured 490 mg tire wear per km per tire when taking bends in 50 km/h compared to 24 mg tire wear per km per tire when driving at 120 km/h on highway straightaways.

[7]Increased vehicle speed has been shown to decrease the mean particle diameter of the tire wear, and this may partially explain the increased coarse airborne particle production reported by some studies (Luhana et al. 2004).

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Baensch-Baltruschat et al. (2020) conducted a literature review of tire particle emission factors for different vehicle types, which showed that emission of tire wear generally increases with increasing vehicle weight. However, tire particle emissions often ranged between one to two orders of magnitude, even for the same vehicle type (Baensch-Baltruschat et al. 2020). For instance, as shown in Table 1 of Baensch-Baltruschat et al. 2020, the tire particle emission results for passenger cars on urban roads ranged from 3.45 to 360 mg/vehicle km; trucks ranged from 539 to 1500 mg/vehicle km, Baensch-Baltruschat et al. (2020) noted that the original tire particle emission data that sources cited in their research was not always given or not publicly available. Therefore, test procedures to arrive at the cited results were not always clear or consistent between studies.

2.2.3. Fate and Transport of 6PPD-q in the Environment

This subsection describes the available information on the fate and transport of TWPs and 6PPD-q.

2.2.3.1. What happens to 6PPD-q before storm events?

TWPs and surface-bound 6PPD-q accumulates on roadways and other deposition areas during dry weather and then washes off during the next stormwater runoff event (Huang, et al., 2021). A study in the Puget Sound region noted that cumulative precipitation appears to be related to coho salmon mortality in less urbanized basins and not in the most urbanized areas (Feist, et al., 2017). The authors proposes that the most urbanized basins are relatively insensitive to periods of drought and subsequent rainfall, because sufficient toxicants (i.e., 6PPD-q) accumulate on roadways over relatively short periods of time, thereby minimizing the influence of antecedent dry intervals.

Little information is available on how release rates of 6PPD and 6PPD-q from TWP are influenced by environmental factors, such as road and air temperature, oxygen, and pH. More research is needed to understand how release rates differ by particle size under variable environmental conditions (Ecology 2022). The size range of solid particles carried in stormwater systems is expected to vary by stormwater velocity, readily available sources of particles (including the buildup of particles between rain events), and maintenance programs, such as street or parking area cleaning.

6PPD-q and other TWP contaminants may also be temporarily stored in snow or ice that is plowed from roadways (Seiwert et al., 2022; Challis, et al., 2021). These studies report that snowmelt contained relatively high concentrations of these contaminants. This is consistent with other pollutants, such as hydrocarbons, metals, solids, nutrients, and chlorides, which accumulate in snow piles and are subsequently released in high concentrations during snowmelt (Oberts, 1994).

Removal (Street Sweeping, Air Transport)

6PPD and 6PPD-q share some similar physicochemical properties, which may inform how long the contaminants persist and how they move through the built environment. Both contaminants have a relatively high log K_{ow} (4.68 to 5.6 for 6PPD and 3.25 to 5.5 for 6PPD-q) and log K_{oc} (4.04 to 4.84 for 6PPD and 3.94 for 6PPD-q), which suggests an affinity for soil and organic matter. This would also suggest that 6PPD and 6PPD-q adhered to soil would not leach from the soil particles and enter groundwater;

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however, additional research is needed to confirm the tendency to adhere and stay adhered to particles under environmental conditions.

While 6PPD and 6PPD-q appear to have an affinity to soil or organic matter, both contaminants are moderately non-polar compounds. This indicates that transport of the contaminants in the dissolved phase is possible but not anticipated to be probable. This is supported by Fugacity Model results: a higher percentage in the environment is predicted to adhere to soil and sediment (approximately 90 percent for both 6PPD and 6PPD-q), though approximately 10 percent is anticipated to remain in the water column (U.S. EPA, 2021b). No lab or field data was reviewed to indicate the prevalence of contaminants in either phase.

Street sweepers are only moderately efficient in collecting fine and ultra-fine particles, which are believed to make up the majority of TWPs on roadway surfaces, particularly when considering realistic sweeping frequencies and equipment types (Amato et al., 2010; Breault et al., 2005; Piscitello et al., 2021; Selbig & Bannerman, 2007).

Typically, most of the mass of tire wear particles deposits relatively quickly. However, fine and ultrafine particles can transport through the air for long distances, even to remote global locations (e.g., the Arctic, mountain wilderness) (Brahney et al., 2021; Evangeliou et al., 2020). Road particles (including tires) have been estimated to compose more than 80 percent of all microplastic air deposition (Brahney et al., 2021). Although these fine and ultrafine particles compose only a small fraction of total mass of tire wear particles, they compose a large fraction of the total number of emitted particles. Therefore, these particles' surface area might make them important vectors for tire chemical transport beyond the immediate roadside area. Due to limited data addressing tire particles across the full particle size distribution, the role and importance of air deposition in tire particle transport within and between watersheds remains largely unknown (SFEI 2021). Better information is needed, in order to determine the deposition of TWP in all sizes—from dust via air deposition, to larger particles thrown from tires onto the roadside—and to understand the distribution of these particles and their effects on the fate and transport of 6PPD and 6PPD-q to surface waters (Ecology 2022).

According to Grigoratos and Martini (2015), 0.1 to 10 percent of tire wear (by mass) is emitted as airborne particulate matter, including particles with an aerodynamic diameter of <10 µm (respirable particles by humans; PM 10). Broeke, et al. (2008) assume that the fraction of fine particulates (PM 10 and PM 2.5) is completely emitted to the atmosphere, whereas the coarse fraction is released to water and soil. They recommend presuming that the fraction of PM 10 amounts to 5 percent of the total tire wear generated by passenger cars; they recommend using this value to calculate the atmospheric fraction caused by other vehicle types, for which the percent values of PM 10 are unknown or scarce (Baensch-Baltruschat 2020).

Degradation

Persistence of 6PPD and 6PPD-q in the environment depends on chemical properties like reactivity or half-life. The degradation of 6PPD and 6PPD-q will likely vary based on the medium and environmental and physical conditions (e.g., temperature, pH, etc.). The estimated half-lives of 6PPD and 6PPD-q are 75 days in soil and 337 days in sediment (meaning soils below water), based on Fugacity Model results

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(U.S. EPA, 2021b). Many more sources (model, lab, and field data) report on the half-lives of 6PPD and 6PPD-q in the water column. The half-life of 6PPD in water is short, and its duration depends on environmental factors, such as oxygen, pH, sunlight, metals, and pH. Studies have found the half-life of 6PPD to be less than 24 hours and as low as approximately 3 hours (OSPAR Commission, 2006; ECHA, 2021), with shorter half-lives noted in warmer waters and those containing heavy metals (OSPAR Commission, 2006). However, long-term stability up to 4 weeks has been noted in cold conditions at a pH of 2 (OSPAR Commission, 2006).

Compared to the half-life of 6PPD in water, the half-life of 6PPD-q in water is less certain; results from the Fugacity Model indicate the half-life of 6PPD-q is 900 hours (U.S. EPA, 2021b), whereas other sources report the half-life as longer than 6PPD or, more specifically, at least 1 day (Tian, 2021). Additional research is needed to better understand the half-lives of both 6PPD and 6PPD-q in the environment.

Degradation of 6PPD and 6PPD-q is expected to result from a combination of abiotic and biotic processes (OSPAR Commission, 2006; ECHA, 2021). In air, 6PPD is expected to be rapidly photodegraded. When on a surface, such as a tire, 6PPD absorbs UV-B radiation and is expected to undergo rapid direct photolysis (OSPAR Commission, 2006) in direct sunlight (OECD, 2004). Moreover, 6PPD is used in tires for its reactivity, as well as to neutralize ozone and, to a lesser extent, oxygen (Seiwert et al., 2022). It is therefore expected that 6PPD on a tire or other surface would degrade in the presence of ozone or oxygen. In the atmosphere, 6PPD undergoes indirect photodegradation via rapid reaction with hydroxyl radicals. Photodegradation is likely a predominant mechanism for 6PPD loss in surficial soils (OSPAR Commission, 2006). In water, 6PPD is not "readily biodegradable," but it is unstable and degrades rapidly by biotic and abiotic processes.

A study by Xu et al. (2023) showed that biodegradation predominated the fate of 6PPD-q in soils. The study results showed that anaerobic, flooded soil conditions (3 cm water table above the soil surface, with dissolved oxygen levels lower than 0.5 mg/L) were conducive to 6PPD-q formation and resulted in a higher accumulation of 6PPD-q than that of wet soil conditions (60 percent of maximal water holding capacity) after an aging period of 60 days. Concentrations of 6PPD-q degraded rapidly in aerobic, wet, and unsterilized soils, whereas sterilized soils exhibited no significant changes in 6PPD-q concentration.

Further research is needed to determine 6PPD-q degradation, how long it remains bioavailable and toxic, and how it is transported outside of wet weather events. This is particularly important in Washington State, with a long dry summer season on the west side and semi-arid environments on the east side of the mountains.

2.2.3.2. What happens to 6PPD-q during and after storm events?

Most TWPs are dense and heavier than water, and most TWPs will settle out when given the chance. The larger the tire particle, the more surface flow is required to transport it from roads to stormwater systems. Particles in surface runoff can settle out in BMPs or in-system features, such as like ditches or catch basins, which slow down stormwater. Many factors, including water depth, time, associated sediments, and deposition rates, influence particle settling. If applicable, the BMP design for either dead storage or location of emergency overflows may also influence particle settling.

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Mobilization

Currently, there is a poor understanding of the temporal distribution of 6PPD-q and other TWP contaminants in the stormwater conveyance network and in the receiving waters during wet weather events. While a few research studies suggest that 6PPD-q transport may closely follow the hydrograph, other studies indicate that tire wear chemical concentrations can peak several hours after peak flow (Ecology 2022; Johannessen et al. 2022). Further studies are needed to examine 6PPD-q transport dynamics using sites with differing distances from roadway sources, times of concentration, concentrations during the entire hydrograph for various storm events, and antecedent dry periods.

Sequestration in Soils and Sediments

The log K_{ow} and log K_{oc} for 6PPD and 6PPD-q (OSPAR Commission, 2006) suggest a tendency for the contaminants to adhere to inorganic soil and organic matter. This is supported with the success of sorptive media in reducing toxicity 6PPD-q and observed toxicity in stormwater treatment devices (see section 2.2.4.2). However, no studies were identified in the literature that tested (in the laboratory or field) whether the contaminants would remain adhered to inorganic soil and organic matter. The degree to which bound 6PPD or 6PPD-q in sediments (below water) can become bioavailable to aquatic biota via biotic and/or abiotic transformation processes is not known.

In conveyance networks and streams, velocity most likely affects the retention and resuspension of TWPs and other pollutants in sediments.

2.2.4. Management and Treatment of 6PPD-q

The following subsections address current information on the effectiveness of source control, stormwater BMPs, and larger regional stormwater facilities, to remove 6PPD-q from stormwater runoff.

2.2.4.1. How effective are source control BMPs for 6PPD-q in stormwater?

Source control BMPs for 6PPD and 6PPD-q can include actions that prevent tires, tire pieces, and TWPs from contacting rainfall, entering runoff, and/or being further transported in the stormwater system. Analyzing the traffic network can help identify where to strategically use source controls. Examples of stormwater source control BMPs for tire chemicals include:

- Roadside tire, tread, and trash clean up
- Routine schedules for maintenance of stormwater infrastructure, such as sweeping streets and parking surfaces, as well as cleaning out catch basins and stormwater conveyance pipes
- Sweeping streets or parking lots instead of hosing them down
- Changing truck routes (1) to reduce tire wear from tight turns and pivots or (2) to reduce stops and starts by vehicles near a particular catch basin or stream
- Use of berms or stormwater wattles (1) to protect inlets and mulches and (2) to slow flows across soil or grassy areas

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- Changes to vehicle washing practices at public and private facilities, including auto sales lots
- Coverings to prevent rain or runoff from interacting with tires, crumb rubber, or piles of street waste
- Education and outreach for garbage pick-up programs, including "Adopt a Highway" (Ecology 2022)

Additional transportation support activities, such as bridge washing, car washing, street sweeping, and tire disposal, are regulated activities in the State of Washington (Ecology 2022). To date, there have not been studies to determine the effectiveness of these source control measures to reduce 6PPD-q and other TWP contaminants.

Local source control programs and policies can add focus on more specifically addressing 6PPD-q with these practices. However, source control BMPs alone cannot prevent all 6PPD-q impacts. To achieve toxicity reduction, a combination of stormwater source control and treatment approaches will likely be needed in basins with heavy vehicle use or other 6PPD sources.

2.2.4.2. How Effective Are Stormwater Treatment BMPs at Removing 6PPD-q?

Distributed treatment BMPs include technologies that treat runoff near to the source. These include such systems as bioretention, grass swales, porous pavement, flow-through filters, and other similar devices meant to treat a relatively small drainage area. Regional stormwater facilities, like stormwater ponds, vaults, and parks, may provide treatment to a large drainage area. Distributed and regional stormwater facilities are described in this section.

Flow control BMPs, such as detention ponds, retention ponds, tanks, or vaults, are designed for (1) controlling stormwater flow rates and volumes and (2) capturing suspended solids transported by stormwater. Routine maintenance is required to maintain BMP performance. For example, accumulated solids layers presumed to contain tire particles, along with other trash, must be regularly removed. The smallest, microscopic tire particles are not expected to settle out in the temporarily pooled areas of flow and treatment BMPs or in catch basin sumps.

To the extent that TWP concentrations are indicative of relative concentrations of 6PPD-q, the concentrations of TWPs found on road surfaces and roadsides has been higher than that of either the water column or the stream sediments (Wagner, et al. 2018). This may indicate that stormwater BMPs located adjacent to road surfaces, or the roadside soils and vegetation themselves, are in an opportunistic location to physically capture TWPs, provide sorption sites for 6PPD-q, and prevent TWP and 6PPD-q from reaching surface waters (Ecology 2022). Table 4, adapted from Ecology's *6PPD in Road Runoff Assessment and Mitigation Strategies* (2022), summarizes which BMP functions are most likely to help prevent and reduce TWPs from being carried by stormwater runoff (and therefore reduce 6PPD and 6PPD-q toxicity). Further study is needed to assess if trapped TWPs within BMPs may be resuspended during future rain events, or if 6PPD-q formed on the TWP surface within a BMP may leach onto suspended particles in treated stormwater (i.e., can trapped TWPs begin acting as a source?).

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Table 4. The BMP Functions to Target for Stormwater Management of TWPs, 6PPD, and 6PPD-q in Runoff (Ecology 2022).

Estimated BMP Effectiveness	Functions associated with stormwater source control BMPs	Functions associated with treatment and flow control BMPs
High	BMPs that completely separate a 6PPD source (e.g., tire wear from roads, parking, high vehicle turning areas) from precipitation and stormwater (e.g., roofs).	Sorption, infiltration, dispersion, and filtration (e.g., bioinfiltration swales).
Medium	BMPs that partially separate 6PPD source from stormwater (i.e. education and outreach efforts). This may prevent 6PPD from entering stormwater from a smaller source (e.g., uncovered storage of new tires).	BMPs that provide sedimentation (removal depending on size/detention time) or filtration (removal dependent on particles size). May need a polishing layer[a]/treatment train including sorption (i.e., sand filter with zero valent iron in layers). May be less feasible due to maintenance, other feasibility. For 6PPD-q, may need to modify BMP to retain in solids for a residence time equivalent to the half-life of 6PPD-q.
Low	Unlikely to provide any measurable separation between 6PPD and stormwater. Unlikely to reduce generation or deposition of tire wear in vehicle land uses.	BMP does not provide infiltration, sorption, filtration, or sedimentation. BMP cannot retain solid longer than the half-life of 6PPD-q.

[a] A polishing layer is an additional media layer typically added under a primary treatment media layer. The polishing layer consists of a different media blend than the primary layer and provides targeted reduction of a particular pollutant(s) that the primary layer may not effectively capture.

Bioretention/Bioswales

Bioretention is a green stormwater infrastructure technology that uses engineered soil media to treat runoff pollutants (Liu et al., 2014; Tirpak et al., 2021). In studies conducted before 6PPD-q was discovered as the primary causal toxicant in stormwater runoff, McIntyre et al. (2015) and Spromberg et al. (2016) found that stormwater that was filtered through laboratory-scale bioretention columns protected coho salmon from the acutely lethal effects of stormwater runoff. Application of urban roadway runoff through bioretention columns installed at a coho salmon hatchery has since been shown to prevent acute mortality of coho alevin (McIntyre et al., 2023), similar to the laboratory-scale studies with older coho juveniles (McIntyre et al., 2015) and adults (Spromberg et al., 2016).

The physicochemical properties of 6PPD-q indicate that it could be partially captured by soil sorption (Rodgers 2022). 6PPD-q is presumed to be bound to particulates if enough time or material is available for the sorption to occur. Sorptive media used in stormwater treatment BMPs, such as bioretention, vary widely among natural to commercial materials. Commercially available sorptive media with carbon content, organic matter, and relatively high surface area are expected to be effective at controlling 6PPD-q in the environment. These media may be present in a manufactured treatment device or incorporated into site soils or custom BMP mixes for testing. Additional research is needed to confirm the sorption potential to reduce microscopic tire particles as well as dissolved 6PPD-q and other tire-derived chemicals.

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Bioretention filtration results in clear benefits to stormwater quality and drastic improvement in the survival of coho alevin. However, studies are needed to assess whether there are long-term impacts from developmental defects due to runoff pollutants still present after bioretention filtration (McIntyre et al., 2023).

Some solids suspended in stormwater are so small, (<0.45 um) they are considered dissolved solids. Presumably, 6PPD-q will sorb to these solids just like any other solids and remain very mobile. Knowing if sorptive media or filters can capture this bound dissolved fraction of 6PPD-q—and knowing the extent to which this fraction contributes toxicity—will guide our understanding of how much treatment is needed to prevent toxicity in surface waters (Ecology 2022).

Porous Pavement

During a permeable pavement study conducted in Tacoma, Washington, effluents from permeable pavements (porous asphalt and pervious concrete) to which TWPs had been applied were analyzed for 6PPD-q and several other tire-derived compounds (Mitchell and Jayakaran 2024). In total, three experiments were conducted to evaluate porous pavement mitigation of tire-associated pollution using cryomilled tire particles (cTP) as an idealized form of tire and roadway particles for their consistent size and ease of identification. The study found that an estimated 52–100 percent of potentially leachable 6PPD-q was removed by the permeable pavement systems between the influent and effluent sampling stations. Background 6PPD-q concentrations in effluents ranged from 0 to 0.0029 µg/L. Effluent 6PPD-q concentrations were not explained by effluent TWP concentrations in experiments 1 or 2 but were significantly correlated in experiment 3, suggesting that leaching of 6PPD-q from TWPs retained in the pavement was minimal during a subsequent storm (Mitchell and Jayakaran 2024).

Proprietary Devices and High Flow Rate Devices

Filters that focus on reducing suspended particles (e.g., total suspended solids) will be effective at capturing tire particles and any other particulate matter with sorbed contaminants, including 6PPD-q. Filters, such as commercial catch basin inserts, reduce solids prior to stormwater entering stormwater conveyance systems in settings where larger than normal amounts of soils and solids are expected in the flows. Such filters are frequently used at construction and industrial sites and, to a lesser extent, in other urban environments. Most of these devices capture trash, soil, and solids, and most can likely capture TWPs.

Regional Treatment Systems

Some larger facilities, such as regional treatment facilities or stormwater parks, are built to handle runoff from large drainage areas; these facilities use the same scaled-up principles as distributed treatment facilities. The Screening Model endpoint is 6PPD-q reaching the conveyance network, and it does not evaluate treatment facilities. This would be a worthwhile extension in future versions of the model or via integration in existing watershed tools (LSPC, VELMA).

Manchester Stormwater Park in Kitsap County, Washington is an example of a regional stormwater treatment facility that treats runoff from a 100-acre drainage basin containing roads, parking lots,

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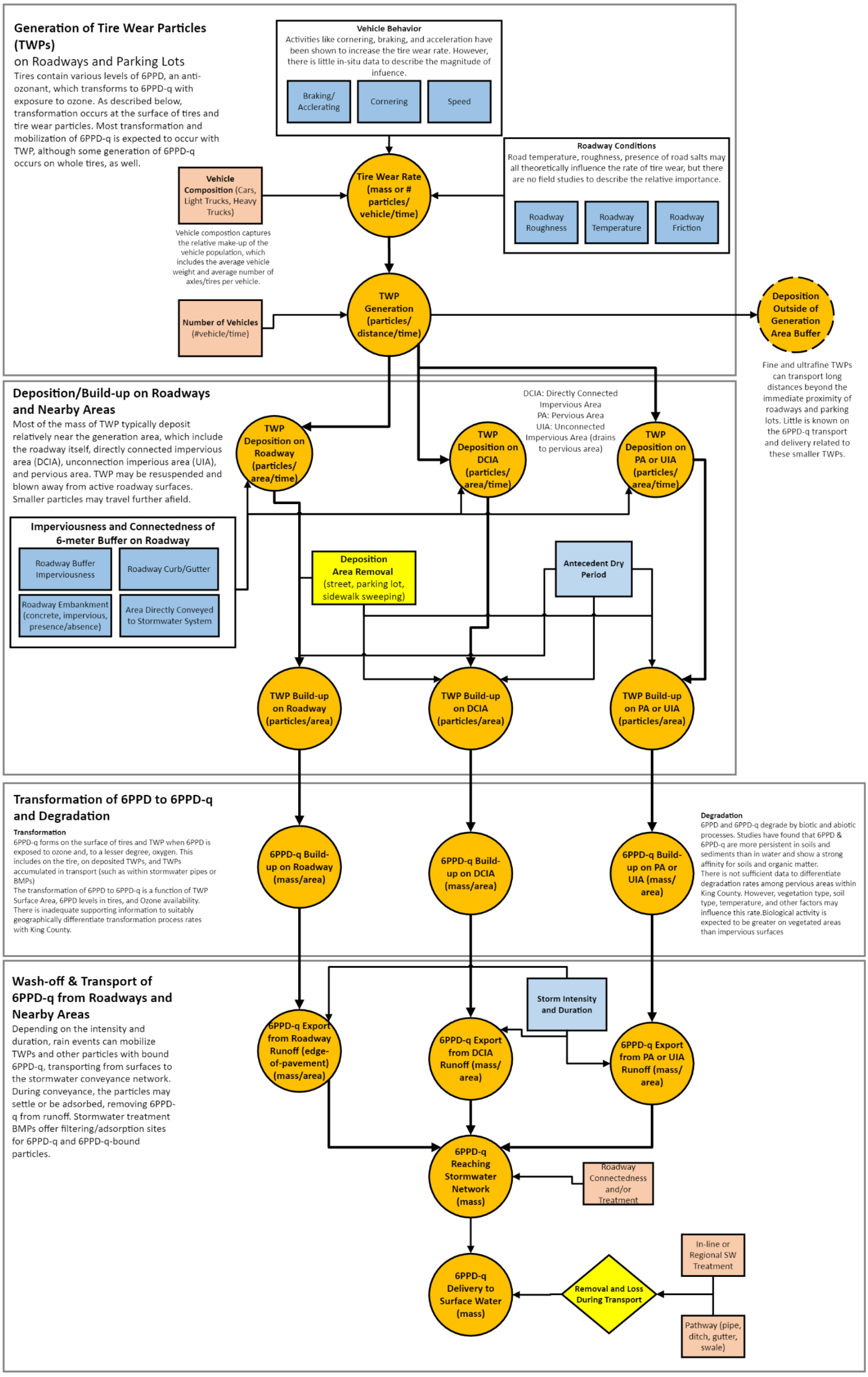
residential, and commercial properties. The stormwater facility is 0.5 acres and provides treatment using engineered filter media and vegetation (Puget Sound Regional Council 2022). The facility is expected to treat 100 million gallons of stormwater per year over the next 10 years (NW Cascade 2024).

2.3. Conceptual Model for 6PPD-q Delivery to Surface Waters

The project team developed a conceptual model for the delivery of 6PPD-q to surface waters, to summarize our current understanding and uncertainty. The conceptual model serves as the foundation for the Screening Model for this project by identifying the key factors that influence the delivery of 6PPD-q to surface water. The conceptual model was developed by the project team based on the literature review (presented in the previous section), with assistance from subject matter experts (SMEs). A SME workshop was convened on August 23, 2023, to provide input on development of a conceptual model. See Section 4.1 for identification of SMEs and Section 6.2.1.3 for a description of how the conceptual model was developed.

Under advisement of SMEs, the conceptual model will be further refined and specified into the Screening Model based on the most influential factors affecting 6PPD-q export and availability of suitable spatial proxies for those factors. The planned endpoint for the Screening Model is the 6PPD-q delivery from roadways to the stormwater drainage network. The conceptual model extends to 6PPD-q delivery from deposition areas other than roadway surfaces (specifically areas near roadways) and delivery to surface waters. Along with the conceptual model presented in Figure 1, a narrative is presented in the following subsection.

Figure 1. Conceptual Model Factor Definitions for 6PPD-q Delivery to Surface Waters from Roadways and Parking Lots.



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2.3.1. Conceptual Model Narrative

While building the conceptual model, the focus was on automobile tires as the primary contributing source of 6PPD-q. Specifically, this model focuses on TWP. Although 6PPD-q leaching may also occur from whole tires, it is expected to be a relatively minor contribution due to its lower overall surface area. Automobile TWP are the focus, because, compared to other types of tires (e.g., bicycle, motorcycle, and plane tires), they are responsible for the vast majority of on-road TWP generation.

Products that reuse tires, including crumb rubber used on recreational fields and rubberized asphalt ("chip seal"), can also be sources of 6PPD-q; however, considering the prevalence of roadways, their use in King County is not as widespread. Therefore, compared to automobile TWP, these products' contributions are expected to be minor. For this reason, reused tires are not included in this model.

The conceptual model is broken into four components: (1) Generation of TWP; (2) Deposition and Buildup of TWP; (3) Transformation of 6PPD to 6PPD-q; and (4) Wash-off and Transport of TWP/6PPD-q.

2.3.1.1. Generation of TWP

Motor vehicle tires emit rubber pieces that range from large, visible chunks found along the roadway to microscopic-size particles created when vehicles drive, turn, brake, and accelerate on the road. The primary factor leading to Tire Wear Generation is the *Number of Vehicles* on the road per unit distance, followed by the vehicle weight, tire width, and number of tires/axles per vehicle. Due to their relatively high weight and large tires, among all vehicle classes, buses and trucks are suspected to have the highest TWP generation rates per distance traveled. During the workshop, it was suggested that vehicle weight and number of tires per vehicle could be summarized for individual roadway segments by categorizing the *Vehicle Composition*, i.e., the typical fraction of each passenger vehicles, light trucks/SUVs, freight trucks, and buses.

Vehicle Behaviors, like turning, braking, and accelerating, have been shown to increase the TWP generation rate in laboratory settings and in a handful of field studies, though the magnitude of impact of vehicle behavior on the *Tire Wear Rate* is not well understood at this time. One expert in the SME workshop cautioned against inferring changes in tire wear rate based on *Vehicle Behavior*, given the paucity of field-verified information. The experts suggested that *Vehicle Behavior*, in contrast to the *Vehicle Composition*, is expected to be less important in predicting *Tire Wear Rate* for an individual roadway segment. Similarly, *Roadway Conditions*, like roughness, temperature, and friction (as influenced by road and tire material), may impact the *Tire Wear Rate*; however, it is generally believed that *Vehicle Composition* will be the most critical determinant of *Tire Wear Rate* on developed roadways.

2.3.1.2. Deposition/Buildup

Most of the mass of TWP typically deposits within a 6-meter proximity of the surface on which it is generated, with exponentially decreasing deposition with distance (by mass). The roadside deposition areas may include *impervious areas* (e.g., road shoulders, parking lots, sidewalks, roofs, and driveways) and *pervious areas* (e.g., roadside ditches, tree lawns, lawns, fields, and forests). In the conceptual model,

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impervious areas that are not directly connected to the stormwater conveyance network (i.e., unconnected impervious areas [UIAs]) are grouped with pervious areas.[8]

The Deposition/Buildup component of the conceptual model includes three deposition areas:

- On the roadway
- On directly connected impervious area (DCIA)
  - DCIA is defined as impervious surface where rainwater has no opportunity to infiltrate by passing over pervious ground before reaching the stormwater conveyance network.
    - The stormwater conveyance network includes catch basins, ditches, pipes, and stormwater treatment devices.
  - For the purposes of this conceptual model, roadways are considered independently from DCIA, to allow consideration of street sweeping devices (see Deposition Area Removal below). This is part of the conceptual model, not necessarily the screening model. It is unlikely for there to be adequate sweeping data for use in the Screening Model. Particularly for unincorporated King County roadways.
- On pervious area and unconnected impervious area (UIA)
  - UIA is defined as impervious surfaces where stormwater runoff first reaches pervious surface before reaching the stormwater conveyance network.

The roadway may or may not be directly connected. However, because the endpoint for the Screening Model is "6PPD-q Delivery to the Stormwater Conveyance Network," removal and loss during the "Wash-off and Transport" component of the model were considered; this is described below. Parking lots may be DCIA, UIA, or (in the case of pervious pavement) pervious area.

After initial release and deposition, TWP on the roadway may be resuspended and redistributed by wind, including turbulence caused by vehicles. Because of this, the expectation is that most TWPs are dispersed away from the active roadway area to the 6-m buffer on either side of the active roadway area (including paved shoulders and against raised curbs). Resuspension may also occur on parking lots, but at a decreased rate of wind turbulence caused by vehicles (due to lower driving speeds). Some TWPs are ground down into roadway surfaces, filling gaps in the roadway surface or becoming finer and subject to redistribution.

Additionally, fine and ultrafine particles can transport through the air for long distances beyond the immediate proximity of the TWP generating surface. Although these fine and ultrafine particles compose only a small fraction of total mass of TWP, they compose a large fraction of the total number of emitted particles. Therefore, their surface area may make them important vectors for tire chemical transport beyond the immediate roadside area. Due to limited data addressing tire particles across the full particle

[8] An example of this unconnected impervious area (UIA) is paved sidewalks where the stormwater runs off as sheetflow onto an adjacent grass strip.

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size distribution, the role and importance of air deposition in tire particle transport within and between watersheds remains largely unknown. These particles are not considered in this conceptual model. They may be more appropriately modeled from a watershed perspective rather than from an individual roadway segment/parking lot perspective.

The conceptual model breaks down deposition/buildup into *TWP Deposition*, which is the mass of TWP per unit area, per unit time (e.g., kg/m^2/day), and *TWP Buildup*, which is the total mass of TWP per unit area that has built up between rain events. *Antecedent Dry Period* is included to capture the number of days that TWP may be accumulating between wash-offs. However, not all TWP are washed off during rain events.

The conceptual model also includes *Deposition Area Removal*. This model parameter includes (1) street-, sidewalk-, and parking-lot-sweeping that removes a portion of accumulated TWP, (2) the "grinding-in" of TWPs into the voids into pavement by vehicles, (3) wind transport, and (4) other unknown causes of TWP removal. Street sweepers are only moderately efficient in collecting particles in the size range of tire wear, particularly when considering realistic sweeping frequencies and equipment types—and that only a portion of the DCIA where TWPs accumulate may be reached by street sweepers. During the development of this QAPP, we did not identify an adequate dataset for street sweeping on King County roadways—nor was there SME confidence in the effectiveness of street sweeping for tire wear particle/6PPD-q removal. Additional research is needed outside of this project.

2.3.1.3. Transformation of 6PPD to 6PPD-q

In the conceptual model, the *6PPD-q Buildup* is directly influenced by *TWP Buildup* on the respective surfaces (roadway, DCIA, and PA/UIA). In the model, "buildup" refers to the buildup of TWP and 6PPD-q that may be mobilized with stormwater runoff.

6PPD-q forms on the surfaces of tires and TWPs when 6PPD is exposed to ozone. A key assumption of this model is that the transformation to 6PPD-q is a function of *TWP Surface Area*, 6PPD levels in tires, and *Ozone* availability. 6PPD levels, along with TWP generation rates, vary between tire brands and models, but this model is concerned with the entire population of automobiles on King County roadways; therefore, the conceptual model assumes spatial homogeneity of tire brands and models. Ozone levels also vary between areas, with ozone levels generally higher downwind of urban areas. A brief literature review by Herrera staff did not find any studies that examined the relationship between 6PPD-q transformation and levels of ozone. Therefore, the importance of the spatial variability of ozone is uncertain. For that reason, it is not included in the conceptual model.

Prior to wash-off, 6PPD-q (and its parent chemical 6PPD) may undergo degradation from a combination of abiotic and biotic processes, including microbial decay, photolysis, and ozonation. There is indication of a strong tendency of 6PPD to absorb to organic matter in soils and sediments. The SMEs generally believed that TWPs deposited on vegetated areas are exposed to higher levels of biological activity, which substantially degrades 6PPD-q.

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2.3.1.4. Wash-Off and Transport

Depending on the intensity and duration, rain events can mobilize TWPs and other particles with bound 6PPD-q, transporting the particles from surfaces to the stormwater conveyance network. During conveyance, the particles may settle or be adsorbed, removing 6PPD-q from runoff. Stormwater treatment devices offer filtering/adsorption sites for 6PPD-q and 6PPD-q-bound particles. Formation of 6PPD-q on TWP surfaces may continue during transport, particularly if TWPs are re-deposited on intermittently dry surfaces that may be washed-off again and transported again at a later time.

The amount of *6PPD-q in Runoff* is determined as influenced directly by *Storm Intensity and Duration*,*6PPD-q Buildup* on *Roadways*, *DCIA,* and *either PA or UIA*. This is an average concentration for stormwater running off from a roadway and its 6-meter buffer area. During transport, 6PPD-q may be subject to *Removal and Loss in Transport*, when particles with bound 6PPD-q are captured in *Stormwater Treatment* BMPs or in the stormwater conveyance network. The capture rate within the network is expected to vary with the *Pathway*. For instance, grassy swales/ditches are expected to cause greater *Removal and Loss in Transport*, whereas pipes are expected to cause less *Removal and Loss in Transport* (although some loss may occur within catch basins). Importantly, loss in the conveyance network may be only temporary because the TWPs may be resuspended during more intense storm events.

This model is specifically concerned with 6PPD-q transported through the stormwater conveyance network. 6PPD-q may also reach surface waters via sheet flow and subsurface flow. Because it is anticipated that the vast majority of 6PPD-q reaches surface water via stormwater conveyance networks—and because the model is meant to inform monitoring site locations and, ultimately, prioritization of roadway stormwater treatment—the model focuses on 6PPD-q transported via the conveyance network.

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3. Modeling Project Description

This section presents the goals and objectives for the project with the associated information and tasks that are required to meet them.

3.1. Modeling Project Goal

The primary project goal is to develop a spatial layer of predicted relative 6PPD-q exported from King County and WSDOT managed roadways, using a spatially explicit Screening Model that uses available spatial data layers. As a secondary goal, the Screening Model may be used to evaluate roadways within the incorporated areas of King County (e.g., the City of Seattle) in consideration of readily available spatial data.

3.2. Modeling Project Objectives

To accomplish the above goals, the project will develop the 6PPD-q Screening Model (Screening Model). The Screening Model will be an expert-knowledge-based spatial model that classifies roadways by the relative expected amount of 6PPD-q delivery to the stormwater drainage network, using available spatial data for model inputs. Model output is a cumulative score based on high-influence factors, such as traffic intensity.

Note the Screening Model will be used to support development of a monitoring plan that will characterize 6PPD-q concentrations in stormwater runoff effluent across the spectrum of the identified major influential factors. That monitoring plan will be documented in a separate *Sampling QAPP* that is anticipated in 2025.

3.3. Information Needed and Sources

Based on the conceptual model, several spatial datasets that may be used to develop the Screening Model (Table 5) have been identified. More detailed information on these datasets is provided in the subsections below. Additional variables may also be identified during the development of the Screening Model.

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Table 5. Spatial Datasets Used in Screening Model.

Model Dataset (Source)	Dataset Recency	Screening Model Attribute	Screening Model Variable	Data Type	Notes
st_address (King County)	November 2022	Primary layer for scoring attributes	Roadway deposition area	Polylines	Unique road ID numbers assigned for each distinct line segment in the st_address source spatial layer. Distinct line segments occur between road intersections, at onramps/ offramps of major roadways, within residential cul-de-sacs, and (less consistently) at unspecified intervals along long rural roadways in the st_address source layer.
SoundCast Travel Model (PSRC)	Baseline modeled 2018; version 3.0.1 modeled 2022	Average Daily Traffic (ADT)	Vehicle counts	Numeric	The PSRC SoundCast links do not directly overlap with st_address lines for roadways. The approach for reconciling is discussed in Section 6.
SoundCast Travel Model (PSRC)	Baseline modeled 2018; version 3.0.1 modeled 2022	Medium Truck Traffic, Heavy Truck Traffic	Vehicle composition	Numeric	The PSRC SoundCast links do not directly overlap with st_address lines for roadways. The approach for reconciling is discussed in Section 6.
Curb_line (King County)	December 2018	Road drainage – curbed	Roadway connectedness	Numeric	Length of curb along road, based on intersection with road polygon footprints and buffered road skirt
Gutter_line (King County)	December 2018	Road drainage – guttered	Roadway connectedness	Numeric	Length of gutter along road, based on intersection with road polygon footprints and buffered road skirt.
SWS Open Conveyances (King County)	May 2022	Road drainage - Presence of open conveyances	Roadway connectedness	Categorical; Numeric	Categorical value (ditch, swale, stream) Length of open conveyance along road, based on intersection with road polygon footprints and buffered road skirt
SWS Closed Conveyances (King County)	May 2022	Road drainage- Presence of closed conveyance	Roadway connectedness	Categorical; Numeric	Categorical value (pipe, culvert) Length of closed conveyance along road, based on intersection with road polygon footprints and buffered road skirt
Land Cover (Ecopia via King County)	2019	Impervious percent cover; Spatial extent of road footprints	Roadway connectedness	Numeric	Road footprint derived from Ecopia land cover class and associated with st_address lines for roadways. The approach for reconciling is discussed in Section 6. Road skirt (6-m buffer around road footprint) generated from road footprint. Skirt imperviousness calculated from impervious land cover within the generated road skirt.
Various Jurisdictional Stormwater Conveyance	variable	Pipe, ditch, and other conveyance lines	Roadway connectedness	Categorical; Numeric	Categorical value (ditch, swale, stream) Length of conveyance along road, based on intersection with road polygon footprints and buffered road skirt

PSRC: Puget Sound Regional Council

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3.3.1. PSRC Soundcast Model

The SoundCast model is an activity-based model system that represents the travel behavior of each individual and household throughout King, Kitsap, Pierce, and Snohomish counties. The following section paraphrases SoundCast Model documentation found on PSRC's GitHub site https://github.com/psrc/soundcast/. The data used in the Screening Model are outputs from SoundCast v3.0.1 aggregated to daily vehicular traffic totals.

The SoundCast model depicts travel behaviors that depend on the built environment, land use, and transportation demand external to King, Kitsap, Pierce, and Snohomish Counties. SoundCast outputs transportation network measures, such as highway volumes in one-hour periods in a future year or the number of boardings on a transit line. It also outputs measures related to people, such as average distance to work by home county or the number of transit trips different types of people will take.

The three main components of the SoundCast model are:

- Person trip demand in the DaySim activity-based model
- Submodels, including external, truck, and special trips (to unique locations like airports and military bases)
- Trip assignment onto road networks

DaySim is a modeling approach and software platform used to simulate resident daily travel and activities on a typical weekday for the residents of a metropolitan region or state. The trips predicted by DaySim are aggregated into trip matrices and combined with predicted trips for special generators, external trips, and commercial traffic into time- and mode-specific trip matrices.

The truck model defines a truck based on relative weight classes and separates medium & heavy trucks for analysis purposes, which are defined to match the definitions used by the WSDOT for collecting truck counts. While these definitions rely primarily on weight, these categories also are loosely correlated to other defining characteristics of trucks for other purposes. The following general categories of trucks are used:

Medium trucks are defined as single unit, six or more tires, two to four axles and 16,000 to 52,000 lbs. gross vehicle weight.

Heavy trucks are defined as double or triple unit combinations, five or more axles, and greater than 52,000 lbs. gross vehicle weight.

In these definitions, the medium trucks are directly correlated to single-unit trucks collected in the WSDOT truck counts, and heavy trucks are directly correlated to the double- and triple-unit trucks in these counts. Commercial vehicle trips (Light Trucks) are not included in the truck model, because they are captured, at least in part, by Daysim (the Activity Based Model engine in SoundCast).

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The submodel relies on WSDOT truck count data and Seattle truck count data. These are primarily from interstate, highway, and arterial roadways.

The truck submodel uses socioeconomic employment/commodity categories within transportation analysis zones (TAZs) to predict truck trips. This process provides more accuracy for truck travel and allows for a direct relationship between the commodities being estimated in the external trip model and the allocation of these commodities to TAZs within the region. The categories used in the truck model are:

- Agriculture/Forestry/Fishing
- Mining
- Construction
- Manufacturing (Products and Equipment)
- Transportation/Communication/Utilities
- Wholesale
- Retail
- Finance, Insurance, and Real Estate Sectors (FIRES)
- Education and Government

3.3.2. Ecopia

Ecopia is a high-resolution vector map of 17 land cover classes[9] with planimetric-level detail, including all natural and impervious features (Figure 2). The dataset is the product of an artificial-intelligence-driven classification of 3-inch resolution aerial imagery in the King County lowlands and 9-inch resolution aerial imagery in the upland area. The source imagery used for automated classification was collected in 2019.

[9] The 17 land cover classes are bareland, forest, grass, tree canopy overlap, unpaved sport ground, water, building, driveway, parking, pavement, road, shrub, sidewalk, sports ground, swimming pool, railway, and bridge.

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Figure 2. A User's View of Ecopia.



Polygons classified as "roads" in Ecopia will be used to improve the spatial accuracy of the st_address (King County) lines by linking these two datasets with shared unique identifiers. The approach for reconciling these two datasets is described in Section 6 and will be further documented in the Screening Model technical memorandum. The Ecopia dataset was also used (1) to generate a 6-meter road "skirt" associated with each roadway and (2) to identify classes of impervious-type coverage (buildings, driveways, parking, pavement, road, sidewalk, etc.) and calculate the percent impervious cover within the road skirt.

3.3.3. King County Road Infrastructure

There are several road spatial layers available in the King County geographic area. In the interest of maintaining consistency with other King County modeling efforts (i.e., the Water Quality Benefits Evaluation), the Screening Model will use the "st_address" road layer as a unifying spatial layer. For this model, each roadway segment in the st_address layer was assigned a unique identifier based on the full road name and a five-digit number. Roadway segments are discrete sections of roadway; breaks are present at intersections and at line breaks in the st_address layer.

Additional datasets from King County Roads that are relevant for the Screening Model are "curb_line" and "gutter_line." Curbs and gutters can capture tire wear particles. Curbs and gutters are related to the "connectedness" of the roadway to stormwater conveyance networks. These spatial layers allow for calculating the length of curb and/or gutter located along a road segment and within the road skirt.

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3.3.4. Stormwater Infrastructure

The Screening Model will rely on existing spatial layers for stormwater conveyance systems along roadways. Per its primary goal, the model will first be constructed focusing on King County and WSDOT managed roadways; therefore, it will use those associated stormwater conveyance datasets. The presence of a publicly owned stormwater conveyance within a set distance of the roadway will be used to determine the "connectedness" of the roadway to the stormwater conveyance network. The screening model endpoint is upstream of stormwater treatment devices. The decision support tool is expected to consider existing infrastructure.

Additionally, the project will evaluate the feasibility of compiling the mapped stormwater for each incorporated jurisdiction within King County. This may be challenging, given the varying structure and completeness of those datasets. The decision to incorporate additional jurisdictions' stormwater infrastructure will be made in consideration of available time and budget resources in consultation with the King County project manager.

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3.4. Tasks Required

The following tasks are required for this project:

- Identify and recruit SMEs to inform development of the 6PPD-q Screening Model.
- Compile spatial datasets for model input and evaluate for quality assurance. Potentially conduct spatial harmonization if features are misaligned.
- Document Screening Model development, input data, and output scores in technical memorandum.
- Use the Screening Model to support identification of sampling stations across a spectrum of estimated 6PPD-q effluent concentrations and spatial input variables (To be accomplished in future *Sampling QAPP*).

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4. Organization and Schedule

This section identifies key individuals that will be involved in the implementation of this project, any required training or certifications, its schedule for completion, and the associated budget and funding sources.

4.1. Key Individuals and Their Responsibilities

Table 6 shows the responsibilities of those who will be involved in this project. A team of SMEs will provide insight and review of the 6PPD-q delivery conceptual model and develop the Screening Model (Table 7). An additional team of Spatial Experts will guide selection of suitable spatial layers for input into the models or suggest proxies where data is lacking (Table 8).

Table 6. Organization of Project Team for Modeling Task.

Staff	Title	Responsibilities
Michelle Myers Washington Department of Ecology	Ecology Project Manager	Provides final review of the QAPP and approves the final QAPP.
Owen Brummel Washington Department of Ecology	Ecology Financial Manager	Provides final review of the QAPP.
Doug Howie Washington Department of Ecology	Ecology Technical Advisor	Provides final review of the QAPP.
Karna Holquist Washington Department of Ecology	Ecology Technical Advisor	Provides final review of the QAPP.
Timothy Clark Herrera Environmental Consultants, Inc.	Screening Model Lead	Co-author of QAPP. Facilitates conceptual model development. Facilitates Screening Model development.
Stacy Luell Herrera Environmental Consultants, Inc.	Technical Support	Research and co-author of QAPP.
John Lenth Herrera Environmental Consultants, Inc.	Consultant Project Manager	Provides internal review of the QAPP, approves the budget, and approves the final QAPP for delivery to the County.
Olivia Wright Herrera Environmental Consultants, Inc.	Consultant Assistant Project Manager	Tracks schedule, budget, and deliverables.
Lauren Ode-Giles Herrera Environmental Consultants, Inc.	Consultant GIS Specialist	Performs spatial analyses in developing of Screening Model.
Jennifer Schmidt Herrera Environmental Consultants, Inc.	Consultant GIS Expert	Oversight and review of spatial analyses methodology.
Carly Greyell King County Water and Land Resources	King County Modeling Task Lead	Manages Consultant contract, part of Internal Review Team.
José Carrasquero King County Road Services	King County Roads Principal in Charge	Approve final deliverables to be sent to Ecology Project Managers.

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Katie Merrell King County Road Services Division	King County Road Services Division Project Manager	Manages the contract with Ecology.

Table 6 (continued). Organization of Project Team for Modeling Task.

Staff	Title	Responsibilities
Todd Hunsdorfer King County Water and Land Resources	King County Stormwater Services Program Manager	Part of Internal Review Team.
Jeff Burkey King County Water and Land Resources	King County Technical Lead	Part of Internal Review Team.
Jenée Colton King County Water and Land Resources	King County Supervisor to Task Leads, Subject Matter Expert	Part of Internal Review Team.
Jennifer Lanksbury King County Water and Land Resources	King County Monitoring Task Lead, Subject Matter Expert	Part of Internal Review Team.
Robin Kirschbaum RKI	Prioritization Tool Lead	Integration of Screening Model into Project

QAPP: Quality Assurance Project Plan

Table 7. Subject Matter Experts for Conceptual Model and Screening Model Development.

Expert	Title	Association
Kathy Peter, Ph.D.	Aquatic Chemist, Research Scientist	University of Washington Center for Urban Waters
Jenifer McIntyre, Ph.D.	Aquatic Toxicologist, Assistant Professor	Washington State University
Rhea Smith	Aquatic Toxicologist	Washington State Department of Ecology
Stephen Conroy	Environmental Scientist	King County Road Services Division
Jennifer Lanksbury	Ecotoxicologist	King County Water and Land Resources Division
Jenée Colton	Supervisor, Toxicology and Contaminant Assessment Unit	King County Water and Land Resources Division
Kelly Moran, Ph.D.	Senior Scientist	Clean Water Program San Francisco Estuary Institute

Table 8. Spatial Expert Team (SpET).

Expert	Title	Association
James (JJ) Bach	Roads Spatial Data Specialist	King County Road Services Division
Jeff Burkey	Hydrologist	King County Water and Land Resources Divisions
Jennifer Schmidt	Geospatial Science Associate Practice Director	Herrera Environmental Consultants
Stephen Conroy	Environmental Scientist	King County Road Services Division

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4.2. Special Training and Certifications

The project requires advanced statistical and spatial analysis techniques using ArcGIS Pro. The project staff have years of experience in spatial analysis with this software.

4.3. Proposed Modeling Project Schedule

The planned project schedule for development of the Screening Model is shown in Table 9.

Table 9. Schedule of Screening Model Development

Step	Responsible Parties	Start	End
Conceptual Model Development	Consultant SME Team	Q3 2023	Q4 2023
Modeling QAPP Development	Consultant King County Ecology (review)	Q4 2023	Q3 2024
Screening Model Development	Consultant SME Team SpET Team	Q1 2024	Q3 2024
Modeling Technical Memorandum	Consultant SME Team (review) SpET Team (review) King County (review) Ecology (review)	Q2 2024	Q3 2024

4.4. Budget and Funding

The project is funded through the National Estuary Program Stormwater Strategic Initiative Lead grant administered by Ecology and through the King County Water Quality Benefits Evaluation program (WQBE). WQBE is jointly funded by the King County Wastewater Treatment Division and the King County Water and Land Resources Division. The United States Environmental Protection Agency (EPA) receives money from Congress to help protect and restore Puget Sound. Under Section 320, EPA provides National Estuary Program and Puget Sound Geographic Program funding and support to help communities make on-the-ground improvements for clean and safe water, protected and restored habitat, thriving species, and a vibrant quality of life for all, while supporting local jobs.

Note that the development of this QAPP and early modeling work were funded and managed through an existing project called the Water Quality Benefits Evaluation (WQBE) Toolkit. The WQBE Toolkit is a King County-funded effort to use modeling to provide consistent, science-based methods for assessing how actions improve water quality outcomes, which is one consideration for King County planning and prioritization processes. Work was already underway to model 6PPD-q as part of the WQBE Toolkit, so

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that work was leveraged to feed into the larger goals of the Multi-Criterion Decision Tool to Address 6PPD-q Tire Wear Particles project.

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5. Quality Objectives

5.1. Data Quality Objectives

The initial development of the Screening Model will not require collection of new environmental data. The Screening Model will rely on expert elicitation, which is described in Section 6.2. Expert responses through workshops, worksheets, and emails regarding model structure will be treated as data. Ensuring that the model is representative of expert knowledge, while minimizing individual bias, it is crucial to develop a model that appropriately captures the collective understanding of the target system. As described in Section 6.2.1, we will be relying on the IDEA protocol ("Investigate", "Discuss", "Estimate" and "Aggregate") to elicit information from experts. When materials are created, each expert gives their initial input privately, individuals' input is shared anonymously with the group followed by a live discussion, the individuals are provided an opportunity to revise their input, and the final output is an aggregate of individual responses. This is intended to reduce biases by any individual expert and maximize the accuracy and representativeness of group judgements (Hemming et al. 2018).

The Screening Model will depend on available spatial datasets. We have identified several anticipated datasets in Section 3.3, but additional datasets may be needed. Spatial datasets will be selected based on the appropriate resolution and temporal representation; selection will also depend on the presence of a quality assurance plan or similar documentation for the development of individual spatial datasets. If additional secondary datasets are needed, the generation of those datasets will be documented with an emphasis on quality assurance.

Several derived spatial datasets will be produced as inputs to the Screening Model. These will include a unifying road polygon layer that represents the spatial footprint of the Ecopia-classified roadway data, split at intersections and associated with the King County st_address layer to improve spatial agreement between these critical source layers and other geospatial files. A road skirt polygon will also be developed from the unified st_address and Ecopia polygon layers. Other files may be produced as interim or final products in the course of developing the Screening Model. All spatial datasets produced for this work will meet the Washington State Geographic Information Council Geospatial Data Guidelines or Federal Geographic Data Committee (FGDC) Content Standards for Digital Geospatial Metadata and National Map Accuracy standards. This will include metadata descriptions of data fields, domain coding schemes, and a summary of the coverage, completeness, and accuracy of data products. Sources of uncertainty and/or inconsistency arising from misalignment or mismatched resolution of spatial data will be clearly documented and reported. Assumptions applied during processing and analysis will also be documented and reported.

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5.2. Acceptance Criteria for Quality of Existing Data

The Screening Model will have multiple inputs that rely on existing spatial datasets. We intend to use spatial datasets that (1) were developed with rigorous quality control procedures and documentation and (2) have sufficient resolution and recency to represent roadway and drainage network conditions. The spatial datasets and their documentation are described in Section 3.3. We will review the quality of datasets and associated metadata documentation prior to dataset inclusion in the Screening Model.

The following acceptance criteria will be applied to all data used for model development:

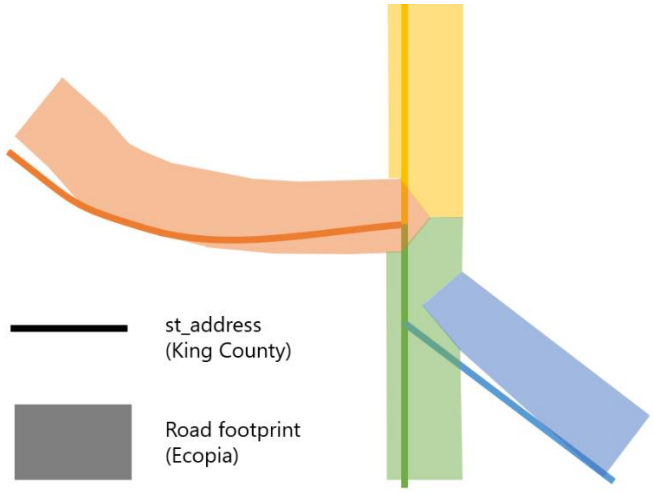
- *Data reasonableness:* The quality of existing data will be evaluated through the review of any written reports and graphics. Anomalous or questionable results will be removed. Statistical tests may be used to identify additional erroneous or outlier data; these observations will also be removed from the data set.
- *Data representativeness:* Data that is used will be reasonably complete and representative of typical conditions at the location under consideration.

Potential inaccuracies, imprecision, bias, and other sources of uncertainty will be summarized in the Screening Model documentation. Metadata associated with the input layers will be carried over in the Screening Model documentation. Generally, existing data will be evaluated for (1) spatial alignment between layers, (2) the plausibility of reported values compared to expected values (e.g., tens-of-thousands of vehicles per day on a suburban street is not plausible), and (3) gaps in the spatial coverage (e.g., areas where stormwater infrastructure is not mapped).

There is a known challenge with reconciling the King County st_address layer with other spatial datasets. The st_address layer represents the mid-point of parcel rights-of-way, rather than the centerline of the associated road footprint. To address this challenge, the unique road segment ID for each st_address line segment will be associated with AI-derived, high-accuracy road footprints from Ecopia (Figure 3). When the st_address line segments and Ecopia-derived road footprints share a unique identifier, spatial attributes aligning with Ecopia-derived footprints can be ascribed back to the target st_address line feature. The spatial coverage, completeness, and accuracy of spatial layers that are to function as inputs to the Screening Model will be compared against the Ecopia-derived road footprints, rather than against the st_address layer, to ensure accurate spatial comparisons. Other datasets from King County GIS and WSDOT that will serve as inputs to the Screening Model (presence of curbs, gutters, stormwater conveyance systems, etc.) are assumed to represent best-available coverage and accuracy of spatial data for the study area based on visual review. However, there may be gaps in data coverage for drainage and connectivity features that cannot be otherwise addressed in this modeling study in the absence of field verification.

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Figure 3. Model for Associating Ecopia-Derived Road Footprints with Non-Coincident st_address Linear Road Segments.



Other data sources for the Screening Model will include data products from the Puget Sound Regional Council (PSRC) SoundCast Model (described in Section 3.3.1). The SoundCast model products provide high temporal and spatial coverage for the study area, with well-documented model assumptions and limitations. The PSRC is subject to compliance with the Washington State Geographic Information Council Geospatial Data Guidelines.

5.3. Model Quality Objectives

The structure of the 6PPD-q Screening Model will be developed using expert elicitation. Spatial data will be selected and, if needed, geographically modified to act as inputs for the Screening Model. Spatial data modification may include harmonizing datasets with misaligned roadway features and interpolating/extrapolating spatial data to proximate features. Spatial inputs and analyses will be rigorously documented. No in-the-field validation of model input data is planned for this effort. Field validation may occur during the monitoring site selection and sampling under the future *Sampling QAPP*.

The Model Quality Objectives for the Screening Model are qualitative, due to the planned purpose of the model's use (to develop categorizations rather than quantitative results). As described in Section 6.2.1, the quality of model will be assessed by both the surveyed expert team (SME Team) and by an additional review team (Internal Review Team).

- The Screening Model should be free of critical flaws, as assessed by the SME team and the Internal Review Team. Critical flaws will be defined at the discretion of the individual SMEs, in consideration of the model objectives and intended use. For example, a critical flaw would be the exclusion of a highly influential factor (e.g., number of vehicles) or relying on a gross misrepresentation of that factor (i.e., it is inaccurate by over an order of magnitude). As another example, a critical flaw would be that the model output is not the right format for input into the *Multi-Criterion Decision Tool*.
- The Screening Model should provide results that are meaningful for selecting monitoring sites across a gradient of input parameters and expected delivery of 6PPD-q to surface waters.

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The objective of the Screening Model is to generate a high-level predictive model that can estimate the relative export of 6PPD-q from roadways to the stormwater conveyance network within the study area. Model quality objectives for assembling spatial data inputs will emphasize rigorous management of the spatial fidelity of inputs and synthesized outputs, to limit uncertainty introduced through these data preparation steps. Known spatial data gaps and sources of uncertainty will be clearly documented, so that their influence may be considered in subsequent phases of model testing, validation, and refinement. Processing steps applied in the assembly of spatial data inputs will be repeatable and clearly documented; quantification of data source certainty and spatial alignment will be calculated for each feature, where relevant.

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6. Model Development Design

6.1. Study Boundaries

The Screening Model study boundary is the King County geographic area, specifically the public roadways. The Screening Model development will primarily target evaluation of King County and WSDOT managed roadways. The application of the Screening Model to incorporated areas of King County and the associated data needs will be evaluated. The model may be extrapolated to other areas for estimating 6PPD-q in stormwater effluent, but modifications may be necessary to consider the effect of meteorological conditions and soils/geology. The model explicitly considers only stormwater runoff from public roadway deposition surfaces and their immediate environs (i.e., a 6-m roadway skirt). This excludes parking lots, crumb rubber recreation fields, raceways, airports, tire piles, and deposition on surfaces outside of the roadway skirt.

6.2. Modeling and Analysis Design

The following sections describe steps that will be performed for Screening Model development and setup.

6.2.1. Screening Model Development

The model development process will closely follow the first four steps of the methods used for the King County WQBE program. This process is documented in WQBE 610TM2, General Methodology for Building Bayesian Networks to Support WQBE (King County 2019) and summarized in Table 10, with further details provided in the following subsections. In King County (2019), the steps are accompanied with the development of an example Bayesian network, which is omitted here. The Screening Model will not be a Bayesian network, so the methods depart from King County (2019) at Step 4.

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Table 10. Development Process for Conceptual Model and Screening Model.

Step	Description	Activity
1. Clear definition of endpoint and model purpose	To ensure proper detail and specificity, it is critical to clearly define the scope, endpoint, purpose, and user of the model.	Accomplished as part of Modeling QAPP development.
2. SME Identification and Recruitment	Subject matter experts (SMEs) are selected based on their knowledge of the issue, capability to communicate their knowledge, awareness of their own knowledge and problem-solving ability, reliability, and freedom from conflicts of interest.	Herrera and the IRT collaboratively identified and recruited SMEs who are experts in 6PPD-q, roadway and parking lot runoff, and tire wear.
3. Conceptual Model Development	A conceptual model for the defined endpoint is developed according to the boundaries and scale relevant to model use. The conceptual model maps influential factors and their relationships leading to the endpoint. The team of SMEs reviews the draft model independently and then discusses their feedback as a group before refining the final model, a process which was intended to reduce bias by any individual expert.	Herrera and the IRT developed a draft conceptual model for SME review and feedback based on a literature review. This is documented in the Modeling QAPP for Ecology approval. Workshop (August 2023)
MILESTONE: CONCEPTUAL MODEL		
4. Identification of Primary Factors and Spatial Proxies	The conceptual model is used to identify appropriate spatial proxies for use in the Screening Model (e.g., modeled vehicle traffic by vehicle weight class; drainage features; adjacent imperviousness). The overall structure of the conceptual model is retained (Figure 1), but the constituent model inputs are generalized for suitability over a large geographic extent (e.g., the presence and length of drainage infrastructure associated with a target roadway is applied as a model input, but the connectivity of the broader stormwater drainage network is not).	SpET Workshop (Fall 2023) SME Workshop (Fall 2023)
5. Compilation and Harmonization of Spatial Data	During the development of this QAPP, an initial evaluation of the input spatial features for the Screening Model identified instances of misalignment between features. This included misalignment of roadway spatial features (between the st_address roads and the psrc SoundCast traffic model links), as well as misalignment between the st_address layer and other non-road model inputs (including stormwater infrastructure and the road skirt). The project team will seek to develop a programmatic process to unify the disparate layers. This will improve the confidence of assigning appropriate attributes to each target road segment.	Q1 – Q2 2024
MILESTONE: SCREENING MODEL		
6. Scoring of Roadway Using the Screening Model	Individual roadway segments are ranked using a simple scoring model. The SME team reviews and provides comment on the initial generalized roadway types and scoring model.	Q3 2024

IRT: King County Internal Review Team; SME: Subject Matter Expert; SpET: Spatial Expert Team

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Throughout model development, we will use a structured process to gather input from relevant experts. This structured process is a modified version of the IDEA protocol described by Hemming et al. (2018), which consists of four steps: investigate, discuss, estimate, and aggregate. When materials are created, each expert gives their initial input privately. Then, individuals' input is shared anonymously with the group, followed by a live discussion. The individuals are then provided an opportunity to revise their input, and the final output is an aggregate of individual responses. This is intended to reduce biases by any individual expert and maximize the accuracy and representativeness of group judgements (Hemming et al. 2018).

Generally, the expert elicitation process includes:

1. Each expert evaluates draft materials privately.
2. Model lead shares anonymized individual evaluations amongst the SMEs.
3. Model lead facilitates live group discussion(s) with the assembled SMEs by conference call, followed by an opportunity for the SMEs to modify their initial evaluations/estimations and input if desired.
4. Model lead aggregates expert input into future versions.

6.2.1.1. Step 1: Clear Definition of Endpoint and Model Purpose

Clear definition of endpoint and model purpose is a crucial component that can often be overlooked as model constructors start mapping out their conceptual model (Marcot et al., 2006). The endpoint must be meaningful and measurable, in consideration of the model's purpose and the management decisions to be made.

A clear model purpose is also necessary to adequately describe the model to others (Marcot et al., 2006; Chen and Pollino, 2012). A clear endpoint and purpose set expectations and influence the level of detail. For example, a model with a purpose of mitigating fire hazard to houses bordering forestlands is very different from a model projecting forest fires under various climate change and undergrowth management scenarios. The former model would include a model endpoint of number of houses burned and factors such as house construction material, building setbacks, and forest fire frequency. The latter model would include an endpoint of acreage burned with nodes such as selective burning, undergrowth density, drought period, latitude, elevation, and tree species. While fire hazard to houses and acreage burned are likely correlated, the important nodes of influence may differ. The use of metal roofs may be the most influential node for fire hazard, but the same node would have marginal influence on forest acreage burned.

The model output end user (e.g., decision-maker, policy-maker, manager), who will ultimately use the Screening Model as a decision-support tool, will be clearly identified. Further, the decision(s) that will be informed by the model will also be identified. Throughout the model development process, the end user will be informed on progress and informed of what information the model can and will provide.

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For the Screening Model, we have identified the following:

- Model Purpose: (1) To inform the selection of monitoring sites by defining the key influential landscape factors to evaluate across, and (2) to provide a relative scoring/ranking of public roadways in terms of the export of 6PPD-q
- Model Endpoint: "Delivery of 6PPD/6PPD-q to Stormwater Conveyance Network" expressed as the relative amount of 6PPD-q or its parent material expected at the point of input to the conveyance network

  Note: the conceptual model extends to "Delivery to Surface Waters" and considers transport and treatment, but this is outside of the scope of the Screening Model.)

- Model Scope: Public roadways in the King County geographic area
- Model User: Technical staff within stormwater management agencies with GIS experience
- Model Output User: Project managers and technical staff who are selecting monitoring sites to characterize 6PPD-q and/or prioritizing drainage areas/roadways for stormwater retrofit

6.2.1.2. Step 2: Subject Matter Expert (SME) Identification and Recruitment

Creating (structuring and parameterizing) the conceptual model and the Screening Model will rely heavily on expert knowledge. Expert knowledge is a viable alternative when data is absent or incomplete (Hemming et al., 2018). As such, there is a need to properly identify what and who is an expert, in consideration of the models' scope and purpose. The project team will select experts, sometimes called subject matter experts (SMEs), to guide construction of the causal models from the conceptual model to the operational Screening Model (described in the following steps). Expert selection will consider several attributes, per Meyer and Booker (1990) and Hart (1986):

- Knowledge of the issue at an appropriate level of detail
- Capability to communicate their knowledge
- Use of knowledge to solve problems effectively and efficiently
- Awareness of their own limitations
- Personal reliability
- Lack of conflicts of interest

Expertise may exist at different spatial and temporal scales, and an expert may not be an expert in all aspects of the causal model (Caley et al. 2014; McBride et al., 2012). Selection of experts should accommodate gaps in expertise and experience among the experts to be complementary.

6.2.1.3. Step 3: Conceptual Model Development

A conceptual model (or influence diagram) is a visual representation of the knowledge of a particular system (Marcot et al., 2006; Chen and Pollino, 2012). Each model node represents a variable—nodes can be an observable quantity or a summary/surrogate variable. Latent variables are inferred based on

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observable variables (e.g., stream habitat quality cannot be directly measured but can be inferred from variables, such as large woody debris and streambed substrate) (Marcot, 2019). Relationships between nodes are denoted with arrows showing the direction of influence. The initial conceptual model may be constructed by one person or by a small team that maps out the influencing factors.

Step 3A. Map Influencing Factors

With the clear endpoint and model purpose in mind, factors influencing the endpoint node should be identified. The parent node (i.e., the cause) should have a direct relationship with the child node (i.e., the result). For simplicity, nodes are not needed for every step in a causal relationship if the intermediate step is not expected to change irrespective of the parent node. When building a conceptual model, it is crucial to identify the boundaries and scale of the analysis. In a conceptual model, input nodes are those that do not have any parent nodes influencing them. Where the conceptual model establishes its boundaries is dependent on the endpoint and model purpose.

Step 3B. Expert Consultation

Following completion of the conceptual model by the project team, it will be reviewed by the relevant experts identified in Step 2 (Chen and Pollino, 2012). The experts will provide feedback on model structure, identify gaps, identify opportunities for simplification, and identify potential data sources and additional experts that can provide information regarding relationships in the model. The identification of data sources and additional experts will benefit from Step 5 described below.

Steps 1 through 3 were accomplished during the development of this Modeling QAPP. The conceptual model is presented in Section 2. The conceptual model was developed using the following steps:

1. Herrera and King County Internal Review Team (IRT) staff developed the draft conceptual model based on a literature review (see Section 2.2).
5. The draft conceptual model was individually reviewed by each SME, with a template for providing feedback.
6. The SME evaluations were anonymized and shared amongst the SMEs via email.
7. Herrera staff facilitated a live group discussion with the SMEs by conference call (i.e., teleconference) to share input and responses.
8. Herrera and IRT staff incorporated the SME input into the final conceptual model, presented in Section 2.3.

This conceptual model does not represent the final structure of the Screening Model. Additional structural changes (i.e., insertion or deletion of model variables or linkages) are anticipated as part of Step 4, to increase model specification.

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6.2.1.4. Step 4: Identification of Primary Factors and Spatial Factors

Step 4A. Clearly Define Model Variables (Nodes)

Each variable (node) within the model must be clearly defined, so that an outside viewer understands what a variable does and does not represent. In some cases, this includes defining the unit of measure for a node. The definitions of nodes should provide adequate clarity and specificity, so that an observer would know exactly how to identify, measure, count, and otherwise denote the condition of the model variables.

Step 4B. Remove Complexity and Add Clarity

The initial conceptual model (influence diagram) defining an environmental system will likely be complex, with numerous variables (nodes) and connections. Often, the model can be simplified at this stage,, which is important in order to (1) make the model more approachable to non-experts and (2) ease the data needs for spatial reconciliation (Step 5). The primary method used to simplify a model is to identify which factors *must* be represented and which factors do not need to be represented. If a factor is unlikely to affect its child node or the endpoint, there is no need to include it in the network. An additional method to simplify the model is to add summary nodes that capture several factors (Marcot et al., 2006; Chen and Pollino, 2012). Often, a child node may have many parent nodes (i.e., multiple variables that influences the value of a child node), which could result in a multitude of inter-relationships too cumbersome to complete and compute. These parents may be combined into intermediate summary nodes, based on logical combinations, causal structures, and potential intermediate calculations of interest.

Step 4C. Spatial Proxies Identification

The model lead will consult with the Spatial Expert Team (SpET), to identify suitable spatial layers that may be used as inputs to the Screening Model and as proxies for the initial inputs identified in the conceptual model. A spatial layer may be used alone or in combination with other layers to develop a proxy. If a factor identified in step 4B must be included in the model, but no suitable data or proxy exists, then the project team will document the importance of this variable in the final model technical memorandum and suggest methods to fill the data gap.

For example, the conceptual model may identify slow-speed cornering as an influential factor for 6PPD-q deposition, but there are no available spatial datasets for occurrence of slow-speed cornering. The SpET would then seek to identify existing datasets that could serve as proxies for slow-speed cornering. In this example, SpET could identify variables that would predict slow-speed cornering through interactions of parking garages/lots or street parking, average daily traffic volume, and congestion/time-limited parking areas.

The model lead will incorporate these proxies into an initial Screening Model structure and document the rationale behind the selection of the proxies and the associated data sources. Alternative structures may be developed, along with other datasets identified.

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6.2.1.5. Step 5: Compilation and Harmonization of Spatial Layers

Initial evaluation of the identified spatial layers indicated there may be misalignment between the lines representing roadways (i.e., the PSRC SoundCast model links and the st_address lines) and the real-world features (e.g., ditches, stormwater conveyance network, and curbs). Further, the actual variation in road footprint between roads of different types (highways vs local roads) was not well-reflected in linear geospatial features. The team will take measures to harmonize the spatial datasets such that the appropriate attributes are assigned to each roadway.

The project team will compile the best-available source data from King County, WSDOT, and other sources (summarized in Table 5). The team will evaluate spatial alignment and conformity of existing features based on a mix of automated and manual assessment. This will include spatially querying layers relative to the st_address layer (i.e., proximity, overlap, intersections) and then visually inspecting partial features not captured in the spatial query. This will be used to characterize the source and magnitude of difference between layers. We will then identify methods to capture and reliably attribute source data to appropriate st_address road segment.

Under advisement of the SpET, the project team will develop processes and tools to resolve and harmonize the dataset such that the identified Screening Model attributes may be assigned to the st_address layer.

6.2.1.6. Step 6: Scoring of Roadways in terms of 6PPD-q Delivery

Roadway Screening Model Scoring

The compiled spatial data will be used to score each roadway segment. A specific scoring system will be developed and documented in the Screening Model technical memorandum. The scoring system will seek to (1) provide relative magnitude approximations of the generation and deposition of TWP and 6PPD-q on and near roadways and (2) develop estimates of the connectedness of a deposited TWP/6PPD-q to the stormwater conveyance network. The scoring system will consider the quality of the input spatial dataset and literature values for vehicle tire wear rates.

Expert Review

The compiled spatial dataset and initial classification and scoring system will be presented to the SME team in early 2024. The model lead will describe the methods used to develop the dataset. The model lead will elicit feedback from SMEs on the classification and scoring systems, based on their collective expertise on and understanding of 6PPD-q. The SME team will provide critical review of the scoring system and provide recommendations to improve evaluation. This may include, but is not limited to, disagreement with the weighting of specific factors, identification of missing factors, or improper use of proxies.

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6.2.2. Screening Model Setup and Data Needs

The Screening Model will be developed in ArcGIS Pro v. 3.1.1, using data inputs described in Section 3.3. The model boundaries encompass all of King County, including incorporated and unincorporated areas. The model will primarily target evaluation of King County and WSDOT managed roadways. The model may be used to evaluate roadways within the incorporated areas of King County (e.g., the City of Seattle), in consideration of readily available spatial data. The project team will compile the best-available source data from King County, WSDOT, and other sources (summarized in Table 5), but additional data sources may be needed.

6.3. Assumptions of Study Design

The Screening Model development process assumes that the team of selected experts will provide appropriately caveated, justified, and defensible input for the development of the conceptual and screening models. The Screening Model is assumed to be representative of the knowledge and uncertainty in the generation and delivery of 6PPD-q for roadways.

The spatial layers used in the development of the Screening Model are assumed to be sufficiently representative for a coarse classification and scoring of roadways. There are inherent uncertainties in the use of spatial data and output of other models. These are summarized below in Table 11.

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Table 11. Assumptions and Uncertainty Assessment for Screening Model Spatial Layers.

Spatial Layer	Assumptions	Uncertainty Assessment
All layers	The Screening Model assumes the geographic accuracy and completeness of coverage within the unincorporated King County area.	
st_address	The Screening Model assumes that a line segment exists for each distinct road segment, with a new origin/terminus of each road segment line at intersections with other roads. The Screening Model assumes that two lines are present for a roadway when a median is present. The st_address feature represents the mid-line of road rights-of-way, which does not align with road centerlines in all cases. This can affect the ability to properly characterize the "roadway skirt" and the presence of conveyance networks. The Screening Model assumes that uniquely-named IDs for maintaining spatial associations between the st_address layer and the derived road footprints from Ecopia are correctly applied, and that the derived road footprints from Ecopia accurately reflect real-world positions of roadways and associated infrastructure within the resolution (6 inches) of the Ecopia source imagery.	We anticipate that some number of roads from the st_address feature will be assigned to an Ecopia-derived road footprint that is longer than the road footprint represented by the st_address. This may include alleys, private driveways (predominantly in rural areas), and other edge cases that are difficult to avoid when processing spatial data at this scale. Additionally, we anticipate that some number of roads from the st_address feature will be assigned to an incorrectly associated road footprint. This is likely to occur where there are many roads intersecting along a relatively short distance and where there are complex changes in road geometry, such as on- and off-ramps, road cloverleafs, and overpasses. Mapping scale and minimum mapping unit not reported
PSRC SoundCast Layer – Harmonization with st_address	The Screening Model assumes that the PSRC SoundCast is generally spatially associated with the st_address layer along main roads, and that the footprint of each local-type road with aggregate scores from the PSRC SoundCast model is mostly contained within a single Traffic Analysis Zone (TAZ).	The SoundCast model is spatially similar to the st_address layer but is not spatially coincident along much of its extent. The road footprints derived from the Ecopia dataset will be used to attribute st_address roads with modeled scores from the PSRC SoundCast dataset and translate those scores onto the st_address layer. Mapping scale and minimum mapping unit not reported
PSRC SoundCast Model – Daily Traffic	The Screening Model assumes that the average daily traffic output is suitable for creating coarse classifications of roadways, particularly with distinctions between local (neighborhood traffic), collector, and higher classes of road traffic.	The SoundCast model is believed to provide appropriate estimates of traffic counts for individual roadway segments to provide order of magnitude distinction. Mass transit buses are not explicitly reflected in this layer. Mapping scale and minimum mapping unit not reported
PSRC SoundCast Model – Medium and Heavy Truck	The model output for Medium and Heavy Trucks is suitable for creating coarse classifications of roadways, specifically areas where heavier truck traffic is expected due to industrial and commercial activities.	The Soundcast Truck Submodel uses socioeconomic employment/ commodity categories within transportation analysis zones (TAZs) to estimate medium and heavy truck traffic. The truck submodel was noted by PSRC staff to be "one of the most unvalidated" components of the Soundcast model. However, it is expected to provide appropriate order of magnitude estimates for this Screening Model. Mass transit buses are not reflected in this layer. Mapping scale and minimum mapping unit not reported
Ecopia[a]	The Screening Model assumes classifications of impervious land cover types is accurate within the resolution of the source imagery for identifying road footprints and distinguishing between impervious and non-impervious land classification types.	Target accuracy for the classified land cover data produced by Ecopia for King County included the following parameters for impervious land cover types: ● False Negatives (reporting impervious surface types as a pervious-type land cover type): <=5% All Polygons ● False Positives (reporting non-impervious surface types as an impervious surface type): <=5% All Polygons ● Valid Interpretation: >=95% All Polygons Additionally, data products from Ecopia had an area coverage target of 100%, with topologically-valid (non-overlapping, gap-free) spatial polygons representing classified land cover types. We believe this level of accuracy is satisfactory for the Screening Model. Source image resolution: 3-inches (urban, lowland); 9-inches (rural, upland)
Stormwater Instructure	The Screening Model assumes that the presence of stormwater infrastructure under the roadway or within 6 meters indicates whether the roadway and its skirt are connected to that conveyance network.	There are likely to be some exceptions to this assumption, but across unincorporated King County we expect this assumption to hold true in most cases. We also anticipate that there are likely some unmapped curbs, gutters, and stormwater conveyance networks.

[a] "Ecopia Vector Maps © [2021] Ecopia Tech Corporation"

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6.4. Possible Challenges and Contingencies

Scheduling with multiple experts to provide input and review of the 6PPD-q Screening Model may be challenging, due to professional time conflicts and personal time conflicts. Structured discussion among experts is critical for uncovering knowledge and/or assumptions and eliminating biases. To counteract this, scheduling efforts will be made as early as possible, and the time commitment for experts will be kept to a minimum. This means that preparatory materials and elicitation forms will be well-prepared and intuitively designed.

The Screening Model will be used in the selection of sites for model validation sampling, as part of the *Sampling QAPP* selection of these sites is scheduled to begin in spring 2024.

Model coverage and completeness is limited to the availability of spatial data. If critical data coverage gaps are identified, they will be documented and reported in the Screening Model technical memorandum. King County is planning to do field recon to prepare for sampling. Confirming attributes as part of screening model is planned as part of preparation for site selection. This may result in the omission of desired inputs from the model until such a time as gaps can be resolved at the discretion and consideration of subject matter experts.

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7. Quality Control

During the development of the Screening Model, there will be numerous touch points with the SpET and SME teams to provide expert review of the data sources and analytical methods, as described in Section 6.2.1. The Screening Model lead will include routine meetings with the consultant GIS specialist to discuss spatial quality concerns and identify corrective actions.

7.1. Corrective Actions

The primary quality control concern is the misidentification of roadway characteristics from disparate spatial layers with varying degrees of precision in the coordinates. For example, King County's st_address is based on mid-point of parcel rights-of-way, rather than the centerline of the associated road footprint, and it is not expected that the polylines will align with the actual road centerline or other spatial datasets (see Section 5.2). For this example and other issues of misalignment, spatial analysts will develop methods for aligning the spatial layers to improve accuracy. These methods will be developed in consultation with the SpET group. These methods will be documented in the Screening Model technical memorandum. Any data quality concerns will be documented in the technical memorandum.

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8. Data Management Procedures

Development of the Screening Model, including structural changes and data selection rationale, will be documented. During meetings with experts, we will take thorough notes and provide follow-up email summaries. We will retain completed elicitation and review documents. Each version of the model will be saved and dated, and changes between versions will be summarized and documented.

8.1. Model Information Management

Screening Model data will be stored and organized using geodatabases on Herrera's cloud servers. Processes for manipulating and transforming will be clearly documented in the Screening Model technical memorandum and will be additionally documented in repeatable Python script tools and ArcGIS Pro ModelBuilder toolboxes.

Spatial data layers that are derived from this process will have complete metadata attribution, in accordance with Washington State Geographic Information Council Geospatial Data Guidelines or FGDC Content Standards for Digital Geospatial Metadata and National Map Accuracy standards. Additional detail will be documented in supporting spreadsheets.

Primary model outputs will include a copy of the st_address layer augmented with scores for target input datasets, as well as associated derived road footprint, skirt, and buffer geometry. The spatial geometry of the st_address layer will not be modified under this effort, but the project team intends to have a 1:1 association with Ecopia-derived road footprints. The Ecopia-derived road footprints are based on aerial photography with 3-inch (in urban lowlands) and 9-inch (in rural uplands) ground resolution. The minimum mapping unit of the aggregated Screening Model data will be a product of the minimum mapping units of the source datasets. The minimum mapping resolution of the source data used to define model attributes is summarized in Table 11.

Model outputs will be designed to match the specifications of the Stormwater Prioritization Tool.

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9. Audits and Reports

9.1. Audits

Not applicable. Intermittent progress reports and coordination with the Internal Review Team will provide suitable oversight.

9.2. Responsible Personnel

Not applicable.

9.3. Frequency and Distribution of Reports

A draft and final technical memorandum detailing the Screening Model will be prepared in 2024 and submitted to the Internal Review Team for comment and later for approval by Ecology.

9.4. Responsibility for Reports

Herrera will prepare the Screening Model technical memorandum.

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10. Data Verification

10.1. Model Quality Assessment

10.1.1. Validation

Under this phase of Screening Model development, there will not be calibration or validation of the model due to a lack of environmental data. However, as described in Section 2.1, the next phase of this project will include field sampling for 6PPD-q. The purpose of this work will be to characterize 6PPD-q export from roadways across a gradient of road use and road drainage characteristics. Ten to twenty candidate sites will be selected based on Screening Model output and additional factors influencing the feasibility and safety of collecting samples of roadway runoff, while ensuring a gradient of Screening Model outputs are represented across the sites. Before a site is selected for model validation sampling as part of the Sampling QAPP, we recommend the attributes identified from the Screening Model are verified via site-specific desktop and/or field reconnaissance. The final report from that 6PPD-q characterization study will include qualitative evaluation of how the measured magnitudes of 6PPD-q concentrations align with the Screening Model scores. The final report from that study may include recommendations for adjustments of the Screening Model to improve performance.

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11. Data Quality (Usability) Assessment

11.1. Process for Determining Project Objectives Were Met

11.1.1. Screening Model

The quality of the Screening Model will be subjectively evaluated by SMEs and IRT, as part of its development and approval. The Model Quality Objectives identified in Section 5.3 will be used for this evaluation. The following specific activities will be performed to ensure project objectives are met:

- SMEs and IRT will provide periodic reviews of the Screening Model during development.
- The spatial analyst will take feedback provided by the SMEs and IRT to revise the Screening Model geospatial processing.
- Where feasible, the spatial analyst will resolve edge cases manually.
- Where systematic error is identified, the spatial analyst will develop programmatic solutions and revise the geospatial processing steps. Where systematic error cannot be programmatically resolved, the incidence of this error and its impact on the final model will be documented.
- The final data product(s) will be spatially complete (i.e., all segments in King County's st_address will be characterized and scored) and will be accurately and completely documented following FGDC guidelines.

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