

Stormwater Heatmap Technical Reference

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Abstract

The Stormwater Heatmap project springs forth from The Nature Conservancy's (TNC) Cities program, which strives to bring TNC's core mission — preserving and protecting the land and waters upon which all life depends — to urban areas. As the leading contributor of toxic pollutants to Puget Sound's streams, rivers, and marine waters, urban stormwater runoff is a key ecological problem generated by Washington's urban landscapes. Urban stormwater runoff has harmed virtually all urban and urbanizing streams and rivers, and delivered massive quantities of toxic contaminants to Puget Sound. As a result, the abundance and survival of aquatic species has declined. A recurrent question asked of stormwater managers, eco-toxicologists and ecologists alike, is how much stormwater intervention is needed, and where would you place it for efficient and effective treatment?

This “how much and where” question serves as the foundation of the stormwater heatmap project. The project quantitatively visualizes a pollution loading threat-map for the Puget Sound watershed. The stormwater heatmap uses land use, landcover, stormwater monitoring data, precipitation data, and hydrological modeling to predictively map stormwater pollution loading across the Puget Sound landscape, and quantifies the pollution load on a 1-m² spatial resolution. This scale allows managers and planners to aggregate data at multiple spatial scales, and allows us to “see” hotspots of pollution loading for a variety of monitored stormwater contaminants. With the pollution visualization layer in place, we can now begin to overlay social-ecological questions in order to develop a stormwater intervention action-map.

Chapter 1

Introduction

1.1 What is stormwater?

One of the primary terrestrial pressures on the Salish Sea estuarine and marine environment is urban stormwater runoff. When rainfall runs across hard, impervious surfaces, rather than soaking into the soil, it picks up and delivers toxic contaminants directly to nearby streams, rivers, and eventually the Salish Sea. In fact, for most toxic substances, surface runoff is the largest contributing source of loading to Puget Sound (Washington State Department of Ecology 2011).

Unfortunately, the Salish Sea's relationship with stormwater effluent is no outlier; stormwater is the fastest growing cause of surface water impairment in the United States as urbanization transitions forested and other natural landscapes to hard, impervious surfaces (United States Environmental Protection Agency 2019). Given that the Salish Sea is expected to house another 5 million people by 2040, stormwater interventions will be necessary in order to break the relationship between urbanization and stormwater-caused ecological degradation.

Fortunately, researchers have uncovered a variety of successful techniques to reduce stormwater impairment of surface and receiving waters, including street sweeping, pervious pavement, and green stormwater infrastructure wherein stormwater is filtered by soil and plant mixtures on its way between the streets and the sea. These interventions are costly (~\$65-132 billion is needed to restore Puget Sound to hydraulically function like a forest), but the costs of stormwater pollution are high as well: the sickening and deaths of Salish Sea organisms. Annual losses due to one contaminant (polycyclic aromatic hydrocarbon exposure) alone are estimated to be between \$4.4 to \$12.1 billion (County 2014; Washington State Department of Ecology and Washington Department of Health 2012).

1.2 Urban stormwater runoff is a two-fold problem, impacting the quantity of water pulsing off the land, as well as the quality of that water.

As a result of stormwater's twin problems, 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 Puget sound have been harmed by stormwater pollution xxx (???)

1.2.1 Water Quantity

Watersheds with as little as 5-10% impervious surface area- such as rooftops, roads, and paved parking areas- exhibit aquatic habitat degradation as a result 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 stream and riverbeds. Flashy hydrology disrupts habitat structure and alters the ecology freshwater ecosystems themselves, but also disrupts larger ecosystem processes in marine environments such as 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.

1.2.2 Water Quality

In addition to altering hydrological flow regimes in watersheds contributing 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 itself. Urban runoff contains complex and unpredictable mixtures of chemicals, including persistent organic pollutants (i.e. PCPs), heavy metals (i.e. copper, zinc), hydrocarbons (i.e. motor oil, tailpipe emissions, rubber tire particles), nutrients (nitrogen, phosphorous), pesticides, and pharmaceuticals . 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.

1.3 Toxic Stormwater Impacts

Researchers have documented 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, reducing species fitness and long-term survival. For example, heavy metal accumulation is common among marine macroalgae and eelgrass (*Zostera marina*), reducing 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 is the case 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, it appears that pre-spawn mortality is linked to the transportation network, where contaminants, like tire wear leachates, are generated (Feist et al. 2017). Thus, development expansion and increasing use intensity of the built environment is significantly impacting the long-term viability of local Coho populations, with far-reaching ramifications for both freshwater and marine food webs alike. And 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 important roles in upholding marine, freshwater, and terrestrial food webs (Anderson et al. 2007; Kayhanian et al. 2012; McIntyre et al. 2015).

1.4 Moving forward- identifying where stormwater pollution is generated on the landscape

A much repeated phrase from stormwater managers is “how much and where” do we need to implement stormwater BMPs (Best Management Practices)? This is a difficult question to answer until we identify our ecological and social goals for stormwater management. The amount and spatial configuration of stormwater interception techniques will look very different depending on whether the goal is to meet permit regulations, recover coho salmon, or recover Southern Resident Killer Whales because 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, n.d.) Answering the “how much and where” question will therefore require integrating ecological data with stormwater monitoring and pollution loading data.

However, a promising starting place to answer the “how much and where” question is to build a predictive map quantifying levels of stormwater pollution loading across the landscape. This type of ‘threat’ heatmap can be coupled with ecological data to produce action maps for stormwater intervention.

To build the predictive stormwater pollution heatmap, we focused on three major steps:

1. Landcover Refinement: we generated a high resolution landcover dataset enabling landcover mapping at the 1-m² resolution. This is a critical level of resolution for urban runoff modeling because impervious surfaces so strongly drive hydrologic response, and therefore pollution loading. Thus, accurate mapping of impervious surfaces was needed to accurately calculate surface runoff.

2. Hydrology: we conducted continuous hydrology simulations for the 32 different hydrologic response units (HRU = combination of landcover, soils, & slope) found within the Puget Sound domain. Using regional precipitation datasets provided by the Climate Impacts Group, we modeled both current and future hydrology in order to assess how climate change will impact stormwater pollution loading across the landscape, generating more than 311 billion rows of data. This dataset alone provides an efficient way to quickly model rainfall-runoff relationships across Puget Sound using the Western Washington Hydrology Model (WWHM).

3. Pollution Statistics: We used Bayesian statistical modeling to link stormwater monitoring data to land use and land cover characteristics to predict pollution concentrations across the landscape. These concentration predictions were then combined with hydrology output to generate the pollution load across the Puget Sound landscape at a 1-m² spatial resolution.

The resulting interactive tool enables users to visualize and aggregate stormwater pollution loading data at several spatial resolutions for local, watershed, and regional-scale planning. The project reveals that areas with high percent cover of impervious surfaces, such as hard cityscapes, as well as industrial and commercial zones, tend to produce higher pollutant loads than high-density residential, low-density residential, and rural areas. Transportation networks—roads and highways—generate very high levels of stormwater contaminants, especially those with higher traffic intensity. These high intensity roads can cut through lower-density areas, lighting up as pollution hotspots. Traffic behavior (i.e. congestion points) also plays a role, indicating that a combination of a static landscape structure and dynamic anthropogenic behavior layered atop that structure can combine to create stormwater pollution hotspots throughout the landscape.

Using the stormwater heatmap as a foundation, we can begin to integrate the ecological layers to understand exactly where on the landscape stormwater interventions will be most efficient and effective at breaking the link between urbanization and aquatic degradation. Examples of spatialized biotic response data generated by robust local monitoring programs include NOAA's Mussel-Watch, King County's Benthic-Index of Biotic Integrity (B-IBI), and NOAA's coho pre-spawn mortality monitoring. WDFW's Salmonscape data represents another source of ecological information, showing the timing and spatial habitat use of different species of salmonids. With respect to human Front and Centered's Environmental Health Disparities Map offers data-driven insights on human health in the region.

1.5 Building an interactive tool to service stormwater manager needs:

The mapping tool is especially timely because the Washington Department of Ecology recently issued a new stormwater permit which increased the number of jurisdictions required to develop and implement stormwater management plans. Historically, just 4 stormwater permittees were required to submit detailed stormwater management plans and models. Now, 85 jurisdictions must develop stormwater management plans and be able to scientifically defend their prioritization and decision-making process.

In order to help move more jurisdictions towards this goal/requirement, The Nature Conservancy embarked on a Design Thinking project to better understand what tools those smaller Phase II cities and counties would need in order to meet permit requirements. The Design Thinking approach centers on a structured interview process that is human-centered. Through interviewing stormwater planners, engineers, and leaders throughout the Puget Sound region, this process identified "pinch" and "release" points that currently prevent or promote effective stormwater management. The Design Thinking project emphasized that a tool supporting stormwater management in the region requires the following elements:

- **Compelling Visuals:** tools should help stormwater managers tell a story to different audiences
- **Multiple Scales:** stormwater planning takes place at the parcel, neighborhood, watershed and regional scale. Data need to be flexibly aggregated at all scales.
- **Make it Mine-able:** serve as a data platform and resource for use with other tools. Land cover, soils, hydrology, and climate change impacts data would help meet multiple modeling needs.

- **Grounded in Science:** data and calculations should be apparent and meet current best practices

For many of the smaller jurisdictions, financial and personnel constraints are significant barriers to effective stormwater management and innovation. Most projects are opportunistic, and many stormwater management departments have only one employee.

This stormwater management tool is targeted for stormwater managers in order to 1) get the best available science and tools into the hands of decision-makers, 2) lower the costs for effective decision making and planning, and 3) improve Puget Sound water quality and recover ecological health.

Thus, in addition to the stormwater pollution loading data layer, the online mapping tool also includes data extraction capabilities and report modules that service requirements outlined by the Department of Ecology's stormwater permit. The modules can be flexibly applied at multiple scales, and include:

- Land Use/Land Cover
 - Land cover classification (% cover)
 - Land use
 - Imperviousness
- Hydrology
 - Hydrologic response units
 - Mean annual runoff
 - Flow-control metrics
 - Climate change impacts
- Pollutant loading
 - 25th, 50th, 75th concentration quantiles
 - 25th, 50th, 75th annual loading quantiles
- Other
 - Age of development
 - Estimated population

1.6 Open data helps us bound forward

Early adopters are currently testing the capabilities of the data, analyses, and approaches generated by the Stormwater heatmap project. King County is using the hydrology modeling output to prioritize and resize culverts for fish passage. Our Green/Duwamish is using the tool for stormwater management action planning, the City of Tacoma is using it for watershed prioritization, EPA's Office of Research and Development are integrating this work with the VELMA runoff model, and the City of Phoenix and Maricopa County are using it for a regional LID study.

The stormwater heatmap is an open-source tool, free for use by the public¹. Code is accessible on Github here. xxx

The Stormwater heatmap can be used as a foundational layer to answer many social-ecological questions to benefit people and nature. It is built for you, with stormwater management in mind. Please use, modify, and distribute this work widely. See where you can take it!

¹[Mozilla Public License 2.0] (<https://www.mozilla.org/en-US/MPL/2.0/>)

Chapter 2

Land Cover

Chapter 3

Hydrology

3.1 Overview

This document provides an overview of hydrology simulation methods and results for the Puget Sound Stormwater heatmap. Continuous hydrology simulation of was performed using regional pre-calibrated parameters. Batched simulations were run for combinations of land cover, soils, and slopes across the Puget Sound domain. Results are stored in a cloud-based database. It is intended to be used in conjunction with data derived from the stormwaterheatmap or other geospatial data sources to quickly model rainfall-runoff relationships across Puget Sound.

3.2 Modeling approach

The hydrologic modeling approach was developed to replicate as much as feasible, commonly applied continuous simulation hydrologic analysis for stormwater in Puget Sound. Ecology developed guidance for continuous simulation modeling as described in the Stormwater Manual for Western Washington (Department of Ecology 2014).

This guidance calls for the application of 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. HSPF is generally used to perform analysis on hydrologic processes related to effects of land cover, interception, surface ponding and soil moisture retention. Although maintenance development of HSPF has not occurred since 1997, it is currently distributed by EPA under the Better Assessment Science Integrating Point and Non-point Sources (BASINS) analysis system. In Western Washington, 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 meteorologic data and modules specific to stormwater analysis.

HSPF contains a number of specialized modules that are not used by WWHM. These include modules related to snowmelt, sediment budgets, and specific water quality routines. The primary HSPF routines used by WWHM are designated as IWATER (water budget for impervious land cover) and PWATER (water budget for pervious land cover). A graphical schematic of the PWATER routine is shown in Figure 3.1.

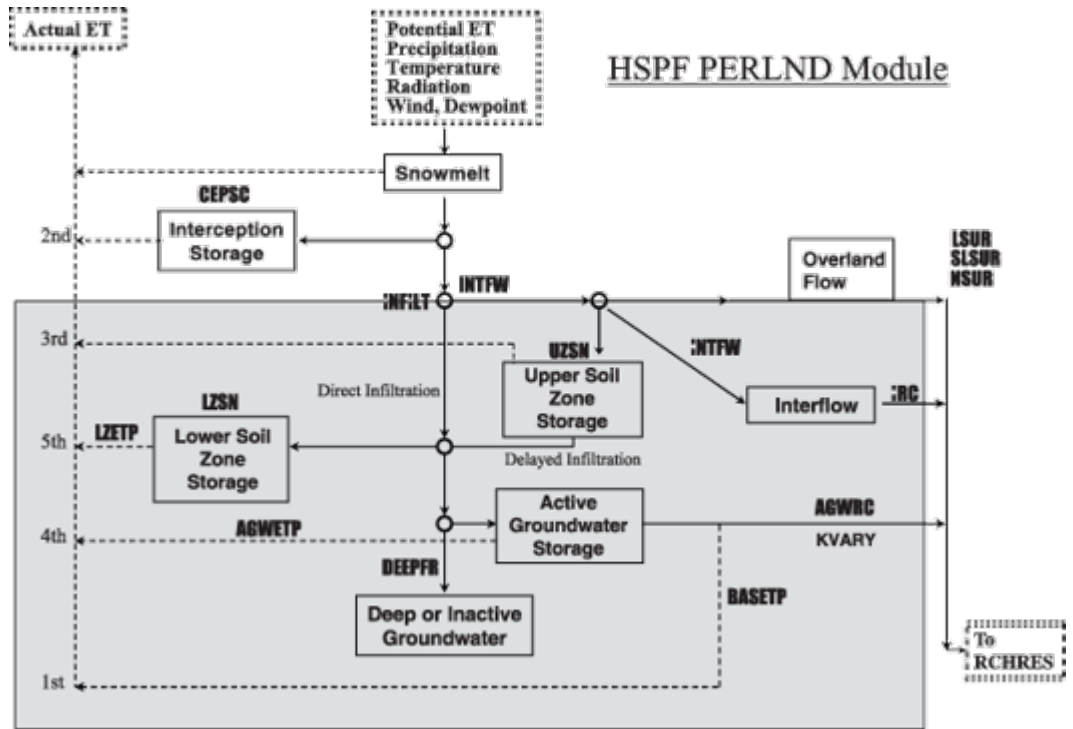


Figure 3.1: HSPF PERLND Conceptual Model

3.2.1 Hydrologic Response Units

Modeling was performed on discretized landscape units based on common soils, land cover, and slope characteristics known as hydrologic response units (HRUs). The HRU approach provides a computationally efficient method of pre-computing hydrologic response for later use. Results for a particular watershed can be calculated by summing or averaging the results for individual HRUs.

Each combination of parameters were modeled in separate batched simulations. HRUs were designated by a three-digit number according to the following convention:

- First digit: Hydrologic Soil Group Number (0 = A/B, 1 = C, 2 = Saturated)
- Second digit: Land cover (0=Forest, 1=Pasture, 2=Lawn, 5=Impervious),
- Third Digit: Slope (0=Flat, 1=Mod, 2=Steep)

For example, a site with Type C soils, with forested land cover, on a moderate slope would be represented by 101. This schema allowed for HRUs to be stored as an eight-bit unsigned integer on a Puget-Sound wide raster, minimizing storage size.

3.2.2 Regional Calibrated Parameters

Regional calibration factors for the Puget Lowlands Ecoregion were developed the USGS in the 1990s (Dinicola 1990) and updated by Clear Creek Solutions for use within WWHM (Department of Ecology 2014). These parameters, referred to as the ‘default parameters’ by Ecology were used in this study and applied to individual HRUs.

Table 1: Regional Calibrated Parameters

| Sub | Land Cover | Slope | LSN | INFLD | LSUR | NSUR | KNUR | AGWRC | INFEXP | INFELD | BASEP | AGWEP | CEPSC | LSN | NSUR | INTW | IRC | LEPZP | INAT | REINC |
|-----|------------|---------|-------|-------|------|------|------|-------|--------|--------|-------|-------|-------|------|------|------|-----|-------|------|-------|
| 1 | AB | Forest | Flat | 5 | 2 | 400 | 0.05 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.2 | 0.5 | 0.55 | 0 | 0.7 | 0.7 | |
| 2 | AB | Forest | Mod | 5 | 2 | 400 | 0.1 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.2 | 0.5 | 0.55 | 0 | 0.7 | 0.7 | |
| 3 | AB | Forest | Steep | 5 | 2 | 400 | 0.15 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.2 | 0.5 | 0.55 | 0 | 0.7 | 0.7 | |
| 4 | AB | Pasture | Flat | 5 | 1.5 | 400 | 0.05 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.15 | 0.5 | 0.5 | 0 | 0.7 | 0.6 | |
| 5 | AB | Pasture | Mod | 5 | 1.5 | 400 | 0.1 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.15 | 0.5 | 0.5 | 0 | 0.7 | 0.6 | |
| 6 | AB | Pasture | Steep | 5 | 1.5 | 400 | 0.15 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.15 | 0.5 | 0.5 | 0 | 0.7 | 0.6 | |
| 7 | AB | Lawn | Flat | 5 | 0.5 | 400 | 0.05 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.1 | 0.5 | 0.25 | 0 | 0.7 | 0.25 | |
| 8 | AB | Lawn | Mod | 5 | 0.5 | 400 | 0.1 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.1 | 0.5 | 0.25 | 0 | 0.7 | 0.25 | |
| 9 | AB | Lawn | Steep | 5 | 0.5 | 400 | 0.15 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.1 | 0.5 | 0.25 | 0 | 0.7 | 0.25 | |
| 10 | C | Forest | Flat | 4.5 | 0.05 | 400 | 0.05 | 0.5 | 0.996 | 2 | 2 | 0 | 0 | 0.2 | 0.5 | 0.55 | 0 | 0.5 | 0.7 | |

Showing 1 to 10 of 10 entries

3.2.3 Python Implementation

To allow for parallel computations, we used a Python adaption of HSPF developed by David Lambert with funding from the United States Department of Energy, Energy Efficiency & Renewable Energy, Bioenergy Technologies Office (Lampert 2019). PyHSPF is able to generate HSPF input files, run simulations, and provide HSPF compatible output. Similar to WWHM, we provided separate output files for three flow-paths. Surface flow, interflow, and groundwater flow. In HSPF, these output classes are referred to as SUR0, INF0, and AGW0 respectively. We developed and ran individual HSPY models for each combination of HRU and Precipitation grid and generated output for each flow patch component. This resulted in 27,990 individual output files.

3.3 Data Sources

3.3.1 Precipitation

A region-wide, simulated precipitation dataset was provided by the University of Washington Climate Impacts Group. Methodology used to develop this dataset is documented in (Mauger et al. 2018). The dataset contains modeled hourly precipitation using the GFDL CM3 global climate model and the Representative Concentration Pathways (RCP) 8.5 scenario.

GCM selection based on stormwater applications. Emphasized winter storm drivers. Downscaled from GFDL CM3. RCP 8.5 (High emissions) “High-High” Hourly precipitation developed through application of regional weather model, the Weather Research and Forecasting (WRF, Skamarock et al. 2005).

The GFDL model was chosen by CIG due to its ability to accurately model winter storm drivers, important for stormwater applications. Combined with the higher emissions scenario, this modeling scenario represents the upper end of expected future climate changes effects.

CIG downscaled GCM results using a statistical-dynamical approach to capture the anticipated changes in extreme events as well as the different drivers of rainfall that affect the Puget Sound Region. Regional simulations were performed using the Weather Research and Forecasting community mesoscale model. This resulted in hourly rainfall predictions at an approximately 12 km grid size across Puget Sound. Predictions were bias-corrected on a quantile-mapping basis (individual mean bias corrections for precipitation in each quantile range) using the historic (1970-2005) WRF data. The WRF Grid in our study area is shown in Figure 3.2.

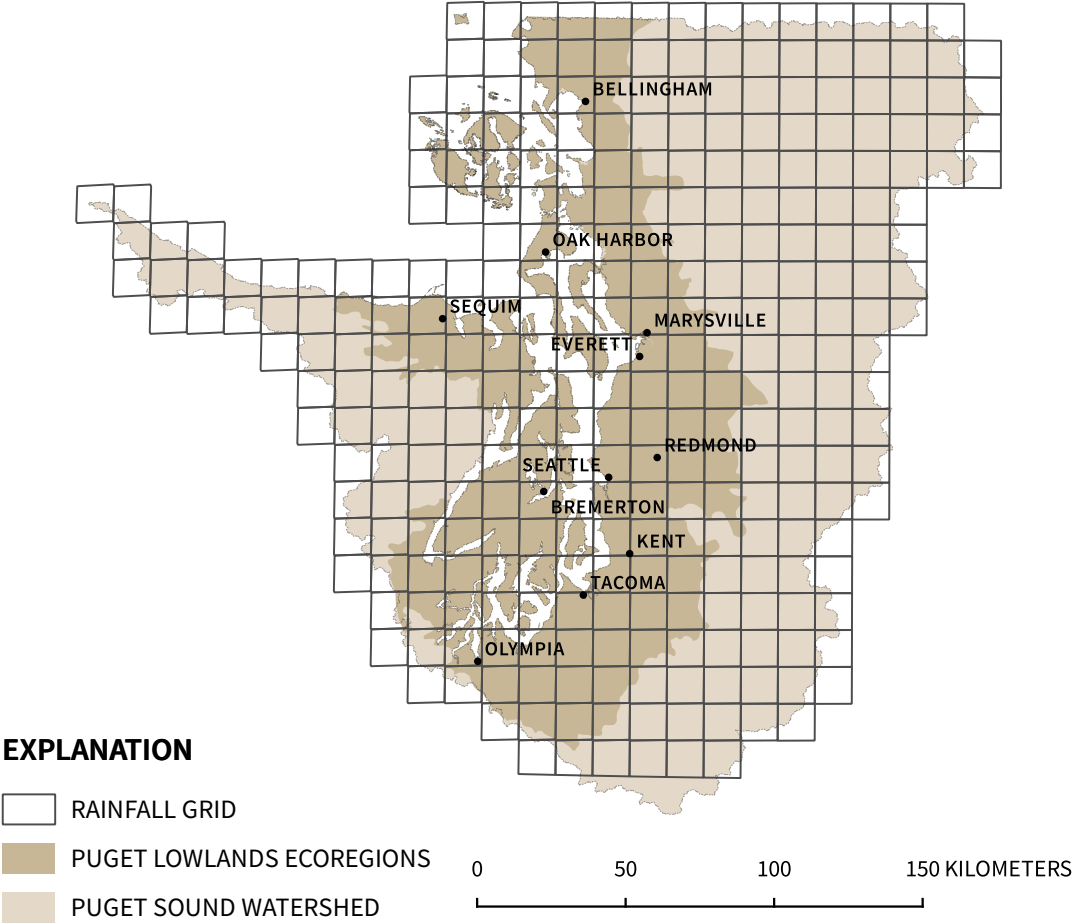


Figure 3.2: WRF Forecasting Grid

3.3.2 Potential Evaporation

Gridded potential evaporation estimates were acquired from the forcing data for the North American Land Data Assimilation System (NLDAS2) (NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) 2019). This dataset combines multiple sources of observations to produce estimates of surface climate variables. Evaporation data was derived from the NCEP North American Regional Reanalysis, consisting of a retrospective dataset beginning

January 1979 through December 2005. Data were acquired in in 1/8th-degree grid spacing; at an hourly temporal resolution. Average monthly potential evaporation rates were calculated and resampled for each grid cell in the heatmap model domain.

3.3.2.1 Land Cover

Land cover was derived from the Nature Conservancy’s high-resolution land cover data set. See Section xx for more informaiton.

3.3.2.2 Soils

3.3.2.2.1 Gridded SSURGO Data The primary source of soils data was the Gridded Soil Survey Geographic Database (gSSURGO), (Soil Survey Staff 2018). The gridded soils database contains 10-meter rasterized coverage of surface soils derived from National Cooperate Soil Survey (NCSS) maps. These maps are generally drawn at 1:24000 scale. NCSS designates soils by a “map-unit name,” which can be joined with other attribute data. Map units in the study area were joined with the soils component table, containing hydrologic-soil group designations. NCSS classifies hydrologic soil groups according to estimates of runoff potential. Soils are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D) as defined below:

- **Group A.** Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.
- **Group B.** Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.
- **Group C.** Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.
- **Group D.** Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that in their natural condition are in group D are assigned to dual classes. In certain locations, data were augmented with the SSURGO Value added tables (Soil Survey Staff 2016) using the Potential wetland soil landscapes field.

3.3.2.2.2 Oak Ridge National Laboratory HYSOGs250m In areas where gSSURGO data were not available, we used the Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling developed by Oak Ridge National Laboratory [RossC.W.L.PrihodkoJ.Y.AnchangS.S.KumarW.Ji2018]. This dataset contains world-wide hydrologic soils groups derived at a 250 meter resolution from machine learning predictions. Hydrologic soil groups were given the same designation as the SSURGO data above.

3.3.2.2.3 GAP/LANDFIRE DATA To account for wetlands and saturated soils not included in the above datasets, we used the USGS GAP/LANDFIRE National Terrestrial Ecosystems data set, which includes nationwide vegetation and land cover data.

3.3.2.3 Slope

Slope values were calculated from the USGS National Elevation Dataset. Elevations were provided in 1/3 arc-second resolution (approximately 10-meters). Slope was calculated and classified into the following categories, consistent with Ecology guidance:

- Flat: < 5%
- Moderate: 5-15%
- Steep: > 15%

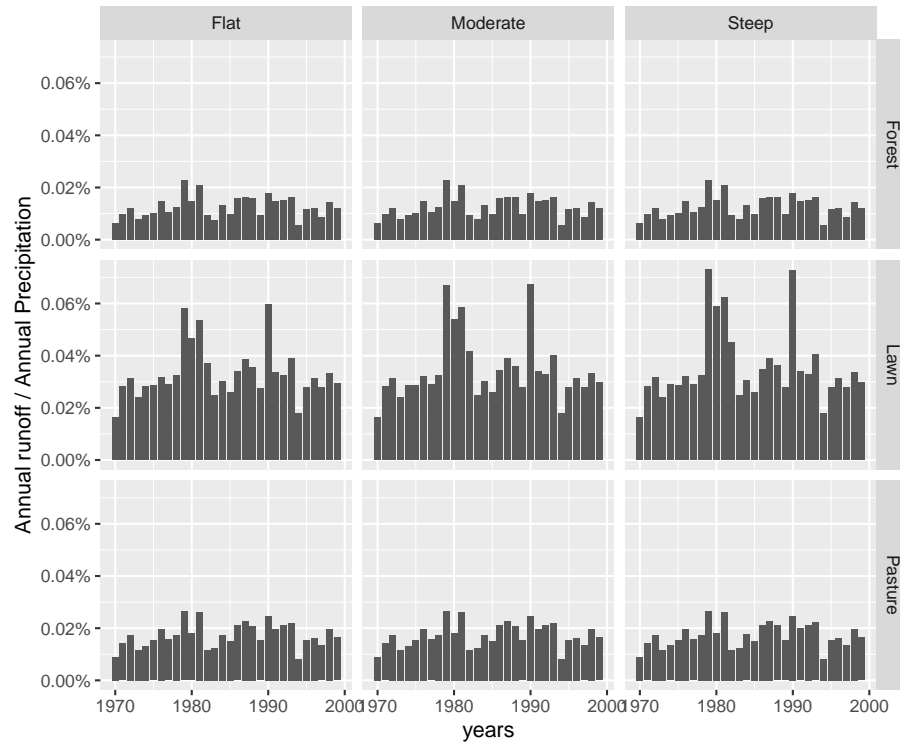
3.4 Verification of Results

Verification of modeling results was performed by evaluating the annual runoff amounts over the historic period of record as a percentage of annual precipitation. Figures ?? through ?? annual runoff results for the Seattle-Tacoma International Airport.

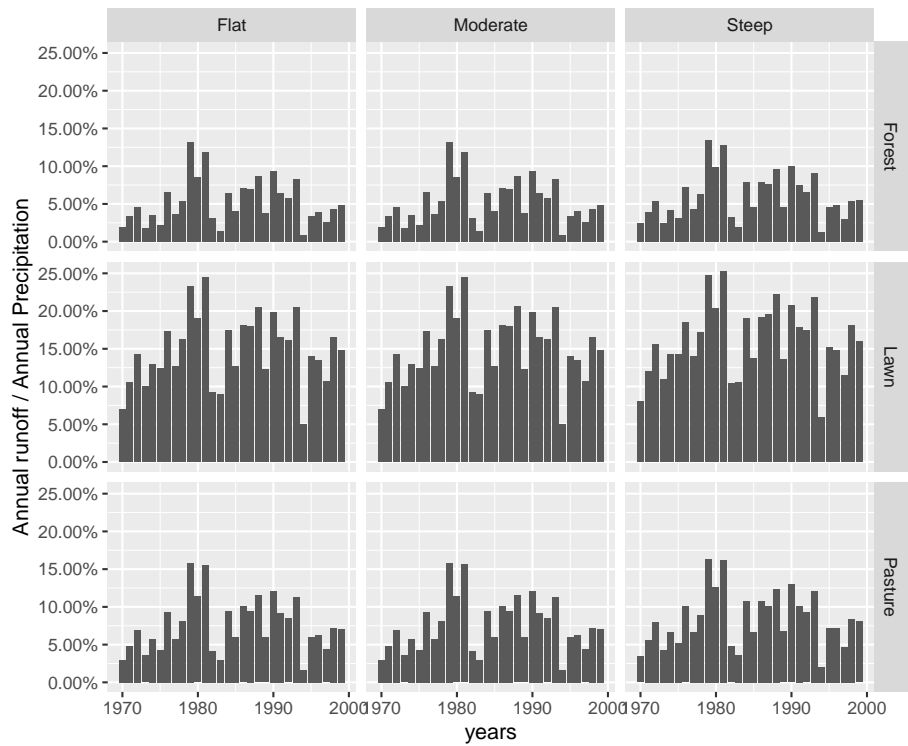
Outwash Soils

HSPY model results – Seatac Airport, WA

Runoff as a percentage of rainfall

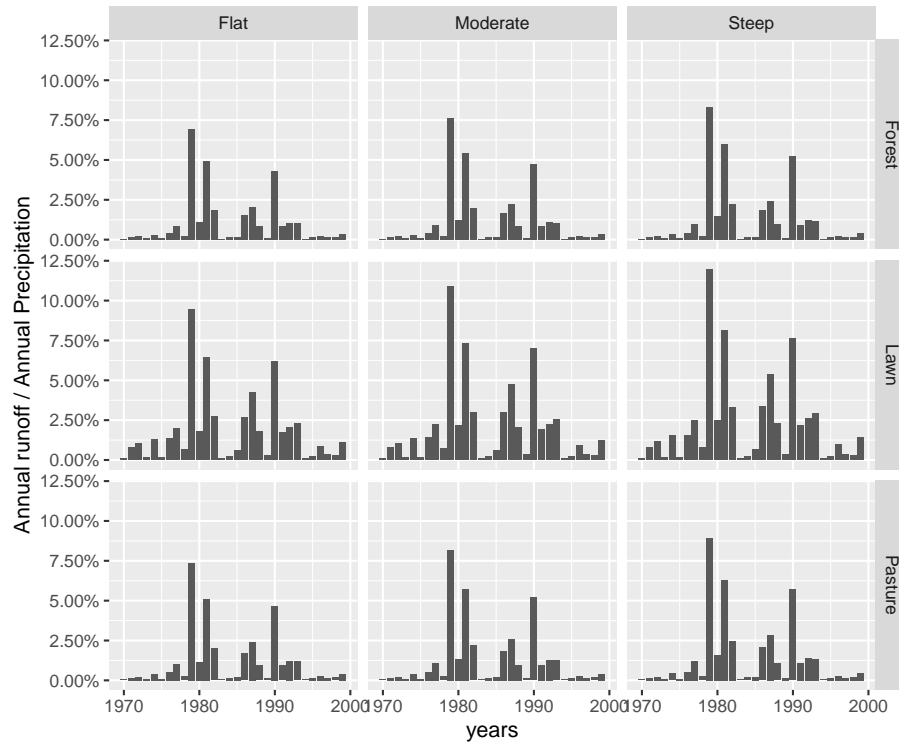


Till Soils
HSPY model results – Seatac Airport , WA
Runoff as a percentage of rainfall



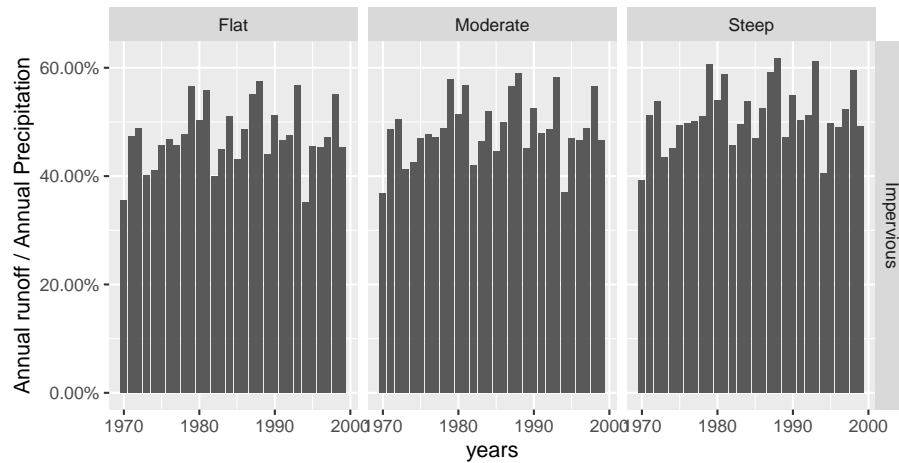
Saturated Soils

HSPY model results – Seatac Airport , WA
Runoff as a percentage of rainfall



Impervious

HSPY model results – Seatac Airport , WA
Runoff as a percentage of rainfall



3.5 Spatially Aggregated Results

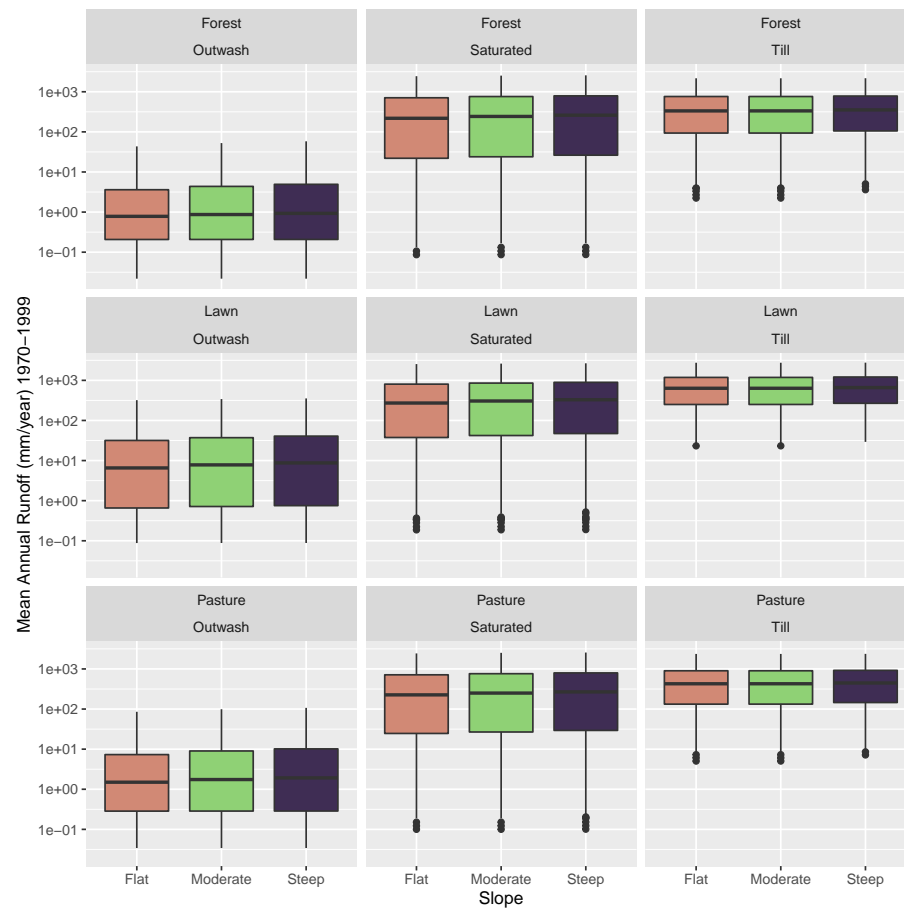
Since the HSPY model is a lumped parameter model, results can be calculated for HRU/precipitation grids individually and then aggregated after calculation.

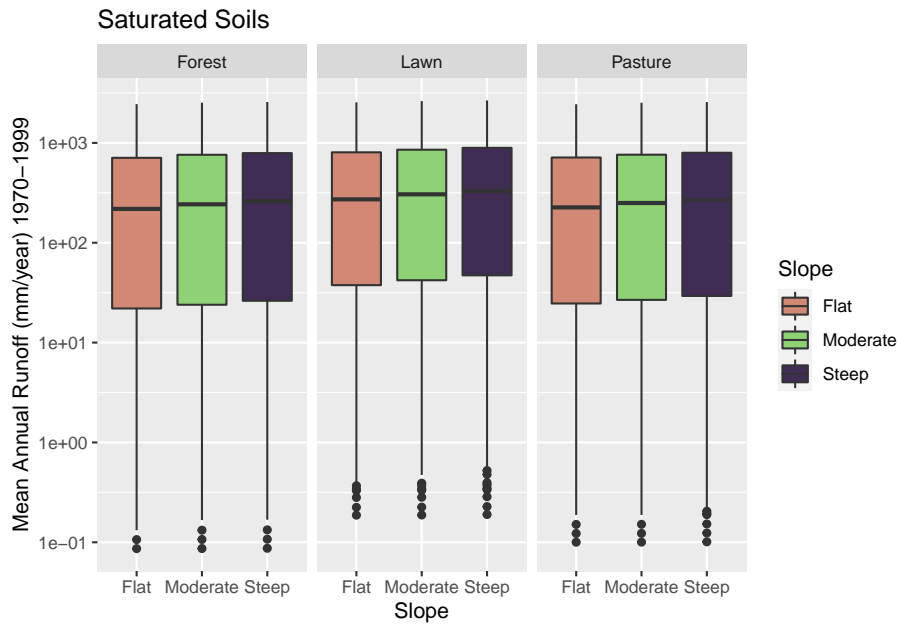
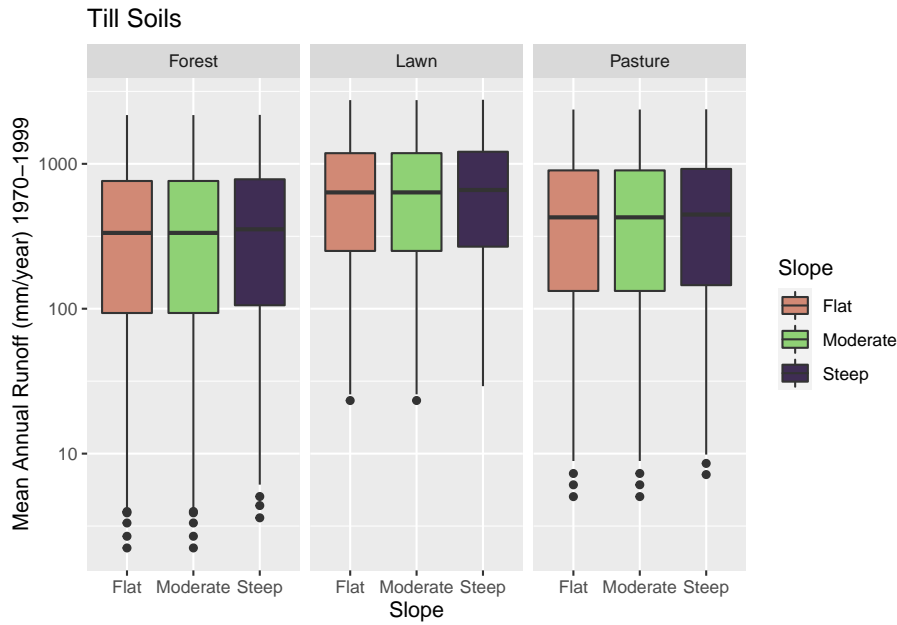
The stormwater heatmap contains two spatial aggregates of hydrology results: Mean Annual Runoff for the historic period (1970-1999) and a new index, termed the Flow Duration Index.

3.5.1 Mean Annual Runoff (1970-1999)

Mean annual runoff for each HRU/grid combination was aggregated from Big-Query for the historic period of record (1970-1999). Consistent with Ecology guidance for stormwater projects, only the surface flow components, **SURO** and **IFWO** were used. **AGWO**, deep groundwater flow, was not included in this calculation.

Total runoff was calculated for each year/hru/grid combination in the period of record, then averaged by hru/grid combination.





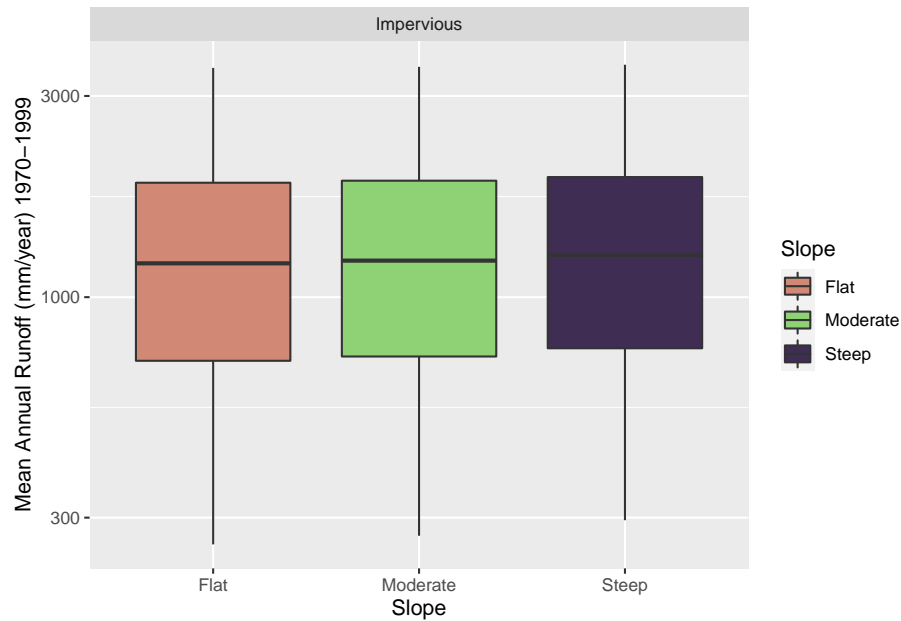


Figure 3.3: fig

3.5.2 Flow Duration Index

3.5.2.1 Ecology Performance Standards

Ecology Stormwater Guidance includes flow-related performance standards to protect receiving waters from degradation caused by changes in the hydrologic regime due to development. These performance standards rely on flow-duration matching, whereby flow durations from developed land are required to match pre-developed flow-durations for a range of discharge values. The flow duration standard is intended to prevent flashy flows in receiving stream channels.

3.5.2.2 Calculation of the Index

We developed an index representing the magnitude of change to the flow-duration curve between flow thresholds. Thresholds were chosen based on Ecology's LID and Flow Control Standards (Department of Ecology 2014), which require flow-duration matching over the range between 8 percent of the 2-year peak discharge (lower threshold of the LID standard) up to the 50-year peak discharge (upper threshold of the flow-control standard).

The flow discharge index is calculated by summing the discharge over the simulation period between a high-flow and low-flow threshold. Figure 3.4 illustrates the summation of flow-duration values used in calculating this index.

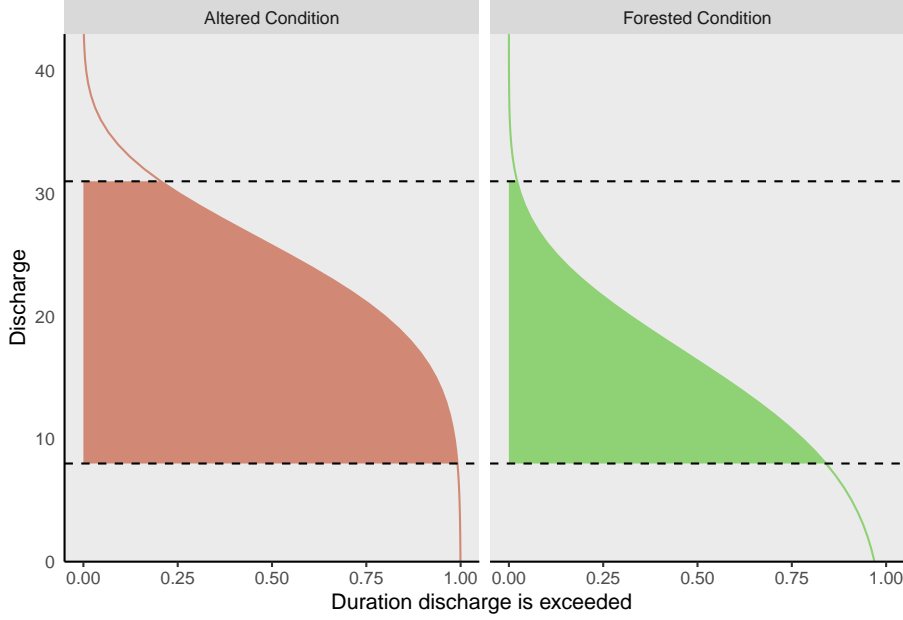


Figure 3.4: Example flow duration curves of altered and forested land covers

The flow duration index can be described by Equation (3.1).

$$\ln \left(\frac{\sum Q \Delta t}{\sum Q_{forest} \Delta t} \right) \quad (3.1)$$

3.6 Tabulated Results via BigQuery

Tabulated hydrology results are available via Google BigQuery, a cloud-based relational database that includes a distributed SQL engine. The data are located on the `tnc-data-v1` data bucket (sign-in require). The table is named `tnc-data-v1:hydrology.gfdl`. BigQuery supports several client libraries. See <https://cloud.google.com/bigquery/docs/reference/libraries> for a list of supported clients libraries.

Using R, the `tnc-data-v1` databucket can be accessed through a database connection using the DBI package:

Table 3.1: BigQuery Table Schema for ‘tnc-data-v1:hydrology.gfdl.’

| Fieldname | Type | Description |
|-------------------|-----------|--|
| grid | STRING | WRF Grid ID Number |
| year | INTEGER | Year of Simulation |
| month | INTEGER | Month of Simulation |
| comp | STRING | HSPF Runoff component (AGWO, IFWO, SURO) |
| hru000 ... hru252 | STRING | Runoff (mm) (one column for each HRU) |
| Datetime | TIMESTAMP | Simulation Hour (UTC) |
| simulation_day | INTEGER | Day of simulation (01-Jan-1970 = Day 1) |
| simulation_day | INTEGER | Day of simulation (01-Jan-1970 = Day 1) |

3.6.1 Schema

The table schema are shown in Table 3.1.

3.6.2 Querying Tabulated Results

The data may be queried through Google Cloud Platform directly, or through a number of available software libraries. Queries are performed through standard SQL language. Some example queries are provided below.

Get all surface flow components from the SeaTac precipitation grid (ID16_V7) for the years 1970-1999:

Get the annual peak flow for surface flow components from the SeaTac precipitation grid (ID16_V7) for the years 1970-1999:

3.6.3 Querying Geometry

Google BigQuery supports PostGIS geometry functions (see https://cloud.google.com/bigquery/docs/reference/standard-sql/geography_functions for instructions).

Grid geometries are available from the `tnc-data-v1.gfdl.geometry` table on Big Query. The table schema is as follows:

| Fieldname | Type | Description |
|-----------|-----------|--|
| grid | STRING | WRF Grid ID Number |
| xy | GEOGRAPHY | Centroid of the grid (PostGIS point)) |
| geohash | String | PostGIS geohash string approximating grid boundary |
| geometry | STRING | Well known text format of the grid boundary |

An example query to return the Grid ID covering the Seattle Center:

Returns the grid ID pertaining to this location:

```
Row  grid
-----
1   ID16_V9
```


Chapter 4

Water Quality Statistics

Chapter 5

References

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