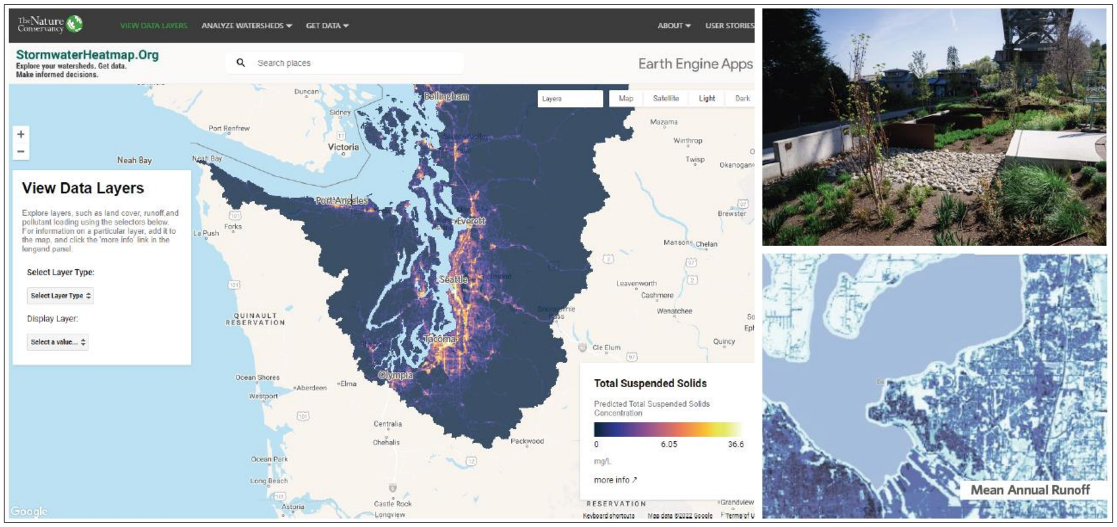
# Quality Assurance Project Plan: Puget Sound Stormwater Heatmap Version 2.0

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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. After completing the study, the author will post the final report online. This QAPP describes a project selected for funding through the Stormwater Strategic Initiative Lead Request for Proposals in Fall 2022 and is described in the February 2023 Investment List for strategic investment of Puget Sound Geographic Program funds. Funds were awarded under Ecology Contract number WQNEPSW-2023-NatCon-00002.

This QAPP is available upon request to Sarah Brunelle: This QAPP is available upon request to Sarah Brunelle at sarah.brunelle@tnc.org. Data for this project is available at https://www.stormwaterheatmap.org. The QAPP is valid for one year from the date of certification. All QAPPs for programs or projects exceeding one year in duration shall be reviewed and recertified annually.
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**COVER PHOTO**: Screenshot of the Puget Sound Stormwater Heatmap Version 1.0 web tool showing TSS concentration across the Puget Sound watershed, a rain garden, and an example of mean annual runoff calculations for the Tacoma area. PHOTO BY COURTNEY BAXTER.

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# Quality Assurance Project Plan
# Puget Sound Stormwater Heatmap

by Christian Nilsen, Emily Howe, Eva Dusek-Jennings, Guillaume Mauger, and Sarah Brunelle
Published February 2024

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# 2.0 Abstract

The Nature Conservancy (TNC) entered an agreement with the Washington Department of Ecology (Ecology or ECY) to improve Version 1.0 and add features to develop Version 2.0 of the Puget Sound Stormwater Heatmap tool. This spatialized stormwater mapping and planning tool uses data, models, and open-source tools to support stormwater management improvements.

The Puget Sound Stormwater Heatmap quantifies the amount of stormwater runoff (flow) and estimates the concentration of chemicals of concern (COCs) generated across the Puget Sound watershed. It provides stormwater managers and conservation practitioners with a cohesive model to understand how much and where stormwater is generated across the landscape. These data can then be used to identify locations where interventions are needed. The Stormwater Heatmap does not conduct flow routing.

This document presents a quality assurance project plan (QAPP) outlining procedures and practices specific to software and model development. This project will neither take environmental samples nor generate lab results. This context of this QAPP is based upon a previous Ecology-approved QAPP developed for the City of Tacoma (Contract No. WQC-2021-TacoES-00090).

This QAPP describes the approaches, study design, and quality assurance measures for developing a Stormwater Heatmap model for the Puget Sound watershed using pre-existing datasets from stormwater outfalls, downscaled climate precipitation models, and spatial landscape predictors. This project will not directly measure environmental conditions, collect samples, or conduct laboratory analysis. This project also does not model flow routing, nor does it include locations of treatment facilities. This project relies on pre-existing data and tools with their own quality assurance and quality management processes. These sources have a known level of quality and are considered vetted and tested.

# 3.0 Background (Version 1.0)

## 3.1 Introduction and Problem Statement

### Problem: Regional Urban Stormwater Runoff

Each year, 370 billion gallons of untreated urban stormwater runoff enter Puget Sound streams, rivers, lakes, and marine waters – posing one of the primary terrestrial pressures on the Salish Sea estuarine and marine environment (Puget Sound Institute 2015).

When rain falls to the ground and meets impervious surfaces such as concrete, roofs, and pavement – rather than soaking into the temperate rainforest's soil – that rainfall runs across those hard surfaces and picks up toxic urban contaminants generated on land. Stormwater travels through a decentralized network of roads, rooftops, aging and over-burdened drainage pipes, and other impervious surfaces, delivering toxic contaminants directly into nearby streams, rivers, and other receiving water bodies such as the Puget Sound.

For most toxic substances, surface runoff is the largest contributing source of toxic pollutant loading to Puget Sound, a sub-basin of the Salish Sea (Washington State Department of Ecology 2011). This means untreated stormwater runoff poses a critical ecological problem that has impacted virtually all urban and urbanizing streams and rivers in the region and the receiving waters of Puget Sound. As a result, aquatic and marine species' abundance, health, and survival have declined at all levels of the food web. Human health also suffers as we live out our lives adjacent to near-ubiquitous pollution, with communities of color shouldering most of the burden.

The Salish Sea's relationship with stormwater effluent is not an outlier in the United States context; stormwater is the fastest-growing cause of surface water impairment in the nation because urbanization across the country transitions forested and other natural landscapes to hard, impervious surfaces (U.S. Environmental Protection Agency 2019).

Given that the existing population of 8.7 million people living along the border of the Salish Sea is projected to reach 10.5 million by 2040, stormwater interventions will continue to be necessary if we intend to break the relationship between urbanization and stormwater-caused ecological degradation and human health impacts (Sobocinski 2021). We also know climate change drives increased storm frequency and intensity, magnifying the need for adaptive flood and infrastructure planning.

To implement effective solutions, it is essential to address both aspects of the two-fold urban stormwater runoff problem: the quantity of water pulsing off the land and the quality of that water (i.e., the contaminants it contains) as it flows into receiving bodies.

**Water Quantity:** Watersheds with as little as 5-10% impervious surface area – such as rooftops, roads, and paved parking areas – exhibit aquatic habitat degradation because of increased surface runoff (Walsh et al. 2005). This changes the timing, magnitude, and frequency of high-flow events, making urban streams "flashier" than those with natural surrounding landcover conditions. These hydrological changes cause combined sewer overflow events, flooding, erosion, and scouring of streams and riverbeds. Flashy hydrology disrupts habitat structure, alters freshwater ecosystems' ecology, and disrupts more extensive ecosystem processes in marine environments, such as nutrient flux, organic matter processing, and ecosystem metabolism (Palmer and Ruhi 2019). While coastal food webs rely on rivers to deliver organisms, nutrients, and detritus from the land to the sea, these fluxes increasingly result in negative impacts, such as eutrophication, hypoxia, and harmful algal blooms. Under climate change, stream flows are expected to exhibit more significant peak flows than seen historically, generating an even greater need to quantify the interaction between land cover change and future surface water runoff.

**Water Quality**: Besides altering hydrological flow regimes in watersheds that contribute to the Salish Sea, urban stormwater also delivers a suite of contaminants that severely impact the water quality of streams, rivers, estuaries, and the Salish Sea. Urban runoff contains complex and unpredictable mixtures of chemicals that include – but are not limited to – heavy metals (i.e., copper, zinc), nutrients (i.e., nitrogen, phosphorous), and particulates. Toxic pollutants entering the Salish Sea may be metabolized in plant and animal tissues, bioaccumulated in tissues, incorporated into sediments, volatilized, degraded, or conserved in marine waters.

As a result of stormwater's twin challenges, urban watersheds and marine receiving waters suffer from "urban syndrome" – a condition that results in low abundance and survival of sensitive aquatic and coastal species (Walsh et al. 2005). Virtually all urban streams and rivers in the Puget Sound portion of the Salish Sea have been harmed by the toxic impacts of stormwater pollution (Booth et al. 2004).

**Urban Stormwater Toxic Impacts**: Researchers have documented the toxic effects of stormwater exposure for a diverse range of aquatic and marine species ranging from primary producers to high trophic-level predators. Some effects are sublethal and reduce species fitness and long-term survival. For example, heavy metal accumulation is common among marine macroalgae and eelgrass (Zostera Marina); this accumulation reduces photosynthetic function (Jarvis and Bielmyer-Fraser 2015; Lyngby and Brix 1984). Other sublethal impacts of stormwater on marine organisms include the reduction of byssus strength in marine mussels (Gaw, Thomas, and Hutchinson 2014), reduced olfactory function in juvenile salmonids (Baldwin, Tatara, and Scholz 2011), reduced growth and lipid storage in juvenile Chinook (Meador, Sommers, and Ylitalo 2006), reduced pathogen resistance in juvenile salmon (Arkoosh et al. 2001), cardiotoxicity in juvenile fish (Incardona, Linbo, and Scholz 2011), decreased reproductive function and immune response in benthic fishes (Rice et al. 2000), seals (Anan et al. 2002), and Southern Resident Killer Whales (Kayhanian et al. 2012; Ross et al. 2000; WDFW 2011).

Some effects are acutely lethal, as for adult coho salmon, where pre-spawn mortality rates in urban streams can be as high as 90% (Scholz et al. 2011). These fish end their years-long journey to the ocean and back with their bellies still full of unfertilized eggs, missing their single chance to spawn the next generation. For coho, pre-spawn mortality is linked to the transportation network, where contaminants, such as tire wear leachates, are generated (Feist et al. 2017). Thus, expanded development and increased use intensity of the built environment significantly impact the long-term viability of local and regional coho populations, with far-reaching ramifications for both freshwater and marine food webs alike. While it is tempting to focus on lethal impacts to iconic species such as coho, road runoff is similarly lethal to lower trophic level organisms, such as mayfly larvae, sea urchins, and amphipods, which all play essential roles in upholding marine, freshwater, and terrestrial food webs (Anderson et al. 2007; Kayhanian et al. 2012; McIntyre et al. 2015).

The good news is that researchers have identified numerous effective techniques to reduce stormwater impairment of surface and receiving waters. These methods include street sweeping, pervious pavement, green stormwater infrastructure (wherein stormwater is filtered by soil and plant mixtures from the streets to the sea), and more.

However, these interventions are costly: around $65-132 billion would be needed to restore Puget Sound to a state of hydraulic function like a temperate forest. Even so, the costs of stormwater pollution are high: the sickening and deaths of Salish Sea organisms. For example, annual losses of aquatic life due to polycyclic aromatic hydrocarbon (PAH) exposure in Washington State are estimated to be between $4.4 to $12.1 billion in "willingness to pay" (King County 2014; Washington State Department of Ecology and Washington State Department of Health 2012).

## Challenge: Stormwater Management Barriers and Needs

Due to the combined factors of increasing population sizes, development growth, and climate change impacts in western Washington, stormwater runoff poses an ever-greater challenge for stormwater practitioners, urban planners, and natural resource managers in the Puget Sound region. At the same time, those responsible for implementing science-based stormwater management plans often face numerous barriers, including the high cost of stormwater interventions (as stated above) and the difficulty of tracking stormwater that flows from disparate sources as it collects and concentrates pollutants.

In response to these barriers, The Nature Conservancy (TNC) in Washington conceptualized a stormwater management tool called the **Puget Sound Stormwater Heatmap** (or "Stormwater Heatmap"). The idea for this project was rooted in the essential role that science-based stormwater management plans play in addressing toxic stormwater impacts across our region – coupled with an acknowledgment that small and under-funded municipalities face a disproportionate hurdle to developing plans effectively without robust access to decision-making tools. The theory of change is that removing or reducing the barriers faced by those responsible for implementing essential science-based stormwater management plans (with a particular emphasis on less-resourced jurisdictions) helps them move toward more stormwater interventions at a more significant impact and less cost, which helps address the twin problems of urban stormwater runoff and its toxic effects. In essence, the Stormwater Heatmap helps:
(a) get the best available science and tools into the hands of decision-makers,
(b) in order to lower the costs for effective decision-making and planning,
(c) thereby improving water quality and socio-ecological health across the Puget Sound.

To build this product with user needs as the focal point, TNC embarked on a design thinking process to enable a deep understanding of the challenges faced by stormwater practitioners. TNC partnered with stormwater leaders, managers, and modelers throughout the region. In partnership, we identified five significant barriers to effective stormwater management plans and science-based interventions. These barriers correspond to five development priorities for the Stormwater Heatmap tool, as outlined below.

## 1. Affordable Stormwater Planning

At the time of the development of Version 1.0, the Washington State Department of Ecology stormwater permit was set to include new stormwater management plan requirements for 85 Phase 2 jurisdictions. However, Phase 2 jurisdictions did not have the funding or staff to develop robust stormwater management plans that would meet permit requirements and still allow them to implement those plans once created. Version 1.0 of the Stormwater Heatmap was developed as a free-to-use open-source tool to help lower the cost of stormwater management planning so that more funding could be directed at placing effective projects in the ground. The provision of usable data and modeling for planning enables jurisdictions to focus on cleaning water rather than expending vast resources, reinventing the model (on a jurisdiction-by-jurisdiction basis). This strengthens environmental justice by allowing less resourced Phase 2 jurisdictions to focus more of their effort on building on-the-ground projects.

## 2. Central Data Clearinghouse

Through the design thinking process, we heard the need for a data clearinghouse, or central location for data ingress, storage, and egress, for the stormwater datasets required to develop and report on stormwater management plans. Modelers said pulling the necessary datasets together could take up to three months. This posed a significant time delay that added cost but also prevented participation in opportunistic projects wherein a stormwater component could be added onto the design plans for another capital project already underway (e.g., parks department, street improvements, urban development, etc.). Without datasets on hand, stormwater work could not be incorporated into opportunistic projects, thereby missing out on cost-saving measures. The Stormwater Heatmap includes links to the core datasets needed to run hydrology models and assess land cover and the ability to download the new pollution and runoff heatmap components. It also includes data extraction capabilities and report modules that service requirements outlined by Ecology stormwater permits.

## 3. Threat Assessment and Storytelling at Multiple Scales

Those tasked with implementing stormwater best management practices (or BMPs) must ask "how much and where" interventions are needed on the landscape to optimize them. Related to the idea of stacking opportunistic projects on top of one another, managers needed a quick mechanism to help them assess whether opportunistic work was cost-effective at site, watershed, and regional scales – and therefore a cost-effective investment of their limited resources. In addition, they needed to translate these assessments into visual stories at the corresponding scales to communicate their decisions to relevant stakeholders such as ratepayers, legislators, and regional leaders. The ability to conduct evaluations and share stories at multiple scales is essential in maintaining and growing political support and financial investments. The Stormwater Heatmap is a predictive map that provides quantitative visualization of stormwater hotspots (in terms of runoff flow and pollution quantities). This allows stormwater managers to rapidly assess if an implementation opportunity is likely to be cost-effective based on the proximity of stormwater hotspots to other points of interest (e.g., critical habitat area for sensitive species, opportunities for multiple benefits to human communities, etc.). In other words, this tool's "threat" heatmap can be coupled with ecological and social data for threat-based decision-making and storytelling through visualizations and built-in reporting modules.

**Note:** The ecological and social goals for stormwater management are essential to threat assessment and stormwater intervention siting decisions. The quantity and spatial configuration of stormwater interception techniques will look quite different depending on whether the goal is to meet permit regulations, recover coho salmon, or recover Southern Resident Killer Whales, for instance. Biological organisms are susceptible to stormwater contaminants for different reasons, in different locations, at different scales, and at different points in time according to their life history traits (Levin, Howe, and Robertson 2021; Hegeman and Levin 2023). To fully answer the "how much and where" question requires integrating social-ecological data with stormwater monitoring and pollution loading data. This tool is meant to be paired with other planning tools, and users should focus on the relative contribution of stormwater runoff and COC loads.

## 4. Expedited Hydrology Modeling & Climate Change Projections

During design thinking, we heard from stormwater engineers that our tool's hydrology component should use the Western Washington Hydrology Model (WWHM) approved by Ecology, as this model was part of their existing design process. WWHM is a modular, process-based hydrology model based on the Hydrological Simulation Program Fortran (HSPF) with parameters pre-calibrated to the Puget Lowlands. WWHM and HSPF are lumped-parameter models whereby watershed processes are simplified into areas of similar hydrologic response. These areas are termed Hydrologic Response Units (HRUs) and typically represent different combinations of slope, soil, and land cover. The Stormwater Heatmap performed, and now stores, batch processing for each of the 30 HRU types present in Puget Sound. These pre-run hydrologic output records and visualizations help jurisdictions save time as they develop their stormwater management plans at the basin scale and design implementation projects. Furthermore, including future runoff projections (one projection in Version 1.0; 12 additional projections in Version 2.0) provides an efficient method to design for the future as runoff increases with climate change.

## 5. Improved Pollution Prediction

Currently, stormwater monitoring occurs in 16 basins across Puget Sound, each representing different land use types. To estimate pollution in non-monitored basins, static concentrations are applied from the monitoring data collected in the same designated land use type. The definitions of these land use types are inconsistent and subjective across jurisdictions. They are not quantifiable based on physical or measurable landscape features, resulting in pollution-loading data that are difficult to apply reliably to non-monitored basins or basins with differing development intensities.

The Stormwater Heatmap improves upon this land-use-only method of mapping expected pollution loads across the landscape. Stormwater Heatmap Version 1.0 developed a statistical method of predicting pollution concentrations outside the few actively monitored basins using a suite of quantifiable landscape predictors. These spatial predictors include physical landscape predictors (e.g., impervious surface area, tree canopy, rooftops, bare ground, slope), temporal predictors (rain intensity, antecedent precipitation, season), and dynamic behaviors (e.g., average annual traffic, $CO_2$). Frequentist statistical models developed using spatial predictors were compared against the land use-only model to discern whether the Stormwater Heatmap Version 1.0 approach improved predictive capability. Stormwater Heatmap Version 2.0 will apply Bayesian approaches to the statistical framework, allowing us to properly develop credible intervals around predicted COC concentration means. This will enable managers to assess variability and certainty around the means, which we cannot currently provide using frequentist approaches (reference Section 4.1 for more information on the statistics planned in Version 2.0).

## Response: Puget Sound Stormwater Heatmap

These barriers and needs informed the development of Stormwater Heatmap Version 1.0: an interactive mapping tool, report generator, and data repository that quantitatively visualizes hotspots of pollution generation and runoff throughout the Puget Sound watershed. The Stormwater Heatmap is a decision-support tool and an interactive platform that combines COC (chemical of concern) concentration estimates with hydrology output to generate a spatialized pollution loading map at previously unattainable scales. The tool utilizes machine learning, cloud computing, and spatial datasets to model where stormwater pollution and runoff hotspots are generated across the landscape. This enables users to visualize and aggregate stormwater pollution loading data at several spatial resolutions for local, watershed, and regional-scale planning. With this tool as a foundation, stormwater practitioners can overlay ecological and social data layers of interest to understand "where" interventions will be most helpful on the landscape and "how much" change is needed.

TNC built Version 1.0 of the Stormwater Heatmap in partnership with Geosyntec Consultants Inc. and Cheva Consultants LLC with collaboration from the University of Washington (UW) Climate Impacts Group (CIG) and EarthLab, Washington Department of Fish & Wildlife, and National Oceanic Atmospheric Administration (NOAA) Office of Coastal Management. The Boeing Company and private donors provided funding for Version 1.0. The U.S. Environmental Protection Agency (EPA) will finance improvements for phase two of project work under assistance agreement PC-01J89501 to the Washington State Department of Ecology (Ecology) (reference Section 4.1 and Section 4.2 for more information on improvements and additional features to be developed in Version 2.0).

Version 1.0 of the Stormwater Heatmap went live to the public in March 2022 and is available online at https://www.stormwaterheatmap.org/. Its spatial data layers, images, and reports can be downloaded for use outside the online tool, and its code and methods are open source.

The tool is comprised of three primary components (reference Figure 1; described in greater detail below): (a) high-resolution land cover layer consisting of seven classes at a one square meter resolution, (b) continuous simulation rainfall-runoff modeling of climate change precipitation, and (c) spatial regressions of stormwater pollutant concentrations.

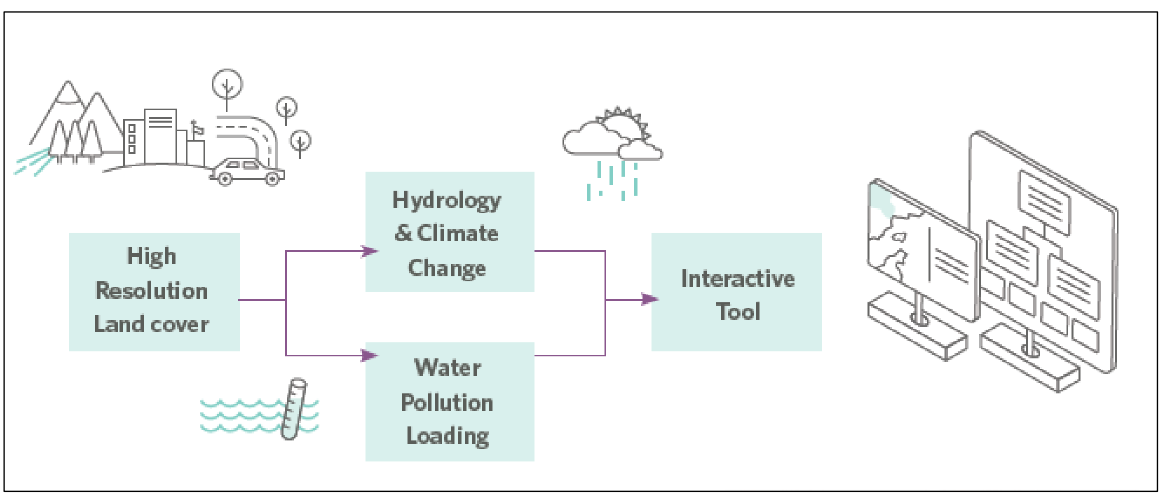


**Figure 1. Architecture of the Stormwater Heatmap Version 1.0 webtool components**

TNC used the high-resolution land cover layer combined with soil layers and topography to develop HRUs that match regional parameters used in the Western Washington Hydrology Model. Combining the watershed layer with the Climate Impact Group's precipitation grids, TNC generated runoff data at an hourly timestep for each HRU within each precipitation grid, resulting in 130 years (1970-2099) of hourly runoff modeling results. To predict stormwater COC concentrations outside the fourteen (14) catchments monitored under the Western Washington NPDES Phase I Stormwater Permit (Hobbs et al. 2015), TNC developed mixed effects linear regression models for five (5, see Section 3.2.3) COCs based on spatial and temporal sets that describe landscape characteristics for the catchments mentioned above. Predicted concentrations were then combined with annual runoff to calculate annual loads.

## Version 1.0 High-Resolution Landcover

We generated a high-resolution landcover dataset that enables landcover mapping at the one square meter (1-$m^2$) resolution in Google Earth Engine. This is a critical level of resolution for urban runoff modeling because impervious surfaces powerfully drive hydrologic response and, therefore, pollution loading. Thus, accurate mapping of impervious surfaces was needed to calculate surface runoff. The landcover refinement portion of the Stormwater Heatmap was completed in Version 1.0 and serves as the foundation for this project.

## Version 1.0 Water Quality Statistical Modeling and Pollution Loading

Under Version 1.0, we generated statistical water quality models that link spatial landscape predictors to stormwater monitoring data, enabling the estimation of pollution concentrations across the landscape. The selection process involved performing a suite of 80-150 models with various spatial landscape predictors for each of five COCs: total copper, total zinc, total phosphorus, total suspended solids (TSS), and total Kjeldahl nitrogen. The suites of models were utilized to identify which spatial landscape predictors should be clustered together in a model for each COC. Under Version 1.0, we identified a single best-fit model for each COC, linking spatial landscape predictors to COC concentrations. We verified that the models fit the data well using the following tests and metrics:

- Likelihood ratio tests to compare nested models and determine the best model structure (frequentist models)
- Examination of residuals to assess for homoskedasticity (a requirement for linear mixed effects models and frequentist models)
- Akaike Information Criterion (AIC) to compare models with different fixed effects and find the best-fit models (frequentist models)
- Single predictor plots to visually assess linear fit to data for one spatial predictor at a time (frequentist models)
- Examination of residuals for patterns indicating that an important predictor is missing from the model (frequentist models)
- Autocorrelation plots for residuals to assess if temporal autocorrelation is present (frequentist models)
- Spatially explicit bubble plots of residuals and variogram plots to visually assess whether spatial autocorrelation is present (frequentist models)

**Note:** We did not validate the models with external data (this is a task for Version 2.0).

Because of the nested structure of the outfall data (repeated sample collection at 14 outfalls that fell into six different agencies), we employed a mixed-effects modeling structure using a frequentist framework. This framework worked well for running many candidate models to select the best spatial landscape predictors for a particular COC and for estimating COC concentrations over the Puget Sound basin. However, the frequentist framework cannot estimate variability around random effects (in our spatial predictor models, the random portion was location-nested within an agency). Therefore, the frequentist framework does not allow estimates of confidence intervals around COC estimates.

## Version 1.0 Hydrology Modeling & Climate Change Projections

Under Version 1.0, we conducted initial continuous hydrology simulations for the 30 different hydrologic response units created within the Puget Sound domain. Using regional precipitation datasets, we modeled current and future hydrology to assess how climate change will impact stormwater pollution loading across the landscape, generating more than 311 billion rows of data (housed in BigQuery). Working with the University of Washington's Climate Impacts Group, we built one (1) climate scenario into Version 1.0.

## 3.2 Study Area and Surroundings

For this QAPP, the Puget Sound watershed refers to watersheds draining into the Washington waters of the Salish Sea. This generally includes the western slopes of the Cascade Mountains and the eastern and northern slopes of the Olympic Mountains. The Puget Sound watershed extends into Canada as part of the Salish Sea (Figure 2 and Figure 3). Still, the modeling effort described in this study is limited to the United States per data limitations related to the architecture of the Stormwater Heatmap web tool (Figure 1).

The 42,800 km$^2$ Puget Sound watershed is the largest estuary in the United States, with over 3,790 kilometers of shoreline. The watershed is characterized by high, mountainous terrain in the headwaters ringing the watershed, followed by broad lowlands in the Puget Trough. The watershed consists of over ten thousand rivers and streams that drain into the Sound. There are 13 significant rivers draining into Puget Sound and adjacent waters, with 80% of the surface water flowing into Puget Sound emanating from major river drainages: Nooksack, Skagit, Stillaguamish, Snohomish, Cedar/Lake Washington, Duwamish/Green, Nisqually, Puyallup, Skokomish, and Elwha.

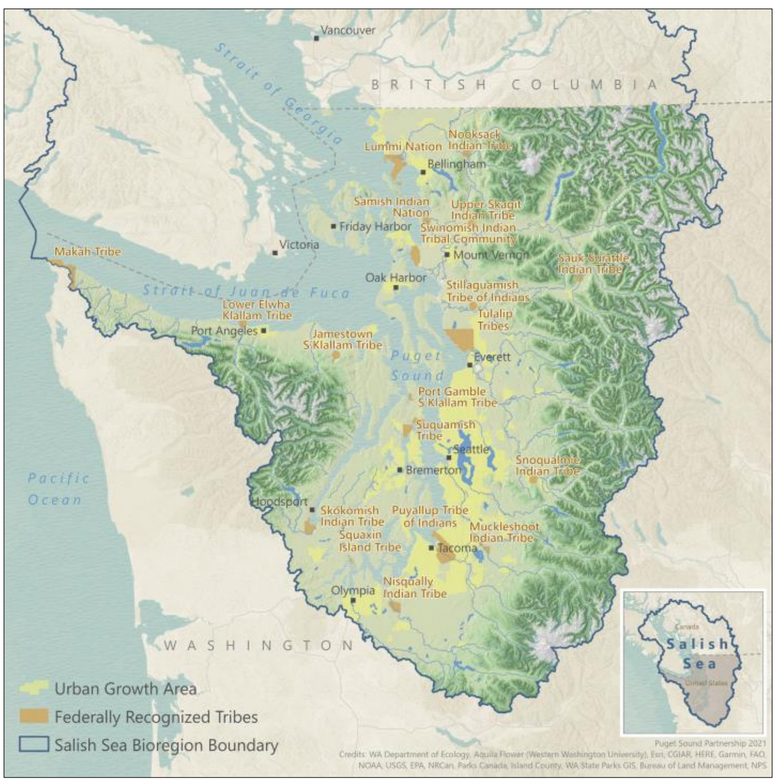


**Figure 2. Map of the Puget Sound watershed as defined by Puget Sound Partnership**
*Credits: WA Department of ECY, Aquila Flower (Western Washington University), Esri, CGIAR, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada, Island County, WA State Parks GIS, Bureau of Land Management, NPS*

Figure 2 demonstrates that TNC defines the Puget Sound watershed in the same way that Puget Sound Partnership (PSP) defines the watershed and uses the same shapefile. The PSP 2023 "State of the Sound Report" highlights the Stormwater Heatmap project: https://stateofthesound.wa.gov/.

Figure 3 is a screenshot taken from the Stormwater Heatmap Version 1.0 "View Data Layers" function, which is available online here: [https://www.stormwaterheatmap.org/](https://www.stormwaterheatmap.org/).

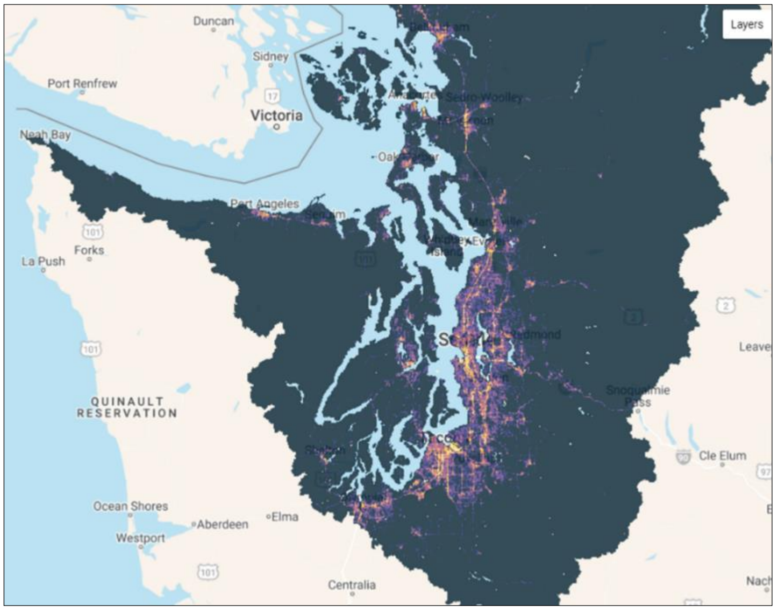


**Figure 3. Map of the Puget Sound watershed boundaries used in this study**

### 3.2.1 History of Study Area

The Puget Sound region includes land cover and land use patterns that affect the generation and delivery of stormwater pollution to waterways. From the Puget Sound Spatially Referenced Regression on Watershed Attributes (SPARROW) QAPP (Publication 22-03-109), the major land cover types in the Puget Sound region include forested land (62%), grassland or scrubland (12%), and developed areas (12%) based on the 2016 National Landcover Dataset (NLDC). Developed land (including major cities and urban lands) is concentrated along the maritime shoreline areas and estuaries of the lowlands. In contrast, the headwaters of watersheds draining into Puget Sound are mainly forested. Agricultural lands and low-density residential land use are spread throughout the floodplains and estuarine deltas, primarily concentrated in the Skagit and Nooksack watersheds, western Puget Sound, and the Kitsap Peninsula.

With an estimated population of 4.6 million people as of 2022, the metropolitan area of Puget Sound (Seattle-Tacoma-Bellevue) and surrounding metropolitan areas is the 15th largest metropolitan area in the United States and home to over half of Washington's population. Urbanization is a key contributor to stormwater pollution in the area, with impervious surfaces driving most stormwater runoff and pollution issues. The more than 375,000 acres of impervious surfaces within the Puget Sound watershed can rapidly accumulate rainwater and surface pollutants, delivering both into nearby waterbodies (Stormwater Heatmap Version 1.0). Recent high-resolution change detection mapping of Puget Sound lands indicates that urbanization is spreading, with over 75,000 acres of canopy removal, 266,002 acres of timber harvest, 20,837 acres of new impervious, and 7,485 new acres of semipervious landcover detected between 2006-2017 ([Project Spotlight: High Resolution Change Detection](#)).

In addition to land use change, climate change also affects the region. Although the total annual precipitation for the Pacific Northwest is only projected to increase slightly, heavy winter precipitation events are projected to become more intense. Specifically, the heaviest daily precipitation totals in Puget Sound are projected to increase by 22% (range 5% to 34%) by the 2080s (relative to 1970-1999), based on results from 10 global climate models and a high (RCP 8.5) greenhouse gas scenario (Warner et al. 2015). Models do not project notable changes in the number, location, or other characteristics of storms; instead, precipitation is projected to become more intense primarily because of warmer air's increased water-holding capacity.

An ensemble of regional climate model projections (Mass et al. 2022) are now available and can be utilized to assess the spatial distribution of precipitation changes across a range of durations and intensities (e.g., Mauger and Won 2019). These climate model projections were not available when we built Version 1.0 and will be used to assess climate change impacts in the current work as part of the development of Version 2.0.

### 3.2.2 Summary of Previous Studies and Existing Data

Foundational datasets used in constructing the Puget Sound Stormwater Heatmap Version 1.0 are described in the technical documentation: [https://www.stormwaterheatmap.org/docs/category/methods](https://www.stormwaterheatmap.org/docs/category/methods). This includes a summary of datasets used in the land cover, hydrology, and water quality statistics modules. Reference section 5.4 and Table 2 for a list of the technical documentation we intend to develop in Version 2.0, including reports.

Statistical modeling of stormwater pollutant loads relies on the S8.D Municipal Stormwater Permit Outfall Data (hereafter referred to as the S8 Data) provided by the Washington Department of Ecology (Hobbs et al. 2015). These data were collected between 2009 and 2013 by eight permittees (two cities, four counties, and two ports) at a total of 20 catchments located throughout Washington state. Stormwater data collected by six permittees at 14 of these catchments are used in the statistical models.

### 3.2.3 Parameters of Interest and Potential Sources

The COCs analyzed in this study are total copper, total suspended solids (TSS), total phosphorus, total zinc, and total Kjeldahl nitrogen (TKN). Note: The project team tried dissolved metals but did not find statistically significant predictors. This study will calculate average annual runoff under different climate scenarios in addition to hourly runoff projections (all of which will be archived in BigQuery).

### 3.2.4 Regulatory Criteria or Standards

Not applicable. The study objectives do not include assessing regulatory compliance status. The Stormwater Heatmap estimates the generation of stormwater pollutants. It does not assess receiving water concentrations.

## 3.3 Water Quality Impairment Studies

Not applicable. This QAPP does not describe a water quality impairment study.

## 3.4 Effectiveness Monitoring Studies

Not applicable. This QAPP does not describe an effectiveness monitoring (EM) study.

# 4.0 Project Description (Version 2.0)

TNC aims to make high-quality, high-resolution data freely available to concerned community members and state, local, and tribal entities involved in stormwater planning and investment decisions. The Stormwater Heatmap was designed to help stormwater practitioners and communities take targeted, high-impact action to break the link between urbanization and the degradation of aquatic and marine ecosystems. Version 1.0 of the decision-support tool, developed through an intensive design thinking process (reference Section 3.1 "Challenge: Stormwater Management Barriers and Needs"), was designed to support stormwater planning at multiple scales – from large watersheds to local neighborhoods. The Version 1.0 pollution and runoff mapping provides new and rigorous insight into where stormwater is generated on the landscape, helping to inform where infrastructure investments may be needed to support water quality improvements in Puget Sound and mitigate the adverse impacts of stormwater pollution on people and nature. To be clear, this tool does not conduct flow routing.

Version 1.0 of the Stormwater Heatmap tool is deployed and operational. Our regional partners have already utilized its data and decision-support capabilities to generate substantial impacts in the region. Examples include our partnerships with the King County Fish Passage Restoration Program (Fish Passage Flow Tool); the Department of Ecology's comprehensive assessment of at-risk ecological zones for 6ppd-q contamination using the Stormwater Heatmap tool to analyze traffic, land cover, land use data, and other sources; and our partnership with Our Green/Duwamish to build their SMAPr tool for lower cost stormwater management action plans; and others.

Version 1.0 of the tool was deployed as a "minimum viable product" for end-users and has proven its value in this initial state. At the same time, it is incomplete and would benefit from numerous enhancements (e.g., it is currently time-consuming and technically complex for users to access 100% of Stormwater Heatmap data layers). The Version 2.0 engagement is intended to complete Version 1.0 development, make needed enhancements, and implement new features into the tool. These efforts will transform Version 1.0, launched in March 2022, into a robust Version 2.0 with a broader reach and impact. Stormwater Heatmap Version 2.0 will continue to be a free-to-use web-based platform to inform stormwater planning processes and decisions within Puget Sound.

## 4.1 Project Goals

The primary reasons for undertaking the Stormwater Heatmap Version 2.0 engagement are to complete Version 1.0 development, iterate upon the Version 1.0 tool (i.e., make improvements to its models), and implement net-new features to create Version 2.0 of the tool. This entails the following actions:

### 1. Resolve Data Gaps and Increase Available Layers

- The tool will incorporate pollution and hydrology information and future climate runoff modeling scenarios.
- For climate data, Version 2.0 improvements include (a) bias correction (the data was not bias-corrected prior) and (b) incorporating an ensemble of 12 projections (Version 1.0 included just one).
- Version 2.0 will incorporate spatial data layers depicting mean annual runoff and change in mean annual runoff (for future climate scenarios) into visualizations and documentation, allowing for runoff modeling under future climate conditions – a profound need given rapidly changing precipitation patterns.
- Version 2.0 will incorporate access to hydrology time series data for runoff under historical, current, and future climate conditions. The intent is to enhance hydrology model outputs by adding an ensemble of future climate models to the hydrology module; this constitutes the bulk of effort for Version 2.0 work.

### 2. Improve User Access

- We will provide access to spatial data layers and temporal datasets.
- We intend to make Version 2.0 of the tool more accessible. Currently, users can access time-series data using the Google BigQuery API and its associated client libraries. This method requires a level of technical expertise that

may be challenging for many of our intended users. To create a more accessible tool, we plan to undertake the tasks outlined in Section 4.4, “User Access Improvements & Guidance.”

## 3. Validate and Share Methods

- This grant will allow TNC to finalize the water quality statistical model equations, finalize the credibility intervals, and explore available datasets needed to validate the water quality models. The team will enhance predicted pollution model outputs by adding confidence intervals around estimated chemical concentrations and exploring model validation.
- Fund staff time to produce technical memos and written reports that detail Stormwater Heatmap modeling methods and results transparently to the public. By exposing how the tool works “under the hood,” jurisdictions and stormwater planners can evaluate its methodology, leverage its tools and data with confidence, and reproduce our methods elsewhere.

## 4. Conduct Outreach and Provide User Support

- Provide user guides and support so stormwater practitioners and other user audiences can readily use the Stormwater Heatmap tool and data layers. Enhance the user assistance, education, and outreach materials.

# 4.2 Project Objectives

The specific work activities relevant to this QAPP are outlined below for each of the three primary components of the tool: (a) high-resolution land cover layer consisting of seven classes at a one square meter resolution, (b) continuous simulation rainfall-runoff modeling of climate change precipitation, and (c) spatial regressions of stormwater pollutant concentrations.

## Version 2.0 High-Resolution Landcover

The landcover refinement portion of the Stormwater Heatmap was completed in Version 1.0 and serves as the foundation for this project.

## Version 2.0 Water Quality Statistical Modeling and Pollution Loading

Under Version 2.0, we plan to run the best-fit spatial landscape predictor model for each COC using a Bayesian framework to obtain credible intervals (the Bayesian equivalent of confidence intervals) around model estimates. The model parameters between the frequentist and Bayesian frameworks should be nearly identical, but the Bayesian models will expand our ability to provide Stormwater Heatmap users with credible intervals around model estimates. Bayesian methods are slow (unsuitable for running 80-150 models per COC), but they provide estimates of variability around random effects. In mixed effects models, they are a preferred method for obtaining credible intervals around model-estimated COC values.

We will also assess model sensitivity (reference Section 13.4.2) and run a model validation with external data.

## Version 2.0 Hydrology Modeling & Climate Change Projections

Version 1.0 of the Stormwater Heatmap included runoff modeling results for a single climate change scenario. The University of Washington Climate Impacts Group supplied a region-specific precipitation dataset, as Mauger et al. detailed (2018). This dataset encompasses hourly precipitation data modeled through the GFDL CM3 global climate model, employing the Representative Concentration Pathways (RCP) 8.5 scenario.

Version 2.0 will expand on this by incorporating an ensemble of 12 additional downscaled regional climate models and a retrospective precipitation data set. In addition, the projections in Version 2.0 will be bias-corrected to ensure an accurate representation of precipitation (in Version 1.0, they were used as-is). We will perform batched modeling runs of continuous simulation using HSPF algorithms. Modeling parameters will conform to Ecology guidance for continuous simulations of rainfall runoff as outlined in section III-2.2 of the 2019 Washington Department of Ecology Water Quality Program.

The output from these models will enable stormwater managers to assess if current or planned stormwater facilities can perform under increased or altered precipitation, thereby guiding necessary adaptations or enhancements to maintain effective stormwater management.

# 4.3 Information Needed and Sources

## Water Quality Statistical Model

Bayesian modeling of chemicals in stormwater relies on the S8 Data already used in Version 1.0 of the Stormwater Heatmap (reference Section 3.2.2). The COCs that will be modeled using a Bayesian framework are total copper, total suspended solids (TSS), total phosphorus, total zinc, and total Kjeldahl nitrogen (TKN).

Following Bayesian model fitting, additional external datasets (to be determined) will be used to validate the pollutant load models in Version 2.0 work. These datasets may include follow-on data collected between 2013 and 2018 at the same catchments as the S8 Data and data collected at other locations throughout Washington state. We depend on identifying high-quality data at other catchments to validate the water quality statistical model equations.

One potential data set may be the data to be collected by Stewardship Partners and Herrera Environmental Consultants, Inc. under their Adopt-A-Downspout sampling plan from the WSDOT I-5 Ship Canal bridge. This distinct body of work will perform water quality monitoring to assess treatment efficiency to obtain approximately ten paired influent and effluent water samples or 40 total water samples (which include data for TSS, zinc, and copper) from 20 qualifying storms by the end of the study.

## Continuous Simulation Hydrology Modeling

Process modeling of stormwater runoff relies on (1) a high-resolution landcover dataset developed in Stormwater Heatmap Version 1.0 (current technical memorandum available here); (2) a suite of input data used to parameterize the Western Washington Hydrology Model (described in the current technical memorandum available here); and (3) the set of dynamically downscaled regional climate models described in Section 3.2.2. These data allow us to perform continuous hydrology simulations using regional, pre-calibrated parameters. Batched simulations have been run for current climate conditions for all combinations of land cover, soils, and slopes across the Puget Sound domain. Adding predictive climate models (reference Section 3.2.2) will allow us to include 12 more simulations, the results of which will be stored in a cloud-based and query-able database.

## Historical and Future Meteorology

Version 2.0 of the tool will build on the one (1) climate scenario in Version 1.0 by adding 12 more downscaled regional climate models.

As noted in Section 3.2.1, we will use dynamically downscaled projections to provide spatially distributed meteorological inputs to the hydrologic modeling component of the Stormwater Heatmap tool (this is the climate component of the “Hydrology & Climate Change” box in Figure 1). The work leverages existing modeling and datasets developed in recent years. We will use results from the Weather Research and Forecasting mesoscale model (WRF; Skamarock et al. 2008; https://www.mmm.ucar.edu/wrf-model-general). Specifically:

1. PNNL developed an observationally based historical simulation driven by meteorological fields obtained from the North American Regional Reanalysis (NARR; https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html). This

simulation was developed using WRF version 3.7 and implemented at a spatial resolution of 6 km, hereafter referred to as "WRF-NARR" (Chen et al. 2019).

2. An ensemble of 12 WRF projections, driven by global climate projections obtained from the Coupled Model Intercomparison Project Phase 5 dataset (CMIP5; Taylor et al. 2012; http://cmip-pcmdi.llnl.gov/cmip5/). All simulations were produced using a high greenhouse gas scenario (RCP 8.5; Van Vuuren et al. 2011), implemented using WRF version 3.7 at a spatial resolution of 12 km. Although results for a lower greenhouse gas scenario are unavailable, the higher RCP 8.5 scenario may be better since it will more clearly illustrate "hot spots" for climate change impacts. Hereafter in the text, these data are referred to as "WRF-CMIP5" (Mass et al. 2022).

All WRF simulations were archived at an hourly time step. Model outputs include a spatially gridded time series of meteorological variables: temperature (°C), relative humidity (%), precipitation (mm), wind speed (m/s), and incoming short- and long-wave radiation (W/m2), among others. These same datasets have been used in several recent regional hydrologic studies (e.g., Mauger and Won 2019, Mauger et al. 2020).

The historical WRF-NARR precipitation estimates will be compared against several precipitation datasets to characterize biases in the dynamically downscaled simulations. These are:

- Parameter Regression on Independent Slopes Model (PRISM; Daly et al. 2008)
- National Centers for Environmental Prediction (NCEP) National Stage IV Quantitative Precipitation Estimate (QPE) Product (Nelson et al. 2016)
- National Aeronautics and Space Administration (NASA) Integrated Multi-satellitE Retrievals for GPM (IMERG, Huffman et al. 2018)
- Sea-Tac precipitation gauge (Wuertz et al. 2018)

## 4.4 Tasks Required

The following tasks are needed to achieve our vision for Version 2.0 development and use.

1. Hydrology Module
    a. Prepare dynamically downscaled climate models for inclusion in hydrology modeling.
        i. Evaluate reference datasets for bias correction potential. There are four (4) potential datasets.
        ii. Select a bias correction approach. Two types of bias correction may be considered: (1) application of a single scaling to each calendar month, derived by comparing a particular metric in WRF and the reference dataset (e.g., the long-term average); and (2) application of different corrections to different precipitation intensities, binned to ensure an adequate sample size.
        iii. Apply bias correction to downscaled models. This task aims to ensure that the bias-corrected WRF-CMIP5 projections reproduce the statistics of the bias-corrected WRF-NARR simulation. This is accomplished by interpolating each WRF-CMIP5 simulation to the 6 km WRF-NARR grid, then bias-correcting the interpolated WRF-CMIP5 time series so that its historical period (1970-2020) matches the statistics of the bias-corrected WRF-NARR simulation (1981-2020). For this bias correction, the team will use a quantile-based approach, in which a scalar correction is applied to each quantile bin (0-1, 1-2, … 99-100).
    b. Conduct continuous simulation modeling and hydrology output accessibility.
        i. Batch simulations for 30 HRUs for each of the 12 bias-corrected climate models.
        ii. Upload the outputs from batch simulations to cloud-based storage (e.g., BigQuery).
    c. Translate hydrology simulation data to quantitative visualizations within the online StormwaterHeatmap.org tool.
    d. Calculate hydrologic change index projections based on an ensemble of climate models.
    e. Describe the methodology and results in the Version 2.0 technical documentation (refer to section 5.4 TNC-ECY Task 3.5 for more details).
2. Water Quality Module: Pollution Loading Predictions
    a. Finalize development of water quality statistical model equations (Bayesian).
    b. Finalize credible intervals for each COC pollution load estimate.

c. Conduct model validation and coordination for current and new data (requires identification of suitable validation datasets).
d. Translate model equations to Stormwater Heatmap for online visualization and data download layers.
e. Calculate pollution-area loading curves at different spatial scales to communicate pollution loading results.
f. Describe methodology and results in the Version 2.0 technical documentation (reference section 5.4 TNC-ECY Task 3.5 for more details).

3. User Access Improvements & Guidance
   a. Conduct User Research: Within the design thinking process (see below), conduct interviews with potential users to understand their challenges and needs. Use interview insights to identify key improvement areas.
   b. Enhance Data Query Capabilities: Prototype and refine access tools that allow users to filter, aggregate, and export data. Potential solutions include Jupyter/Colab data notebooks or Excel templates.
   c. Improve Integration and Accessibility: Develop methods and workflows to help users import time series data directly into their models. The types of models for integration will be determined based on user research insights. Potential solutions include downloading (new) spatial data layers to TNC spatial data servers and providing links to data sources and metadata within the online tool platform.
   d. Develop a user guidance manual for Version 2.0 that includes:
      i. Instructions for use of the online tool interface.
      ii. Instructions for mechanisms to access and download data for use outside of the online tool.
   e. Scope long-term hosting options and cost structures.
4. Design Thinking (DT) Workshops
   a. Identify a diverse suite of possible users and stakeholders.
   b. Contract a design thinking facilitator.
   c. Identify focal points for DT interviews (e.g., user interface, COCs, reporting metrics, use cases, etc.).
   d. Conduct DT interview series.
   e. Compile, analyze, and summarize DT data results.
5. Pilot Testing Conversations
   a. Using information gathered in the DT workshops, identify at least one entity interested in intersecting with Version 1.0 and Version 2.0 tool features and data.
   b. Host or participate in at least two meetings to explore and define the potential intersection. These would be developed under a future and distinct body of work pending receipt of additional funding.
6. Water Quality Nexus Planning
   a. Scope nexus points for the Stormwater Heatmap tool.
   b. Host or participate in nexus point workshops relevant to areas of exploration.
   c. c. Identify tool features in response to nexus workshops. Pending receipt of additional funding, these would be developed as a separate body of work.
7. Outreach and Education
   a. Provide website updates to highlight new features via the embedded blog series in the online tool.
   b. Develop communication materials to highlight features and uses of the Stormwater Heatmap tool.
   c. Provide technical support in the form of FAQs and technical responses to questions received from users.

## 4.5 Systematic Planning Process

Not applicable. This QAPP serves as the systemic planning process for this project.

# 5.0 Organization and Schedule

The Nature Conservancy in Washington and its partners are confident in the feasibility of Stormwater Heatmap Version 2.0 given, in part, the substantial strides made to produce Version 1.0. Funding provided by the United States Environmental Protection Agency (EPA) under assistance agreement PC-01J89501 to the Washington State Department of Ecology will cover the main barrier to developing Version 2.0: project expenses. Section 5.5 outlines the funding for staff time, contract services, technology expenses, etc., needed for V2.0 completion. TNC has the appropriate in-house staff, contract support, contractor relationships, and partnerships for successful project completion.

The Stormwater Heatmap team is characterized by strong leadership, technical expertise, scientific rigor, and robust partner relationships. The project's science and technical support is provided in-house at TNC and through contract relationships; TNC is equipped to identify internal replacements or additional contractors, consulting firms, etc., as needed. Prior TNC grant management experience means project team members are equipped to efficiently carry out all work necessary to meet federal and state grant administration requirements to focus their time and attention on project deliverables.

## 5.1 Key Individuals and Their Responsibilities

Table 1 outlines the titles and responsibilities of those involved in this project.

**Table 1. Organization of project staff and responsibilities**

QAPP: Quality Assurance Project Plan
NEP: National Estuary Program
WQX: Water Quality Exchange

| Staff | Title | Responsibilities |
|---|---|---|
| Sarah Brunelle<br>The Nature Conservancy<br>Phone: 206-343-4344 ext. 385 | Project Manager | Manages QAPP submission along with interim and final audits and reports. Oversees budget, fundraising, Version 2.0 web tool development, team coordination, grant administration, and external outreach to support the work. Ensures that project work progresses on time and on budget. Monitors contractual relationships and re-negotiates or submits amendments as needed. |
| Emily Howe, PhD<br>The Nature Conservancy<br>Phone: 206-384-2059 | Co-Principal Investigator | Lead scientist. Ensures deliverables meet the best available science standards and address user needs. Contributes to the QAPP. |
| Christian Nilsen, PE<br>Geosyntec Consultants<br>Phone: 206-708-3045 | Co-Principal Investigator, Lead Engineer, Hydrologist | Lead hydrologist, stormwater engineer, and technical expert. Manages the coding and tool architecture, hydrology modeling, and integration of the landcover, hydrology, and COC modules. Monitors links between modeling and stormwater manual. Manages Geosyntec Consultants Inc. support staff. Contributes to the QAPP. |
| Eva Dusek-Jennings, PhD<br>Cheva Consulting LLC<br>Phone: 425-256-0045 | Lead Statistician | Lead statistician. Develops statistical approaches for COC loading predictions using landscape predictors. Responsible for all water quality and pollution loading predictions. Contributes to the QAPP. |
| Guillaume Mauger, PhD<br>University of Washington, Climate Impacts Group<br>Phone: 206-685-0317 | Climate Scientist | Serves as a science consultant through the University of Washington. Leads climate projection and ensemble modeling for the hydrology component of the Stormwater Heatmap. Contributes to the QAPP. |
| Ken Nelson<br>Department of Ecology<br>Phone: 360-522-2722 | NEP Quality Coordinator | Reviews the draft QAPP and recommends the final QAPP for approval. |
| Arati Kaza<br>Department of Ecology<br>Phone: 360-480-1960 | Quality Assurance Officer | Reviews and approves the draft QAPP and the final QAPP. |

## 5.2 Special Training and Certifications

**Sarah Brunelle** (she/they) works as the Puget Sound team's Project Manager for Innovation and Technology Solutions. Sarah has a background in Computer Science and Environmental Sciences and brings diverse experience across private sector consulting, government clients, nonprofit (NPO) engagements, and research projects. Sarah previously managed software development engagements at International Business Machines (IBM) and brings thousands of consulting and project management hours for private and NPO clients to this engagement.

**Emily Howe, PhD** (she/her) is an Aquatic and Estuarine Ecologist specializing in interactions across the aquatic-terrestrial margin. She has 15+ years of U.S. West Coast experience, having worked extensively in San Francisco Bay, Sacramento-San Joaquin Delta, Puget Sound, Hood Canal, and the Skagit, Samish, and Stillaguamish River Deltas. Dr. Howe is the Lead Science Advisor on TNC's Port Susan Bay Project, where she develops restoration science and oversees monitoring and research.

**Christian Nilsen, PE** (he/him) is a Senior Water Resources Engineer with 19 years of experience in watershed planning, stormwater management, and stream restoration. His work has spurred the adoption of new decision-support tools to balance infrastructure needs with environmental and community benefits. Christian is a Puget Sound Partnership

Toxics in Fish Workgroup member and is a technical advisor to the WA State Governor's Southern Resident Killer Whale Task Force.

**Eva Dusek-Jennings, Ph.D.** (she/her) is the Principal Consultant at Cheva Consulting LLC and a quantitative ecologist who provides data analysis and statistical modeling expertise in aquatic, biological, and environmental sciences. Eva was an essential partner in developing Stormwater Heatmap Version 1.0 and is responsible for all the water quality and pollution loading predictions.

**Guillaume Mauger, PhD** (he/him) is a research scientist at the University of Washington Climate Impacts Group. Specializing in Climate Science, his work focuses on understanding and adapting to the impacts of climate change on flooding and stormwater in the Pacific Northwest. Guillaume has worked on projects that assess hydrologic changes across a variety of Northwest watersheds, worked to apply climate information in habitat connectivity planning, and collaborated with floodplain managers to integrate climate change into their work. In addition to his research, Guillaume serves as a resource to stakeholders interested in obtaining and understanding the numerous climate and hydrologic projections that are now available.

## 5.3 Organization Chart

Not applicable. Reference Table 1.

## 5.4 Proposed Project Schedule

The Puget Sound Stormwater Heatmap Version 2.0 agreement became effective on April 1, 2023, and will expire on June 30, 2026.

The statement of work for Puget Sound Stormwater Heatmap Version 2.0 includes several summarizing and reporting products. Reference Table 2 for completion timelines on the subset of products that pertain to final reporting. Reference Section 4.4 for detailed Version 2.0 project tasks across all project work (not limited to summarizing and reporting products).

**TNC-ECY Task 2.3 Recipient Close Out Report (RCOR) in EAGL:** At the conclusion of the project, TNC will complete the Recipient Close Out Report (RCOR) in EAGL. The RCOR form will include project accomplishments, challenges, and all relevant project information.

**TNC-ECY Task 3.1 Stormwater Heatmap Version 1.0 Memorandum:** TNC will provide a memorandum describing Version 1.0 that includes definitions, screenshots, an overview of the tool, current data layers, prior uses, and data gaps to be addressed in Version 2.0.

**TNC-ECY Task 3.2 Spatial Data Improvements and Model Validation:** TNC will incorporate (1) Time-Series Hydrology Data, (2) Water Quality Statistics, (3) Water Quality Model Validation, (4) Pollution-Area Loading Curves, and (5) Spatial Data Coordination into Version 2.0 project work. TNC will provide a report to share results from the exercises defined in items (3), (4), and (5).

**TNC-ECY Task 3.5 Stormwater Heatmap Version 2.0 Technical Documentation:** TNC will generate a suite of technical memos and written reports (architecture, water quality, hydrology, and landcover) that document Version 2.0 for users and Ecology review. The intent is to afford greater scientific confidence by exposing development methods, validating modeling efforts, explaining the tool architecture, sharing meta-data (where and how the data were collected or modeled), and outlining relevance to the region.

Table 2 outlines the key activities, due dates, and lead staff for final reporting activities related to this project engagement. The Recipient Close Out Report (RCOR) in EAGL (TNC-ECY Task 2.3) and the Stormwater Heatmap

Version 2.0 technical documentation and memorandums for Architecture, Water Quality, Hydrology, and Land Cover (TNC-ECY Task 3.5) constitute the final reports in tandem with other deliverables outlined below.

**Table 2. Schedule for final reports**

| Task | Due Date | Lead Staff |
|---|---|---|
| TNC-ECY Task 2.3:<br>Recipient Close Out Report (RCOR) | Q2: RCOR must be complete in EAGL within 30 days of contract closeout. | Sarah Brunelle to upload to EAGL and notify SW SIL PM and FM. |
| TNC-ECY Task 3.2:<br>Spatial Data Improvements and Model Validation Outcomes Report | Q3: 2024-09-30 | Sarah Brunelle will upload to EAGL and notify SWSIL PM and FM for a 30-day review and comments. |
| Data Egress Improvements Instructional Documentation | Q3: 2024-09-30 | Sarah Brunelle to upload to EAGL and notify SW SIL PM and FM. |
| TNC-ECY Task 3.5:<br>Stormwater Heatmap Version 2.0 Technical Documentation for Architecture, Water Quality, Hydrology, and Land Cover | Q1: 2026-03-31<br>2025-05-30: First Drafts Generated<br>2025-06-01: Send First Drafts to Peer Reviewers for Feedback<br>2025-12-31: Peer Review Completed<br>2026-01-15: Send Second Drafts to Ecology Administrators and Stormwater SIL Lead for Feedback<br>2026-02-28: Review Completed<br>2026-03-31: Upload Final Versions 2.0 Technical Documentation to EAGL and SWH Website | Stormwater Heatmap team members are to generate first drafts no later than the start of June 2025 in time for six months of peer review. Sarah Brunelle will send second drafts to Michelle Myers, Owen Brummel, and Stormwater SIL Lead for review in January 2026 for feedback within 30-45 days. Sarah Brunelle will upload final versions to EAGL and the Stormwater Heatmap website and notify SW SIL PM and FM for 30-day review and comments. |

## 5.5 Budget and Funding

Tables 3 and 4 show the project budget for the Stormwater Heatmap Version 2.0 scope of work when broken down by cost category and task.

**Table 3. Version 2.0 project budget per cost category**

| Cost Category | Cost ($) |
|---|---|
| Construction | $0.00 |
| Contracts | $221,044.00 |
| Laboratory | $0.00 |
| Personnel Salaries, Benefits, and Indirect Costs | $256,434.00 |
| Sub-Recipient Expenses | $17,000.00 |
| Supplies | $522.00 |
| Training & Meetings | $5,000.00 |
| Travel and Other | $0.00 |
| Total | $500,000.00 |

**Table 4. Version 2.0 project budget per task**

| Task Title | Cost (S) |
|---|---|
| 1: Project Development | $20,285.00 |
| 2: Project Administration and Reporting | $20,285.00 |

| | |
|---|---|
| 3: Development: High-Resolution Data and Access | $250,492.00 |
| 4: Aquatic Toxics and Public Roads Retrofit Planning | $96,944.00 |
| 5: User Guidance, Education, and Communication | $111,994.00 |
| *Total* | $500,000.00 |

# 6.0 Quality Objectives

## 6.1 Data Quality Objectives

The Stormwater Heatmap is designed to help users identify and address stormwater pollution sources in the Puget Sound Region. The primary data quality objectives of the Stormwater Heatmap are to provide:

1. An accurate and detailed representation of where stormwater pollution is generated.
2. Estimates of historical and future climate rainfall-runoff patterns.

This project will not collect new environmental data; however, new data will be generated in the form of model results. As described in Section 4, two independent modeling efforts will be undertaken: Water quality statistical modeling and continuous simulation hydrology modeling. Acceptance criteria for data inputs and model quality objectives are described below.

## 6.2 Measurement Quality Objectives

Not applicable. The study will not involve the collection of new environmental data.

## 6.3 Acceptance Criteria for Quality of Existing Data

### Data Sources for Water Quality Statistical Model

The Stormwater Heatmap 2.0 project will not involve the collection of new environmental data. The water quality Bayesian modeling relies on previously collected data from storm drain outfalls (Hobbs et al. 2015). These data were collected under various Ecology-approved QAPPs:

**King County:** Quality Assurance Project Plan for King County Stormwater Monitoring Under the NPDES Phase 1 Municipal Permit WAR04-4501 (Issued February 2007). Updated November 2010. King County Department of Natural Resources and Parks, Water and Land Resources Division, Science Section. King Street Center, KSC-NR-0600, 201 South Jackson Street, Suite 600, Seattle, WA 98104.

**Pierce County:** Quality Assurance Project Plan for Pierce County Phase I Municipal Stormwater NPDES Permit Section S8.D – Stormwater Characterization. November 5, 2009. Prepared for Pierce County Surface Water Management, 2702 South 42nd Street, Suite 201, Tacoma, WA 98409-7322. Prepared by Herrera Environmental Consultants.

**Snohomish County:** Quality Assurance Project Plan (QAPP) Stormwater Characterization Monitoring S8.D Final. December 2008. Prepared by Snohomish County Public Works, Surface Water Management Division, 3000 Rockefeller Ave, Everett, WA 98201.

**City of Seattle:** Section S8.D – Stormwater Characterization Quality Management System Planning Document, Quality Assurance Project Plan. NPDES Phase I Municipal Stormwater Permit, Permit No.: WAR04-4503. Revision: R2D0 (Final). Draft revised: 03/31/2011.

**City of Tacoma:** Section S8.D – Stormwater Characterization Quality Assurance Project Plan, Phase I Municipal Stormwater NPDES Permit, Permit No.: WAR04-4003. Revision: S8.D-003 (Final). Revision Date: 08/16/2009. City of Tacoma, Tacoma, WA.

**Port of Tacoma:** Quality Assurance Project Plan for Stormwater Monitoring Conducted Under the Phase I Municipal Stormwater Permit by Port of Tacoma. Final August 2009.

### Data Sources for Continuous Simulation Hydrology Model

The primary inputs for the continuous simulation hydrology model are meteorological time-series data that will be extracted from dynamically downscaled climate modeling results. Both precipitation and potential evapotranspiration data sets will be extracted from these sources. These data sets will be validated and bias-corrected using observationally-based data. Listed in Section 3.2.2, these are all well-established datasets that have received extensive quality control before release.

Prior to using each, we will review the literature on each dataset to understand potential limitations and biases that might be present in each. Datasets will be selected for evaluation based on both accuracy and the ability to evaluate metrics that are most relevant to the accurate modeling of stormwater. When making comparisons, existing data quality flags will be used to consider only the observations of sufficient accuracy.

## 6.4 Model Quality Objectives

This project encompasses two companion model components: the (a) water quality statistical model and the (b) continuous simulation hydrology model. These are described in detail below.

### Water Quality Statistical Model

In Version 1.0, we determined that spatial landscape predictors can be successfully used to estimate pollutant loads across the entire Puget Sound basin and that the spatial landscape predictor approach produces stronger predictive power than either a null model or the current categorical land use model. We also identified the best sets of spatial landscape predictors to estimate concentrations of total copper, total zinc, total phosphorus, total suspended solids, and total Kjeldahl nitrogen. However, the frequentist modeling framework used in Version 1.0 does not allow estimates of confidence intervals around chemical concentration estimates.

In Version 2.0 of the Stormwater Heatmap, we will expand on spatial landscape predictor models constructed in Version 1.0 by adding credible intervals (the Bayesian equivalent to confidence intervals) to model estimates of pollutant load. Version 2.0 will use a Bayesian framework to run the best-fit frequentist models we identified in Version 1.0, including the random effects structure (location nested within an agency). We plan to use non-informative priors and estimate variability around random effects. This will allow us to obtain credible intervals around all chemical concentration estimates by location.

A variety of quantitative and qualitative metrics for determining goodness of fit have been used in frequentist models (reference Section 3.1 "Version 1.0 Water Quality Statistical Modeling and Pollution Loading" for more information) or will be used in Bayesian models (Version 2.0). Metrics to be used for assessing Bayesian model fit include the following tests and assessments:

- Leave-one-out cross-validation (LOO) to compare Bayesian models with different variance structures;
- PSIS diagnostic tools for Bayesian models to examine the Pareto shape k parameter and identify points that could be influential outliers;
- Visual examination of Bayesian posterior density plots and chain traces to assess for model convergence and good sampling of the parameter space;
- Visual examination of observed vs. estimated plots to qualitatively assess model fit to the data; and
- Visual examination of credible intervals plotted with S8 Data to qualitatively assess the predictive utility of the models.

Additionally, in Version 2.0, we will perform model validation using external data. This will involve plotting external data with credible intervals around model predictions to determine how well the current models fit to data that were not used for model fitting. Suppose we find that some models do not fit external data. In that case, we will need to explore why and whether the models need to be changed to use different spatial landscape predictors or whether there is too much variability in the data for a particular COC to generate good models.

## Continuous Simulation Hydrology Modeling

The hydrologic modeling component of the Stormwater Heatmap tool aims to project surface water runoff under historical, current, and future climate conditions. We follow the Department of Ecology's guidance, described in the Stormwater Manual for Western Washington (Department of Ecology 2014), which calls for applying continuous simulation models based on the Hydrologic Simulation Program Fortran (HSPF). HSPF is a lumped-parameter rainfall-runoff model developed by the USGS and EPA and is generally used to perform analysis on hydrologic processes related to the effects of land cover, interception, surface ponding, and soil moisture retention. Although maintenance development of HSPF has not occurred since 1997, the EPA currently distributes it under the Better Assessment Science Integrating Point and Non-point Sources (BASINS) analysis system. In Western Washington, the application of HSPF to stormwater design is routinely performed through the Western Washington Hydrology Model (WWHM, a Windows-based graphical user interface program with built-in meteorological data and modules specific to stormwater analysis).

# 7.0 Study Design

## 7.1 Study Boundaries

Stormwater monitoring data for the S8 dataset were collected from stormwater outfalls within Phase 1 city and county stormwater basins. These basins are focused on King, Snohomish, Pierce, and Clark counties (see Figure 4). Spatial landscape predictors used in the water quality modeling span the entire Puget Sound watershed.

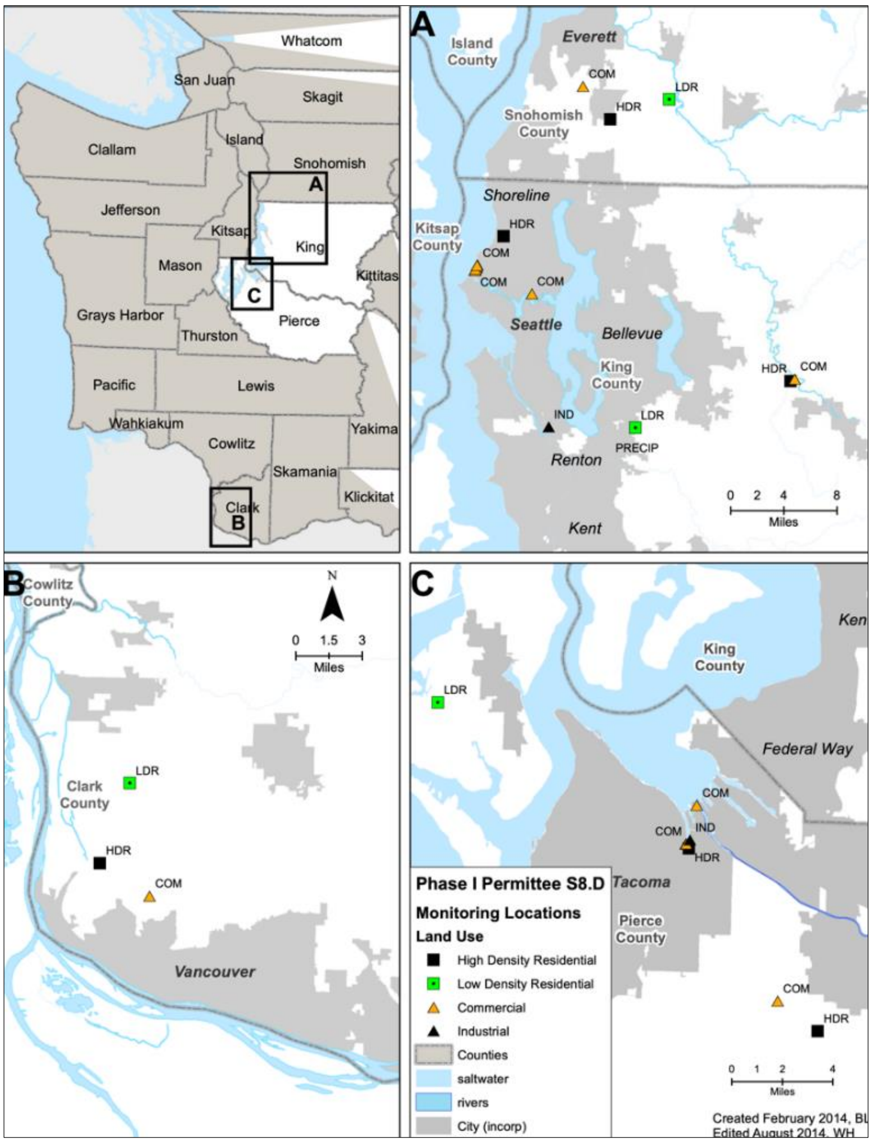


**Figure 4. Map showing locations of outfall monitoring data (from Hobbs et al. 2015)**

## 7.2 Field Data Collection

Not applicable. The study will not involve the collection of new environmental data.

## 7.3 Modeling and Analysis Design

This project encompasses two companion model components: (1) a water quality statistical model and (2) a hydrology model. These are described in detail below.

## 7.3.1 Analytical Framework

### Water Quality Statistical Model

The water quality statistical model is static, empirical, and multi-level (mixed-effects) linear. During the Stormwater Heatmap Version 1.0 (already completed), a suite of water quality models with various spatial landscape predictors was fitted to S8 Data in a frequentist framework to identify the best set of spatial landscape predictors as fixed effects. The frequentist framework allowed quick analysis of tens to hundreds of potential models, allowing us to explore all combinations of one, two, and three predictors.

We will run the best-fit frequentist models for Stormwater Heatmap Version 2.0 in a Bayesian framework. Bayesian multi-level models are much more computationally intensive than frequentist models. A Bayesian framework will allow the computation of credible intervals (the Bayesian equivalent of confidence intervals) around estimated pollutant concentrations. Bayesian models will use the best-fit model structure identified during the frequentist analysis, including the random effects structure (location nested within an agency), and we plan to use non-informative priors.

Water quality model fitting will be completed on a laptop using the open-source statistical programming language R (R Core Team 2021) and the package brms for Bayesian multi-level models (Buerkner 2017).

### Continuous Simulation Hydrology Modeling

The continuous simulation hydrology modeling approach will replicate as much as feasible, commonly applied continuous simulation hydrologic analysis for stormwater in Puget Sound. Ecology developed guidance for continuous simulation modeling described in the Stormwater Manual for Western Washington (Department of Ecology 2019). This guidance calls for applying continuous simulation models based on the Hydrologic Simulation Program Fortran (HSPF).

Calibration parameters for the Puget Lowlands Ecoregion were initially developed by the USGS in the 1990s (Dinicola 1990) and later updated by Clear Creek Solutions for incorporation in WWHM (Department of Ecology, 2019). These parameters, denoted as 'default parameters' by Ecology, will be used in this study. They are commonly referred to as PERLND (referring to pervious land cover parameters) and IMPLND factors (impervious land cover parameters).

The core of this modeling effort for both pervious and impervious land cover is PWATER and IWATER routines. These algorithms will be adapted from their original form to Python for parallel computations. The three distinct flow paths (surface outflow, interflow, and groundwater flow) will be computed separately.

Modeling will be performed for every available rainfall time series on discretized landscape segments, or hydrologic response units (HRUs), comprised of unique combinations of slope, soil, and land cover attributes. By leveraging the HRU methodology, we can pre-calculate hydrologic outcomes efficiently for subsequent applications. One can aggregate or average the outputs from the individual HRUs to determine the results for a specific watershed. For this endeavor, an HRU will be defined by a unique triad of soil, land cover, and slope. We will model every combination of the components listed below, resulting in 30 unique HRUs.

1. Hydrologic Soil Groups
    a. A/B (outwash soils)
    b. C (till)
    c. SAT (saturated or wetland/hydric soils)

2. Land cover
    a. Forest
    b. Pasture
    c. Lawn
    d. Impervious
3. Slope
    a. Flat
    b. Moderate
    c. Steep

## 7.3.2 Model Setup and Data Needs

### Continuous Simulation Hydrology Modeling

The hydrologic model will develop a precomputed runoff time series for each downscaled climate change model. As described in Section 3, downscaled climate change time-series products will be developed at a spatial resolution of 12 km. Figure 5 shows the grid locations within the study area. A total of 311 rainfall grids will be used for each climate change scenario.

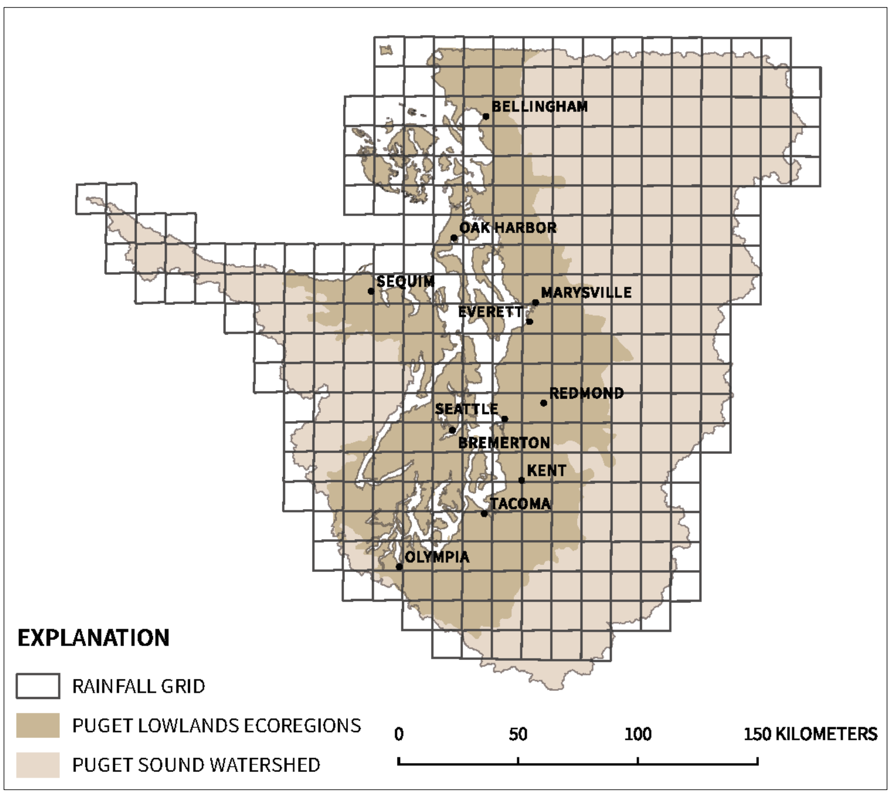


**Figure 5. Geographic scale of continuous simulation modeling**

Modeling will be performed on an hourly timestep and will span the period included in the downscaled climate models (1970 – 2099).

For each rainfall grid, a separate model will be run for each HRU. Approximately 120,000 models will be developed (30 HRUs × 311 grids × 12 scenarios). Calculations will be performed on a batch basis on Google Cloud Platform (GCP) to compute results efficiently. Results will be ingested into BigQuery, a GCP-managed cloud data warehouse. We approximate 2 × $10^{10}$ rows of results will be generated and stored. Based on previous work, we estimate the data storage requirements to be approximately 4 TB.

**Note:** Twelve (12) scenarios deal with climate change. The historical scenario is for validation and bias correction. It could also be used as an observationally based reference for and by practitioners; however, it would not be used for the climate change component.

### Spatial Data Inputs

Spatial data consists of data layers used to develop HRU relationships. Table 5 summarizes spatial data inputs used to create the HRUs in Version 1.0 that will persist in Version 2.0.

**Table 5. Summarized spatial data inputs for hydrology modeling**

| Layer Name | Source | Values | Scale ($m^2$/pixel) |
|---|---|---|---|
| HSPF Land Cover Type | TNC Stormwater Heatmap Version 1.0 | Forest/Trees, Pasture, Grass, Water, Impervious-roof, Impervious-nonRoof | 1 |
| Slope | USGS National Elevation Dataset One-Third (1/3) Arc-Second | Continuous | 10 |
| Soils | TNC Stormwater Heatmap Version 1.0 | Outwash, Till, Saturated, Water | 5 |

## 7.4 Assumptions of Study Design

While this project will not generate new environmental data, it does involve analysis of existing data and environmental modeling.

### Water Quality Statistical Model

In extending the water quality model equations to the Puget Sound basin, we assume that the relationship observed between spatial landscape predictors (transposed or not) and the chemical concentrations in stormwater will continue to be linear at spatial landscape predictor values above or below those found at the sampled catchments. We also assume that the relationship between spatial predictors and stormwater pollutants has not changed dramatically over the last decade. For example, with the traffic predictor, we assume that vehicle components contributing to stormwater pollution have not changed in the last decade in such a way as to alter the relationship between traffic and stormwater pollutant loads. Lastly, because of limits to the number of catchments where data were collected, we had to assume that no interactions between pairs of spatial landscape predictors need to be included in the water quality model equations. Reference Section 10.2 for corrective action procedures if these assumptions prove incorrect and result in greater variance than anticipated.

### Continuous Simulation Hydrology Modeling

The following assumptions pertain to this study specific to continuous simulation modeling:

1. Regional calibration factors (default factors) for HSPF described above will pertain to the entire Puget Lowlands Region. This study will not develop site-specific calibration factors.
2. Streamflow routing will not be incorporated into results. Runoff estimates will be for runoff generation only. Therefore, when aggregating results for an area of interest, results should be limited to small urban catchments with a maximum drainage area of about two hundred (200) acres.
3. More general assumptions regarding applying the lumped watershed model, such as those described in Borah (2011), will also apply to this project. These include specific assumptions on unsaturated soil infiltration, evapotranspiration calculations, and groundwater flow relationships.

## 7.5 Possible Challenges and Contingencies

Apart from the constraints and schedule limitations outlined below, we depend on identifying numerous high-quality data sources (reference Sections 4.3 and 4.4 for more details).

### 7.5.1 Logistical Problems

The project team utilizes GitHub repositories and will follow best practices for repository backups as outlined in GitHub documentation (found here: https://docs.github.com/en/repositories/archiving-a-github-repository/backing-up-a-repository) in the event of malicious actors or disaster recovery needs.

### 7.5.2 Practical Constraints

The total sum of $500,000.00 in project funding is needed to develop Version 2.0, but it is insufficient for development outside the stated project objectives. Further funding will be required if the project team wishes to develop beyond the objectives stated in Section 4.2.

### 7.5.3 Schedule Limitations

Unforeseen project schedule limitations (e.g., policy changes or challenges) will be discussed with the appropriate personnel (i.e., modeling team, project manager, etc.) and documented where needed.

TNC started on Task 2.0, Project Administration and Reporting sub-tasks, in September 2023. However, the TNC award startup memorandum with the associated Project ID, Award ID, and Activity IDs became available in 2023 October 02. This was when TNC staff time on the Version 2.0 project became "chargeable" in the TNC systems.

TNC anticipates this will propagate to impact progress and outcomes during the 2023 October to 2023 December reporting period. QAPP review and approval delays would increase this likelihood.

# 8.0 Field Procedures

Not applicable. The study will not involve field procedures.

# 9.0 Laboratory Procedures

Not applicable. This project will not involve laboratory procedures.

# 10.0 Quality Control Procedures

The Stormwater Heatmap project team will support proactive identification of problems or issues associated with data analysis and modeling while the project is underway through:

- Holding regular project team meetings for TNC personnel with contractors as optional.
- Collecting and reviewing interim work products for audits and reports. Reference Section 12.0 for additional details on the audit and report schedule.

## 10.1 Table of Field and Laboratory Quality Control

Not applicable. This project will not involve field or laboratory procedures.

## 10.2 Corrective Action Processes

If activities are found to be inconsistent with the QAPP, analysis or modeling results do not meet expectations, or some other unforeseen problem(s) arise, the Project Manager will convene project personnel and technical experts to decide on the next steps to improve model performance.

### Water Quality Statistical Model

During model validation with external data, the possibility exists that our models will not fit external data. If this is the case, we will explore why models do not fit the new data. Three possible scenarios for poor model fit to new data are:

1. Spatial predictor values for new data are outside of the range for the S8 Data used for model fitting;
2. Predictors selected during model fitting were not the best predictors for the whole Puget Sound basin, and
3. Variability in the data is too high for a particular COC to generate good models.

These three scenarios have different repercussions. If new data are collected from locations very different from the S8 Data, we may explore different regression approaches, such as non-linear models. If, on the other hand, new data are collected at similar types of locations as the S8 data, and it becomes clear that certain spatial landscape predictors are not broadly suitable in models, we may explore different combinations of spatial landscape predictors for estimating COC concentrations.

If variability in the data is too high for certain COCs, that will indicate that we should reject the hypothesis that stormwater concentrations can be predicted using spatial landscape predictors with the available data. In that case, we will indicate on the Stormwater Heatmap website that a model fit was not achieved.

### Continuous Simulation Hydrology Model

Continuous simulation modeling will utilize pre-calibrated parameters and bias-corrected precipitation time series as the primary inputs. However, discrepancies may arise between our model's outputs and anticipated results. In that event, the following corrective action process will be implemented:

1. **Review of Inputs:** In cases where the model's results do not align with the verification date, we will review the modeling inputs for errors. Potential errors may include time-step discrepancies, missing data, or incorrect transformation processes.
2. **Review of Modeling Code:** If the review of input data does not reveal errors, the next step will be to review the modeling code for potential errors or oversight.
3. **Error Identification and Rectification:** Corrective action will be taken if errors are identified during the review process. This may involve correcting input data, amending data pipelines, or fixing issues with the modeling code. All changes will be documented and tested before implementation.
4. **Documentation of Departures from Validation Data:** In instances where the review process does not reveal any errors, yet the model's output still diverges from expectations, we will proceed with using the model output with

detailed documentation of the departures from validation. This will include analyzing the validation data, hypothesized reasons for these deviations, and potential implications for the project’s objectives.

# 11.0 Data Management Procedures

## 11.1 Data Recording and Reporting Requirements

Not applicable. The recording requirements, reporting requirements, and data upload procedures are not relevant to this scope of work. This project does not involve field or laboratory procedures. Neither field nor lab data will be collected. There will be no recorded data to transfer into the EPA Water Quality Exchange (WQX) portal or the Ecology Environmental Information Management (EIM) portal.

## 11.2 Laboratory Data Package Requirements

Not applicable. This project will not involve field or laboratory procedures.

## 11.3 Electronic Transfer Requirements

Not applicable. This project will not involve field or laboratory procedures.

## 11.4 Data Upload Procedures

Not applicable. The recording requirements, reporting requirements, and data upload procedures are not relevant to this scope of work. This project does not involve field or laboratory procedures. Neither field nor lab data will be collected. There will be no recorded data to transfer into the EPA Water Quality Exchange (WQX) portal or the Ecology Environmental Information Management (EIM) portal.

## 11.5 Model Information Management

This project is expected to ingest and generate multiple terabytes of data. We expect to encounter challenges related to storing, managing, and distributing these data. The following steps will be implemented to manage and document data pipelines and workflows.

1. Google Cloud Storage will be utilized to store geospatial, time-series, and unstructured data. Data will be separated into two GCP projects: one *production* project and one *development* project. Only finalized data that meets QA objectives will be stored under the production project. Other data, such as work in progress or data awaiting review, will be stored under the development project.
2. Data storage will use available versioning tools, whereby objects can be restored if overwritten or deleted. Up to three (3) versions will be available per object. Non-current versions will be stored for 30 days before expiration.
3. All code used to generate data will use a git-style version control system that tracks changes and synchronizes updates to a central repository. The GitHub project site (www.github.com/stormwaterheatmap) will be used for version control.
4. All code will include headers and inline documentation that detail the following:
    a. Description of the script's primary purpose.
    b. List of authors and contributors.
    c. Changelog indicating all modifications, including dates and responsible parties.
5. Each function within the codebase will be documented following Doxygen standards:
    a. A brief description of the function's purpose.
    b. Parameters used, detailing data type and a brief explanation.
    c. Return value type and description.
    d. Relevant preconditions or assumptions, if any.
    e. Example usage, where applicable.

### Storage Schema

All runoff modeling results stored on the cloud data warehouse will have the same schema shown in Table 6.

**Table 6. Data storage schema for runoff modeling results**

| Field Name | Type | Description |
|---|---|---|
| GRID | STRING | WRF Grid ID |
| YEAR | INTEGER | Year (Used for data partitioning) |
| DATETIME | TIMESTAMP | Timestep of simulation value (UTC Time) |
| SIMULATION_DAY | INTEGER | Index of days in simulation (UTC Time) |
| COMP | STRING | HSPF Component. Possible values are SURO (surface flow), INFW (interflow), and AGWO (groundwater flow) |
| HRU | STRING | Hydrologic Response Unit Identifier (e.g., HRU123) |
| MM_HR | FLOAT | Outflow per unit area (mm/hr) |

Data will be partitioned by YEAR and clustered by GRID to reduce query time and costs.

An additional table with GRID geometries will be developed to enable geographic query functions. This table can be joined with other queries to create spatially referenced values.

The storage schema for the grid geometry table is shown in Table 7.

**Table 7. Grid geometry storage schema**

| Field Name | Type | Description |
|---|---|---|
| GRID | STRING | WRF Grid ID |
| XY | GEOGRAPHY | Coordinates of the centroid of the grid cell |
| POLYGON | GEOGRAPHY | Geometry of grid cell |

# 12.0 Audits and Reports

## 12.1 Audits

Not applicable. Reference Section 10.0 for more information on quality control procedures.

## 12.2 Responsible Personnel

TNC is the primary author of these materials. The Project Manager will ensure the completion of these tasks and solicit input from Stormwater Heatmap team members and contractors. For more information on project team members and their responsibilities, reference Section 5.1.

## 12.3 Frequency and Distribution of Reports

The statement of work for Puget Sound Stormwater Heatmap Version 2.0 includes several summarizing and reporting products. For more details, refer to Section 5.4. Table 2 provides completion timelines for the subset of products that pertain to final reporting. Section 4.4 provides detailed Version 2.0 project tasks across all project work (not limited to summarizing and reporting products).

## 12.4 Responsibility for Reports

TNC is responsible for authoring all materials. The Project Manager will ensure the completion of these tasks and solicit input from Stormwater Heatmap team members and contractors as needed. For more information on project team members and their responsibilities, refer to Sections 4.4 and 5.1.

# 13.0 Data Verification

## 13.1 Field Data Verification, Requirements, and Responsibilities

Not applicable. This project will not involve field procedures.

## 13.2 Laboratory Data Verification

Not applicable. This project will not involve laboratory procedures.

## 13.3 Validation Requirements (If Needed)

Not applicable.

## 13.4 Model Quality Assessment

Reference the information provided in the sub-sections to follow.

### 13.4.1 Calibration and Validation

#### Water Quality Statistical Model

Water quality statistical models for the Stormwater Heatmap are mixed effects linear regression models that were fitted to the S8 Data. During Version 1.0 of the Stormwater Heatmap project (already completed), the process of fitting the regression models to data (analogous to model calibration) involved a series of steps that we performed using the methodology of Zuur et al. (2009) to achieve the following:

- Control for heterogeneity using appropriate variance structures.
- Find the proper random effects structure.
- Check for temporal and spatial correlation.
- Find the proper fixed effects structure, including spatial landscape predictors and temporal or spatio-temporal predictors such as precipitation and seasonality.

For Version 2.0 of the Stormwater Heatmap, we plan to run the best-fit models in a Bayesian framework (reference Section 6.4, “Water Quality Statistical Model” for methods to verify the model fit to data).

Stormwater monitoring data suitable for model construction and validation are somewhat scarce in the Puget Sound basin. Suitable S8 data used for model fitting represent only fourteen (14) catchments or fourteen combinations of spatial landscape predictors from which to derive a model. To increase our ability to generate a good model in Version 1.0, we decided to put all fourteen catchments from the S8 data toward model fitting and not set aside a portion of the catchments as testing data.

During Version 2.0, we will search for independent data from the Puget Sound basin that can be used to validate the models, prioritizing data with an associated QAPP or other quality control document. We will also seek out data from a variety of regions within the Puget Sound basin. This will allow us to see how well our model fits data from locations with various land use practices. We may expect better or worse alignment with the models depending on the datasets we can find and the portion of the land cover distribution they represent. The S8 monitoring catchments are located in urbanized areas, so we may expect a better model fit to validation data collected from urbanized areas. As we move out from urban systems into less developed areas, we may observe worse model fit to validation data.

During Version 1.0, the criterion to which we compared models was: Did the spatial landscape predictor model provide an improvement upon chemical concentration estimates generated from the land use category? During Version 2.0 validation, models will be considered sufficiently good if the majority of the testing data fall within the 80% credible intervals for the test data's location. Reference Section 10.2 "Water Quality Statistical Model" for contingencies if the model does not meet validation requirements. Landscape predictor models will only be used in the Stormwater Heatmap if they meet validation requirements. Other approaches may be revisited, for example, land use-based models. Suppose the model validation proves to be a failure (either because we cannot locate suitable datasets or because the models do not fit the test data). In that case, we can recommend where we need more stormwater data to generate a better predictive model for Puget Sound.

### Continuous Simulation Hydrology Model

Rainfall-runoff results will not be calibrated to any measured results. As described in earlier sections, the model will rely on regional calibrated parameters previously developed for the Puget Lowlands area. Modeling results will be validated by comparing modeling results from the historical WRF-NARR simulation modeling run with gaged streamflow from up to three (3) locations in the Puget Lowlands Ecoregion. Locations will be selected based on the available period of record and contributing area characteristics (small catchment size, minimal detention storage, etc.). Validation will focus on the surface runoff and interflow components exclusively. Results will also be compared to WWHM modeling results using meteorologic inputs that coincide with the WRF-NARR analysis.

As described in Section 3.2.2, existing data sources will be used to obtain the meteorological data used as input to the continuous simulation hydrology model. The WRF regional climate model was calibrated and evaluated for accuracy in previous studies (Chen et al. 2019, Mass et al. 2022). Precipitation estimates from the historical WRF-NARR simulation will be compared against a selection of the observed datasets listed in Section 3.2.2. Comparisons will evaluate biases in seasonal and annual precipitation and the probability distribution in hourly precipitation, focusing on high intensities. Based on these comparisons, a simple bias correction will be applied to the precipitation data: either a simple scaling applied to all time steps or a quantile-based adjustment (where different corrections are applied depending on intensity).

## 13.4.1.1 Precision

### Water Quality Statistical Model

Model precision can be assessed by comparing the absolute distance between model estimates and the S8 Data used to fit the model. The precision of the water quality statistical models will be assessed by calculating the root mean square error (RMSE).

### Historical and Future Meteorology

The WRF-NARR historic simulation results will be compared with measured streamflow in up to three (3) locations (percent bias is defined as the average percent difference between predicted and observed values). The following calculations will then be repeated for a companion run in WWHM following Ecology guidance to compare the model performances between this project and WWHM:

- **Root Mean Square Error (RMSE):** Calculation of the average magnitude of the model prediction error. It provides an absolute measure of fit and is sensitive to outliers.
- **Mean Absolute Error (MAE):** The average of the absolute differences between the predicted and observed values. Like RMSE, it provides an absolute measure of fit.
- **Nash-Sutcliffe Efficiency (NSE):** Normalized statistic that ranges from $-\infty$ to 1. A value of 1 indicates perfect model predictions, zero (0) indicates that the model is as accurate as the mean of the observed data, and a value less than zero indicates that the observed mean is a better predictor.

#### 13.4.1.2 Bias

### Water Quality Statistical Model

We will evaluate bias for the water quality models through graphical residual analysis. This involves looking at model residuals after fitting to see if they are evenly distributed around zero (0) without any pattern to the residuals. We will also plot residuals against each spatial landscape predictor to determine whether any patterns are observed in the model residuals, indicating missed predictors.

### Historical and Future Meteorology

Hydrology model verification will calculate the percent bias (percent bias is defined as the average percent difference between predicted and observed values) for the WRF-NARR historical simulation in up to three (3) locations. These calculations will then be repeated for a companion run in WWHM following Ecology guidance to compare the model performances between this project and WWHM. Percent bias measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. Zero PBIAS indicates accurate model prediction, while positive values indicate model underestimation and negative values indicate overestimation.

Biases in the WRF precipitation estimates will be evaluated for annual, seasonal, and hourly precipitation. For hourly precipitation, the focus will be the probability distribution in precipitation intensities. All biases will be assessed regarding the percent difference between the model and observations (“PBIAS”).

#### 13.4.1.3 Representativeness

For the statistical water quality models, we plan to use an independent data set (“test data”) to determine whether the model results are representative of locations outside of the 14 catchments used to fit and calibrate the models (reference Section 10.2 “Water Quality Statistical Model” for contingencies if the model does not meet validation requirements). The test data will be plotted against model predictions using the following tools for visual assessment:

- Graphical evaluation of test data plotted against model predictions (observed versus predicted plots).
- Graphical evaluation of test data plotted atop credible interval bands.

Suppose most test data fall relatively close to the 1:1 observed vs. predicted line and fit within the 80% and 95% credible intervals. In that case, we will conclude that the model is representative of the Puget Sound basin.

#### 13.4.1.4 Qualitative Assessment

### Water Quality Statistical Model

Statistical water quality models will be qualitatively assessed through graphical evaluation of observed vs. predicted plots (i.e., Do plot points roughly line up with the 1:1 line?) and through plots of S8 Data atop credible interval bands.

### Continuous Simulation Hydrology Model

For each hydrology validation comparison, we will perform temporal graphical comparisons that show observed vs. predicted streamflow over time.

## 13.4.2 Analysis of Sensitivity and Uncertainty

## Water Quality Statistical Model

The Bayesian water quality models that we will use are multilevel linear regression models with a specified variance structure. We plan to qualitatively and quantitatively assess model sensitivity to several model components:

1. If the COC data includes potentially influential outliers, are the model conclusions sensitive to those outliers?
2. Does changing the variance structure result in a quantitative change to the parameters for spatial landscape predictors?
3. If our selected random effects structure (samples nested within outfall locations nested within agencies) is incorrect, does a simpler structure result in qualitative differences to the model outcome? For example, if we removed the nesting structure of outfall locations within agencies, would this make a qualitative difference to the model?

The methodology and results of this sensitivity analysis will be presented in the Version 2.0 technical documentation.

## Continuous Simulation Hydrology Model

Sensitivity analysis will focus on assessing the impact of assumptions of potential evapotranspiration on modeling output. This will be performed in conjunction with verification of results. Evapotranspiration time series may be derived from input meteorologic data or publicly available evaporation measurements. Sensitivity analysis will focus on assessing the variability of results across different data sources and varying time periods of aggregation (e.g., monthly averages vs. continuous measurements).

Uncertainty will be evaluated by reviewing the range of results from the ensemble of model simulations. We will quantify the range associated with runoff modeling results at various time scales and for various hydrologic response units.

# 14.0 Data Quality (Usability) Assessment

## 14.1 Process for Determining Project Objectives Were Met

### Water Quality Statistical Model

During the generation of the Stormwater Heatmap Version 1.0, water quality statistical models run in the frequentist framework were evaluated for model quality through several metrics, including:

- AIC to determine whether spatial land use predictor models provide an improvement over models based on land use category.
- Plotting of spatial land use model residuals by catchment location to verify that residuals are centered around 0, indicating that the model predictors well represent COC concentrations.
- For Version 2.0 of the Stormwater Heatmap, the best-fit water quality statistical models from the frequentist framework will be run in a Bayesian framework. Model quality will be evaluated through the following metrics:
    - Comparison of frequentist model parameter values to those generated during the Bayesian model. We will expect to see very similar parameter values for both frameworks.
    - Visual examination of Bayesian posterior density plots and chain traces to assess for model convergence and good sampling of the parameter space.
    - PSIS diagnostic tools for Bayesian models to examine the Pareto shape k parameter and identify points that could be influential outliers. Suppose a model has more than one influential point with a k-value > 0.7. In that case, we will try using a Student-t distribution (rather than a Normal distribution) as the underlying distribution for the data.
    - Visual examination of observed vs. estimated plots to qualitatively assess model fit to the data.
    - Visual examination of credible intervals plotted with S8 Data to qualitatively assess the predictive utility of the models.

Models that pass all these evaluations and examinations will be deemed sufficiently high-quality for use in Version 2.0 of the Stormwater Heatmap (reference Section 10.2, “Water Quality Statistical Model” for contingencies if the model does not meet validation requirements).

### Continuous Simulation Hydrology Model

The usability of continuous simulation hydrology model results will depend on meeting the model quality objectives described in Section 6.4 and successfully completing the model quality assessment described in Section 13.4.

## 14.2 Treatment of Non-Detects

### Water Quality Statistical Model

In the water quality statistical models, non-detects in data will be treated in two different ways, depending on the percentage of data that are censored (non-detect):

- For chemicals where only a small percentage (5% or less) of data are censored, non-detects are substituted with one-half of the reporting limit. This is the case for four of the five pollutants studied in Version 1.0 and is in line with EPA standards, which allow substitution of (0.5 x detection limit) for censored values when less than 15% of samples are non-detect (USEPA 2009).
- However, substitution can add a pattern to the data that differs from the pattern of the data itself, with the likelihood increasing as the proportion of non-detect data increases (Helsel 2012). One pollutant, total Kjeldahl nitrogen (TKN), has a higher level of non-detect data (approximately 10%). In this case, to avoid introducing a

pattern to the TKN data that is different from the data itself (Helsel 2012), we used regression on order statistics (ROS) to calculate statistics for TKN in Version 1.0.

In Version 2.0, we will follow the same principles, utilizing censored statistics methods included in the R package for Bayesian modeling: *brms* (Buerkner 2017).

# 14.3 Data Analysis and Presentation Methods

## Water Quality Statistical Model

After regression equations have been established, they need to be translated to spatial heatmap layers for display. The transformation consists of four main steps, summarized below.

1. **Scaling of Predictor Data:** First, a 'stacked' raster image is created, whereby each spatial predictor is assigned its own raster band. Using statistics of predictor value within the monitored catchment, the spatial data will be centered at the mean value and scaled to a standard deviation of one (1).

2. **Convolution of Scaled Predictor Data:** Once the data is centered and scaled, a convolution operation is carried out to smooth the data across the entirety of a catchment. A circular kernel with a specified radius of one hundred (100) meters is used to compute the average value within its surrounding area.

3. **Clamping of Convolved Data:** Values are clamped in cases where the convolved predictor values are beyond ±3 standard deviations of predictors found in monitored catchments. This is so concentration calculations do not exceed reasonable values from the monitored catchments.

4. **Application of Regression Equations:** After the data is processed, the regression equations will be applied to develop the final heatmap layers. The multiband raster image is multiplied by the regression coefficients and summed. For each pixel in the raster image, the predictor variables are stored as a vector in the form:

$$X = [1,\ x_1,\ x_2,\ \dots,\ x_n]$$

Where:
- The first value, "1," represents the constant term for the intercept.
- $x_1, x_2, \dots, x_n$ are the predictor variables.

The regression coefficients corresponding to the predictor variables are encapsulated in another vector: $\beta = [\beta_0, \beta_1, \beta_2, \dots, \beta_n]$ Where:
- $\beta_0$ is the intercept.
- $\beta_0, \beta_1, \beta_2, \dots, \beta_n$ are the coefficients corresponding to the predictors.

The logarithm of the predicted concentration is then calculated as the dot product of the predictor variables and the regression coefficients. The logarithm of the predicted concentration of the chemical *C* can be represented as:

$$\ln(C) = X \cdot \beta$$

To derive the actual concentration of the chemical:

$$C = e^{X \cdot \beta}$$

## Continuous Simulation Hydrology Model

Hourly time series hydrology modeling results will be aggregated and extracted from the cloud-based data warehouse and stored in raster images of various hydrology metrics. The process involves data extraction, aggregation, rasterization, and visualization and is described below.

**1. Data Extraction from Cloud Database:** Utilize SQL queries to retrieve summaries of runoff data from the hydrology modeling results. Generally, data will be extracted for SURO (surface runoff) and IFWO (interflow) components for every HRU and rainfall grid within the model domain. SQL queries will aggregate the sum of the runoff results and group them by HRU, Rainfall Grid, and the appropriate time component. Save results in a JSON format in a cloud-based staging storage bucket.

**2. Rasterization of Runoff Data:** Convert JSON data to a multi-band raster image collection using the Rainfall Grid ID Geometry as raster cells. Each band will correspond to an individual HRU, and each image within the collection will correspond to an aggregated timestep. For example, if data are aggregated by total runoff per year for a 20-year time series, the image collection would contain twenty (20) images with one band per HRU. Figure 6 illustrates how image collections will be used in this manner.

**3. Joining with HRU Data:** The image collection will be joined with the HRU image layer to map the runoff results to landscape conditions. Similar to the runoff image collection, the HRU image consists of one band per HRU. For each band, values are set to 1 if that band corresponds to the HRU at that pixel and are set to 0 if not. By multiplying the HRU image by the runoff results image collection and summing all the bands, the result is a single-band image collection representing aggregated runoff results.

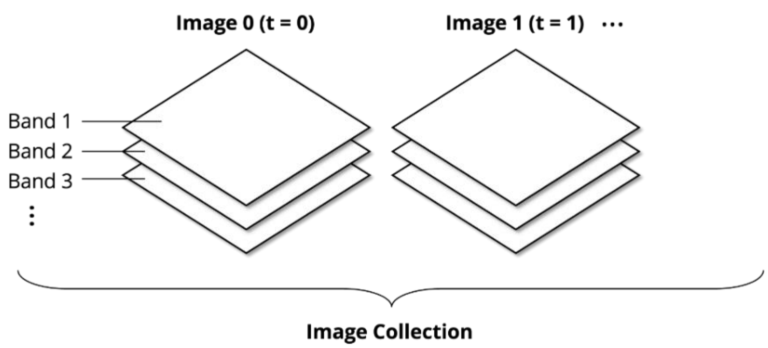


**Figure 6. Visual representation of runoff data aggregation as a time-series image collection**

# 14.4 Sampling Design Evaluation

Not applicable. This project will not involve data sampling.

# 14.5 Documentation of Assessment

Please refer to Section 12.0 for additional details on the reports to be included in this project. These documents are intended to collectively document methods and results for this scope of work.

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# 16.0 Appendices

## Appendix A. Glossaries, Acronyms, and Abbreviations

### Glossary of General Terms

**Effluent:** An outflowing of water from a natural body of water or from a human-made structure. For example, the treated outflow from a wastewater treatment plant.
**Eutrophic:** Nutrient rich and high in productivity resulting from human activities such as fertilizer runoff and leaky septic systems.
**Municipal separate storm sewer systems (MS4):** A conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, manmade channels, or storm drains): (1) owned or operated by a state, city, town, borough, county, parish, district, association, or other public body having jurisdiction over disposal of wastes, stormwater, or other wastes and (2) designed or used for collecting or conveying stormwater; (3) which is not a combined sewer; and (4) which is not part of a Publicly Owned Treatment Works (POTW) as defined in the Code of Federal Regulations at 40 CFR 122.2.
**National Pollutant Discharge Elimination System (NPDES):** National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.
**Nonpoint source:** Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of “point source” in section 502(14) of the Clean Water Act.
**Nutrient:** Substance such as carbon, nitrogen, and phosphorus used by organisms to live and grow. Too many nutrients in the water can promote algal blooms and rob the water of oxygen vital to aquatic organisms.
**Pathogen:** Disease-causing microorganisms such as bacteria, protozoa, viruses.
**Phase I stormwater permit:** The first phase of stormwater regulation required under the federal Clean Water Act. The permit is issued to medium and large municipal separate storm sewer systems (MS4s) and construction sites of five or more acres.
**Phase II stormwater permit:** The second phase of stormwater regulation required under the federal Clean Water Act. The permit is issued to smaller municipal separate storm sewer systems (MS4s) and construction sites over one acre.
**Point source:** Source of pollution that discharges at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.
**Pollution:** Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will,
or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to
(1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.
**Riparian:** Relating to the banks along a natural course of water.
**Salmonid:** Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.
**Sediment:** Soil and organic matter that is covered with water (for example, river or lake bottom).

**Stormwater:** The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.
**Streamflow:** Discharge of water in a surface stream (river or creek).
**Total Maximum Daily Load (TMDL):** A distribution of a substance in a water body designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a margin of safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.
**Total suspended solids (TSS):** Portion of solids retained by a filter.
**Turbidity:** A measure of water clarity. High levels of turbidity can have a negative impact on aquatic life.
**Wasteload allocation:** The portion of a receiving water's loading capacity allocated to existing or future point sources of pollution. Wasteload allocations constitute one type of water quality-based effluent limitation.
**Watershed:** A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.
**90$^{th}$ percentile:** An estimated portion of a sample population based on a statistical determination of distribution characteristics. The 90$^{th}$ percentile value is a statistically derived estimate of the division between 90% of samples, which should be less than the value, and 10% of samples, which are expected to exceed the value.

# Acronyms and Abbreviations

| | |
|---|---|
| BMP | Best management practice |
| COC | Chemical of concern |
| e.g. | For example |
| Ecology | Washington State Department of Ecology |
| EIM | Environmental Information Management database |
| EPA | U.S. Environmental Protection Agency |
| et al. | And others |
| GIS | Geographic Information System software |
| i.e. | In other words |
| MQO | Measurement quality objective |
| NPDES | National Pollutant Discharge Elimination System |
| PCB | Polychlorinated biphenyls |
| QA | Quality assurance |
| QC | Quality control |
| RPD | Relative percent difference |
| RSD | Relative standard deviation |
| S8 Data | S8.D Municipal Stormwater Permit Outfall Data |
| SOP | Standard operating procedures |
| TIR | Thermal infrared radiation |
| TMDL | Total Maximum Daily Load |
| TSS | Total suspended solids |
| USFS | United States Forest Service |
| USGS | United States Geological Survey |
| WAC | Washington Administrative Code |
| WDFW | Washington Department of Fish and Wildlife |
| WQA | Water Quality Assessment |
| WRIA | Water Resource Inventory Area |

# Units of Measurement

| | |
|---|---|
| °C | degrees centigrade |
| ft | feet |
| km | kilometer, a unit of length equal to 1,000 meters |

| | |
|---|---|
| L/s | liters per second (0.03531 cubic foot per second) |
| m | meter |
| mm | millimeter |
| mL | milliliter |

# Quality Assurance (QA) Glossary

**Accreditation:** A certification process for laboratories, designed to evaluate and document a lab's ability to perform analytical methods and produce acceptable data (Kammin, 2010). For Ecology, it is defined according to WAC 173-50-040: "Formal recognition by [Ecology] that an environmental laboratory is capable of producing accurate and defensible analytical data."

**Accuracy:** The degree to which a measured value agrees with the true value of the measured property. USEPA recommends that this term not be used, and that the terms *precision* and *bias* be used to convey the information associated with the term *accuracy* (USEPA, 2014).

**Analyte:** An element, ion, compound, or chemical moiety (pH, alkalinity) which is to be determined. The definition can be expanded to include organisms, e.g., fecal coliform, Klebsiella (Kammin, 2010).

**Bias:** Discrepancy between the expected value of an estimator and the population parameter being estimated (Gilbert, 1987; USEPA, 2014).

**Blank:** A synthetic sample, free of the analyte(s) of interest. For example, in water analysis, pure water is used for the blank. In chemical analysis, a blank is used to estimate the analytical response to all factors other than the analyte in the sample. In general, blanks are used to assess possible contamination or inadvertent introduction of analyte during various stages of the sampling and analytical process (USGS, 1998).

**Calibration:** The process of establishing the relationship between the response of a measurement system and the concentration of the parameter being measured (Ecology, 2004).

**Check standard:** A substance or reference material obtained from a source independent from the source of the calibration standard; used to assess bias for an analytical method. This is an obsolete term, and its use is highly discouraged. See Calibration Verification Standards, Lab Control Samples (LCS), Certified Reference Materials (CRM), and/or spiked blanks. These are all check standards but should be referred to by their actual designator, e.g., CRM, LCS (Kammin, 2010; Ecology, 2004).

**Comparability:** The degree to which different methods, data sets and/or decisions agree or can be represented as similar; a data quality indicator (USEPA, 2014; USEPA, 2020).

**Completeness:** The amount of valid data obtained from a project compared to the planned amount. Usually expressed as a percentage. A data quality indicator (USEPA, 2014; USEPA 2020).

**Continuing Calibration Verification Standard (CCV):** A quality control (QC) sample analyzed with samples to check for acceptable bias in the measurement system. The CCV is usually a midpoint calibration standard that is re-run at an established frequency during the course of an analytical run (Kammin, 2010).

**Control chart:** A graphical representation of quality control results demonstrating the performance of an aspect of a measurement system (Kammin, 2010; Ecology 2004).

**Control limits:** Statistical warning and action limits calculated based on control charts. Warning limits are generally set at +/- 2 standard deviations from the mean, action limits at +/- 3 standard deviations from the mean (Kammin, 2010).

**Data integrity:** A qualitative DQI that evaluates the extent to which a data set contains data that is misrepresented, falsified, or deliberately misleading (Kammin, 2010).

**Data quality indicators (DQI):** Commonly used measures of acceptability for environmental data. The principal DQIs are precision, bias, representativeness, comparability, completeness, sensitivity, and integrity (USEPA, 2006).

**Data quality objectives (DQO):** Qualitative and quantitative statements derived from systematic planning processes that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions (USEPA, 2006).

**Data set:** A grouping of samples organized by date, time, analyte, etc. (Kammin, 2010).

**Data validation:** The process of determining that the data satisfy the requirements as defined by the data user (USEPA, 2020). There are various levels of data validation (USEPA, 2009).

**Data verification:** Examination of a data set for errors or omissions, and assessment of the Data Quality Indicators related to that data set for compliance with acceptance criteria (MQOs). Verification is a detailed quality review of a data set (Ecology, 2004).

**Detection limit** (limit of detection)**:** The concentration or amount of an analyte which can be determined to a specified level of certainty to be greater than zero (Ecology, 2004).

**Duplicate samples:** Two samples taken from and representative of the same population, and carried through and steps of the sampling and analytical procedures in an identical manner. Duplicate samples are used to assess variability of all method activities including sampling and analysis (USEPA, 2014).

**Field blank:** A blank used to obtain information on contamination introduced during sample collection, storage, and transport (Ecology, 2004).

**Initial Calibration Verification Standard (ICV):** A QC sample prepared independently of calibration standards and analyzed along with the samples to check for acceptable bias in the measurement system. The ICV is analyzed prior to the analysis of any samples (Kammin, 2010).

**Laboratory Control Sample (LCS)/LCS duplicate:** A sample of known composition prepared using contaminant-free water or an inert solid that is spiked with analytes of interest at the midpoint of the calibration curve or at the level of concern. It is prepared and analyzed in the same batch of regular samples using the same sample preparation method, reagents, and analytical methods employed for regular samples. Monitors a lab's performance for bias and precision (USEPA, 2014).

**Matrix spike/Matrix spike duplicate:** A QC sample prepared by adding a known amount of the target analyte(s) to an aliquot of a sample to check for bias and precision errors due to interference or matrix effects (Ecology, 2004).

**Measurement Quality Objectives** (MQOs)**:** Performance or acceptance criteria for individual data quality indicators, usually including precision, bias, sensitivity, completeness, comparability, and representativeness (USEPA, 2006).

**Measurement result:** A value obtained by performing the procedure described in a method (Ecology, 2004).

**Method:** A formalized group of procedures and techniques for performing an activity (e.g., sampling, chemical analysis, data analysis), systematically presented in the order in which they are to be executed (USEPA, 2001).

**Method blank:** A blank prepared to represent the sample matrix, prepared and analyzed with a batch of samples. A method blank will contain all reagents used in the preparation of a sample, and the same preparation process is used for the method blank and samples (Ecology, 2004; Kammin, 2010).

**Method Detection Limit (MDL):** The minimum measured concentration of a substance that can be reported with 99% confidence that the measured concentration is distinguishable from method blank results (USEPA, 2016). MDL is a measure of the capability of an analytical method of distinguished samples that do not contain a specific analyte from a sample that contains a low concentration of the analyte (USEPA, 2020).

**Minimum level:** Either the sample concentration equivalent to the lowest calibration point in a method or a multiple of the method detection limit (MDL), whichever is higher. For the purposes of NPDES compliance monitoring, EPA considers the following terms to be synonymous: "quantitation limit," "reporting limit," and "minimum level" (40 CFR 136).

**Parameter:** A specified characteristic of a population or sample. Also, an analyte or grouping of analytes. Benzene and nitrate + nitrite are all parameters (Kammin, 2010; Ecology, 2004).

**Population:** The hypothetical set of all possible observations of the type being investigated (Ecology, 2004).

**Precision:** The extent of random variability among replicate measurements of the same property; a data quality indicator (USGS, 1998).

**Quality assurance (QA):** A set of activities designed to establish and document the reliability and usability of measurement data (Kammin, 2010).

**Quality Assurance Project Plan (QAPP):** A document that describes the objectives of a project, and the processes and activities necessary to develop data that will support those objectives (Kammin, 2010; Ecology, 2004).

**Quality control (QC):** The routine application of measurement and statistical procedures to assess the accuracy of measurement data (Ecology, 2004).

**Relative Percent Difference (RPD):** RPD is commonly used to evaluate precision. The following formula is used:

$$RPD = [Abs(a-b)/((a + b)/2)] * 100\%$$

where "Abs()" is absolute value and a and b are results for the two replicate samples. RPD can be used only with 2 values. Percent Relative Standard Deviation is (%RSD) is used if there are results for more than 2 replicate samples (Ecology, 2004).

**Relative Standard Deviation (RSD):** A statistic used to evaluate precision in environmental analysis. It is determined in the following manner:

$$RSD = (100\% * s)/x$$

where s is the sample standard deviation and x is the mean of results from more than two replicate samples (Kammin, 2010).

**Replicate samples:** Two or more samples taken from the environment at the same time and place, using the same protocols. Replicates are used to estimate the random variability of the material sampled (USGS, 1998).

**Reporting level:** Unless specified otherwise by a regulatory authority or in a discharge permit, results for analytes that meet the identification criteria (i.e., rules for determining qualitative presence/absence of an analyte) are reported down to the concentration of the minimum level established by the laboratory through calibration of the instrument. EPA considers the terms "reporting limit," "quantitation limit," and "minimum level" to be synonymous (40 CFR 136).

**Representativeness:** The degree to which a sample reflects the population from which it is taken; a data quality indicator (USGS, 1998).

**Sample (field):** A portion of a population (environmental entity) that is measured and assumed to represent the entire population (USGS, 1998).

**Sample (statistical):** A finite part or subset of a statistical population (USEPA, 1992).

**Sensitivity:** In general, denotes the rate at which the analytical response (e.g., absorbance, volume, meter reading) varies with the concentration of the parameter being determined. In a specialized sense, it has the same meaning as the detection limit (Ecology, 2004).

**Spiked blank:** A specified amount of reagent blank fortified with a known mass of the target analyte(s); usually used to assess the recovery efficiency of the method (USEPA, 2014).

**Spiked sample:** A sample prepared by adding a known mass of target analyte(s) to a specified amount of matrix sample for which an independent estimate of target analyte(s) concentration is available. Spiked samples can be used to determine the effect of the matrix on a method's recovery efficiency (USEPA, 2014).

**Split sample:** A discrete sample subdivided into portions, usually duplicates (Kammin, 2010).

**Standard Operating Procedure (SOP):** A document which describes in detail a reproducible and repeatable organized activity (Kammin, 2010).

**Surrogate:** For environmental chemistry, a surrogate is a substance with properties similar to those of the target analyte(s). Surrogates are unlikely to be native to environmental samples. They are added to environmental samples for quality control purposes, to track extraction efficiency and/or measure analyte recovery. Deuterated organic compounds are examples of surrogates commonly used in organic compound analysis (Kammin, 2010).

**Systematic planning:** A step-wise process which develops a clear description of the goals and objectives of a project, and produces decisions on the type, quantity, and quality of data that will be needed to meet those goals and objectives. The DQO process is a specialized type of systematic planning (USEPA, 2006).

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