Soos Creek Watershed Modeling & Analysis to Address Bioassessment Impairments

For the Soos Creek Fine Sediment Total Maximum Daily Load Study

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Cover Photo: Big Soos Creek near USGS gage, looking downstream.

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by

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Abstract

The Soos Creek watershed includes Big Soos, Soosette, Little Soos, Jenkins, and Covington Creeks. The watershed covers an area of about 66 square miles in the Puget Lowlands of King County. It has been the focus of several monitoring and modeling studies. Monitoring data show these creeks are impaired for bioassessment/aquatic health based on Benthic Index of Biotic Integrity (B-IBI) scores. Excess fine sediment is one of three identified stressors, in addition to flow alteration and physical habitat degradation, contributing to these impairments. This report presents the technical analysis conducted to address these impairments and to inform a fine sediment Total Maximum Daily Load (TMDL) study.

Washington State Department of Ecology (Ecology) extended and recalibrated an existing HSPF (Hydrologic Simulation Program — Fortran) model of the watershed to simulate flow and sediment for 2001 – 2015. The recalibration process resulted in adequate model performance watershed-wide based on comparisons between simulated and observed flow and sediment.

The calibrated model was used to compare flow and sediment loads between existing/baseline and forested conditions and to calculate the sediment loading capacity (the amount of sediment the creeks can receive and still meet water quality standards). This loading capacity varies with flow since flow is one of the main drivers of sediment pollutant loads.

Statistical analysis between B-IBI scores and other available data demonstrated that while B-IBI scores are highly variable, they are responsive to flashy flows, fine sediment, the extent of impervious and forest cover in the watershed, and other local factors. We recommend the TMDL study take a holistic approach to addressing B-IBI impairments, including establishing load and wasteload allocations to reduce stormwater and its impacts and meet the targeted loading capacity. The TMDL implementation plan will also recommend actions to restore and conserve instream physical habitat.

Introduction

Background

The Soos Creek watershed (hereby referred to as “Soos”) is in King County, Washington. It has several water quality impairments where streams within the watershed have not been meeting state water quality standards for a variety of parameters. The Clean Water Act (CWA) requires the Washington State Department of Ecology (Ecology) to conduct a Total Maximum Daily Load (TMDL) study and develop a Water Quality Improvement and Implementation Plan for all impaired waters that detail the actions needed to reduce those pollutant sources and restore the streams in the watershed to meet water quality standards.

Water Quality impairment listings in the Soos were identified through Ecology’s Water Quality Assessment (WQA) process, which identifies water bodies throughout the state that are not meeting standards for specific parameters, resulting in several segments of the creeks in the watershed being placed on the Category 5 303(d) list. The Soos has 303(d) listings for fine sediment, temperature, dissolved oxygen, and bacteria. The fine sediment listings were originally bioassessment listings that were converted to fine sediment listings after a stressor identification analysis (stressor ID) conducted by Marshalonis and Larson (2018) identified excess fine sediment as one of three stressors — and the only pollutant — impairing the aquatic health of benthic organisms in the streams (see “Fine Sediment Listings” subsection for more details). Other stressors to the biotic community included flashy flows and physical habitat degradation.

This report focuses on the modeling and technical analysis conducted to address the bioassessment impairments and fine sediment listings in the watershed, as initially described in the Quality Assurance Project Plan (QAPP) Addendum (Mohamedali 2018). As outlined in the QAPP, the main goals for this project were to:

1. Develop and use a calibrated sediment HSPF model of the Soos Creek watershed to understand, identify, and quantify the various sources and processes that influence sediment transport and delivery, as well as flow alteration in the watershed.
2. Use a combination of modeling and statistical tools to determine the sediment reduction targets and/or flow alteration targets needed to alleviate the effect of these stressors on the biological community and address bioassessment impairments in the creeks.
3. Use statistical and modeling analysis results to set TMDL load and wasteload allocations, make TMDL recommendations, and determine the implementation actions needed to meet these targets.

All the data used in this study meet credible data policy requirements: these data are collected under established Quality Assurance/Quality Control (QA/QC) programs, using accredited methods equipment, and following Standard Operation Procedures (SOPs), and were collected under a QAPP or Sampling Analysis Plan (SAP) — as outlined in Table 12 of the QAPP (Mohamedali 2018).

Additionally, all the objectives listed in the QAPP (Mohamedali 2018) have been fulfilled via this study, except for calculating the pollutant load reductions needed to meet the loading capacity. This study establishes the loading capacity and the reductions needed for each source and will be a part of the final TMDL report.

Study Area

The Soos is in south King County, in the Puget Sound lowlands, in western Washington State, inside Water Resource Inventory Area 9 (WRIA 9). The Soos Creek watershed drainage is about 66 square miles and includes four main tributaries: Soosette, Little Soos, Jenkins, and Covington creeks. The tributaries drain into the mainstem Big Soos Creek, which then drains into the Middle Green River near Auburn at River Mile (RM) 33.7. The watershed includes the City of Covington and parts of the cities of Auburn, Black Diamond, Kent, Maple Valley, Renton, and unincorporated King County (Figure 1).

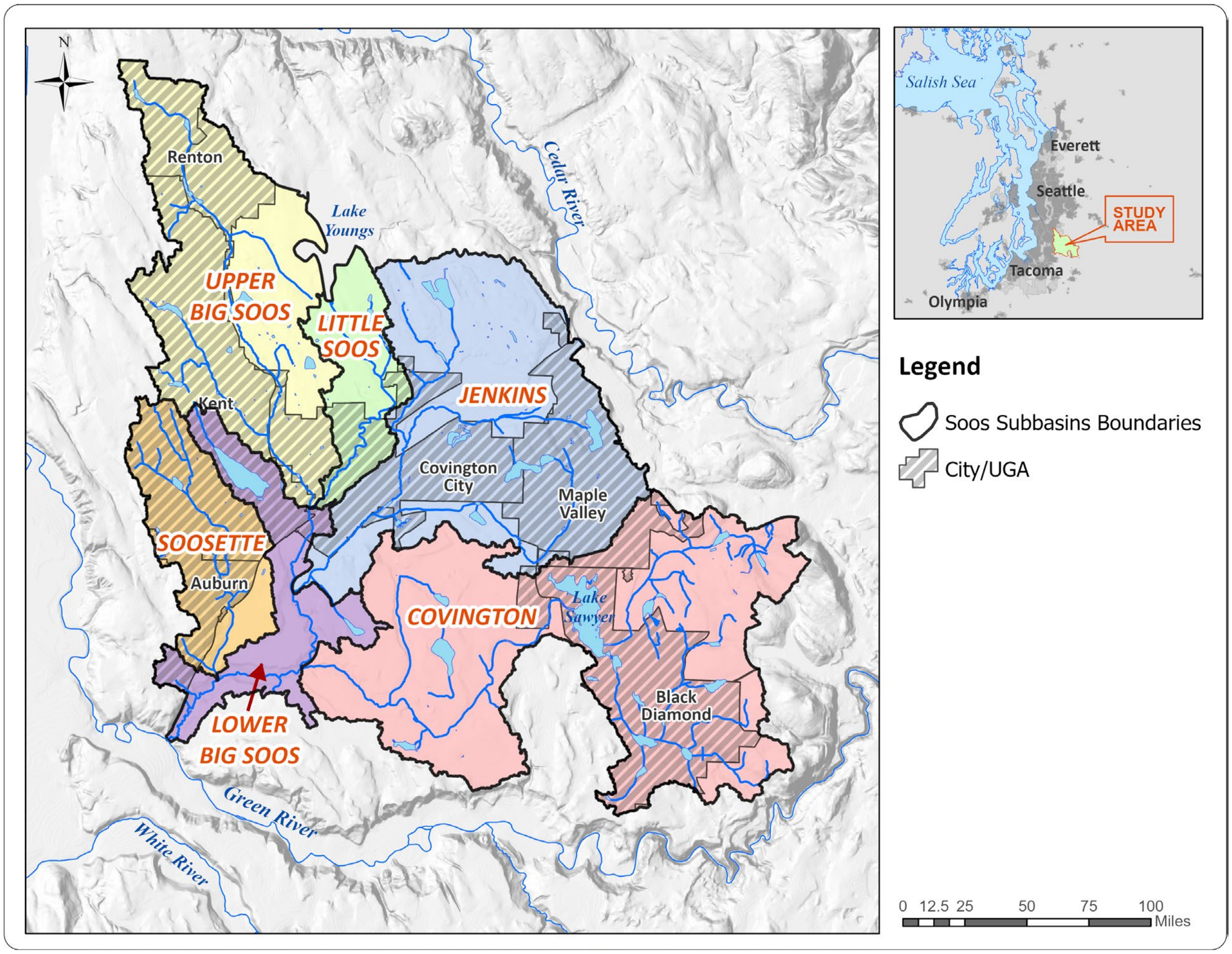

Figure 1. Map of the Soos Creek Watershed showing major subbasins and city urban growth areas (UGAs) that fall within the watershed.

Upper Big Soos is defined as the area just upstream of where Little Soos joins the mainstem of Big Soos Creek.

Climate and Hydrology

The relatively moderate climate of the study area is typical of other Puget Sound lowland watersheds, characterized by warm, dry summers and cool, wet winters. Spring and winter precipitation feeds large runoff and discharge events, while reduced summer flows are primarily maintained by baseflows from groundwater. The annual hydrograph is also typical of rain-dominated western Washington streams, which reflect high precipitation in the form of rain during the winter and relatively low precipitation during the summer months (Figure 2).

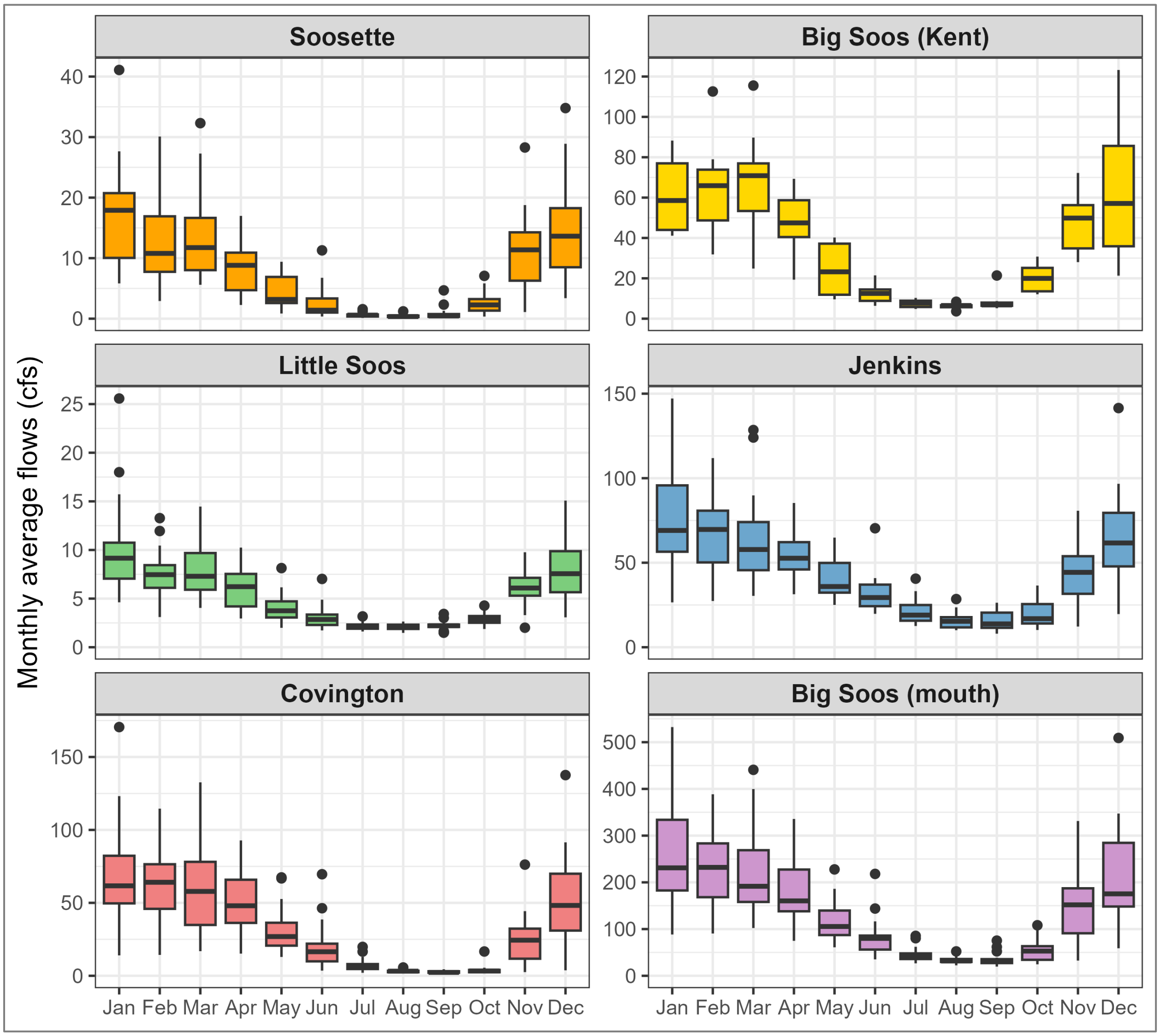

Figure 2. Range in average monthly streamflows between 1998 and 2018 at six gages in the different subbasins of the Soos Creek watershed (the y-axis scale varies for each plot).

Geology and Soils

The headwaters of the Soos originate in a rolling, low-gradient glacial outwash plain with extensive wetlands and an elevated water table. The watershed is hydrologically complex and has an extensive system of interconnected lakes, wetlands, and infiltrating soils (King County 2000). Glacial geology consists of a mix of low permeability Pleistocene continental glacial till with veins of high permeability glacial outwash that mirror surface water features. The *Soos Creek Basin Plan* (King County 1990) further describes the geology of the Soos as follows:

- Glacial geology consists of a Vashon till that forms a nearly continuous low-permeability layer over the entire region.
- Granular deposits of Vashon-age advance outwash or older Auburn gravel directly underlie much of the till in the west and central parts of the basin.
- Soos clay forms a thick, low-permeability barrier to groundwater in the southwest part of the basin.
- Vashon-age recessional outwash is common in the Jenkins and Covington drainages and acts as a thick, unconfined aquifer with direct hydraulic connections to the surface streams and lakes.

The predominant soil categories include outwash, till, and saturated (wetland) soils. These soils respond differently to rainfall events, as is described in the excerpt below from the *Soos Creek Basin Plan* (King County 1990):

> "Outwash soils consist of sand and gravel deposits that have high infiltration rates. Rainfall in these areas is quickly absorbed and percolates to the groundwater table. Creeks draining these areas typically intercept the groundwater table and receive most of their flow from groundwater discharge. The response in the creeks after a storm is therefore slow, with the peak flow in the creek often occurring up to several days after a storm.
>
> Till soils are consolidated, contain large percentages of silt or clay, and have low percolation rates compared to the outwash soils. Only a small fraction of the infiltrated precipitation reaches the groundwater; the rest moves laterally through the thin surface soil, often re-emerging at the base of hillslopes. This shallow, subsurface, lateral movement of flow is called interflow. Interflow travels to the creek much faster than groundwater but slower than surface runoff. Till soils may become saturated in moderate to large storms and produce significant amounts of surface runoff. The peak runoff rate from till areas is therefore typically much higher than from outwash areas.
>
> Wetland soils remain saturated throughout much of the year. Although the runoff from wetland areas is typically constant in the summer, during the wet season they produce significant amounts of surface runoff."

The topography is relatively flat in the upper portions of the watershed and then cuts down to a moderate gradient in the lower five miles of Big Soos as it makes its way into the Green River valley.

Climate Change

In the Puget Sound region, which includes the Soos, the effects of climate change are already being seen and will continue to change our local environment in myriad ways. The report *State of Knowledge: Climate Change in Puget Sound* (Mauger et al. 2015) summarizes the state of the science on climate change and its effects within the Puget Sound region.

Below is a summary of some of the projected changes due to climate change in the Puget Sound region relative to 1970 – 1999, which are relevant to our study in the Soos:

- **Air temperature:** by the 2050s, projected average annual air temperatures are estimated to increase by 4.2°F to 5.5°F for a low and high greenhouse gas emissions scenario, exceeding the range observed in the 20th century.
- **Precipitation:** while projected annual precipitation changes are minimal, effects vary by season. Summer precipitation is projected to decrease, and most models project an increase of 2% – 11% in precipitation in fall, winter, and spring by the 2050s. Changes in extreme precipitation are more significant, with heavy rainfall events expected to intensify by 22% (range of +5% to +34%) in Oregon and Washington by the 2080s for a high greenhouse gas scenario. The frequency of heavy rainfall events is also projected to increase within the design lifetime of most of our stormwater infrastructure.
- **Streamflow**: peak river flows will generally increase due to increases in heavy rainfall events. In mixed rain-snow dominated watersheds like the Green-Duwamish watershed (of which the Soos is a part), the spring peak in streamflow is projected to occur earlier by two to six weeks, on average, by the 2080s for a moderate greenhouse gas scenario. Summer streamflows are projected to decrease by 24% – 31%, and winter streamflows are projected to increase by 28% – 34%, on average, by the 2080s.
- **Sediment transport:** quantitative projections of changes in sediment transport are limited, but increased rainfall and streamflows could result in an increase in erosion and sediment transport in fall, winter, and spring.
- **Biological effects:** the timing of biological events can be altered by warming, as well as species distribution and their geographic range. In a species distribution model that included freshwater taxa data for the conterminous U.S.A., climate change emerged as the strongest predictor of species distribution, including the widespread expansion of warm water taxa (Pound et al. 2020)

The above summary of climate change effects will undoubtedly impact the Soos watershed. Regarding the implications for this TMDL, heavier precipitation and streamflows in the fall, winter, and spring are expected to increase sediment loading during these seasons. Drier summers will impact instream habitat, especially if some of the creeks in the watershed go dry more frequently.

Land Use and Land Cover

The Soos watershed is unique because there is more development in the upper watershed near the headwaters of tributaries and less development in the lower watershed. The watershed was historically comprised of forested lowlands surrounding a dense network of interconnected streams, lakes, and wetlands. After extensive logging in the 19th century, the watershed transitioned to rural/agricultural land use. The late 20th century marked a transition to residential land use, with very little forestry or commercial agricultural practices in the present day. Over the years, the watershed has experienced significant changes in land use. Portions of the Soos Creek watershed experienced some of the most rapid suburban residential development in King County between 1917 and 1970 (King County 2000). The basin now consists of rural and urban residential, agriculture, and highly urban commercial areas. The northern and western portions of the Soosette and Big Soos subbasins have the highest density of urban subdivisions, commercial retail centers, and scattered single-family residences. The western parts of the watershed, which include the cities of east Renton, Kent, Auburn, and central Covington, have been subject to heavy urbanization in recent years. There is also development pressure in the eastern part of the watershed.

Based on the 2019 National Land Cover Database (NLCD), almost 60% of the watershed was considered developed, 20% of which is classified as developed open space. Forests, including evergreen, deciduous, and mixed, represent 27% of the watershed (Figure 3 and Table 1). Table 1 shows a breakdown of the major land cover categories within each subbasin in Soos Creek. Soosette, Big Soos, and Jenkins have the highest levels of development (including developed open space) at 81%, 69%, and 68%, respectively, and the lowest forest cover at 12%, 18%, and 23%, respectively. The Covington subbasin is the most forested and the least developed, with an equal amount (41%) of each.

While development represents 60% of the Soos, 20% of the total drainage area is covered by impervious surfaces. The subbasins with the greatest development have, as expected, the largest percentage of impervious surfaces. Soosette, Upper Big Soos (defined as areas upstream of the confluence with Little Soos), and Jenkins have the highest proportion of impervious surfaces that cover 31%, 24%, and 24% of each subbasin, respectively. In contrast, the Covington Creek drainage has the least impervious cover, at 11% (Figure 3 and Table 1).

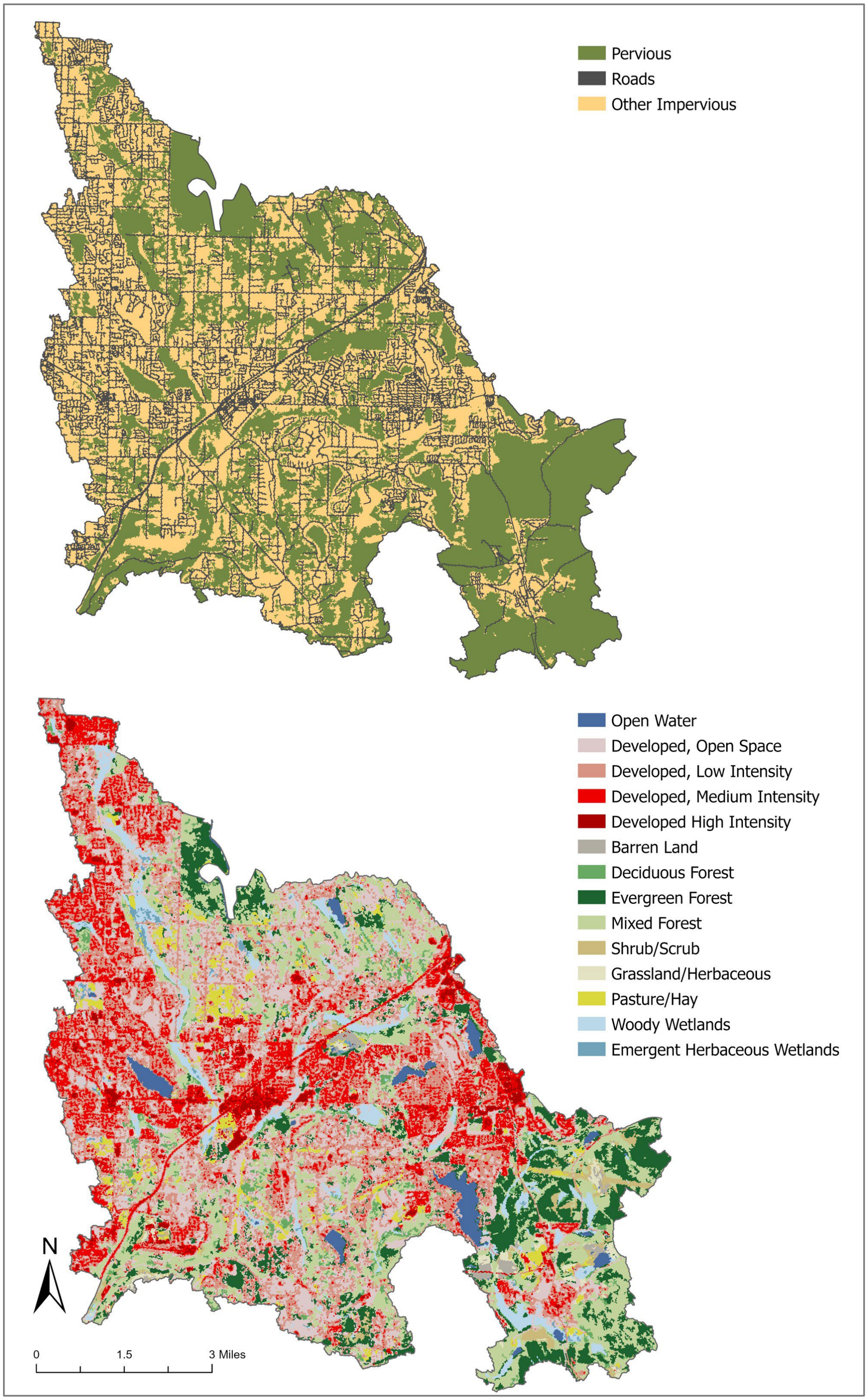

Figure 3. 2021 NLCD land cover distribution (left) and pervious areas, roads, and impervious areas (right) in the Soos Creek watershed (Dewitz and USGS 2023).

Table 1. 2021 NLCD land cover distribution in the Soos Creek Watershed (Dewitz and USGS 2023).

Land Cover	Soosette	Upper Big Soos	Little Soos	Jenkins	Covington	Lower Big Soos	Total Watershed
Barren Land	0.3%	0.1%	0.1%	0.7%	1.2%	0.9%	0.7%
Development[a]	80.9%	71.3%	63.2%	67.8%	40.9%	62.5%	59.8%
Forest	11.6%	15.9%	28.2%	22.8%	43.0%	23.2%	27.7%
Pasture	3.5%	4.1%	4.1%	1.1%	2.2%	3.1%	2.6%
Shrub/Scrub	2.0%	1.2%	1.2%	1.6%	5.7%	4.1%	3.1%
Water	0.0%	0.4%	0.1%	1.7%	2.9%	3.9%	1.8%
Wetland	1.6%	7.1%	3.1%	4.3%	4.3%	2.3%	4.4%
Impervious Cover	31.5%	25.3%	19.8%	24.3%	11.3%	22.4%	20.3%

[a] Percent development includes the sum of low, medium, and high-intensity development as well as developed open spaces.

Addressing Bioassessment Impairments

Water Quality listings for elevated fine sediment at several locations in the Soos watershed were based upon bioassessment listings for low Benthic Index of Biotic Integrity (B-IBI) scores. B-IBI is a multi-metric index used to assess the biotic integrity and aquatic health of freshwater streams in Washington. B-IBI monitoring entails measuring the diversity and abundance of stream macroinvertebrates, which are small aquatic animals (e.g., insects and snails) that spend most of their lives in streams and require healthy stream habitats to survive and thrive. Some species of macroinvertebrates are more sensitive to specific pollutants than others, and some are more tolerant to specific pollutants than others. This makes macroinvertebrates and B-IBI suitable indicators of water quality and stream habitat conditions since they integrate conditions of the entire watershed.

Ecology relies on B-IBI scores to identify bioassessment impairments of aquatic health in freshwater. Ecology's Water Quality Assessment Policy 1-11[1] identifies thresholds for B-IBI scores below which aquatic health is considered impaired. These thresholds are different for each Environmental Protection Agency (EPA) Level III Ecoregion. Ecology has designated that B-IBI scores falling below the 10th percentile of the distribution of reference site scores (for each ecoregion) as indicating degraded biological integrity — the thresholds of impairment are therefore calculated as the 10th percentile of scores collected at reference sites within the

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[1] Water Quality Policy 1-11 is the guiding policy that Ecology uses to assess water quality data, determine if waterbodies are polluted, and decide if further action is needed. More info: https://ecology.wa.gov/Water-Shorelines/Water-quality/Water-improvement/Assessment-of-state-waters-303d/Assessment-policy-1-11

ecoregion. In the Soos, which falls under the Puget Lowland ecoregion, B-IBI scores below a threshold of 65 indicate impaired biological integrity.

The Puget Sound Stream Benthos[2] (PSSB) database is a regional storehouse of benthic macroinvertebrate data collected and submitted by participating agencies (including state, county, cities, Tribes, universities, and other entities) across Puget Sound and Washington State.

Data from PSSB collected within the Soos from 1994 to 2021 were downloaded for analysis. The B-IBI scores were then assigned a qualitative B-IBI Category. While a threshold of 65 is used in this study to distinguish between "fair" and "good" conditions to be consistent with the 65 Ecology's threshold of impairment, this threshold is different from the threshold of 60 used by PSSB. PSSB categories are derived from Karr et al. (1986) and modified by Morley (2000). Table 2 compares this study's B-IBI categories and range in scores associated with each category with those used in the PSSB database.

Table 2. Comparison of this study's B-IBI categories and score ranges compared to those defined used in the Puget Sound Stream Benthos (PSSB) database.

This Study's B-IBI Category Definitions	This Study's B-IBI Score Range	PSSB B-IBI Category Definitions	PSSB B-IBI Score Range
Very Poor	0 to 20	Very Poor	0 to 20
Poor	20 to 40	Poor	20 to 40
Fair	40 to **65**	Fair	40 to **60**
Good	**65** to 80	Good	**60** to 80
Excellent	80 to 100	Excellent	80 to 100

Note. Differences are in bold.

There are 57 monitoring sites in the Soos that have B-IBI and other benthic macroinvertebrate data. These data show that B-IBI scores at multiple locations in the Soos are below 65 and, therefore, the aquatic health is impaired (Figure 4). Many sites in the Soos have been monitored over multiple years using B-IBI. Figure 4 illustrates how individual sites often have a large range in B-IBI scores, i.e., B-IBI scores have a large amount of variability at the same location between sampling events. For example, Site ID 09COV1756 on Covington Creek has B-IBI scores that range from 34.0 (poor) to 87.9 (very good). This variability could be a result of many factors, including changes to stressors that vary from one year to the next, climatic events, and other events in the watershed that affect connectivity with other streams and habitats, e.g., storm events that might flush out the benthic community in an area for a year or two, after which they can re-establish themselves. However, it also points to the potential these sites have to sustain a healthy benthic invertebrate community when the hydrologic, water quality, and habitat conditions they need to thrive exist.

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[2] Puget Sound Stream Benthos Database: https://pugetsoundstreambenthos.org/Default.aspx

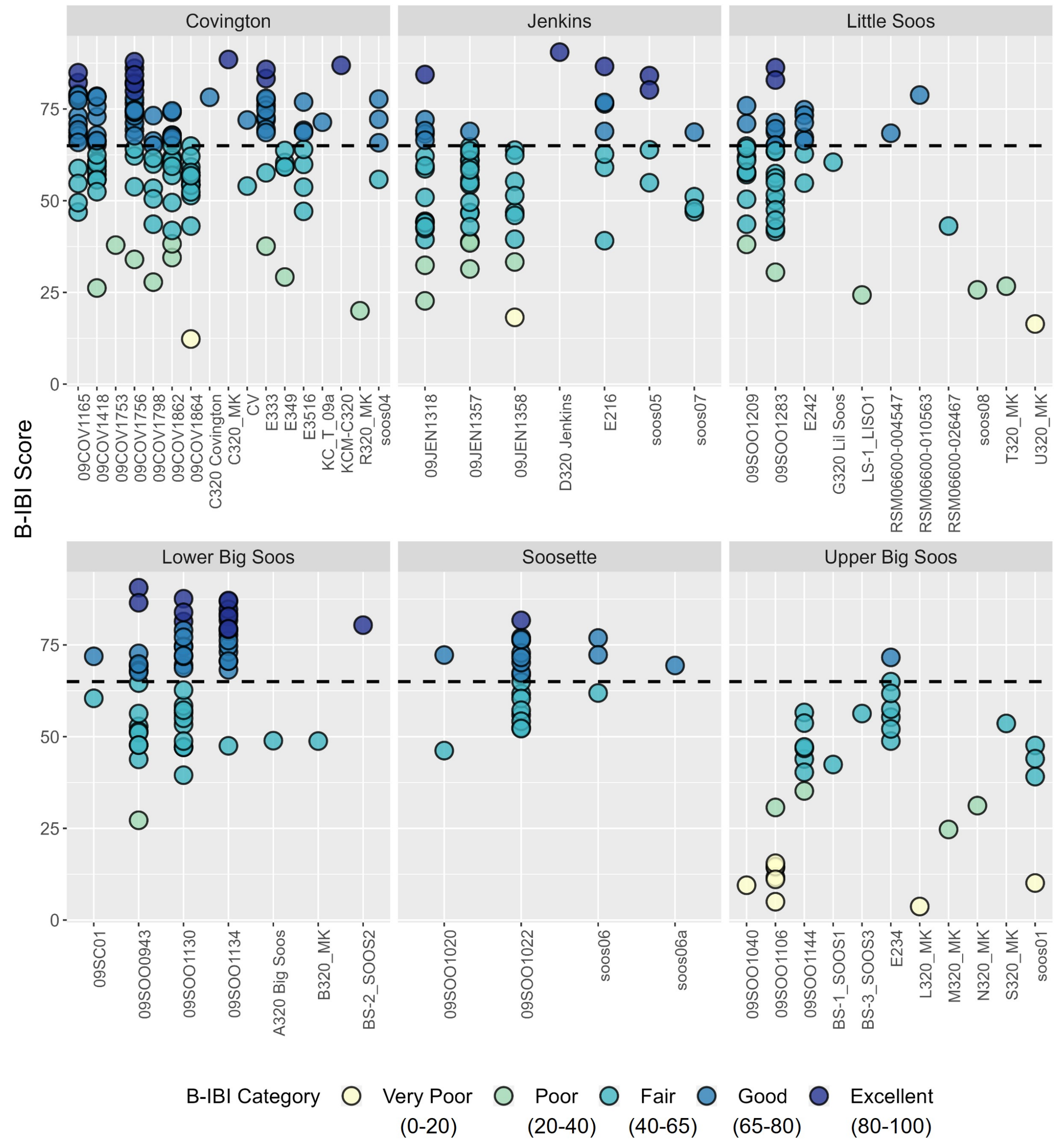

Figure 4. B-IBI scores from data collected at locations in the Soos between 1994 and 2021, grouped by subbasin. Colors represent established B-IBI categories ranging from "very poor" to "excellent."

Fine Sediment Listings

While low B-IBI scores indicate that aquatic health is impaired, the scores alone do not reveal the potential causes of the impairment. Since TMDLs must be developed for specific pollutants, Policy 1-11 states that a stressor identification analysis (stressor ID) must be conducted to identify the stressors contributing to the impairment. Marshalonis and Larson (2018) conducted the stressor ID analysis for the Soos following the EPA's CADDIS (Causal Analysis/Decision Information System)[3] stressor identification framework. Through this weight-of-evidence approach, they found that the three most probable stressors influencing low B-IBI scores in the Soos were 1) flow alteration/flashy flows (measured in terms of High Pulse Count), 2) elevated fine sediments, and 3) physical habitat degradation.

Of these three stressors, only fine sediment is a pollutant that can be directly addressed within the TMDL framework. As a result of these findings, the bioassessment listings were re-listed as fine sediment listings during Ecology's 2018 Water Quality Assessment[4] as per Policy 1-11 (Ecology 2012) and the CWA narrative criteria. Erosion and sediment have also been identified as a problem and habitat-limiting factor in the watershed over several studies conducted by King County since the 1990s (King County 2000).

The Fine Sediment Biotic Index (FSBI) is a diagnostic metric and sub-indicator also calculated from the benthic assemblages and was developed by identifying macroinvertebrate taxa that are sensitive to fine sediment from data sets across the Pacific Northwest (Relyea et al. 2006). FSBI scores are higher when a sample has more benthic macroinvertebrate taxa that are sensitive to fine sediment deposition and, therefore, indicate that there is less fine sediment at the site. FSBI scores in the Soos were calculated using an R script[5]. This script reads in taxonomic hierarchy data that we downloaded from PSSB and then matches those taxa that are known to be sensitive to fine sediment to calculate each site's FSBI score, using taxon-specific values from Relyea (2007) and Relyea et al. (2012). Figure 5 illustrates how lower FSBI scores in the Soos are generally associated with poorer B-IBI scores. Policy 1-11 also states that FSBI values below 89 indicate sediment pollution. FSBI scores are below 89 at multiple sites and locations in the Soos.

Sediment loads above levels that occur naturally are the most prevalent cause of freshwater ecosystem degradation in the United States regarding stream distance impacted (EPA 2000a). While sediment is integral to channel morphology, excess sediment loading, particularly fine sediment, can negatively affect aquatic life. It can smother gravel beds used for fish spawning and egg incubation, smother fish gills, bury aquatic insects that provide food for fish, and cover plants that produce oxygen.

For benthic macroinvertebrates, fine sediment in the stream substrate, also measured or referred to as embeddedness, can result in increased drift, lowered respiration capacity (due to physical blocking of gill surfaces), reduced efficiency in certain feeding activities (e.g., filter-feeding and visual predation), and can increase the time it takes to search for food (Lemly 1982; Waters 1995; Runde and Hellenthal 2000a; Runde and Hellenthal 2000b; Suren and Jowett 2001; Suren 2005; Kent and Stelzer 2008; and Relyea et al. 2006).

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[3] EPA Causal Analysis/Decision Information System: http://www.epa.gov/caddis

[4] 2018 Water Quality Assessment & 303(d) list: https://ecology.wa.gov/Water-Shorelines/Water-quality/Water-improvement/Assessment-of-state-waters-303d

[5] R script was provided by Elizabeth Sosik (King County) on August 25, 2022.

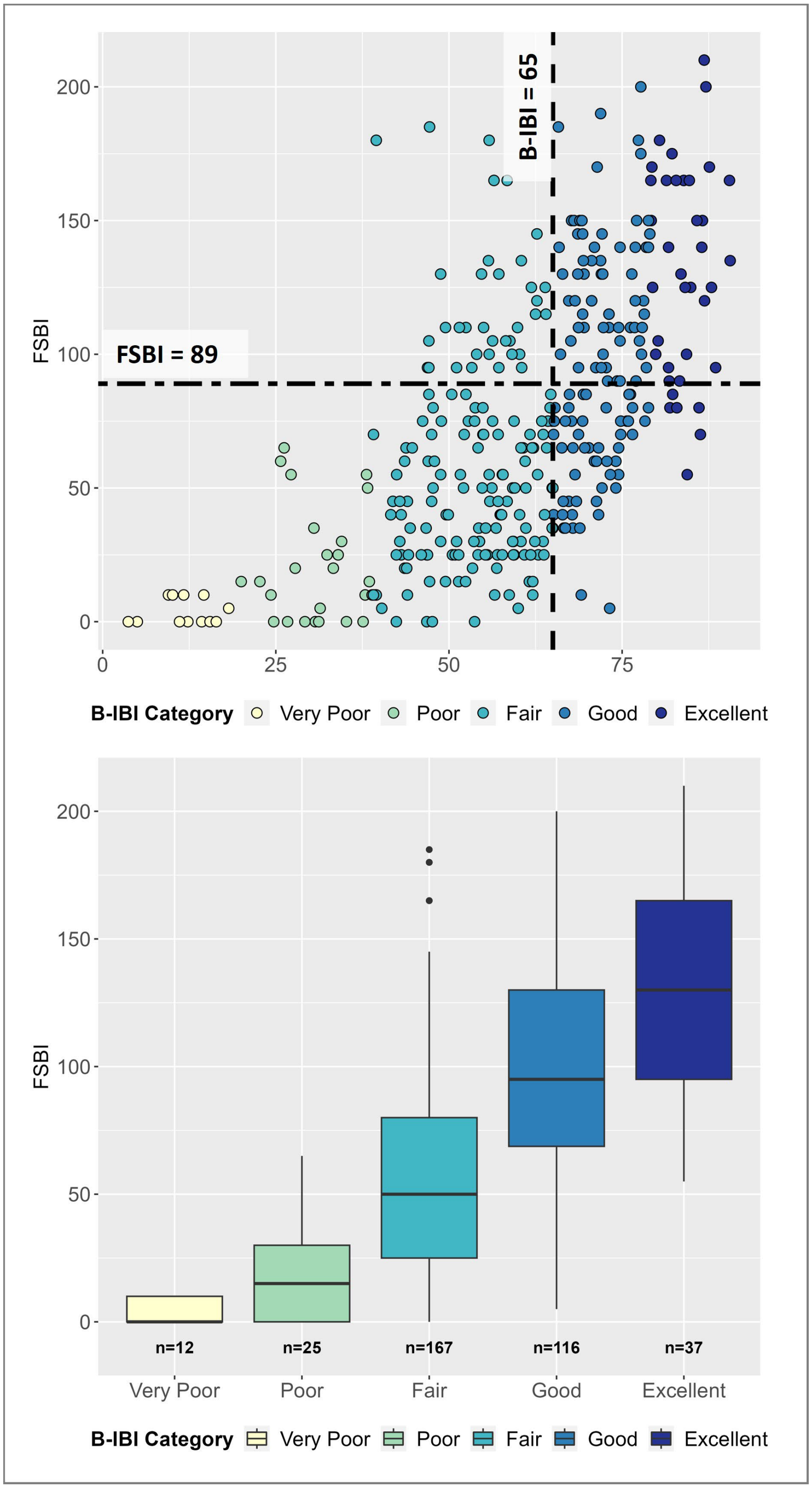

Figure 5. Yearly Fine Sediment Biotic Index (FSBI) and B-IBI scores (left plot) and FSBI boxplot grouped by B-IBI categories (right plot).

TSS as a Surrogate for Fine Sediment

While excess *fine* sediment is problematic to water quality, measurements of suspended sediment in streams are usually made in terms of concentrations of Total Suspended Solids (TSS). TSS includes suspended fine sediment, some of which also gets deposited to the stream bed via instream fate and transport processes. Excess sediment is regulated under WAC 173-201A-260 as a "deleterious material." Ecology does not set numeric thresholds for TSS in Chapter 173-201A WAC but may establish site-specific expectations for sediment levels as part of its TMDL program.

As will be described later in this report, the modeling tools applied in this study model TSS. To provide more meaningful and measurable pollutant loading targets, EPA regulations [40 CFR 130.2(i)] allow other appropriate measures or surrogate measures in a TMDL. The Report of the Federal Advisory Committee on TMDL Program (FAC 1998) includes the following guidance on the use of surrogate measures for TMDL development:

> "When the impairment is tied to a pollutant for which a numeric criterion is not possible, or where the impairment is identified but cannot be attributed to a single traditional "pollutant," the state should try to identify another (surrogate) environmental indicator that can be used to develop a quantified TMDL, using numeric analytical techniques where they are available, and best professional judgment (BPJ) where they are not."

For this TMDL, TSS is being used as a surrogate for the fine sediment. Fine sediment, suspended sediment, and TSS concentrations have all been found to correlate well with changes in macroinvertebrate behavior and survival rates (Ntloko et al. 2021; Runde & Hellenthal 2000b; Shaw & Richardson 2001). TSS is also a widely used numeric parameter consistent with sampling parameters required by some National Pollution Discharge and Elimination (NPDES) permits, which are the primary regulatory tool through which Ecology regulates stormwater discharges to state water bodies. Monitoring of some stormwater discharges and the effectiveness of best management practices (BMPs) to remove solids from stormwater runoff are also usually reported in terms of TSS. Since the fate and transport mechanisms for fine sediment and TSS are related, and TSS can be reasonably measured and estimated, TSS is an acceptable surrogate for the fine sediment that impairs B-IBI scores in the Soos. TSS is particularly appropriate as a surrogate for this study because the size fraction definition for fine sediment in the WAC 173-201A-200(1)(h)[6] includes any size fraction less than 2 mm:

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[6] WAC 173-201A-200: https://apps.leg.wa.gov/wac/default.aspx?cite=173-201a-200

> **(h) Aquatic life fine sediment criteria.** The following narrative criteria apply to all existing and designated uses for fresh water:
>
> (i) Water bodies shall not contain excess fine sediment (<2 mm) from human-caused sources that impair designated uses.
>
> (ii) When reference values are used to demonstrate compliance with the fine sediment criteria, measured conditions shall be compared to those from reference sites or regional *data* that represent least disturbed site conditions of a comparable water body or ecoregion. Reference locations should be comparable in hydrography, geology, ecology, and habitat to that of the water body evaluated.

Accordingly, the regulation covers a wide range of "fine sediment" sizes, from very fine to larger particles closer to sand size (above 2 mm). It is worth noting that the TSS measurement methodology tends to perform better for the finer size fractions (less than 0.1 mm) and underestimates larger size fractions (Gray et al. 2000).

Flow Alteration and Flashiness Metrics

Despite this TMDL's focus on sediment load reductions, there are important and well-established connections between stream flashiness, sediment loading, and instream erosion. These connections support the need for a holistic approach to watershed management in the Soos that considers stormwater flow control, sediment load reductions, and physical habitat restoration. The analysis of flow alteration, in addition to TSS loadings, is, therefore, an important component of our analytical approach.

Flow alteration refers to changes in the hydrologic regime relative to undisturbed or reference conditions. Bunn and Arthington (2002) and Poff and Zimmerman (2010) have summarized the literature on biological responses to altered flows, which include overall reductions in the abundance and diversity of macroinvertebrates.

Studies have also found a high degree of flow alteration in urbanized land use conditions when compared to fully forested conditions. Rosburg et al. (2017) analyzed 25-plus years of flow data in Puget Sound streams to show changes in flow duration curves over time with increased urbanization, including an increase in the magnitude of flow and flashiness. In addition, several other studies have compared modeled pre-developed/forested flows to current flows and found relationships between urbanization, increases in impervious areas and increases in peak flows, stream flashiness, more unstable stream channels, and a reduction in the quality of stream habitat (Booth and Jackson 1997; Booth et al. 2002; King County 2013; and Horner 2013).

Changes in flow regimes due to urbanization also increase the supply of fine sediment to downstream water bodies (Russel et al. 2017). Lastly, Vietz et al. (2012) highlights the importance of addressing flashy hydrology in the context of how it affects the physical form of streams and the importance of considering what kind of flow regimes are necessary to sustain the desired geomorphology. Flashy flows can transport various pollutants, including sediment, from roads, lawns, fields, impervious surfaces, and other land areas within the watershed and deliver these pollutants to surface waters during storm events. Additionally, the physical force and "flashiness" of flows can scour and erode streambanks, result in channel incision, dislodge benthic organisms, and degrade and alter stream channels.

Flashiness metrics and other flow alteration metrics allow us to characterize streamflow patterns and analyze how human activities and land use/land cover affect these patterns. In addition, since stream ecosystems depend on certain flow and hydrologic patterns to maintain and preserve ecological function, these metrics can also be correlated to ecological metrics such as B-IBI scores.

Several studies have shown that hydrologic alteration is correlated to observed biological impairments in urban streams and discuss how hydrologic alteration limits the characteristics (e.g., abundance, richness, diversity, or individual taxa) of macroinvertebrates assemblages (Konrad et al. 2008; Booth and Bledsoe 2009; DeGasperi et al. 2009; and Horner 2013). The Stressor ID analysis found that High Pulse Count (HPC) had a statistically significant correlation to B-IBI scores in the Soos Creek watershed, where higher HPCs were found to be correlated to lower B-IBI scores (Marshalonis and Larson 2018).

The following flashiness metrics were considered in this study:

- **High pulse count (HPC)** — Number of times each water year[7] that discrete high flow pulses occur. A high-flow pulse is defined as the occurrence of daily average flows equal to or greater than a high-flow threshold (defined as two times the long-term mean daily flow).
- **TQ-mean** — Fraction of time in each water year that the daily time step hydrograph exceeds the annual mean discharge for the year.
- **Peak 2-yr: Winter Baseflow Ratio (PK2YR)** — Ratio of the peak flow rate with a 2-year return frequency to the mean baseflow rate from October 1 to April 30.

Physical Habitat Degradation

In addition to fine sediment and flashy flows, the Stressor ID analysis also identified physical habitat degradation as an additional stressor on benthic macroinvertebrates in the Soos (Marshalonis and Larson 2018). Their analysis involved qualitative habitat assessments for each impaired location within the Soos following the EPA guidance for wadeable streams (EPA 1993). This assessment involved qualitative scoring of low and high-gradient stream habitats based on several microscale parameters and secondary habitat parameters such as substrate quality, embeddedness, pool variability, sinuosity, riparian habitat condition, bank structure, and stream canopy. Based on this qualitative habitat assessment, most impaired sites in the Soos scored poorly for microscale habitat quality, while scores for morphology and riparian habitat were more variable. While this assessment does provide some indication that the physical habitat in the Soos is degraded at impaired sites, its conclusions are somewhat limited, given it was only

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[7] Water Year is defined as October 1st if one year through September 30th of the following year.

conducted at impaired sites. Nevertheless, as previous sections have elucidated, sediment loading and stream flashiness contribute to the degradation of physical habitat, and this further underscores the importance of considering physical habitat restoration as part of addressing B-IBI impairments.

Modeling Methods

Ecology used the Hydrological Simulation Program - FORTRAN (HSPF) model of the Soos to understand the hydrology and sediment loading dynamics in the watershed, analyze the relative contribution of sediment loads from different sources, and determine how stormwater events and flashy flows influence sediment loading and instream erosion. The HSPF model was also used to inform the development of TSS load and wasteload allocations.

We used an existing HSPF model of the watershed, which was updated and recalibrated specifically for this study. We consulted with RESPEC Consulting, LLC (RESPEC) throughout the model update and recalibration process. Our consultation with them concluded with a formal peer review performed by RESPEC, which included a review of the model setup, model updates, and model performance of the recalibrated model, including recommendations (Lupo and Donigian 2022). We subsequently incorporated the recommendations from their review in the final calibrated model.

Modeling Framework

HSPF is a process-based and quasi-physically based lumped parameter watershed model that can continuously simulate hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams. It simulates runoff processes, instream interactions, and pollutant loads and concentrations at a sub-daily dynamic time scale. The processes and algorithms within the model have been developed from theory, lab experiments, and empirical watersheds (Duda et al. 2012).

The model simulates fundamental hydrologic processes that make up the water budget, including precipitation, evapotranspiration, interception, surface runoff, interflow, infiltration, and various components of groundwater flow and storage. It is typically run at an hourly time step. Additional modules (e.g., sediment and water quality) can be added once the hydrology has been calibrated. For this study, the sediment module was applied.

These hydrological processes are controlled by associated rates and parameters, which the user specifies for two types of land segments within the watershed: 1) pervious (referred to as PERLNDs) and 2) impervious (referred to as IMPLNDs). The hydrological processes are simulated separately for pervious and impervious surfaces within the PWATER and IWATER submodules, respectively. The submodule HYDR then simulates instream hydraulic processes, which keeps track of the water balance within each reach, including reach level precipitation, evaporation, and all other inflows and outflows. The hydraulic routing is based on relationships between stage, surface area, and storage.

The sediment module in HSPF, which was used in this study, simulates the detachment, removal/wash off (i.e., erosion), and accumulation of sediment on both pervious and impervious surfaces. Erosion is primarily a function of runoff, which is affected by land use, land cover, topographic slope, soil disturbance, and transport properties of soil (EPA 2006). The sediment loading rate from different types of land uses is a calibrated parameter. The submodule SEDMNT simulates the production and removal of sediment from pervious land segments, while the submodule SOLIDS simulates the accumulation and removal of solids from impervious land segments by runoff and other means.

This sediment load that is eroded from the land surface is then transported from the watershed/land surfaces and divided into user-specified fractions of sand, silt, and clay before being delivered to the stream channel/stream reach (referred to as RCHRES). From here, the SEDTRN module simulates the instream sediment fate and transport of sediment.

The SEDTRN module has two submodules: SANDLD and COHESV. Both modules rely primarily on calibrated parameters. The SANDLD submodule simulates the deposition, scour, and transport of the sand fraction of inorganic sediment within the stream. Whether sand is deposited, scoured, or transported downstream is determined by comparing the sand transport carrying capacity and the actual sand transport rate, which are functions of stream velocity. The COHESV submodule simulates the deposition, scour, and transport of silt and clay (also known as cohesive sediments) as a function of advection and bed shear stress. Once in the stream, the sum of sand, silt, and clay is assumed to be equivalent to TSS — which is then compared to observed TSS concentrations to optimize sediment calibration.

The algorithms used to simulate the hydrologic and sediment processes described above are discussed in more detail in the User's Manual (Bicknell et al. 2005) as well as by Donigian and Love (2003) and Duda et al. (2012). The model has been used extensively by the EPA, the USGS, and the academic community and maintains a strong scientific basis. Locally, it has been extensively used and applied by King County in watersheds within their jurisdiction for stormwater retrofit planning and other studies.

Model Setup and Updates

The Soos HSPF model that was updated for this study was originally developed by Aqua Terra Consultants for King County and described in an unpublished report (Aqua Terra 2003). This version of the model was further developed for retrofit and stormwater analysis for the whole of WRIA 9 (which includes the Soos) and documented in a final report by King County (2013). Subsequently, the Muckleshoot Indian Tribe (MIT), in collaboration with KetaWaters, further refined the WRIA 9 retrofit model (only the portion of the model domain that included the Soos) by adding well withdrawals and inter-basin groundwater transfers to improve baseflow hydrology simulation (Carlson and Massmann 2015). This refined version of the Soos HSPF model, which we will call the "MIT version," was the starting point for this study. The MIT version of the model and associated model input files were provided to Ecology by MIT. The MIT version of the model did not include sediment simulation.

The MIT version of the model was calibrated for hydrological parameters for WY 2001 – 2008, using 2007 land use conditions. The model simulation began in 1998 to allow time for the model to spin up and stabilize by the year 2001. Model spin-up is a way to "warm up" the model for a certain amount of time to minimize any error associated with initial boundary conditions parameterization. For this study, the model simulation period was extended through to 2015 to include a longer simulation period and more recent years for which we have sediment data (for calibration) and B-IBI data.

The model time step was increased from 15 min to 60 min. An hourly time step seemed more appropriate to better capture total rainfall received in an hour, especially when storms in the watershed are not spatially homogenous and some are short enough that they can move to different parts of the watershed within an hour. Secondly, the precipitation and evaporation input time series were extended to the new simulation period 2001 – 2015 (described in more detail in subsequent sections of this report).

The HSPF model setup, parameters, and connections to necessary input and output files are all specified in a single User Control Input (UCI) file that has a specific format. This UCI file is organized into different "blocks" that specify different components of the HSPF model setup, user-defined options, and submodules. For this study, the UCI file was edited to initiate the sediment submodules (SEDMNT and SEDTRN) and associated parameters once hydrology calibration was completed.

Watershed Data Management (WDM) files are the main storage of time-series data, each one of which can be defined with specific attributes. At a minimum, all meteorological forcing data for the HSPF model need to be contained as a time series within one or more WDM files. Time series of model output can also be saved in a few different formats, which the user can specify within the UCI file. These include PLTGEN ASCII files, HSPF Binary Output files, or WDM files.

HSPF Catchment Delineation

The Soos HSPF model is segmented into 60 reaches/catchments (Figure 6). These catchment delineations were originally performed by King County staff using the King County GIS hydrography/stream network data layer and were later slightly revised by AQUA TERRA Consultants (Aqua Terra 2003). Each catchment ranges in size from 0.05 to 4.72 square miles. No updates were made to the watershed segmentation in the MIT version of the model.

During this study, an error in the reach connectivity was fixed so that RCHRES 212 now flows to RCHRES 292 (it was originally going to RCHRES 242, but based on the streamflow lines, this was incorrect). This update did not result in any noticeable changes in the hydrology simulation. Apart from this change, no changes were made to the watershed segmentation, catchment delineations, or connectivity between reaches. Appendix A includes a schematic of catchment and reach connectivity in the HSPF model.

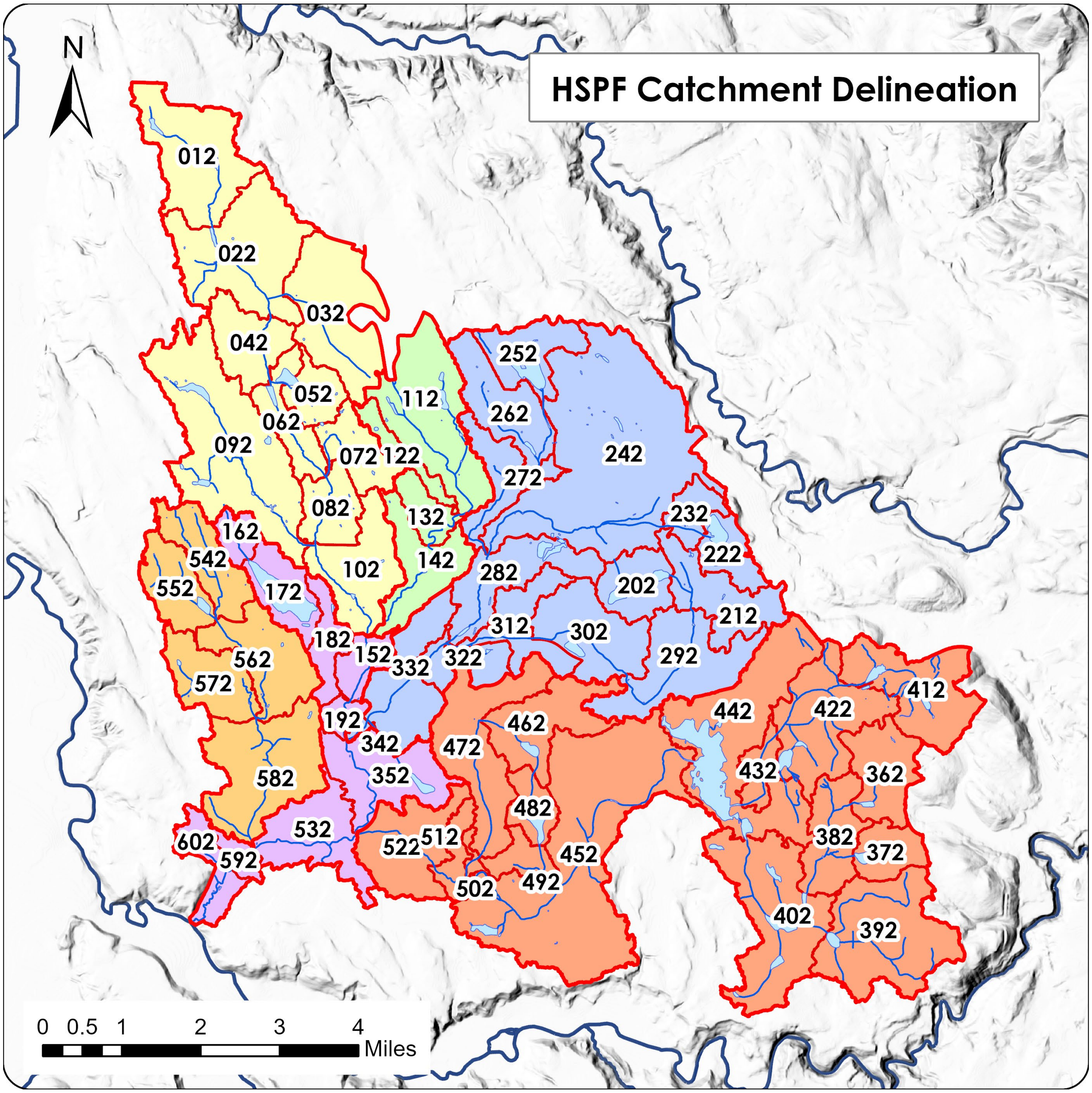

Figure 6. Soos Creek watershed HSPF catchment delineations with reach IDs.

Surficial Geology and Topographic Slope

HSPF requires information about the surficial geology and topographic slope in the watershed to define the relative rates of surface soil infiltration. The geology and slope characterization in the MIT version of the model remains the same for study.

King County (2013) describes how surficial geology for the Soos HSPF model came from data from the USGS (1995) and King County (1997). The following three categories of soils are included: till (low permeability), outwash (high permeability), and saturated (high permeability but with low capacity because of frequent saturation). Figure 7 illustrates the fraction of outwash, saturated, and till soils represented within each HSPF catchment.

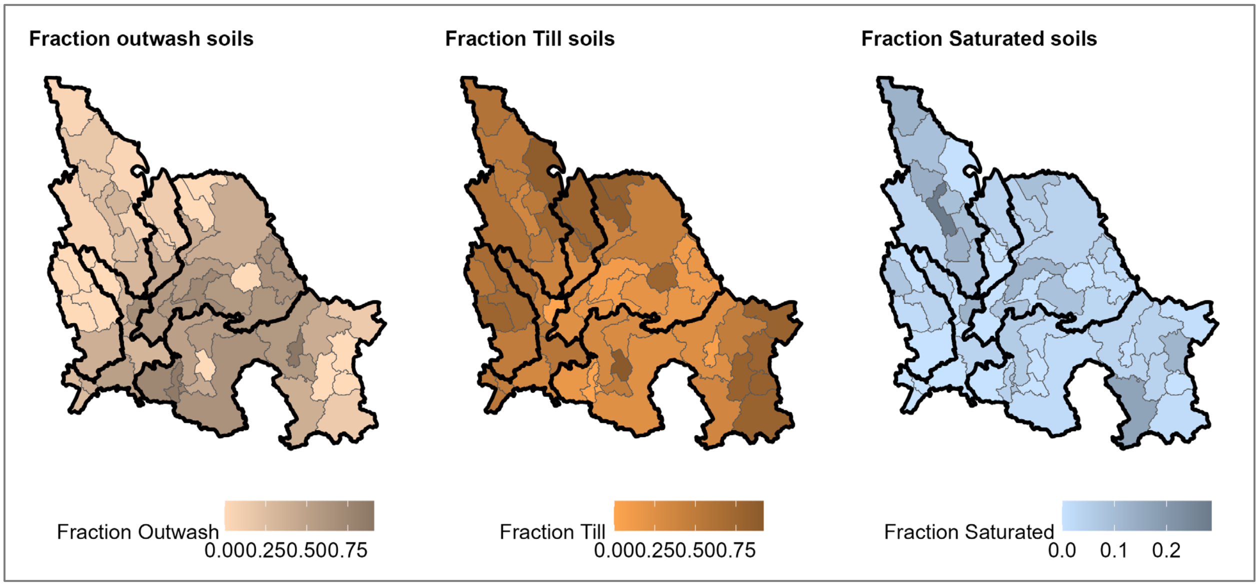

Figure 7. Maps showing the fraction of each HSPF catchment covered by outwash, till, and saturated soils.

Topographic slopes were derived from a digital elevation model that was generated from LiDAR (Light Detection and Ranging) data (King County 2003). Slopes were aggregated into four categories: flat (0% – 5%), low (5% – 10%), medium (10% – 15%), and steep (>15%).

Precipitation

Precipitation is one of the main driving forces of the hydrology within the HSPF model, along with evapotranspiration. For the Soos model, hourly precipitation data from King County rain gages[8] were used to create a composite time series of precipitation for four different precipitation zones in the watershed. This approach represents spatially varying rainfall patterns across the model domain. The creation of a composite time series involved weighting the different gages based on data availability and the location of the gage, where gages with fewer data gaps and those that are closer to the precipitation zone are given a higher weight.

The same composite gage-weighted approach was used to extend the precipitation time from the original simulation period of 2001 – 2008 to 2001 – 2015. Table 3 lists the gages used for each precipitation zone, data availability, and their respective weights. Figure 8 shows the location of the precipitation stations as well as gridded precipitation data showing the distribution of mean annual rainfall across the watershed and monthly precipitation in each of the four zones.

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[8] King County Hydrologic Information Center: https://green2.kingcounty.gov/hydrology/

Table 3. King County precipitation gages used to develop composite precipitation inputs for the model's four zones, including their data availability and the weights applied to each gage when used to develop model precipitation inputs.

Precipitation Zone	King County Site Code	King County Site Name	Data Availability Range[a]	Weight Applied to Create Composite
Zone 1	32u	Lower Green River	11/01/1998–current	0.34
Zone 1	03u	Panther Creek Precip	10/01/1988–current	0.33
Zone 1	SEQU	Sequoia JR High School I&I	10/01/2000–current	0.33
Zone 2	31y	Fairwood	10/01/1994–01/05/2015	0.15
Zone 2	26u	Jenkins Creek	07/01/1991–current	0.25
Zone 2	KANG	Kent-Kangley I&I	10/12/2000–03/18/2023	0.35
Zone 2	54v	Soos Creek	07/01/1991–current	0.25
Zone 3	09u	Covington Creek	07/01/1991–current	0.07
Zone 3	BDIA	Black Diamond I&I	10/13/2000–current	0.30
Zone 3	MVAL	Maple Valley I&I	10/01/2000–10/01/2011	0.06
Zone 3	31w	Layton	10/01/1987–06/14/2013	0.20
Zone 3	26u	Jenkins Creek	07/01/1991–current	0.30
Zone 3	09V	Covington Creek below Lake Sawyer	09/29/2004–current	0.07
Zone 4	26u	Jenkins Creek	07/01/1991–current	0.25
Zone 4	MVAL	Maple Valley I&I	10/01/2000–10/01/2011	0.25
Zone 4	BDIA	Black Diamond I&I	10/13/2000–current	0.50

[a] Date range ending with "current" indicates that these precipitation gages were active at the time we retrieved data on 5/22/2018. We downloaded all available data but only used data from 1/1/1998 to 12/31/2015 to represent precipitation inputs during the model simulation period.

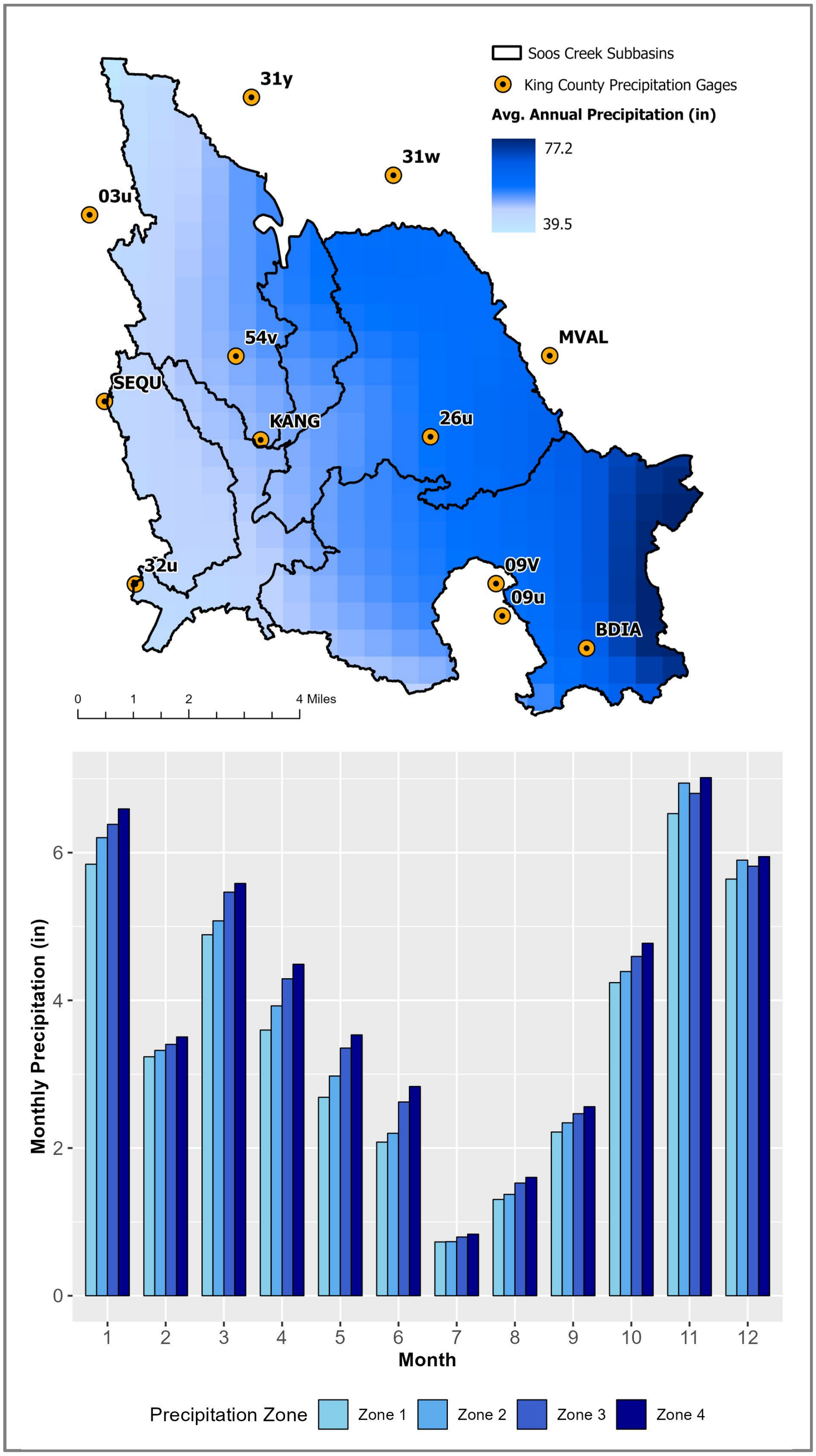

Figure 8. Location of King County precipitation gages and distribution of annual precipitation across the Soos watershed.

Represented by PRISM 30-year normals from 1981 to 2010 (top plot) and monthly average precipitation between 2001 and 2015 in each of the four precipitation zones in the Soos HSPF model (bottom plot).

Evapotranspiration

The MIT model used a single pan-evaporation station with daily data from a weather station operated by Washington State University (WSU) in Puyallup (approximately 15 miles southwest of the Soos). These daily data were disaggregated to hourly time steps (i.e., divided by 24 to represent hourly evaporation) and adjusted to estimate potential evapotranspiration (PET) using a pan evaporation coefficient of 0.78, based on the isopleth of contour lines of pan evaporation coefficients across the continental U.S determined by the National Weather Service, and illustrated in Map 4 of Farnsworth (1982).

For this study, RESPEC updated and extended the evaporation inputs to the model to 2015. Instead of using a single global daily evaporation time series applied to the whole watershed, area-weighted hourly evaporation was computed from gridded (1/8th degree spatial resolution) NLDAS-2 (North American Land Data Assimilation System) forcing datasets[9] for each of four precipitation zones in the model. These forcing data include hourly air temperature, wind speed, humidity, air pressure, and solar radiation, which were used to compute hourly PET using the Penman equation (Penman 1948) and the method from Kohler et al. (1955). A pan evaporation coefficient of 0.61 was also applied; the lower coefficient (relative to the original one of 0.78) accounts for the fact that the PET calculated from NLDAS output has been found to be overestimated in other modeling efforts (TetraTech 2017).

Land Use and Land Cover

The 2007 land cover conditions in the Soos HSPF model were originally derived from 2007 satellite imagery[10] that had a 30 m resolution and included 14 land use categories (King County 2013). No changes to the land cover categories were made for this study. Land use describes how people utilize the land, while land cover defines the elements that make up each land use, e.g., an urban land *use* area might have a combination of forest, grass, and impervious land *cover*. In many cases, different land uses may have substantially similar responses to rainfall and runoff processes. Therefore, for watershed modeling purposes, these land use categories were merged into seven land cover groups that were represented in the MIT version of the model.

These were further divided into “pervious” and “impervious” categories. The division of land cover between pervious and impervious land cover is based on assumed proportions of Effective Impervious Area (EIA) present within each land use category. EIA is less than the total impervious area and represents the fraction of the total impervious area that is effective in generating immediate runoff to streams. These EIA assumptions were initially based on previous studies conducted in the Puget Sound region (e.g., Dinicola 1990, Elmer 2001, and King County 2009).

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[9] NLDAS-2 Forcing Dataset: https://ldas.gsfc.nasa.gov/nldas/v2/forcing

[10] Central Puget Sound 2007 Land Cover Classification from the Puget Sound Regional Synthesis Model (PRISM), University of Washington.

These were then adjusted during calibration as described in King County (2013):

> "Initial estimates of EIA fractions for each land use category were adjusted based on professional judgment regarding the character of particular developed areas. Some roads might be curbed, may have storm sewer networks, etc., which may more efficiently direct runoff to storm drains and/or stream systems. The same density of development in another area may have no curbs and no storm network. Thus, the effect of those impervious areas will behave differently for the same total impervious area.
>
> In addition, not all storm water management infrastructure that may be present in the drainage area was explicitly modeled. Since those ponds are generally designed to mitigate runoff to behave like predevelopment conditions, they become implicit in the system by adjusting the EIA fractions."

These EIA proportions are slightly lower in the Jenkins subbasin relative to the other subbasins. This reflects the fact that this subbasin has a large amount of outwash soils, which have much higher infiltration rates than till soils. During the original model development process, this was represented by using lower EIA values for outwash soils. The land use categories and EIA assumptions were not modified for this modeling effort and are presented in Table 4 for all subbasins.

Table 4. Fraction of pervious and impervious area associated with each land use category in the different subbasins of the Soos Watershed.

Soosette, Little Soos, Covington, and Big Soos	Pervious	Low Density EIA	High Density EIA	Commercial/ Industrial EIA	Roads EIA
Agriculture	0.993	0.002	—	—	0.005
Commercial	0.750	—	—	0.228	0.022
Forest	0.995	—	—	—	0.005
High Density Residential	0.892	—	0.082	—	0.026
Low Density Residential	0.965	0.018	—	—	0.017
Wetland	0.996	—	—	—	0.004
Jenkins	**Pervious**	**Low Density EIA**	**High Density EIA**	**Commercial/ Industrial EIA**	**Roads EIA**
Agriculture	0.995	0.001	—	—	0.004
Commercial	0.825	—	—	0.160	0.015
Forest	0.996	—	—	—	0.004
Grasslands	0.995	—	—	—	0.005
High Density Residential	0.924	—	0.057	—	0.019
Low Density Residential	0.975	0.013		—	0.012
Wetland	0.997	—	—	—	0.003

Land Use Change Analysis

The original model schematic was based on the 2007 land cover, which was towards the end of the original 2001 – 2008 model simulation period. Since we extended the model simulation to 2015 for this study, we analyzed land use change data to see if there had been any significant land use changes in the Soos since 2007.

We used NOAA's C-CAP (Coastal Change Analysis Project)[11] land use change datasets for the Soos for the years 2006 and 2016, which are the available years closest to the years of interest (2007 and 2015). These datasets identify what kind of land use change occurred on the landscape, e.g., a shift from low-intensity to high-intensity development. Land use change (in terms of area of each HPSF catchment and percent area of each catchment) was summarized for each HSPF catchment between 2006 and 2016 to identify which catchments in the watershed experienced large changes in land use and what kind of land use change occurred.

The two main types of land use change observed in the Soos included an increase in development and a decrease in forested areas. Updating the whole model schematic and land use was beyond the scope of this study, so instead, we determined what level of land use change could potentially result in an observable change in hydrology to focus our model schematic updates on just those model catchments that had experienced more significant land use change.

To do this, we ran several hypothetical model scenarios using the Western Washington Hydrology Model[12] (WWHM) to determine what level of deforestation or increase in development would produce a change to peak flows of greater than 3%. This analysis showed that a decrease in forest of ~10% and an increase in development of ~3% both resulted in an increase in peak flows by >3%.

Based on the land use change analysis, the following five HSPF catchments fit these criteria, and their schematic was updated to reflect the 2016 land use:

- RCHRES 212: 4.6% increase in development (in Jenkins subbasin).
- RCHRES 282: 4.8% increase in development (in Jenkins subbasin).
- RCHRES 362: 28.4% decrease in forest (in Covington subbasin).
- RCHRES 412: 42.8% decrease in forest (in Covington subbasin).
- RCHRES 422: 10.8% decrease in forest (in Covington subbasin).

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[11] NOAA C-CAP Regional Land Cover and Change: https://coast.noaa.gov/digitalcoast/data/ccapregional.html

[12] Western Washington Hydrology Model (WWHM) is used widely across Western Washington State to design stormwater control facilities. More information can be find here: https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Stormwater-manuals/Western-Washington-Hydrology-Model

When making the above updates, we made sure that the following did not change:

- The relative distribution of different categories of development (high, medium, low), i.e., these proportions were retained when the total acres of development were increased
- The fraction of a particular land use on different soils
- The proportion of EIA associated with each land cover
- The total amount of area in different precipitation zones

Figure 9 illustrates the fraction developed, fraction EIA, and fraction forested areas within each HSPF catchment.

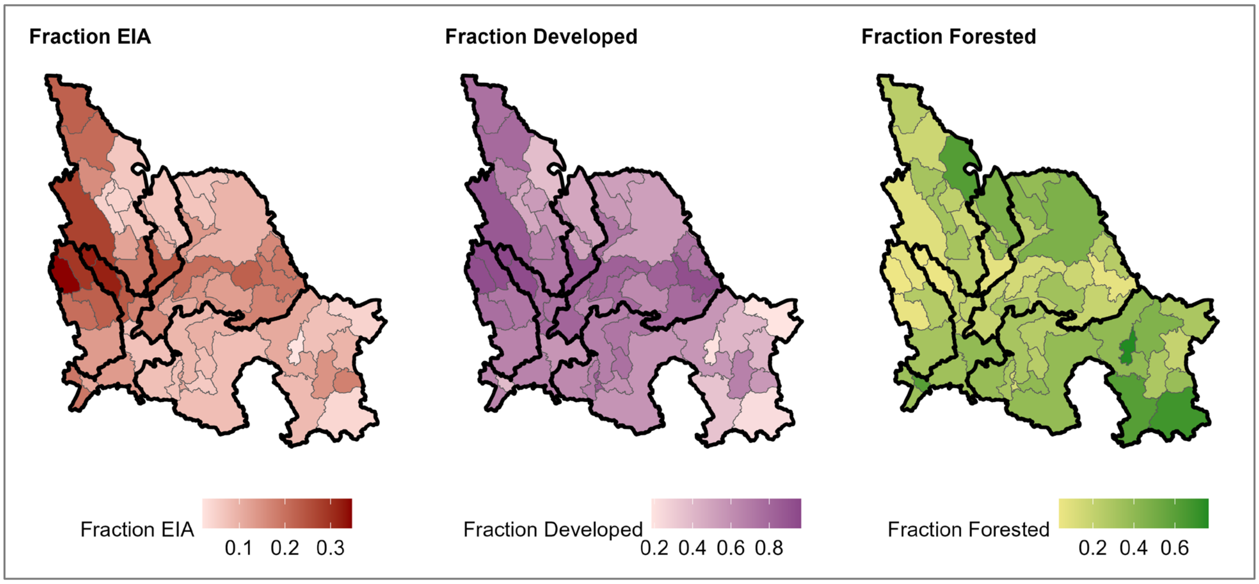

Figure 9. Maps showing the fraction of effective impervious area (EIA), fraction developed (includes all pervious land use categories plus EIA), and fraction forested cover within each HSPF catchment.

Model Schematic

The model schematic specifies the proportion of the area within each catchment represented by different Hydrologic Response Units (HRUs). HRUs are the combination of land use/land cover, surficial geology/soils, and slope. HRUs in the Soos HSPF model represent PERLNDs based on three soil types, seven land use or vegetation covers, and four slope categories. Additionally, four kinds of IMPLNDs are also represented. Table 5 summarizes the HRU number scheme used in the MIT model, which remained unchanged for this study. Runoff responses on outwash or saturated soils are typically not sensitive to slope. Thus, the slope is not differentiated for those HRUs (King County 2013). Each of these HRUs is further assigned into one of four precipitation zones to account for different levels of precipitation across the watershed.

Table 5. Hydrologic Response Unit (HRU) descriptions used in the HSPF model. Each HRU is a unique combination of geology, land cover, and slope.

HRU ID	Type	Surficial Geology	Land Use	Slope[a]
11	PERLND	TILL	Forest	FLAT
12	PERLND	TILL	Forest	LOW
13	PERLND	TILL	Forest	MED
14	PERLND	TILL	Forest	STEEP
21	PERLND	TILL	Pasture/Agriculture	FLAT
22	PERLND	TILL	Pasture/Agriculture	LOW
23	PERLND	TILL	Pasture/Agriculture	MED
24	PERLND	TILL	Pasture/Agriculture	STEEP
31	PERLND	TILL	Forest Residential	FLAT
32	PERLND	TILL	Forest Residential	LOW
33	PERLND	TILL	Forest Residential	MED
34	PERLND	TILL	Forest Residential	STEEP
41	PERLND	TILL	Low Density Residential	FLAT
42	PERLND	TILL	Low Density Residential	LOW
43	PERLND	TILL	Low Density Residential	MED
44	PERLND	TILL	Low Density Residential	STEEP
51	PERLND	TILL	High Density Residential	FLAT
52	PERLND	TILL	High Density Residential	LOW
53	PERLND	TILL	High Density Residential	MED
54	PERLND	TILL	High Density Residential	STEEP
61	PERLND	TILL	Commercial/Industrial	FLAT
62	PERLND	TILL	Commercial/Industrial	LOW
63	PERLND	TILL	Commercial/Industrial	MED
64	PERLND	TILL	Commercial/Industrial	STEEP
71	PERLND	OUTWASH	Forest	NONE
72	PERLND	OUTWASH	Pasture/Agriculture	NONE
73	PERLND	OUTWASH	Forest Residential	NONE
74	PERLND	OUTWASH	Low Density Residential	NONE
75	PERLND	OUTWASH	High Density Residential	NONE
76	PERLND	OUTWASH	Commercial/Industrial	NONE
81	PERLND	SATURATED	Forest	NONE
82	PERLND	SATURATED	Pasture/Agriculture	NONE
83	PERLND	SATURATED	Forest Residential	NONE
84	PERLND	SATURATED	Low Density Residential	NONE
85	PERLND	SATURATED	High Density Residential	NONE
86	PERLND	SATURATED	Commercial/Industrial	NONE
87	PERLND	SATURATED	Wetland	NONE
91	IMPLND	N/A	Low Density Residential	N/A
92	IMPLND	N/A	High Density Residential	N/A
93	IMPLND	N/A	Commercial/Industrial	N/A
94	IMPLND	N/A	Roads	N/A

PERLND = pervious surface.
IMPLND = impervious surface.
N/A = not applicable.
[a] Slope categories: flat (0% – 5%), low (5% – 10%), medium (10% – 15%), steep (>15%).

Model Hydraulics

The current network of 60 reaches range from approximately 0.23 to 4.82 miles in length. Each stream reach is represented by a hydraulic function table called an FTABLE, which defines the flow rate, surface area, and volume as a function of water depth in the channel reach. These were originally developed using observed data or estimated values using cross-section data provided by King County (Aqua Terra 2003).

Except for an error for the FTABLE for Lake Meridian, the model hydraulics and channel geometry were not changed. For Lake Meridian (RCHRES 172), the surrounding elevation had been added to the depth values, resulting in erroneous depths for the lake. The FTABLE was corrected and replaced with values sent by Jeff Burkey from King County based on known Lake Meridian bathymetry.

Groundwater Transfers

Carlson and Massmann (2015) documented the updates that MIT made to the King County version model to better characterize baseflow predictions in the model. Two types of groundwater transfers were added by MIT based on their analysis of groundwater contours and the hydrogeology of the watershed:

1. Internal or *inter*-basin groundwater transfers between reaches within the watershed.
2. External groundwater transfers — where groundwater enters the system from outside the watershed or leaves the watershed.

These transfers were specified as fractions, i.e., at each time step, a certain fraction of the groundwater is moved into or out of the reach. While the fractions vary spatially, they are constant throughout the model simulation. The locations of these transfers are illustrated in Figure 10.

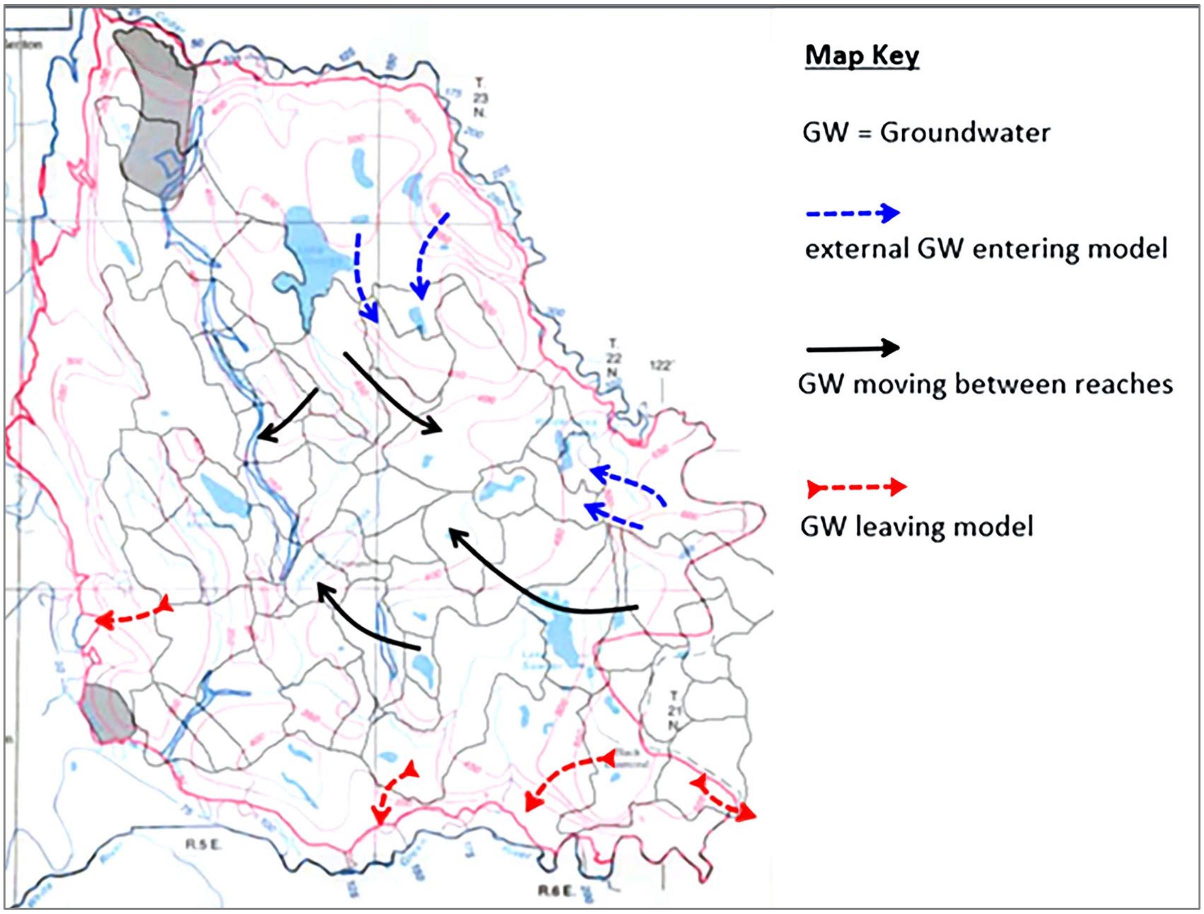

Figure 10. Groundwater contours from the Vashon Advance (Qva) aquifer superimposed on Soos HPSF catchment outlines (figure adapted from Carlson and Massmann (2015)).

These external transfers are set up as fractions at each time step and do not vary seasonally; therefore, they do not capture the seasonal pattern of groundwater movement. Aquifers typically get recharged in the winter and spring, and this recharge decreases in the summer. During hydrology calibration, we found that the model was under-predicting annual volumes, especially in the Covington sub-watershed. After consulting with one of Ecology's hydrogeologists (E. Freeman, pers. comm., February 27, 2020), who reviewed MIT's work within the context of our study, a decision was made to eliminate the external groundwater transfers in the Covington sub-watershed. It is possible that the seasonal patterns in groundwater movement are more pronounced in the Covington sub-watershed and that the external transfers implemented by MIT did not adequately reflect those patterns.

An additional update to the groundwater component of the model included adding seasonal groundwater/seepage loss from Lake Sawyer (RCH 442). Several studies have documented a seasonal loss of groundwater from Lake Sawyer:

- Lake Sawyer Hydrogeological Study (Hart Crowser 1990): Page 9 states that estimated groundwater outflows through the lake bottom average approximately 3 cfs, with the highest outflows occurring during the summer/fall.
- Diagnostic Study of Lake Sawyer (Carroll and Pelletier 1991): Page 34, Table 4.1 presents the lake's monthly water budget and shows groundwater losses of 4 – 8 cfs between September and November.
- Lake Sawyer Management Plan (King County 2000): Page 5-3 mentions how calibration of the Lake Sawyer submodel "was achieved by applying a seasonally varying seepage loss."
- Appendix C to Lake Sawyer Management Plan (King County 2000): a table of monthly and annual water balance presents estimates of residual groundwater between Jan 1994 and June 1995 ranging from 1.7 to 13.7 cfs, with higher values in cooler months and lower values in warmer months.

Given the range of potential groundwater loss from the lake presented in the above studies, we conducted a sensitivity analysis to test different magnitudes of groundwater loss (low, medium, and high) from Lake Sawyer to see what magnitude of loss improved the annual water balance in the Covington subbasin (Table 6). This range of losses was modeled using a WDM time series file, which specifies how much water leaves the RCH 442 (the reach that represents Lake Sawyer) at a daily time step (the actual losses varied by month).

The change resulting from implementing these groundwater losses was assessed in terms of observed vs. simulated seasonal volumes at the downstream gage on Covington Creek (Gage 09a, in Figure 12 and Table 7), as well as by comparing observed and simulated lake levels. The final selection of values (right-most column in Table 6) was based on reducing the difference between observed and predicted fall volumes at the Covington gage. The update did not make a significant change to lake level predictions but significantly improved the over-prediction of fall volumes at the Covington gage.

Table 6. Lake Sawyer's monthly groundwater losses tested from low to high, and the final set of losses implemented in the model.

Month	Season	Low (cfs)	Med (cfs)	High (cfs)	Final (cfs)
January	winter	1	4	9	**1**
February	winter	0	2	3	**0**
March	spring	0	1	3	**0**
April	spring	0	1	3	**0**
May	spring	0	1	3	**0**
June	summer	0	1	3	**1**
July	summer	0	1	3	**1**
August	summer	2	4	6	**2**
September	fall	3	6	12	**6**
October	fall	3	8	12	**7**
November	fall	3	8	13	**7**
December	winter	2	6	11	**1**

Water Withdrawals

MIT had also added large Group A water withdrawals[13] in the watershed to the model. The magnitudes of these withdrawals were not changed, but the time series of withdrawals was extended by MIT through 2015 by acquiring well withdrawal data for the newer time period. The records received were monthly and then parsed into daily time steps. A fraction of each well withdrawal time series was then associated with one or more reaches based on hydrogeological connections.

Overall, the magnitudes of withdrawals are lower in the newer time period (2009 – 2015) relative to the original time period (2001 – 2008) at all wells included in the analysis. Figure 11 compares the magnitude of daily withdrawals between the two time periods being extracted from each model reach and its associated subbasin. MIT provided documentation to Ecology about this update, which is included in Appendix B.

RESPEC did make an update as to how the well withdrawals were configured in the HSPF model to reflect best practices and avoid errors during scenario modeling. This involves modifying how water is removed from the individual reaches where withdrawals occur but does not change the overall water balance (i.e., the magnitude and timing of withdrawals remain the same). Previously, well withdrawals were represented using a negative time series to remove volume stored in the RCHRES, but with the update, the water is now being removed through additional outflow components as a demand time series. The original approach creates a negative

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[13] Group A water withdrawals generally capture the largest groundwater uses and are defined by the Washington State Department of Health as ones that serve 15 or more residential connections, 25 or more people per day for 60 or more days per year (https://doh.wa.gov/community-and-environment/drinking-water/water-system-assistance/tnc-water-systems).

time series that could potentially cause a deficit during a time step (negative storage volume) that would need replenishing in the following model time step and could also produce an unrealistic enrichment of TSS at lower flows because no sediment was associated with the water withdrawal. The updated outflow demand approach ensured that neither of these potential issues would occur.

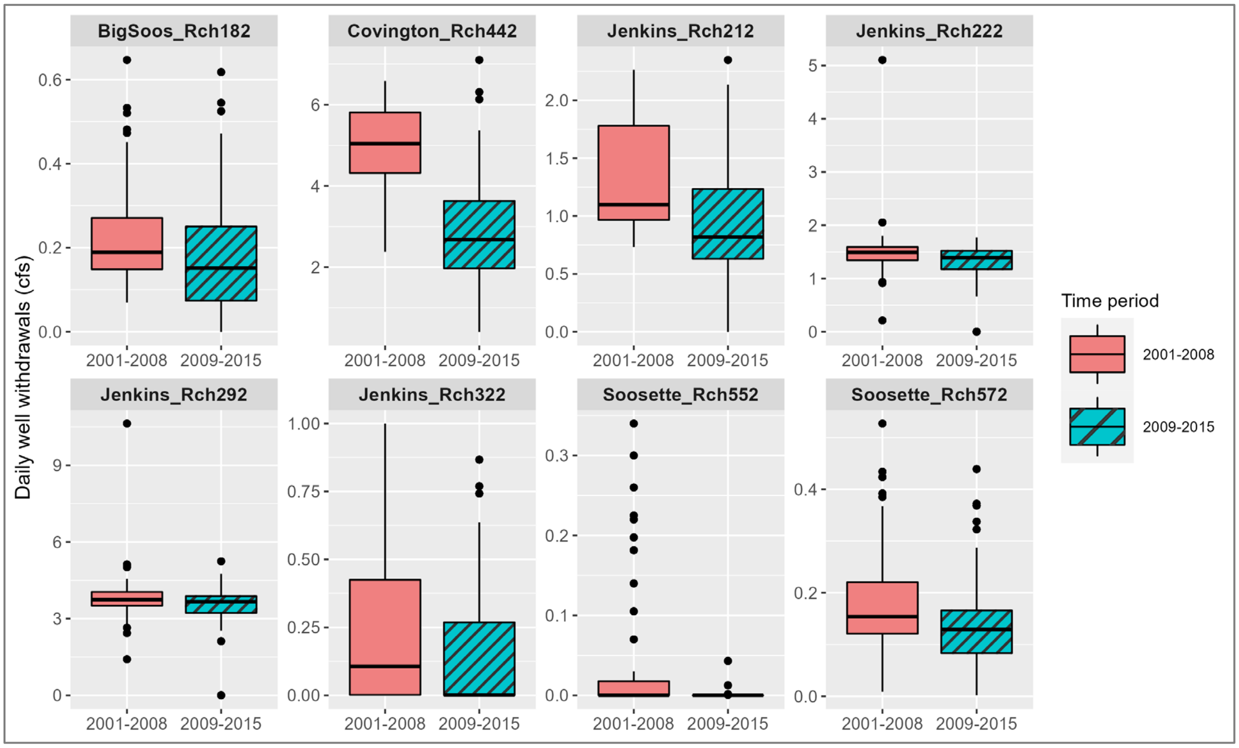

Figure 11. Boxplots comparing the magnitude of daily well withdrawals implemented in different model reaches by MIT between the original 2001 – 2008 time period and the extended 2009 – 2015 time period.

Sediment Module

Lastly, the sediment module of HSPF was activated in the UCI file to enable sediment simulation. Sediment calibration began with the existing sediment initial conditions and sediment parameters, which were included in the King County version of the model. The King County version was calibrated to sediment before MIT made the groundwater and water withdrawal updates, and the sediment parameters in that model reflect the original King County calibration effort. Sediment parameters were adjusted to recalibrate to sediment for this study, as is described in the “Sediment Calibration” section of this report.

Limited documentation could be found on how the initial sediment conditions were determined — some were adjusted, but some remained the same as follows:

SOSED distribution — this defines the distribution of sediment entering the stream reach in terms of the fraction of sand, silt, and clay. The original model had a SOSED distribution of 0.15, 0.60, and 0.25 (sand, silt, and clay). We used the USDA soil mapping tool[14] to calculate the area-weighted average of percent sand, silt, and clay within the watershed. The result of this analysis was a distribution of 0.60, 0.30, 0.10 (sand, silt, clay). A portion of the sand from upland areas gets trapped and does not make it into the stream; we assumed half of the sand reaches the stream (per RESPEC's recommendation, based on past modeling efforts) and distributed the remaining sand fraction between silt and clay. The final SOSED distribution of sand, silt, and clay in the model was, therefore, 0.30, 0.45, and 0.25.

Initial suspended sediment concentrations — this defines the initial concentrations of suspended sand, silt, and clay. Values for this study were not changed from the King County version of the model. Values in all reaches (except reaches with lakes) were set at 0.3 mg/L for sand, silt, and clay — adding up to a total TSS concentration of 1.0 mg/L. Values in reaches with lakes were set at 0.001 mg/L, reflecting the fact that lakes serve as a sink of sediment, and therefore, less TSS will be in suspension. Once the model is run, these initial concentrations do not greatly influence the simulation.

Initial bed depth and composition — the original model had an initial bed depth of 0.2 ft with an initial bed composition of 0.65, 0.15, and 0.20 for sand, silt, and clay, respectively. We did not have any field observations or measurements of sediment bed depth. During calibration, the initial bed depth was increased to 2 ft to ensure there was sufficient initial sediment available for scour (after noticing that the model was running out of sediment in some reaches). The distribution between sand, silt, and clay was also adjusted based on instream sediment bed grain size data[15] (percent sand, silt, and clay) collected in the watershed between 2000 and 2015. Data showed that the distribution of sand, silt, and clay in the stream bed is approximately 0.75, 0.15, and 0.10, respectively, when averaged across all locations in the watershed. The initial bed composition in the model was updated to reflect this distribution across all reaches. The data showed that this distribution was relatively similar across all locations, except at Jenkins, where sediment data had a higher proportion of silt and clay and less sand. This difference was noted, and in-stream sediment calibration parameters in Jenkins were adjusted considering this.

Model Calibration Approach

The original model simulation period of 2001 – 2008 was extended to the years 2009 – 2015. The calibration of the King County version of the model was focused on optimizing model performance across WRIA 9 rather than just in the Soos watershed. MIT's updates, on the other hand, were made only to the Soos portion of King County's WRIA 9 model, but these updates were focused on improving model performance during low flow/baseflow conditions by adding

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[14] USDA Soil mapping tool: https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

[15] Grain size data were collected by King County's Sediment Monitoring Program and Ecology's Regional Stormwater Monitoring Program (RSMP)

groundwater transfers and withdrawals, and they did not make any changes to the model parameters.

The combination of extending the model simulation period through 2015, the focus on stormwater, and the incorporation of the model updates described so far called for a thorough recalibration of the hydrology component of the HSPF model, followed by calibration of sediment. We focused on optimizing model performance within the Soos and improving model performance across all seasons, with a particular focus on stormwater flows and volumes, as well as TSS concentrations and loads. Figure 12 illustrates the location of six flow gages and four TSS monitoring locations – these locations were the focus of the calibration effort, where comparisons were made between modeled and observed flows and TSS concentrations.

EPA Technical Note 6 (EPA 2000b) and EPA Technical Note 8 (EPA 2006) both include a description of the hydrology and sediment parameters in HSPF, respectively. These guidance documents include approaches to estimating parameter values as well as tables that list their possible ranges compiled from previous applications of HSPF across North America. These two Technical Notes were heavily referenced and used throughout the calibration process to maintain parameters within possible values.

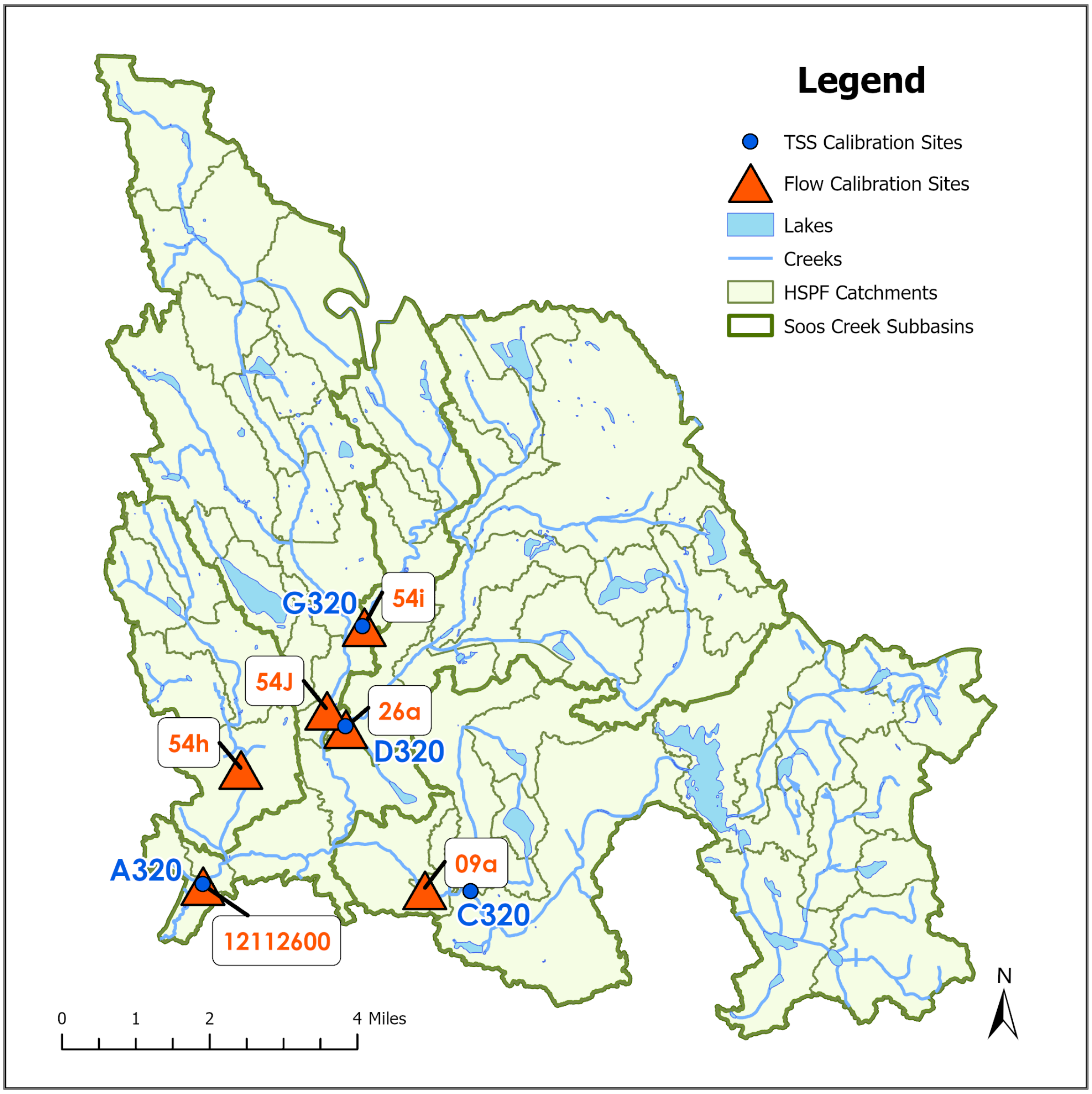

Figure 12. Locations of streamflow gages and TSS monitoring stations in the Soos watershed that were used for hydrology model calibration.

All gages are operated by King County except 12112600, which is a USGS gage.

Hydrology Calibration

The hydrology calibration focused on comparing modeled streamflow against observed streamflow at six continuous streamflow gages in the watershed (there are two additional gages in the Soos just upstream of Lake Sawyer, but these two locations only had data limited to a few months that overlapped with our model time simulation period and were not used to assess model calibration). Table 7 lists the six streamflow gages used for calibration. Five of the six gages are located close to the mouth of each of the major subbasins in the watershed: Soosette, Little Soos, Jenkins, Covington, and Big Soos. An additional gage is located further upstream on the mainstem of Soos Creek, just above its confluence with Jenkins Creek (Figure 12), and is hereby referred to as "Big Soos – Kent." All the gages had data for the full model simulation period except for 54J (Soos Creek at Kent-Black Diamon Rd.), which only had data starting in 2010.

Table 7. Streamflow gages used for hydrology model calibration, including the model reach they are associated with and their data availability.

Site Code	Agency	Model Reach	Site Name	Data Availability[a]
09a[b]	King County	RCH 512	Covington Creek near Mouth	1988–current
26a[b]	King County	RCH 332	Jenkins Creek near Mouth	1987–current
54h	King County	RCH 582	Soosette Creek Above SR 18	1993–current
54i	King County	RCH 142	Little Soos Creek at SE 272nd	1995–current
54J	King County	RCH 152	Soos Creek at Kent-Black Diamond RD	2010–current
12112600[b,c]	USGS	RCH 592	Big Soos Creek above hatchery near Auburn	2007–current

[a] All stream calibration gages were active at the time we retrieved data on 7/9/2018. We downloaded all available data but only used data from 1/1/2001 to 12/31/2015, which was the model calibration period.

[b] Gages used in original model calibration.

[c] This streamflow gage is operated by the USGS but is co-located with King County site 54a, which is also a King County monitoring site for other parameters.

As specified in the QAPP (Mohamedali 2018), hydrology calibration first focused on improving agreement between observed and simulated flows at all six calibration locations for the following metrics:

1. Annual volumes/water balance
2. Seasonal volumes and monthly flows
3. Baseflow
4. Storm events[16]

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[16] Storm events were identified using a baseflow separation technique and also included identifying peak and valley hydrograph dates, to ensure that only stormflows were being included.

Subsequently, we also compared the following additional hydrology metrics:

- Flow percentiles (5th, 10th, 25th, 50th, 75th, and 90th)
- Storms within each season
- High pulse count, TQ-mean, and the PK2YR: Winter baseflow ratio.

Hydrology calibration results are presented in the Model Results section of this report.

Parameter adjustments were made through numerous model runs. Both EPA (2000b) and Dinicola (1990) were used as guidance when adjusting parameter values. Dinicola (1990) focused on modeling rainfall-runoff characteristics in various basins in western King and Snohomish counties. The Soos was included among these basins.

Parameter modifications were made to increase agreement between simulated and observed streamflow and volumes at various timescales using a combination of model statistics and visual plots. Starting with the MIT version of the model (Carlson and Massmann 2015), the following hydrology parameters were modified within each hydrology parameter block[17]:

PWAT-PARM2

- **INFILT** — *infiltration index for division of surface and subsurface flow (inches/hour)*: original values were more than 2.5 times higher than the maximum values within the possible range. Values were halved on Till and Saturated soils and reduced by a factor of four on Outwash soils. Final values are now within the possible range, except on Outwash and Saturated soils, where values are slightly higher but still within the range of Dinicola (1990).
- **KVARY** — *variable groundwater recession (1/inches)*: values were adjusted to improve the simulation of the storm hydrograph recession pattern.
- **AGWRC** — *base groundwater recession (dimensionless)*: values were adjusted to improve the simulation of the storm hydrograph recession pattern.

PWAT-PARM3

- **INFEXP** — *exponent in infiltration equation (dimensionless)*: values on outwash soils changed from 5 to 2 to match values in Dinicola (1990) and reduced from 10 to 3 on Saturated soils to bring values within the possible range.

PWAT-PARM4

- **UZSN** — *nominal upper zone soil moisture storage (inches)*: values were updated to vary monthly using the MON-UZSN block and were reduced by a factor of approximately 0.8 to get them within acceptable values. Values are now lowest in the winter and then increase a little in the spring and get higher in the late summer and fall. This pattern follows the growing season, where more moisture can be stored in the soil's upper zone when vegetation is growing in the summer/fall.

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[17] Other parameter adjustments were also explored, but only those that were implemented in the final model calibration are discussed.

- **INTFW** — *interflow inflow parameter (dimensionless)*: values increased by slope to match those documented in Dinicola (1990).
- **IRC** — *interflow recession parameter (dimensionless)*: values in the original model were consistently 0.91 across all soil and slopes. Values now vary between 0.75 and 0.90 to improve the simulation of the storm hydrograph recession pattern.
- **LZETP** — *lower zone evapotranspiration (dimensionless)*: values were adjusted during calibration to improve the annual water balance. Original values ranged from 0.25 to 0.80, and final values ranged from 0.10 to 0.72.

IWAT-PARM2

- **LSUR** — *length of overland flow (feet)*: reduced from 500 to 100 to bring values within the acceptable range.

The final hydrology parameters are closer to the typical or possible ranges than the ones in the MIT version of the model. Table 8 compares the final hydrology parameters to acceptable ranges in EPA Technical Note 6 (EPA 2000b) as well as ranges in Dinicola (1990).

Table 8. Soos Creek hydrology parameters compared to acceptable ranges in EPA Technical Note 6 (EPA 2000b) and values used in Dinicola (1990).

Parameter Name	Parameter Definition	Units	EPA Min	EPA Max	Dinicola Min	Dinicola Max	Soos Min	Soos Max	Comment
PWAT-PARM2									
LZSN	Lower Zone Nominal Soil Moisture Storage	in	2.00	15.0	4.00	5.00	2.50	5.00	Varies by soil and slope
INFILT	Index to Infiltration Capacity	in/hr	0.00	0.50	0.03	2.00	0.05	1.30[a]	Varies by soil, slope, and land use
LSUR	Length of overland flow	ft	100	700	100	400	150	350	Varies by soil and slope
SLSUR	Slope of overland flow plane	ft/ft	0.00	0.30	0.001	0.200	0.025	0.252	Varies by soil, slope, and land use
KVARY	Variable groundwater recession	1/in	0.00	5.00	0.30	0.50	0.15	1.00	Varies by soil, slope, land use, and precip. zone
AGWRC	Base groundwater recession	none	0.85	1.00	0.996	0.996	0.930	0.992	Varies by soil, slope, land use, and precip. zone
PWAT-PARM3									
INFEXP	Exponent in infiltration equation	none	1.00	3.00	1.50	10.00	2.00	3.0	Varies by soil
INFILD	Ratio of max/mean infiltration capacities	none	1.00	3.00	2.00	2.00	2.00	2.00	Consistent across all PERLNDS
DEEPFR	Fraction of GW inflow to deep recharge	none	0.00	0.50	N/A	N/A	0.00	0.00	Consistent across all PERLNDS
BASETP	Fraction of remaining ET from baseflow	none	0.00	0.20	0.00	0.00	0.00	0.00	Consistent across all PERLNDS
AGWETP	Fraction of remaining ET from active GW	none	0.00	0.20	0.00	0.70	0.00	0.20	Varies by soil
PWAT-PARM4									
INTERCEP[c]	Interception storage capacity	in	0.01	0.40	0.10	0.20	0.16	0.40	Varies by land use
UZSN[c]	Upper zone nominal soil moisture storage	in	0.05	2.00	0.15	3.00	0.34	2.88[a]	Varies by soil, slope, and land use
NSUR	Manning's n (roughness) for overland flow	none	0.05	0.50	0.25	0.50	0.25	0.50	Varies by soil and land use
INTFW	Interflow inflow parameter	none	1.0	10.0	0.0	7.0	2.8	7.0	Varies by soil and slope
IRC	Interflow recession parameter	none	0.30	0.85	0.30	0.70	0.75	0.90[b]	Varies by soil and slope
LZETP[c]	Lower zone ET parameter	none	0.10	0.90	0.25	0.80	0.10	0.72	Varies by soil and land use
IWAT-PARM2									
LSUR	Length of overland flow	ft	50	250	500	500	100	100	Consistent across all IMPLNDs
SLSUR	Slope of overland flow plane	ft/ft	0.00	0.15	0.01	0.01	0.01	0.01	Consistent across all IMPLNDs
NSUR	Manning's n (roughness) for overland flow	none	0.01	0.15	0.10	0.10	0.10	0.10	Consistent across all IMPLNDs
RETSC	Retention storage capacity	inches	0.01	0.30	0.10	0.10	0.30	0.30	Consistent across all IMPLNDs

[a] Value is outside of EPA (2000b) but within Dinicola (1990) parameter range. Further explanation is provided after Table 12.

[b] Value is outside of EPA (2000b) and Dinicola (1990) parameter range. Further explanation is provided after Table 12.

[c] Values vary monthly.

Sediment Calibration

The sediment calibration is always performed after hydrology calibration is complete since hydrology is one of the main drivers of watershed sediment erosion and wash-off processes. The MIT version of the model included sediment parameters, which were likely a remnant of previous King County efforts, but the sediment module was turned off. After activating the sediment module, we began sediment calibration with the original parameters in the UCI file and then followed the steps below, adapted slightly from Donigian and Love (2003) and King County (2013):

1. Estimated expected TSS loading rates from the landscape, which are often a function of topography, land use, and management practices. For this study, we compiled TSS loading from local estimates (Herrera 2007, 2011; and King County 2013) and literature data (Burton 2002 and Shaver 2007).
2. Calibrated the model TSS loading rates to the expected rates from step 1 by adjusting the parameters that influence sediment wash-off and erosion processes (described in Table 9).
3. Estimated initial parameter values and storages for all reaches (described in Table 9).
4. Adjusted scour, deposition, and transport parameters so that scour occurs during high flows and deposition occurs during low flows. These parameters were adjusted iteratively by comparing observed and modeled TSS based on parameter adjustments, with the goal of increasing agreement between the two.
5. Analyzed sediment bed behavior, transport, and the overall sediment budget by reach. This was primarily done by looking at the annual average bed depth in the model, which should not change dramatically over the simulation period.
6. Compared simulated and observed sediment concentrations and loads to both individual grab sample measurements as well as averaged monthly and annual sediment concentrations and loads.
7. Repeated Steps 1 – 6 as needed.

After completing steps 1 and 2 above, we adjusted the model parameters to bring model simulated loading rates to be more consistent with compiled estimates. The sediment parameters that were adjusted during this phase are listed in Table 9.

Once the sediment loading rates from the watershed were calibrated, the next stage of the sediment calibration focused on fine-tuning the channel processes of scour, deposition, and transport to compare simulated and observed instream TSS, defined as the TSS in the water column within the stream reach.

There are several TSS sampling sites throughout the watershed, but only four of the King County sites have sufficient long-term TSS concentration data that could be used for TSS calibration. The TSS calibration focused on these four locations. Each location has between 10 and 32 TSS grab samples per year (Table 10 and Figure 12).

Table 9. Sediment parameters that were adjusted during model calibration relative to the MIT version of the model.

Parameter Name	Parameter Description	How parameter was adjusted for this study relative to the MIT version
SLDS	Initial storage of solids on impervious surfaces (tons/acre)	Original values varied with precipitation zones 1, 2, and 3, where values were higher in higher precipitation zones, but the values in precipitation Zone 4 were equal to those in Zone 1. For consistency, values in Zone 4 were increased to be slightly higher than those in Zone 3 (since Zone 4 experiences the highest precipitation).
DETS	Initial storage of detached sediment (tons/acre)	Values were decreased by a factor of two to better match steady-state values that were determined from model-simulated levels of detached sediment over time.
NVSI	Atmospheric additions to sediment storage (lb/ac-day)	Original values were relatively high and ranged from 4 to 40 and were decreased to range from 2 to 9 to be within acceptable ranges, but the model was insensitive to this change.
KRER	Coefficient in the soil detachment equation	An erroneous value of 64 was corrected. This was likely a decimal point error and was supposed to be 0.0064 for saturated wetlands based on personal communications with Burkey (2022).
AFFIX	Daily reduction in detached sediment	Values were increased to bring them within acceptable ranges.
KSER and JSER	Coefficient and exponent of sediment washoff equation	The lowest KSER values were lower than acceptable minimum values. Both KSER and JSER values were adjusted to different degrees in different PERLNDs and IMPLNDs to represent TSS loadings from different land uses and soil types more accurately.
KEIM and JEIM	Coefficient and exponent of solids washoff equation	Original values were two magnitudes lower than the acceptable range. Values were increased to bring them into the acceptable range during calibration of TSS loading rates.
ACCSDP	Solids accumulation rate on land (lb/ac-day)	Values were halved from original values.
REMSDP	Fraction of solids storage removed when there is runoff (per day)	Fraction was increased from 0.0 to 0.05 to represent some removal from wind, air currents, and traffic.

Table 10. King County sites with long-term TSS data used for sediment calibration.

Site Code	Model Reach	Site Name
A320	RCH 592	Big Soos Creek at USGS Gaging Stn. 12112600
C320[a]	RCH 452	Covington Cr Bridge and Kent Black Diamond Rd
D320	RCH 332	Jenkins Cr Bridge on Kent Black Diamond Rd
G320	RCH 142	Little Soos Creek at Covington Way SE

[a] This is the only TSS site not co-located with a stream gage but is slightly upstream of gage 09a.

Some of the major in-stream sediment parameter updates are described below:

TAU (bed shear stress) scour and deposition — TAU values vary dynamically simulated within each reach at an hourly time step and are a function of channel slope and geometry. Determining thresholds for TAU at which silt and clay are deposited or scoured is a key step in the model calibration process. This step first involved querying the hourly reach TAU values simulated by the model and calculating their distribution in terms of percentiles. Then, specific percentiles were selected as thresholds for scour and deposition for silt and clay for each reach. For example, if the 90th percentile of TAU values is specified as the scour threshold for silt, that means that the model will scour silt when TAU values go above the 90th percentile. Generally, since silt is heavier/larger than clay, it has higher deposition and scour TAU thresholds than clay, i.e., it takes a higher magnitude of bed shear stress for silt to deposit and scour relative to clay. These scour and deposition percentile thresholds were then adjusted to optimize the simulation of predicted TSS to better match observed ranges. Various schemes were explored, for example, varying TAU percentile thresholds based on stream order or subbasin in the watershed. The final TAU values were based on reach type:

- **Reaches represented as lakes**: silt and clay deposition thresholds were set at the 50th percentile, and silt and clay scour thresholds were set at the maximum TAU values. This reflects the fact that lake reaches have high deposition and limited to no scour.
- **Reaches with significant wetlands**: silt and clay deposition TAU thresholds were set at 75th and 70th percentiles, respectively, and silt and clay scour TAU thresholds were set at 99th and 98th percentiles, respectively. Reaches classified as "wetlands" were identified based on a GIS layer from King County[18]. If most of the streamline overlapped with a wetland complex, then that reach was classified as a "wetland," and the relevant TAU thresholds were applied. Significant portions of the upper reaches of the Big Soos, Jenkins, and Covington creeks are influenced by wetlands, and adjusting the TAU values in these reaches was a way to capture the different dynamics and higher deposition that is likely occurring here relative to the faster-flowing reaches of the watershed.

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[18] King County GIS Open Data: https://gis-kingcounty.opendata.arcgis.com/.

- **All other reaches**: silt and clay deposition TAU thresholds were set at 50th and 45th percentiles, respectively, and silt and clay scour TAU thresholds were set at 90th percentiles.

Instream sediment parameters — in addition to TAU, the following instream parameters were adjusted to improve the sediment calibration:

- **W** — *fall velocity of transported silt and clay particles* (in/sec): these were originally set to 0.0035 and 0.0004 and increased to 0.012 and 0.004 for silt and clay, respectively.
- **M** — *erodibility coefficient (lb/ft^2/day)*: these were originally set to 0.5 for both silt and clay and were reduced to 0.01 for silt and 0.02 for clay.
- **KSAND** — *coefficient in sandload power function (complex units)*: values were very high in the original model and varied greatly from reach to reach from values of 0 to more than 8 in some reaches. These were reduced to 0.15 – 0.35. Values of 0.15 were used in reaches that had wetland influence and 0.20 in the Jenkins sub-watershed (which has a different sediment distribution based on particle grain size data) as well as the Covington watershed upstream of Lake Sawyer. Values of 0.25 – 0.35 were applied in all other reaches.
- **EXPSND** — *exponent in sandload power function (complex units)*: values in the original model were set to either 1.4 or 1.7. These were adjusted slightly to vary from 1.5 to 2.0, with variations again depending on whether the reach was wetland-influenced or in the Jenkins or Covington watersheds.

Table 11 compares the final sediment parameters to acceptable ranges in EPA Technical Note 8 (EPA 2006).

Table 11. Soos Creek sediment parameters compared to acceptable ranges in EPA Technical Note 8 (EPA 2006).

Parameter Name	Parameter Definition	Units	Possible EPA Min	Possible EPA Max	Soos Min	Soos Max	Comment
SED-PARM2							
SMPF	Management Practice (P) factor from USLE	none	0.0	1.0	1.00	1.00	Does not vary across PERLNDs
KRER	Coefficient in the soil detachment equation	complex	0.05	0.75	**0.0064**[a]	**0.96**[a]	Varies by precip. zone
JRER	Exponent in the soil detachment equation	none	1.0	3.0	2.0	2.0	Does not vary across PERLNDs
AFFIX	Daily reduction in detached sediment	per day	0.01	0.05	0.01	0.03	Varies by soils
COVER	Fraction land surface protected from rainfall	none	0.00	0.98	0.50	0.98	Varies by land use and month
NVSI	Atmospheric additions to sediment storage	lb/ac-dy	0.0	20.0	2.0	9.0	Varies by land use
SED-PARM3							
KSER	Coefficient in the sediment washoff equation	complex	0.10	10.0	0.10	2.4	Varies by land use
JSER	Exponent in the sediment washoff equation	none	1.0	3.0	1.32	1.60	Varies by precip. zone
KGER	Coefficient in soil matrix scour equation	complex	0.0	10.0	0.0	0.0	Does not vary across PERLNDs
JGER	Exponent in soil matrix scour equation	none	1.0	5.0	2.0	2.0	Does not vary across PERLNDs
SLD-PARM2							
KEIM	Coefficient in solids washoff equation	complex	0.1	10.0	0.10	0.70	Varies by land use
JEIM	Exponent in solids washoff equation	none	1.0	3.0	2.0	3.0	Varies by land use
ACCSDP	Solids accumulation rate on the land surface	lb/ac-dy	0.0	30.0	0.001	0.002	Varies by land use
REMSDP	Fraction of solids removed per day	per day	0.01	1.00	0.05	0.05	Does not vary across IMPLNDs
SAND-PM							
D	Effective diameter of the transported sand particles	in	0.00	0.20	0.005	0.005	Does not vary across RCHRES
RHO	Density of sand particles	g/cm3	1.50	3.00	2.50	2.50	Does not vary across RCHRES
KSAND	Coefficient in sandload power function formula	complex	0.001	10	0.15	0.35	Varies across RCHRES
EXPSND	Exponent in sandload power function formula	complex	1.0	6.0	1.5	2.1	Varies across RCHRES
SILT-CLAY-PM							
D (Silt)	Effective diameter of silt particles	in	0.0001	0.004	0.0006	0.0006	Does not vary across RCHRES
D (Clay)	Effective diameter of clay particles	in	.000005	.00025	.004	.004	Does not vary across RCHRES
W	Fall velocity of transported silt particles in still water	in/sec	0.0	0.1	0.004	0.012	Varies by silt or clay
RHO	Density of silt particles	g/cm3	1.5	3.0	2.0	2.2	Varies by silt or clay
TAUCD	Critical bed shear stress for deposition	lb/ft2	0.001	1.0	0.0058	0.9193	Varies by silt or clay
TAUCS	Critical bed shear stress for scour	lb/ft2	0.01	3.0	0.0540	2.0769	Varies by silt or clay
M	Erodibility coefficient	lb/ft2.d	0.001	5.0	0.02	0.10	Varies by silt or clay

[a] Value is outside of the typical EPA (2006) parameter range. Further explanation is provided after Table 12.

RESPEC review and recommendations

RESPEC's peer review of the HSPF model concluded with a list of comments and recommendations. Table 12 summarizes their list and how each item was addressed.

Table 12. Summary of comments and recommendations provided in RESPEC's peer review of the HSPF model (adapted from Lupo and Donigian 2022).

Comment/Recommendation	Response
Correct various FTABLE spacings for consistency.	The spacings in the UCI file were corrected, and columns were left justified in all FTABLEs.
Verify depth of FTABLE 172 (Lake Meridian). Appears to be extraordinarily deep relative to other lake outflows.	The error in the original FTABLE appeared to be a result of the added surrounding elevation to the depths in the FTABLE. The FTABLE was corrected and replaced with values sent by Jeff Burkey from King County based on known Lake Meridian bathymetry. This change did not influence the hydrology calibration.
Take great care with any future updates to the SCHEMATIC.	No additional updates to the SCHEMATIC were made for this project.
Add a detailed explanation of the withdrawal estimates to the final report with emphasis on why the two periods seem inconsistent for some of the time series. Conduct a test to determine if the inconsistent well withdrawal time series are impacting annual runoff inconsistencies at the Covington gage (RCHRES 512) where runoff is under-predicted.	Water withdrawal estimates developed by MIT were more accurate for the newer (2009–2015) time period relative to the original time period (2001–2008) as a result of improved monthly metering records. It was also noted that groundwater use has declined as cities have shifted to other water sources outside the Soos. A detailed explanation of the methods used to develop these estimates is provided in Appendix B. The final calibrated model did not implement any changes to water withdrawals since both time periods used the best data available at that time. However, a sensitivity model run was conducted by applying the monthly average water withdrawals from 2009 to 2015 to the earlier time period. The resulting effect on model hydrology was not minimal but did result in increasing the overprediction of fall and summer volumes in Covington and Soosette creeks, respectively. Annual runoff was consistently underpredicted in Covington from 2009 to 2015 (average RPD of 13%) relative to 2001–2008 (average RPD of 4.7%). If the well withdrawal estimates for the newer time period are greater than those estimated, then even less water would be staying in the system due to withdrawals, and this would only increase this underprediction.
Correct the KRER value of 64 for PERLND 387 to the intended value of 0.0064 (should not have a significant impact on the sediment calibration results).	This was a typo that was corrected; KRER value was changed from 64 to 0.0064.
Provide justification in the final report regarding some non-typical parameter values and approaches.	Most of the non-typical parameter values were adjusted to bring them into the expected range. Parameter values that are still outside the typical range are summarized below this table.

Comment/Recommendation	Response
Conduct a test where either MON-UZSN parameters are increased in the summer months or the monthly interception table is implemented to determine if these actions would aid the summer storm simulation without producing undesirable results for the other main qualitative and quantitative tests.	Several model runs were conducted using different monthly UZSN values, including increasing values in the summer. Increasing UZSN in the summer months had a negligible impact on summer peak flows and storm events when the model is flashier than observations. Monthly interception was also tested and implemented. The model was relatively sensitive to these values — increasing them improved underpredictions in summer volumes but at the expense of overpredicting fall volumes. Final INTERCEP values were selected to minimize the overall difference between observed and simulated seasonal volumes.
Perform simple watershed-wide scenarios to ensure the system is responding as expected.	Several scenarios were conducted where land use changes were implemented, and we found that the system responded as expected.

Parameters Outside Typical Range

There are a few parameters in the final calibration that are outside the expected range:

- INFILT — final parameter values on Outwash and Saturated soils are 0.52 – 1.3 in/hr, which are above the expected maximum of 0.5 in/hr. However, these values are closer to but still below those in Dinicola (1990), where INFILT values were up to 2 in/hr on Outwash and Saturated soils.
- UZSN — final parameter values only on saturated soils (2.88 in) are above the expected maximum of 2.0 in, but again, these are below the values in Dinicola (1990), where values ranged from 0.5 to 3 in, as well those in TetraTech (2017), where values on saturated soils were as high as 2.9 in. Both these studies include the Soos in their model domain and likely reflect the higher capacity in saturated wetland soils to store moisture relative to Outwash and Till soils.
- IRC — maximum IRC values of 0.90 in the final model are slightly above the expected maximum of 0.85. Values of 0.90 were only applied to Till soils on flat slopes (all other values are less than or equal to 0.85). IRC values of 0.75 – 0.90 were selected after several model sensitivity runs were conducted with varying IRC values to evaluate the model’s ability to match observed storms and the shape of the recession hydrograph.
- KRER — the lowest KRER values are below the expected minimums, but these are only applied to saturated soils/wetlands, where we expect very limited soil detachment. The highest value of 0.96 is also above the expected maximum of 0.75, but the model does not appear to be very sensitive to these values.

Calibration Assessment

As specified in the QAPP (Mohamedali 2018), a “weight-of-evidence” approach was applied to evaluate model performance during the calibration process. In watershed modeling, this approach, which uses a combination of quantitative/statistical and qualitative/graphical methods to determine the quality of model calibration, has become standard practice (Donigian 2002; EPA 2006; Duda et al. 2012; Brown and Caldwell 2013; and USACE, TNC, and IC 2013).

Within the HSPF modeling community, thresholds for specific model metrics are sometimes used to communicate the *general* quality of model calibration. Figure 13 and Table 13 provide examples of how these thresholds can be used to gauge the level of accuracy (e.g., from poor to very good) expected from the application of the HSPF model.

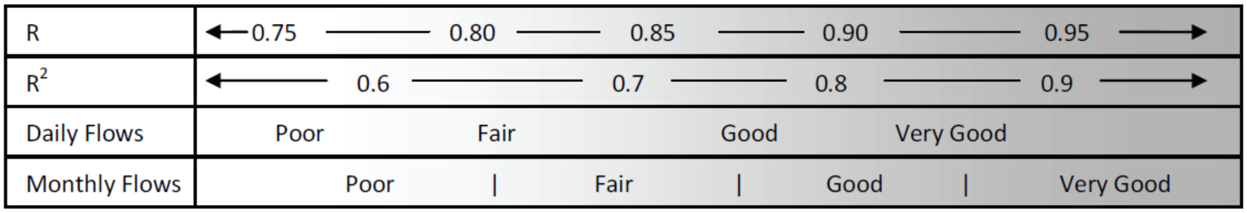


Figure 13. Range of linear correlation coefficients (R) and coefficients of determination (R2) for general assessment of HSPF model performance for daily and monthly flows (source: Duda et al. 2012).

Table 13. General range of relative percent difference (RPD) between simulated and observed values (relative to observed) that can be used for evaluation of HSPF model performance (source: Donigian 2000).

Simulation	Very Good	Good	Fair	Poor
Hydrology	<10%	10%–15%	15%–25%	>25%
Sediment	<20%	20%–30%	30%–45%	>45%

Note.

- Relevant to monthly and annual mean values only; storm peaks may differ more (i.e., individual events or observations may show larger differences and still be acceptable).
- Level of agreement depends on site and application-specific conditions, including the quality and detail of input and calibration data.
- Ranges may vary depending on the purpose of model application.
- If time and resources are available, the use of additional/alternative assessment procedures is recommended and could meet study objectives.

Qualitative evaluation was performed by calculating model skill based on the statistics in Table 11 of the QAPP (Mohamedali 2018). Additionally, various qualitative/graphical plots comparing observed and simulated flows and concentrations were created and evaluated to determine model calibration. These included:

- Annual flows.
- Monthly average flows.
- Daily time series of flows and TSS concentrations.
- Flow duration curves.
- A subset of storm hydrographs.
- Monthly range in TSS concentrations.
- Flashiness metrics.

Forested Conditions

For this phase of the TMDL study, the only model scenario that was evaluated was a forested condition model scenario. Additional model scenarios may be developed for the TMDL to guide the implementation plan and will be described in the final TMDL report.

The forested model scenario is primarily used to compare against the existing/baseline scenario, to evaluate differences in the hydrologic regime and TSS loads, and to assess how much of that change is a result of human development in the watershed. In the absence of an equivalent reference watershed or data collected pre-development, the forested condition scenario allows us to estimate what the TSS load in the watershed would be in the absence of human activities (i.e., under reference conditions). The forested scenario allows us to compare existing flows and sediment loads to a reference condition, which is analogous to approaches used in stormwater management, where the goal is often to match pre-developed (or forested) flows to some extent.

The forested model scenario was represented by converting all land uses, except for open water bodies or wetlands, to the "forest" category within the HSPF schematic. The geology/soils and topographic soils, flow routing, channel geometry, and water withdrawals were unchanged. This model run formed the basis for determining the TMDL loading capacity.

Model Performance

As mentioned previously, RESPEC conducted a peer review of the model setup and recalibration, including an evaluation of model performance (Lupo and Donigian 2022). A few minor changes were made to model parameters after their review, based on their recommendations, as described in the previous section.

Below is a summary of RESPEC's conclusions on the model performance from their peer review:

- Based on the entire weight-of-evidence approach for the full range of model results presented, the hydrology component is confirmed to be calibrated and provides a sound basis for the water quality purposes of this study pending the recommended tests/verifications outlined in the previous sections (these recommendations are addressed in Table 10).
- It is evident the principal investigator (PI) followed standard water quality calibration practices and made a conscious effort to avoid curve fitting (i.e., "driving" the simulation through points by using unrealistic parameter sets). The calibration appears to accurately represent the physical processes involved in sediment washoff and transport, and the results align with what RESPEC would consider an acceptable sediment calibration based on our experience.
- Overall, the model sufficiently predicts TSS concentration/load ranges and seasonal/flow trends found in the observed data, especially at the most downstream reach on Soos Creek (i.e., RCHRES 592). Lower concentrations that occur during the summer months are consistently underpredicted; however, this circumstance is quite common because there is no legitimate mechanism in HSPF that can supply sediment when precipitation is minimal, and stream power is at its seasonal low. In addition, the purpose of this study (and most sediment modeling studies) is focused on higher TSS concentrations.
- Room for improvement exists in any watershed modeling effort; however, in its current state, the Soos Creek HSPF model can provide excellent value in its primary use to develop load allocations and analyze alternatives.

The following sections present the quantitative statistics as well as qualitative graphics related to model performance of the final calibrated model along with a narrative description of model performance.

Hydrology Performance

Relative percent difference (RPD) between observed and simulated flows (relative to observed flows) for various flow metrics are presented in Table 14. Absolute values for observed and simulated flows for these various metrics are included in Appendix C, along with comparisons between observed and simulated annual and monthly runoff for each year and month. Absolute RPD for average annual and monthly runoff across are below 10% at all flow calibration stations, putting them in the "very good" category based on Donigian (2000).

Table 14. Relative Percent Difference (RPD) between observed and simulated flows for different flow metrics, ranging from annual and monthly runoff to low flows and storm volumes, as well as different flow percentiles.

Flow Metric	Soosette	Little Soos	Jenkins	Covington	Big Soos — Kent	Big Soos — mouth
	Reach 582	Reach 142	Reach 332	Reach 512	Reach 152	Reach 592
Annual runoff	-0.23	-3.01	-0.09	-9.94	-3.01	-9.52
Monthly avg. runoff	-0.25	-2.90	-0.21	-9.94	-2.06	-9.62
Spring volume	-14.13	-13.03	-5.36	-21.51	-13.03	-17.87
Summer volume	50.92	8.37	-16.99	-4.90	8.37	-11.74
Fall volume	31.08	20.53	9.53	28.43	20.53	0.71
Winter volume	-6.68	-9.42	6.22	-8.44	-9.42	-6.07
Storm volume	-11.11	-7.74	6.12	-10.62	-7.74	-7.70
Average storm peak	-6.01	-0.05	28.05	-6.14	-0.05	8.47
Spring storms	-18.10	-15.17	-0.14	-20.13	-15.17	-13.45
Summer storms	-34.83	-2.21	-15.58	-26.87	-2.21	-21.05
Fall storms	7.83	24.23	20.87	7.12	24.23	-0.16
Winter storms	-12.72	-11.09	5.54	-7.20	-11.09	-6.04
5 percent high	-12.90	-7.49	5.61	-14.17	-7.49	-6.61
10 percent high	-8.02	-3.69	7.96	-11.09	-3.69	-6.58
25 percent high	-4.40	-3.37	7.50	-11.69	-3.37	-7.14
50 percent low	43.40	2.34	-13.75	27.15	2.34	-11.30
25 percent low	151.11	14.25	-15.78	61.53	14.25	-11.50
75th %tile low flows	174.37	21.85	-16.38	66.36	21.85	-14.15
90th %tile low flows	187.22	28.95	-16.19	68.29	28.95	-15.24
95th %tile low flows	197.82	36.30	-16.06	69.41	36.30	-19.10

Note. All metrics are calculated from 2001 to 2015.

Seasonal performance varies by location. Winter volumes are "very good" across all locations, while performance in other seasons ranges from "very good" to "poor." Poor seasonal performance is limited to summer and fall volumes in Soosette and fall volumes in Covington. The Soosette subbasin is the smallest subbasin in the Soos, with very low summer flow volumes, so a small difference in the magnitude of summer volumes results in a large percent difference. Observed summer flow volumes in Soosette are 0.55 in, while simulated volumes are 0.83 in, resulting in a 51% overprediction. This location in the Soosette subbasin has a drainage area of 1.88 square miles and only four HSPF catchments upstream of the gage. HSPF performance tends to be poorer in such small drainage areas where the model has a difficult time representing the upper and lower bounds of flow because of how the model lumps and routes runoff (Lupo et.al. 2022). Additionally, at this scale and model resolution, a portion of the active groundwater likely comes to the surface downstream of the gage and catchments, but HSPF runoff routines simulate all groundwater being routed to the reach segment in its respective catchment — this results in an overprediction at the gage location.

Overall, storm volumes are “very good” to “good” across all locations, and storm peaks are “very good” (<10% RPD) at all locations except Jenkins, where storm peaks are overpredicted by 28%. This overestimation could possibly be caused by attenuation that occurs in waterbodies and floodplains that may not be adequately captured in the current FTABLE setup. Higher resolution bathymetry or cross-section data would be required to improve this. However, the simulation in Jenkins still shows adequate storm response in terms of timing and volume.

Based on daily simulation plots, summer peak flows are slightly overestimated during summer months (i.e., the model is flashier than what is shown in observed data during the summer). However, the model performs well at capturing total storm volumes as well as predicting the timing and rates of rising and falling limbs of the hydrograph. Daily observed and simulated flow hydrographs for the full model simulation period are included in Appendix D.

Various model fit statistics were calculated to evaluate the model’s ability to predict daily and monthly flows. These statistics were defined in Table 11 of the QAPP (Mohamedali 2018). The final model fit statistics are summarized in Table 15. Correlation coefficient (R) values across all stations range from 0.67 to 0.91 for daily flow predictions and 0.93 to 0.99 for monthly flows. Coefficient of determination (R^2) values across all stations range from 0.45 to 0.83 for daily flow predictions and 0.87 to 0.97 for monthly flows. Nash Sutcliffe Coefficient (NSE) values are all above 0.9 and 0.6 for monthly and daily flows (respectively), except in Little Soos, which has an NSE value of 0.86 for monthly flows and 0.44 for daily flows.

We tested whether the ranked distributions between observed and simulated monthly flows are significantly different using the non-parametric Kruskal-Wallis (KW) procedure at the $\alpha = 0.05$ level. Results of the KW test had *p*-values above 0.05 at all calibration locations for monthly flows, indicating there was no significant statistical difference between observed and simulated monthly flows.

Overall, Little Soos has the poorest model fit statistics. This is likely due to the following factors (as noted by RESPEC in Lupo and Donigian, 2022):

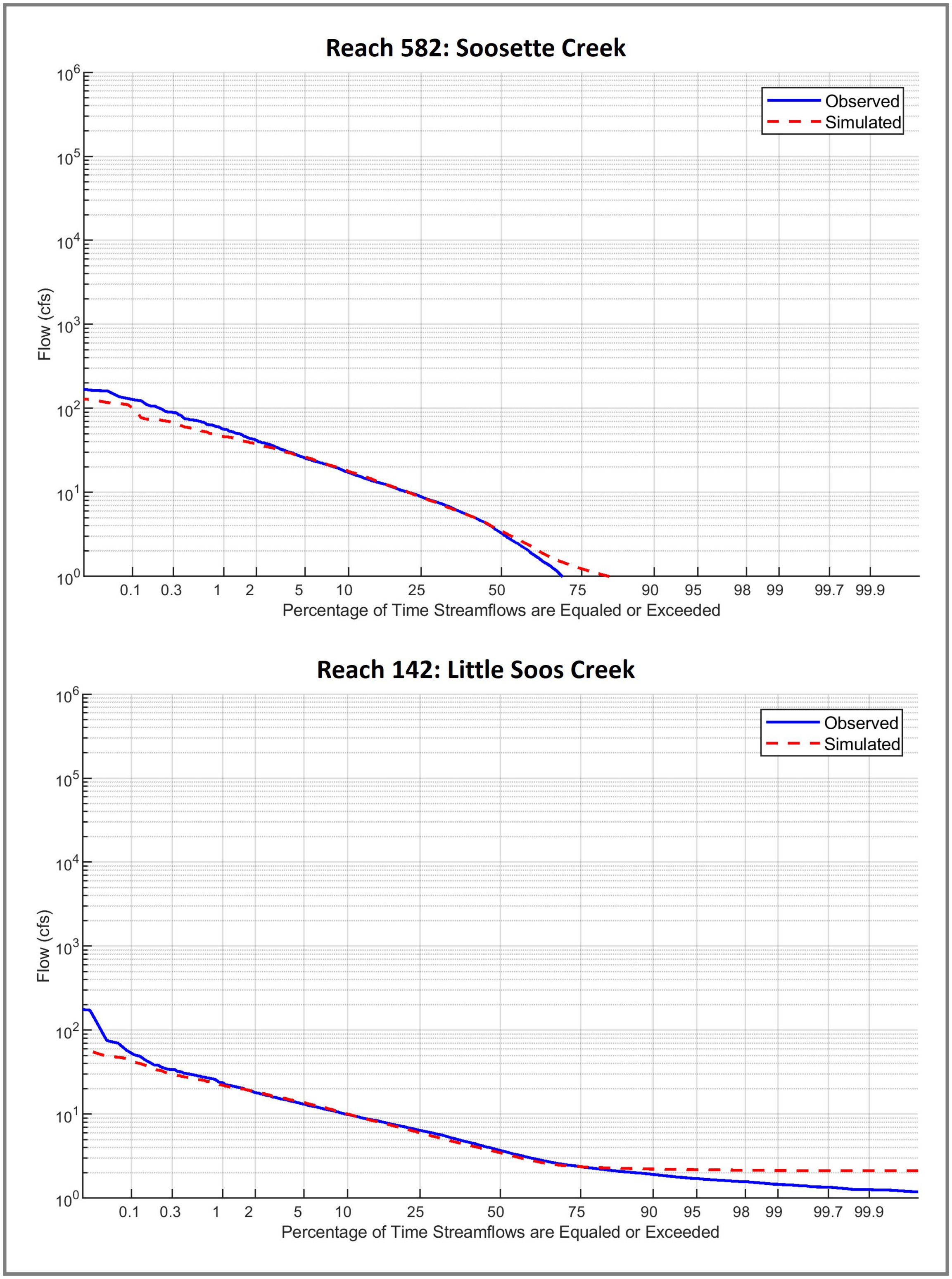
1. The relatively small drainage area, with only four contributing catchments/reaches.
2. Inter-basin groundwater losses at each segment that are being routed to the Big Soos and Jenkins drainages.
3. The model includes a constant inflow of groundwater from Lake Youngs to Little Soos Creek.

At this small scale, HSPF has a difficult time representing the upper and lower bounds of flow because of how the model lumps and routes runoff. This limitation is compounded by the groundwater loss/gain representation that is likely not capturing actual daily variability in inter-basin groundwater flows.

The model captures the full range of flows as illustrated in the flow duration curves in Figures 14, 15, and 16. Note that the y-axis is on a log scale, which accentuates differences between observed and predicted flows, especially at the lowest percentiles, but also minimizes differences in the bulk of the distribution. Additional plots comparing annual and monthly runoff can be found in Appendix D.

Table 15. Daily (top) and monthly (bottom) hydrology model fit statistics across all six calibration locations, calculated for WY 2001 – 2015.

Daily Model-fit Statistics	**Reach 582: Soosette**	**Reach 142: Little Soos**	**Reach 332: Jenkins**	**Reach 512: Covington**	**Reach 152: Big Soos (Kent)**	**Reach 592: Big Soos (Mouth)**
Number of days or months	5112	5112	5112	5112	1758	5112
Correlation Coefficient (R)	0.80	0.67	0.88	0.91	0.82	0.91
Coefficient of determination (R^2)	0.64	0.45	0.77	0.83	0.68	0.83
Nash-Sutcliffe efficiency (NSE)	0.64	0.44	0.72	0.81	0.68	0.82
Mean error (ME)	-0.02	-0.16	-0.04	-3.12	-0.70	-12.42
Mean absolute error (MAE)	3.13	1.56	8.66	8.41	10.97	28.60
Root mean square error (RMSE)	7.08	4.32	15.18	15.83	20.58	48.69
Monthly Model-fit Statistics	**Reach 582: Soosette**	**Reach 142: Little Soos**	**Reach 332: Jenkins**	**Reach 512: Covington**	**Reach 152: Big Soos (Kent)**	**Reach 592: Big Soos (Mouth)**
Number of days or months	168	168	168	168	58	168
Correlation Coefficient (R)	0.97	0.93	0.96	0.97	0.99	0.98
Coefficient of determination (R^2)	0.93	0.87	0.93	0.94	0.97	0.96
Nash-Sutcliffe efficiency (NSE)	0.92	0.86	0.91	0.91	0.94	0.93
Mean error (ME)	-0.02	-0.16	-0.03	-3.16	-0.79	-12.51
Mean absolute error (MAE)	1.46	0.86	5.35	6.39	5.09	17.72
Root mean square error (RMSE)	2.10	1.33	7.37	9.18	6.61	25.08
Kruskal-Wallis p-val (K-W p)	0.161	0.582	0.712	0.698	0.612	0.316


Reach 582: Soosette Creek

Reach 142: Little Soos Creek

Figure 14. Comparisons of observed vs. simulated flow duration curves at Soosette Creek (top) and Little Soos Creek (bottom) calibration stations (y-axis is on a log scale).

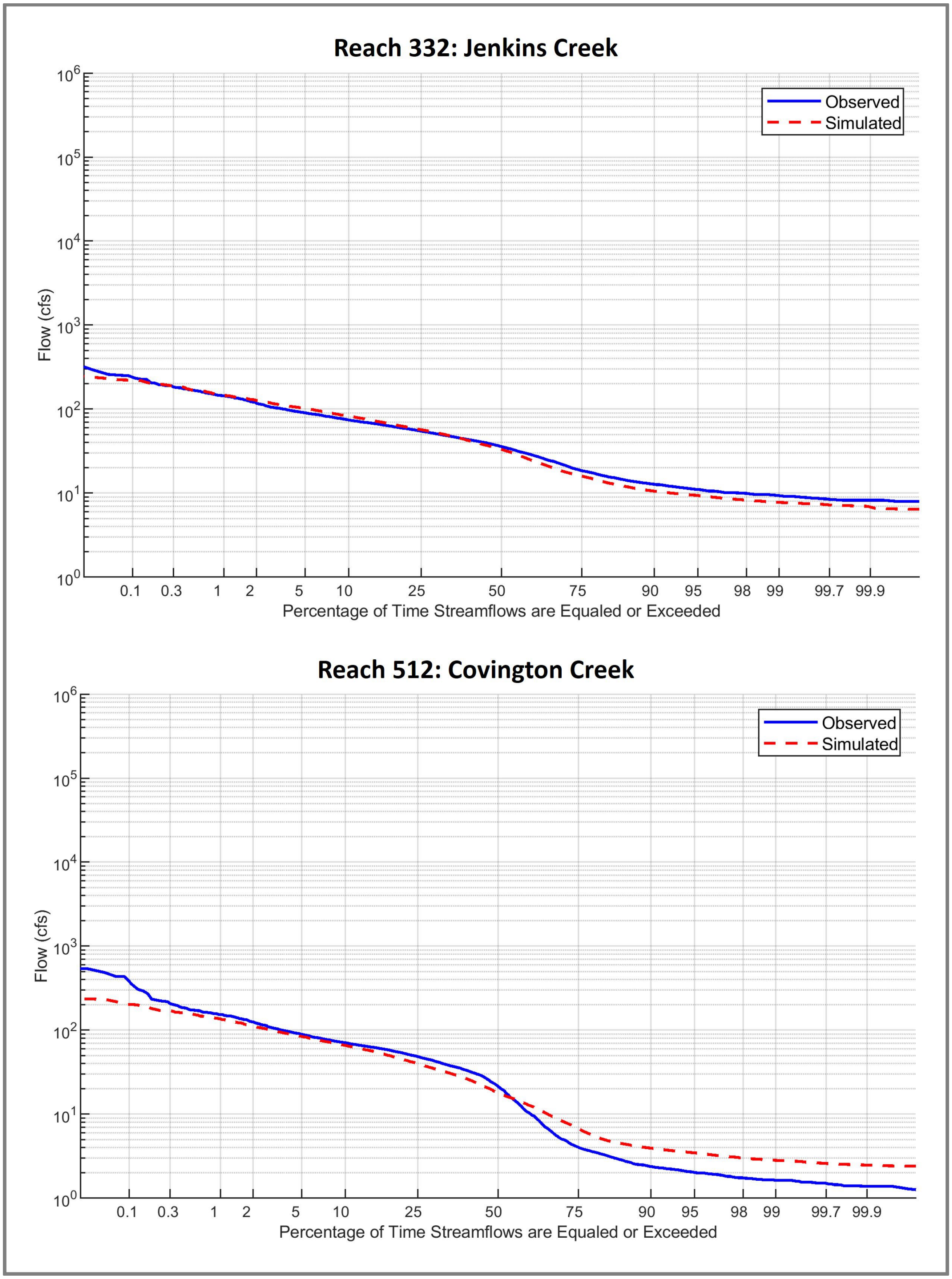
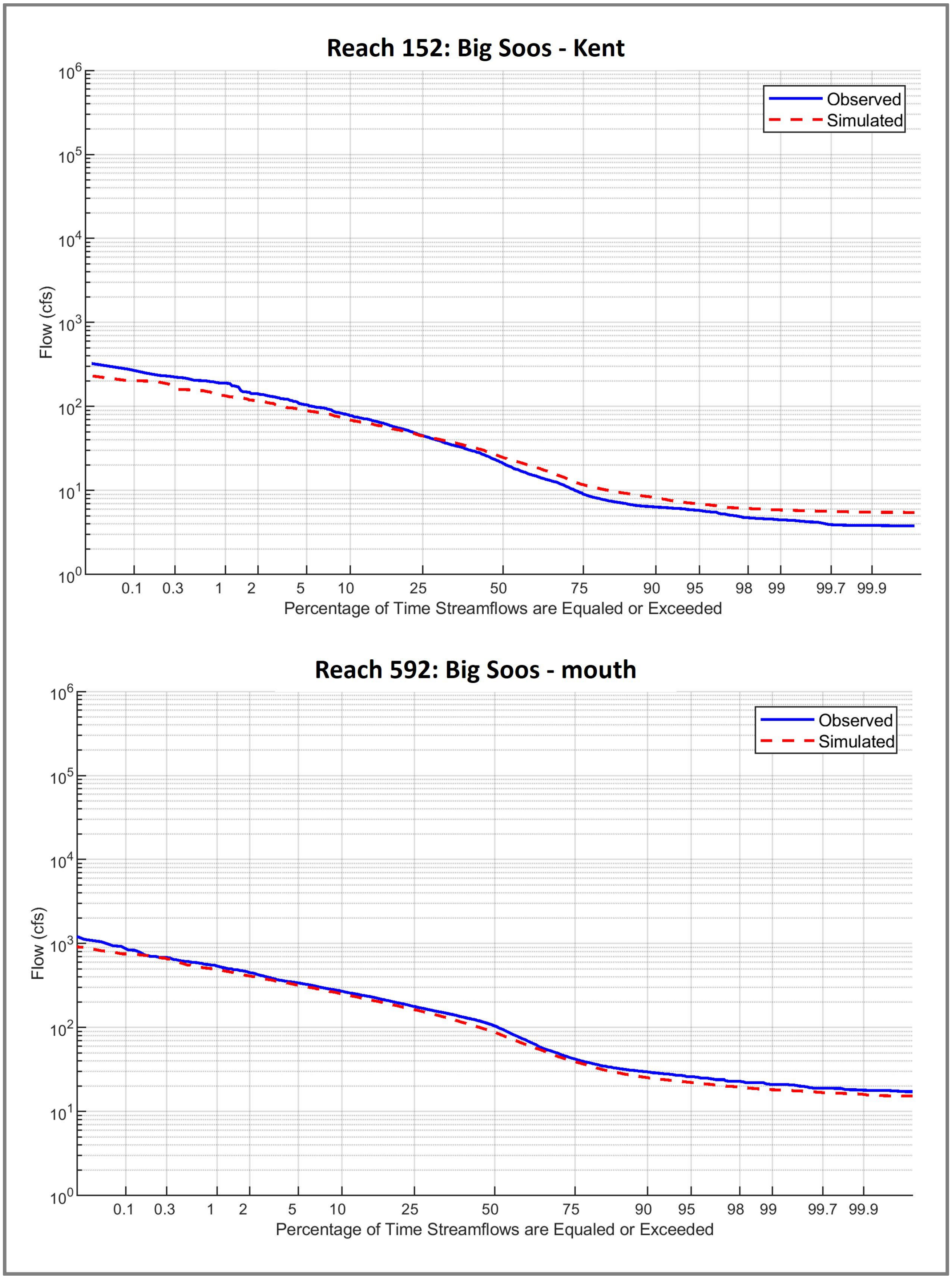


Figure 15. Comparisons of observed vs. simulated flow duration curves at Jenkins Creek (top) and Covington Creek (bottom) calibration stations (y-axis is on a log scale).



Reach 152: Big Soos - Kent

Reach 592: Big Soos - mouth

Figure 16. Comparisons of observed vs. simulated flow duration curves at Big Soos Creek at Kent (top) and Big Soos Creek near mouth (bottom) calibration stations (y-axis is on a log scale).

Flashiness Metrics

Flashy flows, defined by various flashiness metrics, are applied qualitatively in this study to evaluate the *difference* in flashiness between existing and forested conditions. We evaluated the model's ability to simulate flashy flows by comparing observed and simulated HPCs, TQ-Mean, and the PK2YR: Winter Baseflow ratio at five of the six calibration gages (Table 16). The gage at Soos-Kent (RCH 152) had fewer years of data and was not included in this evaluation since some of the flow alteration metrics calculations require a longer time series of gaged data to make adequate comparisons.

Table 16. Summary models statistics for flashiness metrics.

High Pulse Count	**R**	**R^2**	**RMSE**
Reach 582: Soosette	0.71	0.50	3.23
Reach 142: Little Soos	0.52	0.27	2.55
Reach 332: Jenkins	0.74	0.55	1.43
Reach 512: Covington	0.71	0.51	2.23
Reach 592: Big Soos — mouth	0.59	0.34	2.37
TQ-mean	**R**	**R^2**	**RMSE**
Reach 582: Soosette	0.66	0.43	0.04
Reach 142: Little Soos	0.68	0.46	0.06
Reach 332: Jenkins	0.86	0.74	0.04
Reach 512: Covington	0.87	0.76	0.04
Reach 592: Big Soos — mouth	0.86	0.30	0.03
Peak 2 yr: Winter Baseflow[a]	**Obs**	**Sim**	**RPD**
Reach 582: Soosette	15.49	14.12	-8.8%
Reach 142: Little Soos	6.43	7.35	14.3%
Reach 332: Jenkins	3.49	4.17	19.5%
Reach 512: Covington	5.33	4.91	-7.9%
Reach 592: Big Soos — mouth	4.67	5.54	18.6%

RMSE = Root Mean Square Error.

RPD = Relative Percent Difference.

[a] Since this flashiness metric is not calculated yearly, the overall RPD was calculated rather than R and R^2 for individual years, as was done for the other metrics.

Since HPCs are defined as the number of times daily average flows are equal to or greater than a high-flow threshold during each water year, we first had to calculate the observed and simulated high-flow threshold for observed and simulated flows. This high pulse threshold was calculated using observed and simulated WY 2001 – 2015 streamflow. Ultimately, we use the relative metrics for HPCs between simulations of existing and forested conditions, so while we present absolute statistics here to demonstrate the adequacy of model performance for predicting flashiness, as well as inherent limitations, we do not use absolute HPCs as the only indicator of the system's flashiness.

Model simulated HPCs are well correlated with observed HPCs, but the model does seem to be “flashier” than observations, i.e., the model predicts a higher number of HPCs than what is observed (Figure 17). There are three primary reasons that the model is over-predicting the frequency of HPC events:

1. The observed and model-predicted High Pulse Thresholds (HPT, which is two times the mean annual flow) are slightly different.
2. The model predicts HPC events during smaller storms that generate runoff above the simulated HPT, while observed flows during these same small storm events do not exceed the observed HPT.
3. During the higher flow months when there are larger and more frequent storm events, the model predicted flow during the recession portion of the curve sometimes goes below the HPT before climbing back up above it (which counts as two HPCs), while the observed flow stays above the HPT throughout (which counts as a single HPC).

Observed and simulated patterns are illustrated in Figure 18, which compares the daily observed and simulated hydrograph for Reach 592 (Big Soos near the mouth) and observed and predicted high pulse events during WY 2014. For this year, there were eight observed HPCs and 13 simulated HPCs. As illustrated, the model is predicting the observed daily flows very well, but deviations in flows above or below the HPT result in an over-prediction of the HPC for this year.

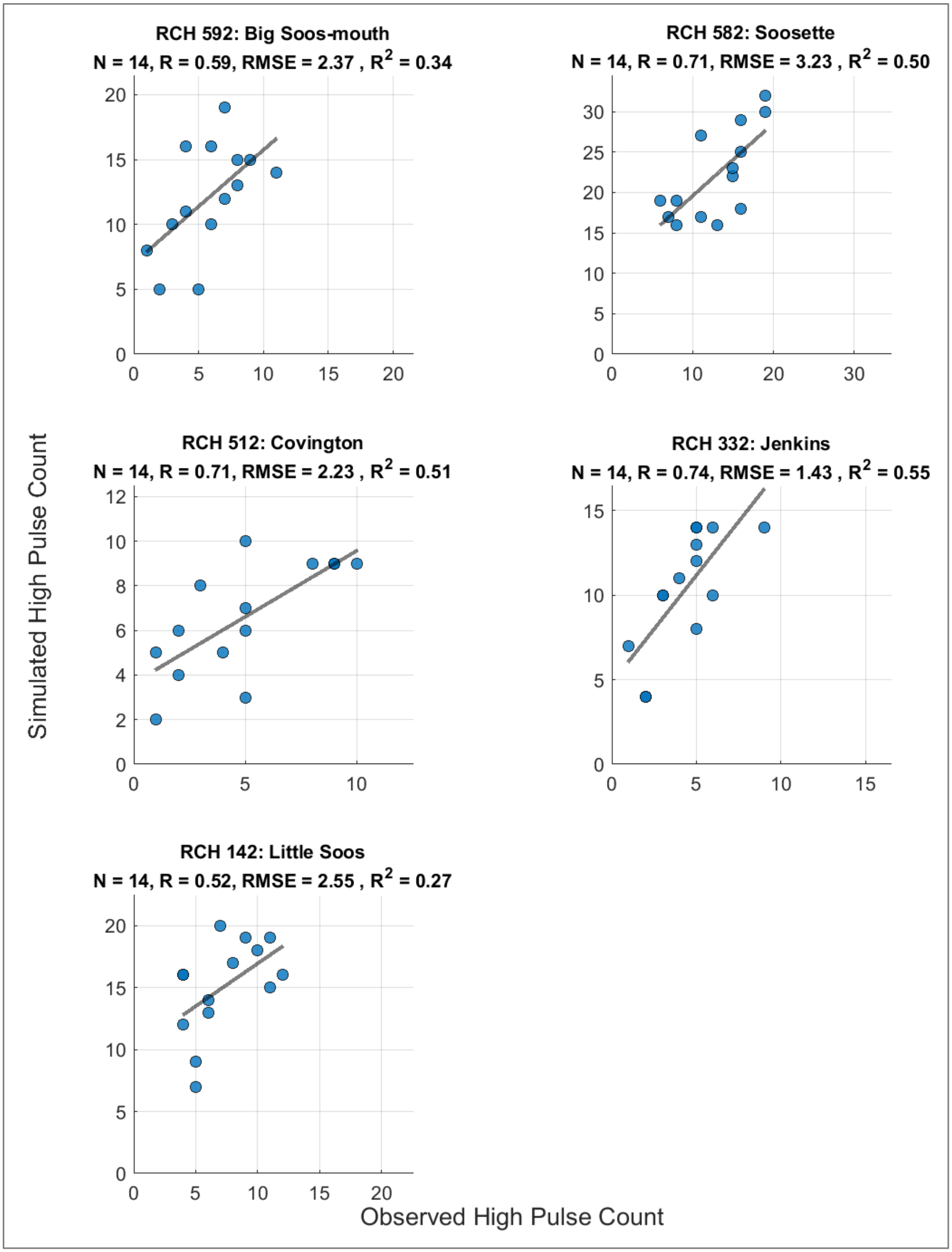


Figure 17. Scatter plots of observed and predicted High Pulse Counts for WY 2001 – 2015 (note differences in scale between plots).

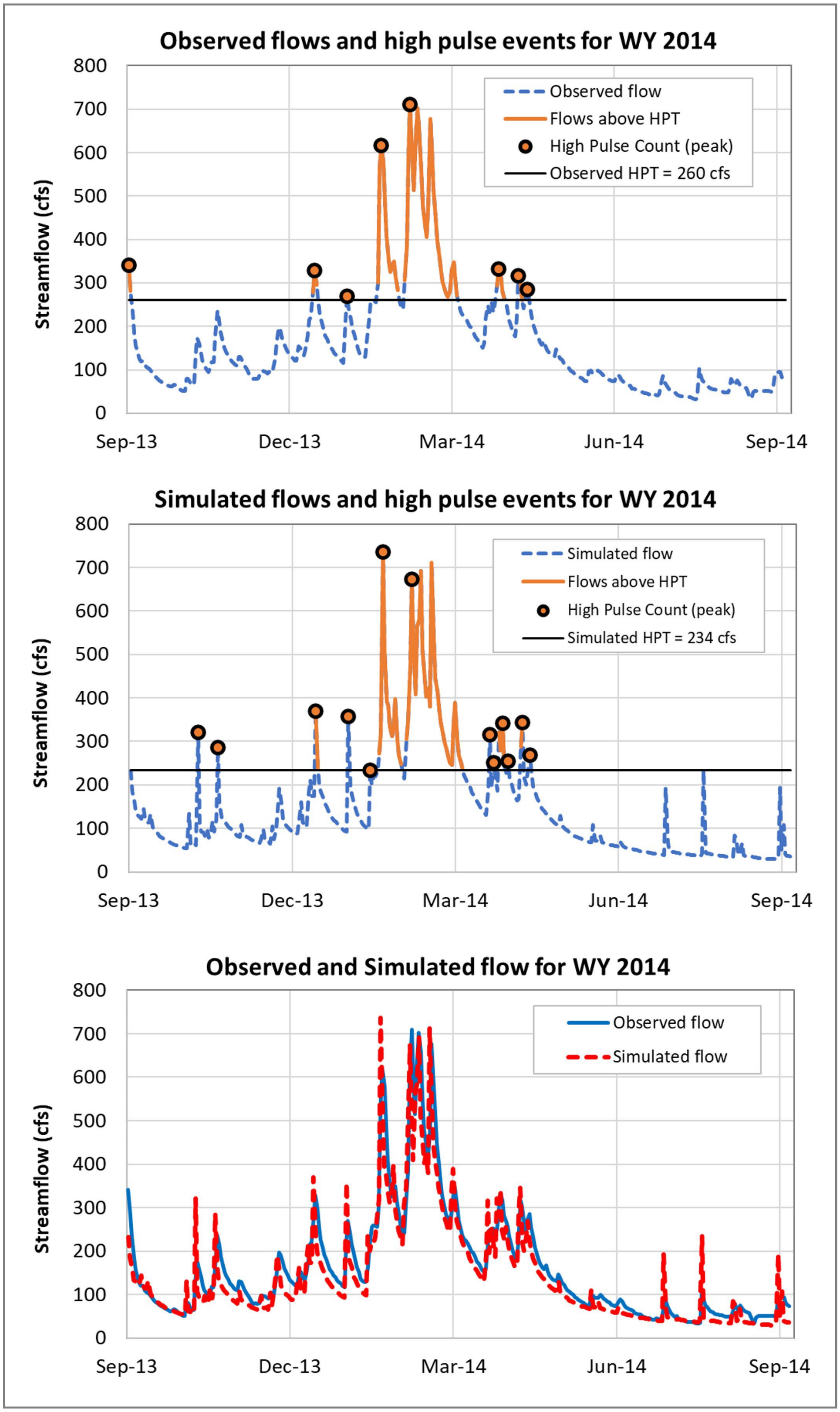


Figure 18. Observed and simulated streamflows for WY 2014 at Reach 592 (Big Soos near mouth), showing the difference in High Pulse Counts.

Model simulated TQ-means are highly correlated to observed values, with R values from 0.66 to 0.86 and R^2 values 0.43 to 0.86 (Figure 19). This shows the model's ability to adequately capture the duration of flows that exceed the annual mean discharge for the year.

Lastly, the RPD between the model simulated and observed PK2YR: Winter Baseflow are all below 20%. Since this metric first involves the calculation of 1) peak 2-year return flows and 2) winter baseflows, we also performed a qualitative comparison of how the model was predicting each of the two values that go into calculating this ratio (Figure 20).

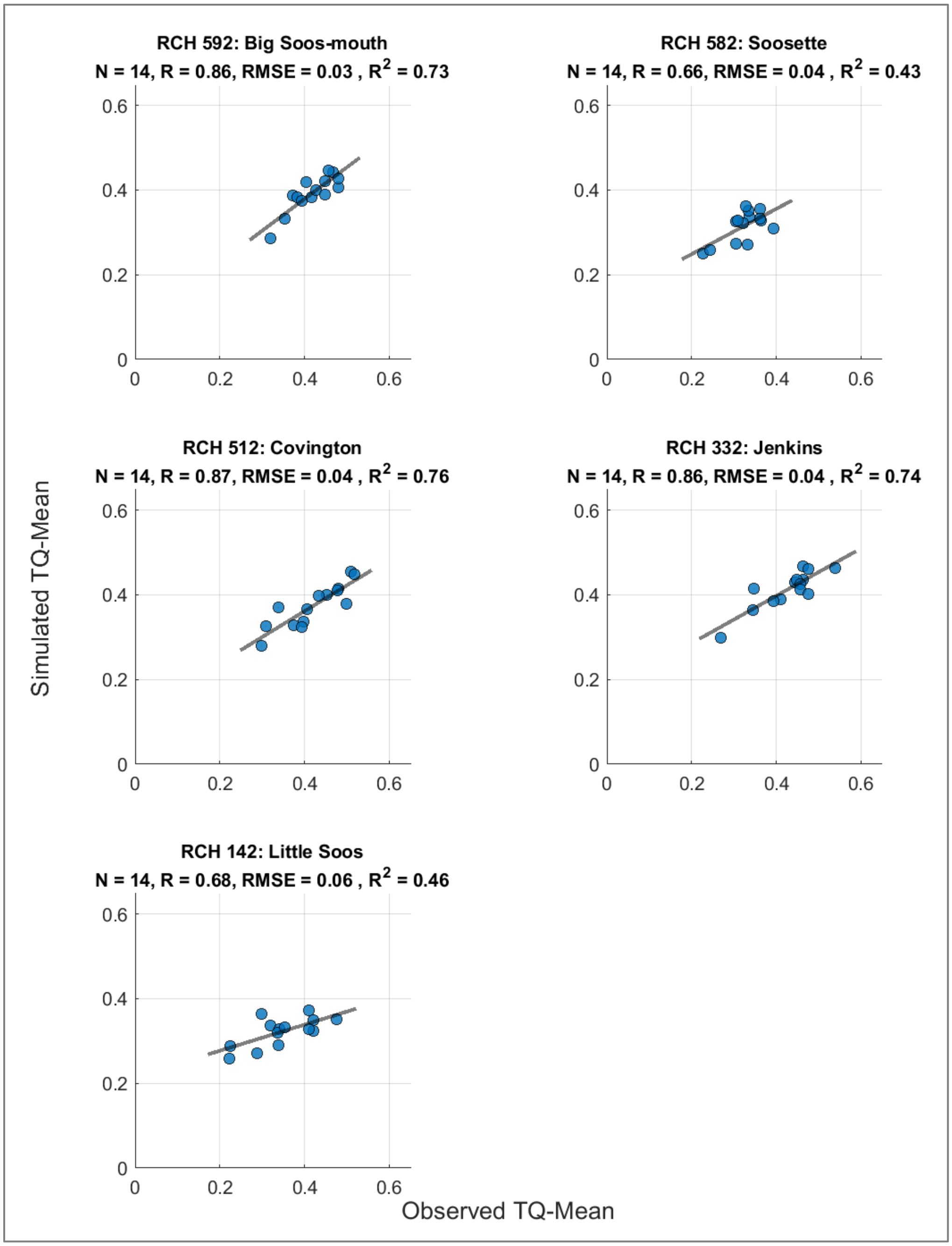
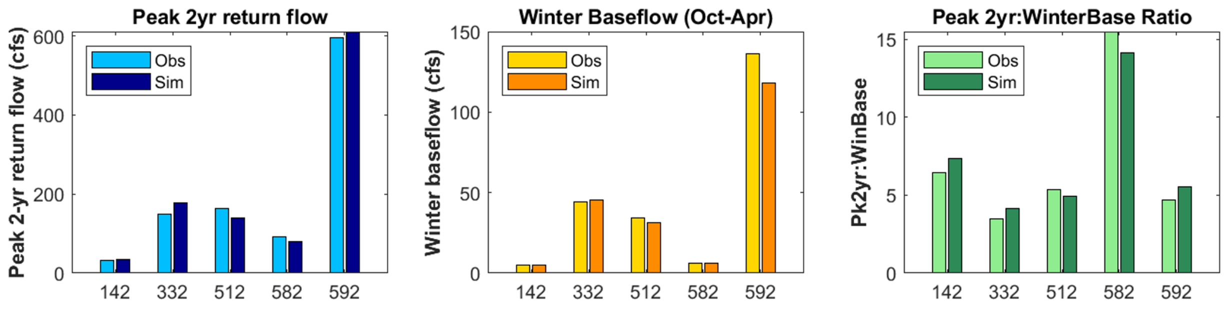


Figure 19. Scatter plots of observed and predicted TQ-mean for WY 2001 – 2015.



x-axis labels represent the following calibration locations:

RCH 142: Little Soos; RCH 332: Jenkins; RCH 512: Covington; RCH 582: Soosette; RCH 592: Big Soos-mouth

Figure 20. Comparisons of observed and simulated Peak 2-year return flows, winter baseflows, and the ratio of the two values for five calibration locations.

Sediment Performance

Before comparing the instream model performance, we first compared the sediment loading predicted by the model to literature ranges and local estimates (Figure 21). Model-predicted TSS loading rates are within literature ranges. The loading rates also follow expected patterns, where TSS loading rates from forested and agricultural land uses are lower than from developed surfaces.

The parameters involved in the simulation of watershed sediment erosion are generally more uncertain than hydrologic calibration (Duda et al. 2012 and King County 2013). This greater uncertainty in TSS predictions is reflected in the general model criteria presented in Table 13, where sediment performance is considered “very good” if the RPD is <20%, but for hydrology, the RPD must be <10% to be considered “very good.”

Sediment calibration also depends primarily on qualitative analysis, and the quantitative (or statistical) analysis component for sediment calibration is more simplified and primarily involves comparing percent differences between observed and simulated TSS against general criteria (Lupo and Donigian 2022). We compared observed annual and monthly average TSS concentrations to simulated annual and monthly average TSS concentrations for the full model simulation period (WY 2001 – 2015). For these calculations, a subset of simulated TSS concentrations was used, which only included simulated daily TSS concentrations for just those days where we had observed TSS concentration data. Using this subset of simulated TSS concentrations, annual TSS concentrations were calculated as the average of yearly mean TSS concentrations across all years, while monthly TSS concentrations were calculated as the monthly mean of TSS concentrations across all years.

Using the general model criteria from Table 13, the sediment calibration ranks “very good” with RPDs below 15% at all four locations from an average annual concentration basis and “very good” to “good” from an average monthly mean concentration basis (all RPDs are <20% except at Jenkins, which has an RPD of 21%, Table 17). Model performance is best at the downstream end of the watershed, at the Big Soos — mouth station. Tables comparing observed and predicted TSS concentrations for individual years and months are included in Appendix C.

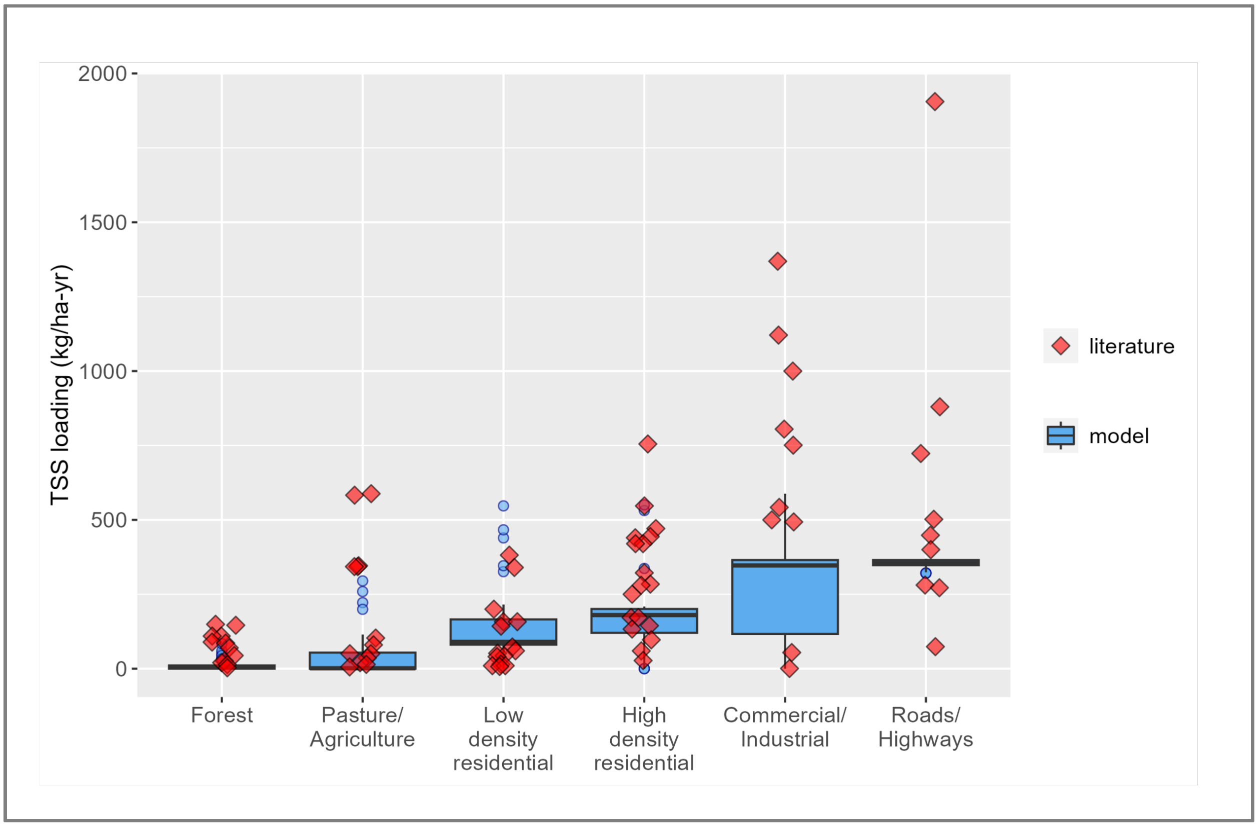


Figure 21. Model predicted TSS loading rates compared to values in literature across different land uses.

Table 17. Observed and coincident simulated annual and monthly average Total Suspended Solids (TSS) concentrations and RPD for each of the four sediment calibration sites calculated for WY 2001 – 2015.

Annual Average TSS	**Observed**	**Simulated.**	**Difference**	**RPD**
Reach 142: Little Soos Creek	3.73	4.21	0.48	**12.96**
Reach 332: Jenkins	2.69	3.08	0.39	**14.39**
Reach 452[a]: Covington Creek	2.01	2.19	0.18	**8.70**
Reach 592: Big Soos — mouth	9.69	9.00	-0.69	**-7.15**
Monthly Average TSS concentrations	**Observed**	**Simulated**	**Difference**	**RPD**
Reach 142: Little Soos Creek	3.74	4.46	0.72	**19.13**
Reach 332: Jenkins	2.73	3.31	0.59	**21.45**
Reach 452[a]: Covington Creek	1.96	2.21	0.25	**12.96**
Reach 592: Big Soos — mouth	9.18	8.78	-0.40	**-4.37**

RPD = Relative Percent Difference.

[a] The sediment calibration site on Covington Creek does not coincide with the same reach as the flow gage on Covington Creek.

While some model fit statistics were calculated for daily, monthly, and yearly TSS predictions (Table 18), more emphasis was placed on qualitative comparisons. Annual R values varied from 0.52 to 0.92, while annual R^2 values varied from 0.27 to 0.85. Model performance for TSS is highest at the mouth of Big Soos and lower at the other three calibration locations.

Again, model-fit statistics alone cannot be used to determine the adequacy of model performance, especially for TSS. For example, the log scale time series plot at RCHRES 592 (Big Soos near the mouth) shown in Figure 22 illustrates that the model captures changes in sediment concentrations for January 2005. The observed TSS concentration on 01/18/2005 was 65.2 mg/L, but the observed concentration on the same day was 17.1 mg/L. However, the model predicted value the day before, on 01/17/2005, is 59.7 mg/L. This means that while the calculated difference between observed and simulated is large, the difference is due to minor timing issues rather than an underprediction in concentrations (i.e., the model predicted peak TSS concentrations a day before the observed peak). This highlights the importance of qualitative evaluation of model performance in addition to calculated metrics. Additional plots comparing monthly average and daily time series of observed and simulated TSS concentrations, as well as scatter plots of daily concentrations for all calibration locations, are included in Appendix E.

Table 18. Model fit statistics for daily, monthly, and yearly TSS concentrations across all four calibration locations, calculated for WY 2001 – 2015.

Daily Model-fit Statistics	Reach 142: Little Soos	Reach 332: Jenkins	Reach 442: Covington	Reach 592: Big Soos — Mouth
Number of days, months, or years	146	189	119	220
Correlation Coefficient (R)	0.34	0.43	0.29	0.92
Coefficient of determination (R^2)	0.12	0.19	0.09	0.85
Mean error (me)	0.74	0.62	0.21	-0.43
Mean absolute error (mae)	3.89	2.42	1.90	5.13
Root mean square error (rmse)	7.15	4.94	3.35	12.28
Monthly Model-fit Statistics				
Number of days, months, or years	12	12	12	12
Correlation Coefficient (R)	-0.38	0.48	0.26	0.97
Coefficient of determination (R^2)	0.14	0.23	0.07	0.94
Mean error (me)	0.72	0.58	0.25	-0.40
Mean absolute error (mae)	2.55	1.03	1.25	1.89
Root mean square error (rmse)	3.54	1.26	1.57	2.59
Yearly Model-fit Statistics				
Number of days, months, or years	11	15	11	15
Correlation Coefficient (R)	0.87	0.62	0.52	0.92
Coefficient of determination (R^2)	0.75	0.39	0.27	0.85
Mean error (me)	0.48	0.39	0.18	-0.69
Mean absolute error (mae)	1.22	1.26	0.74	2.57
Root mean square error (rmse)	1.81	1.91	0.95	3.51

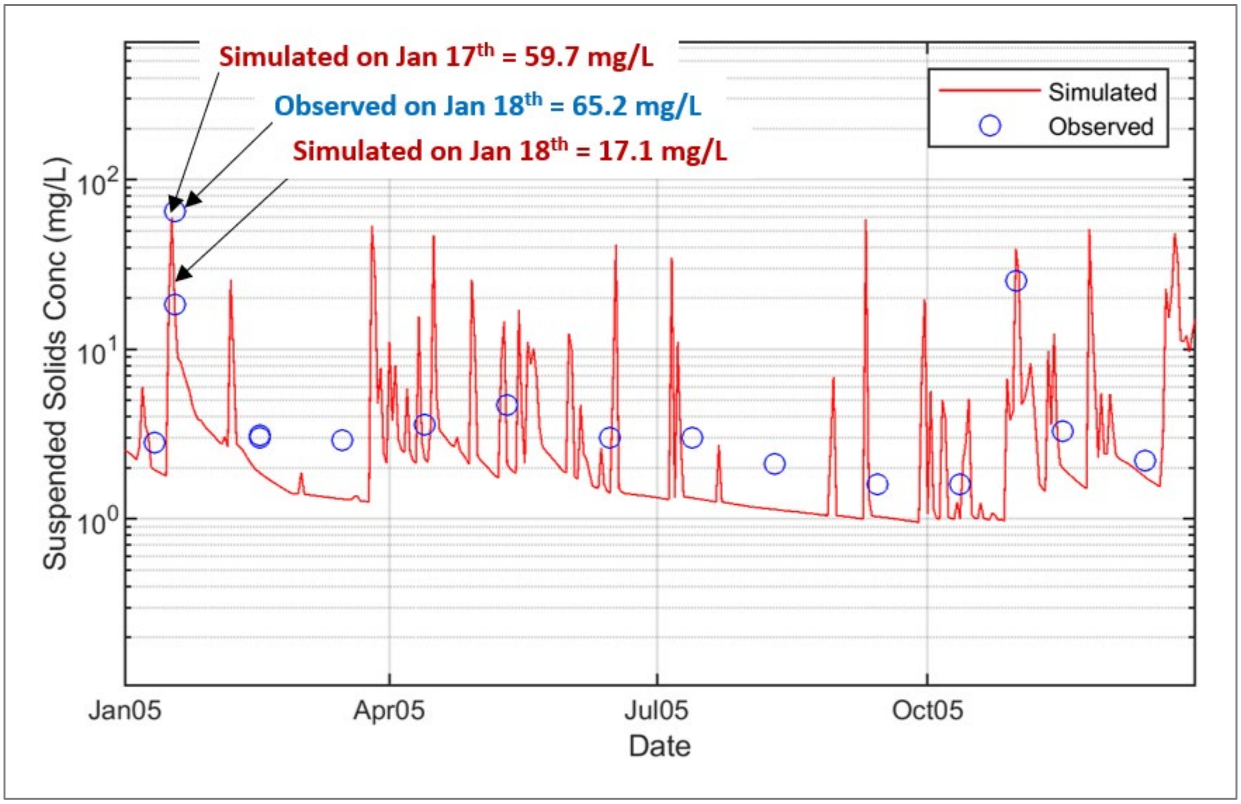


Figure 22. Total Suspended Solids (TSS) time series for 2005 at RCH 592, Big Soos near mouth (y-axis is on a log scale).

Monthly boxplots comparing observed and simulated TSS daily loads by month are presented in Figure 23. The model simulated daily loads overlap with observed loads but also extend beyond the range of observed loads. This makes sense since model simulation output captures daily and sub-daily variation in concentrations and loads, but observed loads only represent the instantaneous load at the time when sampling occurred. Summer loads are consistently under-predicted. Since precipitation is the main driver for the supply of sediment within HSPF, there is no other mechanism in HSPF to supply sediment during the summer when precipitation is minimal and stream power is at its lowest.

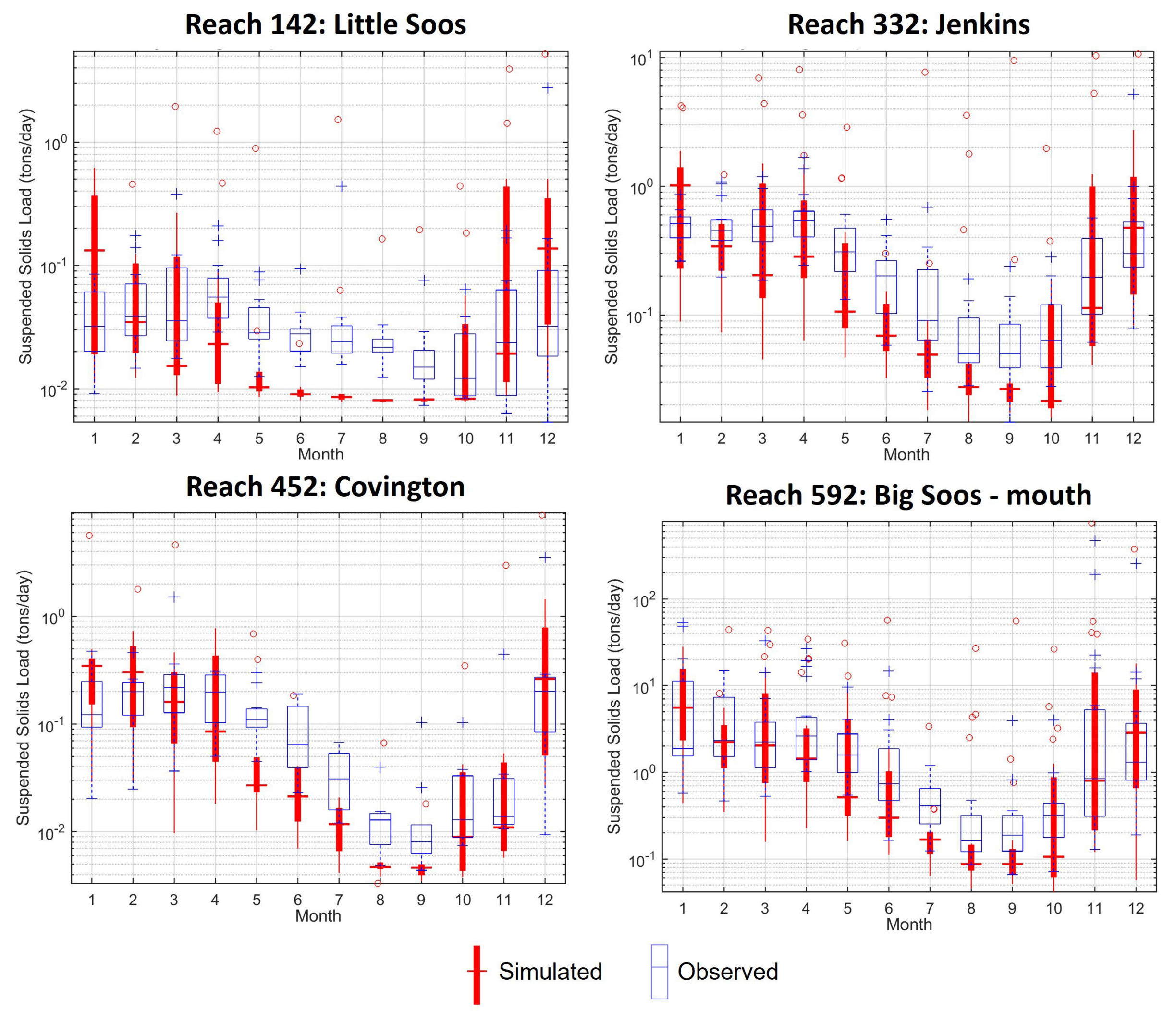


Figure 23. Comparison of daily observed and simulated TSS loads grouped by month at all four calibration locations for WY 2001 – 2015.

Model Limitations and Uncertainty

The model is overall performing well in most locations based on established quantitative model criteria as well as qualitative evaluation. However, some uncertainties remain and are summarized below:

- Many of the upper parts of the watershed are heavily influenced by wetlands and have slow-moving undefined stream channels that move through wetland complexes. This feature of the watershed definitely needs to be considered when evaluating model dynamics and performance.
- Overall model performance at the annual average or monthly average scale in terms of bias/RPDs appears to be well within reasonable ranges/targets at most calibration locations.

However, there are also some large inter-annual variability and fluctuations in the observed vs. predicted bias — so individual years or months do not perform as well as others.

- The model appears to be flashier than observations show. It is responsive to smaller rainfall events, which result in higher peak streamflows than those observed at gages. However, the TMDL relies primarily on the *difference* between existing and forested conditions (as explained in subsequent sections of this report). When comparing two model runs, the model bias (both magnitude and direction) that exists in the existing model run is also present in the forested model run. When comparing the difference between the two model runs, we, therefore, get a precise answer on the difference in flashiness, given that the model bias is the same in both the existing and forested model scenarios.
- In Covington, the MIT model was doing well in the fall but significantly under-predicting annual volumes overall. Adjustments made during hydrology model calibration significantly improved annual TSS volumes but at the expense of over-predicting fall volumes.
- Little Soos Creek overall has the poorest model performance, and Soosette Creek summer and fall volumes are over-predicted. The application of HSPF in small watersheds that have only a few model catchments upstream of the calibration gage is generally challenging since the movement of water through these watersheds happens relatively fast and has less time to equilibrate to long-term hydrogeological processes.
- The model underestimates some of the largest, rare high-flow events in Little Soos and Covington (that occur less than 1% of the time). This means that TSS loads during these larger rare events may also be underestimated.
- Summer TSS concentrations are currently under-predicted at almost all calibration stations. Attempts to correct for this resulted in an over-prediction in concentrations in the winter months. Since this model is being applied to a TMDL where storm events and flashy flows are more important to consider, model calibration focused on improving predictions during the wetter months over drier months. While this under-prediction of summer TSS is a model limitation, this TMDL is focused on upland TSS and instream TSS erosion, which predominantly occur during storm events (which is then available for resuspension and deposition in the summer). On average, across all catchments, summer instream TSS loads contribute to about 5% of the total annual load.
- While the model explicitly simulates upland TSS and instream TSS, including instream scour and deposition, it does not explicitly simulate bank erosion. However, the model skill statistics show adequate performance with respect to estimating the total instream TSS concentrations, so by extension, we also have confidence that the total TSS model outputs represent all erosion (upland, stream bed, and bank erosion) relatively well, even if we cannot distinguish between them. Lastly, how much erosion is from the bank vs. the stream bed during individual events on a steady state process is perhaps not as important, especially in urban streams, since the mechanisms and drivers of this erosion are linked to runoff and overland flow, which the model is calibrated for.

Model Results

Model results are presented both at the scale of each HSPF catchment and subbasin scale. Figure 24 illustrates the subbasins, which represent the four major tributaries (Soosette, Little Soos, Jenkins, and Covington), as well as the Upper Big Soos, which represents the drainage upstream of the confluence of Big Soos and Little Soos.

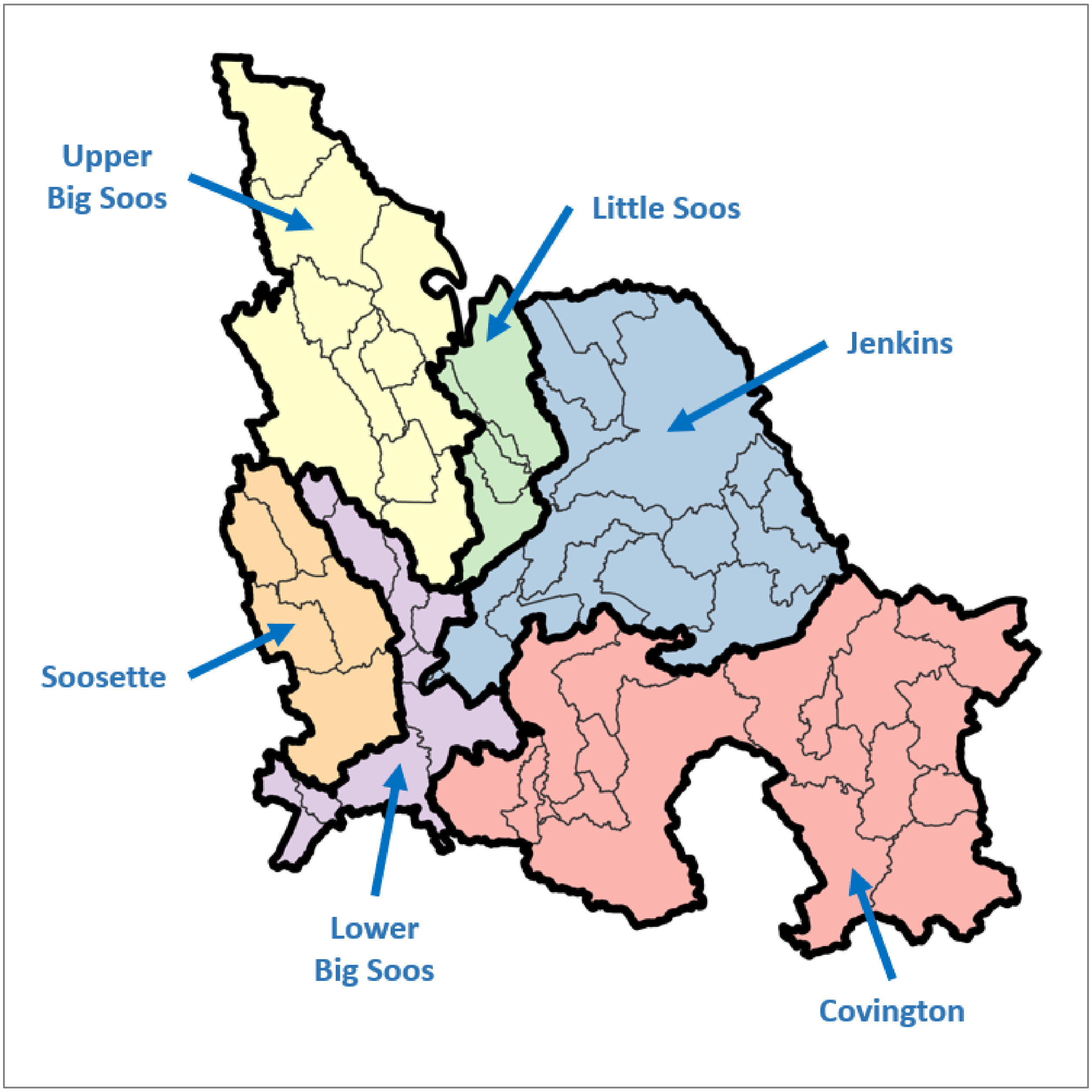


Figure 24. Major subbasins in the Soos watershed that are used to present model results.

Existing TSS Loads

HSPF model results show that developed land and EIA contribute the largest proportion of upland TSS loads (upland refers to TSS loading from the landscape delivered to the stream, but not the actual instream TSS load) in the Soos (Figure 25). EIA makes up just over 13% of the entire Soos watershed but contributes to 39% of the upland TSS load. Pervious developed land, on the other hand, covers 49% of the watershed and contributes to 51% of the upland TSS load. Conversely, forested land cover covers 32% of the watershed and only contributes to 4.1% of the upland TSS load. These patterns show the disproportionate contribution that impervious land sources have to the total upland TSS load.

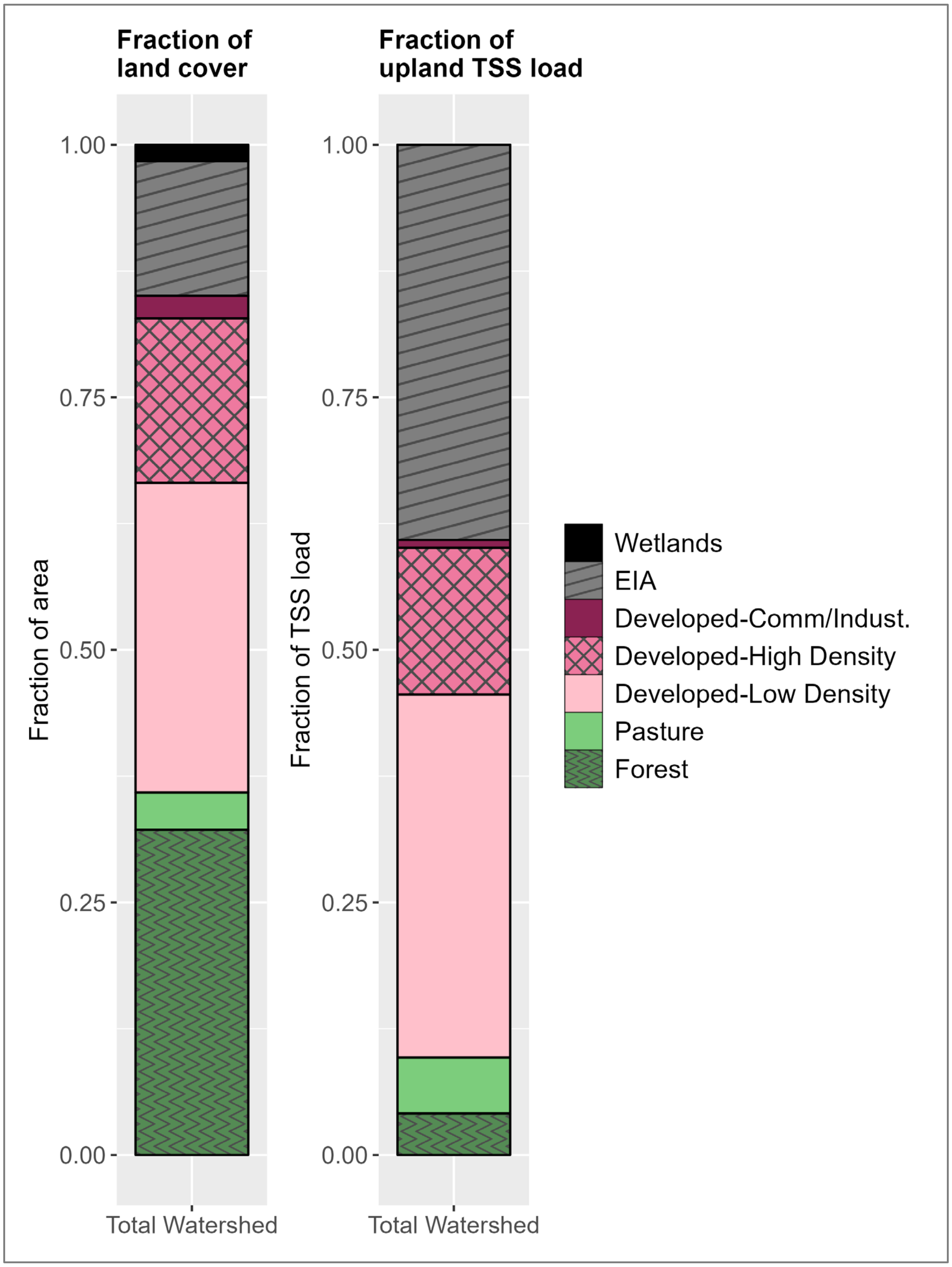


Figure 25. Fraction land cover and their respective contributions to average annual upland TSS loads in the Soos watershed.

Patterns in upland TSS contributions from different land covers vary slightly between different subbasins in the Soos, with EIA contributing 20% – 50% of the upland TSS load in each subbasin, developed pervious cover contributing 47% – 61%, and forested land cover contributing 1.2% – 8.5% (Figure 26 and Figure 27). The Covington subbasin has the largest magnitude of upland TSS loads but is also the largest subbasin by area (33% of the watershed area).

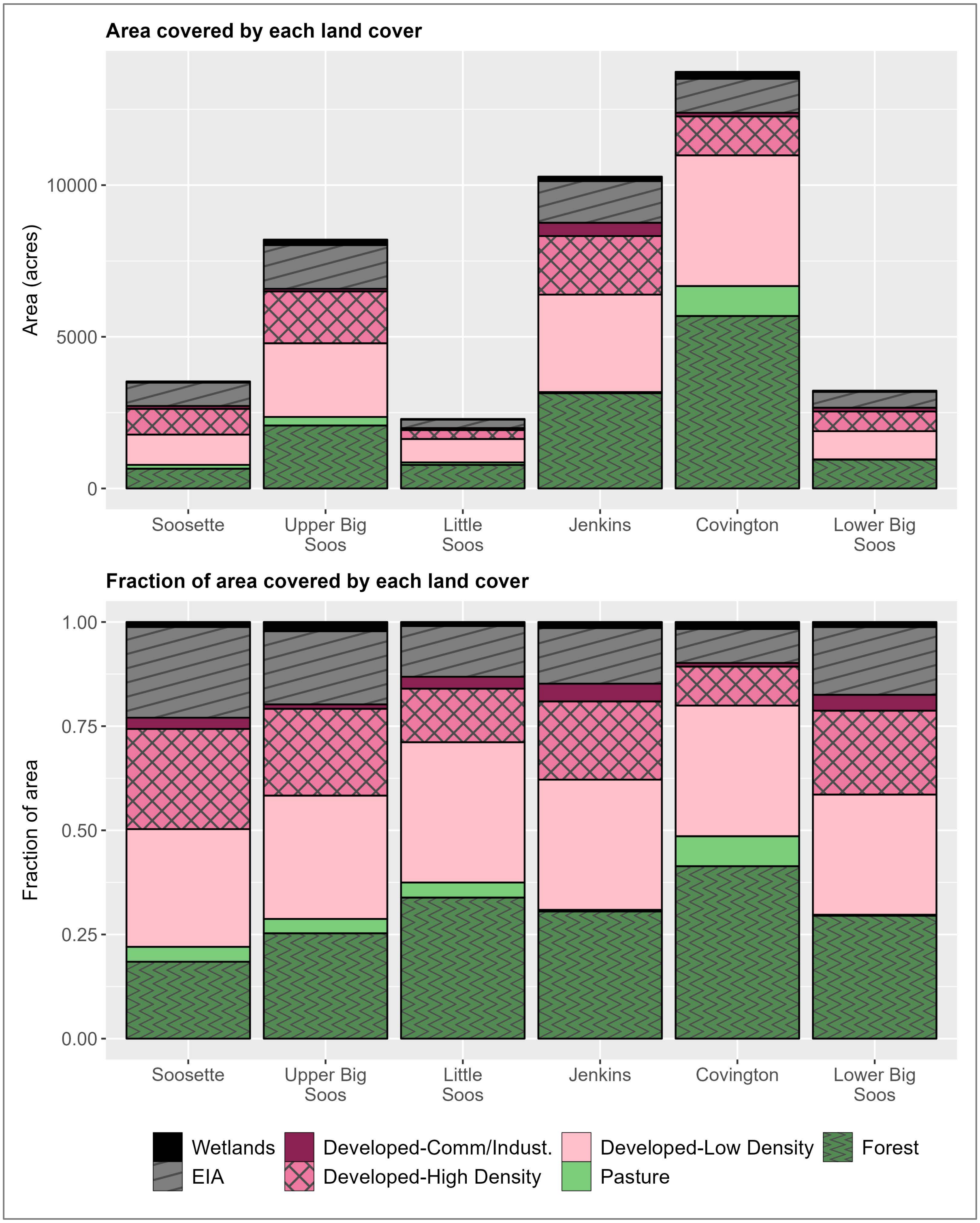


Figure 26. Area and fraction of land cover distribution in each subbasin of the Soos watershed.

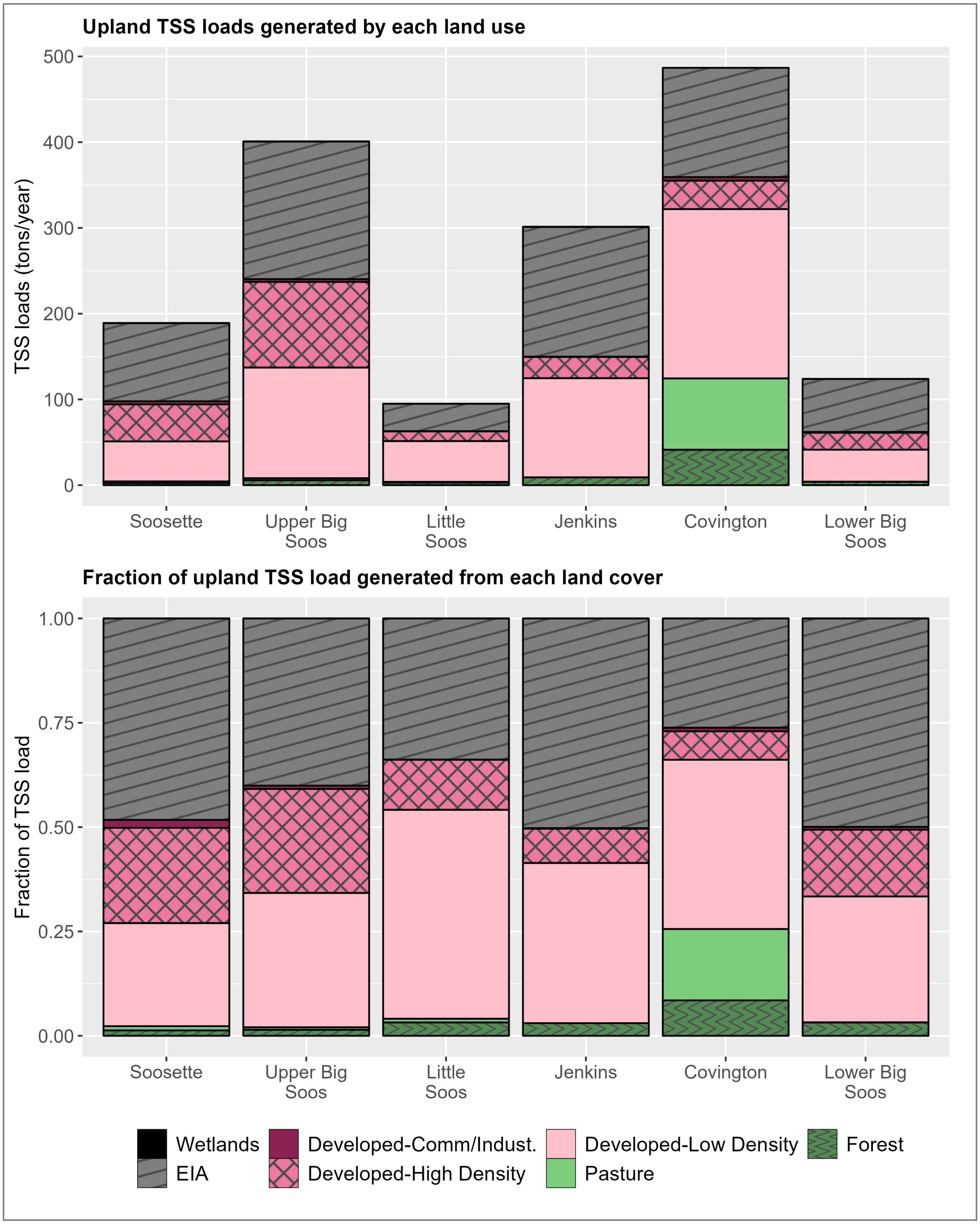


Figure 27. Average annual upland TSS loads and the fraction of TSS load generated from different land covers in each subbasin of the Soos watershed.

In addition to upland TSS sources, we were also able to estimate the additional contribution of instream scour to the TSS load for each model catchment. The TSS load from instream erosion was estimated using HSPEXP+[19], an open-source software developed by RESPEC that aids in the calibration and analysis of HSPF model results. Within the tool, the user can generate "Constituent balance reports," in this case for TSS, which outputs an annual average sediment budget for each reach in the model. This output includes simulated annual average net deposition or scour values for each reach. We used the annual net scour magnitude to represent the TSS loads generated by erosion within the stream. These values are only being used qualitatively to get a sense of which reaches in the watershed experience have higher instream erosion on an annual scale and to compare the relative amounts of instream erosion between catchments.

Figure 28 compares the proportion of TSS loads from instream erosion within each subbasin of the Soos as well as the whole Soos watershed relative to all upland TSS loads from the watershed. Lower Big Soos has the largest proportion of TSS loads from instream erosion at 71% respectively. This is likely reflective of the higher gradient and steeper stream slopes in this part of the creek system. Upper Big Soos, which has lower gradients and significant portions of the stream channel that are within areas classified as wetlands, has an insignificant instream erosion TSS load of 0.1%. At the scale of the whole Soos watershed, TSS loads from instream erosion contribute to 26% of the total TSS load.

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[19] HSPEXP+ open source software: https://www.respec.com/product/modeling-optimization/hspexp/

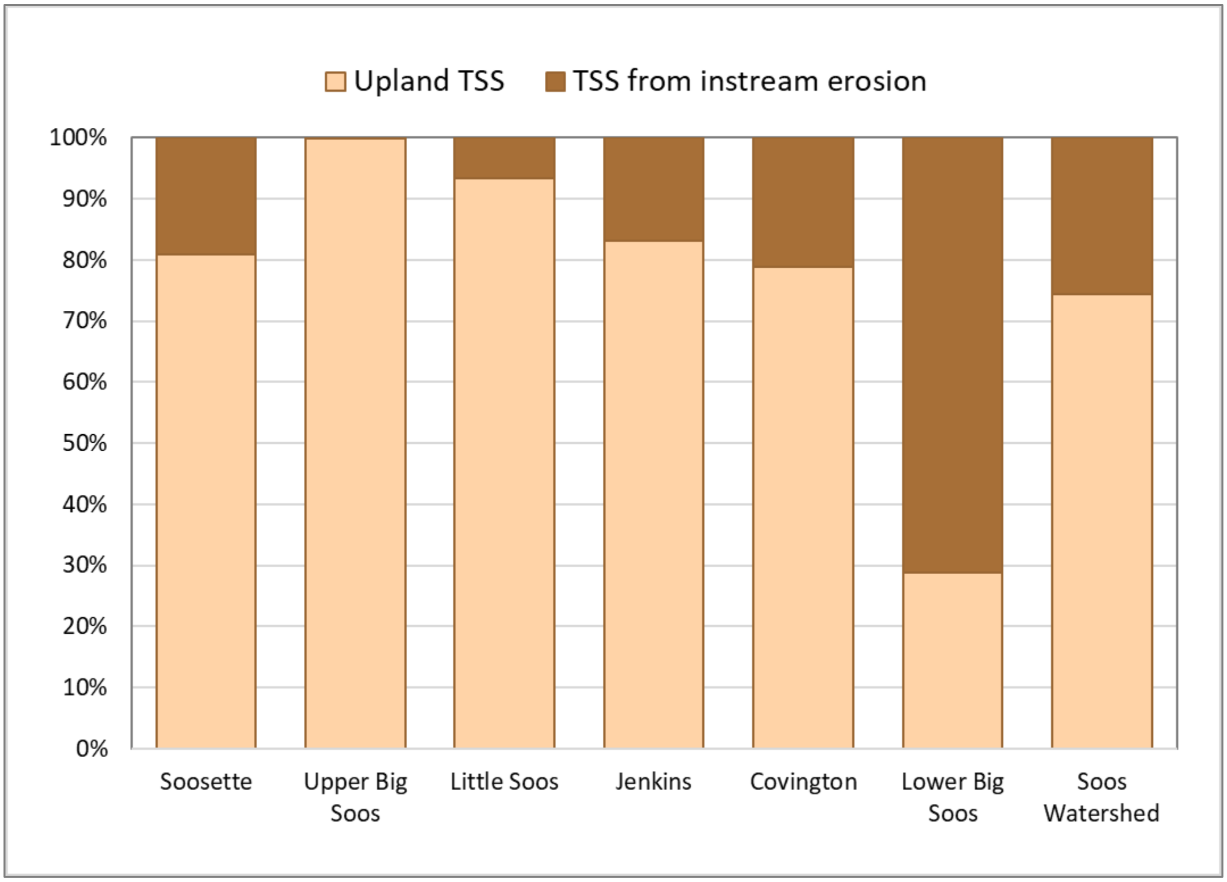

Figure 28. Fraction of total TSS load in each subbasin in the Soos watershed that comes from upland TSS loads vs. TSS loads from instream erosion, on an annual average basis.

Spatial patterns in TSS loads at the catchment scale are illustrated in Figure 29. Upland TSS loads are higher in the upper parts of the watershed, which, as mentioned earlier, is where there is generally more development. Upland TSS yields (which are calculated as the TSS load within a catchment divided by the catchment area or the load normalized by the area of each catchment) are also generally higher in the upper watershed, particularly in upper Covington. However, it is also important to note that the reaches that have a higher fraction of outwash soils (Figure 7) generally appear to generate a lower TSS yield, e.g., in the lower Covington and lower Jenkins subbasins. Instream TSS loads, which account for all instream processes, increase as you move downstream. This is expected since upland TSS from larger areas contribute to the upland TSS load as you move downstream. These also combine with TSS loads from instream erosion and scour, and sediment transport processes move these loads from one reach to the next.

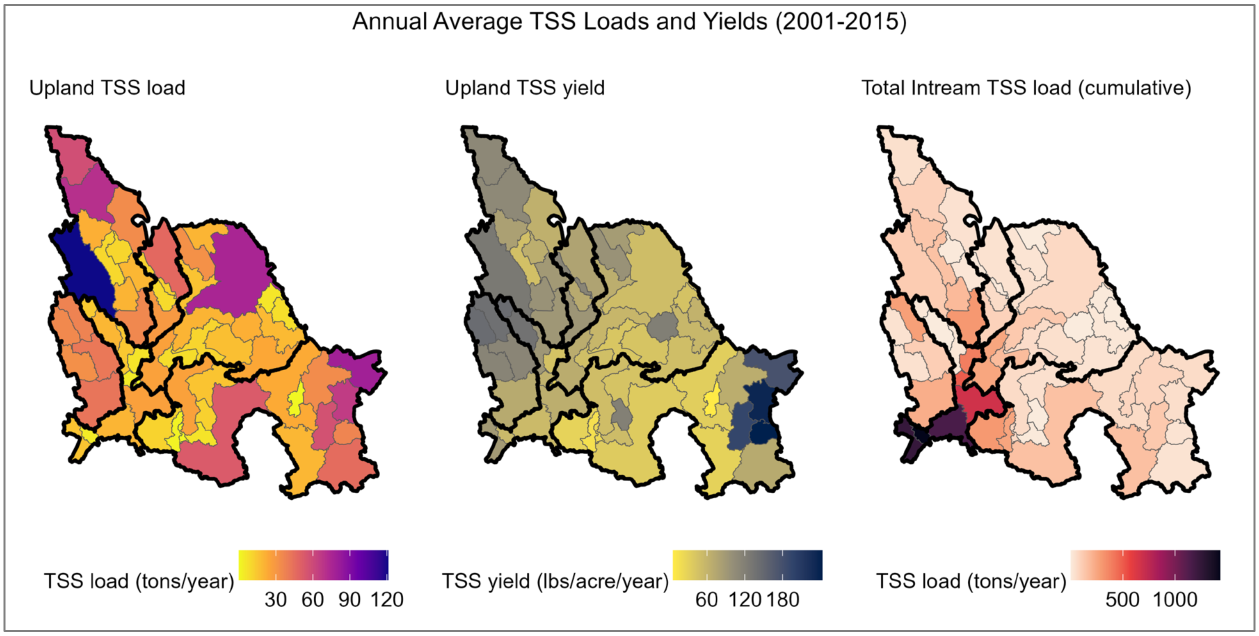

Figure 29. Annual average upland TSS loads, upland TSS yields, and cumulative instream TSS loads by HSPF catchment for 2001 – 2015 existing conditions.

Existing vs. Forested Conditions

The following sections compare the existing (WY 2001 – 2015) model results to the forested model run, where the only change made to the model is converting all non-forest land covers to forested cover — except for wetlands and open water bodies. The modeling of forested conditions is a critical element of this TMDL study since it informs our understanding of the changes in flow and TSS loads due to human development. Pre-developed flows also form the basis for stormwater management in Washington State, where municipal stormwater permits require that new development and re-development treat stormwater to match pre-developed flows for specific return periods and flow frequencies.

Flow Alteration

Figure 30 compares the flow duration curve between existing and forested conditions at the most downstream reach of each subbasin. As expected, low-frequency high flows exceed forested flows in all subbasins. The difference between existing and forested flows for low-flow events is smaller in magnitude (note that the plots are on a log scale), and at some locations, in forested conditions, low flows are predicted to be higher than existing low flows. This mechanism makes sense from a hydrology perspective, where less development means more water infiltrates into the ground and contributes to summer baseflow. However, this pattern is not consistent across all six subbasins — Jenkins, Covington, and Lower Big Soos all show that forested flows are below existing flows even for the highest exceedance percentiles.

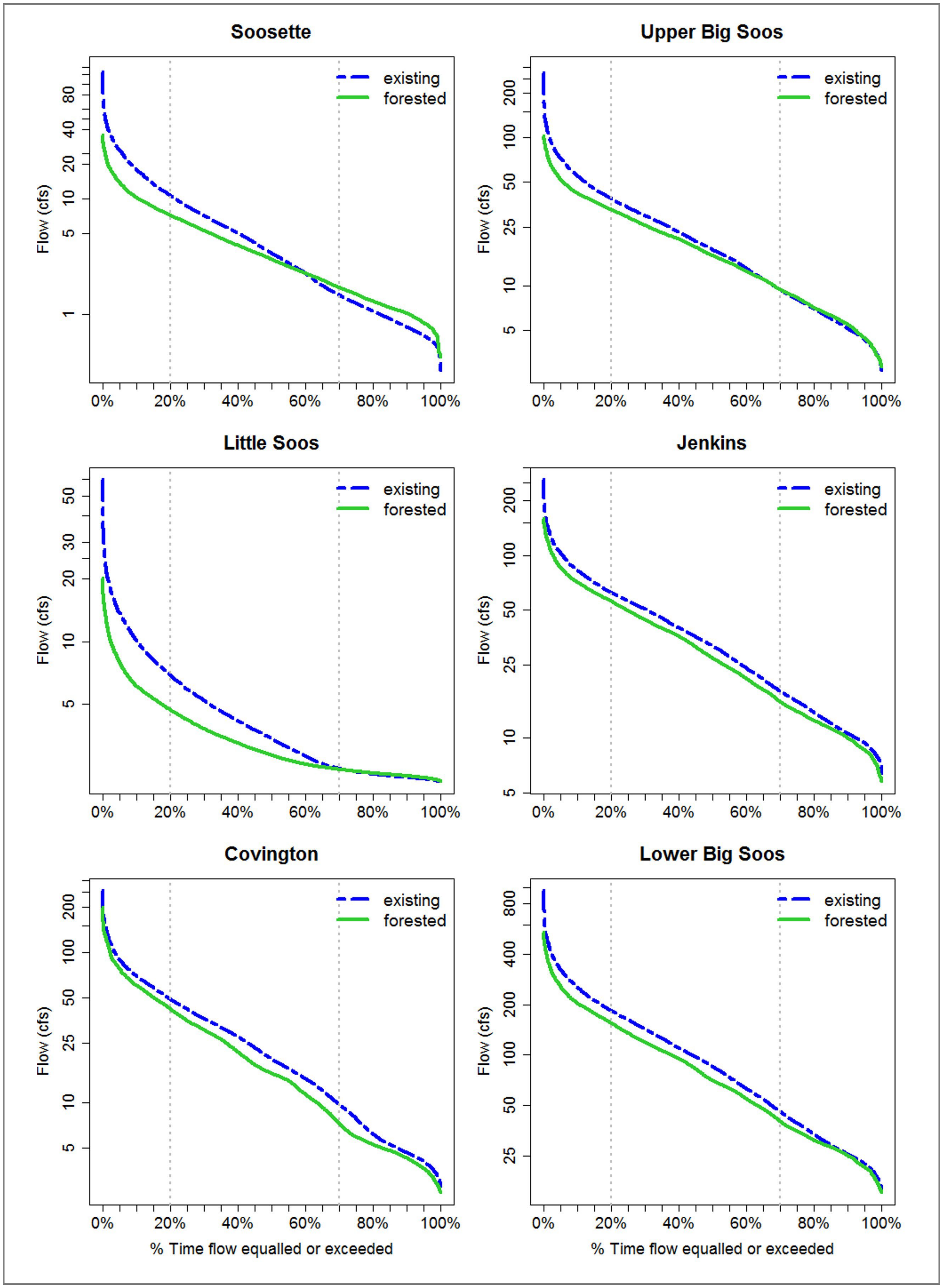

Figure 30. Comparisons of existing and forested flow duration curves at the downstream end of each subbasin of the Soos watershed for WY 2001 – 2015.

Figure 31 compares existing and forested yearly HPCs calculated at all modeled reaches. The existing median HPC value of 11 is significantly higher than the forested median HPC value of four. HPCs correlate to where there is more EIA in the watershed (Figure 32). The increase in HPCs relative to forested conditions is also larger in watersheds that have more EIA compared to those that have less EIA.

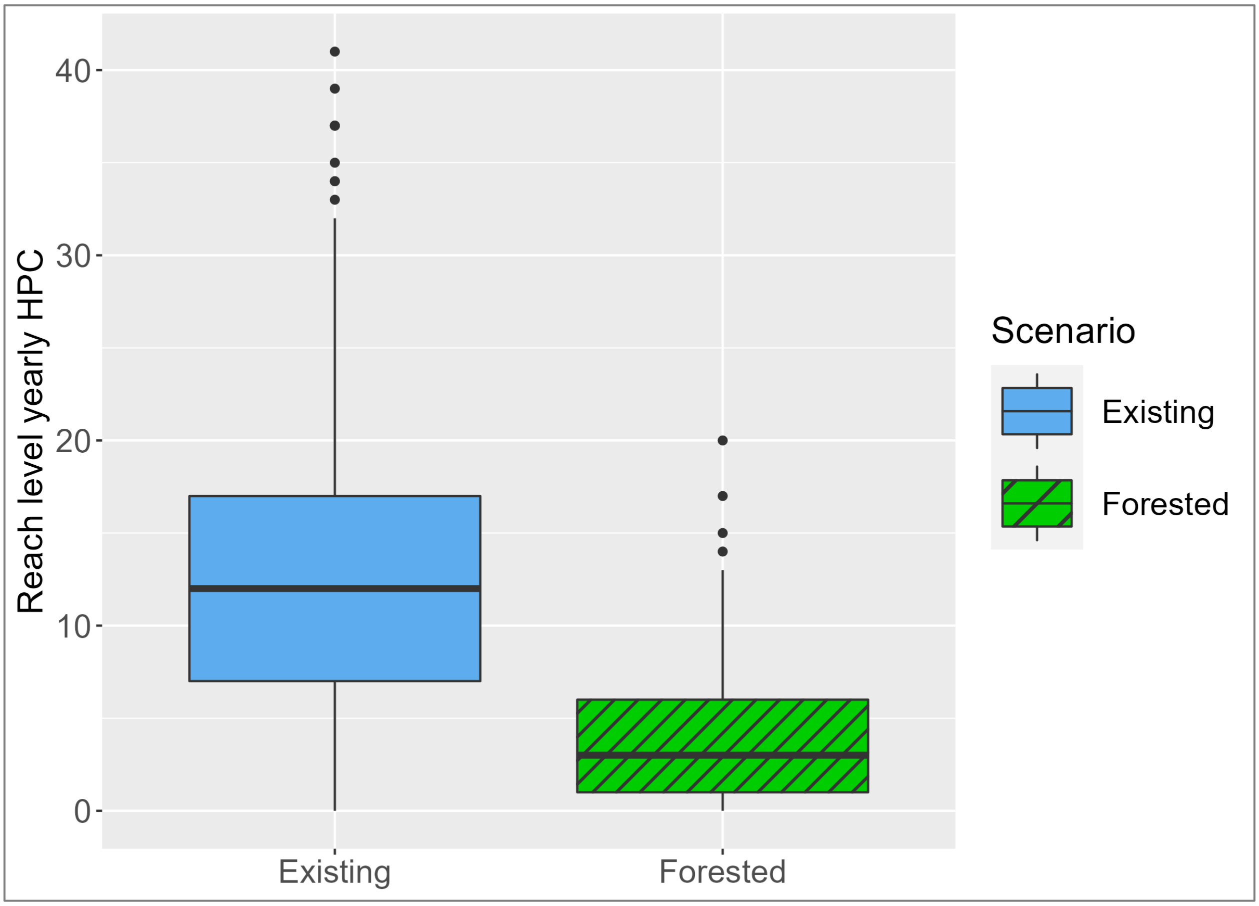

Figure 31. Boxplots comparing existing and forested yearly HPCs at all model reaches.

Also important to note is the influence of the underlying soils and geology – contrasting Figure 32 with Figure 7 shows that reaches with a higher number of HPCs sometimes correspond spatially to those reaches that have a higher fraction of till soils and/or a lower fraction of outwash soils. All these model results are consistent with known patterns and mechanisms of how development and increases in impervious surfaces contribute to an increase in the frequency of flashier storm events.

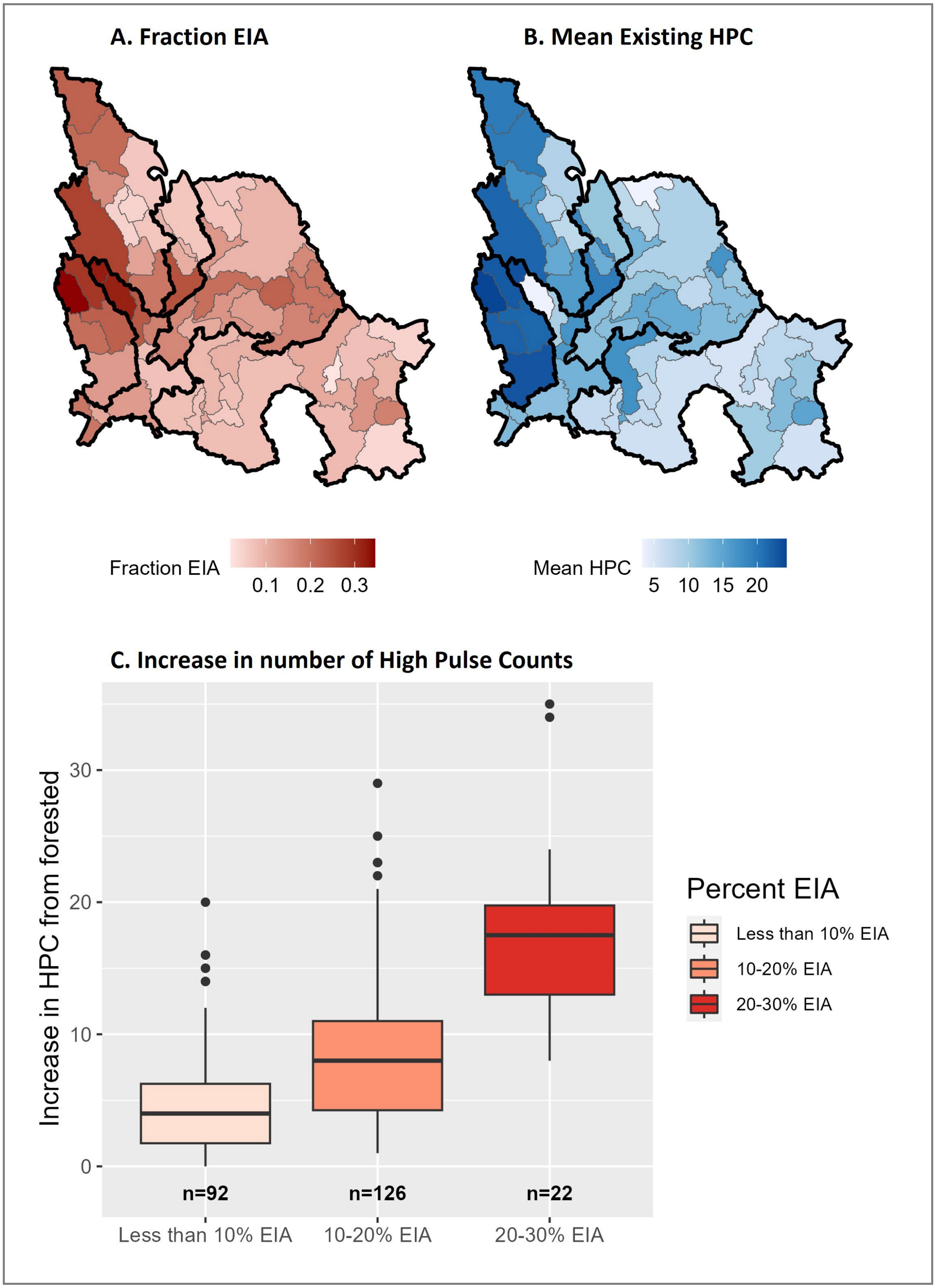

Figure 32. Reach maps illustrating (A) fraction of EIA (B) mean existing HPCs and (C) the increase in the number of HPCs across reaches with different levels of EIA.

Scour occurs when TAU values are above the scour threshold, which, as explained in the model calibration section, varies from reach to reach. Figure 33 compares the range of the number of days per year when the daily mean TAU values are above the silt and clay scour threshold under existing and forested conditions for each subbasin. More development and less forested areas result in a larger potential for scour across the watershed, though the difference is more pronounced in some subbasins (Soosette, Little Soos, and Lower Big Soos) than others. However, it is also important to note that this is a theoretical comparison since the forested condition scenario only involves changing land cover (and its influence on runoff processes) and does not include any changes to channel morphology, complexity, geometry, or instream hydraulics which would further influence instream scour dynamics.

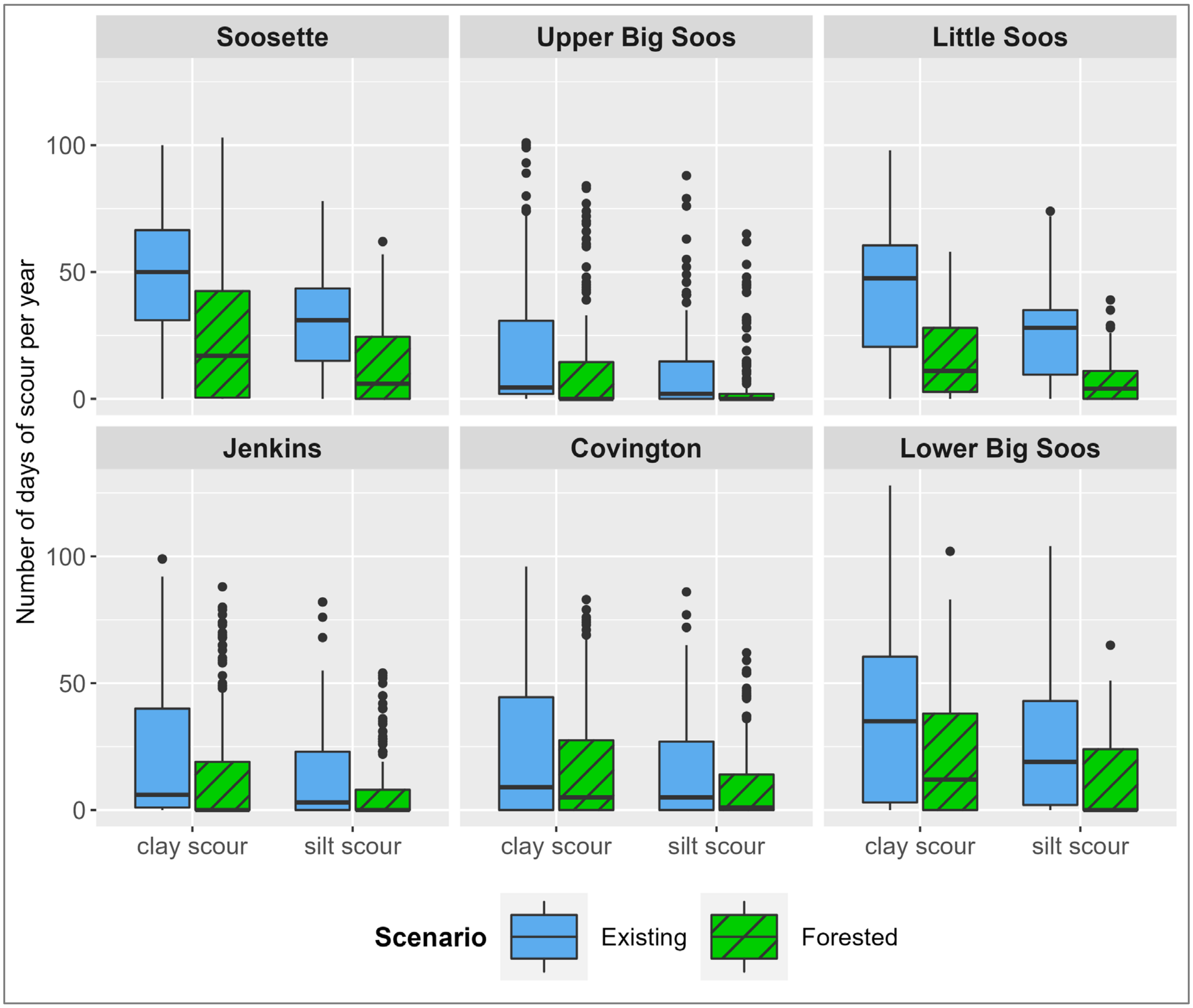

Figure 33. Comparison of the number of days of scour (defined as when the mean daily TAU values were above the scour threshold) under existing and forested conditions.

TSS Concentrations and Loads

Figure 34 compares existing and forested reach level TSS concentrations in different subbasins of the Soos. While median concentrations are only slightly higher than forested concentrations, existing conditions show a wider range in concentrations primarily due to higher concentrations in the upper half of the boxplots, i.e., concentrations above the median are higher under existing conditions.

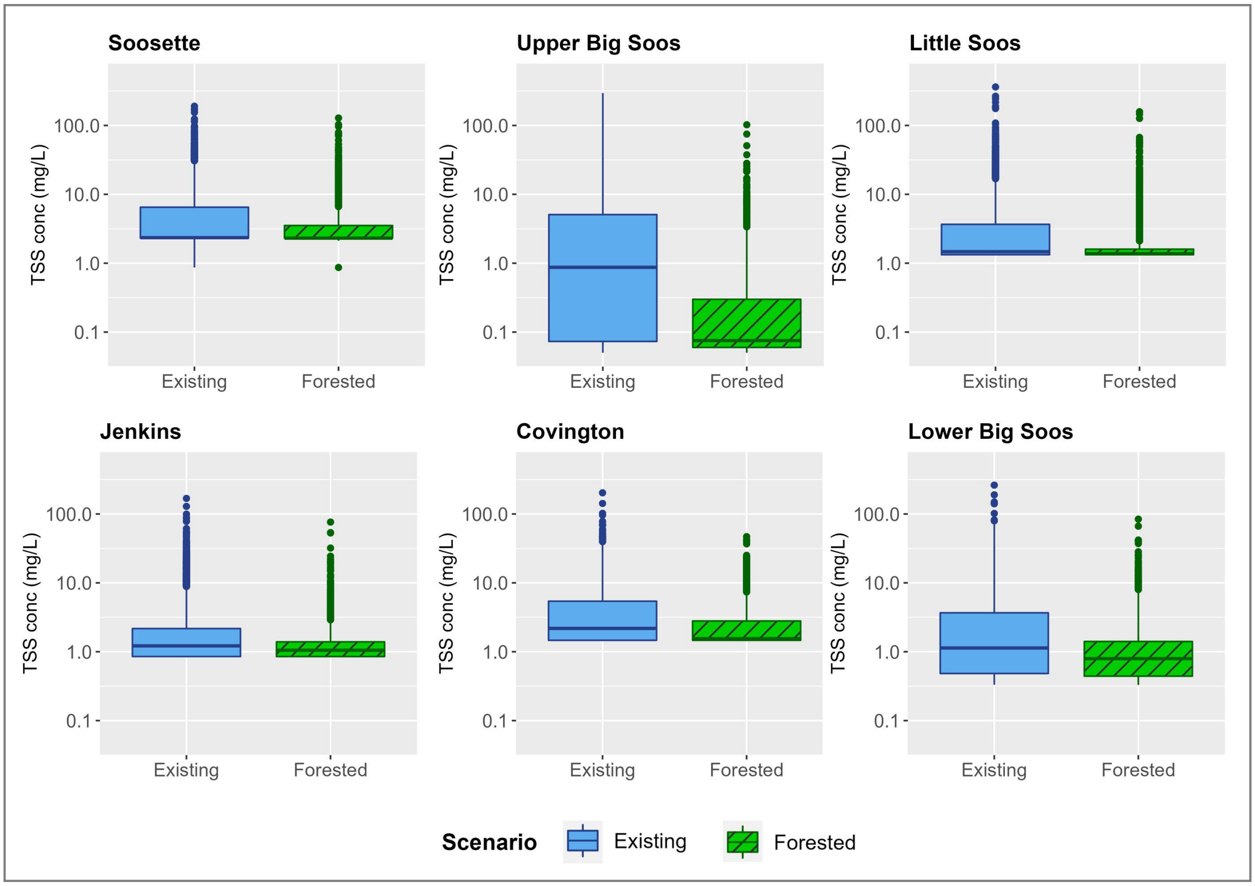

Figure 34. Boxplots showing the range in TSS concentrations under existing and forested conditions in different subbasins of the Soos.

These higher concentrations are primarily generated during higher flow events — Figure 35 shows that median concentrations near the mouth of the Big Soos are similar under existing and forested conditions at lower flow intervals but start becoming more disparate when flows exceed the 40th percentile of all flows.

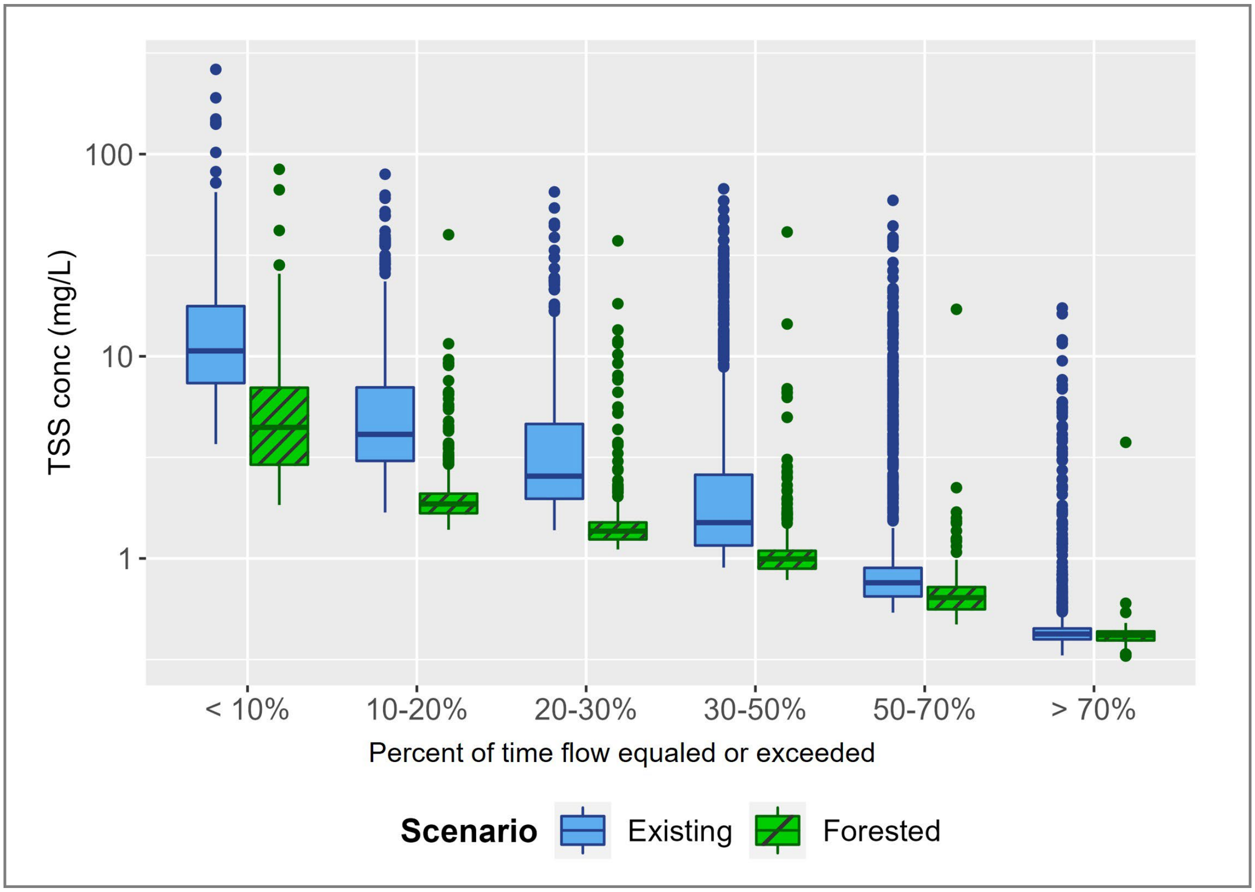

Figure 35. Boxplots showing the range in TSS concentrations generated under existing and forested flow at different flow exceedance categories at the mouth of the Soos.

Annual average instream TSS loads under forested conditions are 58% – 94% below existing TSS loads. The Covington subbasin, which has the highest percentage of forest cover, has the smallest difference between existing and forested TSS loads, where forested TSS loads are 58% below existing loads (Figure 36). In terms of the magnitudes of instream TSS loads, the Lower Big Soos has the largest instream sediment load — this makes sense since sediment loads in the Lower Big Soos include the accumulation of TSS loads from all upstream sources in the watershed.

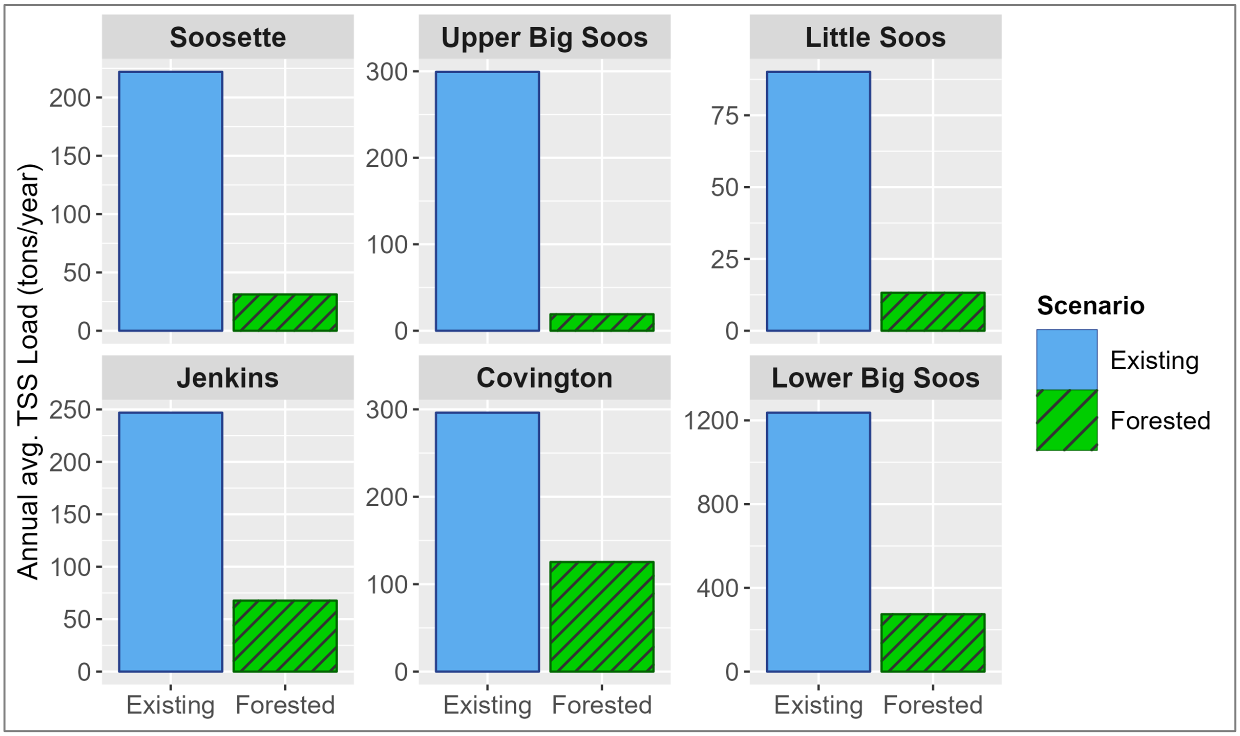

Figure 36. Annual average TSS loads under existing and forested conditions for each subbasin in the Soos.

The difference between existing and forested monthly TSS loads is much higher in the wetter months than in dryer months, which reflects both the combination of higher flows and TSS concentrations during these wetter months (Figure 37).

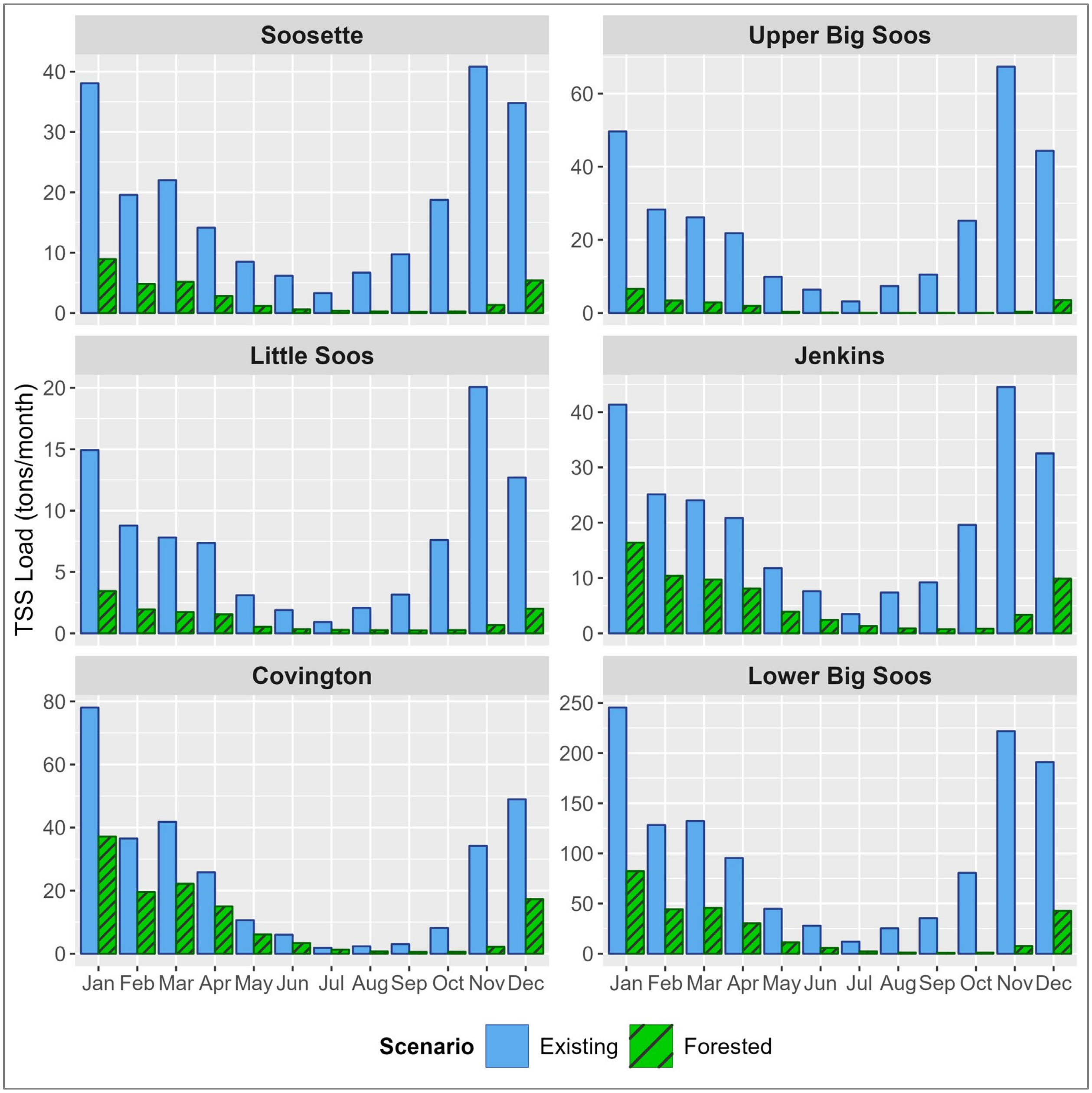

Figure 37. Average monthly TSS loads under existing and forested conditions for each subbasin in the Soos.

The proportion of the TSS load that is composed of sand, silt, and clay also varies by month and between existing and forested conditions. Under existing conditions, the proportion of silt and clay (which together make up fine sediment) is much higher than under forested conditions — this is visible by comparing the left column of plots with the right column of plots in Figure 38. This is a result of higher TAU values when streamflows are higher, which then more frequently exceed the calibrated scour thresholds (as described in the *Sediment Calibration* section) for silt and clay, resulting in increased scour and instream erosion of finer sediment.

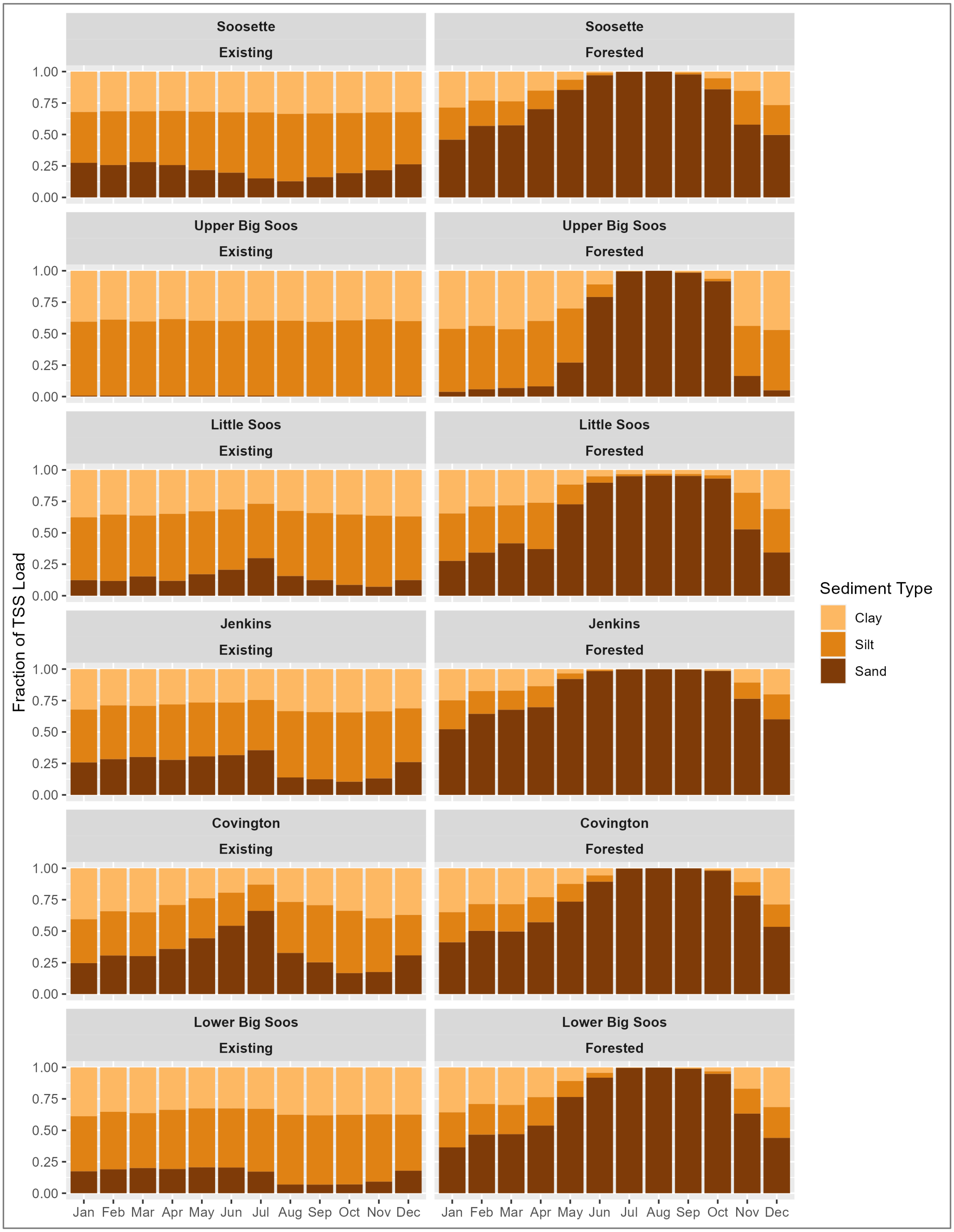

Figure 38. Fraction of monthly instream TSS loads composed of sand, silt, and clay under existing and forested conditions.

Summary of Model Results

In summary, model results comparing existing and forested conditions confirm the following:

- Development and EIA contribute to a higher frequency of high flow events, an increase in HPCs, and an increase in the potential for instream scour and erosion.
- TSS concentrations are generally higher under existing vs. forested conditions, but this difference is largely due to concentrations during higher flow intervals or exceedances.
- TSS loads are significantly higher under existing conditions relative to forested conditions across all subbasins and all months. However, the difference is again more prominent during wetter times of the year.
- The proportion of fine sediment (silt plus clay) in TSS loads is also higher under existing conditions relative to forested conditions.
- Forest cover appears to buffer the effects of development. For example, in the Covington subbasin, which has the highest percentage of forest cover (41%), we found the smallest impact from existing development. Existing TSS loads in Covington are about twice those of the corresponding forested condition, whereas, in other locations, existing loads are about four to almost ten times those of the corresponding forested condition.

B-IBI and TMDL Analysis

B-IBI Analysis

The Stressor ID study established the most probable stressors associated with poor B-IBI scores in the Soos. These stressors included flow alteration (stream flashiness and HPCs), fine sediments, and physical habitat degradation (Marshalonis and Larson 2018). The B-IBI data used in the Stressor ID ranged from 1999 to 2013 and included modeled HPCs averaged for the years 1999 – 2009 from a version of the HSPF model that was being applied by King County at that time. For this phase of the TMDL project, we expanded the B-IBI dataset to include data collected since 2009 and compared those to modeled outputs based on the updated and recalibrated HSPF model described in this report. B-IBI scores were also compared to other metrics that are relevant to the study, including FSBI, percent sand fines, and inferred fine sediment.

As mentioned previously, B-IBI data across the Soos are highly variable over both time and space. Figure 39 shows the spatial distribution of available B-IBI data for each HSPF catchment as well as the B-IBI categories, based on mean B-IBI scores for all available data collected in the Soos from 1994 to 2021.

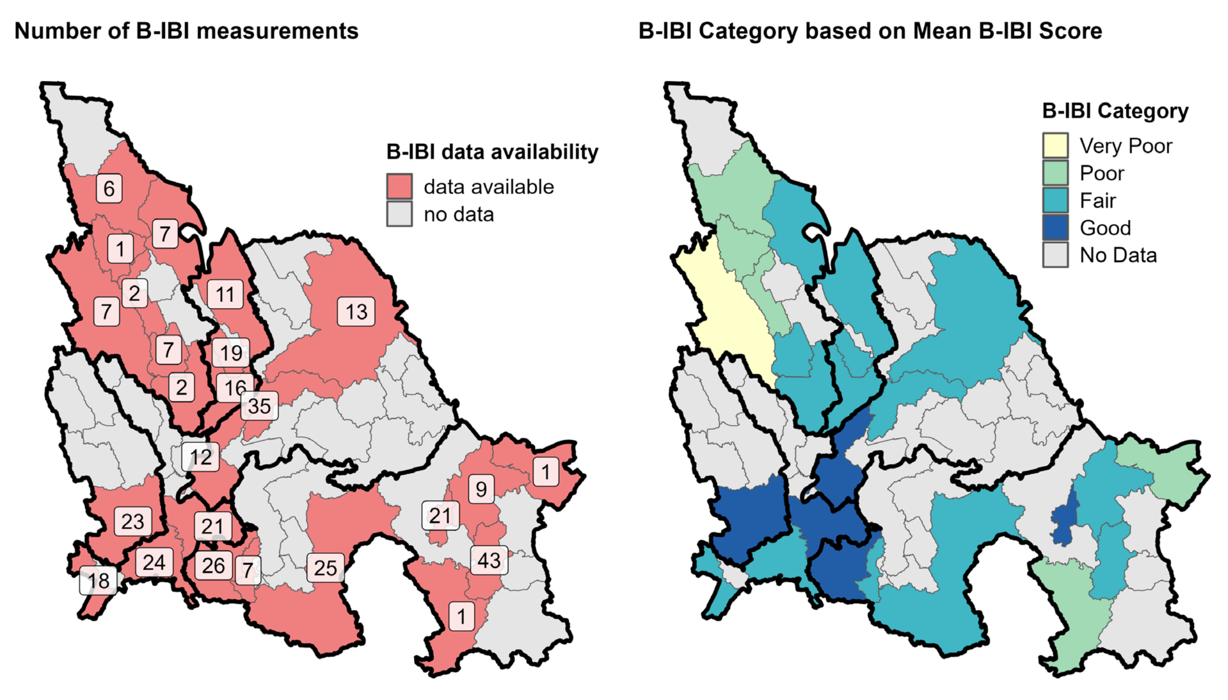

Figure 39. Availability of B-IBI data collected from 1994 to 2021 for each HSPF catchment in terms of number of measurements and their respective B-IBI categories.

B-IBI categories range from “very poor” to “very good” based on mean B-IBI scores.

Overall, when B-IBI scores are grouped by the level of EIA in the catchment, we see that while scores above the 65 threshold for impairment exist at all levels of EIA, there is a higher frequency of scores below the threshold in reaches with greater EIA (Figure 40). We also analyzed other habitat-related variables that are expected to contribute to low BI-BI scores, such as embeddedness, canopy cover, bank stability, and median substrate size (D50). However, data scarcity and other shortcomings with those data do not allow for a more robust analysis.

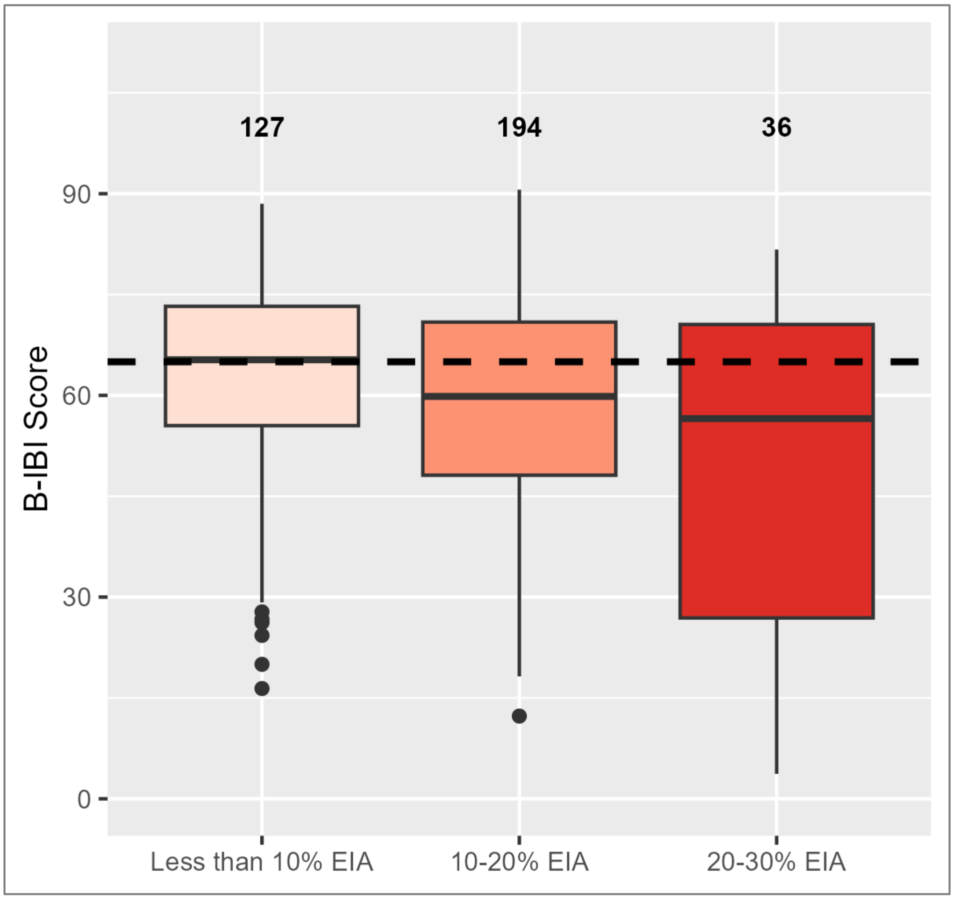

Figure 40. Boxplots of B-IBI scores grouped by level of cumulative percent EIA in the drainage area of the HSPF reaches upstream of where B-IBI data were collected.
The numbers above boxplots indicate the number of samples for each EIA category.

B-IBI scores vary more from year to year at some sites than at others — some locations show consistently good or poor scores, but many locations go above and below the 65 B-IBI threshold of impairment when data are analyzed over multiple years (Figure 41).

Most B-IBI data were collected in the summer or early fall before the wet season begins. While these data are only collected once a year, their benefit as an indicator comes from the fact that the benthic macroinvertebrate community integrates and reflects conditions not just at the time of sampling but over longer timescales (Barbour et al. 1999; Carter et al. 2017 and Karr 1991). However, shorter events, e.g., a major storm, could potentially wipe out the benthic community in one year, and the community might subsequently take some time to reestablish and recover.

Upper Big Soos has some of the most consistent low B-IBI scores, even though there are fewer sites in this subbasin. While there is a high level of development in this area, there are also some upstream wetland complexes that might be influencing the composition of the downstream benthic community in this part of the watershed.

The fact that B-IBI scores often exhibit a large range of values at a single site also reflects the potential for their recovery and improvement if the conditions that allow them to thrive exist. This inter-annual variability can make it challenging to correlate yearly B-IBI scores to other variables that are measured at different spatial and temporal scales compared to what is being collected at the stream reach. However, we do know that B-IBI scores respond to factors at both the reach and watershed scale and that these various factors interact.

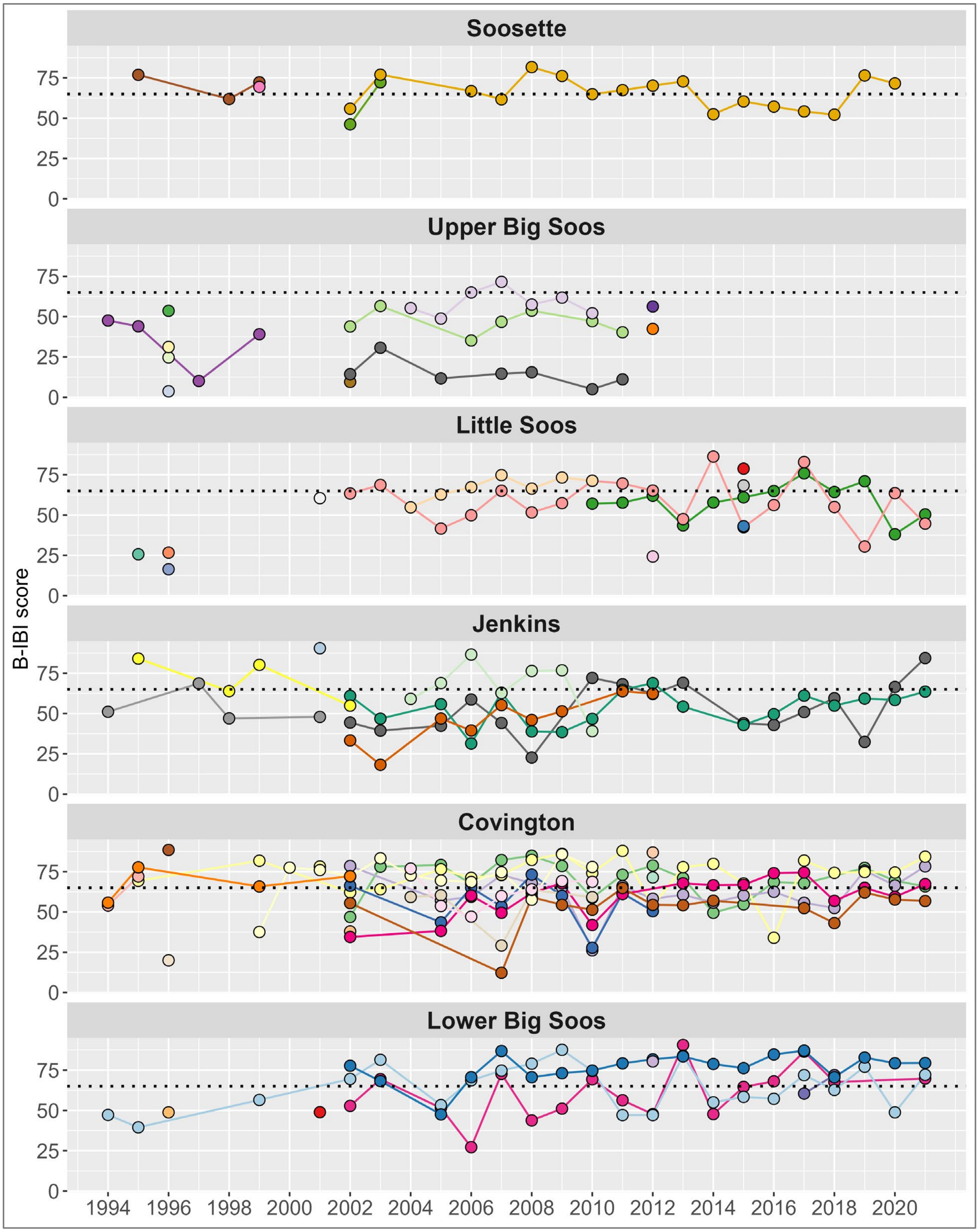

Figure 41. Yearly B-IBI scores at different sampling locations within each of the subbasins in the Soos from data collected from 1994 to 2021 (each color represents a different sampling location).

B-IBI and Sediments

B-IBI and Percent Sand/Fines

While the modeling effort focused on modeling flow and TSS, the fine sediment that affects the benthic community is the portion of TSS that is deposited on the streambed. This is often measured and reported as percent embeddedness or percent sand/fines. Only 20 of the 57 sites that have B-IBI data in the Soos have paired measurements of percent sand/fines collected by King County. In 2013, there was also a method change in how these data were collected (across the bankfull width vs. the wetted width), which precluded our ability to pool all the data together for our analysis since substrate across the bankfull width is highly biased towards sand (King County 2023).

Figure 42 shows scatter plots of B-IBI scores and percent sand/fines data, with data divided into two groups based on the substrate collection method (bankfull width or wetted width). While there is some indication that B-IBI scores are higher where percent sand/fines are higher, the converse is not necessarily true — at lower levels of percent sand/fines, we see a wider range in B-IBI scores.

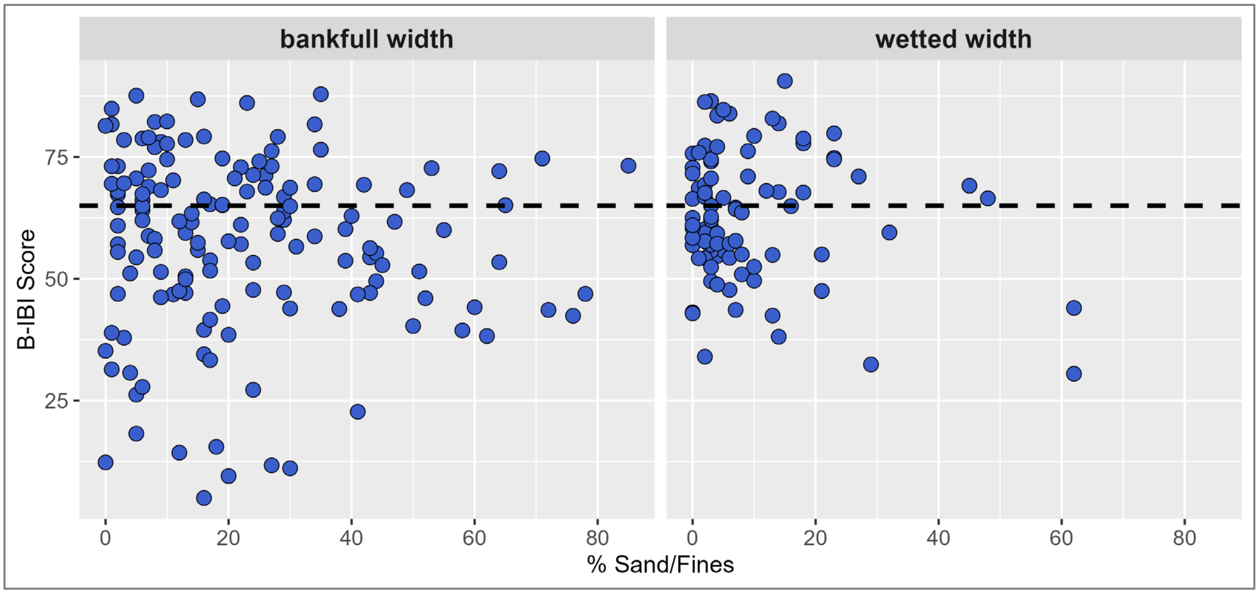

Figure 42. Scatter plots of yearly percent sand/fines collected using two different sampling methods (bankfull width or wetted width) against yearly B-IBI scores at sites where these data are available.

B-IBI and Inferred Sediment

In the absence of larger percent sand/fines or embeddedness datasets, we also calculated *inferred fine sediment* using Yuan's methods (Yuan 2007a, 2007b, and 2014). This approach uses the R *bio.infer* package, which applies a maximum likelihood inference method for estimating environmental conditions — in this case, fine sediment — based on known tolerance data for macroinvertebrate taxa primarily collected in the Pacific Northwest. The method essentially uses biota to predict the percent of fine sediment at a stream reach.

C. Larson (pers. comm., May 2023) compared inferred fine sediment against visual estimates of percent sand/fines using Ecology data collected from nearly 1,500 sites around Washington state from 2009 to 2021 (Figure 43). These data show clear relationships between observed percent sand/fines and inferred fine sediment, even though the variability is large.

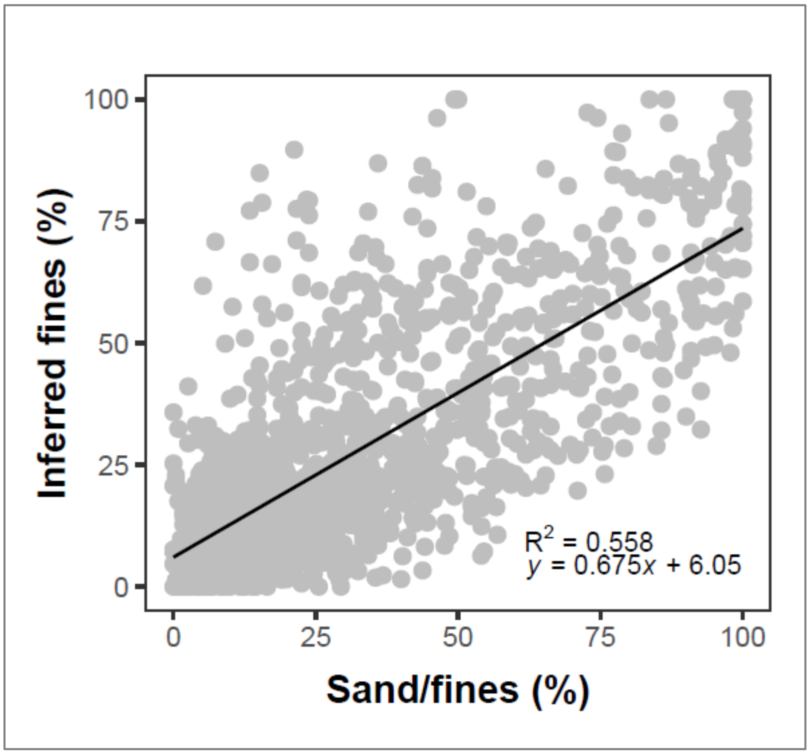

Figure 43. Relationship between observed percent sand/fines and inferred fine sediment from Ecology data from around Washington state.

Figure 44 shows that in the Soos, higher percent inferred fine sediment values are associated with lower B-IBI scores and FSBI values, supporting the findings of the Stressor ID study where fine sediments were found to be a causal mechanism for poor B-IBI.

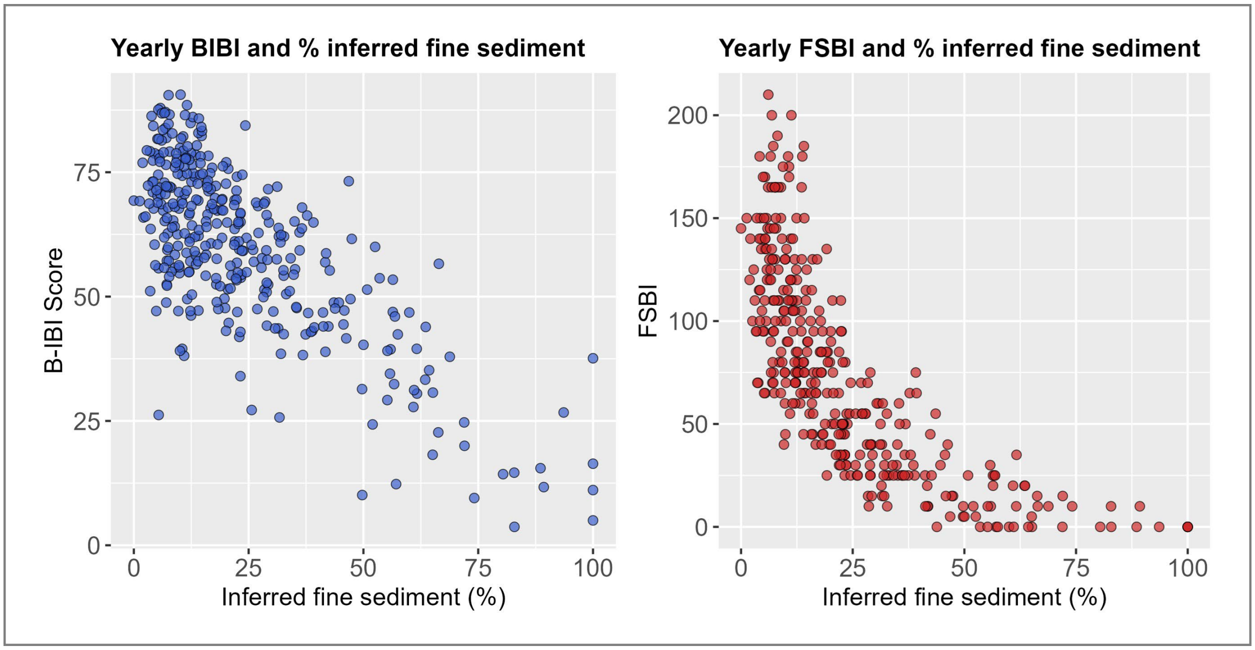

Figure 44. Relationship between percent inferred fine sediment and B-IBI scores (left plot) and FSBI scores (right plot) calculated from macroinvertebrate data collected in the Soos.

B-IBI and High Pulse Counts

When comparing B-IBI scores with model-predicted HPCs, and as planned in the QAPP for this project (Mohamedali 2018), we used a statistical method called "quantile regression" to assess the strength of the relationship between these two variables. Quantile regression estimates relationships between variables for all portions of a probability distribution. The approach involves separating the data (in this case, B-IBI scores) into quantiles and calculating separate regression parameters for each subset of data that fall within each quantile and might have a different functional response to the predictor variable. The approach is useful for ecological data that have unequal variations to predictor variables; this is described in more detail in Cade and Noon (2003) and Schmidt et al. (2012). It has been applied in the analysis of flow alteration and bioassessment to determine the biological status that could be achieved as flow alteration increases or decreases away from a baseline condition (USACE, TNC, and IC 2013). This statistical method aims to address some of the limitations of simple regression techniques in its application to analyze and identify ecological responses to specific collinear environmental variables and various limiting factors.

Figure 45 presents quantile regressions between yearly values of increase in HPC (relative to the forested scenario) and B-IBI data. The lowest two quantiles show a stronger negative relationship between HPCs and B-IBI, indicating that those sites that have poorer scores are potentially more influenced by HPCs. For higher quantiles of data, other factors at sites with higher B-IBI scores appear to buffer the effects of stream flashiness since higher HPCs have a weaker relationship with poor B-IBI scores. Nonetheless, the uncertainty of the slope for the lower quantiles is large, so this analysis once again reveals the large degree of variability inherent in the B-IBI data set.

We also placed all B-IBI sites into categorical groups ranging from low, medium, and high variability sites. This was done using the variance and inter-quartile range of B-IBI data collected over time at each site in combination — as well as the range of B-IBI categories (from "very poor" to "excellent") that B-IBI scores at each site are comprised of. For example, a site that had both excellent and poor scores measured at different times was considered a "high variability" site, even if most scores were in the "fair" category. Once sites were grouped into these categories, we compared the relationship between HPCs and B-IBI scores at just those sites that exhibited "low variability" in B-IBI scores (Figure 46). This process removed much of the "noise" in the data and is used qualitatively to show that in the Soos, there are sites where B-IBI scores are clearly and negatively correlated to HPCs.

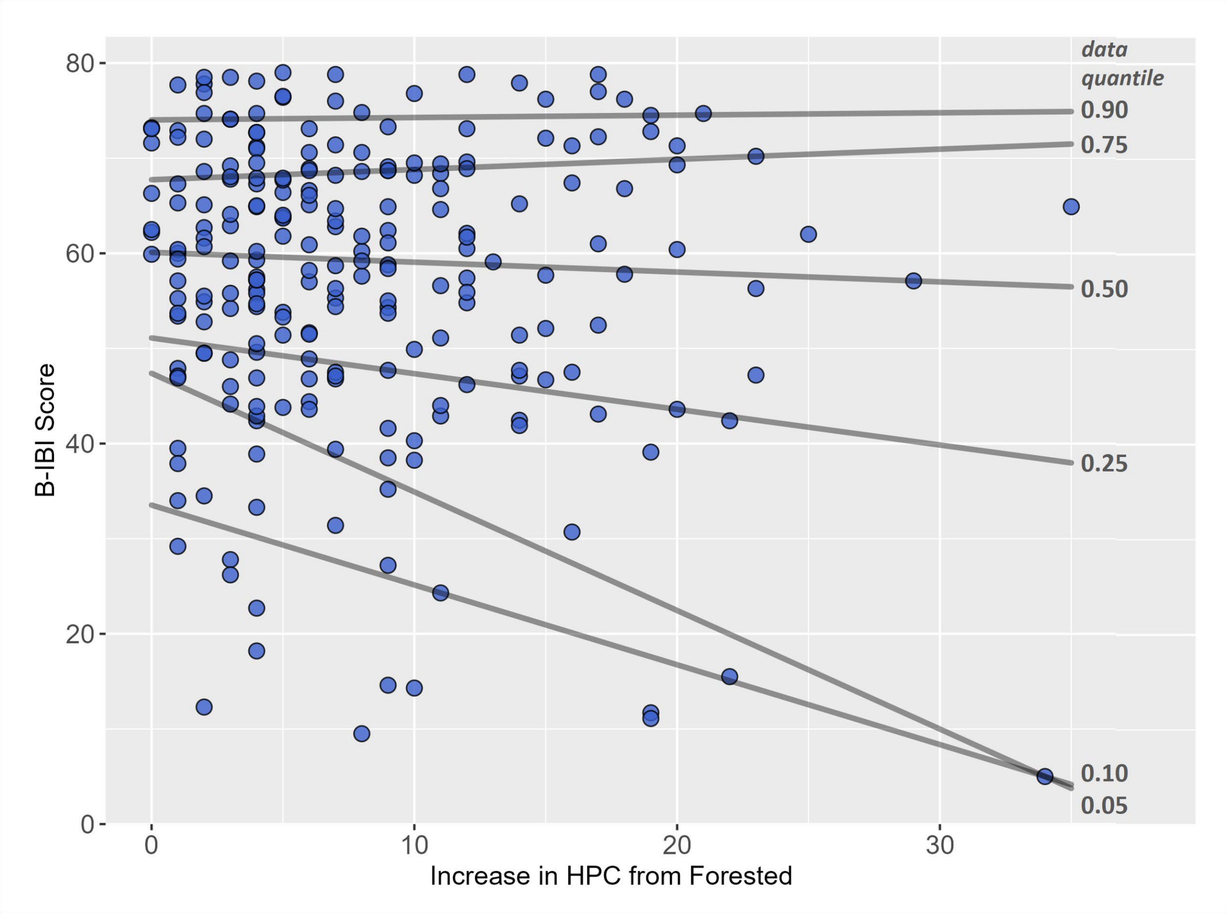

Figure 45. Quantile regression plots between yearly HPCs (relative to forested conditions) and yearly B-IBI scores across all sites and years of data collected within the stream reach.

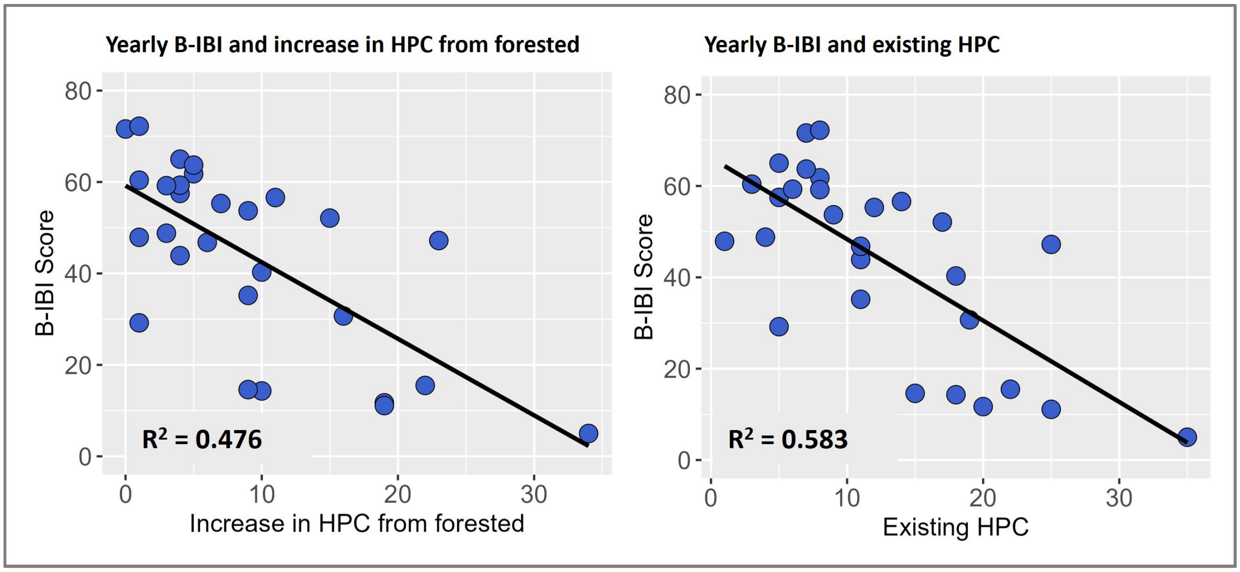

Figure 46. Regressions between yearly HPCs (increase in HPCs from forested conditions on the left and existing HPCs on the right) and B-IBI scores at sites categorized as "low variability" based on B-IBI scores.

Lastly, we correlated the mean of all model-predicted *existing* HPCs (under existing conditions) against the mean of all B-IBI data (mean of all sites within each HSPF reach for the years 1994 – 2021)[20]. We also juxtaposed mean observed HPCs for the four B-IBI sites that are co-located with streamflow gages in the watershed (Figure 47, left plot). While there is one outlier in the data, there is a notable relationship between mean existing HPCs and mean B-IBI scores.

The outlier is near the mouth of the Soosette subbasin (in Reach 582) and is represented by the mean of B-IBI scores collected at four different B-IBI monitoring sites (Site IDs soos60, soos06a, 09SOO1020, and 09SOO1022). Of these sites, only Site 09OO1022 has a long-term dataset of 17 samples, while the others have 1 – 3 samples each. The mean B-IBI score is, therefore, more representative of Site 09SOO1022. This is the same site that was removed from the Stressor ID analysis, where they determined through diagnostic analysis and plots that this single data point had very high leverage with the relationship between B-IBI and HPCs. Notably, even with the inclusion of that point in the Stressor ID analysis, the relationship between B-IBI and HPC was still significant (C. Larson, *pers. comm.,* October 2022). We have included the data point in our plots with the intention of pointing out that there may be factors at this site that allow relatively good B-IBI scores despite a higher level of stream flashiness. The site is in a section of Soosette Creek that flows through a steep wooded ravine with a fully vegetated riparian zone, and the physical habitat at the location may explain the healthier benthic

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[20] We first did this analysis by limiting B-IBI scores collected within the model time-period, but the relationship was stronger when we used all data, rather than restricting it to just those years that were modeled. Additionally, when the mean of all B-IBI scores at a reach were calculated, reaches with less than or equal to two B-IBI observations were removed from the analysis and plots since two observations was not considered a large enough sample size to represent the mean B-IBI score at a site to compare across multiple years of modeled HPCs.

community. The mean B-IBI score at this site is 65.1, with data ranging from 46.2 (fair) to 81.7 (excellent) over the years. This outlier may be an example of how the conservation of forest cover in a basin, particularly in the riparian zone, could provide the needed resilience for benthic organisms to thrive even under flashy conditions.

When the scatter plots are shaded by the level of EIA or forest cover present in the *entire drainage area* represented by the reach where B-IBI data were collected, we can see that the sites with a higher percent EIA appear in the lower right quadrant of the plot, while those that have higher percent forest cover appear in the upper left quadrant of the plots.

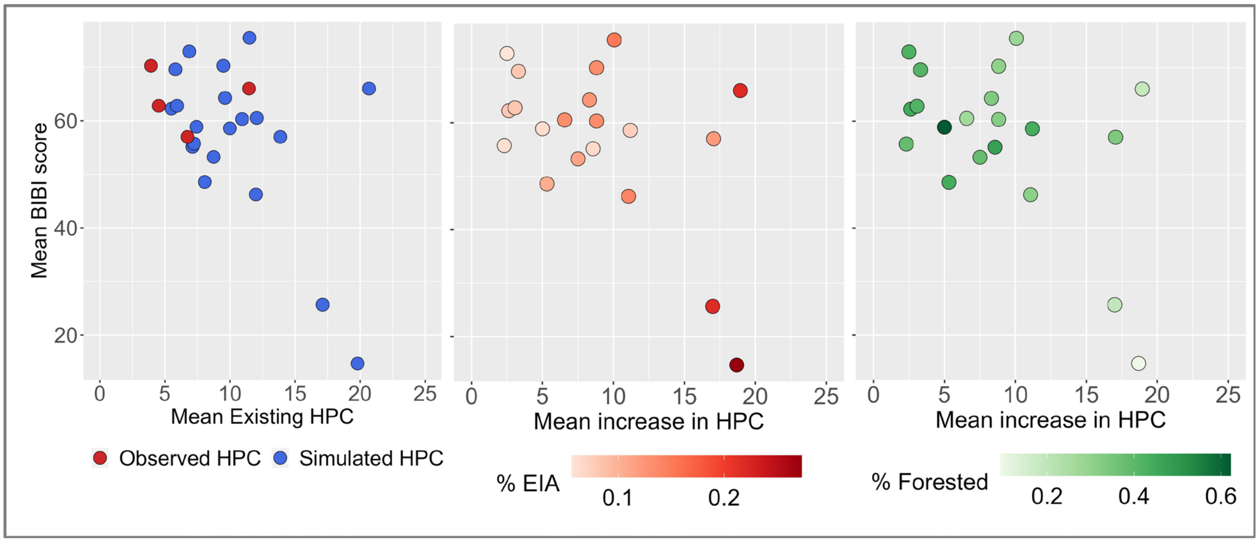


Figure 47. Scatter plots of mean HPC and mean B-IBI scores.
Left plot: Mean existing HPCs (predicted and observed) and mean B-IBI scores in each model reach.
Middle and right plots: The increase in mean HPC (relative to forested conditions) and mean B-IBI scores, but the dots are colored based on the cumulative percent EIA and percent forested area in the drainage area drained by that reach.

Summary of B-IBI Analysis

Our analysis of B-IBI scores against other habitat metrics, inferred fine sediment, high pulse count, and land cover indicates that sites in the Soos are negatively influenced by development, stream flashiness, and fine sediment loading. All these factors are interrelated and point to mechanisms by which urban landscapes negatively affect aquatic health. This points to the need to attenuate and retain stormwater flows to reduce stream flashiness, reduce the fine sediment load (using TSS reductions as a surrogate), and restore and conserve physical habitat. The loading capacity approach described in the next section is developed to address both sediment loading and stream flashiness, but it is important to note that other site-specific factors mentioned above are present at locations that may preclude or enhance the aquatic community. Therefore, while this loading capacity provides a quantitative metric for a target load, a fully successful strategy should include instream restoration and conservation activities.

Loading Capacity

A waterbody's loading capacity is the amount of a given pollutant that a waterbody can receive and still meet water quality standards. Washington State does not have a numeric criterion for fine sediment or TSS, but it does have a narrative fine sediment criterion for freshwater, as described in WAC 173-201A-200(1)(h) (mentioned earlier in this report). This part of the WAC describes how water bodies shall not contain excess fine sediment (< 2 mm) from human-caused sources and how reference sites or data from least disturbed site conditions can be used to demonstrate compliance.

For this study, in lieu of reference watershed data, we adopted a reference stream approach. Given the limited availability of true reference sites within the Soos watershed itself or in a comparable watershed in the Puget lowlands, we used reference data predicted via the calibrated Soos watershed HSPF forested scenario run. As described earlier, this modeled reference condition was represented by converting all land cover in the HSPF model to forested land cover (except wetlands and open water bodies). TSS loads predicted by the forested model run represent the loading capacity for the Soos.

Load Duration Approach

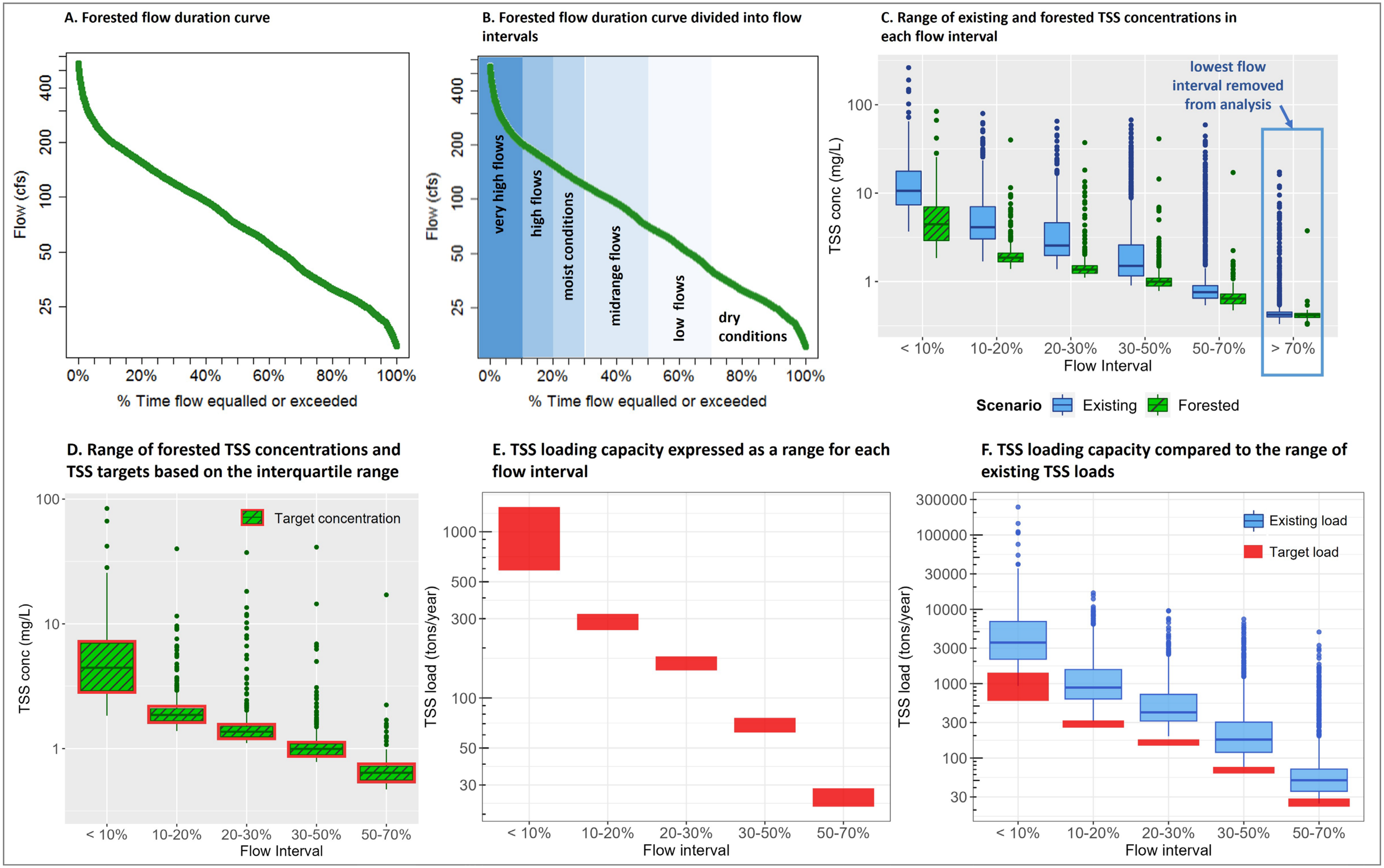
Rather than specify the loading capacity as a single average daily TSS load, we employed a modified "load duration curve" approach to specify different TSS loading capacities and allocations for different flow intervals. The load duration curve approach is recommended by the EPA in TMDLs where streamflow is one of the most important factors driving pollutant loads (in this case, TSS) since it accounts for how streamflow patterns affect pollutant loads and concentrations over the course of the year (EPA 2007).

This approach has the following practical implications and advantages:

- It accounts for the fact that TSS concentrations and loads vary with flow by also allowing the loading capacity to vary with flow. A single daily or annual TSS load that does not vary with flow would ignore known watershed and stormwater dynamics, where flows are one of the main drivers of pollutant loads and concentrations.
- It allows for additional flexibility in implementation, where TSS loads could be reduced by a combination of flow controls, including increases in forested land cover, as well as treatment of TSS in runoff.
- The approach allows for flexibility to adapt the loading capacity due to future changes in precipitation and streamflow patterns as a result of climate change, i.e., with future changes in streamflow, the TSS allocation would shift based on where we are along the flow duration curve.

The loading capacity in the form of a load duration curve for the Soos was established as follows (Figure 48):

1. **Calculated forested flow duration curve (Figure 48a)** — Forested flow duration curves were calculated from the forested condition model run for the most downstream reach in the watershed at the mouth of the Soos.
2. **Identified flow intervals or zones along the flow duration curve (Figure 48b)** — The flow duration curve was divided into the following flow intervals, which serve as general indicators of hydrologic conditions (from dry conditions to very high flows):
    - Dry conditions: > 70th percentile (flows that are exceeded most often, more than 70% of the time)
    - Low flows: 50 – 70th percentile (flows that are exceeded often 50% – 70% of the time)
    - Midrange flows: 30 – 50th percentile (flows exceeded30% – 50% of the time)
    - Moist conditions: 20 – 30th percentile (flows exceeded 20% – 30% of the time)
    - High flows: 10 – 20th percentile exceedance flows (flows exceeded 10% – 20% of the time)
    - Very high flows: <10th percentile exceedance flows (infrequently exceeded only 10% of the time or less)
3. **Identified TSS target concentrations for each flow interval:**
    - We used modeled forested TSS concentrations as the basis of the TSS target concentrations.
    - We first binned all forested TSS concentrations into each flow interval to calculate the range in TSS concentrations within each flow interval. We also compared this range to existing TSS concentrations in each flow interval and found that for flows below the 70th percentile exceedance, there was little to no difference between existing and forested TSS concentrations — this lowest flow interval was therefore removed from further analysis (Figure 48c).
    - We calculated the target TSS concentration as the interquartile range of forested TSS concentrations within each flow interval, i.e., the 25th to 75th percentiles (Figure 48d). This approach incorporates the natural variability in TSS concentrations predicted within each flow interval rather than selecting a single TSS concentration value. Limiting the concentration targets within the interquartile range (as opposed to using the full range of forested concentrations) builds in an implicit margin of safety by excluding forested concentrations above the 75th percentile (Figure 48c shows the instances when forested concentrations exceed the 75th percentile.)
4. **Calculated TSS load targets for each flow interval:**
    - The full range of forested flows in each flow interval was then multiplied by the target range of forested TSS concentrations (25th – 75th concentrations) in each flow interval to calculate a target TSS load range for each flow interval (Figure 48e).
    - The calculated range in TSS load targets is the loading capacity for each flow interval (Table 19). We compared the loading capacity to the range of existing loads within each flow interval (Figure 48f).



A. Forested flow duration curve

B. Forested flow duration curve divided into flow intervals

C. Range of existing and forested TSS concentrations in each flow interval

D. Range of forested TSS concentrations and TSS targets based on the interquartile range

E. TSS loading capacity expressed as a range for each flow interval

F. TSS loading capacity compared to the range of existing TSS loads

Figure 48. Approach for setting TSS loading capacity at the mouth of Big Soos Creek.

Table 19 presents the range of values that define the loading capacity at the mouth of the Soos for each of the five flow intervals.

Table 19. TSS loading capacity at the mouth of the Soos watershed expressed in both tons/year and lbs/day.

Flow Interval	Lower Range of TSS Loading Capacity (tons/year)	Upper Range of TSS Loading Capacity (tons/year)	Lower Range of TSS Loading Capacity (lbs/day)	Upper Range of TSS Loading Capacity (lbs/day)
<10%	586	1408	3211	7715
10%–20%	256	321	1404	1756
20%–30%	147	178	803	975
30%–50%	62	76	340	416
50%–70%	22	29	122	157

We then distributed this loading capacity between each of the six subbasins of the Soos. To do this, we first calculated the magnitude and proportion of each subbasin's contribution to the total upland forested TSS load, as presented in Table 20, and then distributed the loading capacity between the subbasins based on these proportions.

Table 20. Magnitude and proportion of area covered by each subbasin as well as its average annual forested TSS load.

Subbasin	Area (square miles)	% Area	Forested Upland TSS Load (tons/year)	Forested Upland TSS Load (%)
Soosette	5.5	8.4%	11.4	6.3%
Upper Big Soos	12.9	19.5%	19.7	10.8%
Little Soos	3.6	5.4%	9.4	5.2%
Jenkins	16.5	24.9%	27.6	15.2%
Covington	22.4	33.8%	101.9	56.0%
Lower Big Soos	5.3	8.0%	11.8	6.5%
Total Soos watershed	**66.2**	—	**181.8**	—

The final loading capacity for each subbasin is presented in Table 21. This accounts for the size of each subbasin (larger basins have a higher upland TSS load) as well as other subbasin characteristics that influence its TSS loading capacity under forested conditions. For example, the Covington subbasin is the largest of all the subbasins, occupying 33.8% of the total watershed, but it contributes to a higher proportion of the forested TSS load (56%). Conversely, Upper Big Soos makes up 19.5% of the watershed area but only contributes to 10.8% of the total forested TSS loads. These differences in TSS load contributions under forested conditions reflect not just the size of the watershed but also their natural soils and topography, which influence how much TSS load from upland areas eventually gets deposited into the stream.

Distributing the loading capacity estimated at the mouth to upstream basins also takes into consideration the fact that the model's ability to predict TSS was optimal at the mouth (relative to the other TSS calibration locations).

Table 21. Range in TSS loading capacity for each flow interval for each of the major subbasins in the Soos watershed.

Flow Interval	Subbasin	Lower Range of TSS Loading Capacity (tons/year)	Upper Range of TSS Loading Capacity (tons/year)	Lower Range of TSS Loading Capacity (lbs/day)	Upper Range of TSS Loading Capacity (lbs/day)
<10%	**Total Watershed**	**586**	**1408**	**3211**	**7715**
10%–20%	**Total Watershed**	**257**	**320**	**1405**	**1756**
20%–30%	**Total Watershed**	**147**	**178**	**804**	**975**
30%–50%	**Total Watershed**	**62**	**76**	**340**	**416**
50%–70%	**Total Watershed**	**22**	**29**	**122**	**157**
<10%	Soosette	37	89	202	485
10%–20%	Soosette	16	20	88	110
20%–30%	Soosette	9.2	11	51	61
30%–50%	Soosette	3.9	4.8	21	26
50%–70%	Soosette	1.4	1.8	7.7	9.9
<10%	Upper Big Soos	64	153	348	836
10%–20%	Upper Big Soos	28	35	152	190
20%–30%	Upper Big Soos	16	19	87	106
30%–50%	Upper Big Soos	6.7	8.2	37	45
50%–70%	Upper Big Soos	2.4	3.1	13	17
<10%	Little Soos	30	73	165	397
10%–20%	Little Soos	13	17	72	91
20%–30%	Little Soos	7.6	9.2	41	50
30%–50%	Little Soos	3.2	3.9	18	21
50%–70%	Little Soos	1.1	1.5	6.3	8.1
<10%	Jenkins	89	214	488	1172
10%–20%	Jenkins	39	49	213	267
20%–30%	Jenkins	22	27	122	148
30%–50%	Jenkins	9.4	12	52	63
50%–70%	Jenkins	3.4	4.3	19	24
<10%	Covington	328	789	1799	4323
10%–20%	Covington	144	180	787	984
20%–30%	Covington	82	100	450	546
30%–50%	Covington	35	43	190	233
50%–70%	Covington	13	16	68	88
<10%	Lower Big Soos	38	92	209	501
10%–20%	Lower Big Soos	17	21	91	114
20%–30%	Lower Big Soos	9.5	12	52	63
30%–50%	Lower Big Soos	4.0	4.9	22	27
50%–70%	Lower Big Soos	1.4	1.9	7.9	10

Seasonal Variation and Critical Conditions

The load duration approach implicitly accounts for seasonal variation since it considers the full duration of flows and TSS loads that occur year-round from daily model predictions of flow and TSS over a 15-year simulation period. Several HSPF parameters also vary by month to account for seasonal variations in hydrology and sediment loading. This accounts for a wide range of meteorological and hydrological conditions and seasonal effects.

The following figures in this report illustrate how the HSPF model captures variations in monthly and seasonal conditions:

- Figures D1, D2, and D3 in Appendix D show seasonal variations in monthly runoff.
- Figures 14 through 16 show flow duration curves, which capture the full range of flows over the 15-year model simulation period — from dry and low flow conditions to less frequent but higher flow events.
- Figure 23 shows how the model captures seasonal variations in monthly TSS concentrations, with lower concentrations in the summer and higher concentrations in fall, winter, and spring.

Since TSS loads are generated across all frequencies of rainfall and subsequent storm events, there is not a single "critical condition" that can be applied. Benthic macroinvertebrates are also influenced by environmental effects that can vary throughout the year. B-IBI scores, therefore, often reflect the impact of stressors that are not specific to a certain critical condition but rather the cumulative impact of these stressors over sub-annual, annual, and multi-year timescales. A single large acute storm event could stress the benthic community, but chronic habitat conditions and embeddedness from several years of sediment loading also contribute to the poor health of macroinvertebrates.

While large storm events that occur every five or 10 years can mobilize a significant amount of sediment, they do not occur as frequently as smaller storm events that happen multiple times a year, which also result in increased TSS loading from the watershed and instream erosion. Thus, the critical condition for this TMDL would be captured by making sure that the loading capacity is based on a *range* of rainfall conditions and subsequent storm events.

We also wanted to ensure that the 15-year simulation period captured a range of meteorological and hydrological conditions (and did not just represent wet or dry years). To do this, we compared precipitation data during the modeled time period against long-term precipitation data at gage 03u in King County from 1989 to 2022. Of all the gages used to develop precipitation inputs for the HSPF model, station 03u has the longest data record (30-plus years). Figure 49 compares monthly and annual precipitation at the gage from 1988 to 2022 against precipitation from 2001 to 2015 (i.e., the model simulation period).

Monthly precipitation from 2001 to 2015 appears to capture the full range of precipitation from the longer time period and includes some major storms that are greater than 1.5 times the interquartile range (illustrated as points on the boxplot). Additionally, annual precipitation for almost half of the model simulation period (seven of the 15 years) is above the average annual precipitation (red line, calculated as an average from 1989 to 2022). These comparisons show that our model simulation period, on which the loading capacity is based, is not biased towards particularly wet or dry years and adequately captures the full range of flow conditions when compared to longer-term precipitation data.

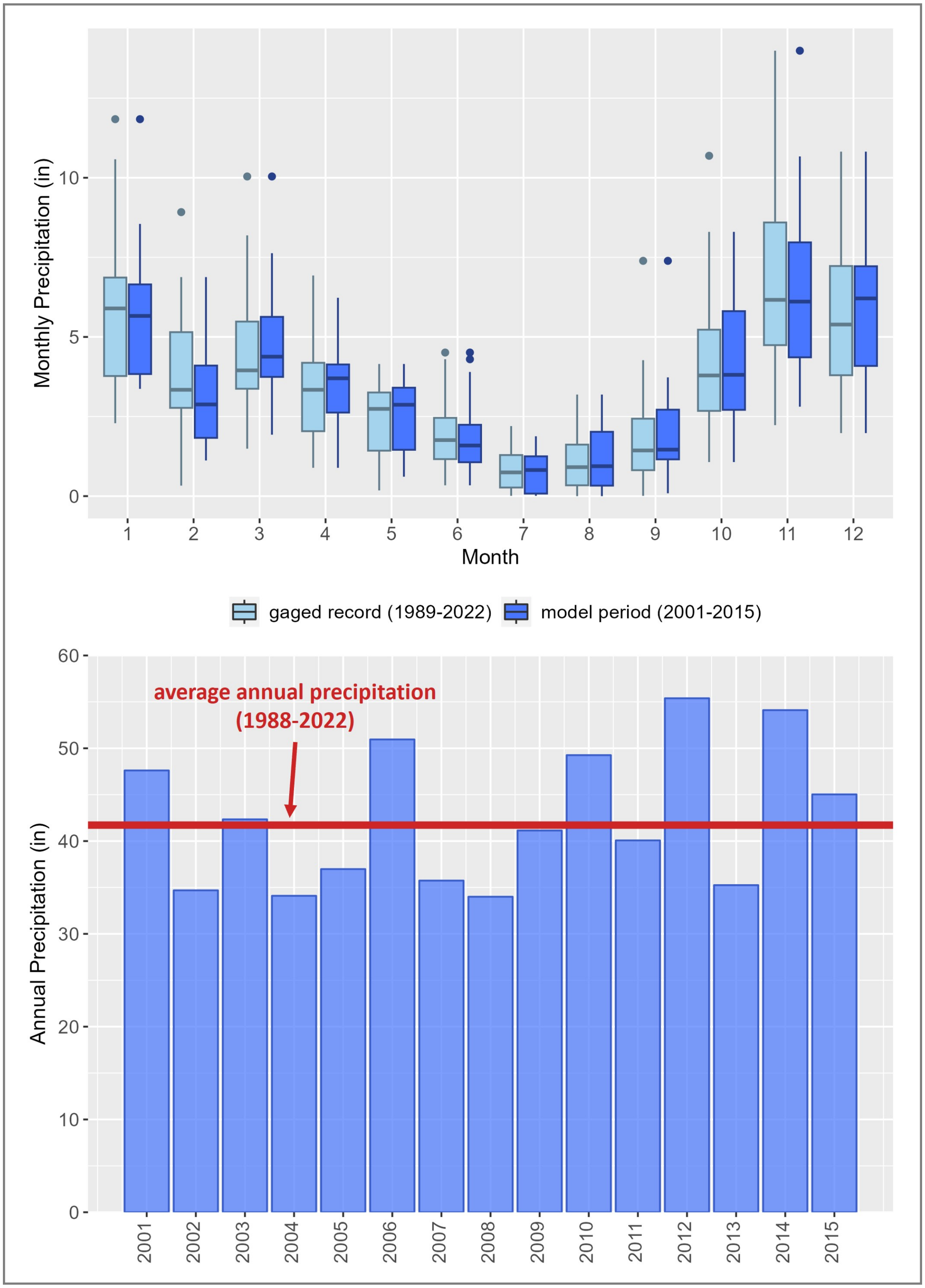


Figure 49. Comparison of precipitation data during the model simulation period (2001 – 2015) against long-term precipitation data (1989 – 2022) at King County gage 03u.
Includes monthly precipitation boxplots (top) and annual precipitation compared to the long-term average (bottom).

Load and Wasteload Allocations

The load and wasteload allocations needed to meet the established loading capacity will be specified in the final TMDL report.

There are several entities with NPDES permits within the Soos, each of which will need a wasteload allocation (WLA). These include jurisdictions covered under the Phase I and Phase II municipal separate storm sewer system (MS4) permit, as well as facilities covered under individual industrial permits, the general industrial stormwater permit, sand and gravel permit, construction stormwater general permit, as well as the Soos Creek Hatchery.

Additionally, any areas in the watershed that don’t fall under these permits will be assigned a load allocation.

Margin of Safety Recommendations

The margin of safety for this TMDL can be implicit, particularly because the loading capacity in each flow interval is expressed as a range (based on the interquartile range of TSS concentrations in each flow interval), and this range is below the highest estimated TSS concentrations for each flow interval. However, when load and wasteload allocations are determined, an additional margin of safety could be added to account for future growth or other factors. We also recommend reviewing the margin of safety approaches used in other similar TMDLs to help inform the final approach applied to this one.

Conclusions

All study goals and objectives outlined in the QAPP (Mohamedali 2018) were met. One of the original goals was to establish load and wasteload allocations — this study establishes the loading capacity but does not define the load and wasteload allocations. Allocations will be determined directly from the loading capacity established in this study and will be defined in the final TMDL report.

The results of this study support the following conclusions:

- In the Soos watershed, development has increased high pulse counts (HPCs), a shift in the flow duration curve (more frequent high flow events), higher TSS concentrations, and higher TSS loads.
- The difference between existing and forested TSS loads increases with higher flows. Less frequent but higher flow events produce greater TSS loads.
- The proportion of TSS composed of fine sediment is higher under existing conditions than in forested conditions.
- The largest magnitude of TSS loads comes from developed areas and impervious cover in the watershed.
- While B-IBI scores in the Soos are highly variable over time and space, multiple lines of evidence show that the extent of impervious areas and development, in general, contribute to reduced B-IBI scores due to flashier flows and loading of fine sediment.
- In general, when looking at mean B-IBI scores, sites with a higher percent EIA and lower percent forest cover tend to have lower B-IBI scores. However, not all sites with high HPCs or stream flashiness have poor B-IBI scores, indicating that sites with higher B-IBI scores and high HPCs appear to be buffered from some of the effects of stream flashiness potentially due to other factors.
- Forested parts of the watershed and potentially locations with more intact local riparian areas might buffer the impact of development on the stressors that negatively affect the benthic community. While we did not conduct a specific analysis, there is one well-buffered site where this appears to be the case.

Recommendations

The results of this study support the following recommendations:

- Load and wasteload allocations (LA & WLAs) should be established to meet each subbasin's estimated TSS loading capacity. Load allocations should be determined for all areas of the Soos not currently subject to NPDES permit requirements, and WLAs should:
    - Account for the extent of impervious cover associated with each of the MS4 permit areas.
    - Account for areas of the watershed impacted by other NPDES-permitted facilities and their activities, e.g., sand and gravel facilities, industrial facilities, and construction activities.
    - Include an analysis of effluent data for the Soos Creek Hatchery based on reported data (flow and TSS) to estimate its existing TSS load to determine its wasteload allocation.
- The TMDL Implementation Plan should outline a comprehensive approach to address bioassessment and aquatic health based on B-IBI scores and fine sediment loading in the watershed. To do this, the TMDL Implementation Plan should include:
    - Incorporate a combination of implementation actions and BMPs that result in a reduction in TSS loading as well as stormwater flow control. Reducing upland TSS loads alone will not address instream erosion and scour resulting from the physical force of flashy flows during storm events.
    - Recommend tracking implementation actions specified in the NPDES permits to measure progress toward meeting load and wasteload allocations.
    - Recommend tracking of actions taken to enhance stream habitat.
    - Emphasize the need for instream physical habitat restoration and protection. Physical habitat degradation is an additional stressor on aquatic health and could preclude improvements in B-IBI scores.
    - Consider the importance of preserving and improving the existing wetlands in the watershed, potentially providing multiple benefits, such as slowing down stormwater flows and settling out fine sediment.
- Use the Scenario Application Manager (SAM) to run HSPF model scenarios to identify where to prioritize implementation actions in the watershed. These scenarios could explore, for example:
    - The relative impact of turning developed land cover into forested cover in different parts of the watershed (e.g., upstream vs. downstream reaches or different subbasins). This hypothetical scenario could help us understand the relative impact of managing runoff to mimic forest conditions in different parts of the watershed.
    - The approximate scale of BMPs needed to meet the loading capacity/allocations is based on user-specified assumptions of TSS load removal and stormwater flow control defined within the SAM tool.

- Identify locations in the watershed where local, site-specific factors might further contribute to B-IBI impairments and impede improvements in B-IBI scores even if actions are taken to address flashy flows and reduce TSS loading. Where possible, localized human-caused features or activities that have a negative impact on the benthic community should be identified (e.g., bank armoring or hydromodifications) and potentially removed or mitigated to reduce their impact.
- Continue B-IBI monitoring of the watershed, with the addition of other measures of stream health:
    - King County's existing B-IBI monitoring network in the watershed is extensive and should be maintained, especially at sites with 10-plus years of data.
    - The addition of embeddedness and percent sand/fines monitoring on the streambed at all B-IBI monitoring sites using consistent field methods and measurement protocols that adequately characterize substrate fine sediments (a recent report by King County (2023) suggested that it is likely that King County's quicker, riffle-based substrate survey may not adequately characterize fine sediments across the sampling reach).
    - Effectiveness monitoring of stream habitat approximately every five years using Ecology's Watershed Health Monitoring (WHM) protocols at key locations. Ecology began baseline monitoring using WHM protocols in the summer of 2023 at eleven locations in the Soos watershed, as described in Mathieu et al. (2023).
- This study was initiated as a pilot effort to explore how Ecology might address B-IBI impairments within the TMDL framework. Addressing biological integrity is a critical part of the CWA, and the science of bioassessments as indicators of stream health is extensive and well-vetted. We, therefore, recommend continuing to address known B-IBI impairments via TMDLs in those instances where the impairments are known to be a result of CWA-recognized pollutants. For future TMDLs that seek to address B-IBI impairments, we recommend:
    - Continuing to employ a stressor identification analysis process (such as the EPA CADDIS approach) to identify pollutants or habitat impairments that are causing the degradation of benthic aquatic communities.
    - Selecting watersheds with an extensive B-IBI monitoring network and long-term data set that captures the spatial and temporal variability inherent in measures of B-IBI.
    - Selecting watersheds with sufficient data related to the potential stressors or where the resources exist to support additional field data collection efforts.
    - Co-locating B-IBI monitoring sites with monitoring of continuous streamflow (or modeled streamflow from a calibrated model, if available) and other field measurements of potential stressors to enable statistical analysis between the multiple variables that can potentially influence B-IBI scores. Teams working on this type of project should attempt to obtain co-located gage, TSS, bed sediment samples, habitat metrics (e.g., embeddedness), and B-IBI datasets in every key segment of the system.
    - Collecting data to support the development of a groundwater budget is necessary for any future B-IBI TMDL.
    - Assessing downstream effects of wetlands. Systems heavily influenced by wetlands may require additional assessments to connect the influence of potentially large

seasonal variations in suspended organic matter with benthic invertebrate communities immediately downstream.

- Applying hydraulic modeling to complement hydrological modeling to estimate the impact of in-channel alterations in TSS entrainment, transport, and deposition would benefit a project of this nature.
- Since B-IBI-driven TMDLs and implementation require diverse data sets over extended periods, commitment to acquiring these data must be part of a long-term monitoring plan.
- Beyond the metrics targeted in a B-IBI-driven TMDL, improvement of B-IBI scores also likely rests upon habitat restoration and conservation. Selection of TMDL projects within communities already engaged in these activities with plans to expand their efforts will help deliver ultimate success.

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Glossary, Acronyms, and Abbreviations

Glossary

Clean Water Act (CWA): A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Effluent: An outflowing of water from a natural body of water or from a man-made structure. For example, the treated outflow from a wastewater treatment plant.

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.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Point source: Sources of pollution that discharge 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 wastewater treatment facilities, and construction sites where one or more acres of land are disturbed.

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; (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.

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.

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting 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.

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.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

90th percentile: A statistical number obtained from a distribution of a data set, above which 10% of the data exists and below which 90% of the data exists.

Acronyms and Abbreviations

BMP	best management practice
CWA	Clean Water Act
Ecology	Washington State Department of Ecology
EIA	Effective Impervious Area
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software
NPDES	National Pollutant Discharge Elimination System (see glossary)
RM	river mile
RPD	relative percent difference
RSD	relative standard deviation
SOP	standard operating procedures
TMDL	Total Maximum Daily Load (see glossary)
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WRIA	Water Resource Inventory Area

Units of Measurement

cfs	cubic feet per second
ft	feet
g	gram, a unit of mass
kg	kilograms, a unit of mass equal to 1,000 grams
kg/d	kilograms per day
m	meter
mg	milligram
mg/d	milligrams per day
NTU	nephelometric turbidity units

Appendices

ADA Accessibility

This appendix contains graphics, images and tables that may not meet accessibility standards. The Department of Ecology is committed to providing people with disabilities access to information and services by meeting or exceeding the requirements of the Americans with Disabilities Act (ADA), Section 504 and 508 of the Rehabilitation Act, and Washington State Policy #188.

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Appendix A. Reach Connectivity

Table A1. HSPF reach connectivity identifying all 60 HSPF reaches/catchments, the subbasin within which they are located, the downstream reach they connect to, their catchment areas, and cumulative drainage areas.

Subbasin	Name	Reach ID	Downstream Reach ID	Catchment Area (mi^2)	Cumulative Drainage Area (mi^2)
Soosette	SOOSETTE CR	542	562	0.840	0.840
Soosette	SOOSETTE TRIB	552	562	0.762	0.762
Soosette	SOOSETTE CR	562	582	1.151	2.752
Soosette	SOOSETTE TRIB	572	582	0.902	0.902
Soosette	SOOSETTE CR	582	592	1.875	5.529
Upper Big Soos	BIG SOOS CR	12	22	1.658	1.658
Upper Big Soos	BIG SOOS CR	22	42	2.047	3.705
Upper Big Soos	BIG SOOS TRIB	32	42	1.713	1.713
Upper Big Soos	BIG SOOS CR	42	62	0.832	6.249
Upper Big Soos	BIG SOOS TRIB	52	62	0.488	0.488
Upper Big Soos	BIG SOOS CR	62	82	0.655	7.392
Upper Big Soos	BIG SOOS TRIB	72	82	0.682	0.682
Upper Big Soos	BIG SOOS CR	82	102	0.651	8.726
Upper Big Soos	BIG SOOS TRIB	92	102	2.977	2.977
Upper Big Soos	BIG SOOS CR	102	152	1.211	12.91
Little Soos	LITTLE SOOS CR	112	132	1.901	1.901
Little Soos	LITTLE SOOS TRIB	122	132	0.319	0.319
Little Soos	LITTLE SOOS CR	132	142	0.409	2.629
Little Soos	LITTLE SOOS CR	142	152	0.967	3.596
Jenkins	LAKE LUCERNE	202	212	0.696	0.696
Jenkins	JENKINS CR	212	292	1.035	1.731
Jenkins	WILDERNESS LAKE	222	232	0.523	0.523
Jenkins	JENKINS TRIB	232	242	0.403	0.926
Jenkins	JENKINS CR	242	282	4.721	5.647
Jenkins	SHADOW LAKE	252	262	0.806	0.806
Jenkins	JENKINS TRIB	262	272	1.034	1.840
Jenkins	JENKINS TRIB	272	282	0.750	2.590
Jenkins	JENKINS CR	282	322	1.126	9.363
Jenkins	SOUTH FORK JENKINS	292	302	1.513	3.243
Jenkins	SOUTH FORK JENKINS	302	312	1.236	4.479
Jenkins	SOUTH FORK JENKINS	312	322	0.816	5.295
Jenkins	JENKINS CR	322	332	0.547	15.21
Jenkins	JENKINS CR	332	342	1.199	16.40

Subbasin	Name	Reach ID	Downstream Reach ID	Catchment Area (mi^2)	Cumulative Drainage Area (mi^2)
Jenkins	JENKINS CR MOUTH	342	352	0.048	16.45
Covington	COVINGTON TRIB	362	382	0.925	0.925
Covington	MUD LAKE	372	382	0.537	0.537
Covington	COVINGTON TRIB	382	402	0.913	2.376
Covington	JONES LAKE	392	402	2.041	2.041
Covington	ROCK CR	402	442	2.072	6.488
Covington	RAVENSDALE LAKE	412	422	1.431	1.431
Covington	RAVENSDALE CR	422	432	1.579	3.010
Covington	RAVENSDALE CR	432	442	0.354	3.364
Covington	LAKE SAWYER	442	452	2.666	12.52
Covington	COVINGTON CR	452	512	4.582	17.10
Covington	GRASS LAKE	462	472	1.146	1.146
Covington	COVINGTON TRIB	472	502	1.638	2.785
Covington	LAKE MORTON	482	292	0.433	0.433
Covington	COVINGTON TRIB	492	502	0.376	0.809
Covington	COVINGTON TRIB	502	512	0.087	3.680
Covington	COVINGTON CR	512	522	0.357	21.14
Covington	COVINGTON MOUTH	522	532	1.227	22.36
Lower Big Soos	BIG SOOS CR	152	192	0.419	16.93
Lower Big Soos	LAKE MERIDIAN TRIB	162	172	0.295	0.295
Lower Big Soos	LAKE MERIDIAN	172	182	0.711	1.006
Lower Big Soos	LAKE MERIDIAN TRIB	182	192	0.488	1.494
Lower Big Soos	SOOS CR	192	352	0.199	18.62
Lower Big Soos	SOOS CR	352	532	1.256	36.33
Lower Big Soos	SOOS CR	532	592	1.157	59.85
Lower Big Soos	SOOS CR AT USGS	592	602	0.232	65.61
Lower Big Soos	SOOS CR AT GREEN	602	N/A	0.551	66.16

Appendix B. Updated large Group A withdrawals for the Soos HSPF Model

June 2, 2021

Written by Carla Carlson (Muckleshoot Indian Tribe)
With formatting edits by Teizeen Mohamedali (Ecology)

The model was updated with water withdrawals for the 2009 to 2015 period. No data were changed in the update for the earlier 2001 to 2008 timeframe. Group A water withdrawal data for 2009 to 2015 were updated via public record requests to the Department of Ecology for the city Kent's wells (which are required to send metered records to Ecology); to the Covington Water District (CWD), and to the King County Water District (KCWD) #111; now known as the Lake Meridian Water District (LMWD). Requests were made and received for monthly records which were then parsed into daily time steps to be consistent with the method used in the model for the 2001 to 2008 period.

These are the three largest Group A water providers that utilize groundwater from within the Soos Creek basin. For the city of Kent well records, data was received on May 2, 2017 from the department of Ecology. The Covington Water District (CWD) provided records to the Muckleshoot Tribe's hydrologist on May 23,2017 and KCWD #111 provided records on July 21, 2017. More detail on data received is provided below.

Covington Water District

Monthly source meter records for Witte Wellfield, and the 222nd Ave. Wellfield for time frame of 1/1/2009 thru 12/31/2015 were obtained. The records for the latter source included five wells (A, C, D, E and F). In this model version as well as the earlier one, these wells were combined since they are located in close proximity to each other and likely impact the same surface water body. Monthly data were evenly parsed into daily time steps and combined for a wellfield total. Data was imported into the WDM as DSN 6. The Witte Wellfield only operates seasonally and rests during the winter months. That record was similarly parsed and resides in DSN 7.

CWD is also a partner in the Second Supply Project with the city of Tacoma and since they have been purchasing water from Tacoma (in 2007), CWD's reliance on wells has been declining.

City of Kent

There are four sources of supply to the City of Kent within the Soos Creek basin; the Soos Well (aka Seven Oaks well), Kent Springs, and Armstrong Springs. The Clark Springs lies in the Cedar River watershed, but groundwater from the springs flows into the Soos Creek basin along its eastern boundary. The Soos Well was used infrequently and is only operated seasonally for 1 month or less during the year due to "long-term lowering of the static water level within the aquifer" (PACE Engineers, Inc. 2011 Water System Plan, p. 4 – 26).

All monthly records were parsed to a daily time step and imported into the WDM file as Data Set Numbers (DSN) 8, 9, 10, and 11 for Kent Springs, Clark Springs, Armstrong Springs, and the Soos/Seven Oaks Well, respectively.

The City of Kent is a partner in the Second Supply Project with the city of Tacoma and has been purchasing supply from them since 2007.

KCWD #111/Lake Meridian WD

Records for Wells 6 and 9 were received via public records request on June 9, 2017 from KCWD #111. The monthly record was pared to daily and imported into DSN 4 for Well 6 and DSN 5 for Well 9.

Incorporation Into the Model

The well water withdrawals for the 2009 to 2015 period were incorporated into the model the same way as the earlier model version, which is discussed in more detail in the Carlson and Massmann (2015). Table B1 below illustrates how much of the daily groundwater values were subtracted from the appropriate reach or RCHRES in the model.

Table B1. Water withdrawals based on well records were subtracted from applicable reaches in the percentages noted below. This was the same method as used in the model version for 2001 to 2008.

Source	Purveyor	Subbasin	Catchment ID	Affected model Reach	Percent withdrawn from reach
Witte Wells	Covington Water	Jenkins	J6	RR212	25%
222nd Place Wells	Covington Water	Covington	C9	RR442	100%
Kent Springs	City of Kent	Jenkins	J5	RR442	50%
Kent Springs	City of Kent	Jenkins	J5	RR292	50%
Armstrong Springs	City of Kent	Jenkins	J8	RR322	50%
Soos Creek Well	City of Kent	Soos	S7B	RR552	50%
Well #9	Water District 111	Soos	S11	RR182	50%
Well #6	Water District 111	Soos	S5	RR572	50%
Clark Springs	City of Kent	Rock Creek	n.a.	RR212	50%
Clark Springs	City of Kent	Rock Creek	n.a.	RR292	25%
Clark Springs	City of Kent	Rock Creek	n.a.	RR222	25%

Comparison of 2001 – 2008 and 2009 – 2015 water withdrawals.

Covington Water District

For the original model for the temperature portion of the TMDL, the data used for withdrawals for CWD was based on reported production amounts in a water system plan (Table 1, HDR, 2005a). That table was a summary of monthly values for two wellfields for the period from 1999 to 2003. Two of those years were drought years, 2000 and 2001) so water use was high; i.e., skewed for high use years.

Also, it is well-reported that municipal water use has declined from the 1990s to now; both regionally and nationally. Therefore, the CWD values are skewed high in the model as the 1999 to 2003 averages were applied to the 2001 to 2008 period. That was the only data available to the team during the time.

For the updated timeframe of 2009 to 2015, actual monthly metered data was available for use per a public records request made by MITFD staff to CWD.

Averages for the well withdrawals for the two time periods for the Witte Wellfield and 222nd Wellfield are shown below in Table B2. Much less water is withdrawn for the updated time period which is due to both the change in methodology and that CWD groundwater use has been declining. For example, CWD currently obtains 80% of its water supply from the Green River as a regional water supply partner with Tacoma and 20% is from its wellfields which are mostly used for summer peaking (CWD 2016).

Table B2. Average withdrawals values used in the HSPF model for Covington Water District

Wellfield	2001–2008 Avg. (cfs)	2009–2015 Avg. (cfs)	% Difference
222ND WELLFIELD	3.220	1.220	-62.0%
WITTE WELLFIELD	0.985	0.177	-82.0%

City of Kent

For the 2001 – 2009 model run, metered values were obtained from the Department of Ecology, but based on other sources, including the city's water system plan, the metered values reported for 2002 and 2004 were erroneously high, so the average metered values for 2006 to 2008 were used for the whole 2001 to 2008 timeframe. For the 2015 update, metered data was again obtained from Ecology and the 2009 to 2015 data was used in the model. The comparison between the two timeframes is shown in Table B3 below. The two largest supply sources, Clark and Kent Springs were less than the earlier model period while the Soos Well and Armstrong Springs wells were much less. Kent reports in their 2019 water system plan, that water from Tacoma is now their third largest supply source and that other wells are not used frequently.

Table B3. Average withdrawals values used in the HSPF model for City of Kent.

Wellfield	2001–2008 Avg. (cfs)	2009–2015 Avg. (cfs)	% Difference
Soos Well	0.05	0.001	-98.0%
Armstrong Springs	0.47	0.30	-36.2%
Clark Springs	5.79	5.24	-9.50%

KCWD 111 (Lake Meridian Water District)

KCWD #111 just recently changed its name to Lake Meridian Water District (LMWD).

For the earlier model for the 2001 to 2008 period, water withdrawals for wells 6 and 9 were estimated from Water District 111's Water System Plan (Roth Hill 2008) which had data for all wells; but not individual well data. For the update to 2015, metered records of monthly use for Wells 6 and 9 were used. Table B4 shows the average values for the two time periods, which shows a reduction in water use from wells between the two periods.

The District purchases most of its water supply from the Covington Water District as reported in its 2019 Consumer Confidence Report (LMWD 2019); likely from the regional water supply (i.e., TPU). So is also relying less on groundwater than before. Lake Merdian (KCWD #111) will soon have an updated water system plan that should have more complete information on its supply sources and use.

Table B4. Average withdrawals values used in the HSPF model for Lake Meridian Water District (formerly known as KCWD #111).

Wellfield	2001–2008 Avg. (cfs)	2009–2015 Avg. (cfs)	% Difference
WELL 6	0.368	0.266	-27.60%
WELL 9	0.455	0.350	-23.10%

References

CWD [Covington Water District]. 2016. Final Water System Plan https://www.covingtonwater.com/DocumentCenter/View/67/Water-System-Plan-FINAL---May-2016

LMWD [Lake Meridian Water District]. 2019 Annual Water Quality Report: https://www.lakemeridianwater.com/forms/000026

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PACE Engineers, Inc., 2011. *City of Kent 2011 Water System Plan*, prepared for City of Kent Public Works Department.

Roth Hill Engineering Partners, LLC, 2008. *King County Water District 111 Agency Draft Review Water Comprehensive Plan, 2008,* prepared for King County Water District 111.

Appendix C. Detailed Model Calibration Statistics

Tables C1 through C6 presents the RPD for various annual flow metrics for each of the six hydrology calibration locations.

Table C1. Observed and simulated flow metrics and RPD for Soosette Creek (Rch 582) for WY 2001 – 2015.

Metric	Units	Observed	Simulated	Difference	RPD (%)
Annual volume	(inches)	12.08	12.05	-0.03	-0.23
5 percent high	(inches)	3.87	3.37	-0.50	-12.90
10 percent high	(inches)	5.64	5.19	-0.45	-8.02
25 percent high	(inches)	8.73	8.35	-0.38	-4.40
50 percent low	(inches)	0.87	1.25	0.38	43.40
25 percent low	(inches)	0.14	0.36	0.21	151.11
15 percent low	(inches)	0.06	0.18	0.11	174.37
10 percent low	(inches)	0.04	0.11	0.07	187.22
5 percent low	(inches)	0.02	0.05	0.03	197.82
Storm volume	(inches)	8.06	7.16	-0.89	-11.11
Average storm peak	(cfs)	42.97	40.38	-2.58	-6.01
Spring volume	(inches)	3.67	3.16	-0.52	-14.13
Summer volume	(inches)	0.55	0.83	0.28	50.92
Fall volume	(inches)	1.95	2.55	0.61	31.08
Winter volume	(inches)	5.91	5.51	-0.39	-6.68
Spring storms	(inches)	2.17	1.78	-0.39	-18.10
Summer storms	(inches)	0.07	0.05	-0.02	-34.83
Fall storms	(inches)	1.16	1.25	0.09	7.83
Winter storms	(inches)	4.30	3.75	-0.55	-12.72

RPD = relative percent difference.

Table C2. Observed and simulated flow metrics and RPD for Little Soos Creek (Rch 142) for WY 2001 – 2015.

Metric	Units	Observed	Simulated	Difference	RPD (%)
Annual volume	(inches)	16.89	16.39	-0.51	-3.01
5 percent high	(inches)	3.37	3.12	-0.25	-7.49
10 percent high	(inches)	5.18	4.99	-0.19	-3.69
25 percent high	(inches)	8.99	8.69	-0.30	-3.37
50 percent low	(inches)	3.95	4.04	0.09	2.34
25 percent low	(inches)	1.58	1.81	0.23	14.25
15 percent low	(inches)	0.87	1.06	0.19	21.85
10 percent low	(inches)	0.54	0.70	0.16	28.95
5 percent low	(inches)	0.26	0.35	0.09	36.30
Storm volume	(inches)	10.53	9.72	-0.82	-7.74
Average storm peak	(cfs)	19.05	19.04	-0.01	-0.05
Spring volume	(inches)	4.95	4.30	-0.64	-13.03
Summer volume	(inches)	2.03	2.20	0.17	8.37
Fall volume	(inches)	3.01	3.62	0.62	20.53
Winter volume	(inches)	6.91	6.26	-0.65	-9.42
Spring storms	(inches)	3.14	2.66	-0.48	-15.17
Summer storms	(inches)	0.13	0.13	0.00	-2.21
Fall storms	(inches)	1.24	1.55	0.30	24.23
Winter storms	(inches)	5.58	4.96	-0.62	-11.09

RPD = relative percent difference.

Table C3. Observed and simulated flow metrics and RPD for Jenkins Creek (Rch 332) for WY 2001 – 2015.

Metric	Units	Observed	Simulated	Difference	RPD (%)
Annual volume	(inches)	14.25	14.24	-0.01	-0.09
5 percent high	(inches)	2.13	2.25	0.12	5.61
10 percent high	(inches)	3.55	3.83	0.28	7.96
25 percent high	(inches)	6.85	7.36	0.51	7.50
50 percent low	(inches)	3.51	3.03	-0.48	-13.75
25 percent low	(inches)	1.18	1.00	-0.19	-15.78
15 percent low	(inches)	0.61	0.51	-0.10	-16.38
10 percent low	(inches)	0.38	0.32	-0.06	-16.19
5 percent low	(inches)	0.17	0.15	-0.03	-16.06
Storm volume	(inches)	6.77	7.18	0.41	6.12
Average storm peak	(cfs)	87.31	111.81	24.49	28.05
Spring volume	(inches)	4.43	4.19	-0.24	-5.36
Summer volume	(inches)	1.98	1.64	-0.34	-16.99
Fall volume	(inches)	2.17	2.38	0.21	9.53
Winter volume	(inches)	5.67	6.02	0.35	6.22
Spring storms	(inches)	1.64	1.64	0.00	-0.14
Summer storms	(inches)	0.17	0.15	-0.03	-15.58
Fall storms	(inches)	0.89	1.07	0.19	20.87
Winter storms	(inches)	3.71	3.92	0.21	5.54

RPD = relative percent difference.

Table C4. Observed and simulated flow metrics and RPD for Covington Creek (Rch 512) for WY 2001 – 2015.

Metric	Units	Observed	Simulated	Difference	RPD (%)
Annual volume	(inches)	11.57	10.42	-1.15	-9.94
5 percent high	(inches)	2.46	2.11	-0.35	-14.17
10 percent high	(inches)	3.90	3.47	-0.43	-11.09
25 percent high	(inches)	7.15	6.32	-0.84	-11.69
50 percent low	(inches)	1.18	1.50	0.32	27.15
25 percent low	(inches)	0.25	0.40	0.15	61.53
15 percent low	(inches)	0.12	0.20	0.08	66.36
10 percent low	(inches)	0.07	0.12	0.05	68.29
5 percent low	(inches)	0.03	0.06	0.02	69.41
Storm volume	(inches)	7.68	6.86	-0.82	-10.62
Average storm peak	(cfs)	86.84	81.51	-5.33	-6.14
Spring volume	(inches)	4.25	3.34	-0.91	-21.51
Summer volume	(inches)	1.02	0.97	-0.05	-4.90
Fall volume	(inches)	0.94	1.20	0.27	28.43
Winter volume	(inches)	5.36	4.91	-0.45	-8.44
Spring storms	(inches)	2.28	1.82	-0.46	-20.13
Summer storms	(inches)	0.25	0.18	-0.07	-26.87
Fall storms	(inches)	0.61	0.66	0.04	7.12
Winter storms	(inches)	4.21	3.90	-0.30	-7.20

RPD = relative percent difference.

Table C5. Observed and simulated flow metrics and RPD for Big Soos Creek near Kent (Rch 152) for WY 2001 – 2015.

Metric	Units	Observed	Simulated	Difference	RPD (%)
Annual volume	(inches)	16.89	16.39	-0.51	-3.01
5 percent high	(inches)	3.37	3.12	-0.25	-7.49
10 percent high	(inches)	5.18	4.99	-0.19	-3.69
25 percent high	(inches)	8.99	8.69	-0.30	-3.37
50 percent low	(inches)	3.95	4.04	0.09	2.34
25 percent low	(inches)	1.58	1.81	0.23	14.25
15 percent low	(inches)	0.87	1.06	0.19	21.85
10 percent low	(inches)	0.54	0.70	0.16	28.95
5 percent low	(inches)	0.26	0.35	0.09	36.30
Storm volume	(inches)	10.53	9.72	-0.82	-7.74
Average storm peak	(cfs)	19.05	19.04	-0.01	-0.05
Spring volume	(inches)	4.95	4.30	-0.64	-13.03
Summer volume	(inches)	2.03	2.20	0.17	8.37
Fall volume	(inches)	3.01	3.62	0.62	20.53
Winter volume	(inches)	6.91	6.26	-0.65	-9.42
Spring storms	(inches)	3.14	2.66	-0.48	-15.17
Summer storms	(inches)	0.13	0.13	0.00	-2.21
Fall storms	(inches)	1.24	1.55	0.30	24.23
Winter storms	(inches)	5.58	4.96	-0.62	-11.09

RPD = relative percent difference.

Table C6. Observed and simulated flow metrics and RPD for Big Soos Creek near mouth (Rch 592) for WY 2001 – 2015.

Metric	Units	Observed	Simulated	Difference	RPD (%)
Annual volume	(inches)	14.13	12.78	-1.34	-9.52
5 percent high	(inches)	2.47	2.30	-0.16	-6.61
10 percent high	(inches)	4.10	3.83	-0.27	-6.58
25 percent high	(inches)	7.64	7.09	-0.55	-7.14
50 percent low	(inches)	2.67	2.37	-0.30	-11.30
25 percent low	(inches)	0.84	0.75	-0.10	-11.50
15 percent low	(inches)	0.45	0.38	-0.06	-14.15
10 percent low	(inches)	0.28	0.24	-0.04	-15.24
5 percent low	(inches)	0.13	0.11	-0.03	-19.10
Storm volume	(inches)	7.58	7.00	-0.58	-7.70
Average storm peak	(cfs)	340.63	369.46	28.84	8.47
Spring volume	(inches)	4.59	3.77	-0.82	-17.87
Summer volume	(inches)	1.51	1.33	-0.18	-11.74
Fall volume	(inches)	2.06	2.07	0.01	0.71
Winter volume	(inches)	5.97	5.61	-0.36	-6.07
Spring storms	(inches)	2.03	1.76	-0.27	-13.45
Summer storms	(inches)	0.13	0.11	-0.03	-21.05
Fall storms	(inches)	1.01	1.01	0.00	-0.16
Winter storms	(inches)	4.02	3.77	-0.24	-6.04

RPD = relative percent difference.

Tables C7 through C12 present yearly observed and simulated runoff and RPD for each of the six hydrology calibration locations.

Table C7. Yearly observed and simulated runoff and RPD for Soosette Creek (Rch 582) for WY 2001 – 2015 (all units in inches).

Year	Observed	Simulated	Difference	RPD (%)
2001	6.31	6.34	0.03	0.49
2002	11.17	10.73	-0.44	-3.91
2003	13.03	12.36	-0.67	-5.15
2004	9.15	9.35	0.20	2.20
2005	10.11	9.45	-0.67	-6.58
2006	19.93	17.52	-2.41	-12.10
2007	11.70	12.48	0.78	6.71
2008	9.78	9.38	-0.40	-4.07
2009	11.34	12.45	1.11	9.80
2010	14.96	15.00	0.04	0.24
2011	12.95	13.61	0.66	5.06
2012	17.78	16.61	-1.16	-6.55
2013	9.81	10.79	0.98	9.96
2014	16.49	17.49	1.00	6.07
2015	6.71	7.25	0.53	7.96
Avg	**12.08**	**12.05**	**-0.03**	**-0.23**

RPD = relative percent difference.

Table C8. Yearly observed and simulated runoff and RPD for Little Soos Creek (Rch 142) for WY 2001 – 2015 (all units in inches).

Year	Observed	Simulated	Difference	RPD (%)
2001	7.50	7.57	0.06	0.83
2002	15.65	16.56	0.90	5.78
2003	17.08	17.64	0.56	3.26
2004	15.82	15.13	-0.69	-4.37
2005	15.35	15.00	-0.35	-2.29
2006	23.51	22.80	-0.71	-3.03
2007	18.27	17.21	-1.06	-5.80
2008	15.75	14.90	-0.85	-5.42
2009	18.20	17.31	-0.88	-4.85
2010	21.07	17.41	-3.67	-17.40
2011	19.04	17.91	-1.14	-5.97
2012	19.77	19.42	-0.35	-1.77
2013	16.85	15.20	-1.65	-9.82
2014	19.66	21.07	1.41	7.18
2015	9.86	10.66	0.80	8.12
Avg	**16.89**	**16.39**	**-0.51**	**-3.00**

RPD = relative percent difference.

Table C9. Yearly observed and simulated runoff and RPD for Jenkins Creek (Rch 332) for WY 2001 – 2015 (all units in inches).

Year	Observed	Simulated	Difference	RPD (%)
2001	4.40	5.71	1.31	29.77
2002	12.22	13.70	1.48	12.10
2003	13.23	14.10	0.88	6.63
2004	13.99	12.76	-1.23	-8.79
2005	12.46	11.55	-0.91	-7.29
2006	17.98	19.92	1.94	10.80
2007	13.41	14.95	1.54	11.48
2008	12.38	12.64	0.27	2.14
2009	15.34	14.91	-0.43	-2.77
2010	18.39	16.46	-1.93	-10.50
2011	17.86	17.02	-0.84	-4.69
2012	17.10	17.78	0.68	3.95
2013	13.99	14.11	0.13	0.90
2014	20.59	18.94	-1.65	-8.01
2015	10.39	8.96	-1.43	-13.79
Avg	**14.25**	**14.23**	**-0.01**	**-0.10**

RPD = relative percent difference.

Table C10. Yearly observed and simulated runoff and RPD for Covington Creek (Rch 512) for WY 2001 – 2015 (all units in inches).

Year	Observed	Simulated	Difference	RPD (%)
2001	4.10	4.24	0.14	3.51
2002	10.62	9.31	-1.30	-12.27
2003	8.99	8.88	-0.11	-1.23
2004	8.92	8.56	-0.36	-4.04
2005	7.48	7.39	-0.09	-1.26
2006	17.26	15.23	-2.04	-11.80
2007	11.21	10.67	-0.54	-4.78
2008	9.33	8.84	-0.50	-5.30
2009	13.17	10.99	-2.18	-16.57
2010	14.33	13.15	-1.19	-8.28
2011	16.69	13.01	-3.68	-22.04
2012	16.00	14.32	-1.68	-10.49
2013	11.58	10.11	-1.47	-12.68
2014	16.26	14.95	-1.31	-8.08
2015	7.60	6.65	-0.95	-12.56
Avg	**11.57**	**10.42**	**-1.15**	**-9.93**

RPD = relative percent difference.

Table C11. Yearly observed and simulated runoff and RPD for Big Soos Creek near Kent (Rch 152) for WY 2001 – 2015 (all units in inches).

Year	Observed	Simulated	Difference	RPD (%)
2001	no data	no data	no data	no data
2002	no data	no data	no data	no data
2003	no data	no data	no data	no data
2004	no data	no data	no data	no data
2005	no data	no data	no data	no data
2006	no data	no data	no data	no data
2007	no data	no data	no data	no data
2008	no data	no data	no data	no data
2009	no data	no data	no data	no data
2010	3.18	2.52	-0.66	-20.81
2011	15.69	15.73	0.03	0.21
2012	18.10	17.47	-0.62	-3.44
2013	12.79	13.08	0.29	2.30
2014	18.40	18.60	0.20	1.10
2015	9.59	8.74	-0.85	-8.82
Avg	**12.96**	**12.69**	**-0.27**	**-2.07**

RPD = relative percent difference.

Table C12. Yearly observed and simulated runoff and RPD for Big Soos Creek near mouth (Rch 592) for WY 2001 – 2015 (all units in inches).

Year	Observed	Simulated	Difference	RPD (%)
2001	5.14	5.45	0.31	6.12
2002	11.82	12.04	0.22	1.87
2003	11.94	12.41	0.47	3.95
2004	11.06	11.01	-0.05	-0.47
2005	11.13	10.06	-1.07	-9.63
2006	19.88	18.22	-1.66	-8.34
2007	13.83	13.32	-0.51	-3.68
2008	12.93	10.99	-1.94	-15.00
2009	14.81	13.34	-1.47	-9.96
2010	17.31	15.20	-2.11	-12.17
2011	18.90	15.17	-3.73	-19.73
2012	19.70	16.54	-3.16	-16.02
2013	14.79	12.35	-2.44	-16.53
2014	19.27	17.51	-1.76	-9.14
2015	9.37	8.09	-1.28	-13.63
Avg	**14.13**	**12.78**	**-1.35**	**-9.52**

RPD = relative percent difference.

Tables C13 and C18 present monthly observed and simulated runoff and RPD at all six calibration locations.

Table C13. Monthly observed and simulated runoff and RPD for Soosette Creek (Rch 582) for WY 2001 – 2015 (all units in inches).

Month	Observed	Simulated	Difference	RPD (%)
JAN	2.59	2.27	-0.32	-12.30
FEB	1.39	1.34	-0.05	-3.52
MAR	1.83	1.56	-0.27	-14.75
APR	1.26	1.06	-0.20	-16.00
MAY	0.69	0.64	-0.05	-7.87
JUN	0.40	0.40	0.00	0.15
JUL	0.09	0.22	0.13	140.05
AUG	0.07	0.22	0.15	233.02
SEP	0.14	0.32	0.19	132.99
OCT	0.37	0.68	0.31	83.14
NOV	1.44	1.55	0.11	7.76
DEC	1.81	1.79	-0.02	-1.04
Avg	**1.01**	**1.00**	**0.00**	**-0.25**

RPD = relative percent difference.

Table C14. Monthly observed and simulated runoff and RPD for Little Soos Creek (Rch 142) for WY 2001 – 2015 (all units in inches).

Month	Observed	Simulated	Difference	RPD (%)
JAN	2.91	2.50	-0.41	-14.25
FEB	1.75	1.62	-0.13	-7.19
MAR	2.14	1.87	-0.27	-12.75
APR	1.79	1.50	-0.29	-16.03
MAY	1.17	1.07	-0.10	-8.64
JUN	0.81	0.84	0.02	3.05
JUL	0.60	0.67	0.07	11.01
AUG	0.61	0.69	0.08	12.84
SEP	0.61	0.76	0.15	24.57
OCT	0.80	1.05	0.25	30.59
NOV	1.59	1.81	0.22	13.90
DEC	2.10	2.01	-0.09	-4.49
Avg	**1.41**	**1.37**	**-0.04**	**-2.90**

RPD = relative percent difference.

Table C15. Monthly observed and simulated runoff and RPD for Jenkins Creek (Rch 332) for WY 2001 – 2015 (all units in inches).

Month	Observed	Simulated	Difference	RPD (%)
JAN	2.23	2.38	0.15	6.65
FEB	1.65	1.70	0.05	3.21
MAR	1.74	1.78	0.04	2.02
APR	1.62	1.50	-0.12	-7.39
MAY	1.21	1.06	-0.15	-12.34
JUN	0.92	0.77	-0.14	-15.62
JUL	0.61	0.49	-0.13	-20.65
AUG	0.45	0.38	-0.07	-14.78
SEP	0.45	0.40	-0.04	-9.43
OCT	0.59	0.63	0.03	5.56
NOV	1.14	1.35	0.22	19.04
DEC	1.65	1.79	0.15	8.91
Avg	**1.19**	**1.19**	**0.00**	**-0.21**

RPD = relative percent difference.

Table C16. Monthly observed and simulated runoff and RPD for Jenkins Creek (Rch 332) for WY 2001 – 2015 (all units in inches).

Month	Observed	Simulated	Difference	RPD (%)
JAN	2.21	1.97	-0.24	-10.94
FEB	1.62	1.35	-0.27	-16.42
MAR	1.78	1.50	-0.28	-15.89
APR	1.60	1.21	-0.38	-24.11
MAY	1.00	0.74	-0.26	-26.24
JUN	0.68	0.55	-0.13	-18.72
JUL	0.24	0.26	0.02	9.26
AUG	0.10	0.16	0.05	52.42
SEP	0.08	0.15	0.07	85.21
OCT	0.14	0.25	0.12	82.96
NOV	0.72	0.80	0.08	11.24
DEC	1.40	1.48	0.07	5.09
Avg	**0.96**	**0.87**	**-0.10**	**-9.94**

RPD = relative percent difference.

Table C17. Monthly observed and simulated runoff and RPD for Big Soos Creek near Kent (Rch 152) for WY 2001 – 2015 (all units in inches).

Month	Observed	Simulated	Difference	RPD (%)
JAN	2.27	2.08	-0.19	-8.44
FEB	2.06	1.88	-0.17	-8.43
MAR	2.82	2.44	-0.38	-13.60
APR	1.97	1.80	-0.17	-8.58
MAY	1.08	1.23	0.15	13.85
JUN	0.56	0.72	0.16	29.27
JUL	0.33	0.49	0.16	47.16
AUG	0.27	0.43	0.15	56.55
SEP	0.39	0.49	0.10	24.73
OCT	0.62	0.72	0.10	16.00
NOV	1.15	1.11	-0.04	-3.48
DEC	2.04	1.85	-0.18	-8.89
Avg	**1.30**	**1.27**	**-0.03**	**-2.06**

RPD = relative percent difference.

Table C18. Monthly observed and simulated runoff and RPD for Big Soos Creek near mouth (Rch 592) for WY 2001 – 2015 (all units in inches).

Month	Observed	Simulated	Difference	RPD (%)
JAN	2.35	2.23	-0.12	-5.15
FEB	1.75	1.54	-0.21	-12.04
MAR	1.93	1.66	-0.27	-13.85
APR	1.67	1.34	-0.33	-19.71
MAY	1.14	0.89	-0.24	-21.36
JUN	0.77	0.65	-0.12	-16.07
JUL	0.43	0.38	-0.04	-10.00
AUG	0.31	0.30	-0.01	-3.36
SEP	0.33	0.32	-0.01	-1.81
OCT	0.51	0.53	0.02	3.59
NOV	1.22	1.22	0.00	0.18
DEC	1.72	1.71	-0.01	-0.63
Avg	**1.18**	**1.06**	**-0.11**	**-9.62**

RPD = relative percent difference.

Tables C19-C22 present annual observed and simulated TSS concentrations and RPD for each of the four TSS calibration locations. For TSS, where we do not have daily observations, a subset of simulated TSS concentrations was used, which only included simulated daily TSS concentrations for just those days where we had observed TSS concentration data.

Table C19. Yearly observed and simulated TSS concentrations and RPD for Little Soos Creek (Rch 142) for WY 2001 – 2015 (all units in mg/L).

Year	N	Observed	Simulated	Difference	RPD (%)
2001	10	4.81	5.50	0.69	14.28
2002	10	3.01	3.94	0.93	31.03
2003	12	3.71	3.71	0.01	0.16
2004	11	3.55	3.11	-0.44	-12.29
2005	12	2.93	1.39	-1.54	-52.50
2006	11	4.16	2.95	-1.21	-29.03
2007	12	2.80	3.09	0.29	10.18
2008	12	2.89	2.00	-0.89	-30.90
2009	no data	no data	no data	no data	no data
2010	no data	no data	no data	no data	no data
2011	no data	no data	no data	no data	no data
2012	no data	no data	no data	no data	no data
2013	13	3.67	4.92	1.25	34.17
2014	17	5.87	10.64	4.77	81.36
2015	26	3.62	5.07	1.45	40.06
Avg		**3.73**	**4.21**	**0.48**	**12.96**

Note. Number of paired samples (N) varies for each year.
RPD = relative percent difference.

Table C20. Yearly observed and simulated TSS concentrations and RPD for Jenkins Creek (Rch 332) for WY 2001 – 2015 (all units in mg/L).

Year	N	Observed	Simulated	Difference	RPD (%)
2001	10	2.55	3.22	0.67	26.47
2002	10	1.88	2.18	0.30	15.95
2003	12	2.61	1.94	-0.66	-25.45
2004	11	2.20	1.80	-0.40	-18.16
2005	12	2.47	1.03	-1.44	-58.29
2006	11	1.96	2.00	0.05	2.29
2007	11	2.48	1.96	-0.51	-20.66
2008	12	2.65	1.34	-1.31	-49.47
2009	16	2.55	5.45	2.89	113.41
2010	16	3.64	8.60	4.97	136.51
2011	12	3.47	2.18	-1.30	-37.37
2012	12	3.09	2.26	-0.84	-27.10
2013	14	2.73	3.06	0.33	12.05
2014	17	3.52	6.70	3.18	90.34
2015	13	2.60	2.48	-0.12	-4.57
Avg		**2.69**	**3.08**	**0.39**	**14.39**

Note. Number of paired samples (N) vary for each year.
RPD = relative percent difference.

Table C21. Yearly observed and simulated TSS concentrations and RPD for Covington Creek (Rch 452) for WY 2001 – 2015 (all units in mg/L).

Year	N	Observed	Simulated	Difference	RPD (%)
2001	9	2.92	2.71	-0.21	-7.09
2002	9	1.61	1.59	-0.02	-1.52
2003	11	1.53	1.50	-0.04	-2.42
2004	11	1.58	1.46	-0.13	-7.90
2005	11	1.52	0.64	-0.89	-58.27
2006	11	2.08	3.41	1.32	63.58
2007	12	1.86	2.98	1.12	60.50
2008	12	2.26	1.42	-0.84	-37.12
2009	no data	no data	no data	no data	no data
2010	no data	no data	no data	no data	no data
2011	no data	no data	no data	no data	no data
2012	no data	no data	no data	no data	no data
2013	10	2.18	1.22	-0.96	-44.12
2014	12	2.20	3.78	1.58	71.50
2015	11	2.37	3.35	0.98	41.53
Avg		**2.01**	**2.19**	**0.18**	**8.70**

Note. Number of paired samples (N) vary for each year.
RPD = relative percent difference.

Table C22. Yearly observed and simulated TSS concentrations and RPD for Big Soos Creek near mouth (Rch 592) for WY 2001 – 2015 (all units in mg/L).

Year	N	Observed	Simulated	Difference	RPD (%)
2001	13	35.95	31.16	-4.78	-13.31
2002	21	5.00	9.45	4.45	89.02
2003	21	7.19	6.47	-0.72	-9.98
2004	13	8.39	6.21	-2.18	-25.95
2005	14	7.21	5.39	-1.82	-25.28
2006	14	15.57	7.46	-8.11	-52.09
2007	14	20.43	15.79	-4.64	-22.70
2008	14	4.11	8.13	4.03	98.04
2009	16	6.65	7.34	0.69	10.41
2010	16	10.49	13.86	3.36	32.04
2011	12	4.45	4.08	-0.36	-8.17
2012	12	5.31	5.24	-0.07	-1.32
2013	16	2.96	4.43	1.47	49.55
2014	13	7.52	7.61	0.08	1.11
2015	11	4.14	2.34	-1.80	-43.50
Avg		**9.69**	**9.00**	**-0.69**	**-7.15**

Note. Number of paired samples (N) vary for each year.
RPD = relative percent difference.

Tables C23-C26 present monthly observed and simulated TSS concentrations and RPD for each of the four TSS calibration locations. For TSS, where we do not have daily observations, a subset of simulated TSS concentrations was used, which only included simulated daily TSS concentrations for just those days where we had observed TSS concentration data.

Table C23. Monthly observed and simulated TSS concentrations and RPD for Little Soos Creek (Rch 142) for WY 2001 – 2015 (all units in mg/L).

Month	N	Observed	Simulated	Difference	RPD (%)
JAN	11	2.32	6.28	3.96	171.06
FEB	12	3.28	3.46	0.17	5.29
MAR	11	4.04	5.13	1.09	26.85
APR	13	4.26	4.48	0.22	5.25
MAY	12	3.56	2.88	-0.67	-18.89
JUN	11	4.35	1.37	-2.97	-68.42
JUL	14	6.95	3.53	-3.42	-49.26
AUG	13	4.00	1.60	-2.41	-60.12
SEP	11	3.82	2.31	-1.52	-39.69
OCT	12	2.49	3.14	0.65	26.12
NOV	12	2.77	9.18	6.41	231.51
DEC	14	3.05	10.12	7.07	231.60
Avg		**3.74**	**4.46**	**0.72**	**19.13**

Note. Number of paired samples (N) vary for each month.
RPD = relative percent difference.

Table C24. Monthly observed and simulated TSS concentrations and RPD for Jenkins Creek (Rch 332) for WY 2001 – 2015 (all units in mg/L).

Month	N	Observed	Simulated	Difference	RPD (%)
JAN	15	3.58	4.25	0.67	18.59
FEB	15	3.37	2.17	-1.20	-35.52
MAR	16	4.21	4.75	0.54	12.78
APR	17	3.60	3.99	0.39	10.81
MAY	16	2.97	2.58	-0.39	-13.22
JUN	14	2.21	1.15	-1.06	-47.92
JUL	17	2.18	2.93	0.75	34.42
AUG	16	1.61	3.94	2.33	144.85
SEP	14	1.57	2.95	1.37	87.33
OCT	15	1.68	1.87	0.18	10.78
NOV	16	2.58	4.34	1.77	68.40
DEC	18	3.16	4.84	1.68	52.99
Avg		**2.73**	**3.31**	**0.59**	**21.45**

Note. Number of paired samples (N) vary for each month.
RPD = relative percent difference.

Table C25. Monthly observed and simulated TSS concentrations and RPD for Covington Creek (Rch 452) for WY 2001 – 2015 (all units in mg/L).

Month	N	Observed	Simulated	Difference	RPD (%)
JAN	9	1.74	5.06	3.32	190.65
FEB	11	1.84	3.32	1.48	80.83
MAR	10	3.05	3.56	0.51	16.78
APR	11	2.53	2.69	0.16	6.44
MAY	11	2.71	1.64	-1.07	-39.64
JUN	10	2.13	0.76	-1.37	-64.22
JUL	11	1.63	0.53	-1.11	-67.85
AUG	11	1.33	0.62	-0.72	-53.81
SEP	10	1.98	0.51	-1.47	-74.34
OCT	7	1.44	1.18	-0.26	-17.75
NOV	7	0.90	2.33	1.43	158.44
DEC	11	2.21	4.34	2.13	96.22
Avg		**1.96**	**2.21**	**0.25**	**12.96**

Note. Number of paired samples (N) vary for each month.
RPD = relative percent difference.

Table C26. Monthly observed and simulated TSS concentrations and RPD for Big Soos Creek near mouth (Rch 592) for WY 2001 – 2015 (all units in mg/L).

Month	N	Observed	Simulated	Difference	RPD (%)
JAN	19	11.06	9.57	-1.49	-13.43
FEB	18	7.44	6.53	-0.91	-12.21
MAR	18	7.94	9.85	1.91	24.05
APR	19	10.11	7.65	-2.46	-24.32
MAY	18	7.47	7.45	-0.02	-0.29
JUN	18	6.19	6.53	0.34	5.52
JUL	15	3.09	2.10	-0.98	-31.80
AUG	20	2.28	6.30	4.02	176.74
SEP	16	3.42	5.18	1.76	51.53
OCT	20	3.87	4.75	0.88	22.71
NOV	20	29.82	23.80	-6.02	-20.19
DEC	19	17.46	15.60	-1.86	-10.63
Avg		**9.18**	**8.78**	**-0.40**	**-4.37**

Note. Number of paired samples (N) vary for each month.
RPD = relative percent difference.

Appendix D. Observed and simulated flow plots

Figures D1, D2, and D3 compare observed and simulated annual and monthly runoff at each of the six calibration locations.

Figure D1. Annual (left) and monthly (right) observed and simulated runoff in Soosette Creek and Big Soos Creek (near Kent).

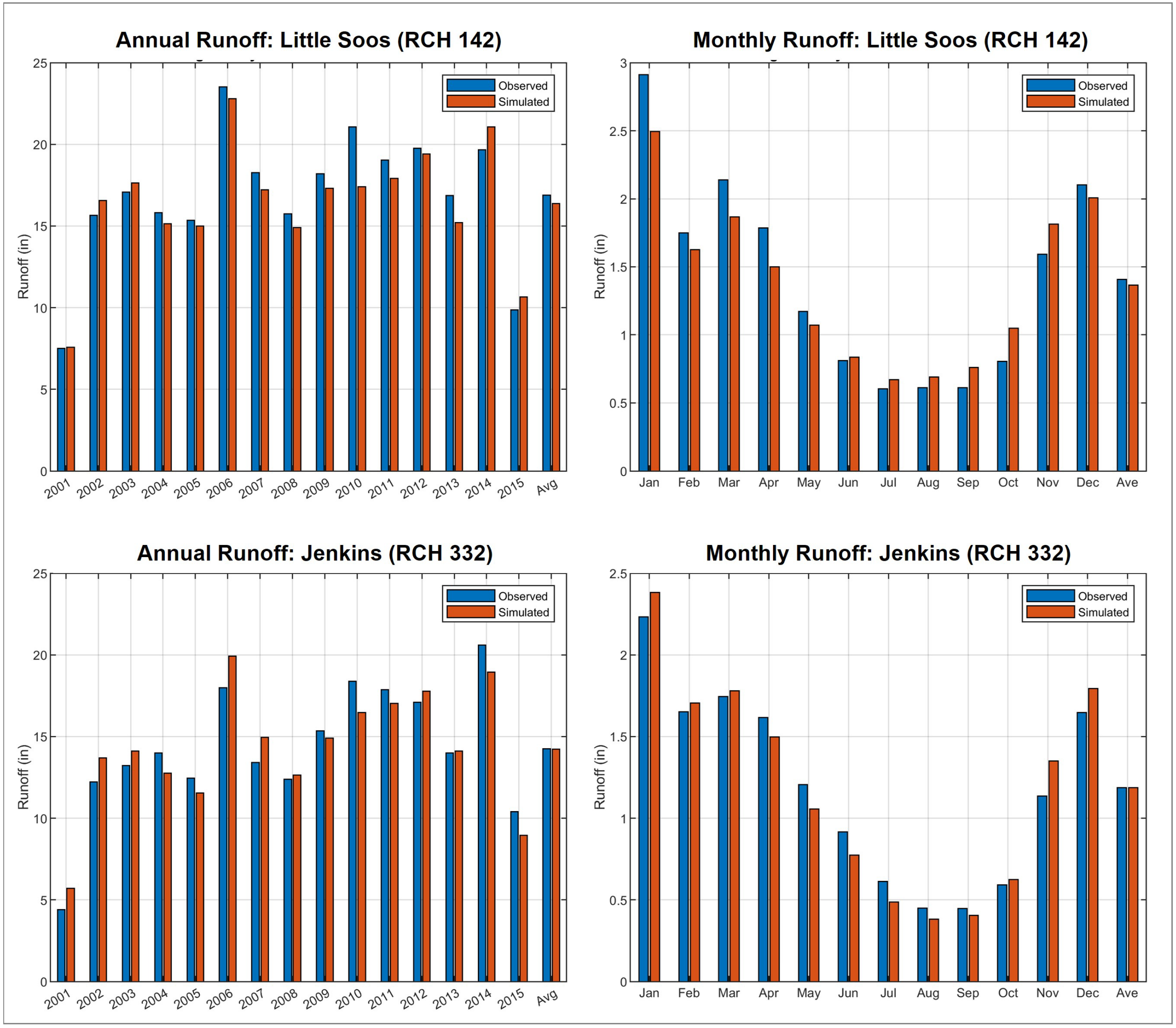

Figure D2. Annual and monthly observed and simulated runoff in Little Soos Creek and Jenkins Creek.

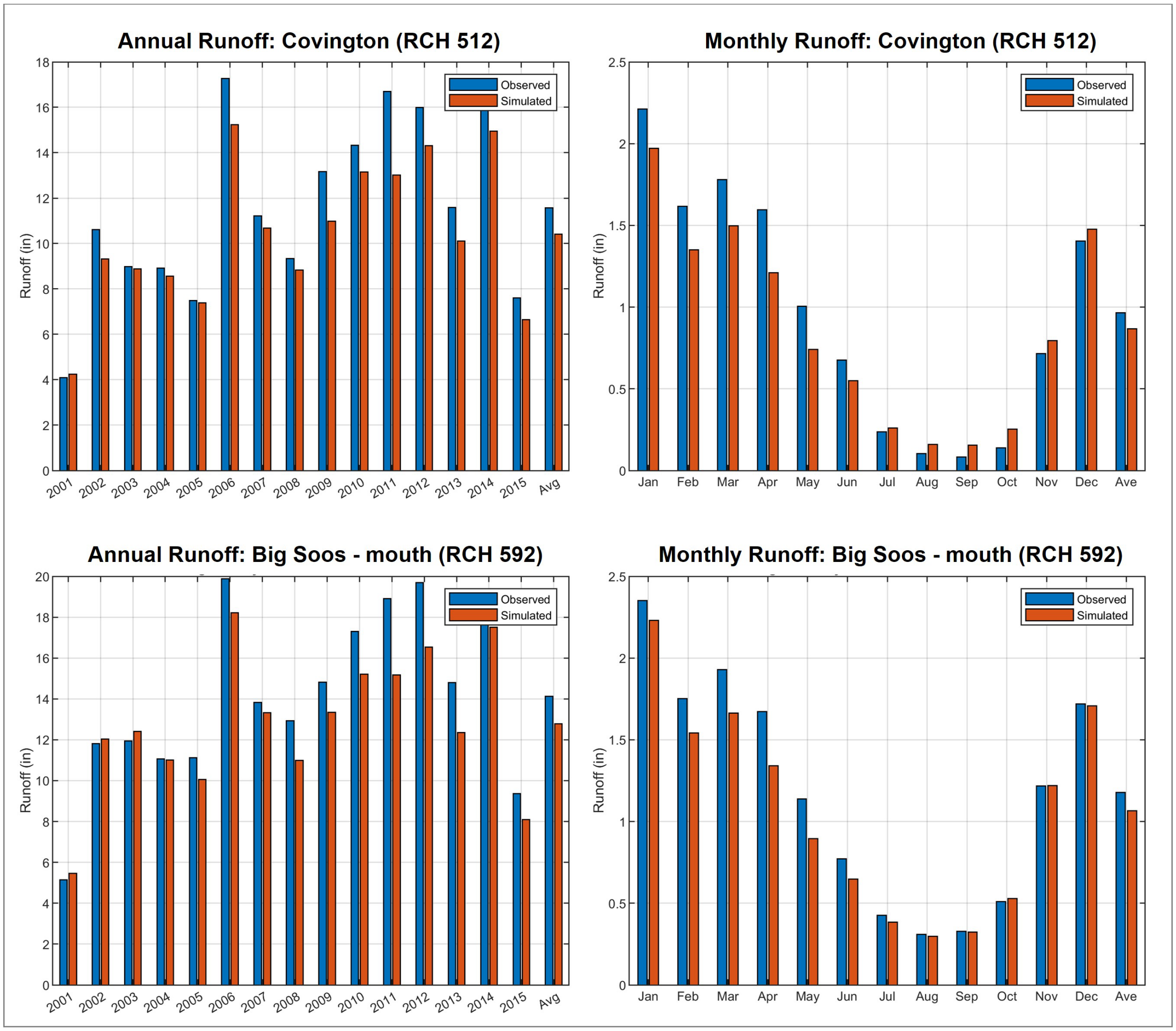

Figure D3. Annual and monthly observed and simulated runoff in Covington Creek and Big Soos Creek (near mouth).

Figures D4, D5, and D6 compare daily observed and simulated stream flow at each of the six calibration locations.

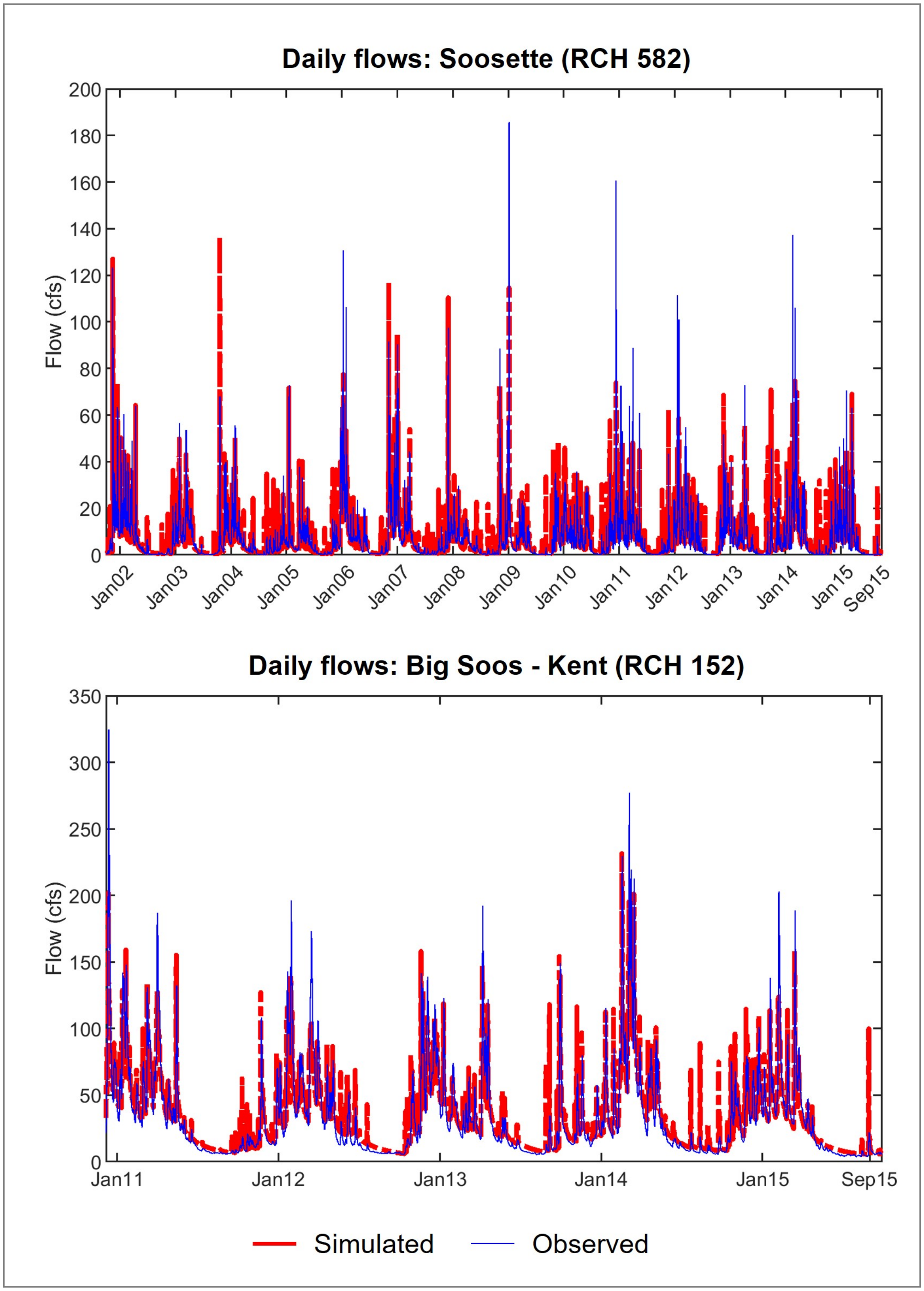

Figure D4. Daily observed and simulated flows in Soosette and Upper Big Soos (near Kent).

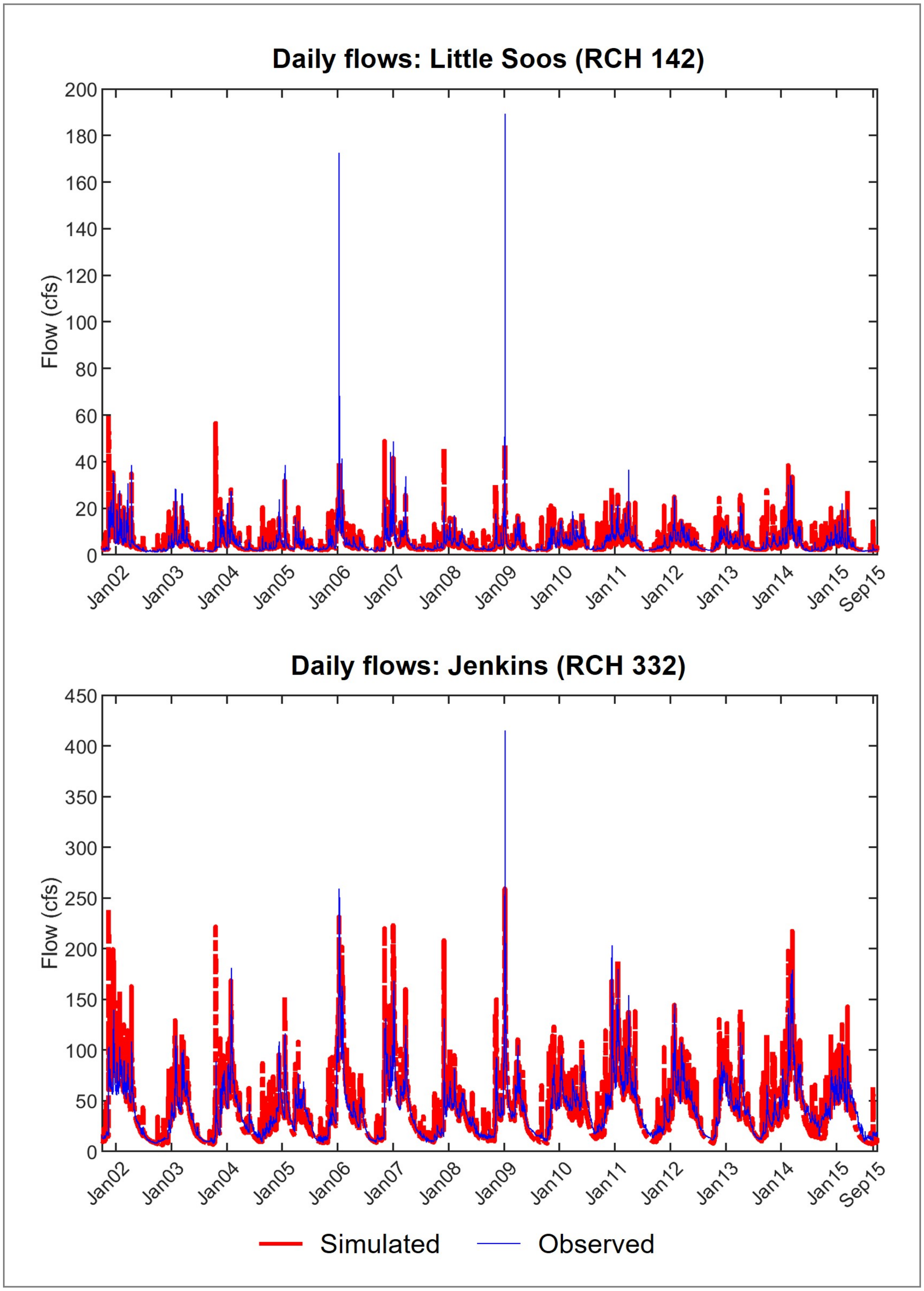

Figure D5. Daily observed and simulated flows in Little Soos and Jenkins.

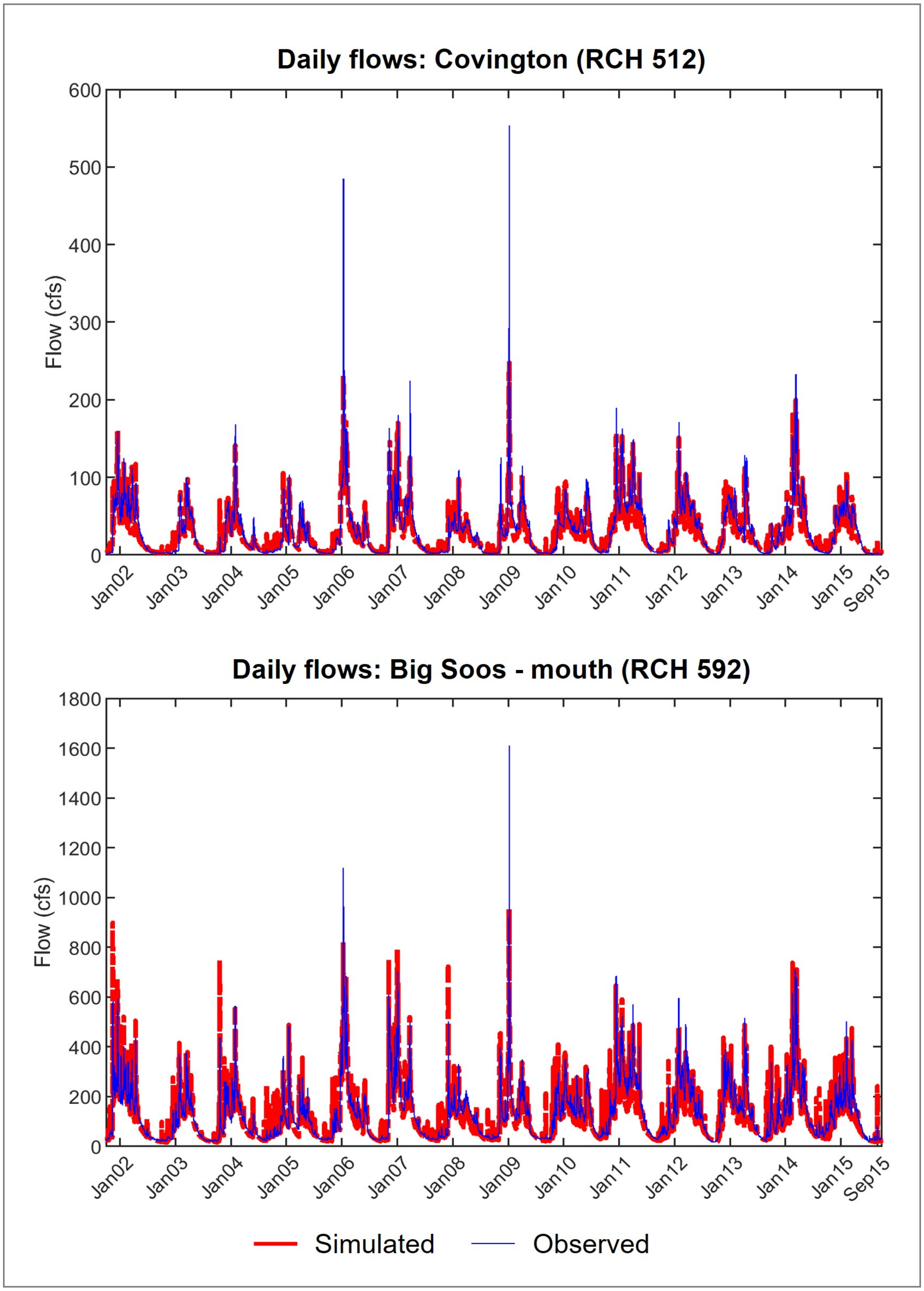

Figure D6. Daily observed and simulated flows in Covington and Lower Big Soos (near mouth).

Appendix E. Observed and simulated Total Suspended Solids (TSS)

Figure E1 compares monthly observed and simulated TSS concentrations. Figure E2 presents scatter plots of daily observed and simulated TSS concentrations. Figure E3 compares a time series of daily observed and simulated TSS concentrations.

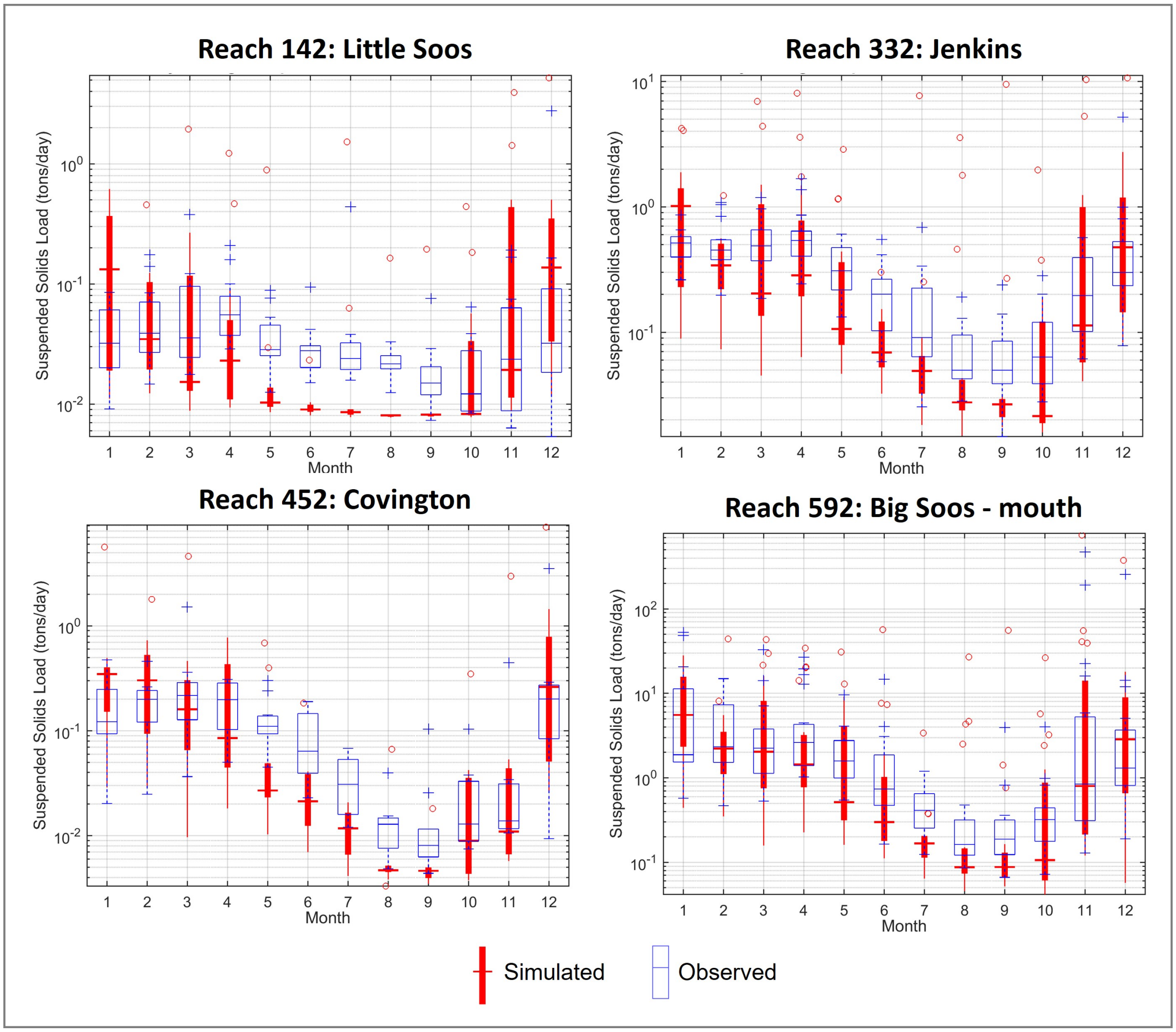

Figure E1. Monthly average observed and simulated TSS concentrations at all four TSS calibration locations (the y-axis is on a log scale)

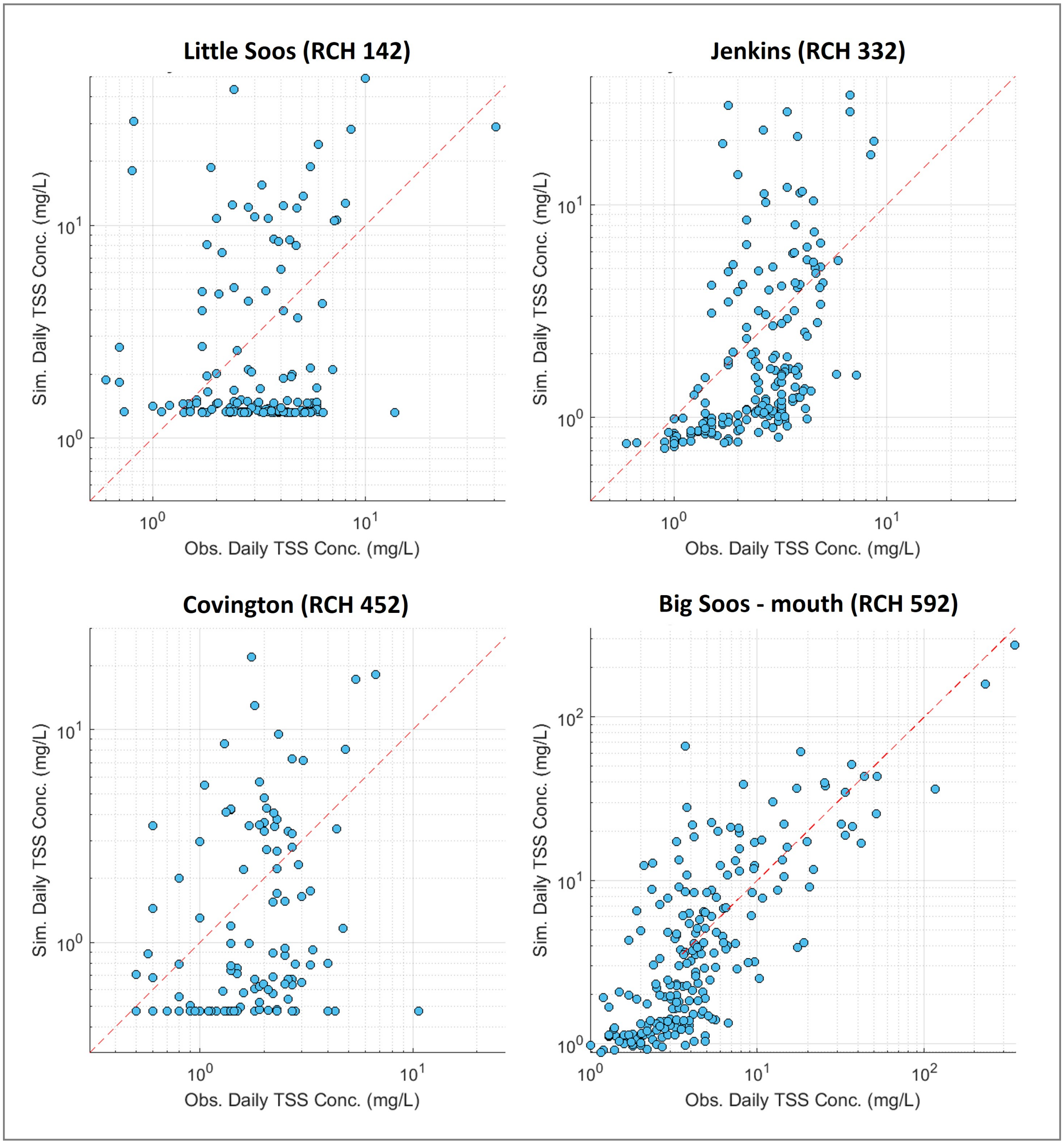

Figure E2. Scatter plots of daily observed and simulated TSS concentrations (both axes are on a log scale)

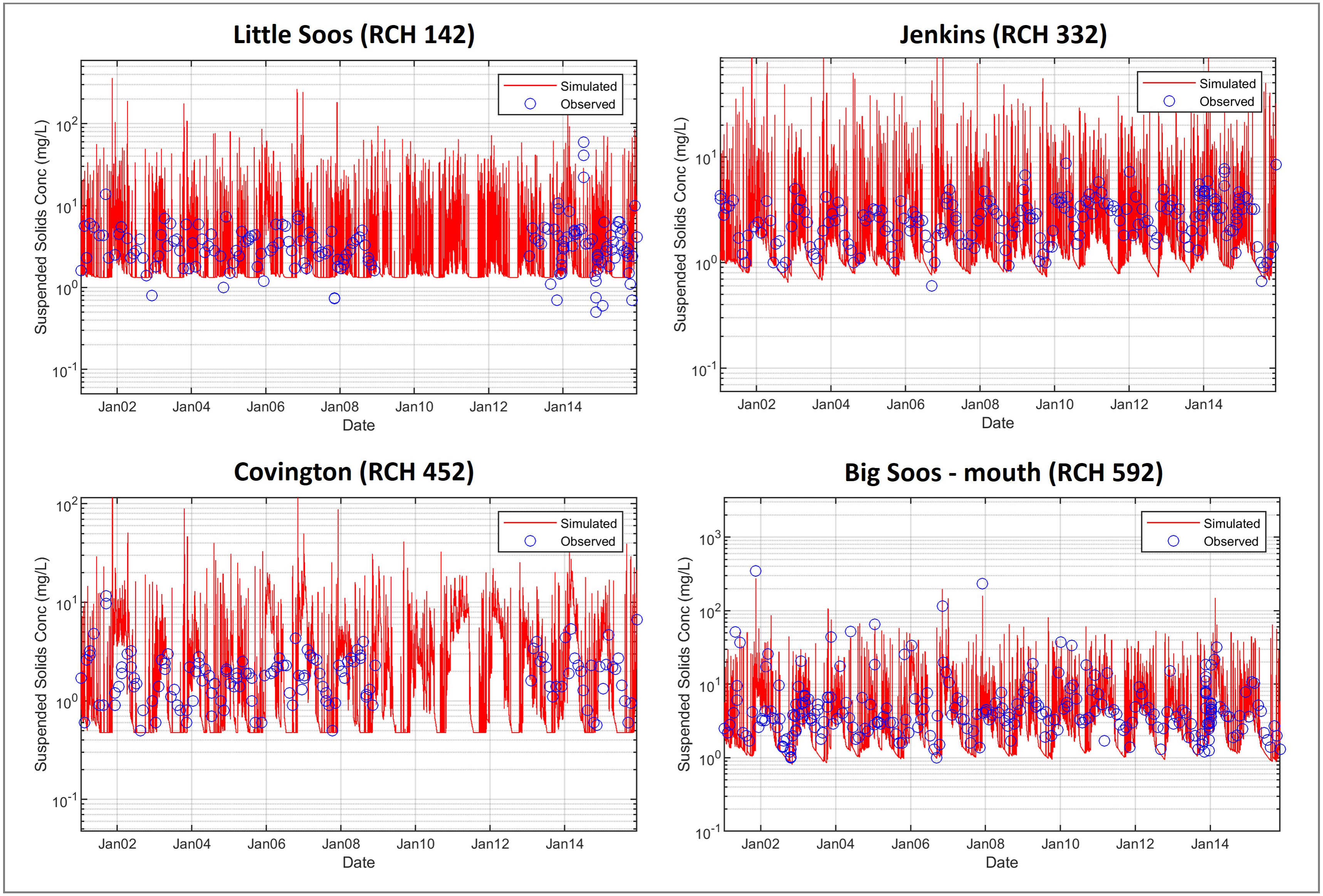

Figure E2. Daily observed (blue dots) and simulated (red) TSS concentrations at all four TSS calibration locations (y-axis is on a log scale).