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State of Washington

Lacamas Creek
Bacteria, Temperature, and Nutrients

Source Assessment Report

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Contact Information

Publications Team
Environmental Assessment Program
Washington State Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600
Phone: 360-407-6764

Washington State Department of Ecology — https://ecology.wa.gov

- Headquarters, Olympia 360-407-6000
- Northwest Regional Office, Shoreline 206-594-0000
- Southwest Regional Office, Olympia 3 60-407-6300
- Central Regional Office, Union Gap 509-575-2490
- Eastern Regional Office, Spokane 509-329-3400

Cover Photo: Molly Gleason, 2020. Lacamas Creek at creek mile 13.3.

Lacamas Creek
Bacteria, Temperature, and Nutrients

Source Assessment Report

by

Gaylen Trant-Sinclair, Molly Gleason, and John Gala

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington

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Abstract

The Lacamas Creek watershed does not meet Washington State's water quality standards (Washington Administration Code (WAC) Chapter 173-201A for fecal bacteria (*E. coli*), temperature, and dissolved oxygen (DO). This report completes the source assessment study for the Lacamas Creek watershed. It uses data from the initial sampling effort (2010-2011), a second sampling effort (summer of 2021), data collected by Clark County, and ambient monitoring data collected by the Washington State Department of Ecology (Ecology) between 2020 and 2022.

Summer fecal bacteria concentrations consistently exceed WQS at nearly all locations in the watershed. Dry season fecal bacteria concentrations are usually higher than wet season concentrations, and a comparison of fecal bacteria concentrations collected in 2011 and 2021 indicates that fecal bacteria concentrations have changed little in the past decade. Nutrient concentrations are generally highest in the lower reaches of Lacamas Creek, the Spring Branch tributary, and the China Ditch sub-watershed. In addition, a land use analysis revealed that higher nutrient concentrations are often associated with drainage basins that have a higher percentage of developed and pasture land and a lower percentage of evergreen forest.

All sites monitored in 2011 did not meet DO standards, and the only site in 2011 that met temperature standards is likely influenced by groundwater discharge to the creek. A shade analysis suggests that two regions on Lacamas Creek have high shade deficits and may be good targets for riparian restoration efforts: the two-mile stretch between river miles 9 and 11 and the upper section of the creek above river mile 14.

This report includes general recommendations for improving the watershed's temperature and water quality conditions. These recommendations are intended to help guide restoration efforts in the watershed to meet Washington State's WQS.

Executive Summary

Introduction

Washington State's Department of Ecology (Ecology) selected the Lacamas Creek watershed in 2010 for a water quality improvement project because segments of Lacamas Creek and its tributaries did not meet water quality standards (WQS) for temperature, dissolved oxygen (DO), and fecal bacteria (referred to as "bacteria" in this report). In addition, nutrient concentrations in the watershed are historically very high. Ecology conducted water quality sampling in 2010 – 2011 and published a summary of watershed groundwater conditions in 2013. In 2021, Ecology elected to conduct the water quality study as a Source Assessment study. Ecology staff also conducted additional bacteria sampling in 2021. This report summarizes the water quality data collected in 2010 – 2011 and 2021, presents a technical analysis of potential sources of pollution in the watershed, and outlines recommendations for improving the watershed's water quality.

Watershed Description

The Lacamas Creek watershed covers approximately 67 square miles in Clark County in Southwest Washington. Lacamas Creek flows 18 miles from publically-owned forested headwaters, through the former Camp Bonneville military installation, and then through rural, agricultural, and residential/commercial areas above Lacamas Creek.

The watershed includes several larger tributaries, including China Ditch, Fifth Plain Creek, and Shanghai Creek in the northern portion and Matney Creek in the western portion. It also includes many minor creeks and tributaries in the watershed. This study focuses on three minor tributaries in the lower portion of the watershed: Big Ditch, Spring Branch Creek, and Dwyer Creek.

Lacamas Creek is a major source of water (and therefore pollutants) to Lacamas Lake, so remediating pollution sources in the creek and its tributaries will help improve the lake's water quality.

Goals and Objectives

This source assessment report analyzes data from field collections in 2010 – 2011 and 2021 and supplementary data from both Clark County and Ecology to characterize pollutants in the watershed and identify potential pollutant sources. The technical analysis of bacteria, nutrients, temperature, and DO presented here includes the following:

- A summary and comparison of temperature, pH, and DO data collected in 2010 – 2011 with WQS.
- A summary of fecal coliform (FC) data collected in 2010 – 2011. We also analyze FC concentration and loading data seasonally.

- A comparison of FC data collected in 2021 with 2010 – 2011 data to identify any changes in current conditions since the earlier sampling effort.
- A summary and comparison of *E. coli* data collected in 2021 with revised WQS.
- A summary of nutrient samples collected in 2011. We supplement this data with data collected by Clark County and Ecology's Lacamas Creek ambient station at Goodwin Rd to identify seasonal patterns in nutrient data.
- A comparison of bacteria and nutrient data with land use in the watershed. We use this comparison to identify if land use patterns are related to pollutant concentrations.
- Estimated system effective and potential shade on Lacamas Creek from Ecology's shade model. We use this to identify areas with shade deficits that may be targeted for riparian restoration efforts.

Conclusions and Recommendations

Conclusions

The bacteria analysis supports the following conclusions:

- *E. coli* concentrations during the summer of 2021 consistently did not meet WQS at nearly all sites sampled in the watershed.
- Fecal Coliform and *E. coli* bacteria concentrations in Shanghai Creek, Dwyer Creek, and Lower Lacamas Creek (ca. river mile 9.1) were especially high.
- Available data for on-site septic system (OSS) inspection compliance and permit date are not related to observed *E. coli* concentrations.
- On several occasions, Ecology staff observed potential non-point sources of bacteria in the watershed. These included:
    - Livestock with access to creeks.
    - Manure on the stream-side of fences and manure spraying near creeks.
- Dry season (June – October) bacteria concentrations are consistently higher than wet season (November – May) concentrations. However, FC loadings do not have a consistent seasonal pattern between sites.

The nutrient analysis supports the following conclusions:

- Nutrient concentrations are consistently very high in the watershed. These high nutrient concentrations will eventually enter Lacamas Lake and contribute to nutrient pollution in the Lake.
- The highest nutrient concentrations occur in the watershed's western (nitrogen) and northwestern (phosphorus) areas. The watershed's eastern areas, including upper Lacamas Creek, Shanghai Creek, and Matney Creek, have generally lower nutrient concentrations.

- Nutrient pollution occurs in the wet and dry seasons, with higher nitrate concentrations in wet months.
- Nutrient data collected from Clark County and Ecology's temporary ambient monitoring station between 2020 and 2022 have similar ranges compared to those collected in 2011. This suggests few changes in sources of nutrients to the watershed over the past decade.

The land use analysis supports the following conclusions:

- Land use in the watershed changed little between 2011 and 2019. The most notable changes were an increase in forested areas in the northwest portion of the watershed and increased development and development intensity in the western and southwest parts of the study area.
- There was a wide range of bacteria concentrations across land use categories in 2010 – 2011 and 2021. However, more forested areas were less likely to have high bacteria concentrations than developed and agricultural areas.
- Nutrient data indicate that higher nitrogen and phosphorus concentrations are generally associated with drainage areas that have a higher percentage of land cover in the developed and pasture land use categories

The pH and DO analysis supports the following conclusions:

- All sites monitored during two 2011 surveys had daily minimum levels that did not meet DO criteria.
- Low DO concentrations are correlated with higher total phosphorus and orthophosphate concentrations.
- Sites with potential groundwater influence (with low temperatures despite poor shade conditions) in China Ditch and Spring Branch Creek had low DO concentrations.
- Most sites met pH criteria during both surveys. The sites with lower pH values (including one that did not meet standards—28-FIF-0.2) are associated with known groundwater sources.

The temperature analysis supports the following conclusions:

- Most sites monitored during the 2011 dry season exceeded the 7-DADMax temperature criteria. The only sites that met temperature criteria were associated with cold groundwater input to the creeks.
- Ecology staff observed poor shade conditions in many locations in the watershed. Improving riparian shade coverage will likely improve temperature conditions in the study area's streams.
- A shade model conducted for the main stem of Lacamas Creek found that the current effective shade on the creek is approximately 43.6%.

- Two regions have a particularly high modeled shade deficit and may be good targets for riparian restoration efforts to improve temperature conditions in the creek.
    - The two-mile stretch between 28-LAC-9.1 and 28-Lac-11.1.
    - The headwaters of the creek above site 28-LAC-14.8.
- The downstream portion of the Lacamas mainstem requires further system potential shade analysis. However, reforestation efforts in this area may also be feasible.

Recommendations

This report provides the following recommendations:

- Perform more intensive sampling to identify potential sources of bacteria in streams in the Lacamas Creek watershed. Sampling can include microbial source tracking (MST) to more accurately identify which species (e.g., humans, livestock, pets) contribute the most bacteria to the creeks.
- Priority areas for MST include Shanghai Creek, Dwyer Creek, and Lower Lacamas Creek. These areas had the highest observed *E. coli* concentrations in the watershed.
- Maintain more detailed records of OSS issues, including identifying failing OSS and investigating whether elevated *E. coli* concentrations occur in areas with failing OSS.
- Conduct investigative stream walks along tributaries to identify and sample unknown and unmapped outfalls (e.g., pipes and culverts) during the wet and dry seasons. In particular, investigative stream walks should be conducted at sites in the China Ditch sub-watershed, where field staff have observed unmapped pipes with associated high bacteria concentrations.
- The following areas should be prioritized for identification and remediation of sources of nutrients: China Ditch, Spring Branch Creek, Dwyer Creek, and Lower Lacamas Creek
- Perform water quality modeling to identify potential solutions for improving DO and nutrient conditions in the areas identified above.
- Increase riparian restoration through native vegetation plantings on streambanks to increase riparian shade.
- In Lacamas Creek, focus riparian restoration efforts on those areas along Lacamas Creek with high shade deficits identified by the shade model, including the two-mile stretch between river miles 9 and 11 and the headwaters area above river mile 14. Note that this work has already begun in the headwaters area in Camp Bonneville by Clark County.
- Continue education and outreach work in the watershed community about nonpoint sources of pollution, particularly livestock access to creeks and planting native vegetation to improve shade conditions.

Introduction

Lacamas Creek and its major tributaries do not comply with Washington State water quality standards (WQS) for fecal bacteria (refered to as “bacteria” in this report), dissolved oxygen (DO), pH, and temperature. The goal of this source assessment is to present a detailed summary of these water quality parameters across the Lacamas Creek watershed, identify potential sources of pollution to the watershed, and present recommendations for improving surface water conditions in Lacamas Creek.

Source assessments and Total Maximum Daily Load (TMDL) Advanced Restoration Plans (ARPs) are increasingly important tools for water quality improvement in addition to TMDLs. Source assessments allow water quality results to be more rapidly spread for use in ARPs. ARPs are near-term plans that can improve water quality more immediately. Source assessments are also particularly useful in identifying and prioritizing nonpoint sources of pollutants. Nonpoint sources of bacteria and nutrients are known to harm Lacamas watershed’s water quality (Giglio and Erickson 1996; Wildrick et al. 1998; Beak Consultants and Scientific Resources Incorporated 1985).

The Washington State Department of Ecology (Ecology) started a TMDL study in 2010 to address water quality impairments in the Lacamas Creek watershed. From September 2010 to October 2011, Ecology collected fecal coliform (FC) bacteria and nutrient samples, as well as measurements for temperature, DO, pH, streamflow, and stream channel morphology. The Lacamas Creek Quality Assurance Project Plan (QAPP) includes more details regarding the study design for the 2010 – 2011 field collection efforts (Swanson 2011).

Ecology also completed a groundwater assessment to determine how groundwater influences stream flows and surface water quality in Lacamas Creek and surrounding tributaries. The 2013 *Groundwater Interactions and Near Stream Groundwater Quality* report summarizes those findings (Sinclair and Swanson 2013).

In 2021, Ecology decided to complete the study as a source assessment and TMDL ARP. In addition, bacteria sampling was conducted in 2021 to find current sources of pollution and evaluate changes since the original 2010 – 2011 FC data collection. The design of this field collection effort and the source assessment are described in a 2021 Lacamas Creek Source Assessment QAPP (Gleason and McCarthy 2021) and Ecology’s Programmatic QAPP for water quality impairment studies (McCarthy and Mathieu 2017).

Water Quality Standards and Beneficial Uses

Washington State’s WQS listed under the Washington Administration Code (WAC) Chapter 173-201A are the basis for protecting and assessing the health of water bodies. The purpose of these standards is to protect public health and recreation in state waters as well as protect fish, shellfish, and wildlife. Based on guidance from the Clean Water Act, the standards specify the designated beneficial uses for different water bodies and assign numeric and narrative criteria based on those uses. The anti-degradation policy provides additional protections for waters that meet a higher quality than the limits set in the standards and are considered an outstanding resource.

The main beneficial uses protected under the WQS include:

- Aquatic life use — salmonid spawning, rearing, and migration.
- Primary contact recreation — activities where direct contact with water to the point of complete submergence is possible.
- Water supply uses — domestic consumption, industrial production, and agriculture or hobby farm livestock.
- Miscellaneous uses — wildlife habitat, harvesting, commerce/navigation, boating, and aesthetics (WAC 173-201A-600).

Washington Administrative Code (WAC) 173-201A-600 also states that lakes and feeder streams to lakes that do not have individual use designations are protected for the designated uses of "core summer salmonid habitat" and "primary contact recreation." Since Lacamas Creek and the major tributaries are a sizeable source of surface water to Lacamas and Round Lakes, this beneficial use protection extends across all watershed areas above the Round Lake outlet. Table 1 includes the designated use classifications and water quality criteria for each water quality parameter monitored in this study.

As of December 2020, Chapter 173-201A WAC designates *E. coli* as the primary indicator to protect water contact recreation due to the strong correlation with illness from waterborne diseases. These state guidelines also require *E. coli* data to be evaluated within a consecutive 90-day period.

Table 1. Washington State freshwater use designations (WAC 173-201A-600) and criteria for specific parameters (WAC 173-201A-200) for listed parameters in Lacamas watershed.

Water Quality Parameter	Designated Use Classification	Criteria
Temperature	Core summer salmonid habitat, spawning, rearing, and migration	16°C 7-day average of the daily (DAD) maximum temperature[a]
Dissolved Oxygen	Core summer salmonid habitat, spawning, rearing, and migration	10 mg/L or 95% saturation 1-Daily-Min[b]
pH	Core summer salmonid habitat, spawning, rearing, and migration	6.5–8.5 units[c]
Bacteria (*E.coli*)	Primary contact recreation	Geometric Mean should be less than 100 cfu/100 mL No more than 10% of samples, or any single sample when less than ten, should exceed 320 cfu/100 mL

[a]7-DAD Max represents the highest annual running 7-day average of daily maximum temperatures.
[b]1-Daily Min represents the lowest annual daily minimum oxygen concentration in the water body.
[c]For pH, a human-caused variation within the above range of less than 0.2 units is acceptable.

Watershed Description

The Lacamas Creek watershed is located within Watershed Resource Inventory Area (WRIA) 28 in Southwest Washington in Clark County. The watershed has an area of 67 square miles of forest, agricultural, residential, commercial, and industrial land. It extends from Hockinson in the north to the City of Camas in the south. The cities of Vancouver and Camas border the western edge of the watershed. Lacamas Creek flows 18 miles from state and county-owned forested headwaters through the former Camp Bonneville military installation before flowing through rural, agricultural, and residential land above Lacamas and Round Lakes.

Below the lakes, Lacamas Creek enters the lower Washougal River, which flows to the Columbia River. The watershed has a complete fish passage barrier at a dam below Lacamas Lake. This dam is owned and operated by the City of Camas. Restoration practitioners have prioritized removing the fish passage barriers to support salmon recovery.

The study area for this monitoring project lies within the Lacamas Creek watershed above Lacamas Lake, which includes Lacamas Creek and its five major tributaries and ends at the confluence of Lacamas Creek and Lacamas Lake (Figure 1). The five tributaries include Matney Creek, Upper Lacamas Creek, China Ditch, Fifth Plain Creek, and Shanghai Creek. China Ditch and Shanghai Creek enter Fifth Plain Creek above its confluence with Lacamas Creek, while Matney Creek flows directly into Lacamas Creek upstream up the Fifth Plain Creek confluence. Many smaller creeks and channelized streams, including Spring Branch Creek, Big Ditch, and Dwyer Creek, flow into Lacamas Creek.

Since Lacamas Creek is the major input to the lake, focusing on the watershed upstream of Lacamas Lake provides insight into the main sources of pollution flowing into the lakes.

Segments of both the mainstem of Lacamas Creek and its tributaries are currently listed on the 303(d) list for bacteria, temperature, DO, and pH (Figure 2).

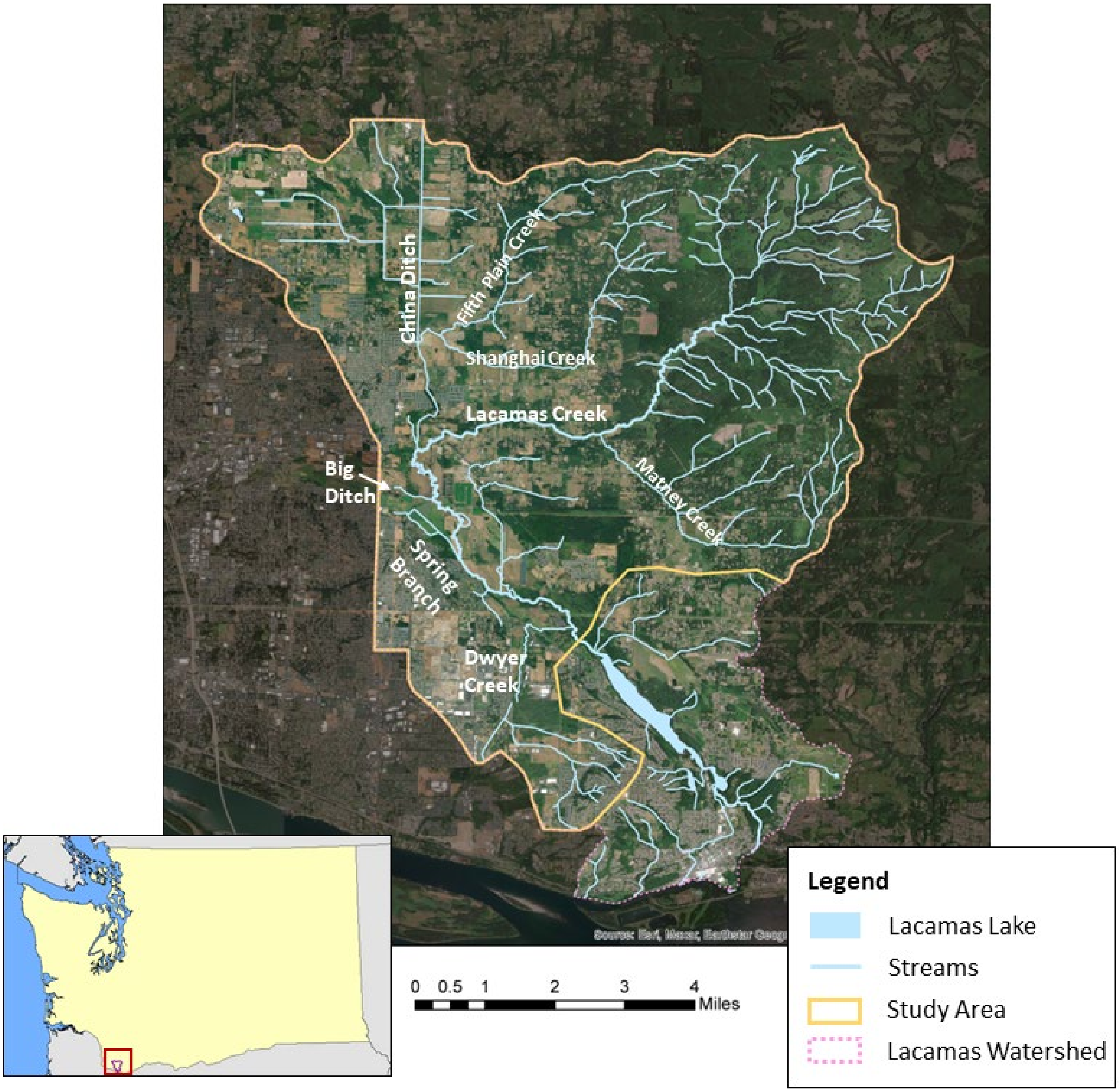

Figure 1. Map of study area.

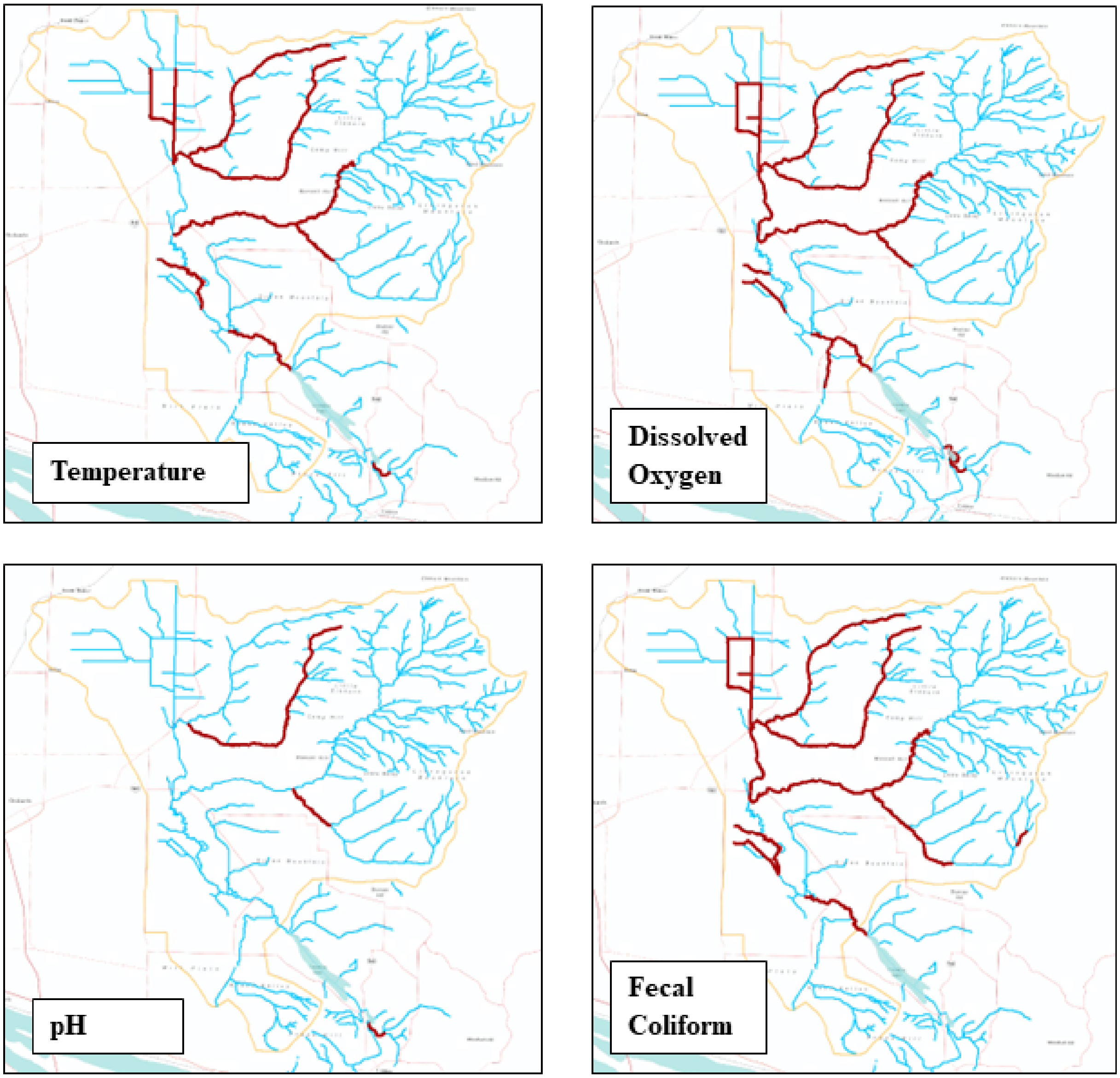

Figure 2. Current (2018) 303(d) listings for temperature, dissolved oxygen, fecal coliform, and pH in the Lacamas watershed.

Climate

The Lacamas Creek watershed is in a region of Southwest Washington that experiences mild, wet winters and relatively cool, dry summers. Temperatures are moderated by the Columbia River and the nearby Pacific Ocean, as well as the coastal Willapa Range to the west and Cascade Mountain Range to the east. Average maximum monthly air temperatures in Vancouver range from 44°F in January to approximately 80°F in August. Severe temperature extremes are infrequent. However, heat waves such as the June 2021 "heat dome" in the Pacific Northwest will likely become more frequent and severe due to human-driven climate change (Philip et al. 2021).

The average annual rainfall in Vancouver is just over 40 inches, with approximately 75% falling from October to March. July and August are generally the driest months. The foothills in the upper Lacamas Creek watershed in the northwest part of the watershed have slightly more rainfall than the lower elevation areas near Vancouver and Camas.

Southwest Washington is experiencing changes associated with long-term global climate change that are consistent with those being observed across the Pacific Northwest (Snover et al. 2013). These changes include increasing air temperatures, decreased snowpack, a longer frost-free season, and increasing stream temperatures (Snover et al. 2013; Mass et al. 2022).

Hydrology & Hydrogeology

The Lacamas watershed is situated on the eastern edge of the Portland Basin, a sediment-filled structural depression underlain by Oligocene-age basalt and basaltic andesite (Evarts 2006; Swanson et al. 1993). A 2013 groundwater study has additional details about the geologic setting of the study area (Sinclair and Swanson 2013).

Ecology installed three short-term gages in 2010 to examine the flow conditions of Fifth Plain Creek, China Ditch, and Matney Creek. These gages remained until February 2012. Figure 3 shows the hydrographs of these three gages, and Figure 4 shows their locations in the watershed. The hydrographs generally match precipitation patterns in the watershed, with higher flows during the wet months of November through March and lower flows in the generally dryer period between June and October. Accordingly, this report refers to June through October as the dry season and November through May as the wet season.

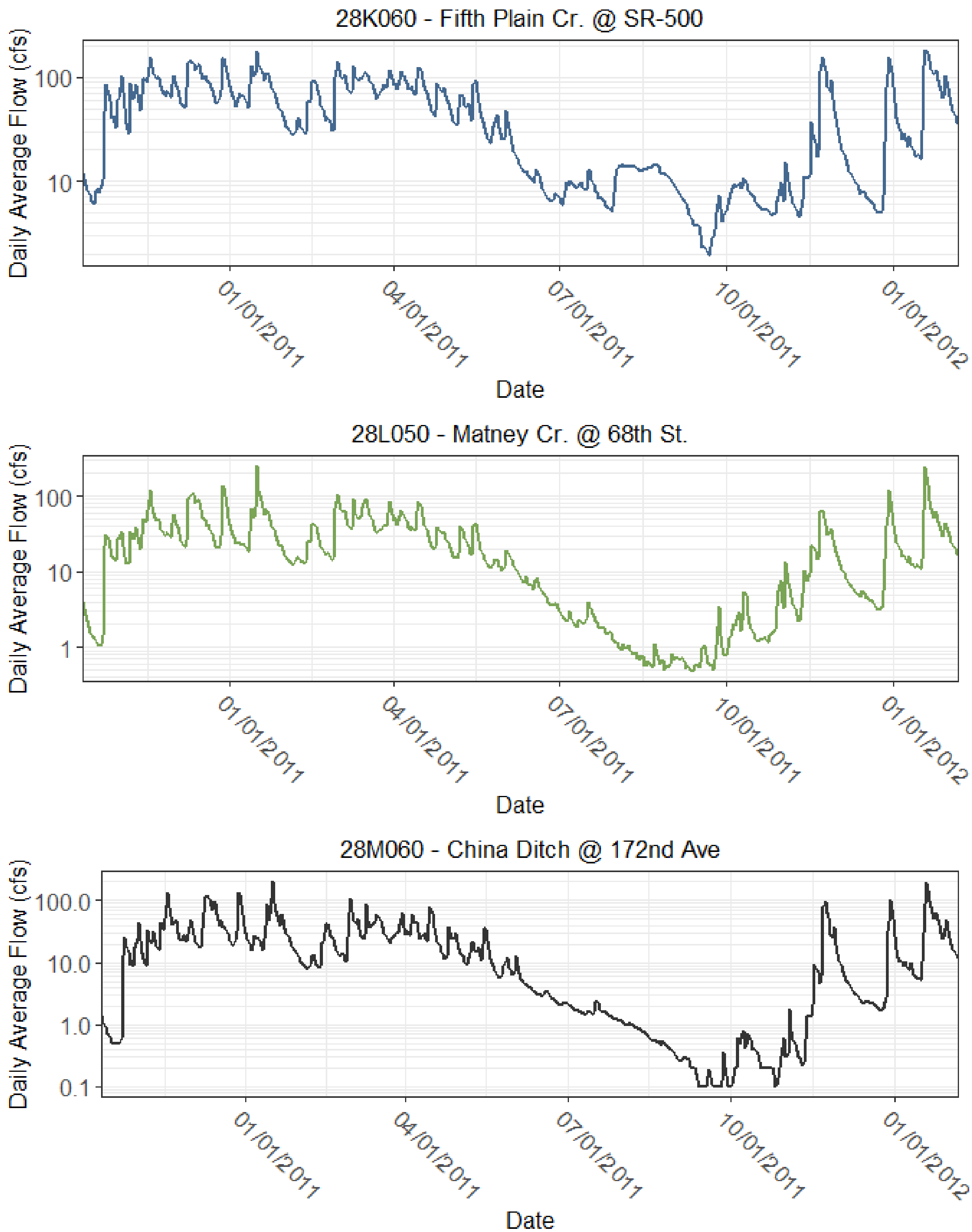

Figure 3. Hydrographs of short-term gages established in the study area.

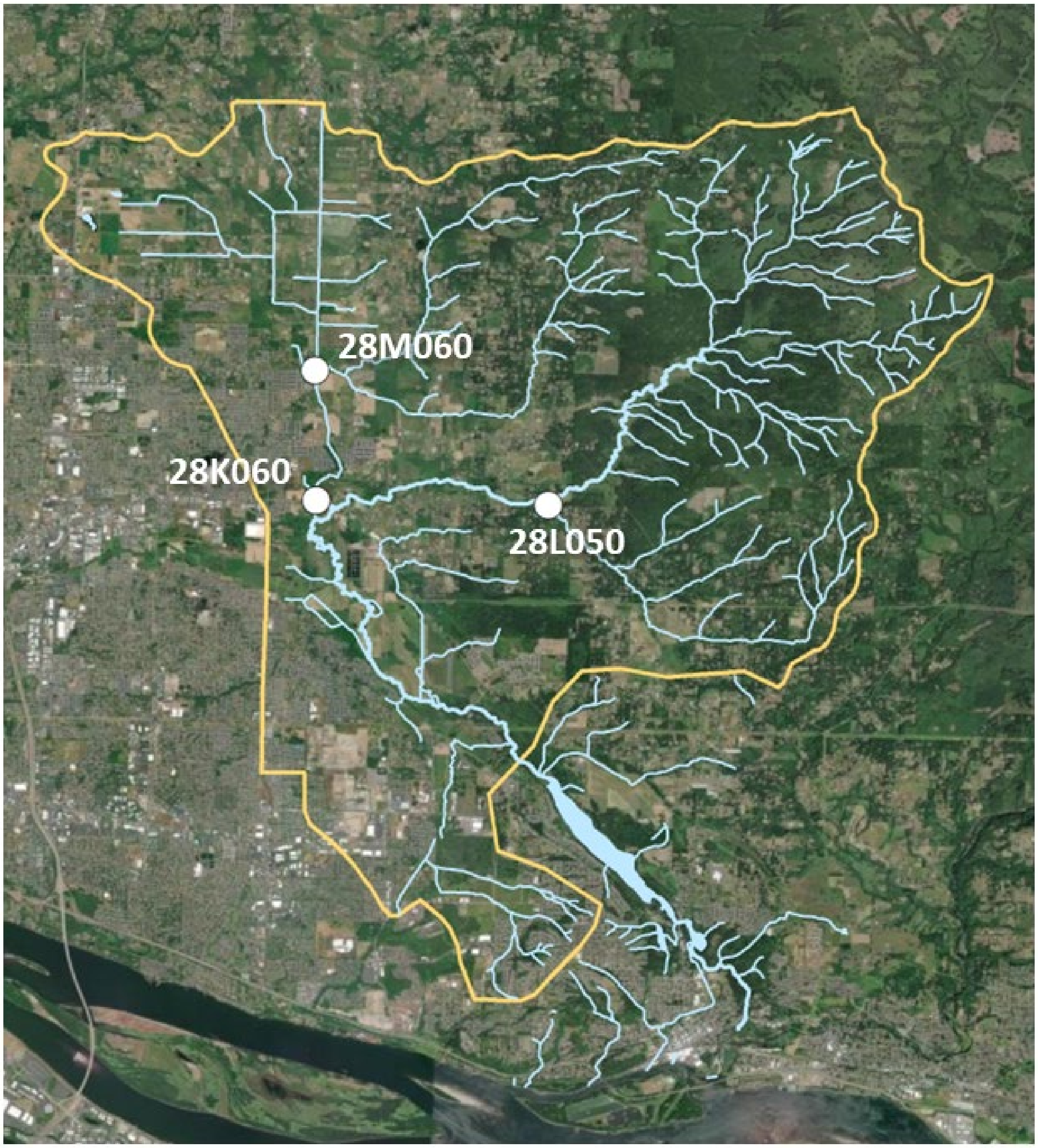

Figure 4. Locations of three short-term flow gages established by Ecology in the study area.
28M060 is located on China Ditch, 28K060 on Fifth Plain Creek, and 28L050 on Matney Creek.

As part of the originally planned TMDL, Ecology conducted a groundwater assessment to evaluate the influence of groundwater discharge on streamflow and temperature in the study area. This study included stream seepage evaluations, installation and monitoring of piezometers, collection and evaluation of groundwater samples, and monitoring of streambed thermal profiles.

The 2013 *Groundwater Interactions and Near Stream Groundwater Quality* report summarizes the results of this groundwater study (Sinclair and Swanson 2013). This assessment determined that Lacamas Creek experiences alternating gains and losses in streamflow driven by groundwater discharge during summer months. In July, several reaches experienced net groundwater gains, but these same reaches experienced net losses in August of the same year.

In the July and August synoptic surveys, dissolved orthophosphate and dissolved total phosphorus concentrations ranged from non-detections below 0.003 mg/L to detections of 0.276 mg/L (ortho-phosphate) and 0.0221 – 0.602 mg/L (total phosphorus). Phosphorus and ortho-phosphate measurements from near-surface groundwater were sometimes higher than and sometimes lower than surface water samples collected at the same location. A national USGS study found the median concentration of ortho-phosphate in near-surface groundwater was 0.01 mg/L, lower than many of the groundwater samples collected in the Lacamas watershed (Nolan and Hitt 2003).

Groundwater samples collected approximately 700ft downstream of a manure lagoon had total nitrogen and ammonia concentrations an order of magnitude higher than other sample locations, indicating local manure management may contribute to groundwater nutrient concentrations. When the samples downstream of the manure lagoon were excluded, total nitrogen, nitrate, and ammonia concentrations were 0.056 – 0.284 mg/L, <0.01 – 0.0235 mg/L, and 0.0275 – 0.2445 mg/L, respectively. Studies by Ecology and the USGS suggest groundwater nitrate concentrations below 1 – 3 mg/L do not have a significant human-produced nitrate source (Morgan 2016; Nolan and Hitt 2003).

Point Sources

Point sources refer to sources of pollution discharged from a specific location, such as pipes, outfalls, and conveyance channels, to surface water. Point source permits in the watershed include construction stormwater general permits, industrial stormwater general permits, and sand and gravel general permits. Figure 5 shows the location of properties covered under the specific permit types.

Additionally, there are currently two documented dairies in the study area. The Washington State Department of Agriculture (WSDA)'s Dairy Nutrient Management Act regulates and performs routine inspections of these dairies. Since WSDA currently has permit authority to regulate these dairies, Ecology does not administer Concentrated Animal Feeding Operation (CAFO) permits to these dairies. Both dairies recently closed; the closure was overseen by the Washington Department of Agriculture (WSDA). Ecology now oversees the current operation in lower Lacamas Creek. The former dairy land is currently being utilized for hay production and pasture-based beef cattle, and the dairy lagoons are in the process of being closed out as of summer 2023, with technical assistance from the USDA National Resources Conservation Service.

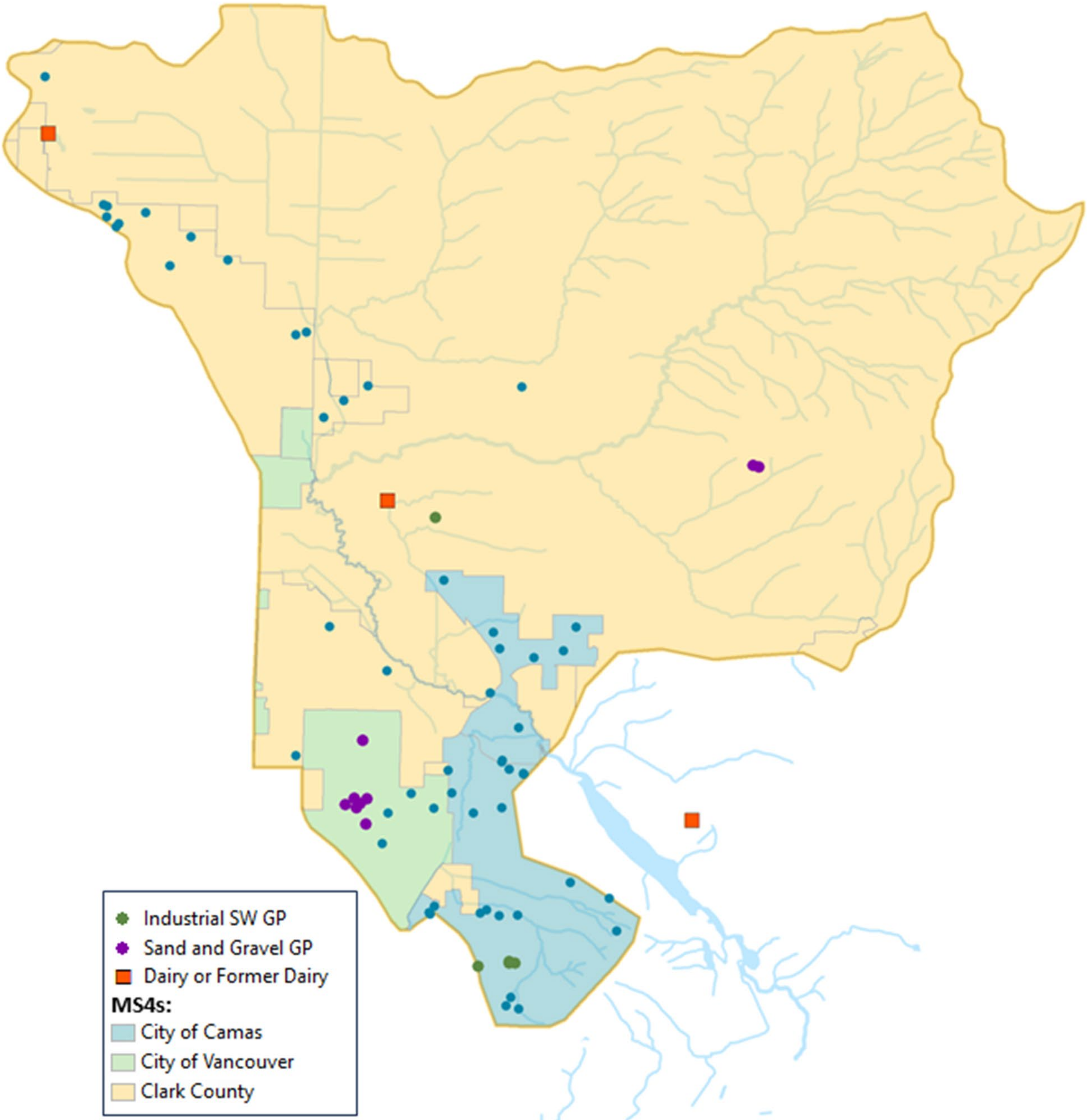

Figure 5. Map of National Pollutant Discharge Elimination Systems (NPDES) permits, locations of dairies, and stormwater jurisdictions in the Lacamas Creek watershed.
GP: General Permit; MS4: Municipal Separate Storm System; SW: stormwater.

Stormwater

During significant rain events, stormwater runoff can accumulate pollutants and transport them to receiving waters, degrading water quality. Ecology regulates stormwater discharge under the

National Pollutant Discharge Elimination Systems (NPDES) Municipal Stormwater Permit program. More information on NPDES permits can be found on Ecology's Stormwater Permittee Guidance webpage[1].

Phase I Municipal Stormwater Permit

A Phase I Municipal Stormwater Permit regulates all discharges from municipal separate storm sewer systems (MS4s) owned or operated by the state's largest cities and counties. Ecology issued an NPDES Phase 1 Municipal Stormwater Permit to Clark County and six other Western Washington jurisdictions in July 2019. This covers a five-year period from August 1, 2019, through July 31, 2024, and covers approximately 88% of the Lacamas Creek watershed. In 2020, Clark County released a Stormwater Management Plan outlining county responsibilities to protect water through stormwater management. This plan is located on the Clark County Stormwater Webpage[2].

Phase II Municipal Stormwater Permit

Phase II Municipal Stormwater Permits regulate discharges from smaller MS4s in Washington to manage stormwater before it discharges to surface water. The cities of Vancouver and Camas, which cover 7% and 4% of the watershed, respectively, have western Washington Phase II Municipal Stormwater Permits issued by Ecology.

The City of Vancouver issued a 2020 Stormwater Management Plan, including information about changes to the City's Municipal Codes relating to stormwater management. This plan is on the City of Vancouver's Public Works Stormwater Management Plan webpage[3].

In addition, Ecology reissued a Phase II permit to the City of Camas on July 1, 2019. The City of Camas' management plan is on the City of Camas' Public Works Stormwater Management webpage[4].

WSDOT Municipal Stormwater Permit

Ecology issues a WSDOT-specific municipal stormwater permit that covers stormwater discharge from state highways, roughly 1% of the Lacamas Creek watershed. State highways in the Lacamas Creek watershed include SR 500 and SR 503. The current permit went into effect on April 5, 2019, and expires on April 5, 2024. Ecology's WSDOT Municipal Stormwater Permit webpage has more details about this permit.

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[1] https://ecology.wa.gov/regulations-permits/guidance-technical-assistance/stormwater-permittee-guidance-resources
[2] https://clark.wa.gov/public-works/stormwater
[3] https://www.cityofvancouver.us/government/department/public-works/water-sewer-and-stormwater/stormwater-management-plan/
[4] https://clark.wa.gov/public-works/stormwater-management/regulations

Nonpoint Sources

Nonpoint pollution originates from diffuse sources that are not regulated by point source regulatory tools, such as the discharge permits described above. Potential nonpoint sources within the Lacamas Creek watershed include:

- Livestock with direct access to the stream.
- Livestock manure, either applied to fields or leached from storage areas.
- Pet manure from parks and residential areas.
- Failing on-site septic systems.
- Runoff from properties adjacent to the creek.

Land Use

The current land use in the study area is approximately 35% forest, 31% development (including developed open spaces as well as low, medium, and high-intensity development), and 24% pasture and agricultural hay production. The remainder of the land use includes approximately 5% of land in the shrub/scrub and grassland categories, 5% wetlands, and a small fraction of the land use is cultivated crops (0.03%) and open water (0.11%). Figure 6 shows the land use according to the 2019 National Land Cover Database (NLCD) survey (note that clear-cut areas in the northeastern portion of the watershed are listed as "Shrub/Scrub" by the NLCD).

About 22% of the watershed is public property (Figure 7). Federal or local governments in the watershed (i.e., the City of Camas and Vancouver) own approximately 1% of the land. Clark County and the State of Washington own 13% and 8% of the public lands in this watershed, respectively.

A portion of the upper section of Lacamas Creek flows through the Camp Bonneville property (Figure 8). This property was a military installation from 1909 to 1995. Ownership of the property passed to Clark County in 2006, and from 2006 to the present day, they have been cleaning up the property by removing hazardous munitions (Clark County 2017). The valley floor area, including the Lacamas Creek riparian zone, was intensively managed from 2006 to 2021, with most vegetation on the valley floor removed or reduced to 3 inches in height to permit minesweepers in the area. Clark County is currently leading riparian restoration efforts in the valley and plans to develop the property into a county park (Hunter Decker, pers. comm., Sep 8, 2023).

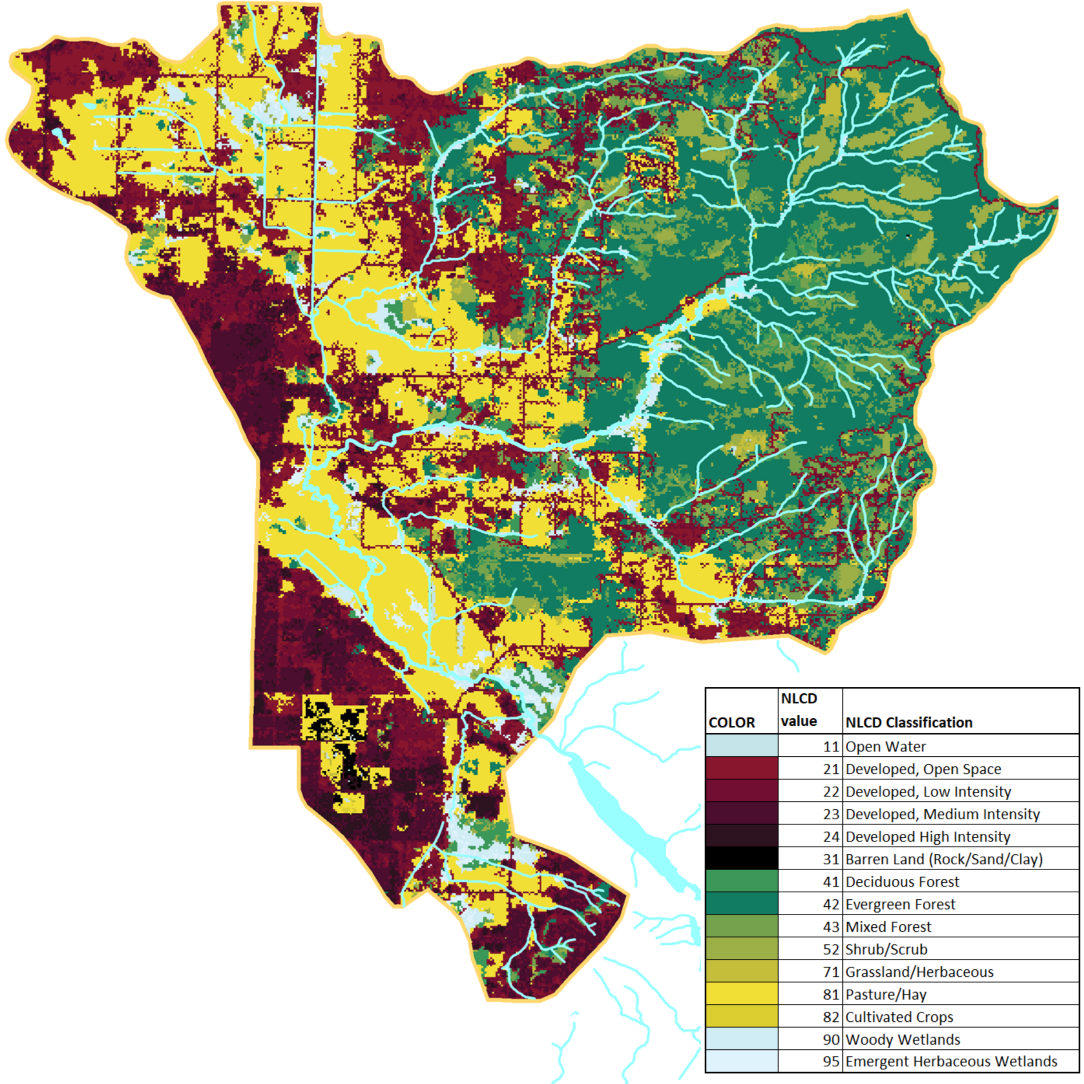


Figure 6. Map of land use in the Lacamas Creek watershed.

"NLCD value" refers to the National Land Cover Database legend found at https://www.mrlc.gov/data/legends/national-land-cover-database-class-legend-and-description.

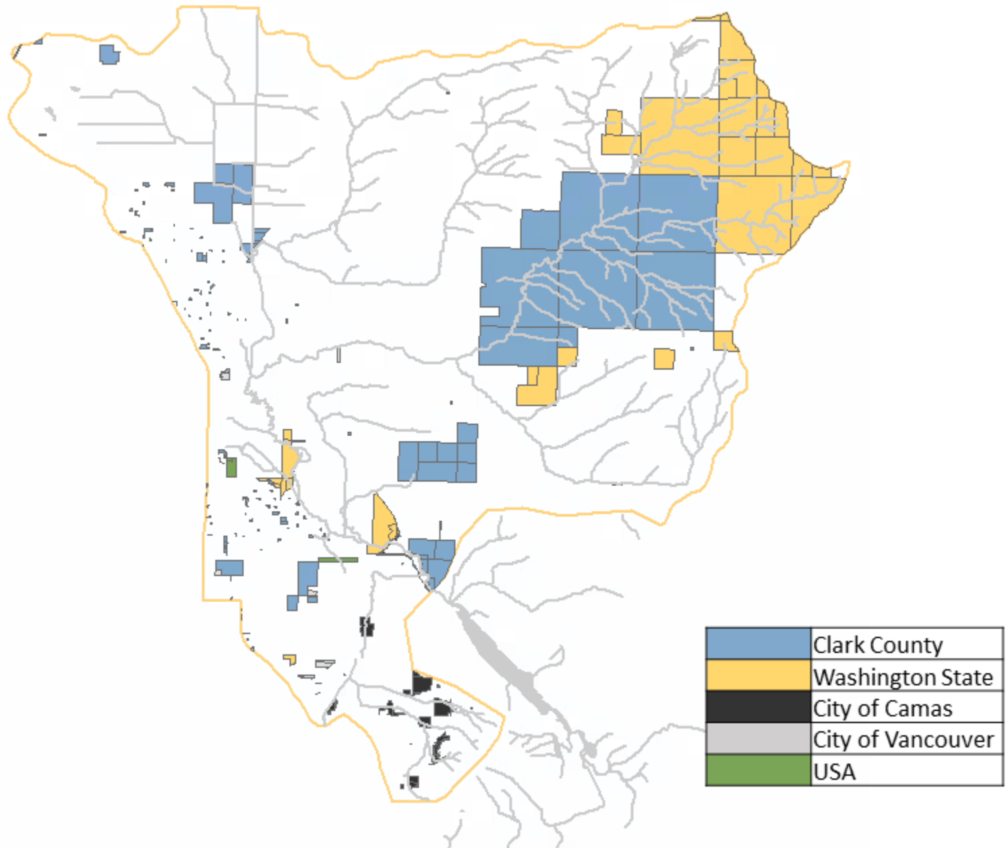


Figure 7. Map of public lands in the study area.

Figure 8: Photograph of the valley floor area of Camp Bonneville.

Study Design

This source assessment study is designed to identify parts of the Lacamas Creek watershed where bacteria, temperature, pH, and DO exceedances occur and to characterize the nutrient concentrations in the watershed and their relationship to land use. This report's Appendix B, the 2011 and 2021 QAPPs, and the 2017 Programmatic QAPP (Swanson 2011; Gleason and McCarthy 2021; McCarthy and Mathieu 2017) contain a detailed description of the field and analytical methods used in this source assessment. The technical analysis was completed using field data collected as outlined below.

Field data collected during the 2010 – 2011 effort included the following (Swanson 2011):

- FC sampling from a network of 30 fixed and nine investigative sites. The investigative sites had between 1 and 10 samples, which were collected opportunistically from small tributaries to identify potential sources of bacteria.
- Nutrient sampling during three synoptic surveys of 17 sites in the summer of 2011.
- Continuous surface water and air temperature data collected at 18 sites from May to October of 2011.
- Short-term deployments of multi-parameter water quality sondes at 14 sites to collect pH and DO information during two synoptic surveys in the summer of 2011.
- Hemispherical photographs were collected at six locations during the summer of 2011 to validate Ecology's shade model.

Supplemental field data were collected in the summer of 2021, including:

- FC and *E. coli* sampling collected at 22 fixed sites and four investigative sites

These field data were supplemented by water quality data collected at an ambient monitoring station established from October 2020 to September 2022 and nutrient data collected by Clark County in 2016 – 2017 and 2020 – 2011.

The technical analysis involved the following:

- A summary of temperature, pH, and DO data compared with WQS to determine which stream segments do not meet water quality criteria.
- A summary of FC data collected in 2010 – 2011.
- An analysis of FC data collected in 2010 – 2011 to identify seasonal patterns in bacteria concentrations.
- A simple loading analysis of FC data collected in 2010 – 2011 to identify seasonal patterns in FC loading.

- A comparison of FC data collected in 2021 with data collected in 2010 – 2011 to determine whether current conditions have changed substantially since the earlier sampling effort.
- A comparison of *E. coli* data collected in 2021 with the new water quality criteria established in December 2020 to identify which stream segments do not meet WQS.
- A comparison of paired *E. coli* and FC data to determine if patterns in *E. coli* concentrations are similar to FC concentrations in the study area.
- A summary of nutrient samples collected in 2011. This data was supplemented with data collected by Clark County and Ecology's ambient station at Lacamas Creek at Goodwin Rd to identify seasonal patterns in nutrient data.
- Simple method calculations to estimate the amount of nutrient loading at the sub-watershed scale based on the region's land use and precipitation data.
- A comparison of nutrient and bacteria data to land use data at the sample scale to identify how patterns in land use may be related to nutrient concentrations in the study area.
- Ecology's shade model predicted system effective and potential shade on Lacamas Creek. This information was used to identify areas with large shade deficits that may be targeted for riparian restoration efforts.

This study also references the key findings from the following report using data collected during the 2010 – 2011 field collection effort:

- *Surface Water/Groundwater Interactions and Near-Stream Groundwater Quality, Lacamas Creek, Clark County* (Sinclair and Swanson 2013).

Data Quality

The QAPPs for this study outline the quality procedures used to collect and analyze field measurements and water quality samples (Swanson 2011; Gleason and McCarthy 2021; McCarthy and Mathieu 2017). Additionally, the *Quality Assurance Monitoring Plan: Statewide River and Stream Ambient Water Quality Monitoring* outlines the quality procedures for data collected by Ecology's Freshwater Monitoring Unit (FMU) at the ambient monitoring station (28I120) on Lacamas Creek at Goodwin Road (Von Prause 2021). Ecology assessed all data for quality before using them in this report.

The overall quality objectives for the bacteria sampling were to collect and analyze data at the appropriate spatial and temporal scale to characterize pollution at a sub-watershed and watershed level. Ecology reviewed all data and confirmed that it met the QAPP's quality objectives (Gleason and McCarthy 2021).

Data collected by Ecology for this study are available in Ecology's Environmental Information Management (EIM) database:

- The study ID for the 2010 – 11 field collection is TSWA0003.
- The study ID for the 2021 field collection is LacamasSA.

Appendix D contains more details about the quality assurance (QA) review of the water quality data from both field collections. QA information for data from the *Groundwater Interactions and Near Stream Groundwater Quality* study cited in this report can be found in the 2013 report (Sinclair and Swanson 2013).

Results

Bacteria Results

Summary Statistics

Bacteria standards state that 1) the geometric mean for *E. coli* must not exceed 100 cfu/100mL and 2) no more than 10 percent of all samples (or any single sample when less than ten sample points exist) should exceed 320 cfu/100mL. The *E. coli* results for each rolling 90-day period and comparison to bacteria criteria are summarized in Table 2, and the geometric means (Geomean) for each quarter at each site are displayed in Figures 9 and 10.

No sites met both bacteria criteria for the full summer season, and all fixed sites exceeded the 90th percentile criterion for July – September.

Only a single site on Fifth Plain Creek near the confluence with Lacamas Creek (28-FIF-0.2) met the geometric mean criteria for all 90-day periods. This site is downstream of the confluence of China Ditch and Shanghai Creek with Fifth Plain Creek, so it might be expected to have high *E. coli* concentrations. However, this site was identified as a location with significant groundwater inputs based on Ecology's groundwater surveys in the summer of 2011. The groundwater survey indicated that there was little to no input of fecal coliform bacteria from groundwater to surface water in the watershed (Sinclair and Swanson 2013). Therefore, the influx of groundwater at this site may dilute bacteria concentrations at creek mile 0.2.

The highest mean bacteria concentrations in the watershed during the summer of 2021 occurred in Dwyer Creek and the northwest tributaries (Shanghai and the upper reaches of Fifth Plain Creek). Dwyer Creek, at mile 0.1, had the highest overall 90-day geometric mean in the study area, at 578 cfu/100mL during the July – September period. Appendix B has more detailed descriptions of sub-watershed patterns of bacteria concentrations.

Table 2. *E. coli* statistics compared to geometric mean and 90th percentile exceedance criteria.

Site[a]	June–Aug # of Samples	June–Aug Geomean[b]	June–Aug % Noncompliance[c]	July–Sept # of Samples	July–Sept Geomean	July–Sept % Noncompliance[c]	Aug–Oct # of Samples	Aug–Oct Geomean	Aug–Oct % Noncompliance[c]
28-LAC-5.6	6	**111**	0%	6	**177**	**17%**	6	**204**	**17%**
28-LAC-7.5	6	**187**	0%	6	**235**	**17%**	6	**201**	**17%**
28-LAC-9.1	5	**259**	**20%**	6	**329**	**33%**	6	**298**	**33%**
28-LAC-11.1	6	**197**	**33%**	6	**223**	**50%**	6	**227**	**50%**
28-DWY-0.1	5	**463**	**80%**	5	**578**	**100%**	5	**267**	**60%**
28-SPR-0.3	6	**124**	0%	6	**153**	**17%**	6	**155**	**17%**
28-MAT-0.1	6	**120**	**17%**	6	**158**	**17%**	6	**161**	**17%**
28-MAT-1.4	6	**221**	**17%**	6	**203**	**33%**	6	**173**	**33%**
28-FIF-0.2	6	61	0%	6	88	**17%**	6	97	**17%**
28-FIF-1.9	6	**159**	**17%**	6	**185**	**17%**	6	**182**	**17%**
28-FIF-4.3	6	**240**	**17%**	6	**261**	**17%**	6	**225**	**17%**
28-SHA-1.3	6	**289**	**17%**	6	**384**	**33%**	6	**305**	**33%**
28-SHA-2.7	6	**317**	**50%**	6	**374**	**50%**	6	**247**	**33%**
28-SHA-3.4	4	**303**	**25%**	3	**300**	**33%**	4	**156**	**25%**
28-CHI-0.0	6	**211**	**17%**	6	**233**	**33%**	6	**139**	**33%**
28-CHI-1.2	6	**229**	**33%**	6	**190**	**17%**	6	94	0%
28-CHI-1.9	6	**186**	**17%**	5	**242**	**20%**	5	**112**	0%
28-CHB-0.0	3	54	0%	2	—	**50%**	3	73	**33%**
28-CHB-0.8	3	**369**	**67%**	2	—	**100%**	2	—	**50%**

Note: Bolded values highlighted in yellow represent noncompliance with criteria. Only sites with a calculated geometric mean and at least three samples for a 90-day period are included.
[a]A map of all sites is in Appendix A.
[b]Geomean = Geometric mean.
[c]Noncompliance % is the percent of samples exceeding 320 cfu/100 mL.

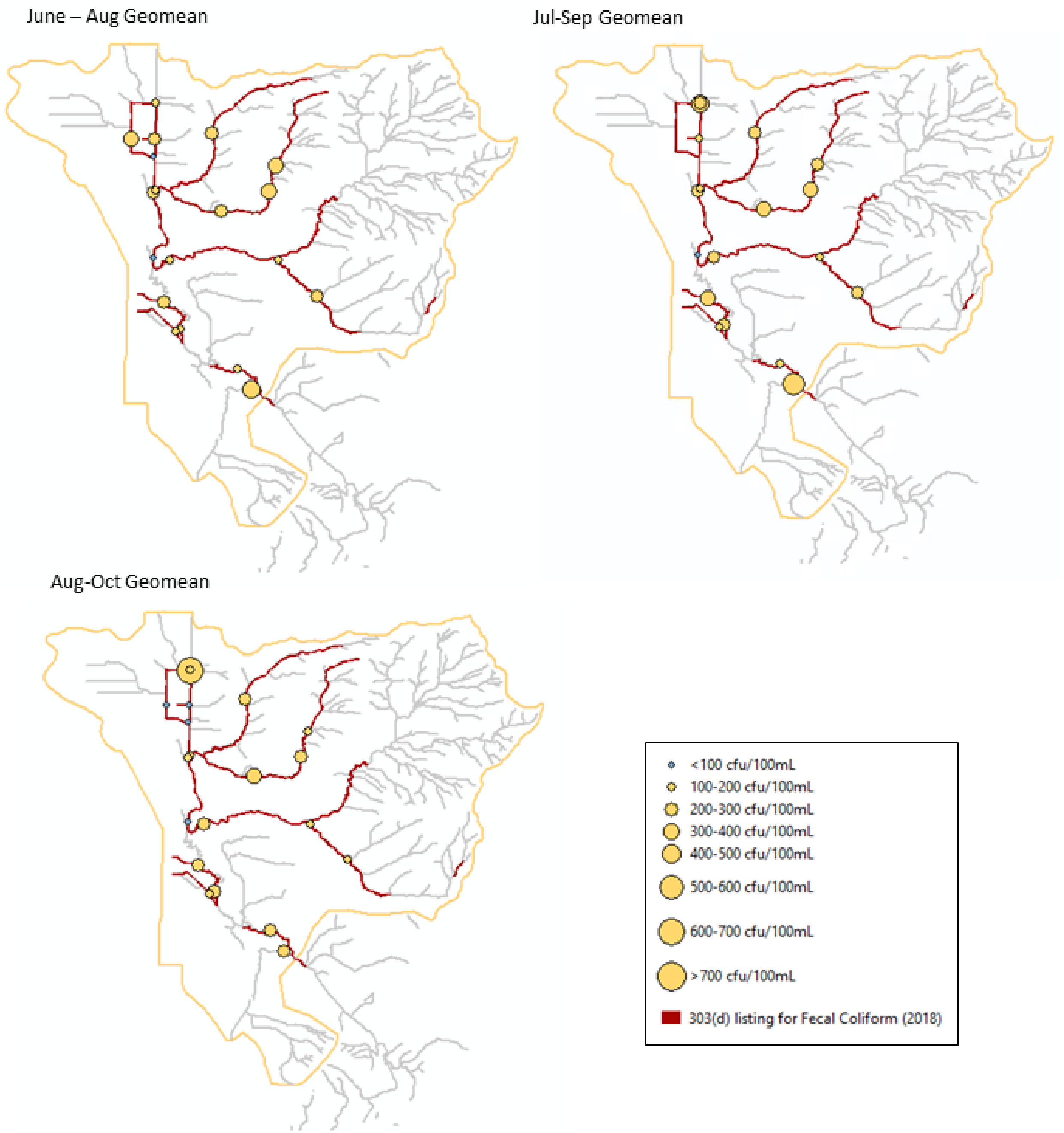


Figure 9. Geometric means of *E. coli* concentrations from samples collected in 2021.
Segments on the 303(d) list for bacteria are also included. Yellow points indicate exceedance of the geometric mean Water Quality criteria.

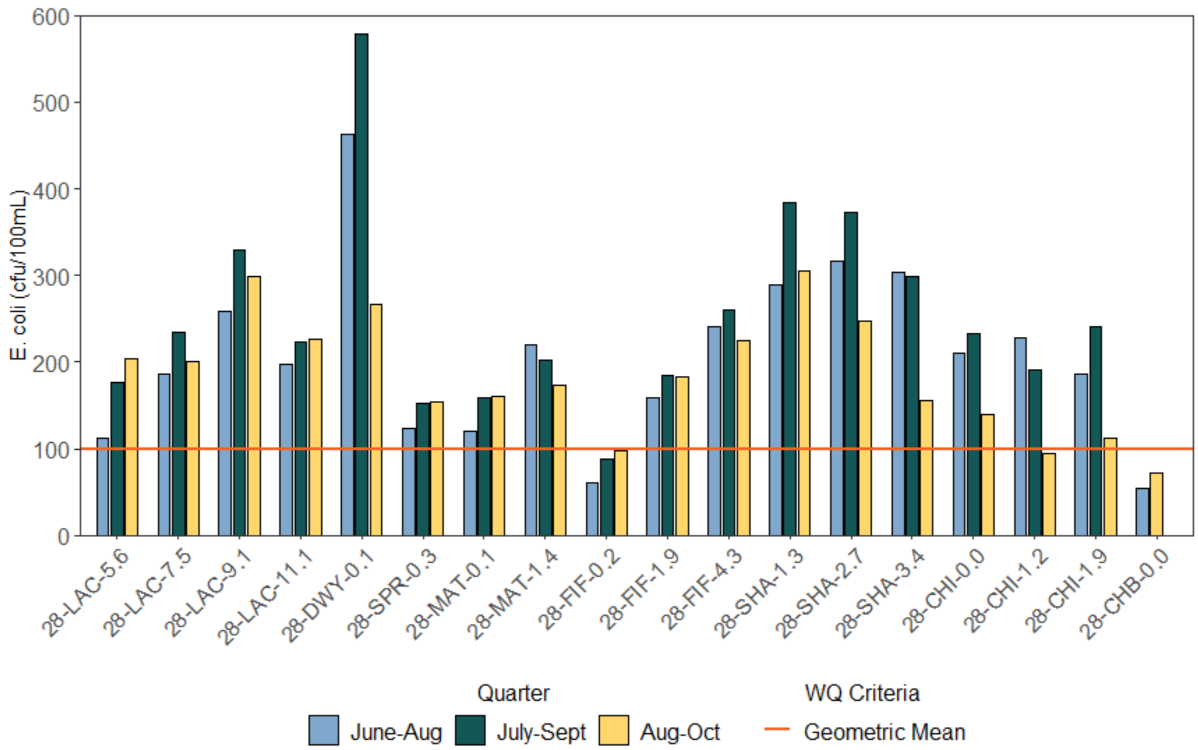


Figure 10. *E. coli* geometric mean for each three-month quarter from June to October 2021.

Seasonal Patterns in Bacteria Data

The 2010 – 2011 field collection effort included FC sampling in wet (November – May) and dry (June – October) seasons. Figures 11, 12, and 13 compare the wet and dry season geometric means at the 2010 – 2011 field sites. The geometric means of dry season samples are higher than wet season geometric means at all sites. The difference is especially prominent in samples from the more agriculturally dominated sites in the China Ditch, Shanghai Creek, and Fifth Plain Creek watersheds. In nearly all sites, the dry season geometric mean is at least 50 cfu/100 mL higher than the wet season geometric mean. The only exceptions to this are the single site on Lacamas Creek below Lacamas Lake (28-LAC-0.2), where the wet season geometric mean (18 cfu/100 mL) is nearly the same as the dry season geometric mean (19 cfu/100 mL), and the upstream Shanghai Creek site (28-SHA-5.0), where the dry season geometric mean is 39 cfu/100 mL, only 29 cfu/100 mL higher than the wet season geometric mean (10 cfu/100 mL).

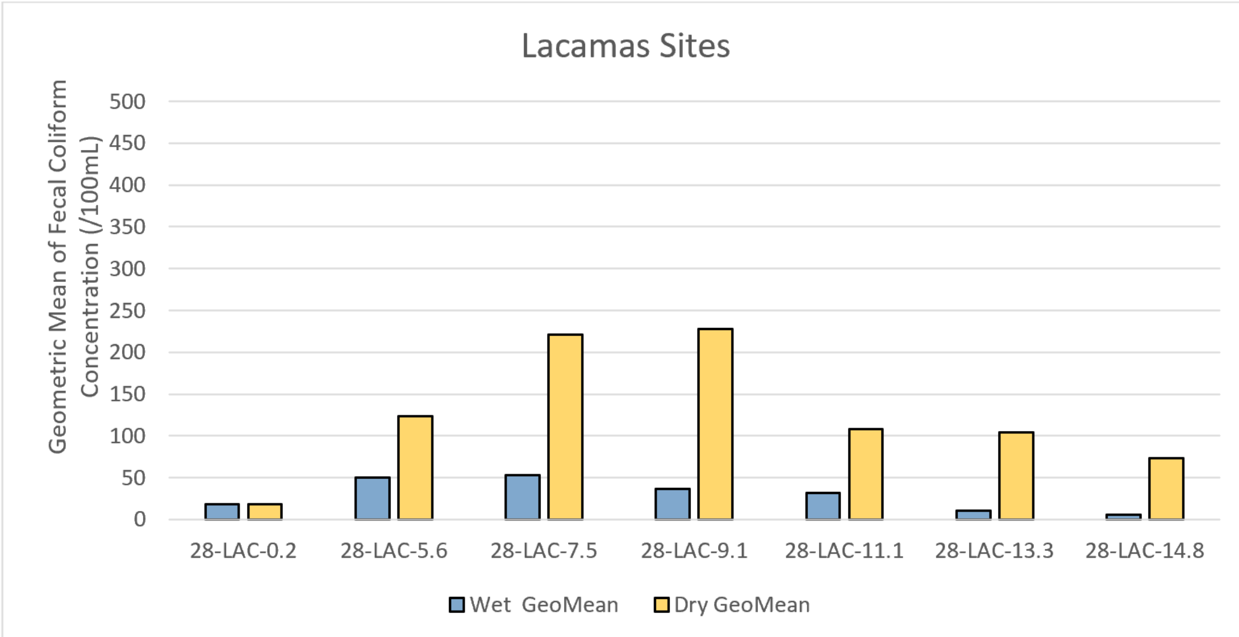


Figure 11. Geometric means of fecal colliform concentrations on Lacamas Creek sites.
Wet season (November – May) means are on the left in blue, and dry season (June – October) means are on the right in yellow.

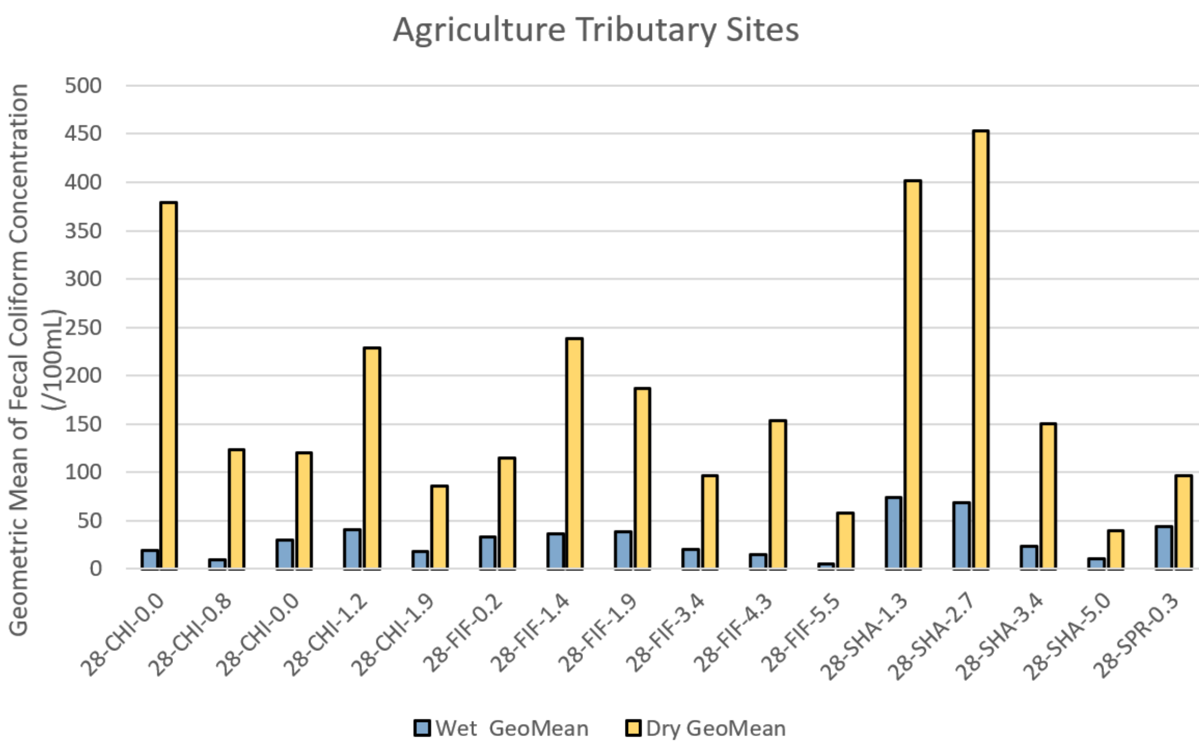


Figure 12. Geometric means of fecal colliform concentrations on sites from agriculture-dominated tributaries (China Ditch, Fifth Plain Creek, Shanghai Creek).
Wet season (November – May) means are on the left in blue, and dry season (June – October) means are on the right in yellow.

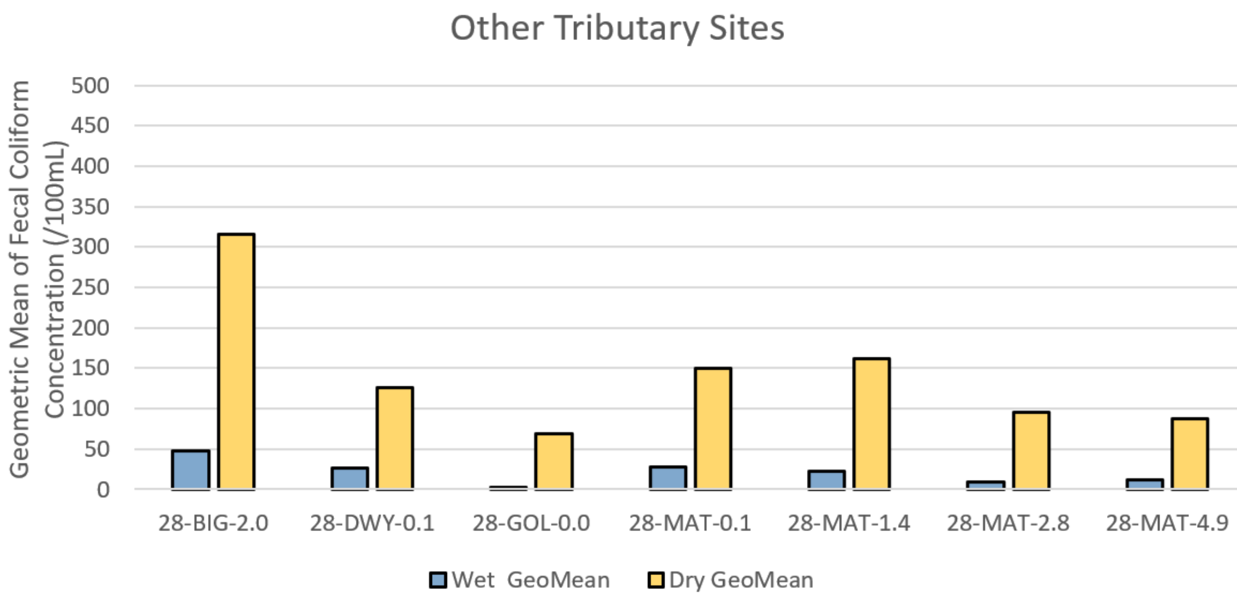


Figure 13. Geometric means of fecal coliform concentrations from sites on minor Lacamas Creek tributaries and Matney Creek.

Wet season (November – May) means are shown on the left in blue, and dry season (June – October) are on the right in yellow.

These data indicate that noncompliance events with water quality criteria are more likely in the dry season than in the wet season. Higher FC concentrations during the summer months may be attributed to increased FC inputs during dry months. However, lower flows in the summer months can also lead to higher concentrations during those periods, with higher winter flows diluting FC. To address this, a simple loading analysis was performed using all FC samples collected in 2010 – 2011 that had associated flow measurements.

Bacterial loads estimate the total amount of bacteria passing through a given point on a waterway over a defined period of time. While bacterial loads are not used to identify WQ noncompliances, they are useful to determine the total amount and distribution of bacteria passing through the system during different flow conditions. Figures 14, 15, and 16 show the average FC loadings calculated for the wet and dry seasons, and Figure 17 shows a map of these loadings in the dry and wet seasons. FC loads in 2010 – 2011 were generally higher on the larger tributaries and the main stem of Lacamas Creek and increased moving downstream in the study area.

The strong seasonality observed in FC concentrations is less apparent in the loading analysis. Of 22 sites with loading estimates for both dry and wet seasons, 15 sites have higher average loadings in the wet season. Also, four out of the five FC loads greater than 100 billion cfu/day occurred during the wet season, with the highest FC load (232 billion cfu/day) calculated for a site on Fifth Plain Creek (28-FIF-1.9) on 4/26/2011. This suggests that the significantly higher FC concentrations observed in the dry season data may be driven more by lower flows during the summer rather than more bacteria being delivered to the creeks during the dry season.

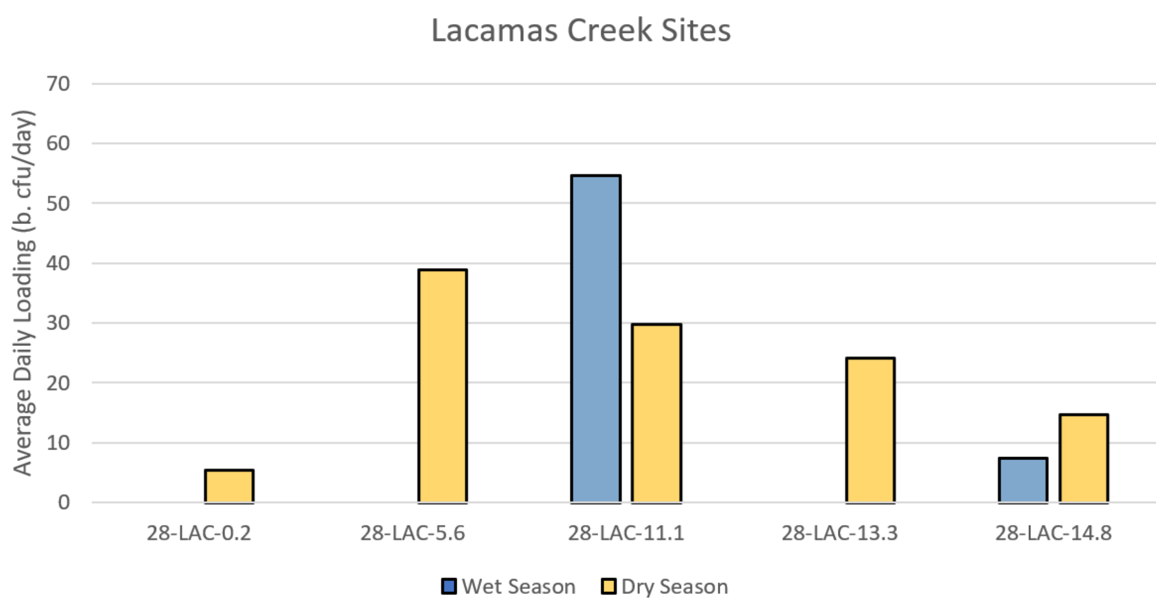


Figure 14. Average daily fecal coliform loadings on Lacamas Creek sites.
Wet season (November – May) means are on the left in blue, and dry season (June – October) means are on the right in yellow.

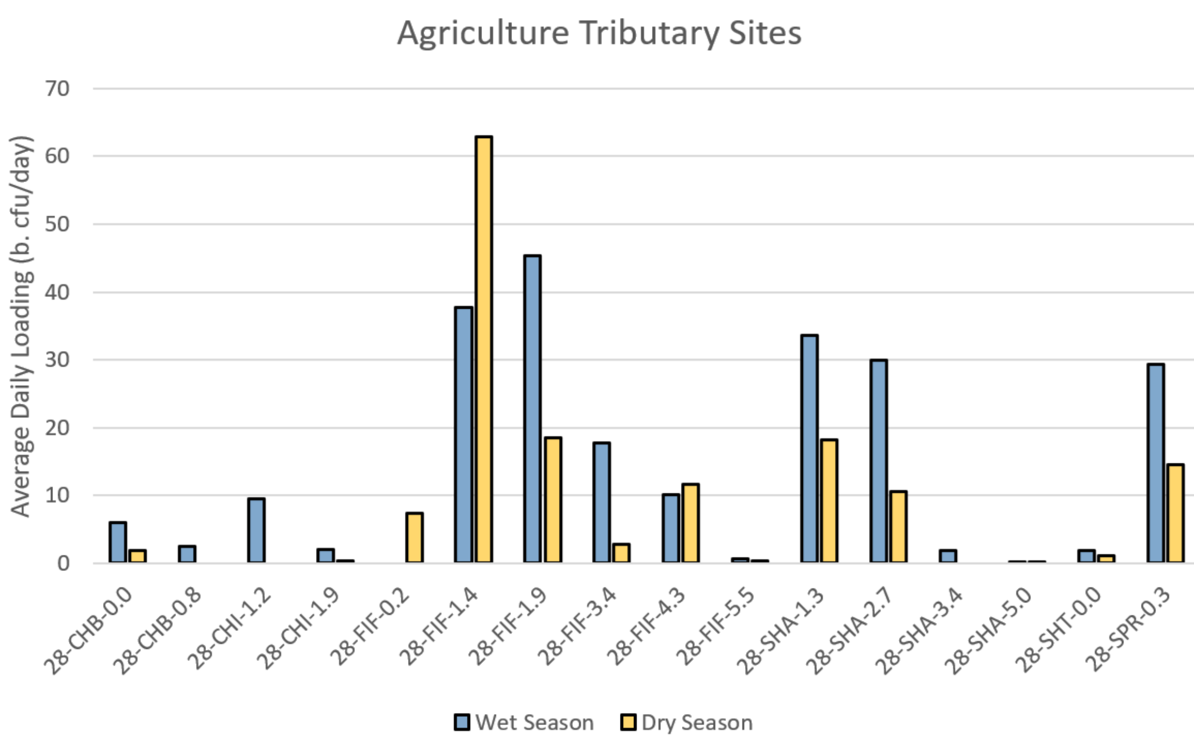


Figure 15. Average daily fecal coliform loadings on sites from agriculture-dominated tributaries (China Ditch, Fifth Plain Creek, Shanghai Creek).
Wet season (November – May) means are on the left in blue, and dry season (June – October) means are on the right in yellow.

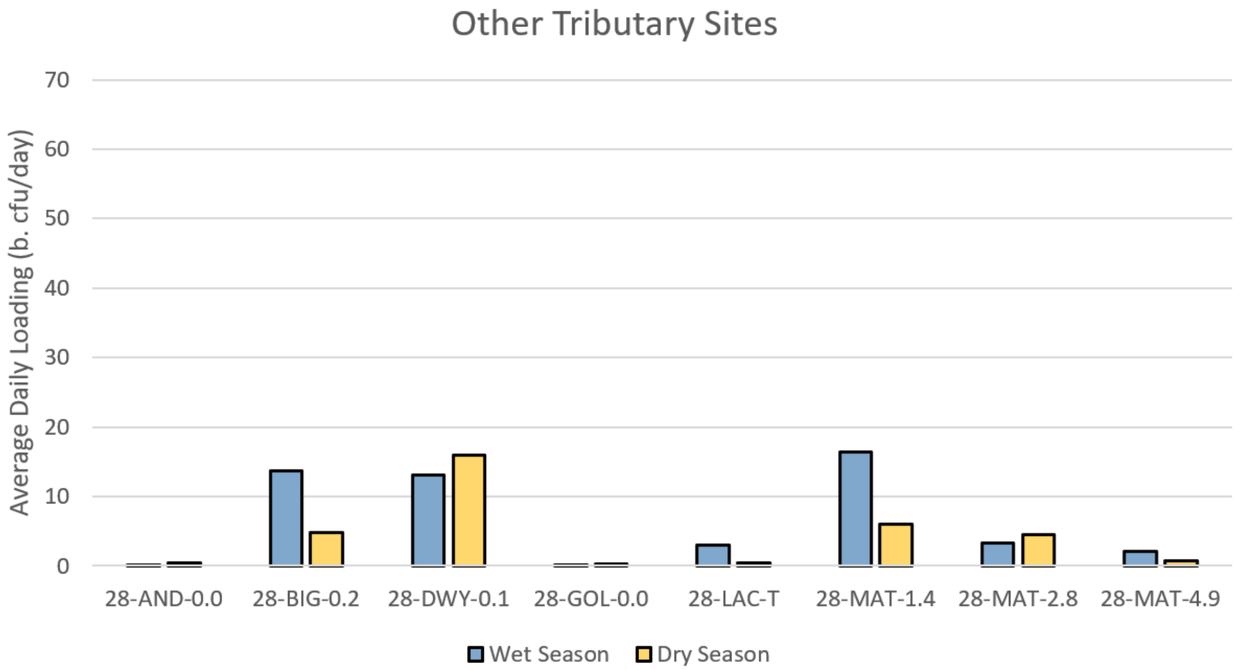


Figure 16. Average daily fecal coliform loadings from sites on minor Lacamas Creek tributaries and Matney Creek.

Wet season (November – May) means are on the left in blue, and dry season (June – October) means are on the right in yellow.

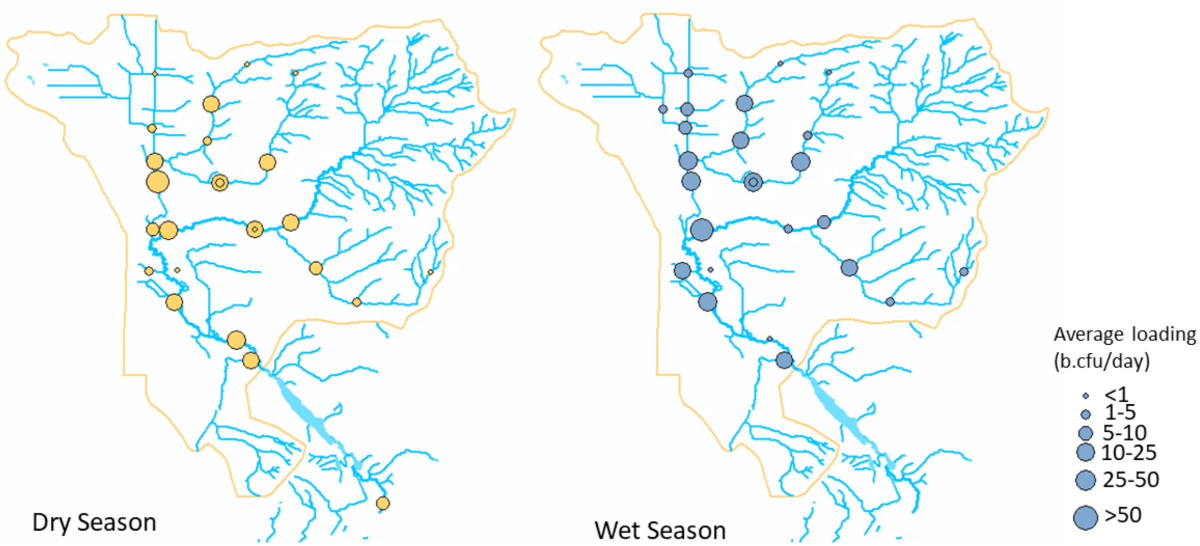


Figure 17. Map of calculated dry season and wet season average daily fecal coliform loadings.

Dataset Comparison

2010 – 2011 to 2021 Data Comparison

The previous FC-based WQS expired in 2020, so FC samples collected during the 2010 – 2011 season were not compared to WQS. However, this data is still useful for investigating potential seasonal patterns in bacteria concentrations and loadings (see the previous section). In addition, we compared 2011 dry season FC data to FC data collected in 2021 to identify any potential changes in bacteria concentrations in the intervening decade.

Similar to the 2021 *E. coli* data, the 2011 FC mean concentrations during the dry season were highest at tributaries in the upper watershed, including China Ditch, Shanghai Creek, and Fifth Plain Creek. In addition, Big Ditch, a constructed drainage channel that feeds to Lacamas Creek, had high FC levels relative to the rest of the watershed during this time period. Fifth Plain Creek, above its confluence with China Ditch, Matney Creek, and upper Lacamas Creek, had generally lower FC concentrations (Figure 18).

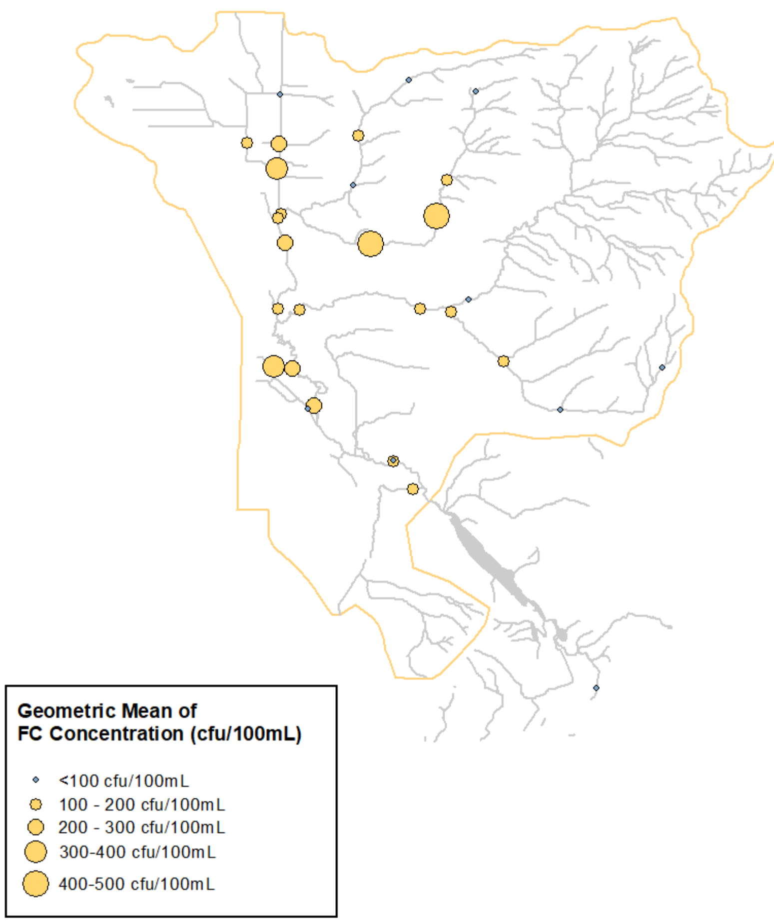


Figure 18. Dry season geometric mean concentrations of fecal coliform (FC) samples collected in 2011.

Note that all wet season geometric means were below 100 cfu/100 mL and would, therefore, be in the lowest category on this map.

The 2010 – 2011 dataset also captured one high-bacteria "event": four of the six samples with FC concentrations greater than 10,000 cfu/100mL were collected on the same day, 6/21/2011. These four samples were collected from China Ditch and its tributaries, and high bacteria concentrations persisted downstream of China Ditch. Figure 19 shows the FC concentrations from all samples collected on 6/21/2011 and 6/22/2011. The highest FC concentrations occur at two locations on a tributary to China Ditch—28-CHB-0.8 (67,000 cfu/100mL) and 28-CHB-0.0 (69,000 cfu/100mL)—and continue below the confluence of the tributary and China Ditch. Elevated FC concentrations continue past the China Ditch confluence with Fifth Plain Creek and into Lacamas Creek to the last sample site above Lacamas Lake (28-LAC-5.6).

The site at Fifth Plain Creek, just above the confluence with Lacamas Creek (28-FIF-0.2), was sampled on 6/21/2011 and 6/22/2011. FC concentrations decreased markedly from 9,400 cfu/100mL on 6/21/2011 to 1,300 cfu/100mL on 6/22/2011.

This pulse of high FC concentrations in June 2011 indicates the potential for single-source events in the upper watershed that can be measured at all points downstream of the pollution source.

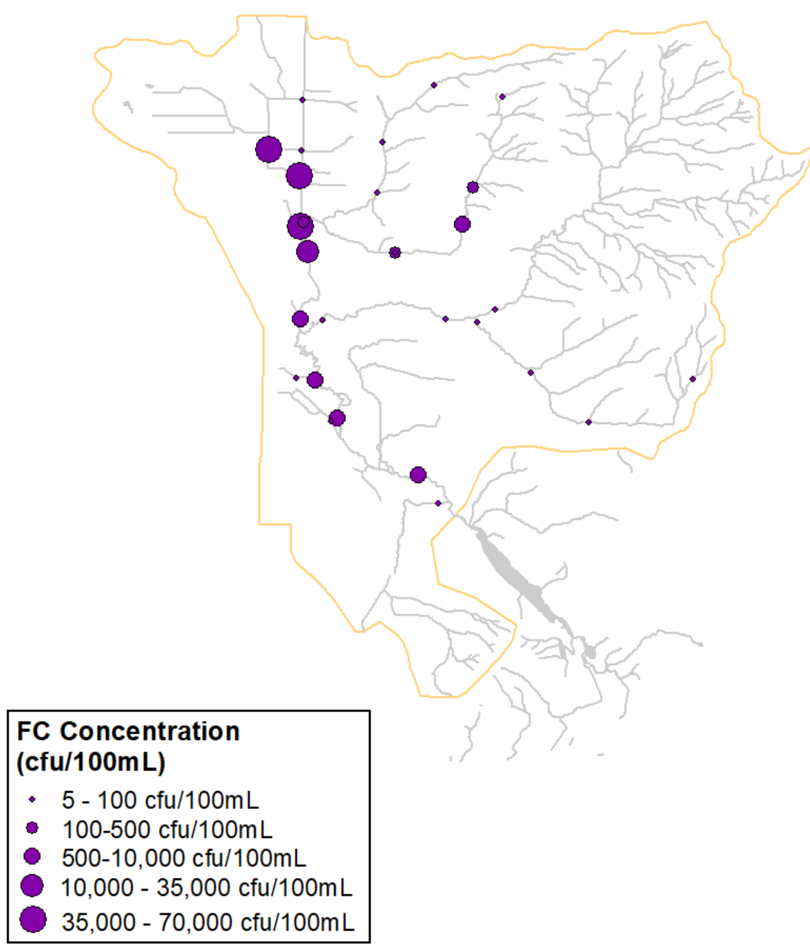


Figure 19. Fecal coliform (FC) concentrations of samples collected on 6/21/2011 and 6/22/2011.

Figure 20 shows the geometric means of all dry season samples at sites sampled for FC in 2011 and 2021. There were geometric mean increases at all Lacamas Creek sites. For the 2011 and 2021 datasets, 28-LAC-9.1 had the highest geometric mean and highest detected FC concentrations for Lacamas Creek. However, two sample t-tests comparing the populations of FC results from the 2011 and 2021 dry seasons indicated that there was no statistically significant change in FC concentrations between the two sampling years (p=0.05), except for the Dwyer Creek sample (28-DWY-0.1).

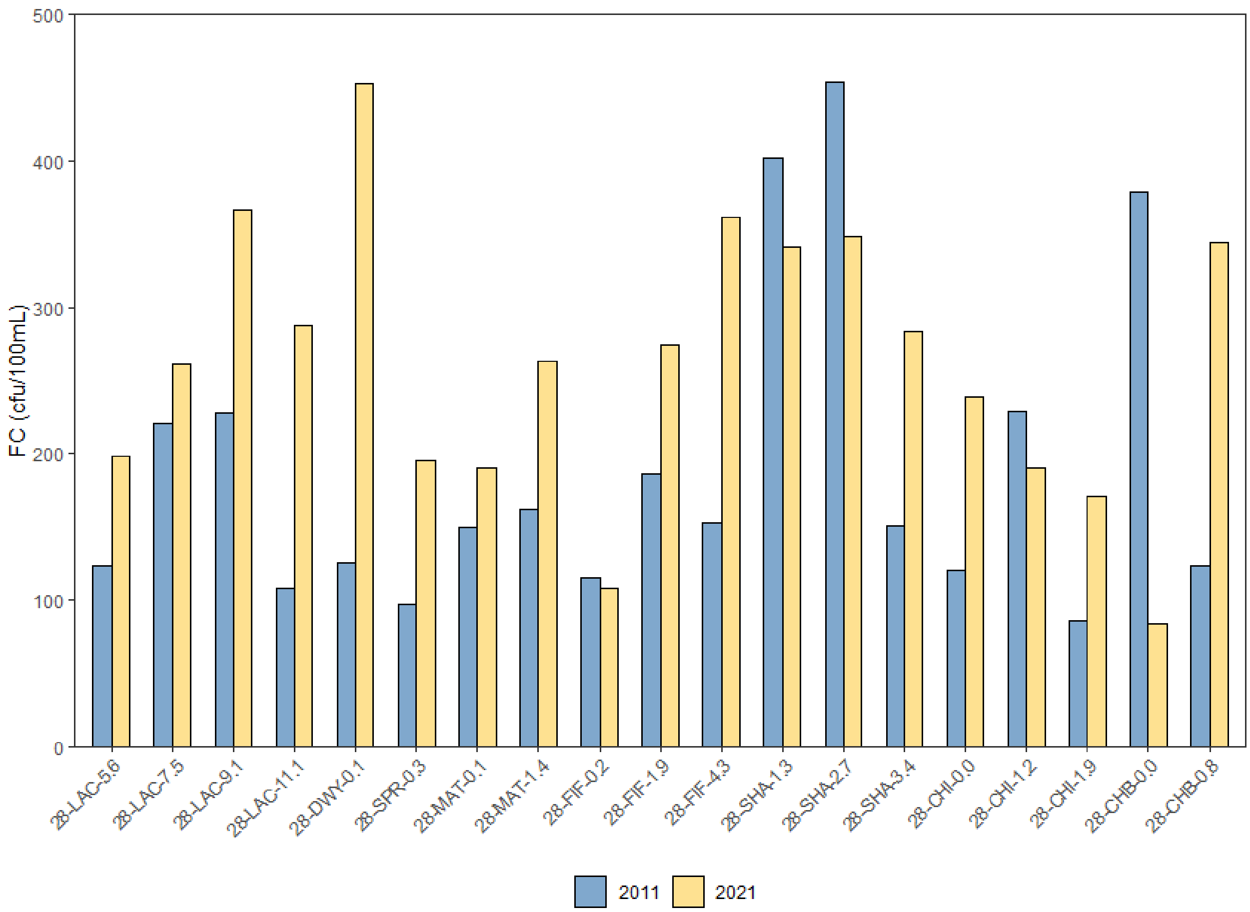


Figure 20. Geometric mean of fecal coliform (FC) concentrations of samples collected during the dry season in 2011 (blue/left) and 2021 (yellow/right).

Dwyer Creek had the greatest FC geometric mean increase from 126 cfu/100mL in 2011 to 452 cfu/100mL in 2021. The summer of 2021 was a particularly dry season with record high temperatures, and Dwyer Creek was noticeably low yet still flowing throughout the summer. Ecology collected 5 samples in 2021 since low conditions prevented sampling during a single sample event. The high temperatures and low flow may have generated increased bacteria levels.

Fecal Coliform/E. coli Comparison

We compared FC and *E. coli* concentrations collected from the same sample to determine the nature of the relationship between FC and *E. coli* in the study area. Figure 21 compares paired FC and *E. coli* samples collected during the summer of 2021. All creeks sampled have a linear relationship between FC and *E. coli* values, with R^2 values between 0.77 and 0.96.

The regression equations vary between the sampled creeks and should not be used to extrapolate FC values from *E. coli* concentrations and vice-versa. However, they do show that the FC and *E. coli* concentrations are related in the study area. In addition, the seasonal patterns in FC concentrations and loadings observed in the 2010 – 2011 data may be reflected in *E. coli* concentrations.

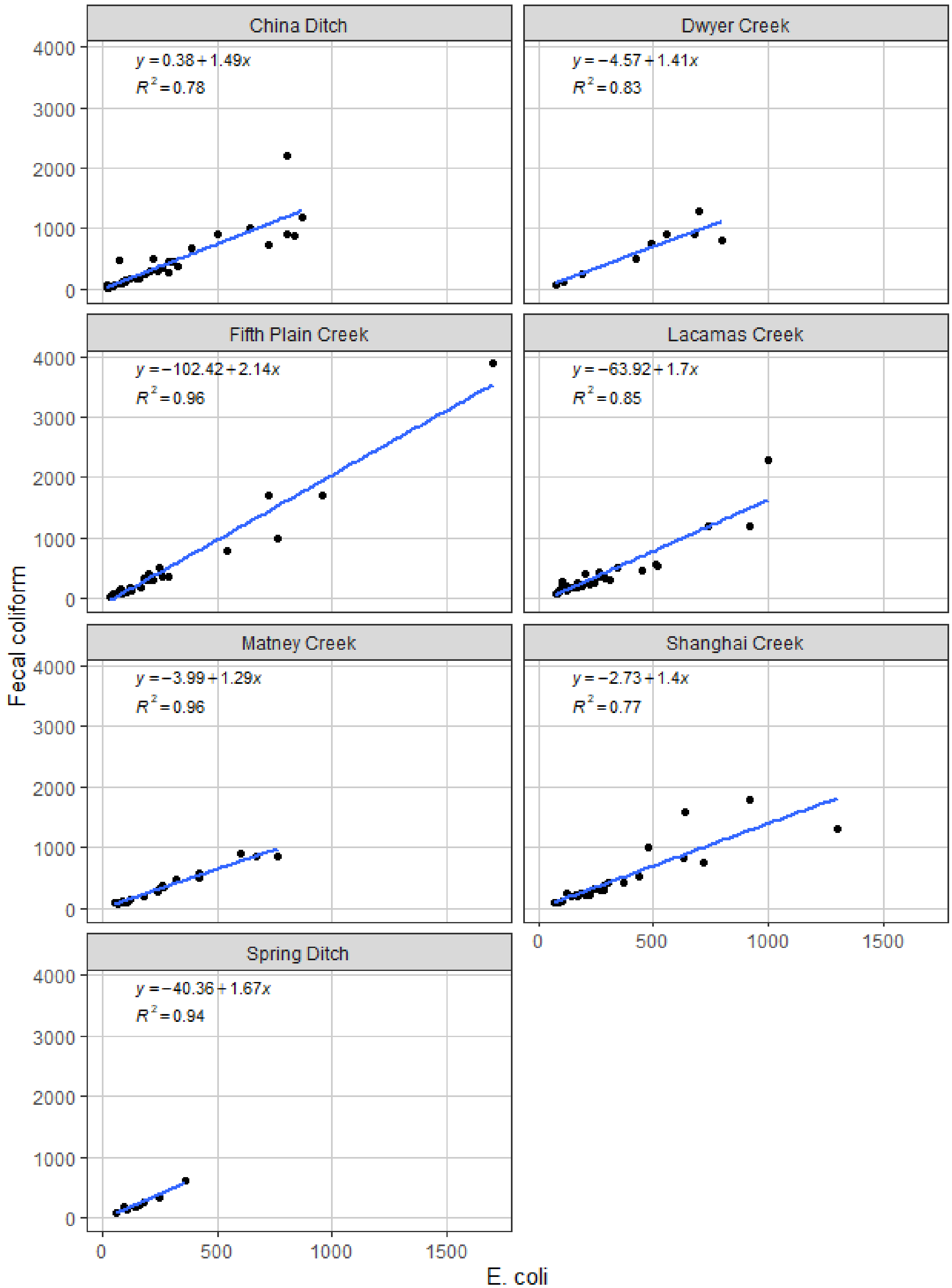


Figure 21. Comparison of paired *E. coli* and fecal colifrom concentrations from samples collected during the summer of 2021.

Nutrients

Summary Statistics

Ecology collected nutrient samples at 17 sites during three synoptic surveys on July 26th, August 30th, and October 5th of 2011. Samples were not collected at Dwyer Creek on August 30th due to insufficient flow. Table 3 displays the average nutrient results for each site, and Figures 22 and 23 display the average and distribution of results for each site.

Table 3. Average nutrient results from 2010 – 2011 data collection.

Site	Total Persulfate Nitrogen	Nitrate + Nitrite as N	Ammonia/ Ammonium	Total Phosphorus	Ortho-Phosphate	Total Organic Carbon	Dissolved Organic Carbon
28-LAC-0.2	0.651	0.481	0.017	0.048	0.020	2.120	1.780
28-LAC-5.6	1.906	1.782	0.015	0.087	0.039	1.560	1.520
28-LAC-7.5	1.346	1.222	0.023	0.060	0.021	1.680	1.520
28-LAC-9.1	1.336	1.262	0.017	0.059	0.023	1.660	1.500
28-LAC-11.1	0.270	0.198	0.011	0.032	0.010	1.800	1.620
28-LAC-13.3	0.264	0.203	0.011	0.031	0.009	1.660	1.560
28-LAC-14.8	0.225	0.177	0.010 (ND)[a]	0.033	0.009	1.560	1.460
28-DWY-0.1	0.392	0.095	0.016	0.079	0.026	4.500	4.167
28-SPR-0.3	3.308	2.958	0.241	0.174	0.089	1.480	1.300
28-AND-0.0	0.704	0.359	0.254	0.171	0.016	2.780	1.760
28-MAT-0.1	0.433	0.338	0.010 (ND)	0.053	0.011	2.140	2.040
28-FIF-0.2	2.634	2.578	0.010	0.086	0.043	1.420	1.280
28-FIF-1.9	0.319	0.192	0.026	0.059	0.014	2.760	2.480
28-FIF-3.4	0.315	0.165	0.033	0.054	0.012	2.740	2.480
28-SHA-1.3	0.340	0.228	0.025	0.075	0.013	2.540	2.260
28-CHI-0.0	0.555	0.260	0.019	0.235	0.059	3.840	3.500
28-CHB-0.0	1.142	0.675	0.016	0.287	0.109	6.100	5.700

Note. All values are in mg/L.
N = Nitrogen
[a]Nondetects (ND) are included in the averages at their detection limit. An ND indicates no samples from that location had detectable levels of Ammonia/Ammonium.

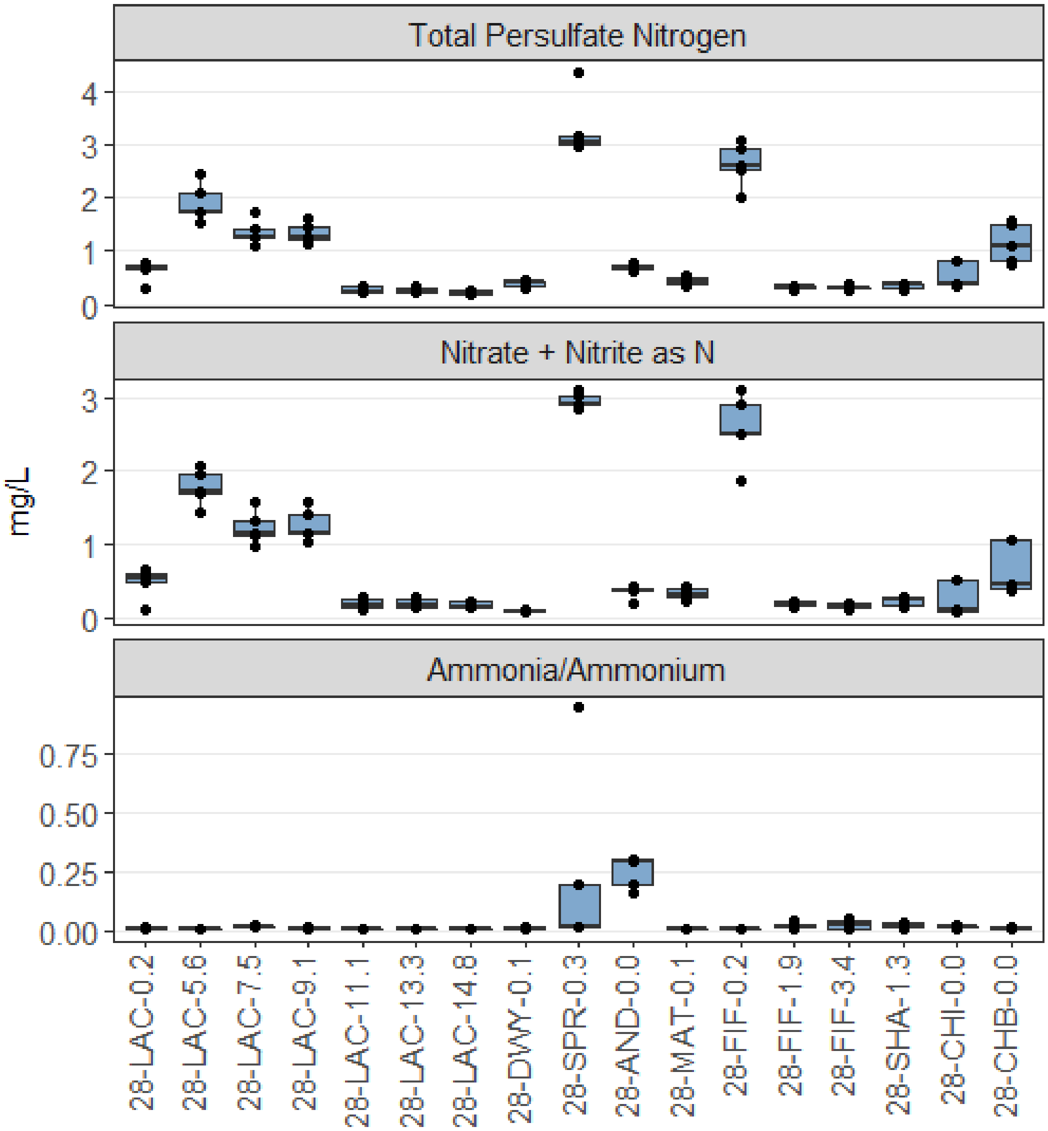


Figure 22. Nitrogen levels as total persulfate nitrogen, nitrate + nitrite as nitrogen, and ammonia/ammonium (mg/L) from 2010 to 2011 data collection.

Black bars represent average result.

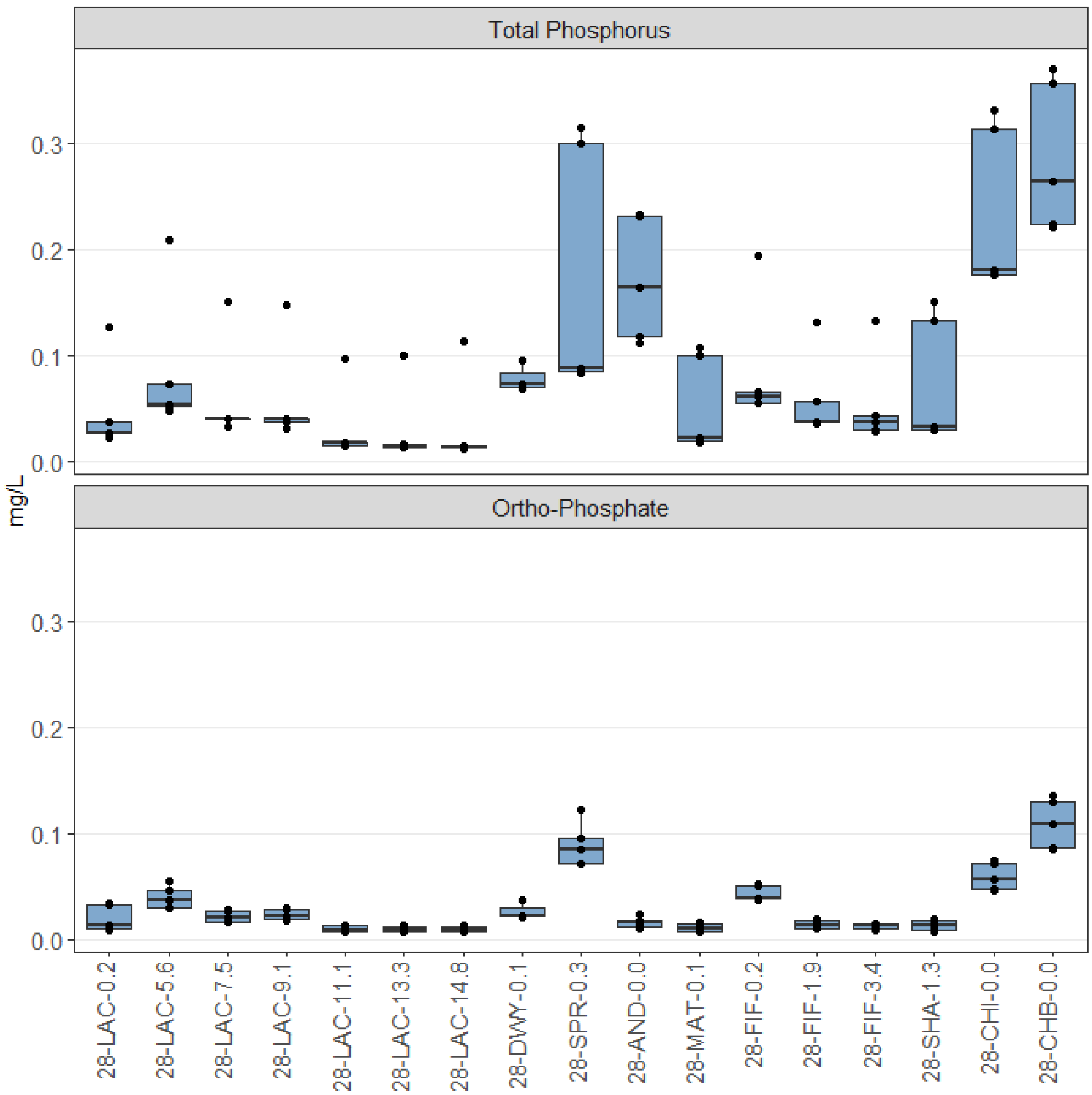


Figure 23. Phosphorus levels as total phosphorus and ortho-phosphate (mg/L) from 2010 to 2011 data collection.
Black bars represent average result.

Figures 24 through 26 show the spatial distribution of nitrogen and phosphorus concentrations in the watershed (additional nutrient fractions are included in Appendix E). Nutrient concentrations are noticeably higher in the watershed's western (downstream) portions. The upper portions of Lacamas Creek (28-LAC-11.1 and sites upstream), as well as Matney Creek, Shanghai Creek, and Fifth Plain Creek upstream of its confluence with China Ditch, have lower nutrient concentrations relative to the western portions of the watershed.

In contrast, China Ditch, Fifth Plain Creek downstream of its confluence with China Ditch, and the small lower tributaries to Lacamas Creek, like Spring Branch Creek and Dwyer Creek, have generally higher nutrient concentrations.

The highest total nitrogen, nitrate/nitrite, total phosphorus, and ortho-phosphate concentrations in Lacamas Creek occurred from rive mile 9.1 (28-LAC-9.1) to the confluence with Lacamas Lake. These locations are all downstream of the confluence with Fifth Plain Creek, which enters Lacamas Creek between locations 28-LAC-11.1 and 28-LAC-9.1. In turn, Fifth Plain Creek has much higher concentrations of these nutrients downstream of its confluence with China Ditch, which occurs between locations 28-FIF-1.9 and 28-FIF-0.2.

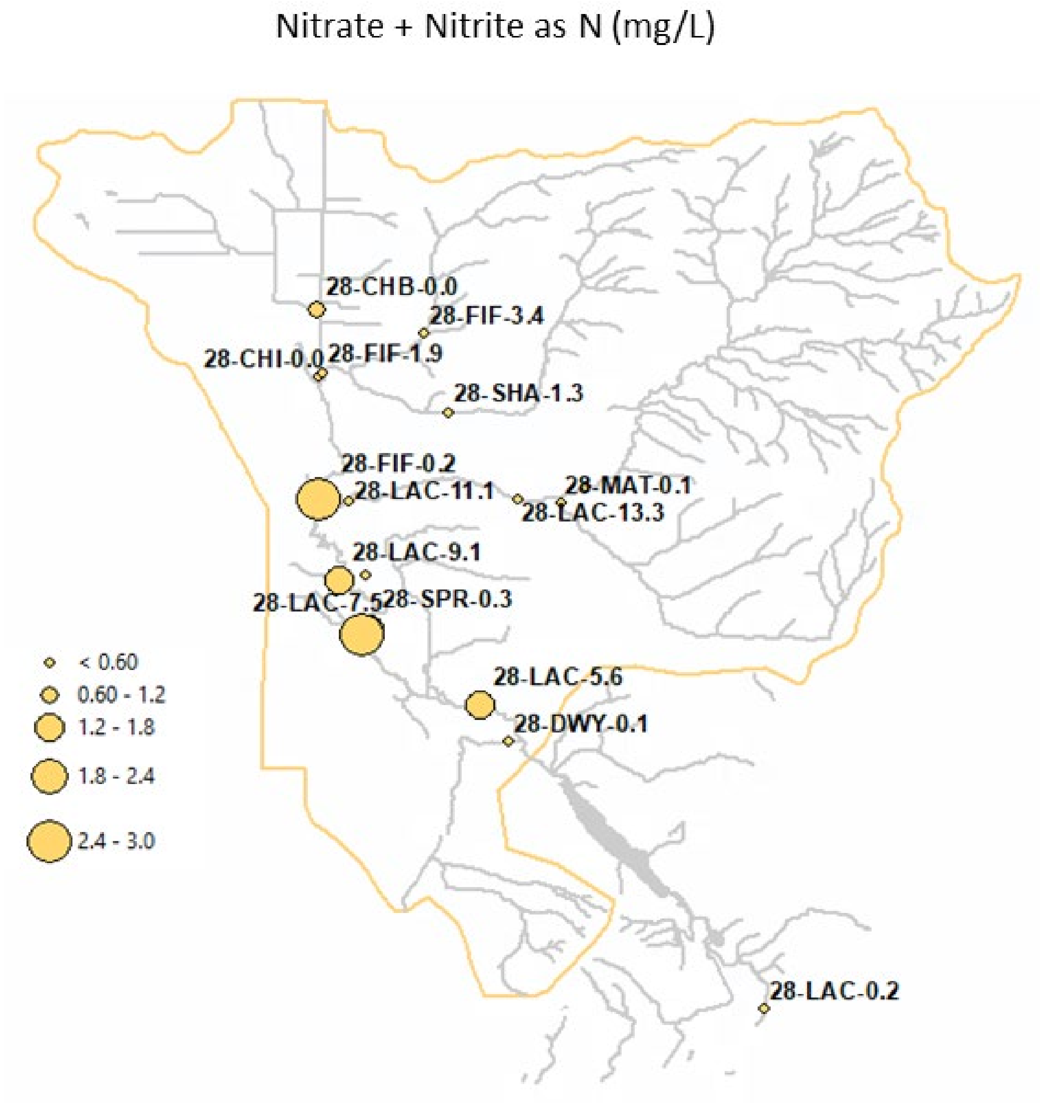


Figure 24. Average nitrate + nitrite as N concentrations in the study area from 2011 synoptic surveys.

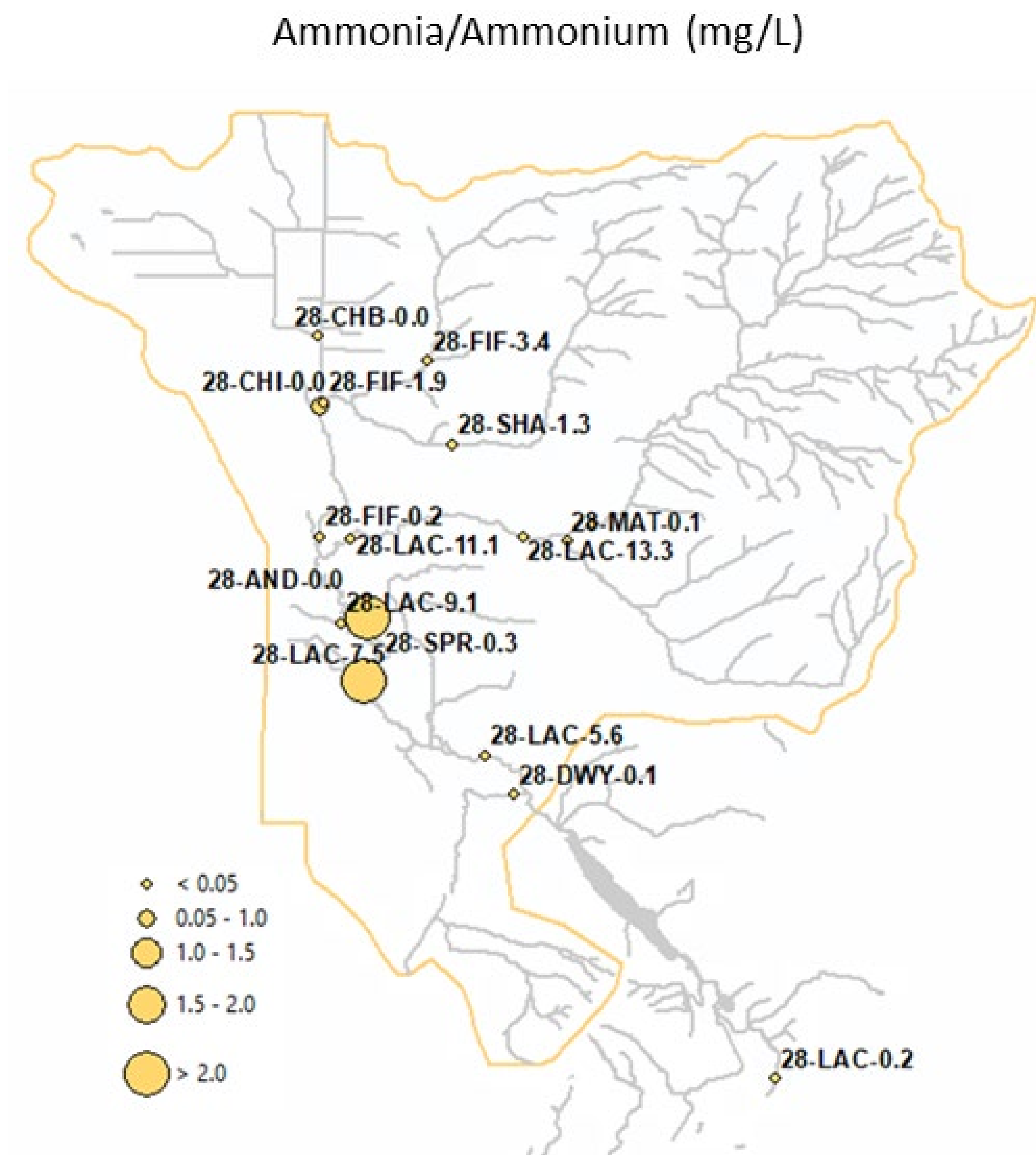


Figure 25. Average ammonia/ammonium concentrations in the study area from 2011 synoptic surveys.

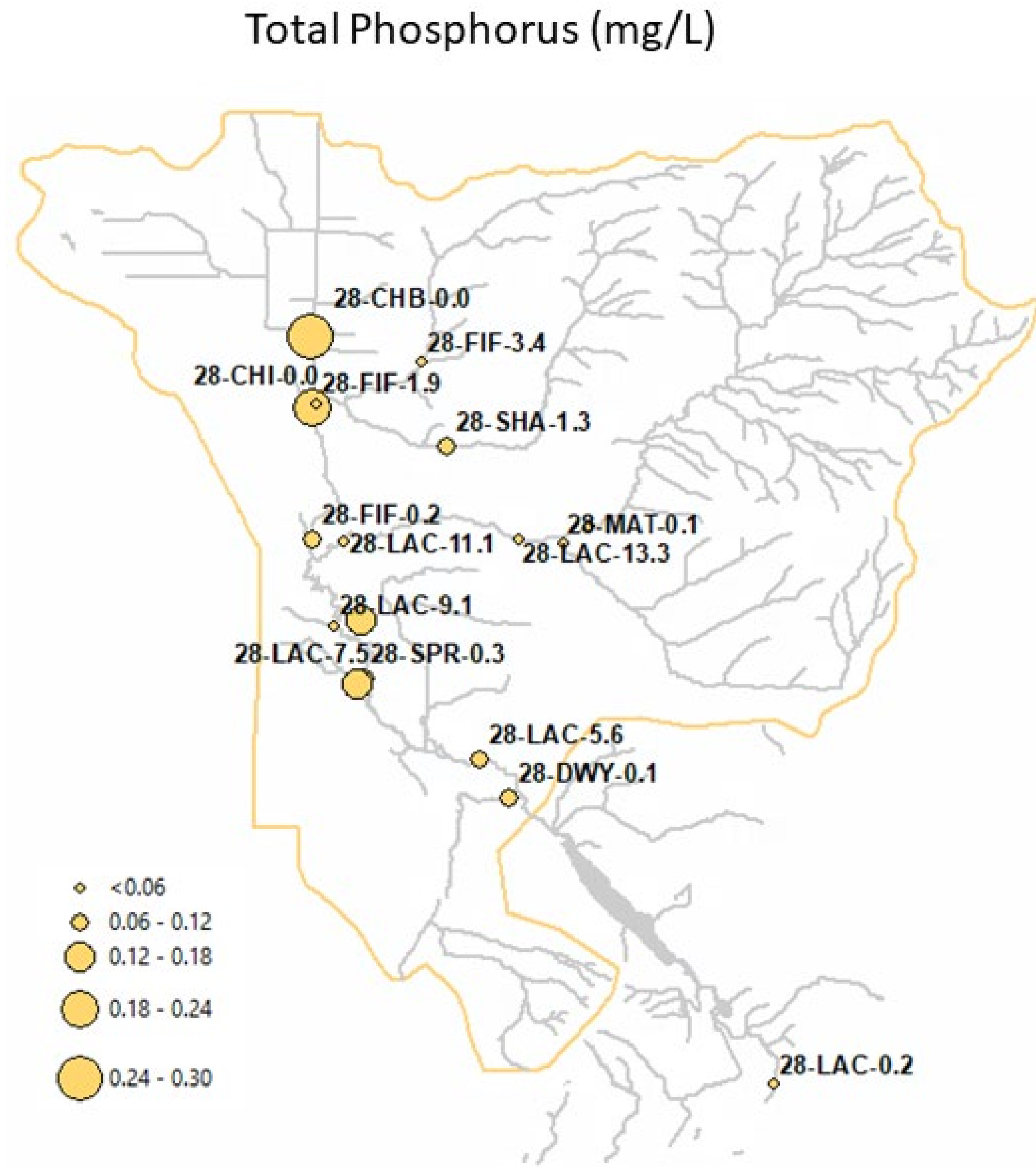


Figure 26. Average total phosphorus concentrations in the study area, from 2011 synoptic surveys.

This suggests that the major inputs of nitrogen and phosphorus in the larger streams in the watershed occur in the China Ditch, Lower Fifth Plain Creek, and Lower Lacamas Creek sub-watersheds. This portion of the watershed is more developed and has more pasture and agricultural activity than the generally more forested portions of the upper watershed. The China Ditch sub-watershed, in particular, might be a source of phosphorus — average total phosphorus concentrations at a China Ditch and a small tributary (0.235 mg/L and 0.287 mg/L) are about 0.06 mg/L higher than the next highest average total phosphorus at Spring Branch Creek (0.174 mg/L).

The groundwater report suggests that some phosphorus may be entering China Ditch from groundwater — groundwater total phosphorus at China Ditch was relatively high (0.110 mg/L) (Sinclair and Swanson 2013). However, flows in China Ditch are often low during the summer months compared to Fifth Plain and Lacamas Creek.

The smaller tributaries in the lower part of the watershed also have high nutrient concentrations. The highest Total Nitrogen and Nitrate/Nitrite concentrations occurred in Spring Branch Creek, and while Dwyer Creek had relatively low nitrogen concentrations, phosphorus and ortho-phosphate concentrations were high compared to most Lacamas Creek sites. The 2013 groundwater report noted slightly elevated nitrate + nitrite as N concentrations (2.92 mg/L) at the groundwater spring site that discharges to Spring Branch (Sinclair and Swanson 2013). Big Ditch was not sampled for surface water nutrients. However, groundwater samples from Big Ditch had the highest total phosphorus measured in groundwater in the watershed (0.602 mg/L).

Two sites have ammonia/ammonium concentrations that are close to an order of magnitude higher than most other ammonia/ammonium concentrations in the watershed—28-SPR-0.3 and 28-AND-0.0. These elevated ammonia/ammonium concentrations may be explained by a now-closed dairy operation in the area. 28-AND-0.0 is located on a ditch flowing south to Lacamas Creek at the southeastern corner of the dairy's manure lagoons, and Spring Branch Creek flows through the dairy property.

According to the Ecology's 2013 Surface-Water/Groundwater Report (Sinclair and Swanson 2013), the highest groundwater nutrient concentrations were detected at a site that discharges to 28-LAC-9.1 and is located approximately 700 feet from the manure lagoon adjacent to 28-AND-0.0. The groundwater concentrations of ammonia/ammonium and TPN-N were an order of magnitude higher at this site relative to the values found at other groundwater sites. The report suggests that the lagoon complex and/or local manure management practices might be a contributing source of nutrients to groundwater and, consequently, to local surface water.

The dairy operation closed in spring of 2022 and is now a hay and pasture-raised beef operation, with plans to decommission the 19 manure lagoons.

Comparison to Published Nutrient Thresholds

When nutrient concentrations pass certain thresholds, they can contribute to the eutrophication of water bodies. When water bodies become eutrophic, excessive plant and algal growth can lead to DO deficits, lowered species diversity, and potentially fish kills. The precise concentrations of nitrogen and phosphorus that cause eutrophic conditions vary with creek size, flow conditions, light availability, and other conditions. However, several studies have suggested potential nutrient ranges for crossing thresholds of productivity. For example:

- An experimental study found growth-rate saturation occurring at 0.086 mg/L dissolved inorganic nitrogen (DIN) and 0.016 mg/L soluble reactive phosphorus (SRP). In this study, the saturating concentrations for peak biomass occurred at 0.308 mg/L DIN and 0.038 mg/L of SRP (Rier and Stevenson 2006).

- An earlier study of the lower Thompson River in British Columbia found much lower growth-rate saturation concentrations, closer to 0.003 – 0.004 mg/L SRP (Bothwell 1985)
- Dodds (2006) proposed that eutrophication in streams could occur at 0.714 mg/L total N and 0.071 mg/L total P, based on reference streams across the US.
- The EPA proposed ecoregion-specific trophic boundaries based on cumulative frequency distributions of observed nutrient concentrations in streams in the ecoregion. For Ecoregion I (Willamette and Central CA Valleys), the EPA proposed placing the mesotrophic-eutrophic boundary at 1.5 mg/L TN and 0.075 mg/L TP (EPA 2001).

Comparing these thresholds to the data collected in 2011 in the Lacamas watershed indicates ortho-phosphate concentrations exceed growth-rate saturating and peak biomass concentrations in both the China Ditch sub-watershed and in the lower part of the watershed, including Lower Lacamas Creek below river mile 11 and the smaller tributaries in the lower watershed (Dwyer Creek and Spring Branch Creek). Total Phosphorus concentrations in Lower Lacamas Creek, Lower Fifth Plain Creek, and China Ditch also exceed the EPA-proposed limits for eutrophic conditions.

Dissolved Inorganic Nitrogen concentrations (the sum of Nitrate + Nitrite as N and Ammonium) exceed growth-rate saturation and peak biomass concentrations in Lacamas Creek below river mile 11, Lower Fifth Plain Creek, Matney Creek, and Spring Branch Creek. Total Nitrogen concentrations exceed the EPA-proposed mesotrophic-eutrophic boundary less frequently. However, we do observe especially high TPN concentrations in Lacamas Creek at river mile 5.6, Spring Branch Creek, and Fifth Plain Creek just above its confluence with Lacamas Creek.

Figure 27 includes photographs of three sites in the watershed with excessive plant growth and especially high nutrient concentrations, which may be contributing to stream eutrophication.

Figure 27. Site photographs of the three sites with eutrophic conditions based on nitrogen and phosphorus concentrations.

Nitrogen/Phosphorus Ratios

The mass ratios of dissolved inorganic nitrogen (DIN) and ortho-phosphate (OP) can be compared to the Redfield ratio to estimate whether nitrogen or phosphorus is more likely to be the limiting nutrient (Redfield 1958; Borchardt 1996). Figure 28 shows the DIN:OP ratios for samples collected in 2011. The majority of sites are likely to be phosphorus-limited. However, Dwyer Creek, China Ditch, and the China Ditch tributary (28-CHB-0.0) have samples with lower DIN:OP ratios, which suggest possible nitrogen limitation in these three creeks.

While high nutrient concentrations are harmful to the water quality of the creeks and tributaries of the watershed, many nutrients entering Lacamas Creek are eventually delivered to Lacamas Lake. Alleviating nutrient loadings in the Lacamas Creek watershed will therefore be important for decreasing nutrient pollution in Lacamas Lake.

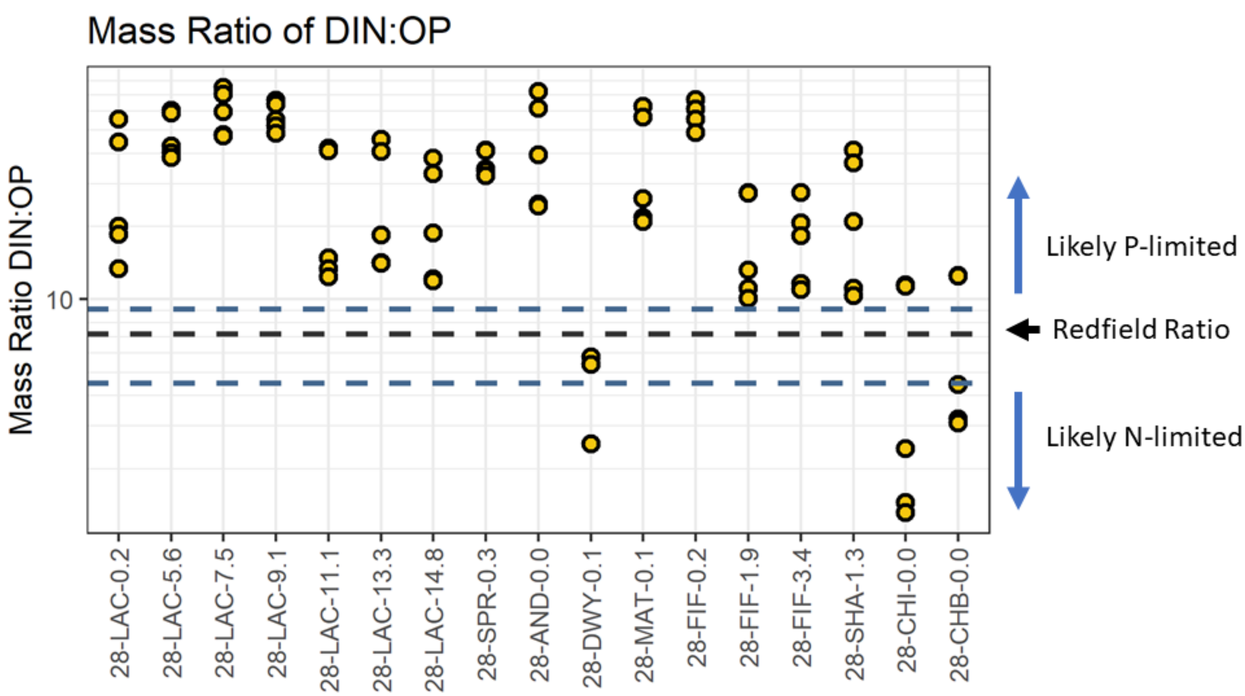


Figure 28. Mass ratios of dissolved inorganic nitrogen and orthophosphate.

Dataset Comparison

Comparison with Clark County Data

Nutrient sampling for this study was limited to dry season samples collected in the summer of 2011. However, additional data collected by Clark County in 2016 – 2017 and 2021 – 2022 as well as Department of Ecology ambient monitoring data collected monthly from 2020 to 2022 provides some additional information about both seasonal patterns in nutrient concentrations and information about nutrient conditions in the study area since the initial sampling occurred in 2010 – 2011.

Figures 29 and 30 show the distribution of nutrient values from samples collected by Clark County in 2016 – 2017 and 2021 – 2022, and Figure 31 is a map of the locations of these samples. Additional information and analysis on these samples can be found in the Clark County Stream Health reports (Clark County 2010 and 2020).

Overall, those sites with the highest summer nutrient concentrations are also those with the highest winter nutrient concentrations; however, the seasonal pattern differs for nitrogen and phosphorus. Both nitrate + nitrite and ammonium concentrations are generally higher in the wet season than in the dry season, while orthophosphate concentrations are higher in the dry season than in the wet season. The two sites where dry season nitrate concentrations are higher than wet concentrations (FPL010 and LAC050) are the two sites with the highest dry season nitrate concentrations. Total phosphorus varies, but wet and dry season concentrations are generally closer to each other than the other parameters. The same patterns occur in the 2016 – 2017 sampling and the 2020 – 2021 sampling. Stormwater may contribute to the elevated nitrate concentrations observed during the wet season. With the exception of China Ditch, nitrate has the highest loadings of the three parameters estimated with the simple method. However, additional and broader wet season sampling would be required to identify the precise causes of these seasonal patterns.

Overall, the nutrient values collected in the 2020 – 2021 sampling effort are in a similar range to those collected in 2016 – 2017, indicating there was no dramatic change in nutrient concentrations in the study area measured at these seven locations between 2016 and 2021.

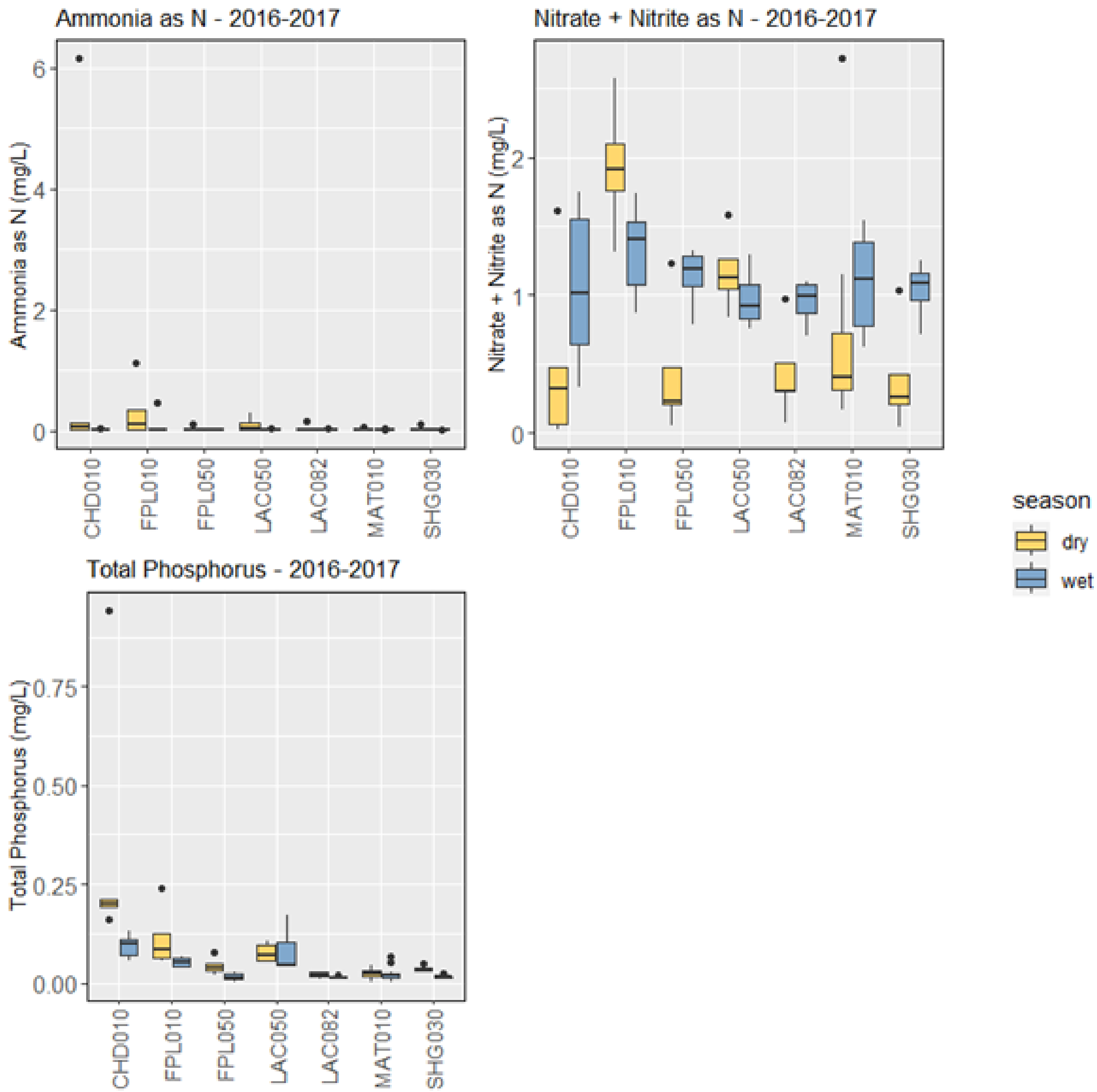


Figure 29. Boxplots of nutrient samples collected by Clark County in 2016 – 2017.
Ammonia as N (top left), Nitrate + Nitrite as N (top right), and Total Phosphorus (bottom left).

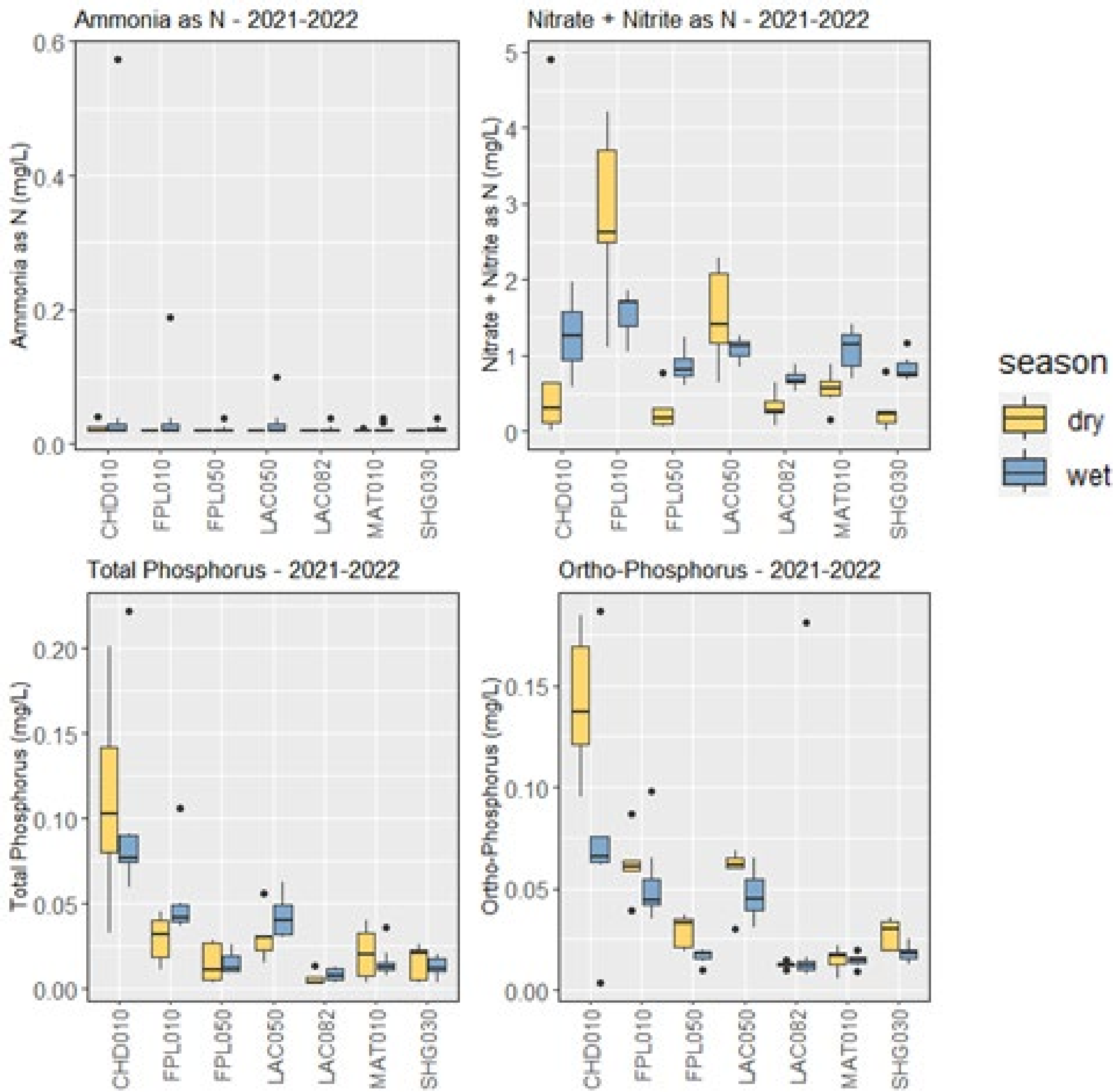


Figure 30. Boxplots of nutrient samples collected by Clark County in 2021 – 2022.
Ammonia as N (top left), Nitrate + Nitrite as N (top right), Total Phosphorus (bottom left), and Ortho-Phosphorus (bottom right).

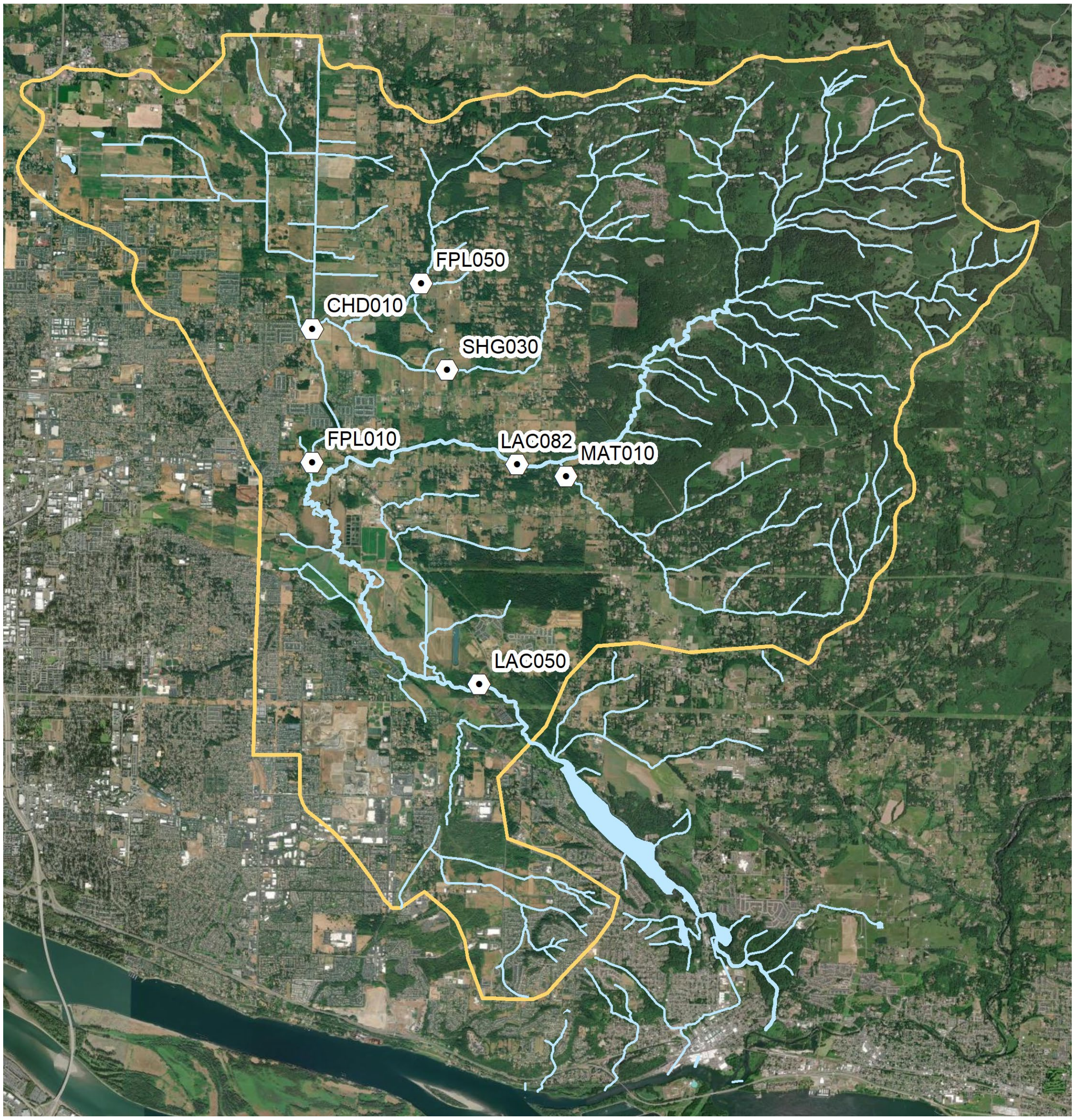


Figure 31. Locations of Clark County sampling locations in 2016 – 2017 and 2021 – 2022.

2020 – 2022 Ambient Monitoring Analysis

Ecology collected monthly samples and measurements at Lacamas Creek at Goodwin Road from October 2020 through September 2021 (at the same location as the 28-LAC-5.6 data).

The FC and *E. coli* samples collected at Lacamas Creek at Goodwin Road from October 2020 through September 2022 give some limited seasonal bacteria information (figure 32). The geometric mean of dry season FC concentrations (112 cfu/100mL) is higher than the wet season geometric mean (75 cfu/100mL). *E. coli* samples have a higher dry season geometric mean (90 cfu/100 mL) than the wet season geometric mean (82 cfu/100mL), though the difference is less pronounced than the FC concentrations. The *E. coli* concentrations sampled during ambient monitoring are slightly lower than those sampled at the adjacent site (28-LAC-5.6) during the summer of 2021 for this study.

The nutrient values collected at Goodwin Road in 2020 – 2022 are in a similar range to those collected at the same site in 2011. This indicates that similar to the Clark County data, there has not been a large change in nutrient concentrations in Lacamas Creek in the decade since the initial sampling was conducted for this study.

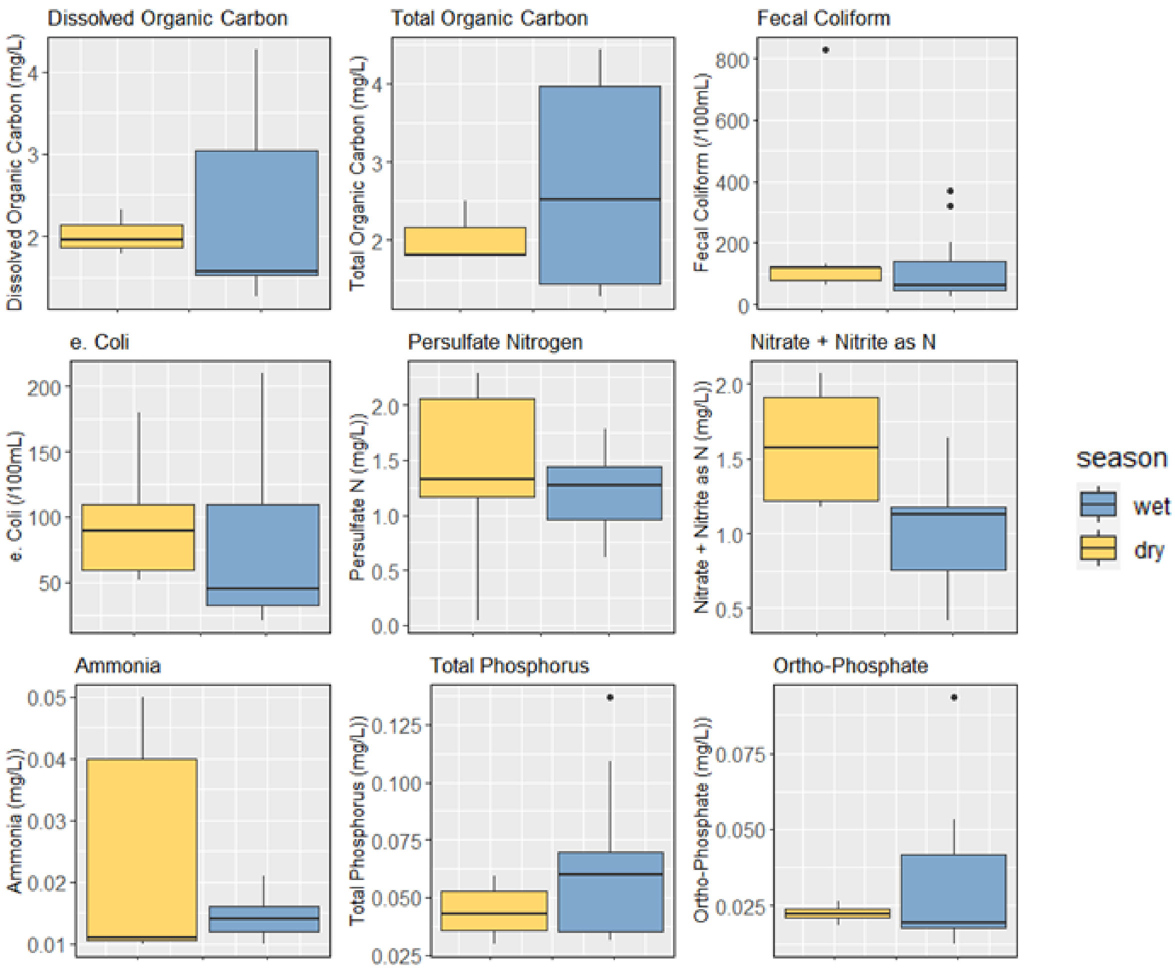


Figure 32. Boxplots of bacteria and nutrient concentrations from samples collected in 2020 – 2022 at Ecology's ambient monitoring station at Lacamas Creek at Goodwin Rd.

Dissolved Oxygen and pH

Ecology collected continuous DO and pH data during two surveys in 2011. Multi-parameter water quality sondes were installed at select sites for short-term deployments from July 25 to July 28 for the first survey and from August 30 to September 1 for the second survey. DO and pH were not collected at 28-LAC-14.8 during the July survey and 28-LAC-9.1 and 28-CHI-0.0 during the

August/September survey. pH was also not collected at 28-SHA-1.3 during the July survey due to sensor issues.

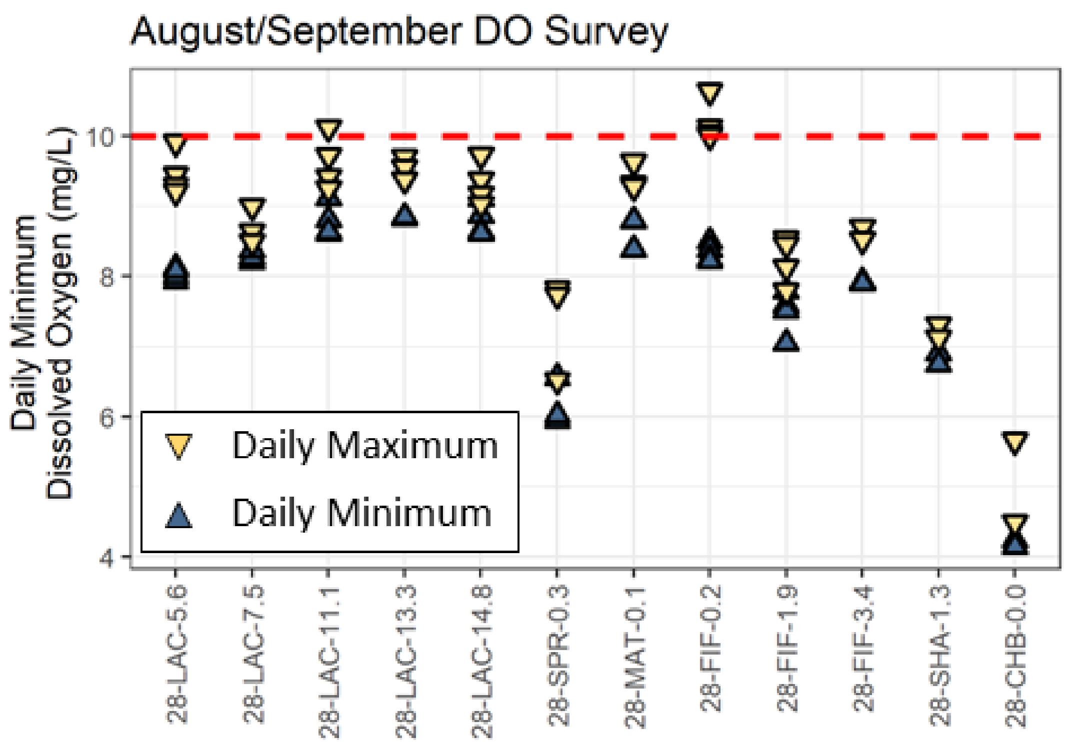
Dissolved Oxygen

No sites met the DO criteria during the August/September survey (Figures 33 – 34, Table 4). In the July survey, three sites (28-LAC-13.3, 28-MAT-0.1, and 28-FIF-3.4) did have daily minimum DO saturations that met water quality criteria. However, the majority of sites did not meet the saturation criteria, and no sites met the concentration criteria for the July survey.

Table 4. Dissolved oxygen (DO) minimums during 2011.

Location ID	July 25–28 Minimum DO (mg/L)	July 25–28 Minimum Saturation (%)	Aug 30–Sep 1 Minimum DO (mg/L)	Aug 30–Sep 1 Minimum Saturation (%)
28-CHB-0.0	5.7	57.2	4.2	40.6
28-CHI-0.0	4.6	45.8	N/A	N/A
28-FIF-0.2	8.4	82.1	8.2	80.2
28-FIF-1.9	8.1	84.7	7.1	75.7
28-FIF-3.4	9.0	94.0	7.9	78.5
28-LAC-11.1	8.8	93.2	8.6	91.1
28-LAC-13.3	9.4	97.5	8.8	91.4
28-LAC-14.8	N/A	N/A	8.6	91.1
28-LAC-5.6	8.5	85.3	7.9	79.3
28-LAC-7.5	8.1	82.7	8.2	84.8
28-LAC-9.1	8.4	85.7	N/A	N/A
28-MAT-0.1	9.3	97.1	8.4	88.2
28-SHA-1.3	8.5	85.3	6.8	68.2
28-SPR-0.3	7.0	65.6	6.0	56.6

Note. Minimum values below the DO or Saturation Criteria are highlighted.
N/A = not applicable.



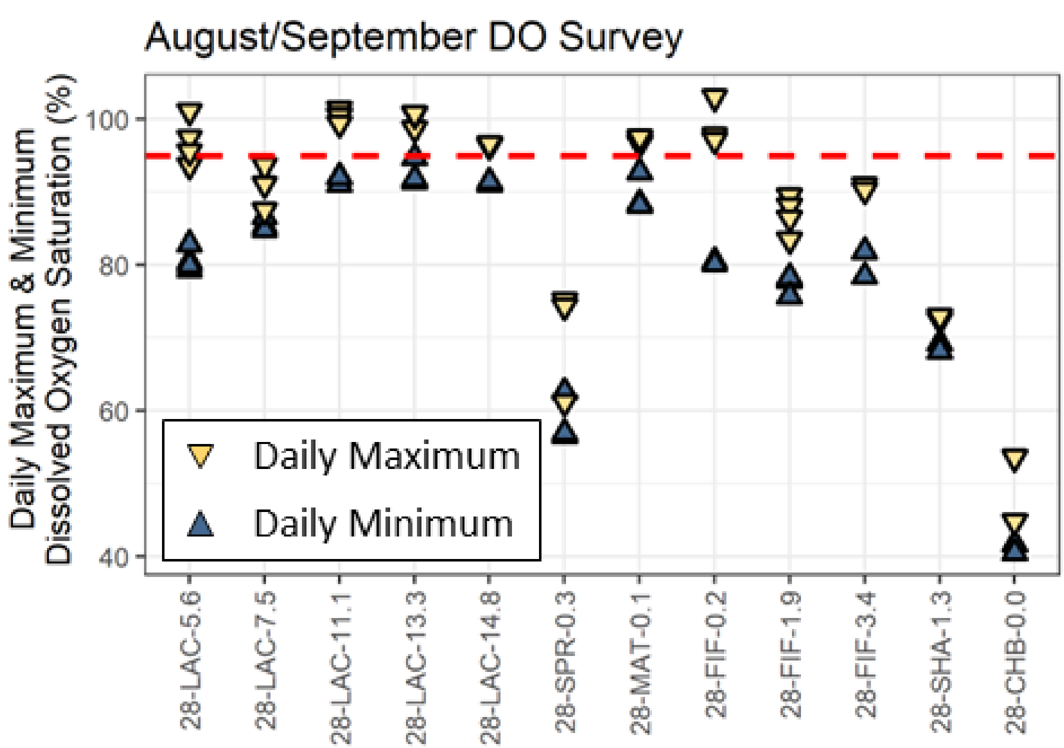
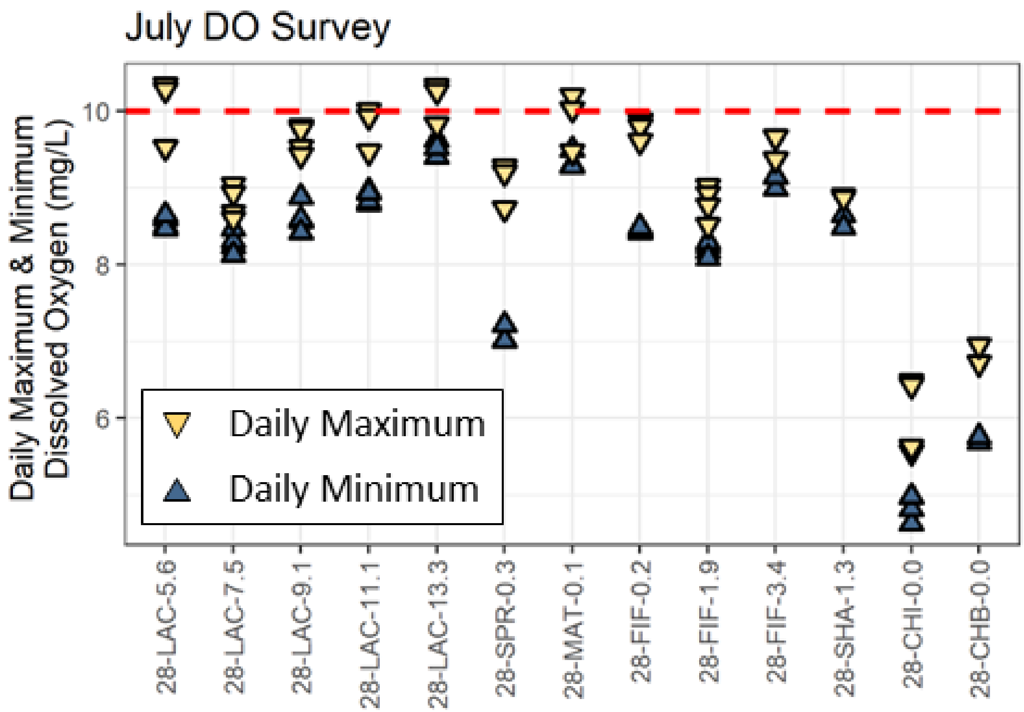


Figure 33. Daily maximum and minimum dissolved oxygen (DO) concentrations (top) and saturation (bottom), August/September 2011 surveys.
Red dashed line is the water quality criteria.



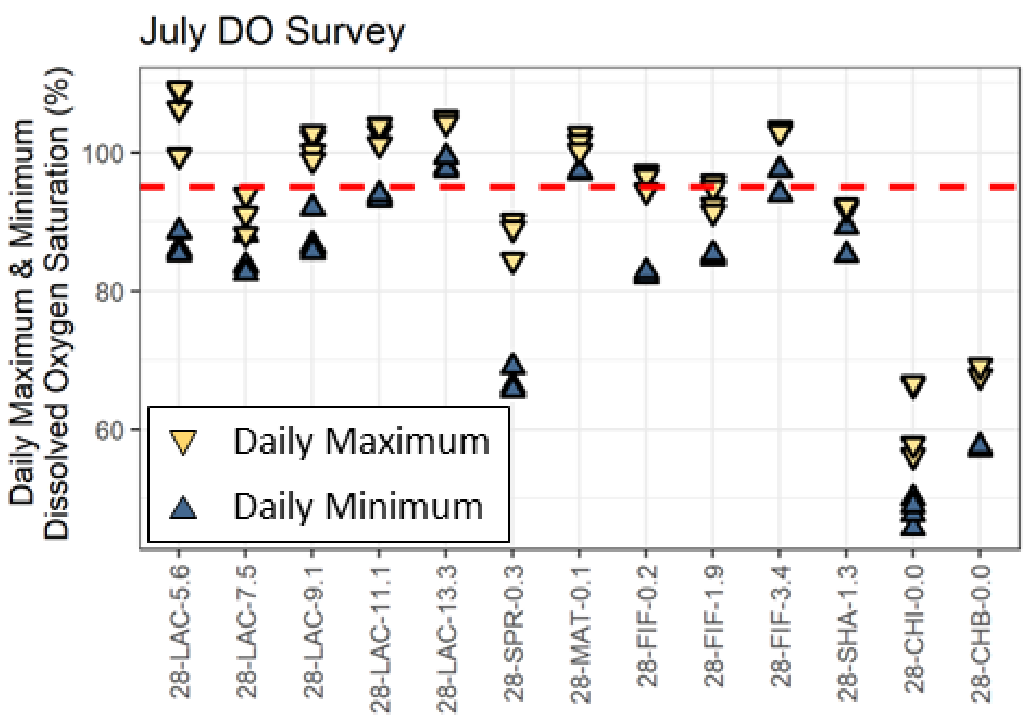


Figure 34. Daily maximum and minimum dissolved oxygen (DO) concentrations (top) and saturation (bottom); July 2011 survey.

Red dashed line is the water quality criteria.

Figure 35 shows the spatial distribution of minimum DO concentrations. The upper reaches of Lacamas Creek, as well as Matney Creek, have relatively high DO concentrations compared to the rest of the study area. China Ditch and Spring Branch Creek both have low DO concentrations, and in the August/September survey particularly low DO concentrations were recorded in Shanghai Creek, Fifth Plain Creek, and Lacamas Creek at Goodwin Road (28-LAC-5.6).

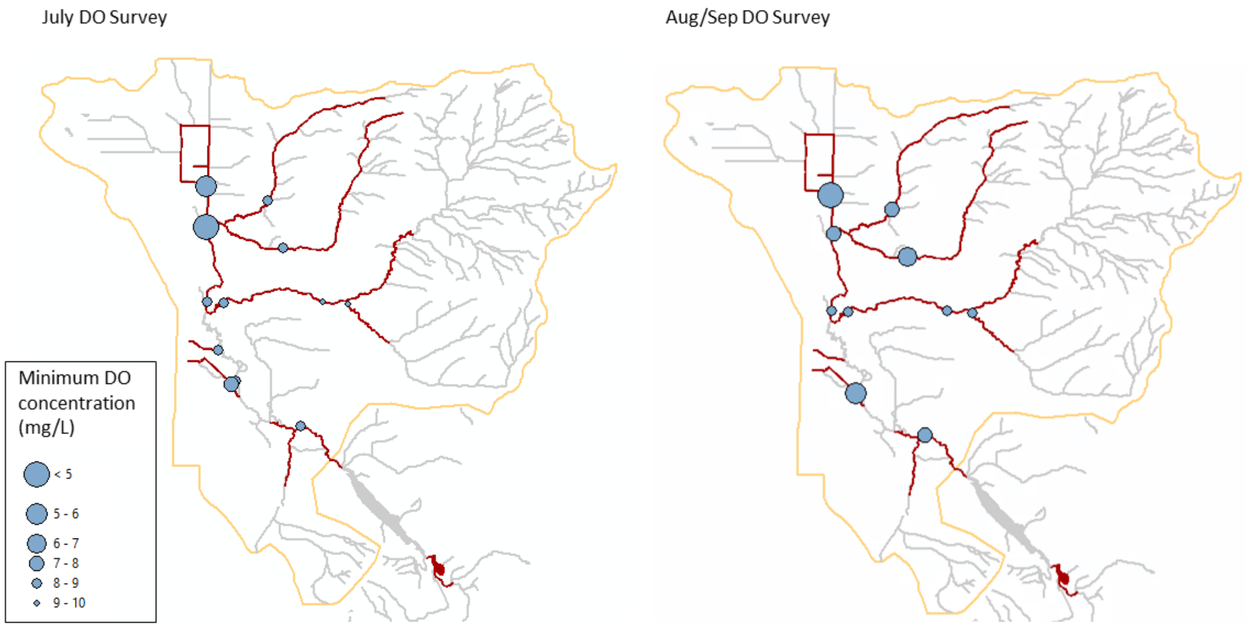


Figure 35. Minimum dissolved oxygen (DO) concentrations during the July and August/September 2011 synoptic surveys.

Current 303(d) listings for DO are marked in red (larger circles used to represent smaller values to highlight locations where lower DO was found).

High nutrient levels, such as those observed in the study area, can lead to higher algal productivity, which can influence DO. In Lacamas, we observe that lower DO concentrations are generally correlated with higher nutrient levels — in particular, those sites with high observed phosphorus levels have the lowest minimum DO concentrations recorded during the DO surveys (Figure 36; see the full suite of nutrient comparisons in Appendix E). While mechanistic or statistical modeling to determine the precise relationship between phosphorus and DO is beyond the scope of this study, reducing phosphorus loading in creeks in this watershed may improve DO concentrations in the watershed.

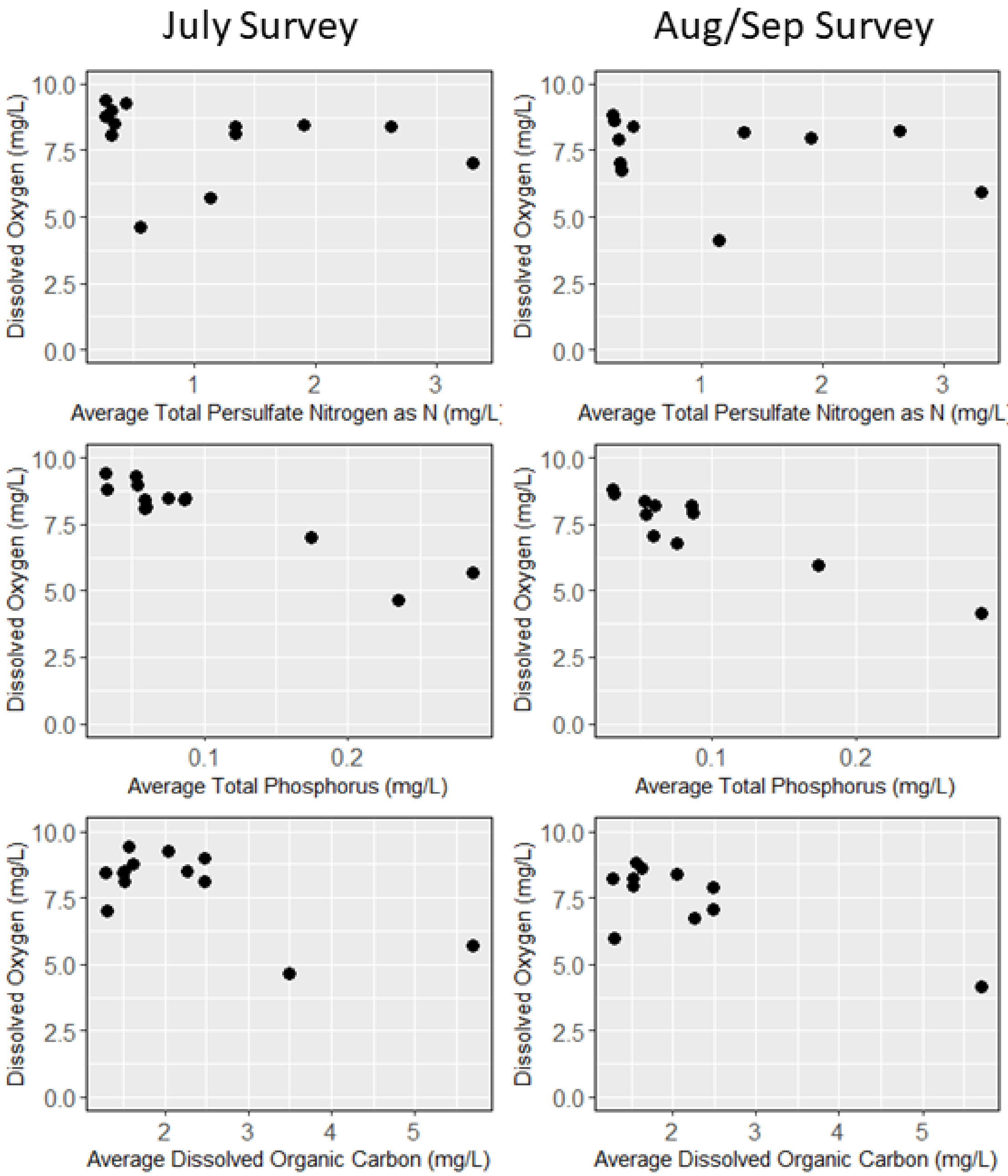


Figure 36. Minimum dissolved oxygen (DO) measurements compared with selected nutrient concentrations in the study area.

The two streams with the lowest DO concentrations, China Ditch and Spring Branch Creek, have some of the highest phosphorus (China Ditch) and nitrogen (Spring Branch Creek) concentrations in the watershed. The high nutrient concentrations may partially contribute to low DO, but these two creeks are also likely influenced by low DO groundwater entering the streams. Spring Branch Creek is a spring-fed creek, and on several occasions, Ecology staff observed pipes flowing into

China Ditch during times when there had been no recent precipitation in the watershed, and there was no evidence of any surface water inputs (e.g., watering) nearby. In addition, both creeks have relatively low temperatures despite a lack of shade cover (discussed further in the next section).

Additional analysis on low DO in the watershed should include the effect of low flow conditions on DO. Both China Ditch and Spring Branch Creek have periods of low and/or sluggish flow. In one sampling event in 2021, the surface layer of Spring Branch Creek was not moving, though water deeper in the column was moving and able to be sampled. Ecology staff also often observed a layer of duckweed on the surface of this creek (Figure 37).

Figure 37. Photograph of site 28-SPR-0.3 showing sluggish conditions and a layer of duckweed on the surface.

pH

Most sites met pH criteria during both surveys (Table 5), yet lower Fifth Plain Creek (28-FIF-0.2) reached the lower limit of 6.5 pH during the July survey. Generally, sites with lower pH, such as 28-FIF-0.2 and Spring Branch 28-SPR-0.3, tended to have known groundwater sources (Sinclair and Swanson 2013).

Table 5. pH minimum and maximum during 2011 surveys and pH criteria.

Location ID	July 25–28 Max pH	July 25–28 Min pH	Aug 30–Sept 1 Max pH	Aug 30–Sept 1 Min pH	pH Criteria
28-LAC-5.6	7.21	6.93	7.54	7.32	6.5–8.5
28-LAC-7.5	7.35	7.25	7.31	7.21	6.5–8.5
28-LAC-9.1	7.21[a]	7.04[a]	N/A	N/A	6.5–8.5
28-LAC-11.1	7.44	7.19	7.33	7.11	6.5–8.5
28-LAC-13.3	7.47	7.14	7.64	7.29	6.5–8.5
28-LAC-14.8	N/A	N/A	7.62	7.49	6.5–8.5
28-SPR-0.3	6.78	6.7	7.73	6.72	6.5–8.5
28-MAT-0.1	7.47	7.29	7.54	7.36	6.5–8.5
28-FIF-0.2	6.55	**6.49**	6.68	6.58	6.5–8.5
28-FIF-1.9	7.16	6.93	7.21	7.01	6.5–8.5
28-FIF-3.4	7.55	6.99	7.29	7.03	6.5–8.5
28-SHA-1.3	N/A	N/A	6.84	6.78	6.5–8.5
28-CHI-0.0	7.03	6.98	N/A	N/A	6.5–8.5
28-CHB-0.0	7.28	7.22	7.31	7.18	6.5–8.5

Note. Bolded values highlighted in yellow represent criteria was not met.
N/A = not applicable.
[a]Value considered an estimate.

Temperature

Summary Statistics

Ecology collected continuous surface water and air temperature data from May to October 2011 along Lacamas Creek and major tributaries (Figure 38). Big Ditch (28-BIG-0.2) and Dwyer Creek (28-DWY-0.1) sites were not monitored for the full summer period due to stagnant flow, and temperature data collection stopped in mid-August at these sites. Table 6 summarizes the peak daily maximum (1-DMax), 7-day average daily maximum (7-DADMax), and average temperature for each site.

Most of the sites exceeded the 7-DADMax criteria during the 2011 summer season. For sites with a full period of record (May through October), the hottest stream temperatures occurred on August 25 and August 26, 2011. These 2011 dates correspond to periods where the 7-day maximum air temperatures were greater than the historical 90th percentiles.

Ecology staff observed poor shade conditions at several locations in Lacamas Creek (discussed in the next section) and its tributaries (see Figure 39 for examples), which may contribute to the high temperatures and high rates of noncompliance in the Lacamas Creek watershed. Increasing riparian vegetation throughout the watershed will decrease the influx of solar radiation to creeks in the watershed, helping to lower temperatures.

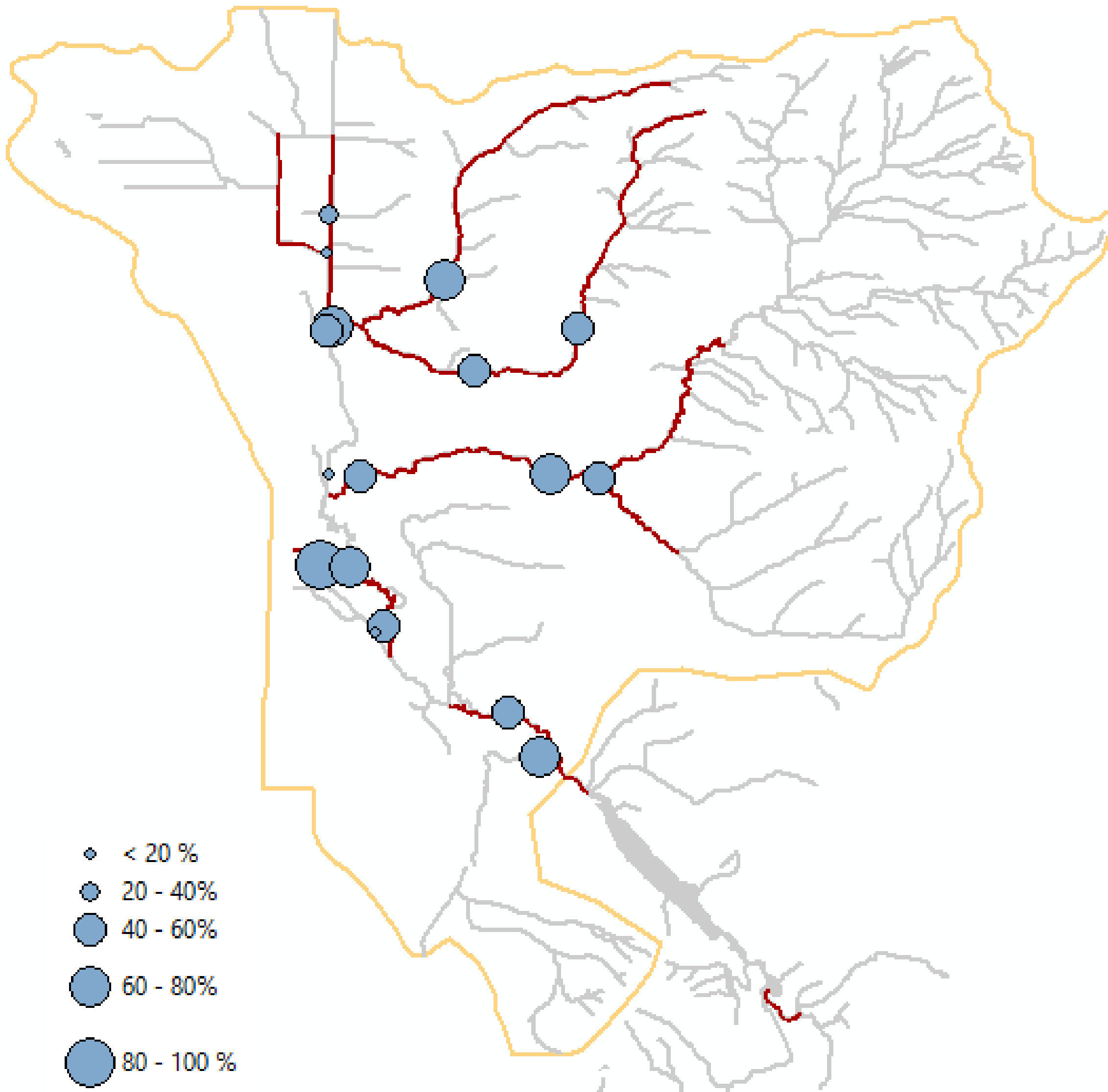


Figure 38. Map of the percent of days exceeding the 7DADMax temperature criteria at each site monitored with temperature in 2011.
Segments that are currently on the 303(d) list for temperature are bolded in red.

Table 6.Temperature results (2011).

Site	Temperature Criteria (°C)	Total Days Sampled	% of Days Data Exceeded Criteria	1-Dmax (°C)	7DADMax (°C)	Average (°C)
28-LAC-5.6	16.0	154	53%	19.6	**19.0**	14.7
28-LAC-7.5	16.0	154	59%	20.3	**19.7**	14.8
28-LAC-9.1	16.0	154	61%	20.9	**20.1**	14.7
28-LAC-11.1	16.0	158	59%	22.7	**21.7**	14.6
28-LAC-13.3	16.0	126	71%	22.0	**21.2**	16.2
28-LAC-14.8	16.0	155	56%	21.5	**20.7**	14.0
28-DWY-0.1	16.0	87	65%	19.6	**18.7**	15.0
28-SPR-0.3	16.0	154	0%	15.7	14.9	12.9
28-BIG-0.2	16.0	97	90%	19.6	**19.0**	15.5
28-MAT-0.1	16.0	154	58%	21.7	**20.7**	14.6
28-FIF-0.2	16.0	154	0%	16.2	15.5	13.2
28-FIF-1.9	16.0	131	71%	22.0	**21.1**	14.9
28-FIF-3.4	16.0	151	66%	23.5	**22.4**	14.9
28-SHA-1.3	16.0	155	49%	19.9	**19.3**	14.1
28-SHA-2.7	16.0	155	50%	20.2	**19.6**	13.7
28-CHI-0.0	16.0	153	46%	19.4	**18.7**	14.3
28-CHI-1.2	16.0	154	27%	17.9	**17.3**	13.9
28-CHB-0.0	16.0	153	18%	17.9	**17.3**	14.1

Note. Bolded values highlighted in yellow indicate the site exceeded the temperature water quality criteria.

Figure 39. Photographs of tributaries with exposed banks and lacking tree coverage on banks.

The only sites that met temperature criteria were Spring Branch (28-SPR-0.3) and Fifth Plain Creek (28-FIF-0.2). The Surface Water and Groundwater Exchange study (Sinclair and Swanson 2013) results showed that groundwater temperatures were lower than surface water temperatures and caused cooling of the creek temperatures in gaining reaches. The stream temperature results of two groundwater seepage and synoptic surveys conducted on July 26th and August 30, 2011, showed that Spring Branch (28-SPR-0.3) and Fifth Plain Creek (28-FIF-0.2) were several degrees cooler than the mainstem of Lacamas Creek. This suggests these tributaries receive relatively large inputs of low-temperature groundwater prior to entering Lacamas Creek. China Ditch may also receive groundwater inputs, and while this stream and its tributary did not meet temperature criteria, it had fewer days of noncompliance than other tributaries.

Note that the relatively low temperatures at Spring Branch Creek, Fifth Plain Creek at river mile 0.2, and China Ditch were recorded despite low shade conditions at these channels (Figure 40). If riparian restoration efforts restore shade coverage in these locations, it is possible that water temperatures will decrease further and help to improve stream temperatures downstream of these groundwater sources.

Figure 40. Photographs of Spring Branch Creek and China Ditch

Shade Analysis

We ran the Ecology Shade Model on the mainstem of Lacamas Creek to further investigate shade conditions on Lacamas Creek and identify potential stretches of the creek with the most potential for riparian shade improvement.

The Shade Model predicted that on average 42.6% of the solar flux to the stream is intercepted by either vegetation or topographic features for August 1st of 2013. Modeled effective shade as well as shade deficit can be seen in Figures 41 and 42.

Based on the Soil Survey Geographic Database (SSURGO), we estimate that the system potential shade from the headwaters to 28-LAC-9.1 is 73% (system potential shade is the natural maximum potential shade that a system can realize). The shade deficit, or difference between effective shade and system potential shade, for this upper portion of Lacamas Creek is 28%.

SSURGO data for the lower portion of Lacamas from 28-LAC-9.1 to the mouth consisted primarily of poorly drained silty alluvium but had limited information regarding tree species. Without SSURGO tree species information and since a quick review of surveys (Bureau of Land Management 2023) from the mid-1850s showed that various tree species are feasible in this region, it was beyond the scope of this effort to establish system potential shade for this portion of Lacamas Creek. Washington Department of Fish and Wildlife (2023) priority and habitat species map similarly did not report system potential tree heights for this area despite having predictions for the remainder of the watershed.

Three areas were identified by the model to have inadequate effective shade, including the headwaters of the creek above site 28-LAC-14.8, the two-mile stretch between 28-LAC-9.1 and 28-LAC-11.1, and the downstream portion of the creek from 28-LAC-9.1 to the mouth. Both the two-mile stretch between 28-LAC-9.1 and 28-LAC-11.1 and the upstream section of the creek have relatively high potential shade deficits. This combination of high potential shade deficits and low effective shade makes these two areas good targets for riparian restoration efforts. In contrast, to address low effective shade in the downstream portion of the watershed, future studies may consider reviewing General Land Office Records (GLO) from the 1850's (Bureau of Land Management 2023) to ascertain the system potential shade dominant tree species. This will allow shade deficits to be estimated.

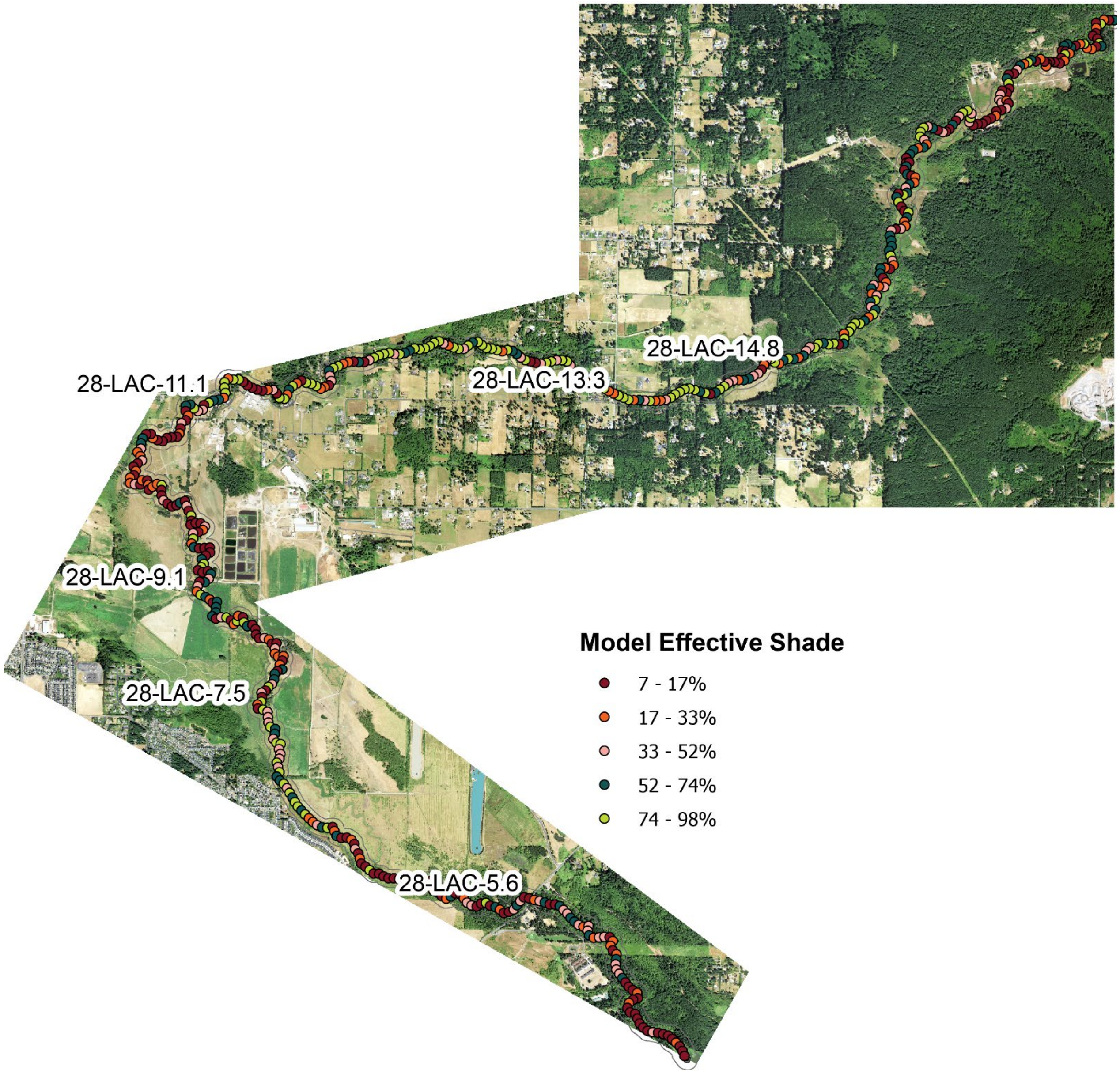


Figure 41. Model effective shade conditions for 2013 along the Lacamas Creek watershed.

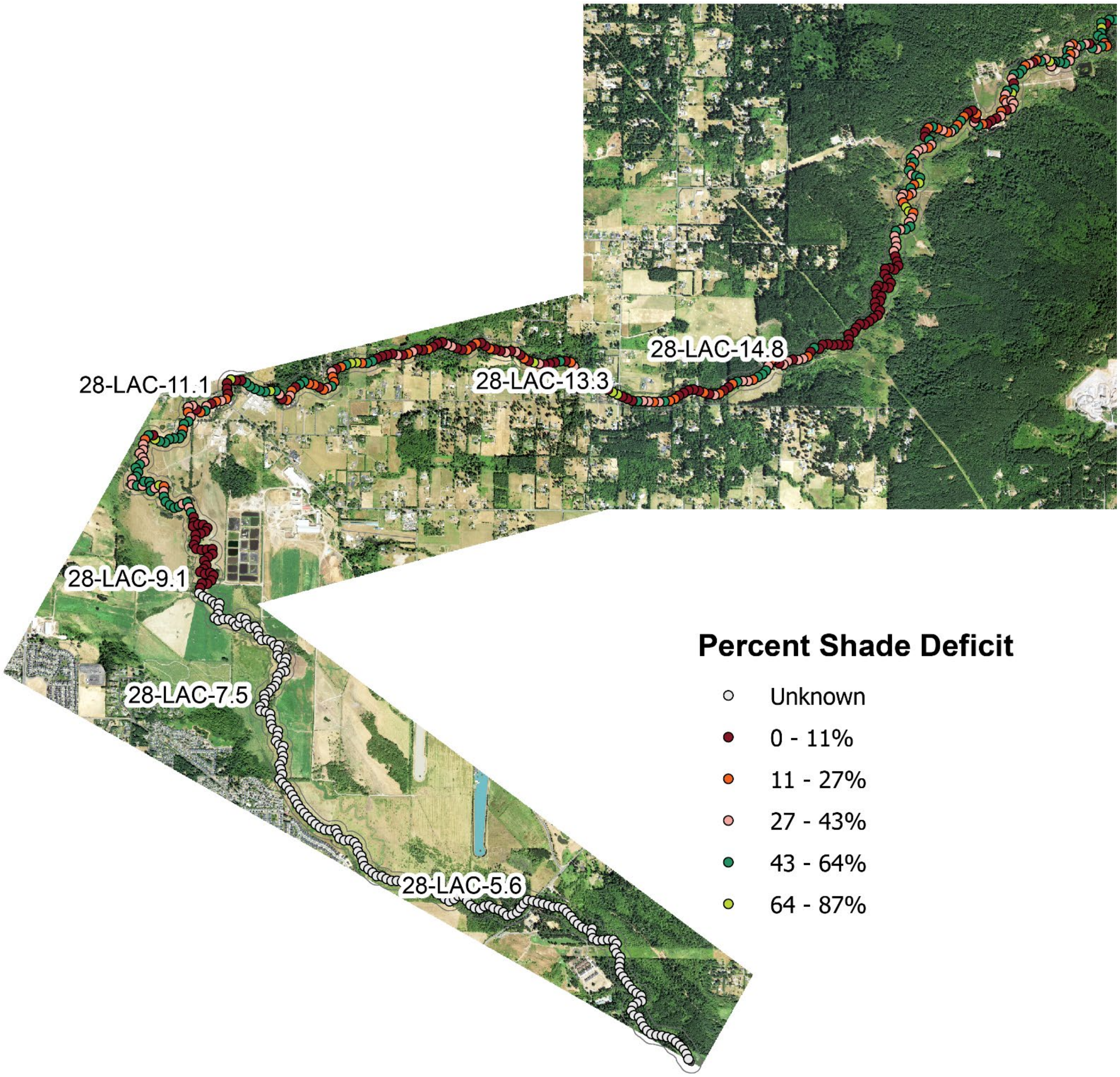


Figure 42. Model percent shade deficit along Lacamas Creek.

The valley floor area upstream of 28-LAC-14.8 is located in the former Camp Bonneville site. Figure 43 shows photographs of this valley floor area. The valley floor, including around the creek, has very young vegetation, and trees around the creek are relatively sparse. Between 2006 and 2021, all vegetation in the valley floor was either removed or cut to a few inches to allow minesweepers to access the area as part of the munitions cleanup effort at Camp Bonneville. Clark County is currently leading riparian restoration efforts in this area, including test plantings of potential species and planning for future plantings along Lacamas Creek upstream of 28-LAC-14.8.

Figure 43. Photographs of Lacamas Creek in the Valley Floor area of Camp Bonneville upstream of 28-LAC-14.8.

Satellite imagery between 28-LAC-11.1 and 28-LAC-9.1 confirms there are fewer trees between 28-LAC-11.1 and 28-LAC-9.1 than in other parts of the creek (Figure 44). This area may be a good target for riparian restoration efforts to improve shade and decrease temperatures on Lacamas Creek.

Figure 44. Photographs of 28-LAC-11.1 and 28-LAC-9.1, with satellite imagery of Lacamas Creek between the sites.

The effective shade model was in good agreement with photographs analyzed using GLA software, with model predictions on average within 9% of effective shade calculated from the hemispherical photographs.

Progress towards addressing the shade deficit was assessed indirectly by using the National Land Cover Dataset (NLCD) and Rangeland Condition Monitoring Assessment and Project (RCMAP) data for canopy cover. The most recent NLCD and RCMAP datasets were available for 2021 and were compared with 2011. Both datasets showed only minor changes in canopy cover in the watershed: NLCD predicted a 4% average increase in canopy cover, while RCMAP predicted almost no change in the intervening decade.

In 2023, Ecology staff collected four hemispherical photographs at sites that were originally photographed in 2011. While these photographs cannot be used to infer changes in shade cover at other locations, they have two purposes.

First, the hemispherical photographs were compared to the most recent NLCD and RCMAP datasets to determine which dataset might most accurately capture recent (2021 – present) shade conditions on Lacamas Creek. This RCMAP canopy estimates agreed slightly more with the hemispherical photos at two out of the four sites sampled. However, both datasets under-predicted conditions at river mile 7.5 (28-LAC-7.5).

Second, we compared the hemispherical photos collected in 2023 to those collected at the same locations in 2011 to determine if there had been any substantial changes in shade conditions at those four locations. Analysis of the photos revealed no substantial changes in canopy cover: the average canopy cover decline of 2.5% is within the variability we expect when taking hemispherical photos at the same locations 12 years apart (Note that we observed some change in effective shade at two of the sites due to changes in canopy distribution, discussed further in Appendix C).

If Lacamas Creek was heading towards achieving system potential change in the intervening 10 years, we might expect an increase in canopy cover at those locations. This may be directly related to the type of trees that are currently growing at the sites, which are primarily deciduous and not the evergreens that are estimated to be needed for system potential shade.

Overall, with the limited evidence regarding current (2021 – 2023) shade conditions we have, we do not see any indications of major changes in effective shade at Lacamas Creek between 2011 and 2021, indicating the results of the shade model likely identify good targets for riparian shade restoration projects. In addition, although analysis of hemispherical photos showed improvements in effective shade for the typical hottest day, the lack of meaningful change at the 2023 hemispherical photo sites may indicate that Lacamas is currently not on track to reach system potential shade.

See Appendix C for additional details regarding the shade model and results.

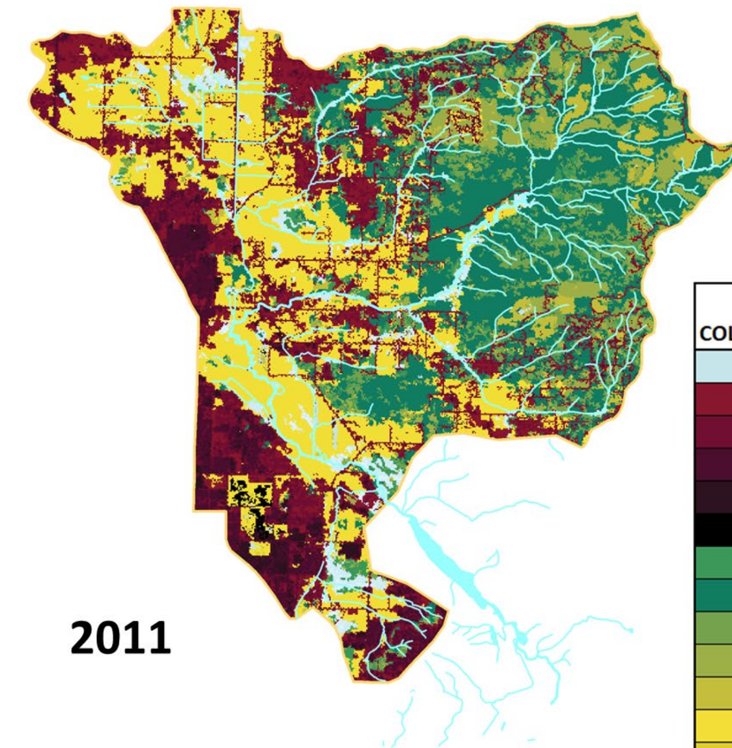
Exploratory Source Analysis

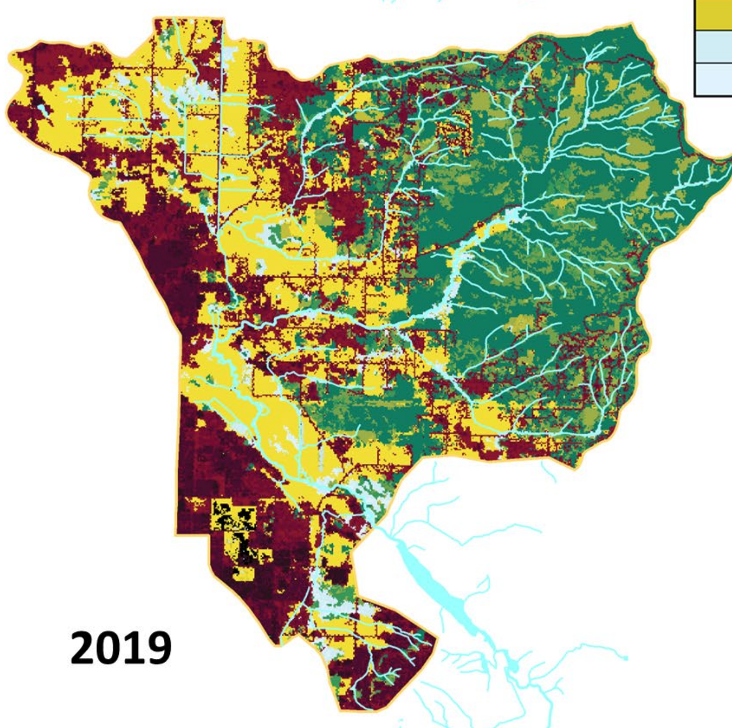
Land Use

Figure 45 shows the land cover patterns derived from the National Land Cover Database (NLCD) in 2011 and 2019, and Table 7 shows the percentage of the study area in each NLCD classification.

Note that here we are using a land cover database to infer land uses. The terms land use (how people use the land, e.g., “forestry”) and land cover (the actual physical coverage of the landscape, e.g., “forests”) are different, but in this case we can use land cover as a surrogate for land uses. The “developed” and “pasture/hay” land cover categories are most likely to be related to increased bacteria and nutrients, and these land covers are directly related to the human use of the landscape.

Overall, land cover changes were minor across the study area between 2011 and 2019. Some areas, particularly in the western portions of the study area, have seen increased development and increased intensity of development, and there was an increase in evergreen forest in the northeastern portion of the study area.





COLOR	NLCD value	NLCD Classification
	11	Open Water
	21	Developed, Open Space
	22	Developed, Low Intensity
	23	Developed, Medium Intensity
	24	Developed High Intensity
	31	Barren Land (Rock/Sand/Clay)
	41	Deciduous Forest
	42	Evergreen Forest
	43	Mixed Forest
	52	Shrub/Scrub
	71	Grassland/Herbaceous
	81	Pasture/Hay
	82	Cultivated Crops
	90	Woody Wetlands
	95	Emergent Herbaceous Wetlands

Figure 45. National Land Cover Database (NLCD) land use classifications for the study area in 2011 (top) and 2019 (bottom).

Table 7. Land cover classifications in 2011 and 2019.

Land Cover Classification	2011 Land Use (%)	2019 Land Use (%)
Open Water	0.2	0.1
Developed, Open Space	11.8	11.7
Developed, Low Intensity	10.9	11.1
Developed, Medium Intensity	5.4	6.4
Developed High Intensity	1.3	1.5
Barren Land (Rock/Sand/Clay)	0.3	0.3
Deciduous Forest	3.0	2.9
Evergreen Forest	21.9	25.8
Mixed Forest	6.5	6.4
Shrub/Scrub	6.4	4.2
Grassland/Herbaceous	2.9	1.2
Pasture/Hay	24.9	24.0
Cultivated Crops	0.0	0.0
Woody Wetlands	3.3	3.4
Emergent Herbaceous Wetlands	1.2	1.1

Land Use — Bacteria

Figure 46 shows the relationship between the percentage of land area in each sample's drainage area and the *E. coli* concentrations in that sample (similar graphs for the 2011 data are included in Appendix E). Note that some samples have been excluded from this analysis. In particular, we exclude all samples from the China Ditch sub-watershed besides the site just upstream of its confluence with Fifth Plain Creek (28-CHB-0.0). This is because the StreamStats application did not produce accurate drainage areas for several sampling locations in the study area. While some recent literature finds potentially lower *E. coli* concentrations in forested areas (e.g., Hubbart et al. 2022; Tong and Chen 2002), we do not see a clear relationship between *E. coli* concentrations and land use in the watershed.

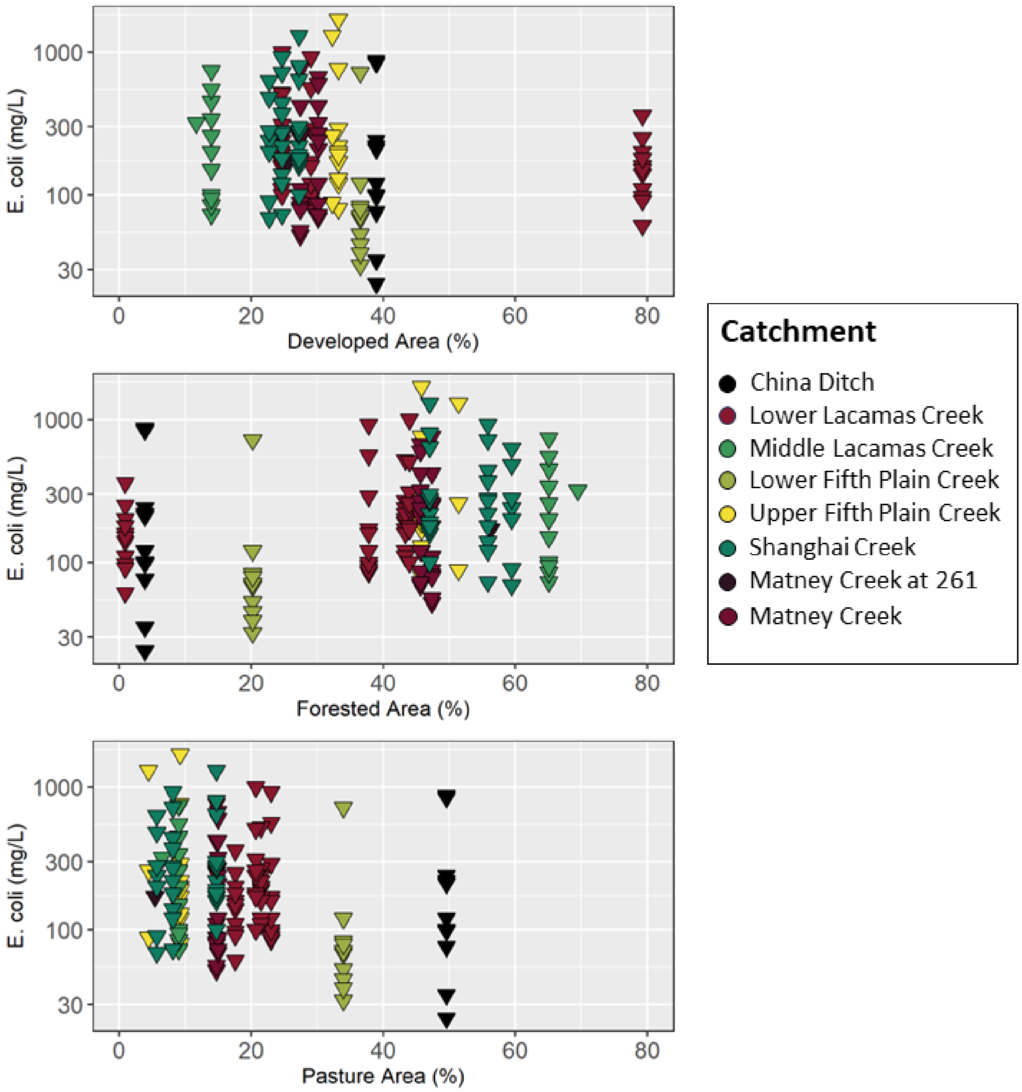


Figure 46. Relationship between *E. coli* concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (Top: developed area; middle: forested area; bottom: pasture area).

Land Use — Nutrients

In contrast, there is evidence that higher nitrogen and phosphorus concentrations are related to land use in the study area. Figures 47 – 49 show the relationships between nutrient concentrations collected during the summer 2011 synoptic studies and the land use distributions in each sample's drainage area (additional nutrients are shown in Appendix E).

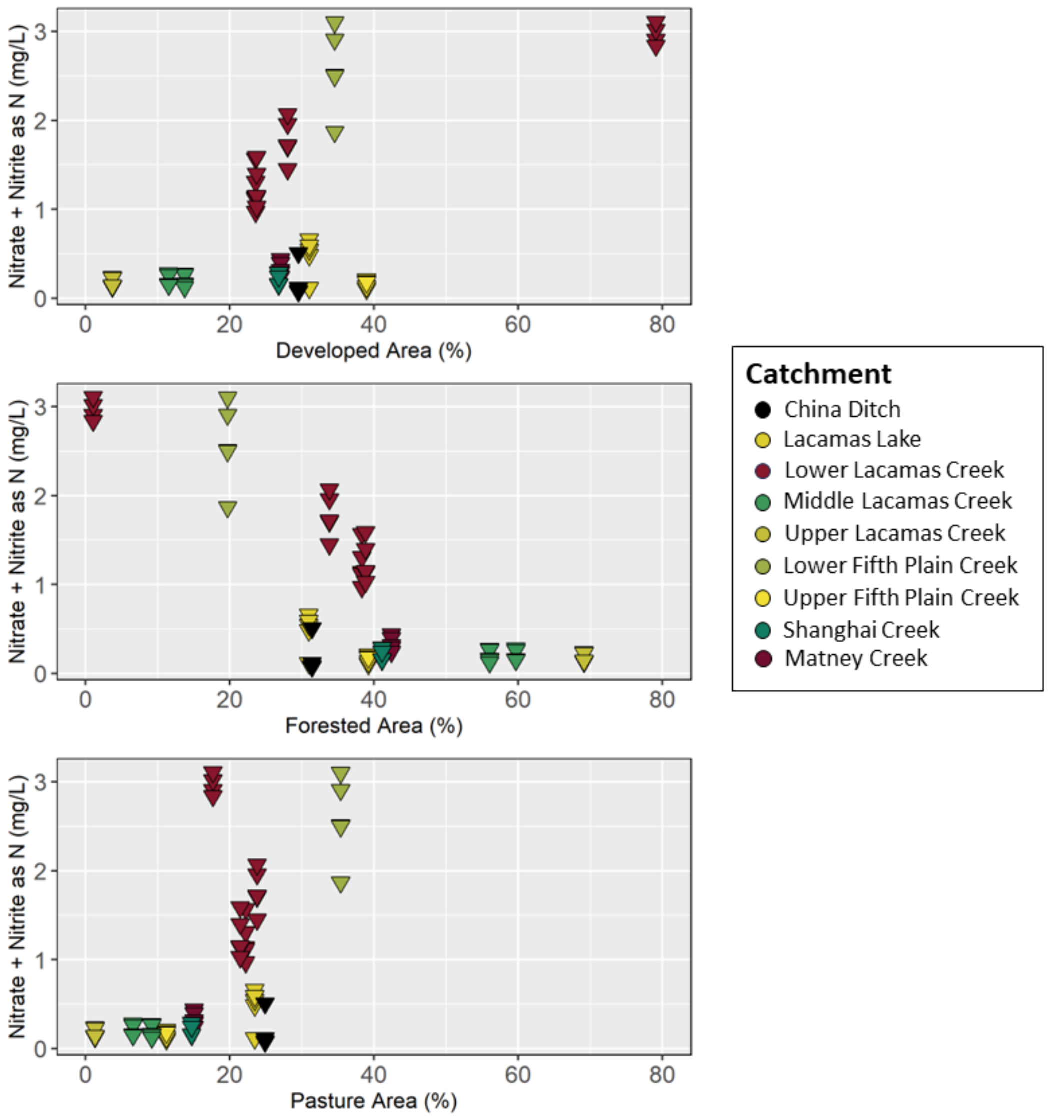


Figure 47. Relationship between Nitrate + Nitrite concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (Top: developed area; middle: forested area; bottom: pasture area).

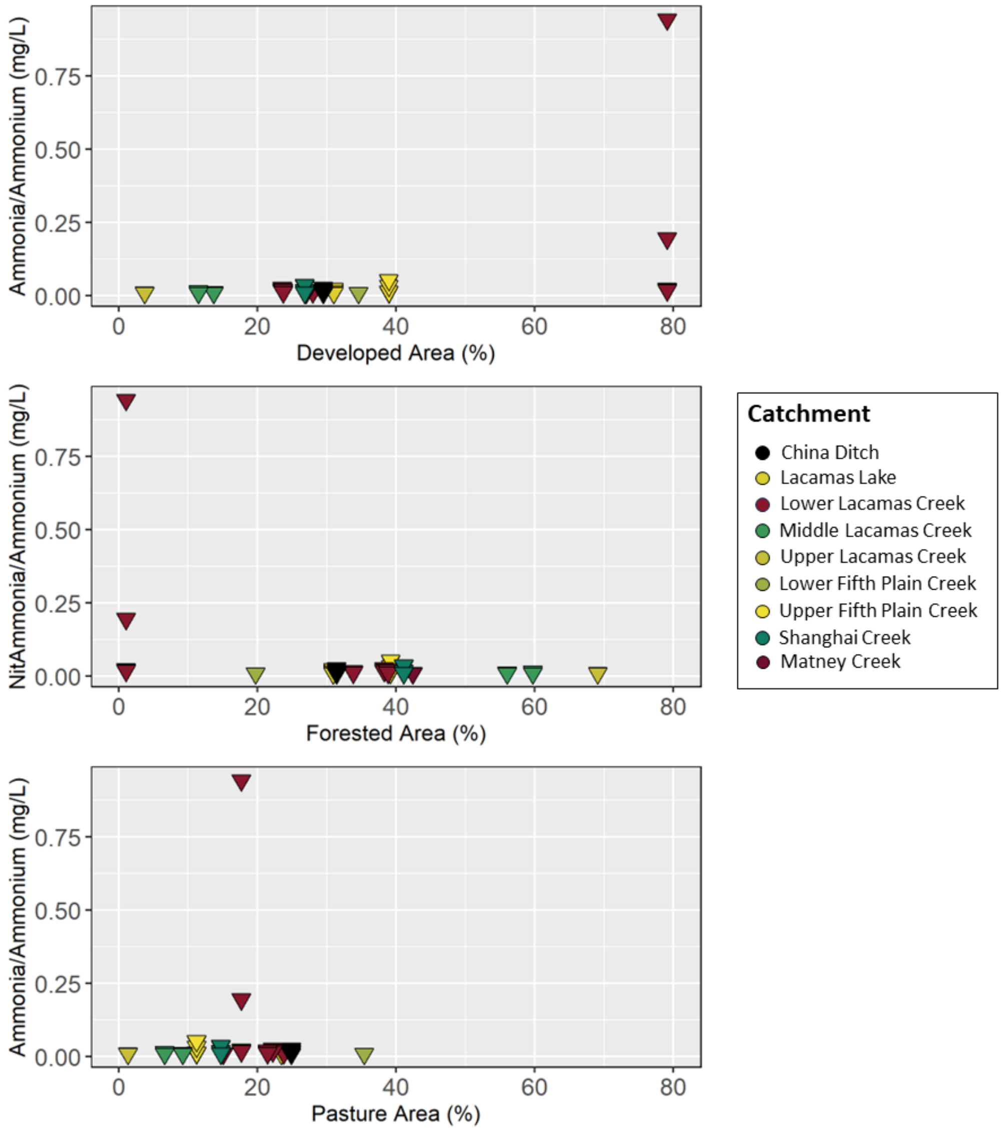


Figure 48. Relationship between ammonium concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (Top: developed area; middle: forested area; bottom: pasture area).

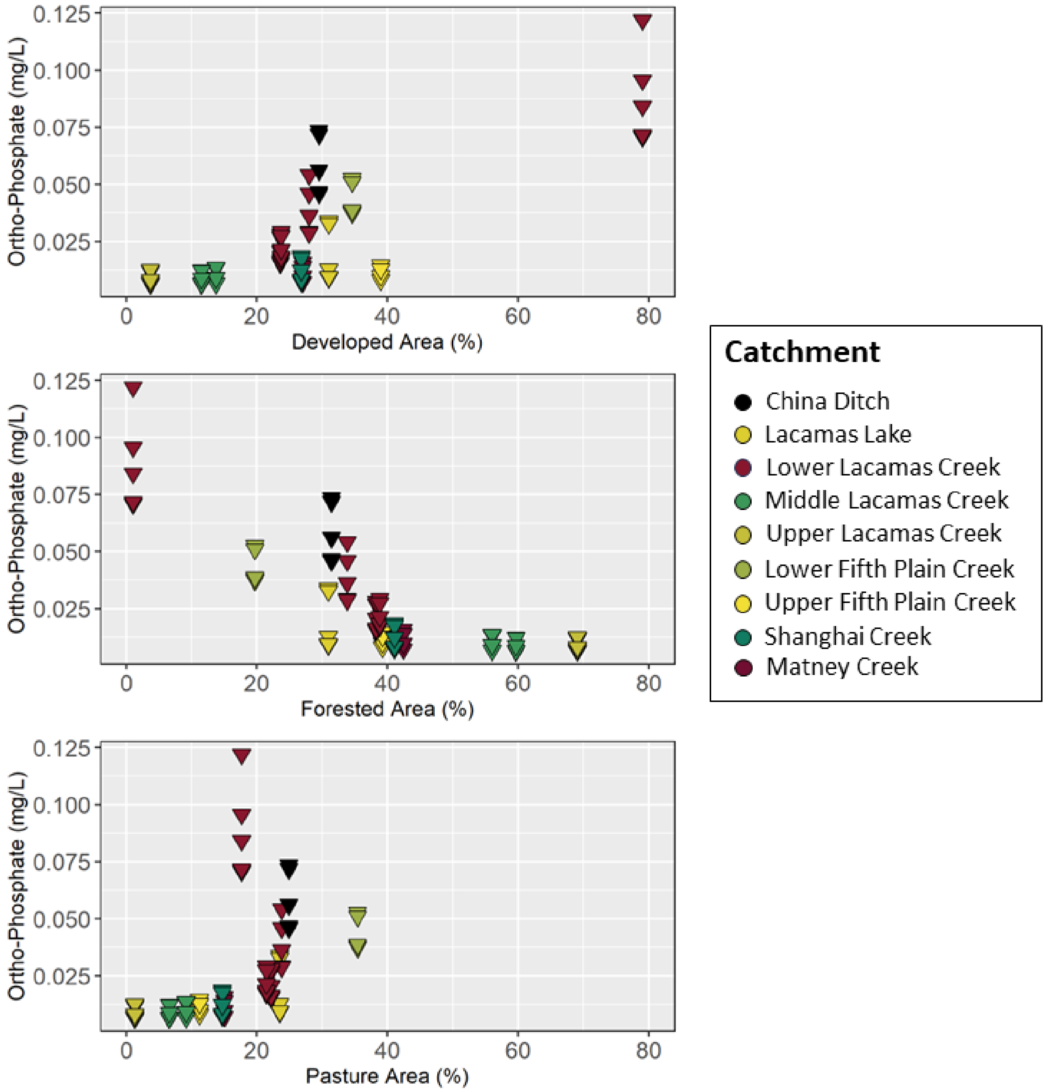


Figure 49. Relationship between ortho-phosphate concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (Top: developed area; middle: forested area; bottom: pasture area).

Higher concentrations of nitrate + nitrite are associated with higher fractions of developed land and pasture land, while sample drainage basins with a higher percentage of coverage from forest are associated with lower concentrations. A similar pattern occurs in the total persulfate nitrogen data presented in Appendix E.

The trend is not apparent in ammonium concentrations, which as expected are low in the watershed. The highest ammonia/ammonium concentrations detected during the study period were found in the Lower Lacamas Creek sub-watershed. The two sites with the highest ammonia/ammonium concentrations, 28-AND-0.0 and 28-SPR-0.3, were located on (28-AND-0.0) or downstream of (28-SPR-0.3) a now-closed dairy farm.

Ortho-phosphate (and total phosphorus in Appendix E) results vary with different land use categories, with higher total phosphorus results generally associated with sample drainage areas that have a higher percentage of developed and pasture area and a lower percentage of forested and shrub/scrub area.

Soil Phosphorus

We considered the possibility that some of the high phosphorus concentrations observed in the watershed might be explained by soil phosphorus derived from the underlying geology of the region. The Pacific Northwest, specifically the area near Lacamas Creek, has slightly higher soil phosphorus than the rest of the country, based on a USGS survey of nearly 5,000 sites in the coterminous United States (Figure 50). This may be because soils in Washington and Oregon are often developed from igneous rocks, which contain apatite, a mineral that is resistant to weathering and may persist longer than other minerals in soil (Smith et al. 2019). However, background soil phosphorus cannot explain the variability in phosphorus concentrations in the watershed, nor can it explain the remarkably high phosphorus concentrations observed in this study.

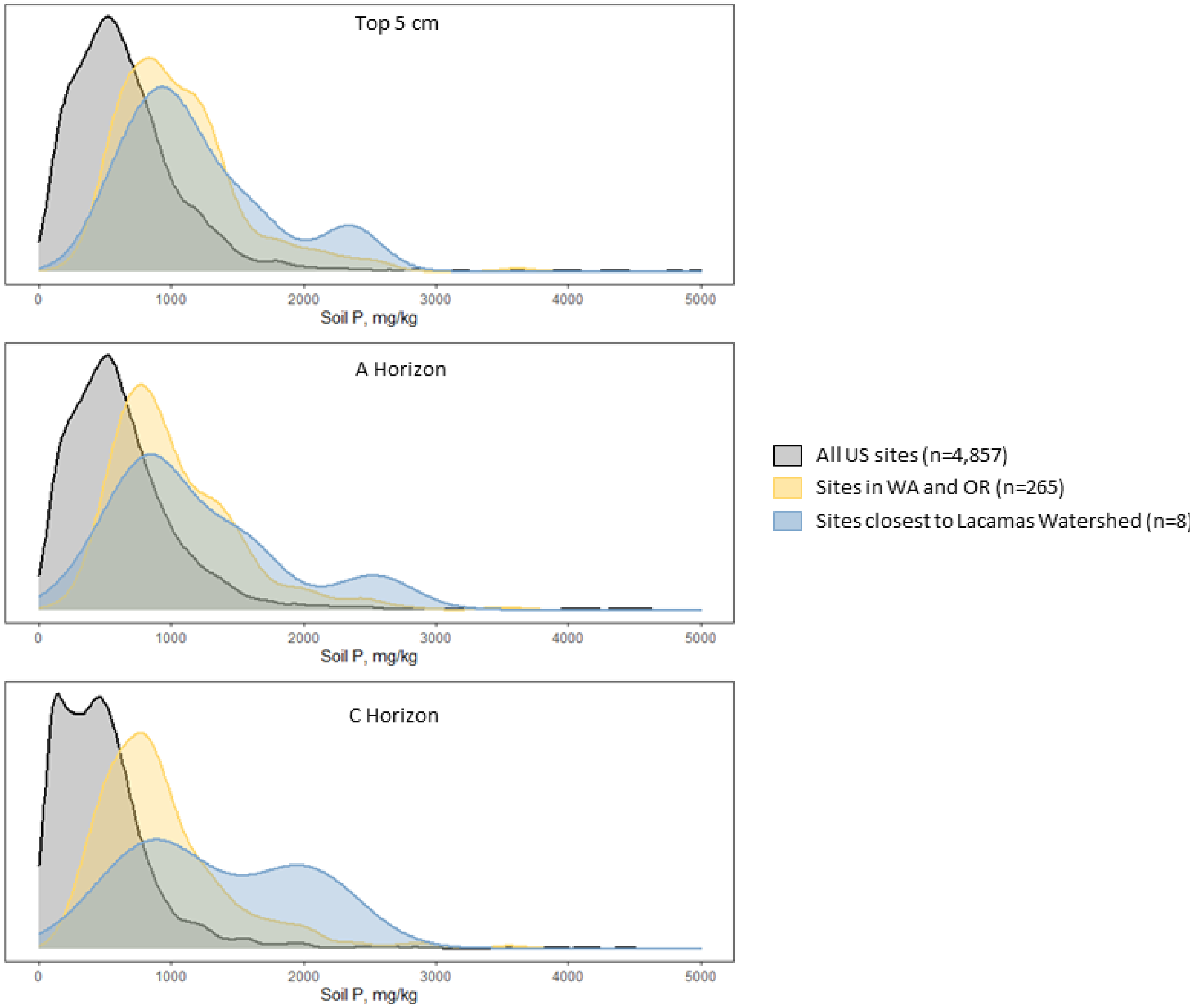


Figure 50. Kernel density plots of soil phosphorus levels from sites near Lacamas Creek, in WA and OR, and across the coterminous United States.
Produced using data from Smith et al. 2014.

Simple Method

We used the simple method to complement the land use analysis. The simple method is a basic unit-area stormwater runoff loading model, with loads calculated only from local drainage basins; it does not consider upstream nutrients or sub-surface groundwater loads. For example, the high nutrient loads predicted for Lower Fifth Plain Creek cannot be explained in the simple method by high nutrient inputs from the China Ditch sub-watershed because the simple method does not include upstream inputs in the runoff calculation.

In this application, the simple method uses localized land use patterns, the impervious area, and observed rainfall to predict theoretical nutrient loadings from overland runoff flow in smaller subbasins (Figure 51). This will allow us to investigate the possible contribution of stormwater runoff to nutrients in the watershed. The analysis also complements the 2011 dataset, which mainly focuses on dry season nutrient concentrations that likely enter the system via shallow groundwater from nearby pollutant sources.

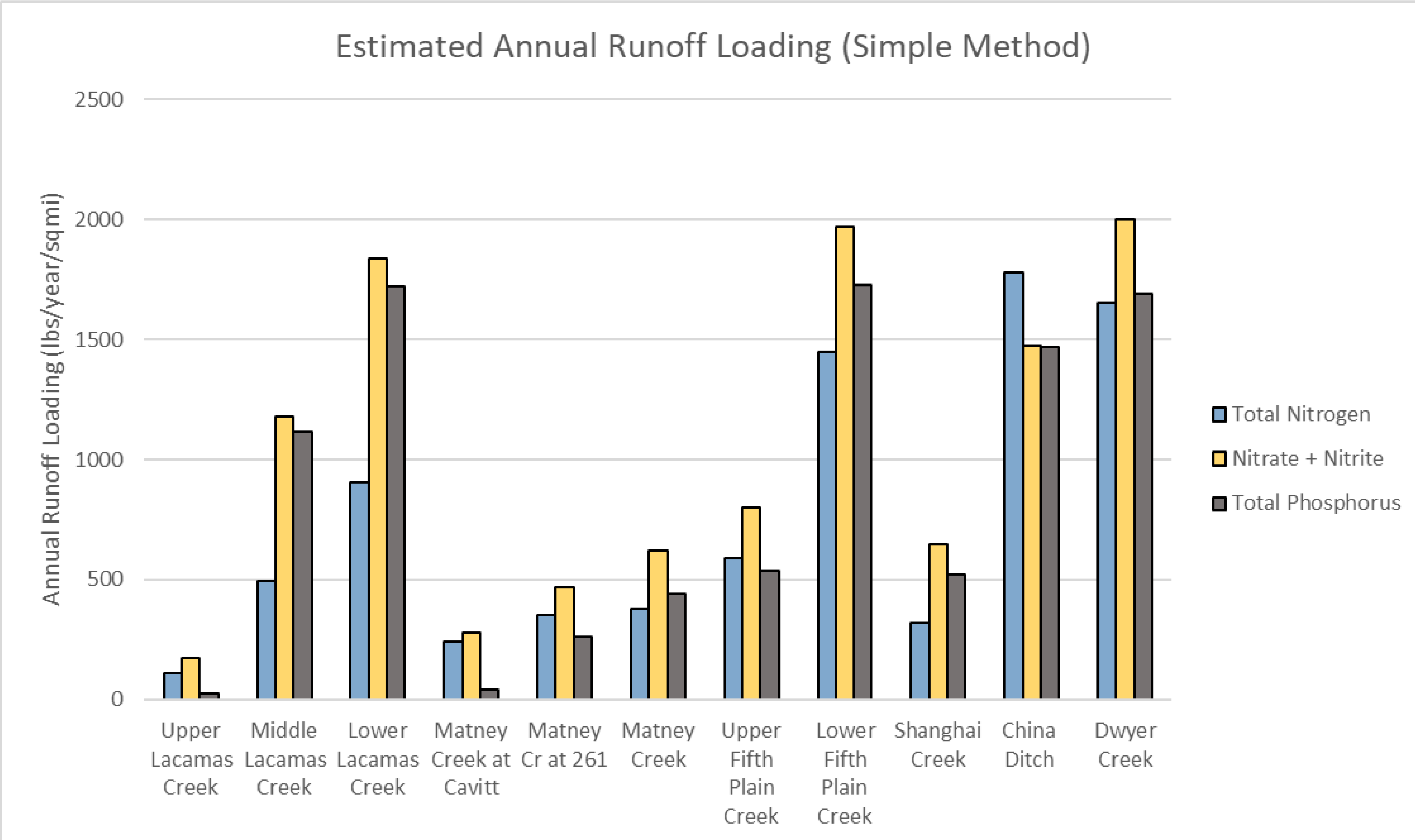


Figure 51. Theoretical overland runoff nutrient loads for each sub-watershed.
See Figure A3 in Appendix A for sub-watershed definitions**.**

While we cannot directly compare these estimated loadings with the measured nutrient concentrations in the watershed, the general pattern of loadings estimated by the simple method is similar to the pattern of nutrient concentrations discussed in the previous section. With one exception (discussed below), the predicted nutrient loads are high in the locations where we measured high nutrients, and the relative amounts of nitrogen and phosphorus within sub-watersheds are similar to those predicted by the simple method. This has two potential implications.

First, variability in nutrient concentrations may at least partially be explained by variability in land use in the watershed since land use forms the basis of simple method predictions. The areas with a higher percentage of developed area and hay/pasture area have increased predicted nutrient loads, while the more forested areas in the upper parts of Lacamas, Fifth Plain, and Shanghai Creeks have lower predicted nutrient loads. See the land use section of this document for additional discussion.

Second, the simple method predicts only nutrient input to the system as a result of stormwater runoff, which is more likely to occur in the wet months (though runoff events can occur during the summer "dry" months). Nutrient sampling occurred only in dry months with little runoff. So, the fact that the patterns of estimated nutrient loadings and observed concentrations are similar to each other suggests the sub-watersheds in the eastern portion of the study area are likely to be targets for nutrient reduction efforts during both the wet and dry seasons.

Dywer Creek is one exception to this general pattern. The simple method predicts high nitrogen and phosphorus in runoff in the Dwyer Creek sub-watershed. However, while Dwyer Creek did have high total phosphorus and orthophosphate concentrations in 2011, nitrogen concentrations were relatively low. It is possible that the ecology of Dwyer Creek influences the relative concentrations of nutrients. If nitrogen is the limiting nutrient in this creek, as indicated by the DIN:OP ratios, it is possible duckweed or other aquatic plants remove it from the water column (Figure 52), leaving a relatively higher concentration of phosphorus in the creek. Since the simple method has no parameters for creek ecology, it would not be able to predict this disparity in nitrogen and phosphorus loadings.

Figure 52. Duckweed growing on Dwyer Creek in October of 2021.

On-Site Septic Systems

Several studies have identified failing on-site septic systems as significant sources of *E. coli* to watersheds, particularly during periods of lower flow such as summers and under drought conditions (e.g. Verhougstraete et al. 2015, Sowah et al. 2014, Oliver et al 2014). The study area contains 3866 on-site septic systems (OSS), so it is possible that failing OSSs contribute to the high bacteria levels in the watershed.

Clark County inspects OSSs and maintains records of which systems comply with inspections at any given point in time (Table 8). Note that a system is considered "in compliance" only if it has an up-to-date inspection, regardless of if any issues were identified by the inspection.

We were unable to find a clear relationship between septic system compliance rates and *E. coli* concentrations in the watershed. In addition, there is no apparent relationship between the compliance rate of septic tanks on properties adjacent to sampling locations and *E. coli* concentrations (Figure 53). This likely indicates that inspection compliance status does not clearly predict whether a septic system is failing or not.

Table 8. Septic system inspection compliance rates for sub-watersheds in the study area.

Lacamas Sub-watersheds	Current	Past Due	Total	Compliance Percentage
China Ditch	493	241	734	67.20%
Dwyer Creek	169	53	222	76.10%
Lower Fifth Plain Creek	85	31	116	73.30%
Lower Lacamas Creek	544	191	735	74.00%
Matney Creek	480	208	688	69.80%
Shanghai Creek	412	113	525	78.50%
Upper Fifth Plain Creek	322	124	446	72.20%
Upper Lacamas Creek	132	40	172	76.70%

Note. Compliance rates as of August 1st and 2nd, 2023.

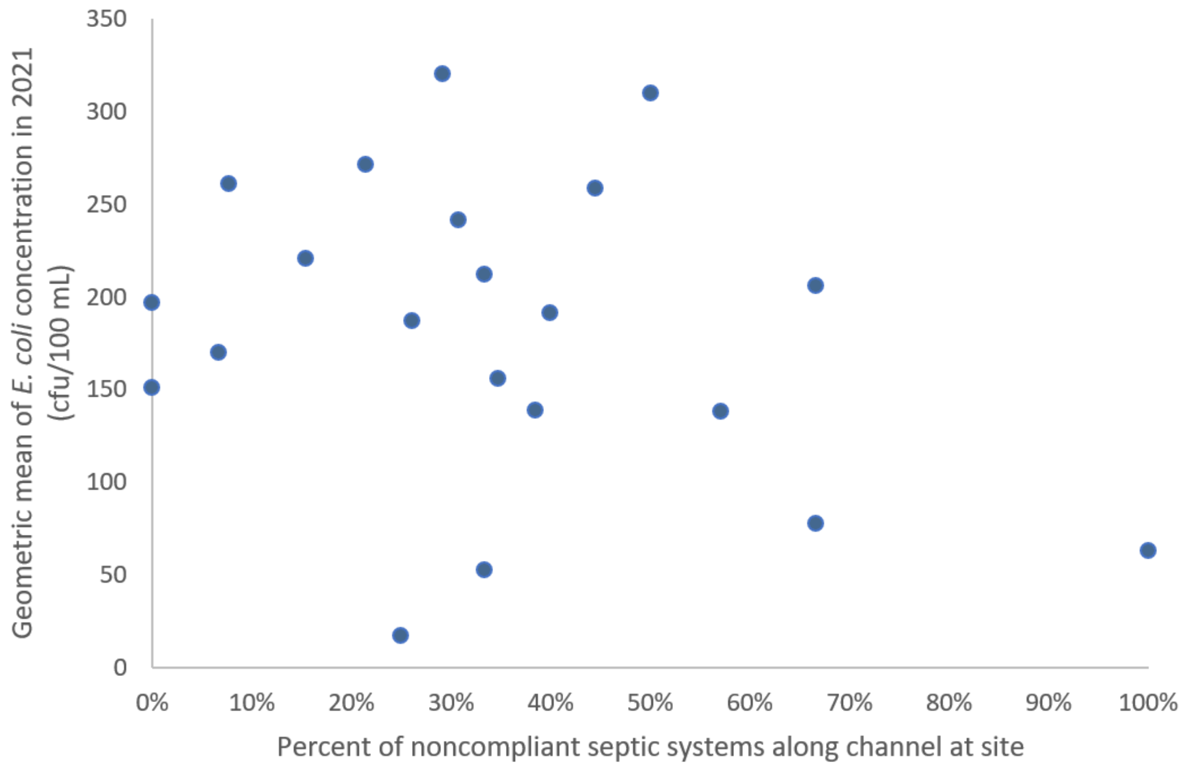


Figure 53. Noncompliant septic systems versus *E. coli* concentrations in 2021.

Failing on-site septic systems may contribute *E. coli* to surface water in the Lacamas Creek watershed. However, the currently available septic data do not explain any of the variability of *E. coli* concentrations in the watershed. While it is important to ensure on-site septic systems are not failing and maintain current inspections, additional information will be required to identify target areas in the watershed where septic systems might contribute bacteria to the watershed. This could include maintaining detailed records of identified failing septic systems and using microbial source tracking (MST) to identify which species (e.g., humans, livestock, pets) contribute bacteria to the creeks in the watershed.

Ecology Observations of Potential Bacteria Sources

Four sites were sampled for bacteria during the 2021 field effort outside of the fixed monitoring sites. These investigative samples were collected between one and four times over the course of the summer when field staff directly observed a potential source of bacteria. This limited sampling was not intended to directly link bacteria sources with elevated *E. coli* concentrations but rather to identify good targets for future sampling to investigate local bacteria sources.

Three investigative sites (28-CHB-1, 28-CHB-2, and 28-CHC-1) are located in the China Ditch sub-watershed, and one (28-FIF-5.5) is located in the Upper Fifth Plain Creek sub-watershed. With the exception of 28-CHC-1, these sites had also been sampled during the 2010 – 2011 sampling effort. Table 9 includes the *E. coli* concentrations for the four investigative sites in 2021. Samples from a fixed site, 28-CHI-1.9, are included for comparison with site 28-CHC-1.

Table 9. *E. coli* values (cfu/100mL) collected for investigative sites during the 2021 sampling effort.

Site	6/16/2021	7/12/2021	8/10/2021	9/1/2021	10/26/2021
28-FIF-5.5	—	—	1300	260	88
28-CHB-1	310	—	—	—	9
28-CHB-2	17	—	—	—	—
28-CHC-1	—	160	980	510	—
28-CHI-1.9	97	96	240	—	27

Note. Site 28-CHI-1.9 is included for comparison with site 28-CHC-1.

Sites 28-CHB-1 and 28-CHB-2 were collected to bracket Hockinson Golf Course. In addition, livestock were observed upstream of 28-CHB-1 (Figure 54). On 6/16/2021, the downstream sample (28-CHB-1) had a higher *E. coli* concentration (310 cfu/100mL) than the sample upstream of the golf course (28-CHB-2, 17 cfu/100mL), suggesting an input of bacteria between the two sites. An additional sample was collected at the downstream site (28-CHB-1) on 10/26/2021 after the golf course closed and appeared to be unused. This site had a lower *E. coli* concentration (9 cfu/100mL), similar to the upstream sample collected earlier in the summer.

Figure 54. Photographs of investigative sites 28-CHB-2 (upstream of golf course) and 28-CHB-1 (downstream of golf course), showing livestock near creek.

Site 28-CHC-1 was collected as a source tracing sample downstream of fixed site 28-CHI-1.9. The samples were collected at the outflow from a pipe draining into the creek (Figure 55). On 7/12/2021, field staff observed the pipe was flowing clear but consistently despite the lack of rain or evident source upstream. There was no evidence of active watering on the agricultural fields adjacent to the site. 28-CHC-1 and the upstream site 28-CHI-1.9 were sampled on the same day twice (7/12/2021 and 8/10/2021). On both dates, 28-CHC-1 had higher concentrations of *E. coli* than the upstream sample at 28-CHI-1.9.

Figure 55. Flowing drain at site 28-CHC-1.

Site 28-FIF-5.5 was classified as a fixed site during the 2010 – 2011 sampling effort but was not included on the list of fixed sites for sampling in 2021. Field staff observed high turbidity at this site on 8/10/2021 and collected a sample to investigate possible bacteria sources upstream of the site. On 9/8/2021, the stream continued to be very turbid (note that staff also observed cattle with direct access to the stream immediately downstream of the sampling site). *E. coli* levels were elevated in August (1300 cfu/100mL) and September (260 cfu/100mL); however, they were not much higher than other elevated *E. coli* concentrations across the watershed in 2021. On 10/26/2021, the creek was less turbid than earlier in the summer, and the sample had a lower *E. coli* concentration (88 cfu/100mL). Figure 56 shows photographs of the creek immediately downstream of the sampling site.

Figure 56. Photographs taken just downstream of site 28-FIF-5.5 showing turbid conditions and livestock access to the stream.

In addition to these observations, on several occasions Ecology staff observed potential sources of bacteria in the watershed. These included:

- Cow patties on the fence-side of creeks, indicating direct livestock access to creeks at Lacamas Creek between river mile 7 and 9.
- A deceased cow in Lacamas Creek near river mile 9.
- Manure application on fields upstream of Big Ditch and Lacamas Creek sampling sites.
- Manure piles near the creek at Fifth Plain Creek just upstream of its confluence with Lacamas Creek.
- Livestock (chickens) upstream of the sampling site in Shanghai Creek.

These observations cannot (and are not intended to) explain all or even the majority of bacteria and nutrients in Lacamas Creek. However, the investigative sites and the additional observations by Ecology staff indicate some of the general types of sources that likely exist in the watershed, including locations we could not directly observe. In addition, these locations are potential targets for additional investigation and removal of bacteria sources from the watershed.

Conclusions

The results of this study support the following conclusions:

Bacteria

- *E. coli* concentrations during the summer of 2021 consistently did not meet water quality standards (WQS) at nearly all sites in the Lacamas Creek watershed. One location on Fifth Plain Creek (28-FIF-0.2) was the only location that met the geometric mean standard for all quarters sampled. This site has a groundwater source that is likely diluting bacteria concentrations.
- Bacteria concentrations in the following creeks are particularly high, indicating that these sub-watersheds may be priority targets for more precisely identifying and addressing *E. coli* sources:
  - Shanghai Creek
  - Dwyer Creek
  - Lower Lacamas Creek (ca. river mile 9.1)
- Available data about On-Site Septic System (OSS) inspection compliance and permit date are not related to observed *E. coli* concentrations. This does not necessarily mean that OSSs are not a source of bacteria. Additional research would be required to more precisely pinpoint which septic systems may be failing in the watershed.
- On several occasions, Ecology staff observed potential non-point sources of bacteria in the watershed. These included:
  - Livestock with access to creeks.
  - Manure on the stream-side of fences, including manure piles and individual cow patties.
  - Dead livestock within a creek.
  - Manure spraying near creeks.
- A seasonal analysis of Fecal Coliform (FC) concentrations collected in 2010 – 2011 indicated that dry season (June – October) bacteria concentrations are consistently higher than wet season (November – May) concentrations. However, FC loadings do not have a consistent seasonal pattern between sites.
- The only site with a significant change in FC concentration between 2011 and 2021 was Dwyer Creek, which saw an increase in FC concentration over the past decade.
- Paired *E. coli* and FC concentrations from samples collected in 2021 indicate that FC and *E. coli* are linearly related in creeks across the watershed; however, the relationship varies between water bodies.

Nutrients

- Nutrient concentrations are consistently very high in the watershed. These high nutrient concentrations in the watershed will eventually enter Lacamas Lake and contribute to nutrient pollution in the Lake.
- The highest nutrient concentrations occur in the watershed's western (nitrogen) and northwestern (phosphorus) areas. The eastern areas of the watershed, including upper Lacamas Creek, Shanghai Creek, and Matney Creek, have generally lower nutrient concentrations.
- The following creeks have particularly high phosphorus concentrations:
  - China Ditch
  - Spring Branch Creek
  - Dwyer Creek
- The following creeks have particularly high nitrogen concentrations:
  - Lower Lacamas Creek
  - Spring Branch Creek
  - Fifth Plain Creek at river mile 0.2 (site: 28-FIF-0.2)
  - China Ditch
- Seasonal data provided by Clark County indicates that nutrient input to the creeks occurs in the wet and dry seasons, with nitrate concentrations in particular tending to be higher in wet months.
- Nutrient data collected by Clark County and by Ecology from a temporary ambient monitoring station between 2020 and 2022 have similar ranges to those collected in 2011, suggesting few changes in the sources of nutrients to the watershed over the past decade.

Land Use

- Overall, land uses in the watershed changed little between 2011 and 2019. The most notable changes in land use were an increase in forested areas in the northwest portion of the watershed and increased development and development intensity in the western and southwest parts of the study area.
- There is a wide range of bacteria concentrations across land use categories in 2010 – 2011 and 2021, and we do not see a relationship between land use and bacteria concentrations.
- Nutrient data indicate that higher nitrogen and phosphorus concentrations are generally associated with sub-watersheds that have a higher percentage of land cover in the developed and pasture land use categories, consistent with existing literature (e.g., Tong and Chen 2002; Hobbs et al. 2015).

pH, DO

- All sites monitored during two 2011 surveys had daily minimum DO levels that did not meet DO criteria.
- Low DO concentrations are correlated with higher total phosphorus and orthophosphate concentrations.
- Those sites with potential groundwater influence (with low temperatures despite poor shade conditions) in China Ditch and Spring Branch Creek have low DO concentrations.
- Most sites met pH criteria during both surveys. The sites with lower pH values (including the one that did not meet standards—28-FIF-0.2) are associated with known groundwater sources.

Temperature

- Most sites monitored during the 2011 dry season exceeded the 7-DADMax temperature criteria, with the hottest stream temperatures on August 25 and August 26, 2011. Tributaries with the greatest percentage of days that did not meet the criteria include:
  - Big Ditch
  - Fifth Plain Creek above river mile 0.2
  - Dwyer Creek
  - Lacamas Creek
- Ecology staff observed poor shade conditions in many locations in the watershed. Improving riparian shade coverage will likely improve temperature conditions in the streams in the study area.
- The only sites that met temperature criteria were on Spring Branch Creek and Fifth Plain Creek at river mile 0.2 (28-FIF-0.2). These sites are both associated with groundwater inputs to the creeks.
- A shade model conducted for the mainstem of Lacamas Creek found that the current effective shade on the creek is approximately 43.6%.
- Two regions have particularly high modeled shade deficit and may be good targets for riparian restoration efforts to improve temperature conditions in the creek.
  - The two-mile stretch between 28-LAC-9.1 and 28-Lac-11.1
  - The headwaters of the creek above site 28-LAC-14.8.
- The downstream portion of the Lacamas mainstem requires further system potential shade analysis. However, reforestation efforts in this area may also be feasible.

Recommendations

Reduce Bacteria Concentrations

To reduce concentrations of harmful bacteria in the Lacamas Creek watershed, Ecology recommends the following:

- Perform more intensive sampling to identify potential sources of bacteria in streams in the Lacamas Creek watershed. This sampling can include Microbial Source Tracking (MST) to identify more precisely which species (e.g., humans, livestock, pets) contribute the most bacteria to the creeks.
- Shanghai Creek, Dwyer Creek, and Lower Lacamas Creek are priority areas for MST. These areas had the highest observed *E. coli* concentrations in the watershed.
- Continue education and outreach work in the watershed community about nonpoint sources of pollution, particularly livestock access to creeks. On several occasions, Ecology staff directly observed livestock with direct access to creeks and manure piles close to creeks.
- Maintain more detailed records of issues identified with on-site septic systems (OSS), including identifying failing OSS and investigating whether failing OSS occur in areas with elevated *E. coli* concentrations.
- Conduct investigative stream walks along tributaries to identify and sample unknown and unmapped outfalls (e.g., pipes and culverts) during wet and dry seasons. In particular, investigative stream walks should be conducted at sites in the China Ditch sub-watershed, where field staff have observed unmapped pipes with associated high bacteria concentrations.

Reduce Nutrient Concentrations

To reduce concentrations of nutrients in the watershed and, therefore, to reduce nutrient inputs to Lacamas Lake, Ecology recommends the following:

- The following areas should be prioritized for phosphorus source identification and remediation:
  - China Ditch,
  - Spring Branch Creek
  - Dwyer Creek
- The following areas should be prioritized for nitrogen source identification and remediation:
  - China Ditch

    - Spring Branch Creek
    - Lower Lacamas Creek

- Perform water quality modeling to identify potential solutions for improving DO and nutrient conditions in the areas identified above (China Ditch, Spring Branch Creek, Dwyer Creek, and Lower Lacamas Creek).
- Continue education and outreach work in the watershed community about nonpoint sources of pollution, particularly in areas with open lawns and pasture areas associated with elevated nutrient concentrations.
- Educate community members regarding the importance of limiting nonpoint sources of nutrient pollution, particularly phosphorus, to decrease nutrient pollution in Lacamas Lake and maintain Lacamas Lake as an important recreation area in Clark County.
- Continue to monitor shut-down operations of local dairies to prevent accidental discharge of nutrients to local creeks. Monitor ammonium concentrations in waters near former dairy areas/lagoons to identify whether dairy closure and lagoon decommissioning reduce ammonium delivery to Spring Branch Creek and Lower Lacamas Creek.

Reduce Stream Temperatures

To address high water temperatures in the Lacamas Creek watershed, Ecology recommends the following:

- Increase riparian restoration through native vegetation plantings on streambanks to increase riparian shade.
- In Lacamas Creek, focus riparian restoration efforts on those areas along Lacamas Creek with high shade deficits identified by the shade model, including the two-mile stretch between river miles 9 and 11 and the headwaters area above river mile 14. Note that this work has already begun in the headwaters area in Camp Bonneville by Clark County.
- Investigate the potential for riparian cover improvements in the downstream portion of the Lacamas main stem.
- In other regions, protect and restore natural floodplains and riparian habitats to increase the amount of cold water refuges available to fish species. While all tributaries had temperatures that did not meet the criteria, those with the greatest number of temperature exceedances and, therefore, the best targets for restoration efforts include:
    - Big Ditch
    - Fifth Plain Creek
    - Dwyer Creek
- Educate local landowners about restoration activities on properties that border creeks to improve temperature conditions in the creeks. These include planting native trees and vegetation and installing livestock-exclusionary fencing.

- Continue to maintain and enforce county riparian buffer requirements for new development in the study area.

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Glossary, Acronyms, and Abbreviations

Glossary

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

Geometric mean: A mathematical expression of the central tendency (an average) of multiple sample values. A geometric mean, unlike an arithmetic mean, tends to dampen the effect of very high or low values, which might bias the mean if a straight average (arithmetic mean) were calculated. This is helpful when analyzing bacteria concentrations, because levels may vary anywhere from 10- to 10,000-fold over a given period. The calculation is performed by either: (1) taking the n^{th} root of a product of n factors, or (2) taking the antilogarithm of the arithmetic mean of the logarithms of the individual values.

Land Cover: The physical coverage of the landscape, including, forests, wetlands, impervious surfaces, and other land and water types.

Land Use: How people use the landscape.

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.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

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.

Salmonid: Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.

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.

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

CAFO	confined animal feeding operation
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
Ecology	Washington State Department of Ecology
EC	*E. coli*
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
FC	Fecal Coliform
GIS	Geographic Information System software
MS4	Municipal separate storm sewer system
MST	microbial source tracking
NLCD	National Land Cover Database
NPDES	National Pollutant Discharge Elimination System (see glossary)
OP	Ortho-Phosphate
OSS	On-Site Septic System
TMDL	Total Maximum Daily Load (see glossary)
USDA	United States Department of Agriculture

USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WRIA	Water Resource Inventory Area
WSDA	Washington State Department of Agriculture
WSDOT	Washinton State Department of Transportation

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
cms	cubic meters per second, a unit of flow
ft	feet
g	gram, a unit of mass
mg	milligram
mg/L	milligrams per liter (parts per million)
mL	milliliters

Appendices

Appendix A. Methods

Field Methods

Field sampling for the original study began in September 2010 and continued through November 2011. During that period, Ecology field staff collected fecal coliform and nutrient samples and measured dissolved oxygen (DO), temperature, and pH. Ecology staff also collected hemispheric photographs to estimate riparian shade cover at several locations along the main stem of Lacamas Creek.

In addition, we completed a more limited field sampling study in 2021. This second sampling focused on collecting fecal coliform (FC) and *E.coli* samples. We supplemented this field sampling with monthly ambient water quality monitoring data collected by Ecology's Freshwater Monitoring Unit (FMU) at Lacamas Creek at Goodwin Road (28120).

The Quality Assurance Project Plans (QAPPs) provide more detailed information about the field sampling and laboratory analysis procedures for this study (Swanson 2011; Gleason and McCarthy 2021; McCarthy and Mathieu 2017). Figure A1 shows the locations of sites sampled by Ecology during the 2010 – 2011 and 2021 field seasons and referenced in this report.

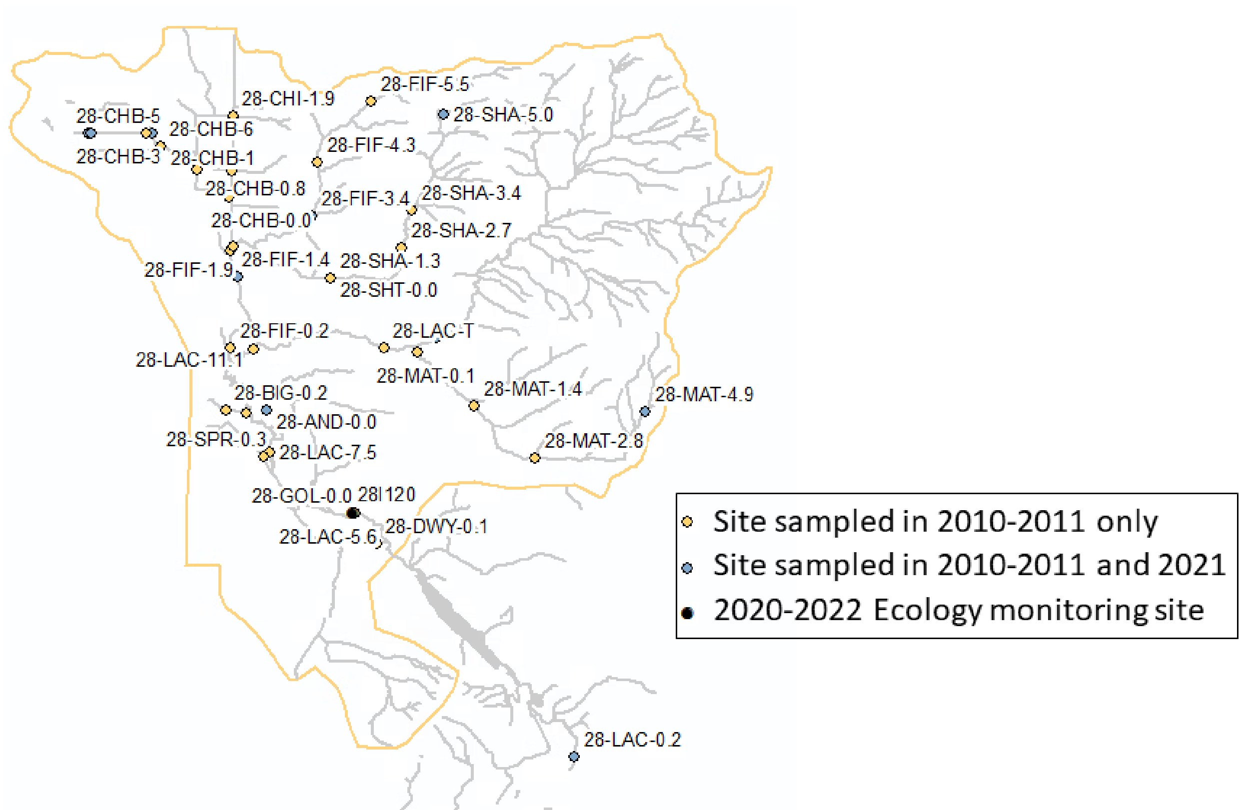

Figure A1. Map of field sampling locations during Ecology's 2010 – 2011 and 2021 sampling efforts.

Bacteria Sampling

During the 2010 – 2011 sampling effort, Ecology staff collected FC samples twice a month from a fixed network of 30 sampling sites in the watershed. Staff sampled most sites 21 – 28 times during the year. We sampled one site (28-GOL-0.0) 16 times between December 2010 and June 2011. Fixed sites included seven on the main stem of Lacamas Creek, six sites on Fifth Plain Creek, four sites each on Matney Creek and Shanghai Creek, and three sites on China Ditch. The remaining fixed sites were on smaller creeks and tributaries, including Dwyer Creek, Spring Creek, and unnamed tributaries of China Ditch and Lacamas Creek.

In addition, staff sampled nine tributaries and irrigation ditches between 2010 and 2011. These investigative sites give additional information about specific land uses and potential sources of pollution. The investigative sites were each sampled between one and 15 times. Six of these sites are located within the China Ditch sub-watershed, and the remaining three are located within the lower Lacamas Creek, middle Lacamas Creek, and Shanghai Creek sub-watersheds.

In 2021, Ecology collected bacteria samples from 26 sites to determine changes in bacteria levels since 2011 and compare bacteria levels to current standards. Of the 26 sites sampled in 2021, 23 were from fixed sites sampled during the 2010 – 2011 sampling period, two were from investigative sites sampled in 2010 – 2011, and one new investigative site (28-CHC-1) was sampled. We sampled each site between one and ten times from 6/16/2021 to 10/26/2021, and each sample included a fecal coliform sample and an *E. coli* sample.

Table A1 presents a summary of the bacteria sampling sites, including the site type and location and the number of samples collected at each site during both the 2010 – 2011 and 2021 field collection efforts.

Table A1. Bacteria samples collected during the 2010 – 2011 and 2021 sampling efforts.

Site ID	Water body	Station Type	Number of FC Samples (2010–2011)	Number of FC Samples (2021)	Number of *E. coli* Samples (2021)
28-AND-0.0	Ditch	Investigative	10	—	—
28-BIG-0.2	Ditch	Fixed	25	1	1
28-CHB-0.0	China Ditch Tributary	Fixed	25	6	6
28-CHB-0.8	China Ditch Tributary	Fixed	25	5	5
28-CHB-1	China Ditch Tributary	Investigative	1	2	2
28-CHB-2	China Ditch Tributary	Investigative	10	1	1
28-CHB-3	China Ditch Tributary	Investigative	10	—	—
28-CHB-4	China Ditch Tributary	Investigative	4	—	—
28-CHB-5	China Ditch Tributary	Investigative	3	—	—
28-CHB-6	China Ditch Tributary	Investigative	1	—	—
28-CHC-1	China Ditch Tributary	Investigative	—	3	3
28-CHI-0.0	China Ditch	Fixed	25	10	10
28-CHI-1.2	China Ditch	Fixed	25	10	10
28-CHI-1.9	China Ditch	Fixed	25	9	9
28-DWY-0.1	Dwyer Creek	Fixed	21	9	9
28-FIF-0.2	Fifth Plain Creek	Fixed	45	10	10
28-FIF-1.4	Fifth Plain Creek	Fixed	25	—	—
28-FIF-1.9	Fifth Plain Creek	Fixed	28	10	10
28-FIF-3.4	Fifth Plain Creek	Fixed	25	—	—
28-FIF-4.3	Fifth Plain Creek	Fixed	25	10	10
28-FIF-5.5	Fifth Plain Creek	Fixed	25	3	3
28-GOL-0.0	Unnamed Tributary	Fixed	16	—	—
28-LAC-0.2	Lacamas Creek	Fixed	21	—	—
28-LAC-11.1	Lacamas Creek	Fixed	25	10	10
28-LAC-13.3	Lacamas Creek	Fixed	25	1	1
28-LAC-14.8	Lacamas Creek	Fixed	24	—	—
28-LAC-5.6	Lacamas Creek	Fixed	25	10	10
28-LAC-7.5	Lacamas Creek	Fixed	25	10	10
28-LAC-9.1	Lacamas Creek	Fixed	25	9	9
28-LAC-T	Lacamas Creek Tributary	Investigative	10	—	—

Site ID	Water body	Station Type	Number of FC Samples (2010–2011)	Number of FC Samples (2021)	Number of *E. coli* Samples (2021)
28-MAT-0.1	Matney Creek	Fixed	28	10	10
28-MAT-1.4	Matney Creek	Fixed	25	10	10
28-MAT-2.8	Matney Creek	Fixed	25	1	1
28-MAT-4.9	Matney Creek	Fixed	25	—	—
28-SHA-1.3	Shanghai Creek	Fixed	25	10	10
28-SHA-2.7	Shanghai Creek	Fixed	25	10	10
28-SHA-3.4	Shanghai Creek	Fixed	25	7	7
28-SHA-5.0	Shanghai Creek	Fixed	21	—	—
28-SHT-0.0	Shanghai Creek Tributary	Investigative	15	—	—
28-SPR-0.3	Spring Branch Creek	Fixed	25	10	10

FC = fecal coliform.

Nutrient Sampling

Ecology collected nutrient samples at 17 sites during three synoptic surveys on 7/26/2011, 8/30/2011, and 10/5/2011. We analyzed each nutrient sample for the following parameters:

- Total Persulfate Nitrogen
- Nitrate + Nitrite as N
- Ammonia/Ammonium
- Total Phosphorus
- Ortho-Phosphate
- Total Organic Carbon
- Dissolved Organic Carbon

Table A2 Lists the locations and number of nutrient samples collected during the summer 2011 synoptic surveys.

Table A2. Nutrient samples collected during the 2011 synoptic studies.

Site ID	Water body	Number of Nutrient Samples
28-AND-0.0	Ditch	5
28-CHB-0.0	China Ditch Tributary	5
28-CHI-0.0	China Ditch	5
28-DWY-0.1	Dwyer Creek	3
28-FIF-0.2	Fifth Plain Creek	5
28-FIF-1.9	Fifth Plain Creek	5
28-FIF-3.4	Fifth Plain Creek	5
28-LAC-0.2	Lacamas Creek	5
28-LAC-11.1	Lacamas Creek	5
28-LAC-13.3	Lacamas Creek	5
28-LAC-14.8	Lacamas Creek	5
28-LAC-5.6	Lacamas Creek	5
28-LAC-7.5	Lacamas Creek	5
28-LAC-9.1	Lacamas Creek	5
28-MAT-0.1	Matney Creek	5
28-SHA-1.3	Shanghai Creek	5
28-SPR-0.3	Spring Branch Creek	5

Note. Samples were not collected at Dwyer Creek on August 30th due to insufficient flow.

Temperature Sampling

Ecology collected continuous surface water and air temperature data from May to October 2011 at 18 sites along Lacamas Creek and major tributaries. Temperature data collection stopped in mid-August at Big Ditch (BIG-0.2) and Dwyer Creek (DWY-0.1) due to stagnant flow. Table A3 includes the locations where continuous temperature measurements were collected.

pH and DO Sampling

Ecology performed two synoptic surveys during the summer of 2011, which included the collection of continuous pH and DO measurements at 14 sites. We installed multi-parameter water quality sondes at select sites for short-term deployments from July 25 to July 28 for the first survey and from August 30 to September 1 for the second survey. DO and pH were not collected at LAC-14.8 during the July survey and LAC-9.1 and CHI-0.0 during the August/September survey. Staff could not collect pH at SHA-1.3 during the July survey due to sensor issues. Table A3 includes the locations where pH and DO measurements were collected during the two periods of short-term deployments.

Table A3. Locations of 2011 Temperature and DO/pH surveys.

Site ID	Water Body	2011 Temp Survey	2011 Jul DO/pH	2011 Aug/Sep DO/pH
28-BIG-0.2	Ditch	Y[a]	—	—
28-CHB-0.0	China Ditch Tributary	Y	Y	Y
28-CHI-0.0	China Ditch	Y	Y	—
28-CHI-1.2	China Ditch	Y	—	—
28-DWY-0.1	Dwyer Creek	Y[a]	—	—
28-FIF-0.2	Fifth Plain Creek	Y	Y	Y
28-FIF-1.9	Fifth Plain Creek	Y	Y	Y
28-FIF-3.4	Fifth Plain Creek	Y	Y	Y
28-LAC-11.1	Lacamas Creek	Y	Y	Y
28-LAC-13.3	Lacamas Creek	Y	Y	Y
28-LAC-14.8	Lacamas Creek	Y	—	Y
28-LAC-5.6	Lacamas Creek	Y	Y	Y
28-LAC-7.5	Lacamas Creek	Y	Y	Y
28-LAC-9.1	Lacamas Creek	Y	Y	—
28-MAT-0.1	Matney Creek	Y	Y	Y
28-SHA-1.3	Shanghai Creek	Y	Y[b]	Y
28-SHA-2.7	Shanghai Creek	Y	—	—
28-SPR-0.3	Spring Branch Creek	Y	Y	Y

Note. A "Y" indicates the survey was performed, and a single dash indicates data was not collected at that location. DO = dissolved oxygen.

[a]Temperature data collection stopped in mid-August at Big Ditch (28-BIG-0.2) and Dwyer Creek (28-DWY-0.1) due to stagnant flow.

[b]pH was not collected at 28-SHA-1.3 during the July survey.

Hemispherical Photographs

Ecology staff took hemispherical photographs at six locations along the main stem of Lacamas Creek (Locations 28-LAC-14.8, 28-LAC-13.3, 28-LAC-11.1, 28-LAC-9.1, 28-LAC-7.5, and 28-LAC-5.6). These photographs were taken on the 20th of July and 14th of August 2011, and on September 22, 2023 at a subset of these sites with a camera placed upright on a tripod in the center of the stream to capture canopy cover (Figure A2). Appendix B contains additional details regarding the hemispherical photographs and their analysis.

Figure A2. Photograph of hemispherical photo camera setup.

Analytical Methods

Information and Data Used

Ecology Information and Data

We used the data from the 2010 – 2011 Ecology field collection efforts to characterize pH, DO, temperature, bacteria, and nutrient conditions in the watershed, identify seasonal patterns in bacteria concentrations and loading, and validate the shade model. This data is uploaded to Ecology's Environmental Information Management (EIM) database. Ecology staff reviewed the EIM data for completeness and accuracy.

We use supplementary data from FC and *E. coli* sampling in 2021 to evaluate changes in bacteria levels from the 2010 – 2011 sampling effort and to determine compliance with current water quality standards (WQS).

In addition, Ecology established a temporary ambient monitoring station at Lacamas Creek at Goodwin Road (Location ID: 28I120). Ecology sampled this station monthly from October 2020 through September 2022 for water quality parameters, nutrients, and bacteria. We used bacteria data from the Goodwin Road site to compare seasonal patterns in 2020 – 2022 compared to 2010 – 2011 data. We compared nutrient data from this site to data collected at Goodwin Road in 2010 – 2011 to determine whether nutrient concentrations changed significantly in this part of Lacamas Creek since the initial sampling effort.

Additional Information and Data

Ecology completed a groundwater assessment to determine how groundwater influences stream flows and surface water quality in Lacamas Creek and surrounding tributaries, and a *Groundwater Interactions and Near Stream Groundwater Quality* report was published in 2013 summarizing those findings (Sinclair and Swanson 2013).

The Clark County Wadeable Streams Status Monitoring Project collects water quality data from nine index sites and 43 rotating panel sites from around Clark County (Clark County 2020). Of these sites, one index site on Matney Creek (MAT010) and six rotating sites are located in the Lacamas Creek watershed.

The six rotating sites were sampled in 2016 – 2017 and 2021 – 2022 for the following nutrient parameters:

- Ammonia (NH_3) as Nitrogen (N)
- Nitrate-Nitrite as N
- Total Phosphorus
- Ortho-Phosphorus as P (only sampled in 2021 and 2022)

This data as well as the continuous data from the index site supplement Ecology data collected across the watershed in 2010 – 2011 and at the Goodwin Road site in 2020 – 2022. We used this data to identify if any changes in nutrient concentrations occurred in the time since Ecology completed initial sampling of the watershed.

Several Geospatial Information System (GIS) layers were compiled from various sources to complete the technical analysis in this study. We used sub-watershed and catchements defined by Clark County Public Works. We supplement these definitions with drainage basin delineations for specific sites calculated using the USGS Streamstats Application (https://www.usgs.gov/streamstats). We use the National Land Cover Database (NLCD) layers for 2011 and 2019 to evaluate land cover patterns in the study area and changes in land cover over the course of the field collection.

Temperature, pH, and Dissolved Oxygen

We summarize temperature, pH, and dissolved oxygen data collected in 2010 – 2011 and compare this data to WQS to determine which stream segments do not meet water quality criteria. In addition, we use a shade model to identify priority areas for riparian restoration projects.

Bacteria

Since the previous criteria expired prior to the supplemental field collection in 2021, we compare only *E. coli* data collected in 2021 to the new water quality criteria to determine which sites and stream segments exceed the current water quality standard.

Seasonal Comparison

FC sampling in 2010 – 2011 included both wet season (November – May) and dry season (June – October) samples. We compare wet and dry season geometric means to determine if the wet or dry season included more water quality criteria exceedances and if there were any spatial trends in the seasonal comparison across the watershed. This analysis was limited to the FC data from 2010 to 2011 because bacteria sampling in 2021 only occurred during the dry season (June – October).

Simple Loading Analysis

While bacteria concentrations are used to determine whether water quality criteria are met and the safety of water for beneficial use, in some cases, a loading analysis can be useful to determine the total amount of bacteria passing through a water body at a specific point over a specified period of time. During the 2010 – 2011 sampling period, several locations periodically included flow measurements on the same dates as FC samples were collected. This allowed the calculation of FC loads for 29 sites. Of these sites, 26 have calculated FC loads for the dry season, 25 have wet season loads, and 22 locations have both dry and wet season loading calculations.

We calculate daily loads by multiplying the FC concentration (cfu/100mL) by the paired instantaneous flow measurement (cfs) (excluding field replicates). We applied a conversion factor to convert the units to billions of colony forming units per day. We then average FC loads annually and seasonally (wet and dry) for each site with loads available.

These FC loads can be used to help identify areas with high annual and seasonal loading, and potentially identify sources of high bacteria loads.

2011 vs 2021 Comparison

While the FC-based water quality criteria expired in December 2020, additional FC samples were collected in 2021 during the bacteria sampling effort. FC samples collected in 2021 were not compared to the expired water quality criteria; instead, we compared them to FC results from the 2010 – 2011 sampling effort to determine if there were any significant changes in bacteria concentrations in the watershed between 2010 and 2021.

FC and *E. coli* Comparison

During the summer 2021 sampling effort, Ecology staff measured both FC and *E. coli* from the same samples. These paired results were compared at each site, and we calculated linear regressions to determine the relationship between FC and *E. coli* concentrations in the Lacamas watershed. While these regression equations should not be used to calculate FC from *E. coli* and vice-versa either in the study area or in other river systems, they can illustrate how FC and *E. coli* concentrations are related in this system.

Nutrients

2011 – 2021 Comparison

Ecology staff collected nutrient samples only during the summer of 2011. The temporal analysis is, therefore, more limited for nutrient samples than bacteria data. However, nutrient samples collected during ambient monitoring at Lacamas Creek at Goodwin Road (28I120) in 2020 – 2022 were compared to 2011 data to determine whether there was a significant change in nutrient concentrations at this site.

Simple Method Runoff Loading Analysis

The simple method for runoff loading analysis is a way to quickly estimate potential nutrient loads in watersheds from overland runoff by multiplying the annual runoff in a watershed by the estimated pollutant concentration and the area of the watershed (Schueler 1987):

$$L = 0.226 * R * C * A$$

Where:

L = Annual load (lbs)
R = Annual runoff (inches)
C = Pollutant concentration (mg/l)
A = Area (acres)
0.226 = Unit conversion factor

Runoff is calculated from the following equation:

$$R = P * Pj * Rv$$

Where:
R = Annual runoff (inches)
P = Annual rainfall (inches)
Pj = Fraction of annual rainfall events that produce runoff (usually 0.9)
Rv = Runoff coefficient

The runoff coefficient is calculated from the impervious area of a watershed:

$$Rv = 0.05 + (0.9 * Ia)$$

Where:

Ia = Impervious Fraction

The simple method is essentially a unit-area loading model and can only estimate steady-state pollutant loads (Lubliner 2007). However, it can be a way to quickly estimate nutrient concentrations derived from stormwater runoff. Here, nutrient load estimates were compared to nutrient concentrations to investigate how and if land use influences nutrient concentrations from overland flow in smaller subbasins.

We estimated nutrient concentrations using the same process as a recent Ecology TMDL study (Watson et al. 2022). First, we estimated potential runoff concentrations of total nitrogen, nitrate + nitrite, and total phosphorus for different land uses from a variety of literature sources:

- A study from western Washington streams for forested and vegetated nutrient concentrations (McIntyre et al. 2018).
- The USDA Manage Nutrient Loss database (version 5) for agricultural nutrient concentrations. We selected and averaged all sites within seven degrees of the study area in the database.
- The arithmetic mean of observations collected from western Washington (Hobbs et al. 2015) for residential, commercial, and industrial nutrient concentrations.

We then produced weighted-average nutrient concentrations for each sub-watershed in the watershed by multiplying each reference concentration by the fraction of land in each land use category in a given watershed. So, for example, more heavily developed sub-watersheds would have proportionally more contribution from the commercial and industrial land uses than more forested sub-watersheds.

We derived land uses from the 2011 National Land Cover Database (NLCD) layer since these estimates were compared with nutrient data collected in 2011. Similarly, we use the 2011 impervious layer from the NLCD to estimate the impervious fraction (Ia) for each sub-watershed.

We use the annual rainfall from Vancouver, WA (38.87 inches) for all sub-watersheds.

Seasonal Analysis

The initial nutrient sampling in 2011 occurred during the dry season months. However, we perform a limited seasonality analysis using the ambient monitoring data collected at Lacamas Creek at Goodwin Road (28I120) in 2020 – 2022, supplemented with nutrient samples collected by Clark County in 2016 – 2017 and 2021 – 2022 at the Matney Creek index site and six additional rotating sites.

Land Use Analysis

A key goal of this study was evaluating land use changes across the study area and determining whether certain land use patterns are associated with elevated bacteria and nutrient levels in the Lacamas watershed. Overall changes in land use categories across the watershed were calculated by comparing the 2011 and 2019 National Land Cover Database (NLCD) layers for the study area.

In addition to a comparison across the study area, we divided the watershed into sample-specific drainage areas to directly compare land use patterns to nutrient data in 2010 – 2011 and bacteria data in 2010 – 2011 and 2021. We used drainage areas calculated for each sampling location using the USGS Streamstats Tool. The StreamStats application uses a digital elevation model to estimate the theoretical drainage basin for each point on a waterway, allowing us to build site-specific drainage basins. However, the StreamStats application can produce basin delineations that have errors, particularly in flat areas. In this study, the drainage areas derived from the StreamStats application were not accurate in several areas, especially the China Ditch region, where the application did not capture the drainage channels established in the 1890s.

We therefore excluded most samples from China Ditch from the analysis. However, we did include land use information from one sample (28-CHI-0.0). Since this sample was taken just above the confluence of China Ditch with Fifth Plain Creek, we used the China Ditch sub-watershed defined by Clark County to delineate the sample's drainage area (Figure A3).

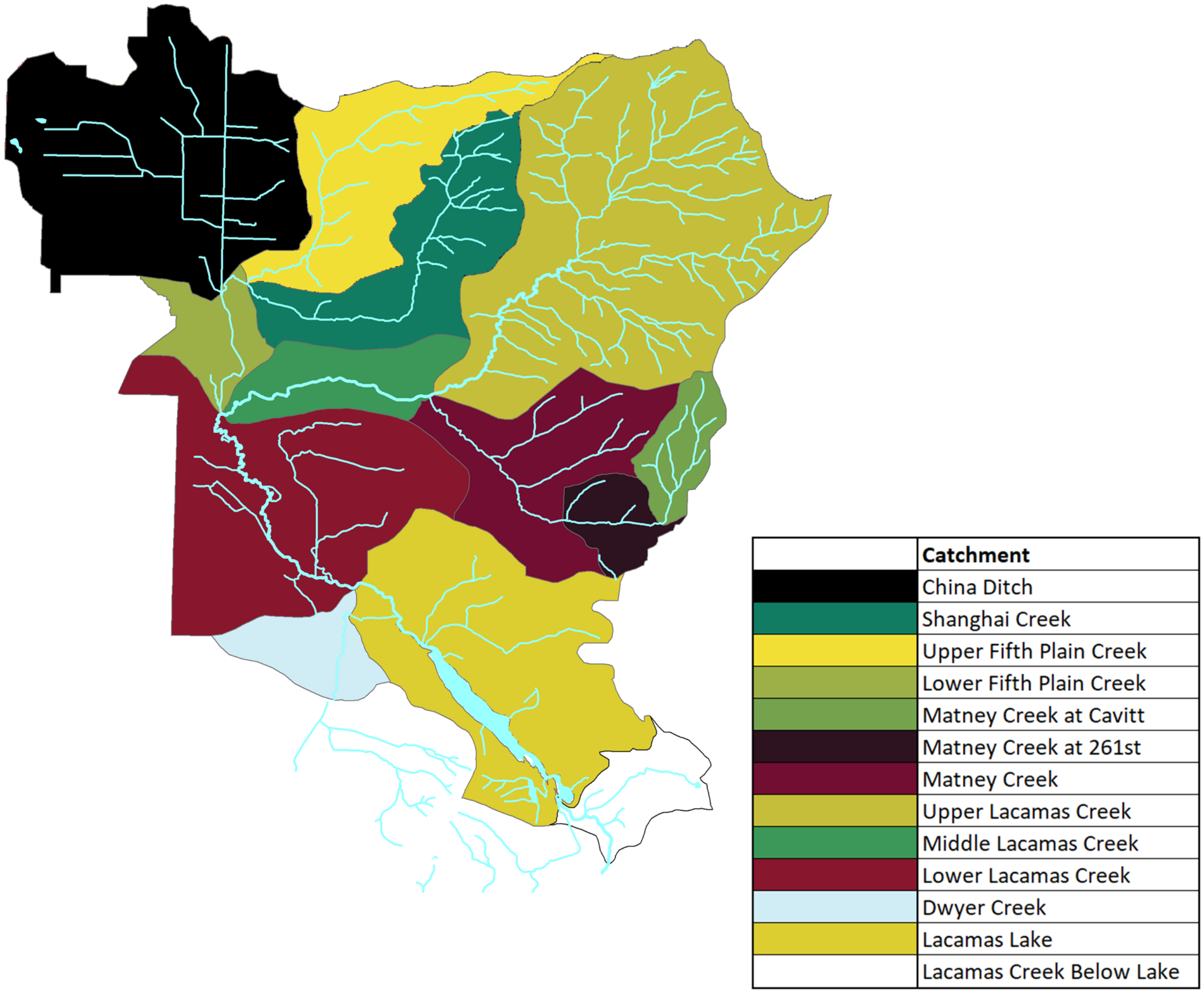

Figure A3. Study area sub-watersheds for land use analysis.

Appendix A References

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Appendix B. Sub-watershed Summaries

Table B1. Heat map of selected parameters in the study area.

Site[a]	Temp[b]	Jul DO[c]	Aug/Sep DO[c]	Ammonia[d]	Nitrate + Nitrite as N[d]	Total Persulfate Nitrogen[d]	Total Phosphorus[d]	Ortho-Phos-phate[d]	TOC[d]	DOCd	2011 — FC[e]	2021 — EC[e]
CHB-0.8	—	—	—	—	—	—	—	—	—	—	124	206
CHB-0.0	17%	5.7	4.2	0.02	0.67	1.14	0.29	0.11	6.1	5.7	379	63
CHI-1.9	—	—	—	—	—	—	—	—	—	—	86	139
CHI-1.2	27%	—	—	—	—	—	—	—	—	—	229	138
CHI-0.0	46%	4.6	—	0.02	0.26	0.56	0.24	0.06	3.8	3.5	120	151
SHA-5.0	—	—	—	—	—	—	—	—	—	—	39	—
SHA-3.4	—	—	—	—	—	—	—	—	—	—	151	220
SHA-2.7	50%	—	—	—	—	—	—	—	—	—	453	261
SHA-1.3	49%	8.5	6.8	0.02	0.23	0.34	0.07	0.01	2.5	2.3	402	271
FIF-5.5	—	—	—	—	—	—	—	—	—	—	58	310
FIF-4.3	—	—	—	—	—	—	—	—	—	—	153	241
FIF-3.4	66%	9.0	7.9	0.03	0.17	0.31	0.05	0.01	2.7	2.5	97	—
FIF-1.9	71%	8.1	7.1	0.03	0.19	0.32	0.06	0.01	2.8	2.5	186	191
FIF-1.4	—	—	—	—	—	—	—	—	—	—	238	—
FIF-0.2	0%	8.4	8.2	0.01	2.58	2.63	0.09	0.04	1.4	1.3	115	78
MAT-4.9	—	—	—	—	—	—	—	—	—	—	87	—
MAT-2.8	—	—	—	—	—	—	—	—	—	—	96	170
MAT-1.4	—	—	—	—	—	—	—	—	—	—	162	212
MAT-0.1	58%	9.3	8.4	0.01	0.34	0.43	0.05	0.01	2.1	2.0	150	156
LAC-14.8	56%	—	8.6	0.01	0.18	0.23	0.03	0.01	1.6	1.5	74	—
LAC-13.3	71%	9.4	8.8	0.01	0.20	0.26	0.03	0.01	1.7	1.6	104	320
LAC-11.1	59%	8.8	8.6	0.01	0.20	0.27	0.03	0.01	1.8	1.6	108	187
LAC-9.1	61%	8.4	—	0.02	1.26	1.34	0.06	0.02	1.7	1.5	227	258
LAC-7.5	59%	8.1	8.2	0.02	1.22	1.35	0.06	0.02	1.7	1.5	221	197
LAC-5.6	53%	8.5	7.9	0.02	1.78	1.91	0.09	0.04	1.6	1.5	123	158
LAC-0.2	—	—	—	0.02	0.48	0.65	0.05	0.02	2.1	1.8	19	—
AND-0.0	—	—	—	0.25	0.36	0.70	0.17	0.02	2.8	1.8	—	—
GOL-0.0	—	—	—	—	—	—	—	—	—	—	68	—
DWY-0.1	65%	—	—	0.02	0.10	0.39	0.08	0.03	4.5	4.2	126	345
BIG-0.2	90%	—	—	—	—	—	—	—	—	—	315	1800
SPR-0.3	0%	7.0	6.0	0.24	2.96	3.31	0.17	0.09	1.5	1.3	97	142

Note. Lighter reds indicate better conditions and darker reds indicate relatively worse conditions. The highest value in the watershed has the darkest color, the lowest value is white, and a proportional color gradient fills in the remainder of values.

DO = dissolved oxygen; DOC = dissolved organic carbon; EC = *E. Coli*; FC = fecal coliform; N = nitrogen; TOC = total organic carbon.

[a]Site IDs are presented without the leading "28-" (e.g., 28-CHB-0.8 is listed as CHB-0.8).

[b]Temperature results in % of days of record exceeding 7DAD-Max temperature standard.

[c]DO results presented as the minimum DO result of record (mg/L).

[d]Average concentration (mg/L).

[e]Bacteria concentrations presented as dry season geometric mean (cfu/100mL).

China Ditch

The China Ditch sub-watershed is characterized by low dissolved oxygen (DO), lower temperatures than other parts of the watershed, and high nutrient concentrations (Table B1). In particular, the phosphorus and organic carbon concentrations in China Ditch are higher than anywhere else in the study area. Nutrient data from Clark County indicates the high phosphorus concentrations in this watershed have continued since initial Ecology samples were collected in 2011. The sub-watershed may be a significant source of nutrients to the watershed, and in particular should be prioritized for phosphorus reduction.

E. coli concentrations from each quarter of 2021 are shown in Figure B1. While bacteria samples were, on average, lower than other parts of the watershed in both 2010 – 2011 and 2021, Ecology staff noted a few potential bacteria sources. The highest FC concentrations recorded during either sampling season were recorded in June 2011 in the China Ditch sub-watershed, originating from the China Ditch tributary (at or upstream of location 28-CHB-0.8). In 2021, investigative samples bracketing the now-closed Hockinson Golf Course indicated higher bacteria concentrations downstream of the golf course. A sample downstream of the golf course after it closed was similar to the upstream site. However, we recommend additional sampling in this area to determine if there is an ongoing source of bacteria in the area.

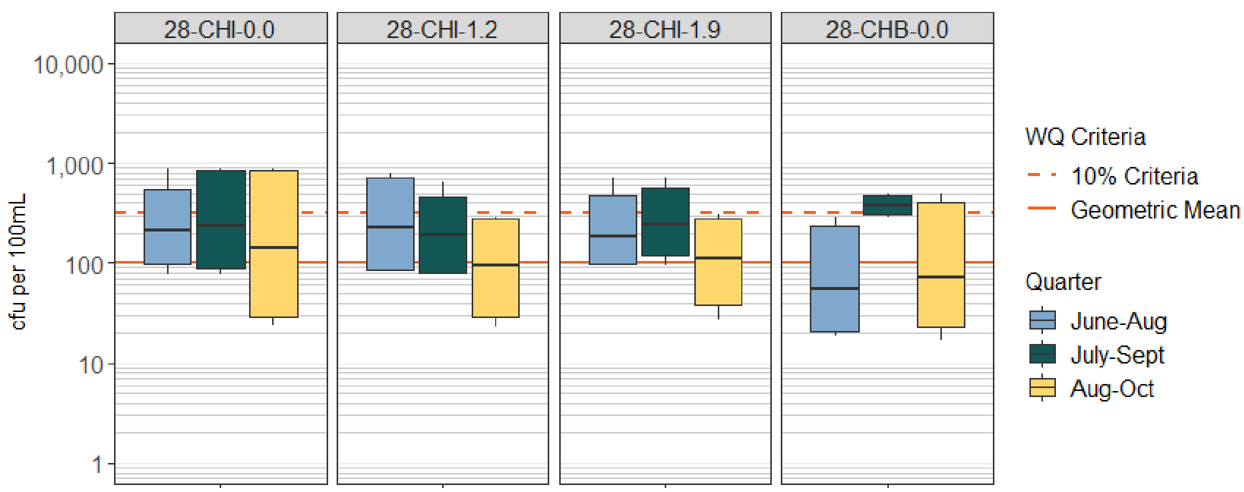
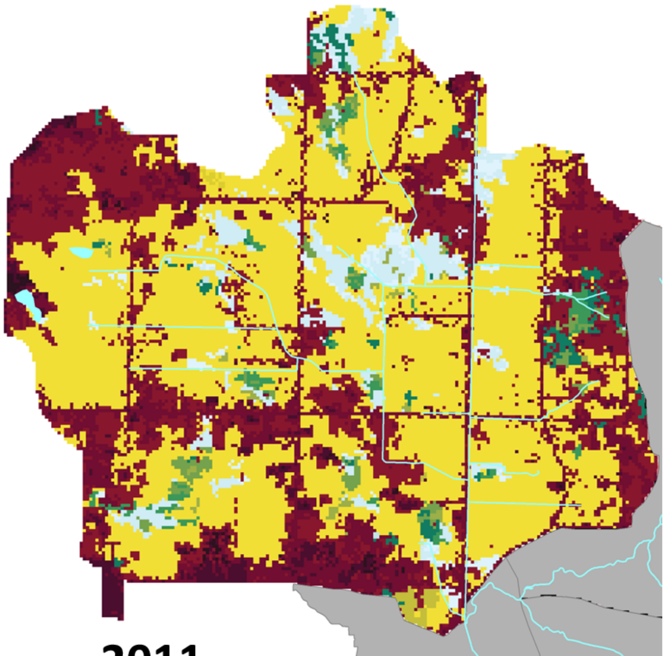


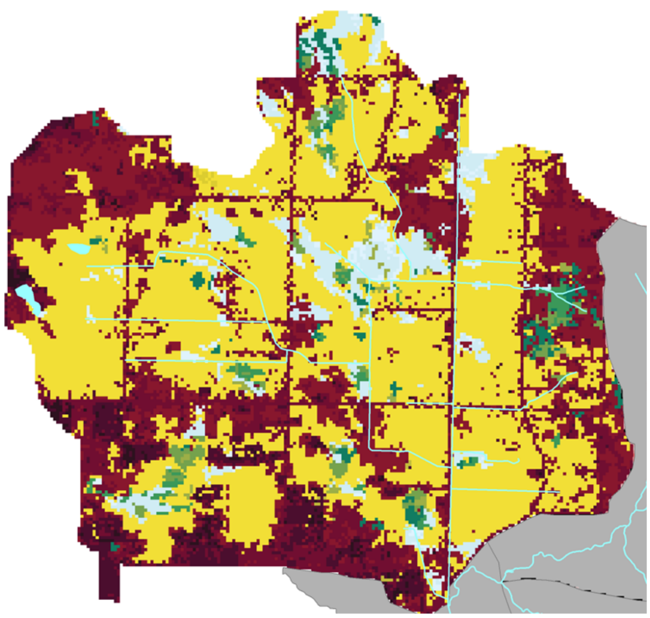
Figure B1. *E. coli* levels for each three-month quarter in the China Ditch sub-watershed from June to October 2021.

E. coli geometric mean indicated by black solid line in boxplot. Water quality (WQ) criteria are displayed as horizontal lines.

The main land use change in the sub-watershed is an increase in development, particularly in the southwest portion of the sub-watershed (Figure 72). Since most of the samples were collected upstream of this major land use change we cannot determine whether it has a major influence on bacteria levels, which did not change significantly between 2011 and 2021 (Figure 73).



2011



2019

COLOR	NLCD value	NLCD Classification
	11	Open Water
	21	Developed, Open Space
	22	Developed, Low Intensity
	23	Developed, Medium Intensity
	24	Developed High Intensity
	31	Barren Land (Rock/Sand/Clay)
	41	Deciduous Forest
	42	Evergreen Forest
	43	Mixed Forest
	52	Shrub/Scrub
	71	Grassland/Herbaceous
	81	Pasture/Hay
	82	Cultivated Crops
	90	Woody Wetlands
	95	Emergent Herbaceous Wetlands

Figure B2. Land use changes in the China Ditch sub-watershed, 2011 (top) to 2019 (bottom).

In 2021, Ecology staff identified higher bacteria concentrations immediately downstream of an outflow pipe to China Ditch than those upstream of the pipe collected on the same day.

Additional, more comprehensive sampling and investigation of flowing drains into China Ditch and its tributaries may reveal sources of bacteria in the creek.

Finally, while China Ditch had fewer temperature noncompliances than other creeks in the watershed, much of the creek has poor shade cover. Increasing riparian buffers on this creek may help further lower temperatures in this creek, decreasing the number of days with temperature noncompliances in this creek.

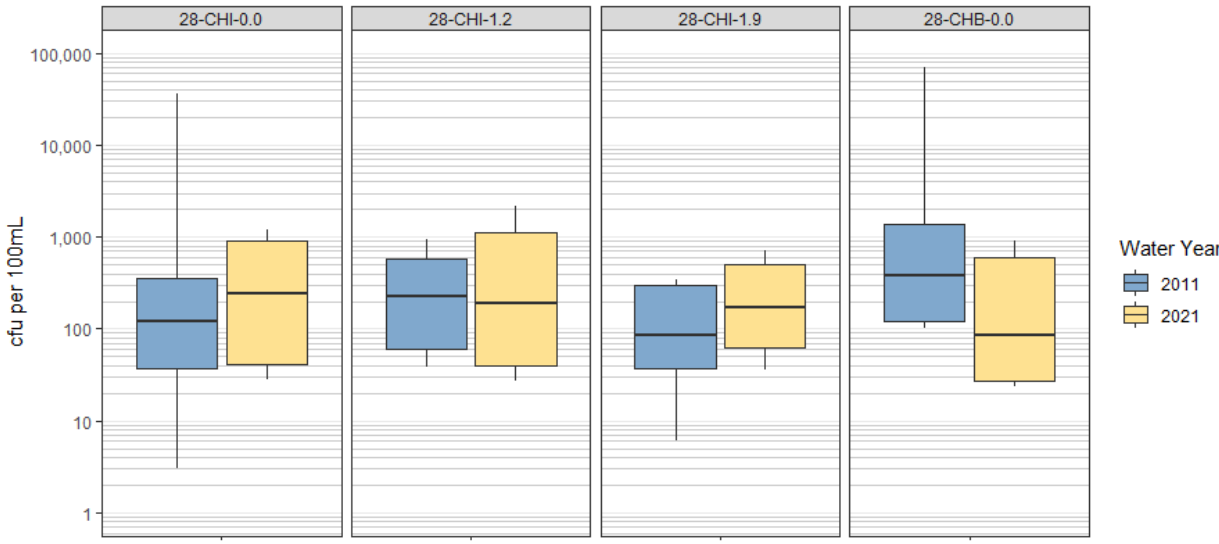
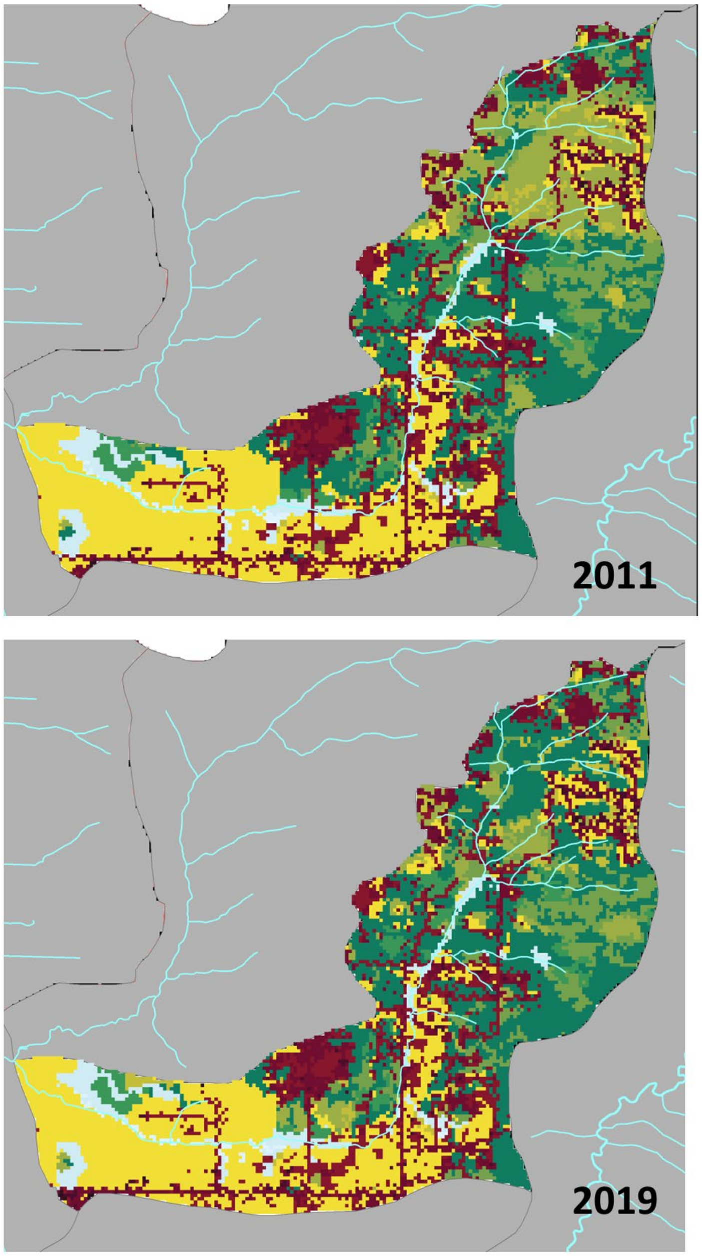


Figure B3. Dry season fecal coliform levels for 2011 and 2021 with geometric mean (black solid line in boxplot) for sites in the China Ditch sub-watershed.

Shanghai Creek

Shanghai Creek had high bacteria levels during both years sampled, and high temperatures in 2011. However, it has relatively lower nutrient concentrations than the more downstream sub-watersheds (Figure B4). In addition, during the August 2011 synoptic survey, Shanghai Creek recorded one of the lowest minimum DO readings (though DO was only recorded at one site on Shanghai Creek). The main change in land use in this sub-watershed was an increase of ~4.4% coverage of evergreen forest (Figure B5). The already relatively high FC concentrations did not change significantly between 2011 and 2021 (Figure B6). Table B1 shows that bacteria concentrations at the downstream sites (28-SHA-2.7 and 28-SHA-1.3) are high, indicating worse conditions relative to the rest of the watershed.

Ecology staff did not directly observe any potential sources for the high bacteria concentrations in this sub-watershed, which were observed at all sites in Shanghai Creek except the most upstream site at 28-SHA-5.0 (this location was only sampled in 2011). The Shanghai Creek sub-watershed had the highest rate of OSS inspection compliance in the watershed as of August 2023, and Ecology staff did not observe any instances of livestock with direct access to the creek or manure piles near the creek. Microbial Source Tracking (MST) may help identify bacteria sources, and the high rates of bacteria in Shanghai Creek in the past decade make it a priority location for additional sampling and MST sampling.



COLOR	NLCD value	NLCD Classification
	11	Open Water
	21	Developed, Open Space
	22	Developed, Low Intensity
	23	Developed, Medium Intensity
	24	Developed High Intensity
	31	Barren Land (Rock/Sand/Clay)
	41	Deciduous Forest
	42	Evergreen Forest
	43	Mixed Forest
	52	Shrub/Scrub
	71	Grassland/Herbaceous
	81	Pasture/Hay
	82	Cultivated Crops
	90	Woody Wetlands
	95	Emergent Herbaceous Wetlands

Figure B4. Land use changes in the Shanghai Creek sub-watershed, 2011 (top) to 2019 (bottom).

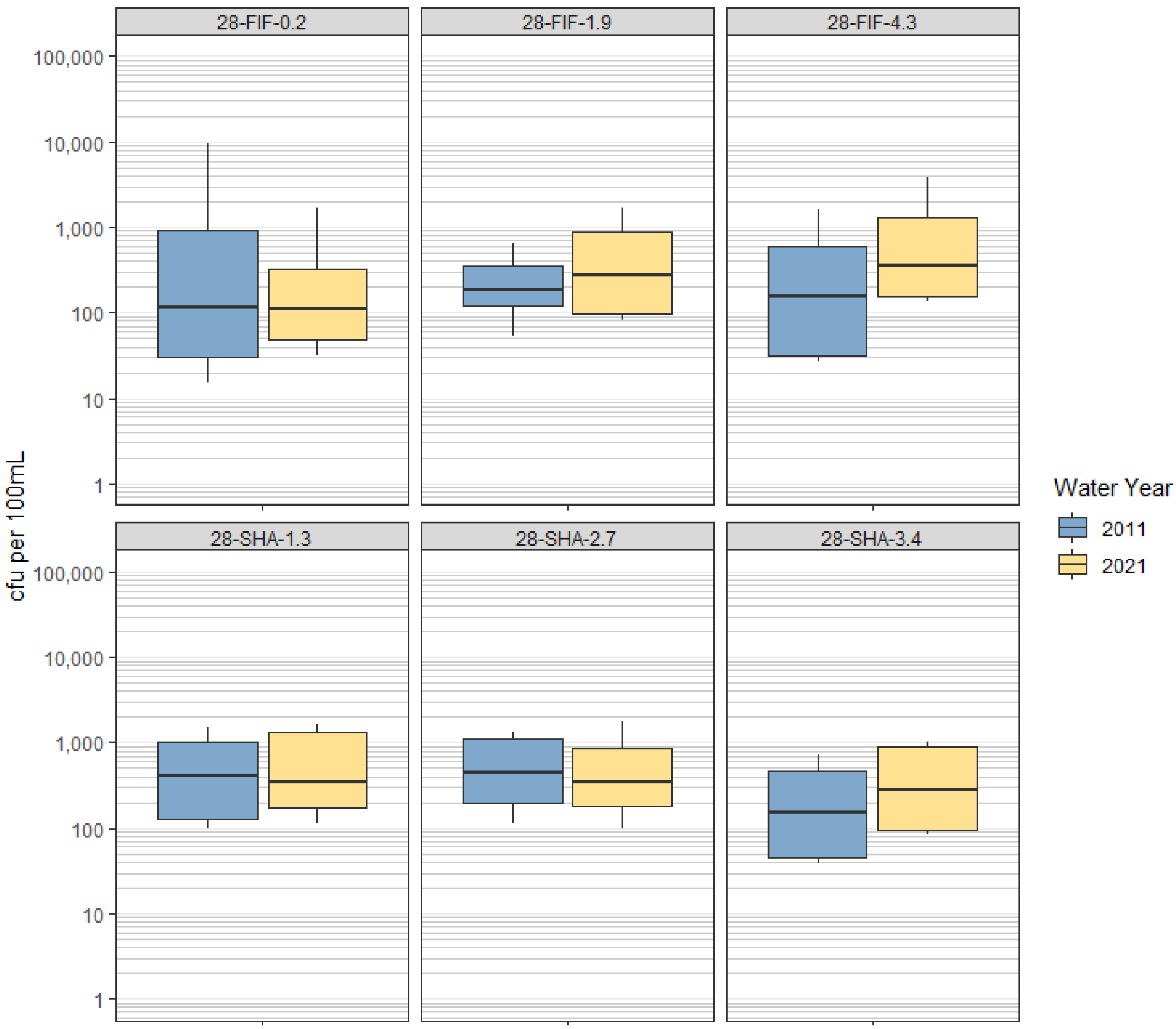


Figure B5. Dry season fecal coliform levels for 2011 and 2021 for sites in the upper watershed (Fifth Plain Creek and Shanghai Creek).

Geometric mean is indicated by the solid black line in the boxplot.

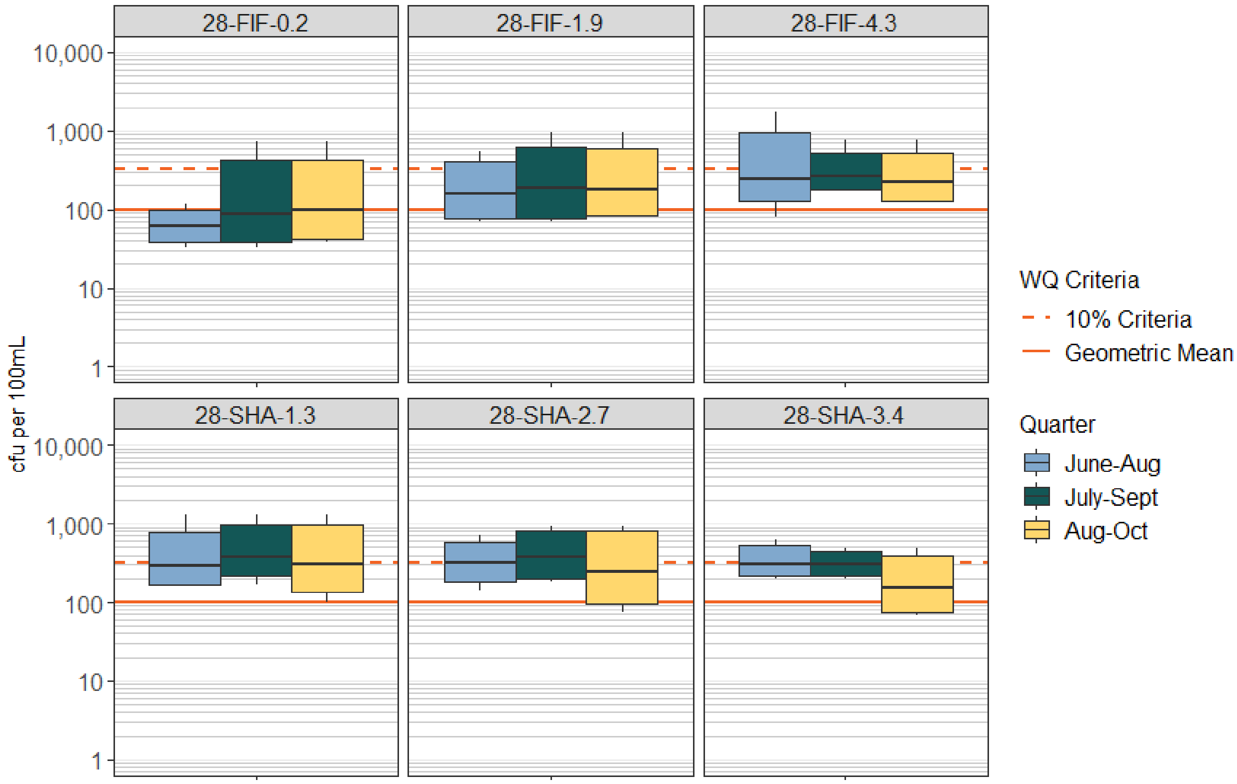


Figure B6. *E. coli* levels for each three month quarter in the Fifth Plain and Shanghai Creek sub-watersheds from June to October 2021.

Geometric mean indicated by the solid black line in the boxplot. Water quality (WQ) criteria are displayed as horizontal lines.

Fifth Plain Creek

Fifth Plain Creek has more complicated spatial and temporal patterns than the other tributaries in the upper part of the watershed, which may reflect the influence of its two tributaries, Shanghai Creek and China Ditch, as well as the groundwater source at 28-FIF-0.2 (Table B1, Figure B6).

In 2010 – 2011, FC bacteria concentrations were higher downstream of the confluence with Shanghai Creek between 28-FIF-3.4 and 28-FIF-1.9 than they are upstream, suggesting that the high bacteria concentrations from Shanghai Creek may influence bacteria in Fifth Plain Creek. This pattern was less clear during the 2021 sampling. However, Ecology staff observed potential bacteria sources in the upper reaches of Fifth Plain Creek in 2021 (including livestock with direct access to the creek just downstream of 28-FIF-5.5). A particular high hit at 28-FIF-4.3 corresponded with lawn maintenance work in the area (1700 cfu/100mL in June). Field staff noted in 2021 that 28-FIF-1.9 often appears to be cloudy or murky, and these dates often correspond to higher bacteria levels (Figure B7)

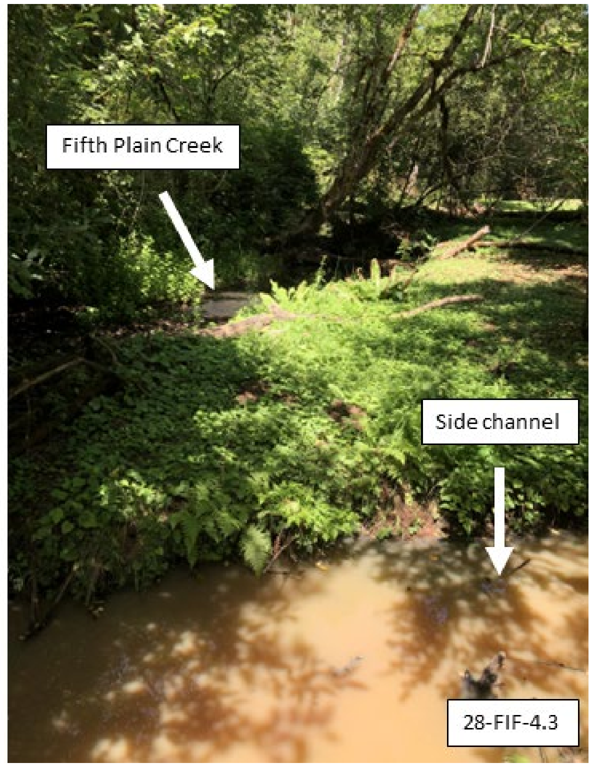
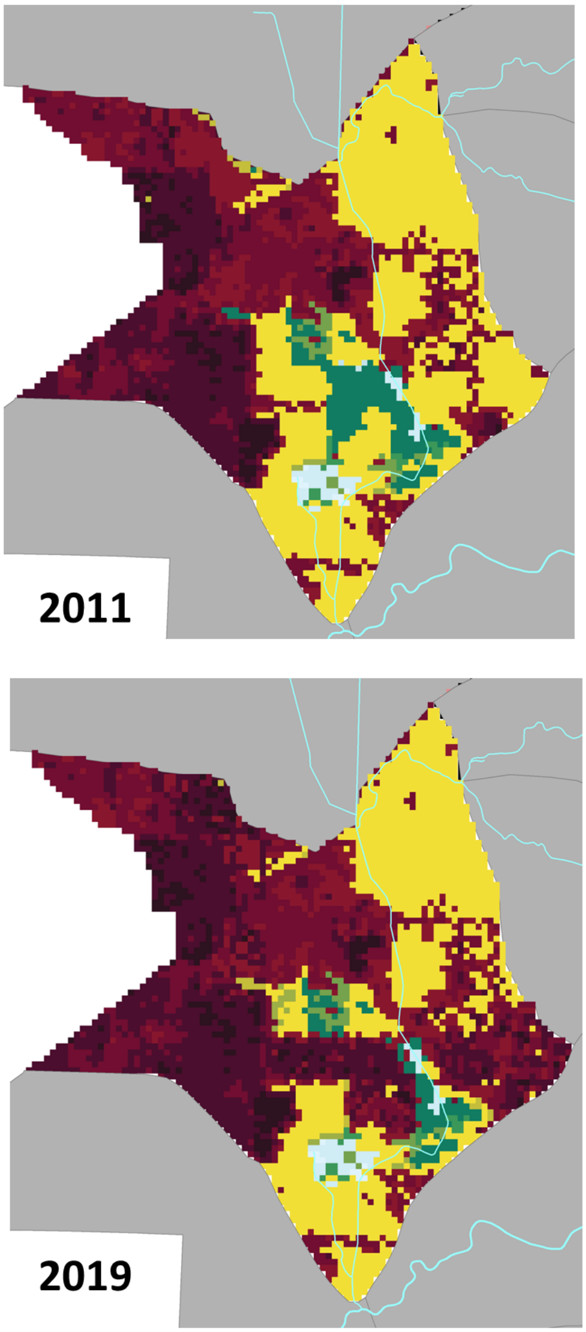


Figure B7. Photographs of site 28-FIF-1.9 and 28-FIF-4.3 showing the cloudy appearance of water in the creek.

Nutrient concentrations, particularly nitrate and total phosphorus, increase in Fifth Plain Creek below its confluence with China Ditch (between 28-FIF-1.9 and 28-FIF-1.4), which, as noted above, has relatively high nutrient concentrations. In addition to the inputs from China Ditch, there are probably more local sources of nutrients in Lower Fifth Plain Creek—for example, the simple method predicts relatively higher nutrient loading in Lower Fifth Plain Creek derived from local runoff.

Temperature, pH, and bacteria (in both 2010 – 2011 and 2021) all decrease at 28-FIF-0.2. This site is consistently clear and swift and was the only site in the study area that met the *E. coli* geometric mean criterion for all sampling periods, with only one high *E. coli* result (720 cfu/100mL) observed at the end of September. In addition, despite an increase in development land use categories between 2011 and 2019 (Figure B8), there was virtually no change in FC concentrations at 28-FIF-0.2 (Figure B5), the site downstream of the most intensive development.



COLOR	NLCD value	NLCD Classification
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	23	Developed, Medium Intensity
	24	Developed High Intensity
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	42	Evergreen Forest
	43	Mixed Forest
	52	Shrub/Scrub
	71	Grassland/Herbaceous
	81	Pasture/Hay
	82	Cultivated Crops
	90	Woody Wetlands
	95	Emergent Herbaceous Wetlands

Figure B8. Land use changes in the Lower Fifth Plain Creek sub-watershed, 2011 (top) to 2019 (bottom).

Ecology's 2013 groundwater survey reported that Fifth Plain Creek was several degrees cooler than Lacamas Creek during both the July and August 2011 surveys, indicating Fifth Plain Creek receives measurable inputs of groundwater prior to entering Lacamas Creek (Sinclair and Swanson 2013). In comparison, other major tributaries, such as Matney Creek and Dwyer Creek, had comparable temperature profiles to Lacamas Creek. The report also concluded that groundwater inputs to Lacamas Creek and its tributaries were not significant sources of FC bacteria. This suggests groundwater inputs to Fifth Plain Creek and Spring Branch may influence bacteria levels by diluting surface water at the sites prior to entering Lacamas Creek.

Matney Creek

Matney Creek is characterized by relatively lower (but still non-compliant) bacteria concentrations and some of the lower nutrient concentrations in the watershed (Table B1). This is consistent with the upper reaches of Lacamas Creek discussed below, as well as lower predicted nutrient loadings from the simple method. DO and temperature conditions, while still not compliant with standards, are better than other parts of the watershed. Every catchment feeding Matney Creek had evidence of reforestation between 2011 and 2021, with an increase in evergreen forest land cover and an associated decrease of grassland/herbaceous and shrub/scrub data (Figure B10 shows the lower Matney Creek catchment as an example).

The highest bacteria concentrations at Matney Creek were found in the upstream sites, particularly 25-MAT-1.4, which had higher geometric means of *E. coli* values in every quarter of 2021 than the downstream site (28-MAT-0.1) (Figure 82). A single sample was collected at an additional further upstream site (28-MAT-2.8) on September 9th to investigate the potential influence of upstream properties. On this date, the *E. coli* concentration at 28-MAT-2.8 was 170 cfu/100mL, higher than the upstream site (28-MAT-1.4; 87 cfu/100 mL) but lower than the downstream site (28-MAT-0.1; 260 cfu/100 mL). This single sample is inconclusive, and future investigation of this creek should focus on potential upstream sources of *E. coli*.

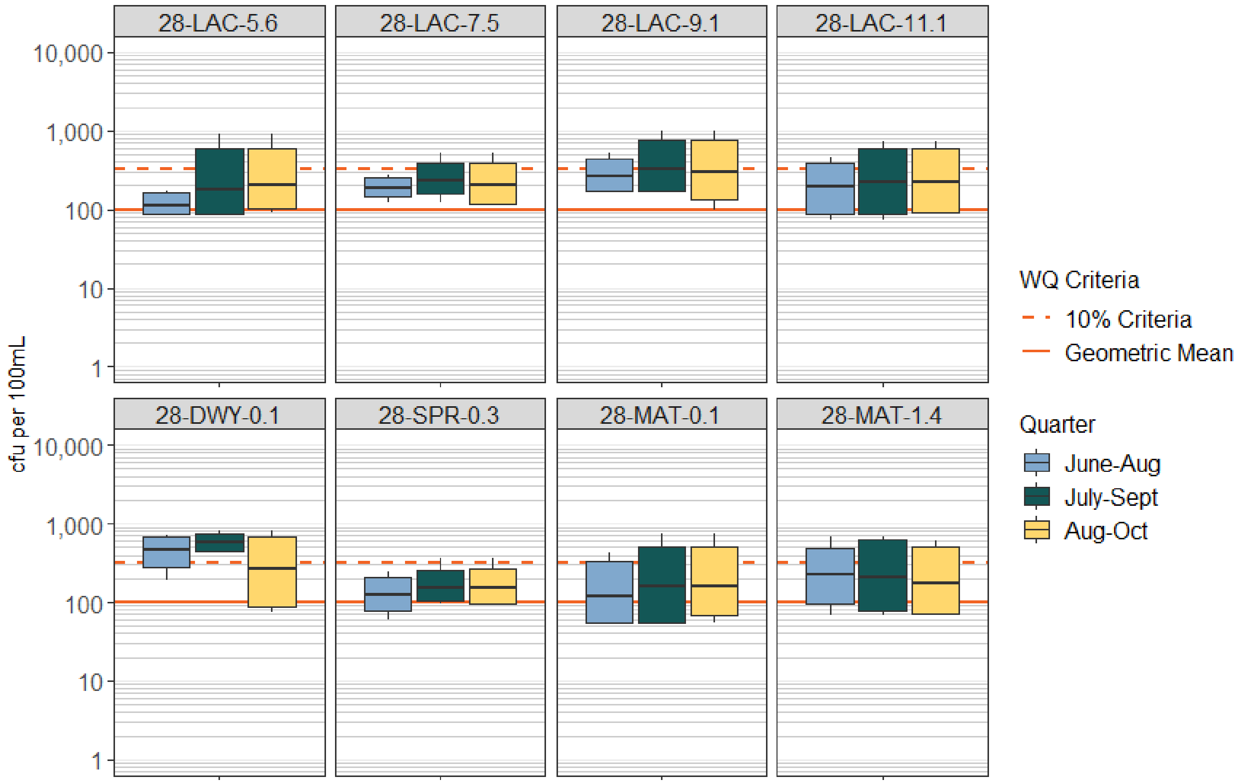
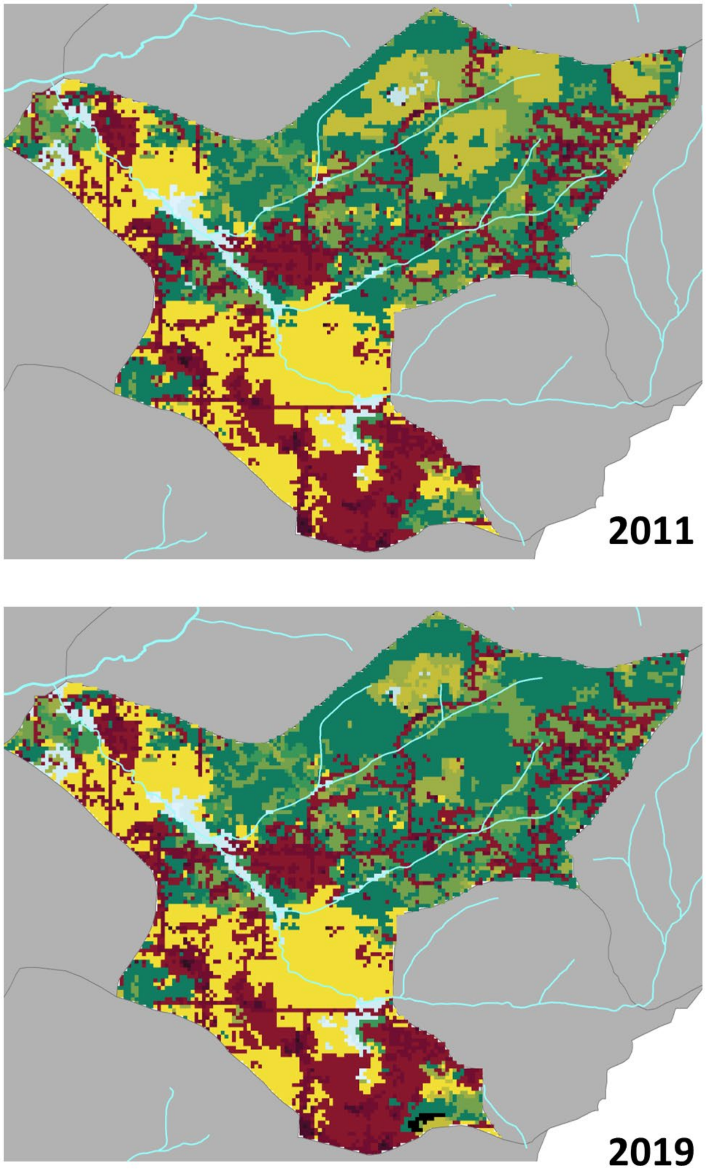


Figure B9. *E. coli* levels for each three-month quarter from June to October 2021 for sites in the lower watershed (Lacamas Creek, Dwyer Creek, Spring Branch, and Matney Creek).
E. coli geometric mean is indicated by the solid black line in the boxplot. Water quality (WQ) criteria are displayed as red horizontal lines.



COLOR	NLCD value	NLCD Classification
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	43	Mixed Forest
	52	Shrub/Scrub
	71	Grassland/Herbaceous
	81	Pasture/Hay
	82	Cultivated Crops
	90	Woody Wetlands
	95	Emergent Herbaceous Wetlands

Figure B10. Land use changes in the Lower Matney Creek catchment, 2011 (top) to 2019 (bottom).

Lacamas Creek and Smaller Tributaries

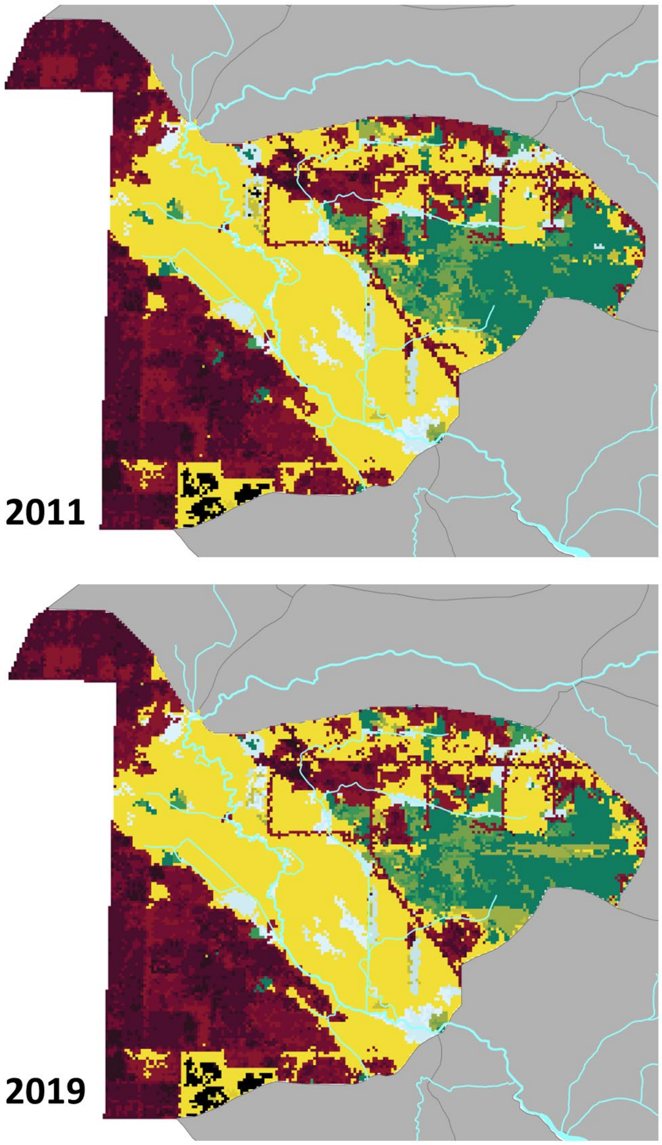
Similar to Fifth Plain Creek, conditions in Lacamas Creek vary through the watershed (Table B1). The upper reaches of Lacamas Creek (between 28-LAC-14.8 and 28-LAC-11.1) are characterized by relatively lower nutrient conditions and lower but increasing bacteria conditions.

DO, nutrient, and bacteria conditions all worsen after the confluence of Lacamas Creek with Fifth Plain Creek between 28-LAC-11.1 and 28-LAC-9.1 (though note that site 28-LAC-13.3 may be one exception to this—the single *E. coli* sample collected at this site was 530 cfu/100mL). In addition to inputs of bacteria and nutrients from Fifth Plain Creek, Lacamas Creek flows through an agricultural area between 28-LAC-11.1 and 28-LAC-7.5. 28-LAC-9.1 consistently had the highest *E. coli* geometric mean out of the 13-mile stretch of the creek sampled in 2021 (Figure 82). Big Ditch, which enters Lacamas Creek directly above 28-LAC-9.1, had consistently high FC levels in 2011. This site (28-BIG-0.2) was only sampled once in 2021, but it had a very high *E. coli* concentration (1800 cfu/100 mL). Ecology staff observed livestock with direct access to Lacamas Creek in this area, and the two highest ammonia/ammonium concentrations in the watershed were observed at tributaries to Lacamas Creek on a former dairy farm (28-SPR-0.3 and 28-AND-0.0). The area should continue to be monitored now that the dairy farm is closed to see if high nutrient and bacteria conditions persist in this stretch of creek.

There is some minor improvement in bacteria conditions between 28-LAC-7.5 and 28-LAC-5.6; however, nutrient conditions remain high at the site closest to Lacamas Lake. Dwyer Creek, which enters Lacamas Creek below 28-LAC-5.6, may be another good target for MST sampling. This site was the only site in the watershed where fecal coliform concentrations had a statistically significant increase between 2010 – 2011 and 2021 (Figure B11). The summer geometric mean of FC increased from 109 cfu/100mL in 2011 to 315.29 cfu/100mL. There is some small shift from open-space to medium- and high-intensity development in the area (Figure B12), but there are not many septic systems in this sub-watershed compared with other sub-watershed. MST sampling in this creek may be able to more precisely identify the sources of bacteria in Dwyer Creek.

Figure B11. Dry season fecal coliform levels for 2011 and 2021 for sites in the lower watershed (Lacamas Creek, Dwyer Creek, Spring Branch Creek, and Matney Creek).

Geometric mean is indicated by the solid black line in the boxplot.



COLOR	NLCD value	NLCD Classification
	11	Open Water
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	43	Mixed Forest
	52	Shrub/Scrub
	71	Grassland/Herbaceous
	81	Pasture/Hay
	82	Cultivated Crops
	90	Woody Wetlands
	95	Emergent Herbaceous Wetlands

Figure B12. Land use changes in the Lower Lacamas Creek sub-watershed, 2011 (top) to 2019 (bottom).

Appendix C. Shade Model

Background

Lacamas Creek and its tributaries were placed on the 303(d) list in 2008 for exceeding Washington State water quality standards (WQS) for temperature as well as dissolved oxygen (DO), pH, and bacteria (Swanson 2011). A Total Maximum Daily Load (TMDL) study was started in 2010 and consisted of collecting field data needed for each of the 303(d) listed parameters. The study additionally identified several data products following the completion of the study. Some of these deliverables, including a shade model for the Lacamas Creek watershed, were never completed. In 2021, a Quality Assurance Project Plan (QAPP) for Lacamas Creek identified a need to complete the shade model and addressed steps to be taken for creating the model (Gleason and McCarthy 2021). Modeling needs outlined in the 2021 QAPP include:

- Calculation of current shade conditions (effective shade) along the mainstem of Lacamas Creek.
- Calculation of potential shade conditions for Lacamas Creek. Potential shade will be calculated by considering shade conditions after vegetation has reached maturation and following hypothetical riparian restoration in areas where soil or land use conditions permit growth.
- Determination of shade deficit (difference between effective and potential shade).
- Qualitative assessment of model through comparison of model predicted shade with shade determined from in-stream hemispherical photos.

Methodology

Shade conditions were calculated for Lacamas Creek with the Ecology Shade model (Ecology 2003a) using inputs from Ecology's Ttool's ArcGIS extension. Ttools calculates several attributes that influence shade, including elevation, topographic angles, near-stream vegetation height, and near-stream vegetation canopy cover. All these attributes are calculated at a user-defined distance along the stream channel. Ttools calculates topographic and riparian conditions along a stream centerline shapefile. Therefore, the first step was to create a stream centerline shapefile.

The stream centerline polyline was delineated manually in ArcMap using a combination of National Agriculture Imagery Program (NAIP) imagery and light detection and ranging (LIDAR) data. LIDAR data was downloaded from the Washington State DNR Lidar Portal (Washington Lidar Portal[5]), and NAIP imagery was available in Ecology's ArcGIS database[6]. Manual delineation of stream centerlines was necessary to ensure greater accuracy for shade model inputs.

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[5] https://lidarportal.dnr.wa.gov/

[6] https://imagery-public.watech.wa.gov/arcgis/rest/services/NAIP/Statewide_NAIP_2017_3ft_4band_wsps_83h_img/ImageServer

NHD stream layers were not used as suggested in the QAPP (Gleason and McCarthy 2021), as neither medium resolution (1:100,000) nor high resolution (1:24,000) NHD were found to perfectly follow the stream channel. NHD layers, on several occasions, were even found to completely veer off the actual stream channel (Figure C1). Manual delineation of the Lacamas stream shapefile was initially challenging. Lacamas Creek is heavily forested near the headwaters and towards the mouth of the watershed. As a result, there is substantial vegetative overhang in these areas that makes it difficult to discern the location of the river channel through aerial photography. Despite the difficulties encountered with aerial imagery, 1-meter resolution hillshade rasters from the Washington State Lidar Portal made it relatively easy to define approximate stream channel boundaries and, therefore, to create the stream centerline shapefile. Every segment of the finalized stream centerline shapefile was checked against the hillshade raster for accuracy.

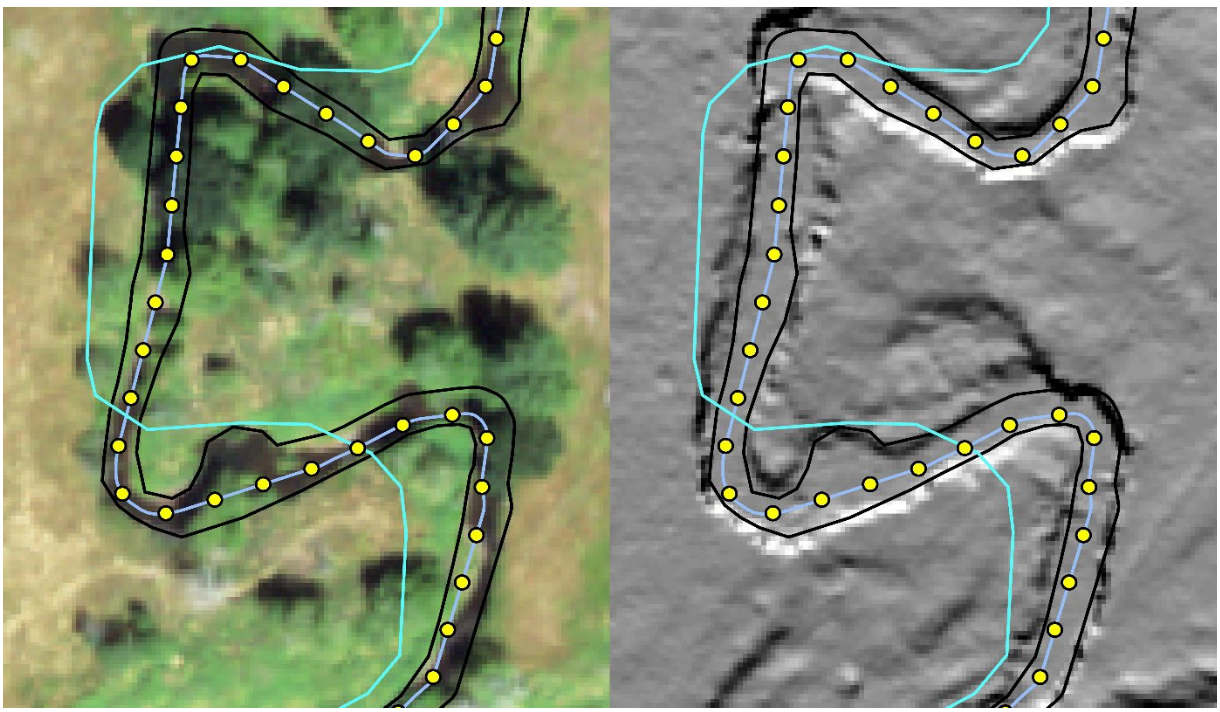


Figure C1. High-res NHD stream layer (light blue) veering off the stream channel vs. manually delineated streamline (dark blue).

Model nodes are shown in yellow. Both NAIP imagery (left) and Hillshade raster (right) were used for delineating channel wetted width.

Following the generation of the stream centerline, model nodes were created. Shade model nodes are created at user-defined intervals along the stream centerline polyline and are responsible for storing any attribute calculated by Ttools. The “Segment/Calculate Aspect” function in Ttools was used to construct the model nodes and, additionally, to calculate the angle (aspect) in which a given model node is facing. The aspect for a given model node is calculated by drawing a line starting at the model node and terminating 0.5 meters along the model streamline (Figure C2). After several iterations, it was determined that model nodes at 10-meter intervals along the approximately 22 Km stretch of Lacamas Creek would sufficiently represent spatial variation in shade conditions. With a 10-meter model resolution, model validation sites, which will be discussed later, were all approximately collocated with at least one model node, allowing for direct comparison of model performance.

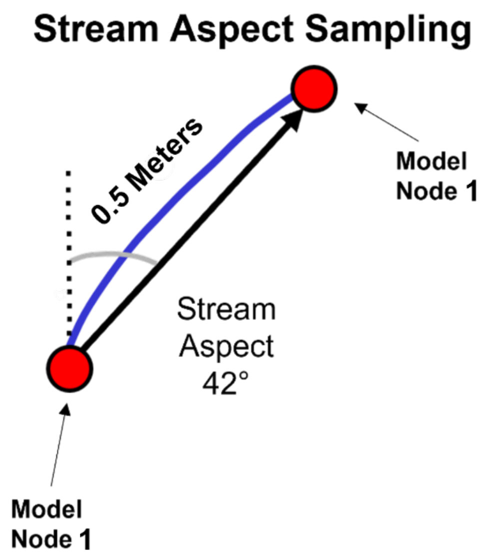


Figure C2. Example of stream aspect calculation.
Stream aspect is calculated between a given model node and itself at a 0.5-meter distance along stream channel.

Before proceeding to the next Ttools calculation step, the channel wetted width was determined. Using the ArcGIS "Buffer" tool, a 30-foot buffer around the stream centerline (9.1 meters) was initially used to approximate the channel geometry in Lacamas Creek. A preliminary observation found the wetted width to be around 30 ft in many areas. Unfortunately, the 30-foot buffer did not adequately approximate channel geometry on a broader scale, and therefore, the channel geometry shapefile was manually edited for the entire creek so that it matched the channel boundaries defined by the hillshade raster as well as NAIP imagery as much as possible (Figure C1). Channel width was then calculated at each of the model nodes using Ttools step 2.

The remaining Ttools steps that were performed for each of the model nodes included determining elevation and gradient (step 3), calculating maximum topographic angles to the east, west, and south (step 4), and finally, sampling vegetation canopy heights on the left and right side of the channel (step 5). All the processes listed above utilized either a Digital Surface Model (DSM) or a Digital Terrain Model (DTM) from the Washington Lidar Portal. Steps 3 and 4, listed above, are, for the most part, completely automated by Ttools, only requiring a DTM raster and the model nodes shapefile as input. For step 3, however, default options were not used. For step 3, the elevation assigned to each model node was selected as the minimum of 9 samples from the DTM.

The last Ttools step requires the user to supply an estimate of the vegetative canopy height. This can be accomplished either by the user creating polygons for a given area and assigning a dominant tree species and canopy height or by using a Canopy Height Model (CHM) raster. The former option uses previous survey results to broadly classify entire areas with a given canopy height and density. The use of CHM rasters, conversely, provides relatively high-resolution approximations of vegetative conditions and are defined as the difference between a DSM (includes buildings and vegetation) raster and a DTM (barren terrain) raster. For this project, DSM and DTM rasters were available for the Lacamas Creek watershed, and thus, the CHM approach was used.

The selection of the year to be used for calculating CHM rasters was influenced by the availability of hemispherical photos by which the final shade model is to be compared. Hemispherical photos of Lacamas Creek were collected in July and August of 2011. DSM and DTM rasters used in this project were downloaded for the year 2013, which was the closest available option to the 2011 target year. Unfortunately, however, a small segment of the northern portion of the Lacamas watershed is unrepresented in both the DSM and DTM for 2013. For the unrepresented watershed segment, DSM and DTM from 2017 were used as a substitute (Figure C3).

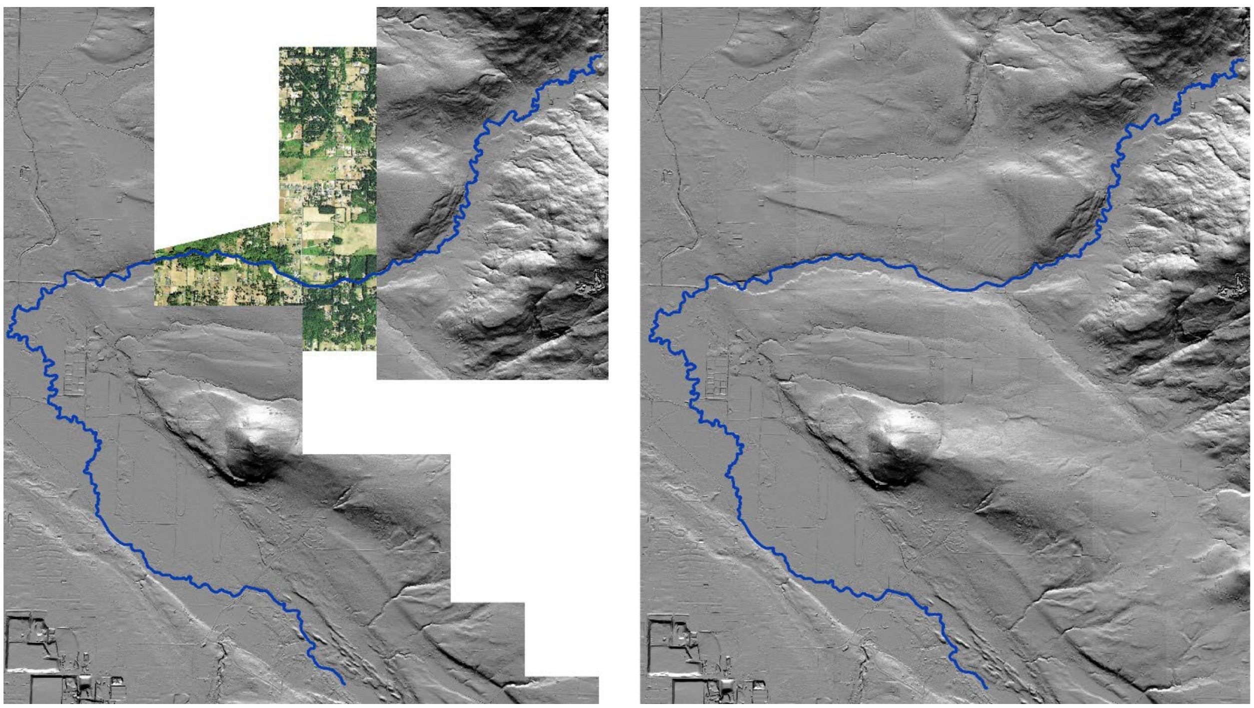


Figure C3. Lidar map of Lacamas watershed from 2013 (left) and 2017 (right).
Left panel shows extent of 2013 lidar data. Right panel shows that 2013 missing lidar data was filled in with 2017 lidar data.

Both DSM and DTM rasters were converted to meters, and a CHM was generated by calculating the difference between DSM and DTM using the ArcGIS raster calculator (Farrell et al. 2013). The CHM raster was then clipped to a 200 feet riparian zone buffer from the wetted width shapefile, and areas with developed landscapes (buildings, etc.) were removed to avoid these areas from being considered in calculations of both effective shade and future potential shade (Figure C4). Despite a lot of effort, however, it was not always possible to remove all roads from the CHM. Fortunately, the few locations where roads were not completely removed predicted essentially barren vegetation and thus were minimally impactful. Coffin et al. (2011) similarly found that roads minimally impacted vegetation height predictions for the shade model they created for the Green River Basin.

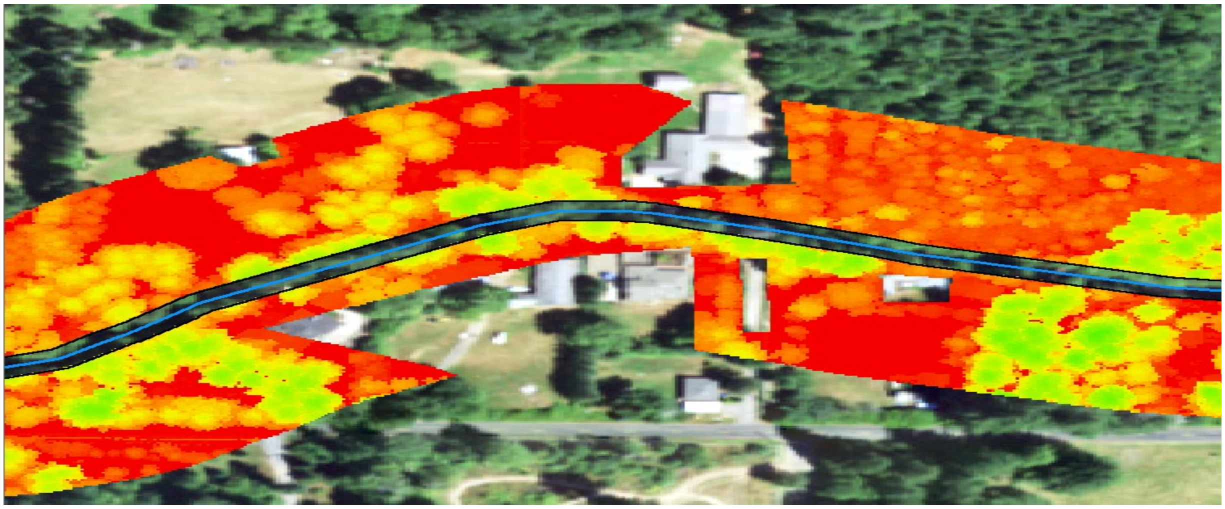


Figure C4. Canopy Height Model raster for riparian zone with developed landscape masked out.

Using the CHM raster, Ttools sampled canopy height for each model node measured perpendicular (rather than star pattern) from the channel bank (rather than stream center) for 9 vegetation sampling zones spaced at variable distances apart from each other (Figure C5). The 9 vegetation sampling zones were placed so that the first few zones near the stream bank would be close together and the remaining zones would be incrementally spaced away from each other (Table C1). This setup was selected over the default 6-meter constant sample zone spacing so that we could have a high-resolution sampling of canopy height in the areas that will be most important (near stream) and lower resolution in areas that are less impactful for effective shade calculations (farther from the stream). For canopy height samples measured by Ttools, vegetative overhang was not included directly and was, in fact, masked out (CHM masked channel out but maintained riparian zone) (Figure C5).

Table C1. Vegetation sample zone spacing (meters). Zone 1 is the distance from the stream channel, while all subsequent zone spacings refer to the distance away from the previous zone.

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
2	3	3	4	6	8	8	10	20

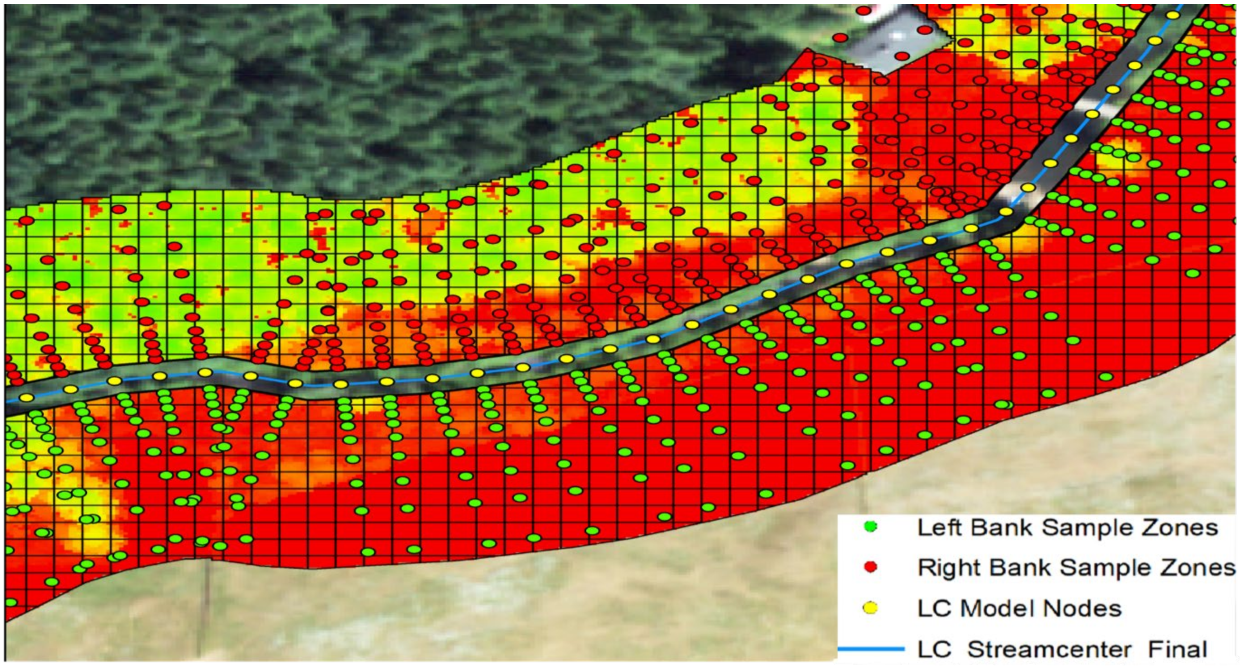


Figure C5. Canopy height in the riparian zone CHM raster is sampled at left (green) and right (red).

Canopy height values sampled from each sample zone are stored in the model nodes shapefile. Canopy density is calculated as the percentage of vegetation above 2 meters within each grid cell.

This was done to simplify the process where potential shade is calculated by considering the stream channel as a place where shade-producing vegetation cannot grow, which is true, but for highly sinusoidal segments such as what is shown in (Figure C6), this means that overhang at model node 123 for example, will not be considered in shade calculations for model node 116. In other words, overhang was considered independently for each model node alone and did not consider the interdependency of shade impacts between model nodes. This is not anticipated to have major impacts on shade calculations as zone 1, which is the most influential (most near stream) location, never had this issue. Additionally, this situation does not occur in general for the vast majority of Lacamas Creek; the circumstances shown in Figure C5 were much more common.

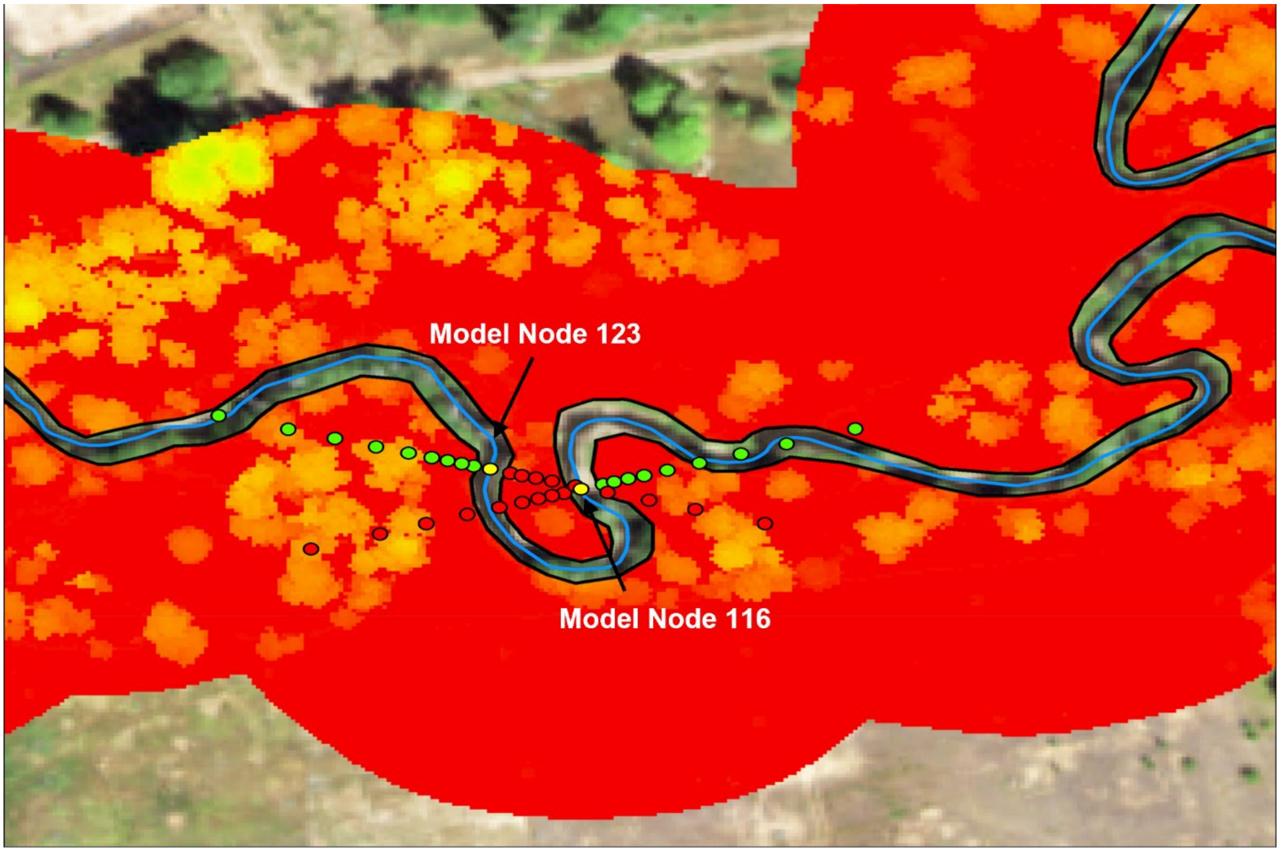
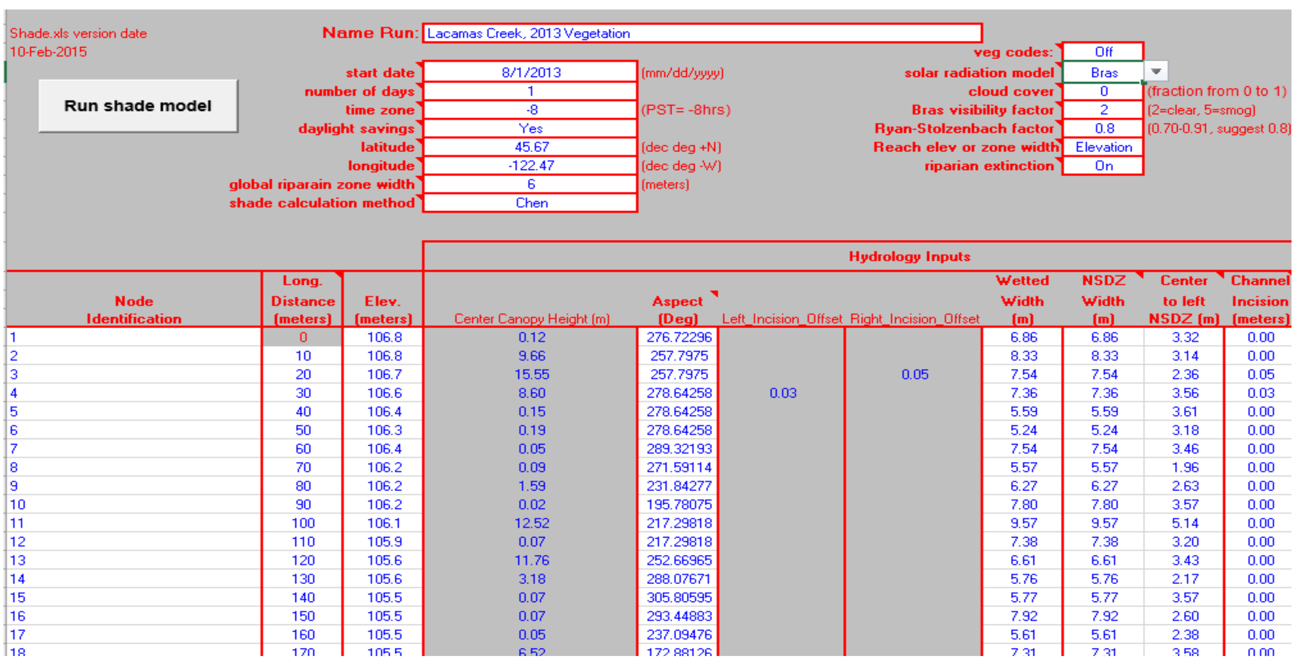


Figure C6. Instances in which left (green) or right (red) bank sample zones cross into the river channel of another node.
For illustrative purposes, only model nodes 33 and 35 are displayed.

For each individual model node, the overhang was approximated using a CHM raster without the stream channel masked out. If there was vegetation present at the stream center greater than 2 meters (to account for potential noise or impacts of smoothing), then the overhang width for each respective channel side (right or left) was approximated as the distance to the center of the channel. While Ttools measures canopy height, it does not have a method for determining canopy density. Canopy density GIS approximation in the literature was generally found to require creating a grid of an appropriate size, devising a criterion to test for whether shade-producing vegetation is present, and then finding the proportion that meets that criterion. Farrell et al. (2013) calculated the percent canopy cover using a 10-meter grid (with CHM of 2m resolution) and calculated the proportion of the CHM in each grid cell that is greater than or equal to 1 meter. Percent canopy cover for this project was calculated in a similar fashion to Farrell et al. (2013), except we used a 1-meter resolution CHM and a 6-meter grid, and considered CHM values of 2 meters or greater as shade-producing vegetation for canopy cover calculations. Therefore, canopy cover was calculated for each grid cell as the proportion of vegetation greater than or equal to 2 meters using the raster calculator tool in ArcGIS (Figure C5). For example, if 80% of vegetation in a given 6-meter (20 ft) grid cell were greater than 2 meters in height, then the canopy cover for the grid cell would be approximated as 80%. Our approach was found to be almost identical to the approach used by DeGasperi (2005), Ma et al. (2017), Moran et al. (2018), and Richardson (2008), all of which used a 2-meter threshold for lidar-derived canopy cover calculations. Canopy cover values were assigned to each of the 9 sampling zones to the left and to the right of the channel for each model node by using the extract by values tool in ArcGIS.

The outputs of Ttools, as well as the canopy cover calculations previously mentioned, were used as inputs to the Ecology Shade Model. Before the model could be run, however, overhang width and channel incision adjustment all had to be estimated. The process for approximating overhang width was addressed earlier and only occurred for locations with vegetation overhangs of 2 meters or greater that reached the channel center. Channel incision was already taken into consideration during the Ttools process by recording left and right bank elevation as well as center elevation. However, there were a few instances in which right or left bank elevation was found to be lower than stream center elevation. In these rare circumstances, a channel incision offset was applied as the absolute value of the difference that resulted in a negative incision.

The shade model for existing conditions was run for a typical hottest day of the year, which we determined to be August 1st. The model was run with many of the default configurations, including the Chen method for shade calculation, Bras solar radiation model, cloud cover of 0, and Bra's visibility factor of 2 (Figure C7). As previously mentioned, we ran the model using variable widths for the riparian sample zone found in Table C1.



Node Identification	Long. Distance (meters)	Elev. (meters)	Center Canopy Height (m)	Aspect (Deg)	Left_Incision_Offset	Right_Incision_Offset	Wetted Width (m)	NSDZ Width (m)	Center to left NSDZ (m)	Channel Incision (meters)
1	0	106.8	0.12	276.72296			6.86	6.86	3.32	0.00
2	10	106.8	9.66	257.7975			8.33	8.33	3.14	0.00
3	20	106.7	15.55	257.7975		0.05	7.54	7.54	2.36	0.05
4	30	106.6	8.60	278.64258	0.03		7.36	7.36	3.56	0.03
5	40	106.4	0.15	278.64258			5.59	5.59	3.61	0.00
6	50	106.3	0.19	278.64258			5.24	5.24	3.18	0.00
7	60	106.4	0.05	289.32193			7.54	7.54	3.46	0.00
8	70	106.2	0.09	271.59114			5.57	5.57	1.96	0.00
9	80	106.2	1.59	231.84277			6.27	6.27	2.63	0.00
10	90	106.2	0.02	195.78075			7.80	7.80	3.57	0.00
11	100	106.1	12.52	217.29818			9.57	9.57	5.14	0.00
12	110	105.9	0.07	217.29818			7.38	7.38	3.20	0.00
13	120	105.6	11.76	252.66965			6.61	6.61	3.43	0.00
14	130	105.6	3.18	288.07671			5.76	5.76	2.17	0.00
15	140	105.5	0.07	305.80595			5.77	5.77	3.57	0.00
16	150	105.5	0.07	293.44883			7.92	7.92	2.60	0.00
17	160	105.5	0.05	237.09476			5.61	5.61	2.38	0.00
18	170	105.5	6.52	172.88126			7.31	7.31	3.58	0.00

Figure C7. Configurations used to run the Ecology Shade Model for current effective shade.

After determining effective shade conditions, we were interested in exploring system potential shade. For system potential shade conditions, the model was run with the exact same settings as the effective shade model (Figure C7). However, we allowed vegetation to reach mature canopy height and additionally included hypothetical restoration efforts in areas where soil conditions would permit it. More formally, we used SSURGO soil survey data to determine which areas were well drained and could support the growth of dominant tree species in Lacamas (primarily Douglas Fir and Red Alder). If soil conditions (well drained and noted that trees could grow there) supported the growth of any of the dominant tree species found in Lacamas Creek, then we considered it a location for riparian restoration and allowed the trees to reach maturation. We considered mature canopy height to be 32 meters based on the system potential tree heights for coniferous tree species used by Coffin et al. (2011) in their shade model for the Green River. Further, if trees were already present but soil conditions were not considered ideal, we retained the current canopy height. Finally, for this hypothetical scenario, any trees that already had a canopy height of 32 meters or greater were left as is.

Results and Discussion

The Ecology Shade Model predicted that, on average, 42.6% of the solar flux to the stream is intercepted by either vegetation or topographic features for the hottest day in 2013. System potential shade was predicted to be approximately 73%. This estimate did not include the lower portion of Lacamas from LAC-9.1 to the mouth. SSURGO data for the lower portion of Lacamas from 28-LAC-9.1 to the mouth consisted primarily of poorly drained silty alluvium but had limited information regarding tree species. Without SSURGO tree species information and since a quick review of surveys (Bureau of Land Management 2023) from the mid-1850s showed that various tree species are feasible in this region, it was beyond the scope of this effort to establish system potential shade for this portion of Lacamas Creek. The shade model, however, found a 28% shade deficit in the upper watershed from the headwaters to LAC-9.1.

A sensitivity analysis was also performed to identify how much of an impact increasing the mature canopy height would have on system potential shade. A study by McCarthy (2020) analyzed SSURGO soil data for 100-year average mixed species (douglas fir, grand fir, red cedar, hemlock, alder, and maple) system potential tree canopy height in Burn Bridge Creek, a watershed that neighbors Lacamas Creek. McCarthy (2020) determined the average 100-year system potential tree canopy height to be 41 meters. The potential shade model was run again using 41 meters for mature canopy height instead of 32 meters. System potential shade for Lacamas Creek under this scenario was approximately 74%. Therefore, there was very little change in potential shade for canopy heights beyond 32 meters.

Qualitative Assessment of Model Performance

The performance of the effective shade model was assessed qualitatively by analyzing hemispherical photos at the locations shown in (Figure C8) and comparing the effective shade estimates from hemispherical photos to the model predictions for effective shade. Hemispherical photos for LAC-14.8, LAC-13.3, LAC-11.1, LAC-9.1, LAC-7.5, and LAC-5.6 were taken on either the 20th of July or the 14th of August of 2011. For hemispherical photos, a camera is placed on a tripod in the center of the stream, and the camera is angled upwards to capture canopy cover. These photos were processed using Gap Light Analyzer (GLA) canopy analysis software (Frazer and Lertzman 1999), which estimates canopy cover and effective shade at the stream center. Each of the photos was analyzed using procedures outlined in EAP's SOP for analyzing hemispherical photos (Stohr et al. 2019). Following the recommendations of the SOP, the GLA software was configured with the settings shown in (Figure C9). For each individual photo, specific settings were also specified, including the latitude and longitude, altitude, magnetic declination (calculated using NOAA Declination Calculator[7]), and projection distortion set to polar.

Figure C8. Hemispherical locations (in orange) for 2011 that will be compared with shade model predictions.

[7] https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml

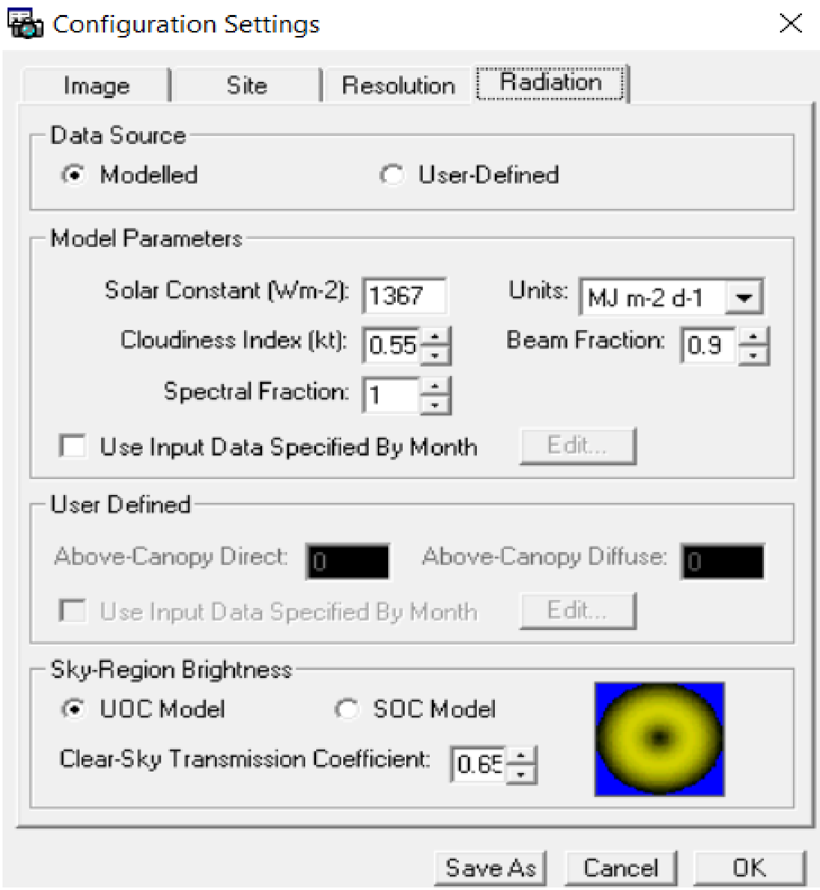


Figure C9. Gap Light Analyzer Software configuration settings used for all hemispherical photos analyzed.

To begin the analysis, a given photo is first registered by selecting the north-facing corner (marked by a red box) and dragging the selection until the south-facing corner is reached (marked by a white box) (Figure C10). In certain situations, there are objects in the photo that can interfere with the shade calculation (such as the bridge in Figure C10). To address this, we can determine if an object will impact shade calculations by using the “plot sunpath” tool under utilities (Figure C11). In this example, we can see that the bridge will have a minimal impact on shade calculations as it is, for the most part, not following the sun path. To ensure that pixels in the image are properly classified, we used the fill color blue as recommended by the SOP for GLA (Stohr et al. 2019), shown in (Figure C12). The working photo is then converted to black and white, and an appropriate transparency is set (it should still capture all distinct features if done correctly) (Figure 13). For the processed image, the effective shade is calculated by the program as the fraction of solar radiation that can pass through the canopy for a given time-period. All hemispherical photos were analyzed for the same day as the shade model (August 1) to allow a direct comparison. Gap Light Analyzer calculations return the total percent transmission, which is then converted to percent effective shade using the formula below (Stohr et al. 2019).

Percent Effective Shade = 100% - %Total Transmission

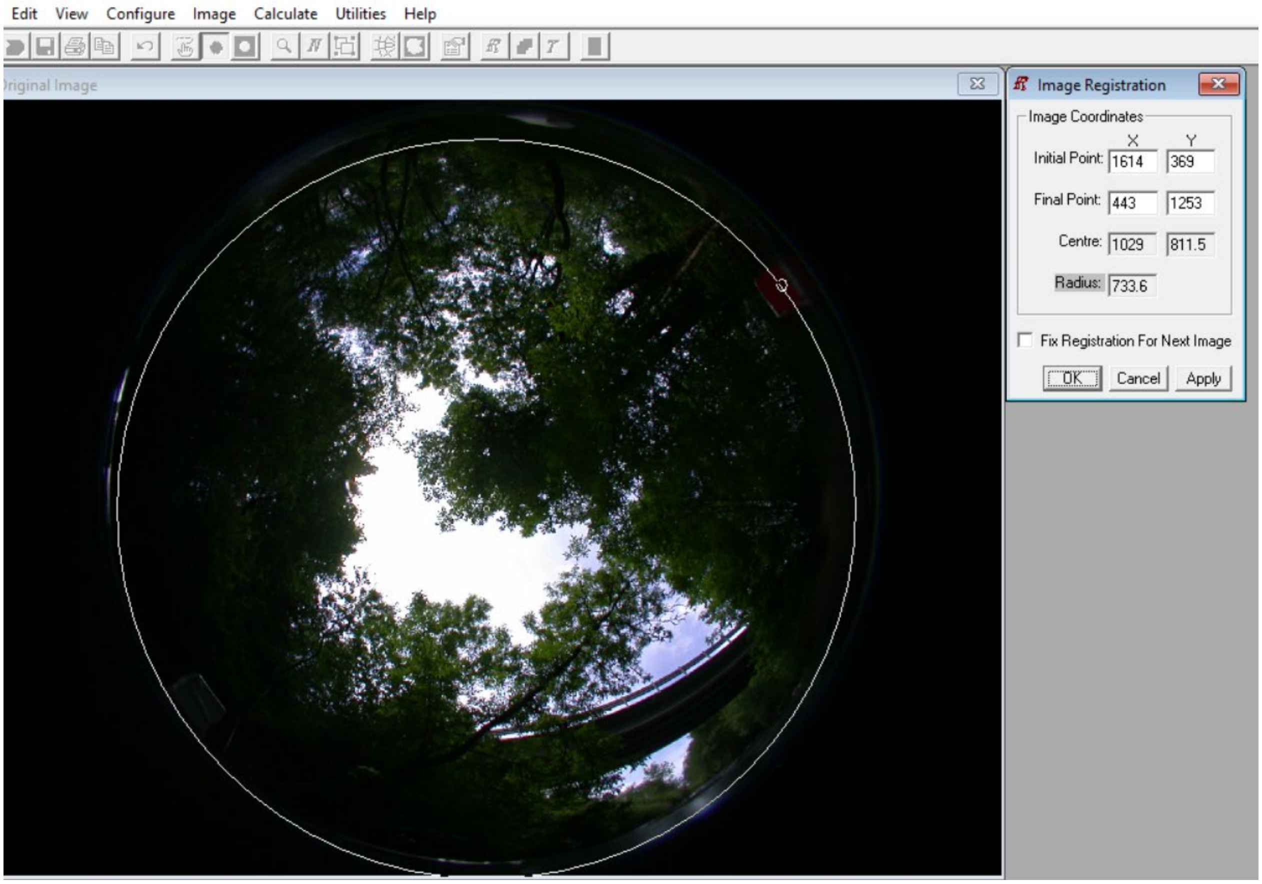


Figure C10. Registering an image in Gap Light Analyzer software.
This consists of dragging the edge of the photo from the north indicating box (shown in red) to the south indicating corner (indicated by a white marker).

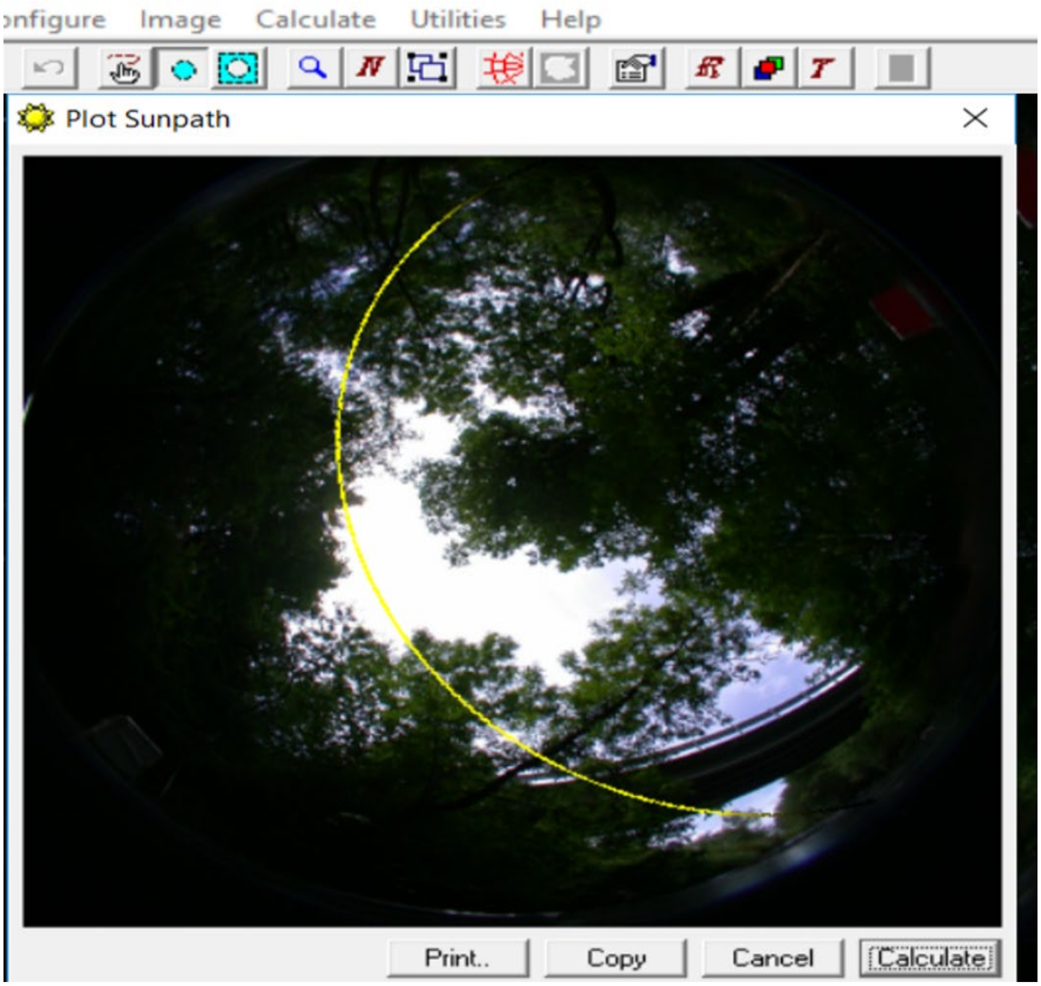


Figure C11. Sun path superimposed on LAC-13.3 hemiview photo
The sun path does not include a large portion of the bridge, indicating that shade calculations will be minimally impacted by it.

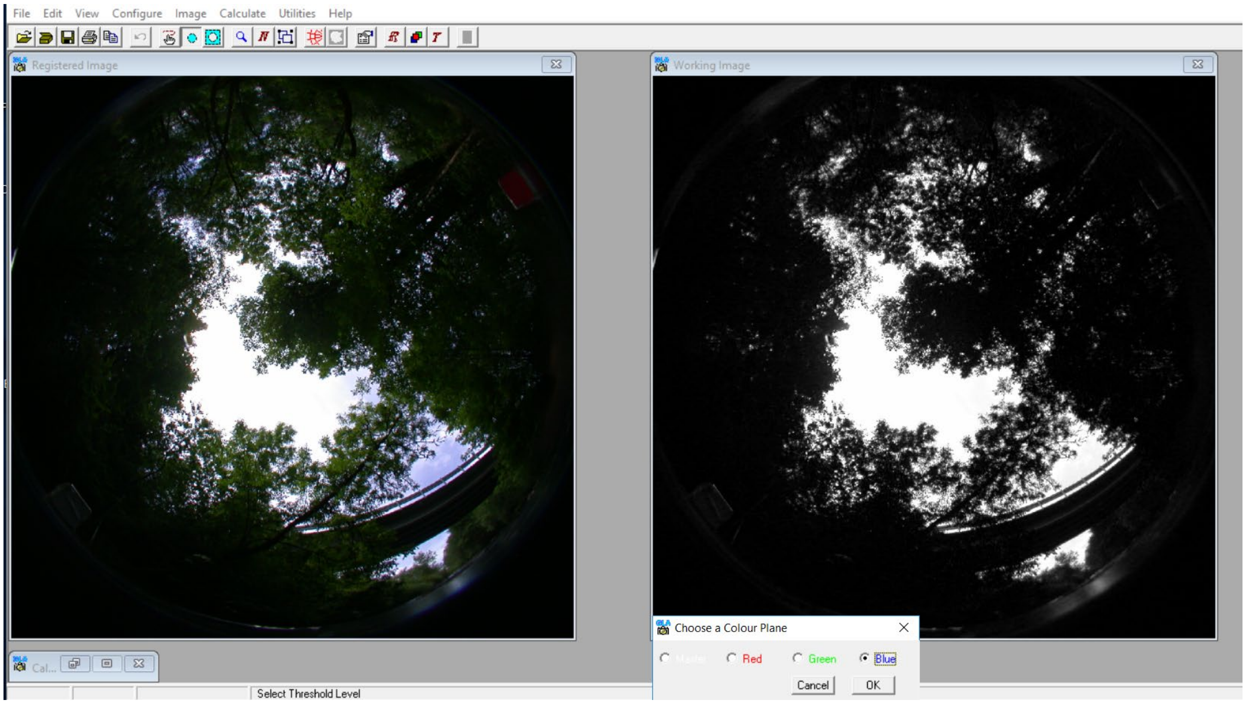


Figure C12. Example reclassification of a hemiview photo for gap light analysis.
Left: original image. Right: image has been modified to estimate effective shade. Blue was selected as the best color plane to classify pixels as suggested in the SOP (Stohr et al. 2019).

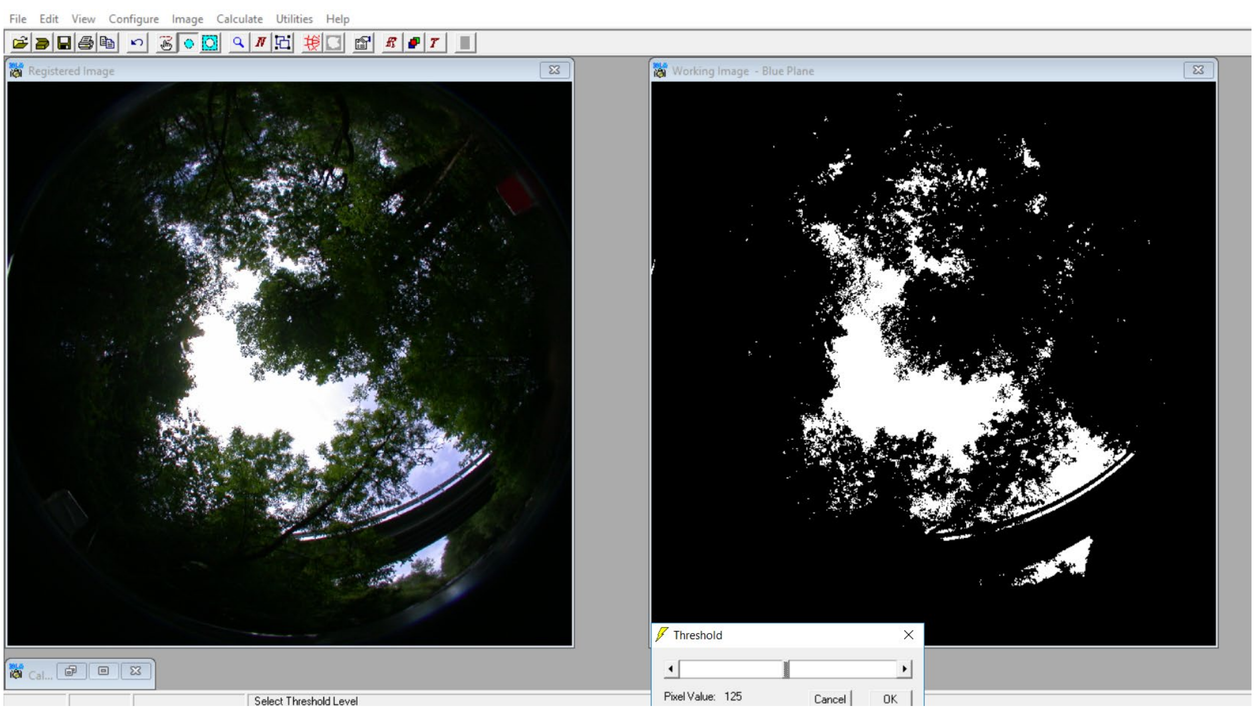


Figure C13. Example of transparency adjustment on hemiview photo.
Left: Original image. Right: Adjusted transparency on working image is set so that it appropriately captures the distinct features present in the original image.

With the hemispherical data that was available, the effective shade model for Lacamas Creek was found to be in good agreement with photos that were processed using GLA software (Figure C14). Gap Light Analyzer shade calculations were, on average, within 9% of the model effective shade predictions (Figure C14), indicating a good model calibration. Model performance was particularly good for the sites assessed in the upper portion of the watershed (LAC-14.8, LAC-13.3, and LAC-11.1) as well as LAC-5.6 near the mouth of the watershed, with an average of 3% difference between modeled and GLA estimated effective shade. LAC-9.1 had the least agreement between modeled and GLA effective shade, with our model deviating around 24% from the GLA estimated shade. The higher deviation at LAC-9.1 could possibly be the result of a change in vegetation conditions in this location from 2011 (the year the hemispherical photo was taken) and the 2013 Lidar derived CHM as the same model calibration settings were used for all other sites, and led to high levels of agreement between GLA and modeled predicted effective shade.

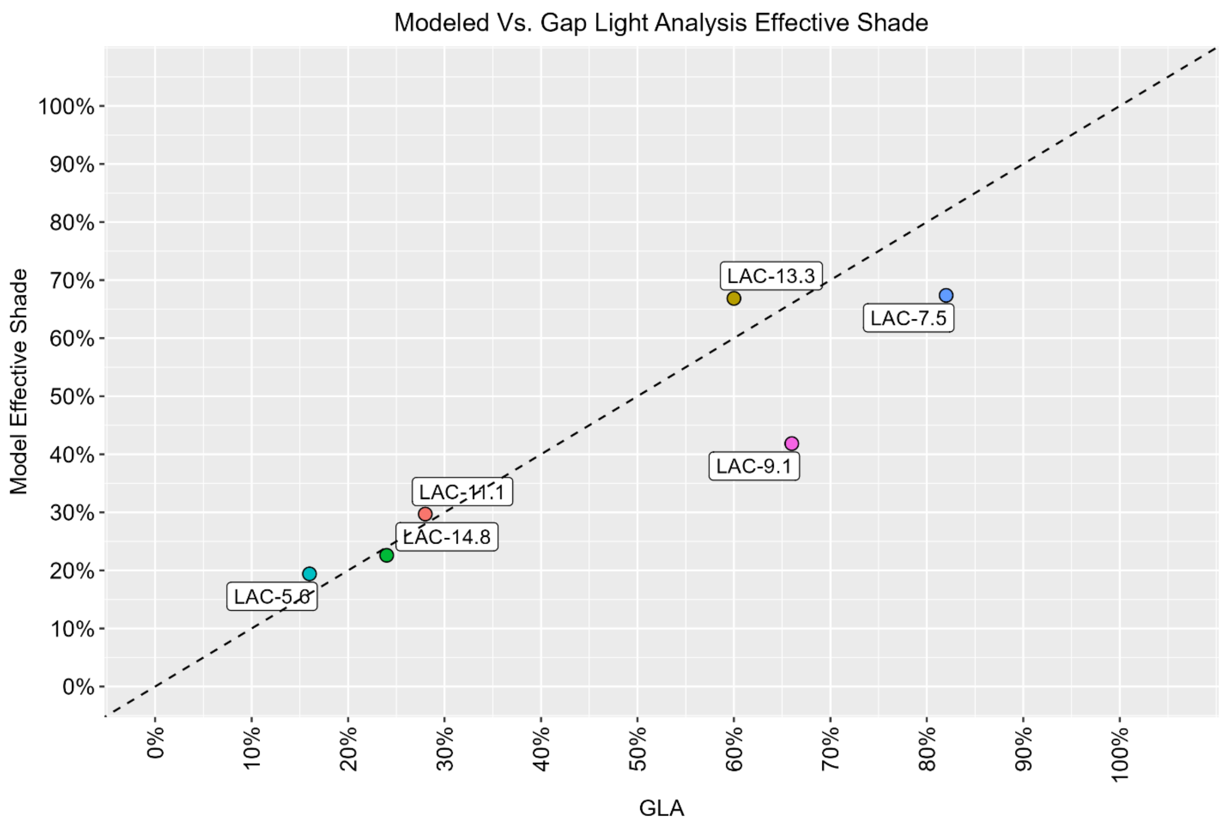


Figure C14. Model effective shade predictions compared with effective shade estimates derived from Gap Light Analysis of 2011 HemiView photos.

Shade deficit for the Lacamas Creek watershed was calculated as the difference between the model scenarios for potential and existing shade conditions in 2013. Shade deficit for a majority of the watershed was relatively low, with most deficits being between zero and eleven percent (Figure C15). Shade deficit was found to be greatest near the headwaters as well as the midsection of the creek near LAC-11.1 (Figure C15). Effective shade conditions for 2013 showed nearly inverse trends to shade deficit as expected, with low effective shade near the headwaters of the creek as well as near LAC-11.1 (Figure C16).

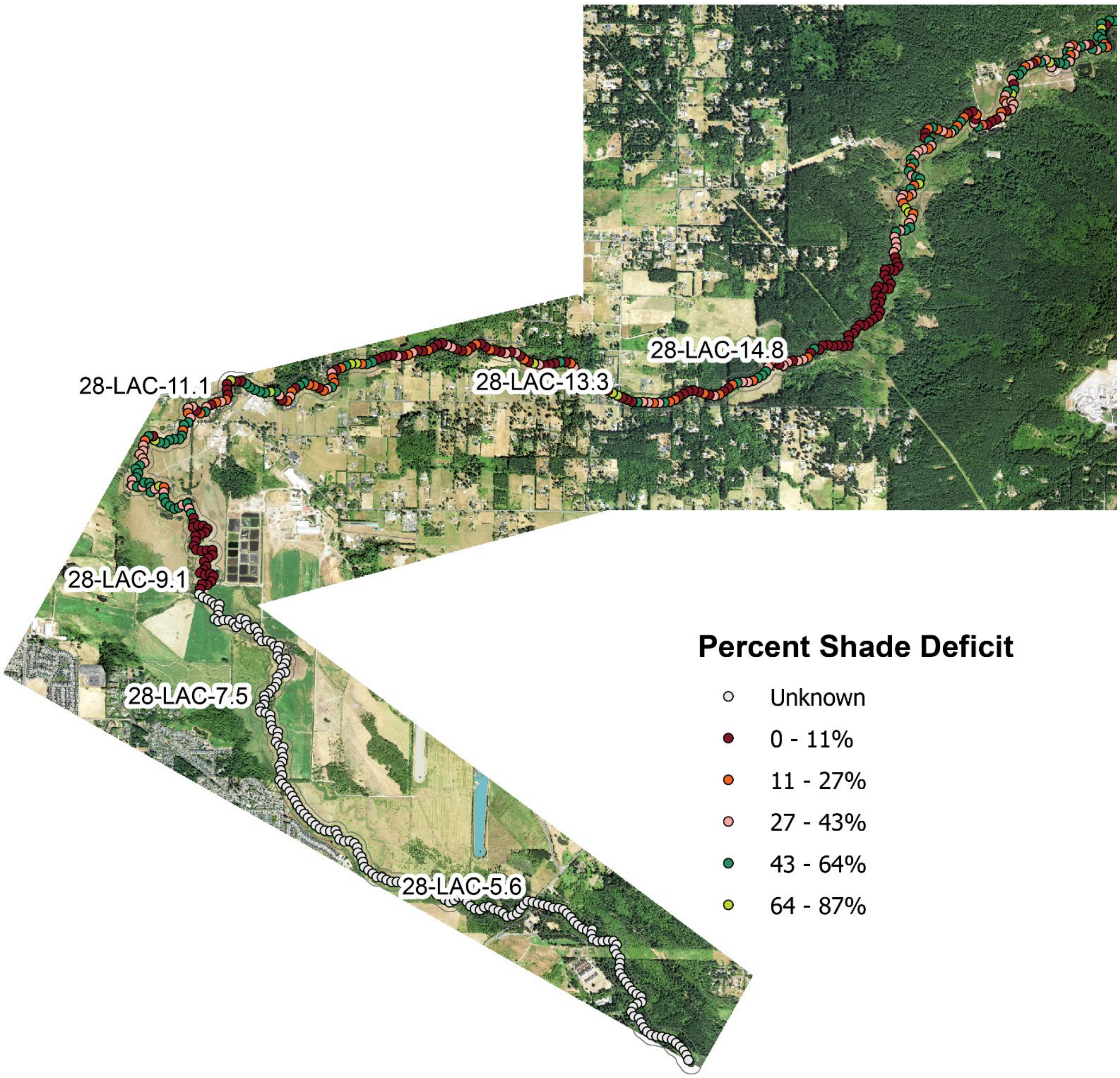


Figure C15. Percent shade deficit along the Lacamas Creek watershed.

Shade deficit is the difference between model scenarios of potential shade and current effective shade.

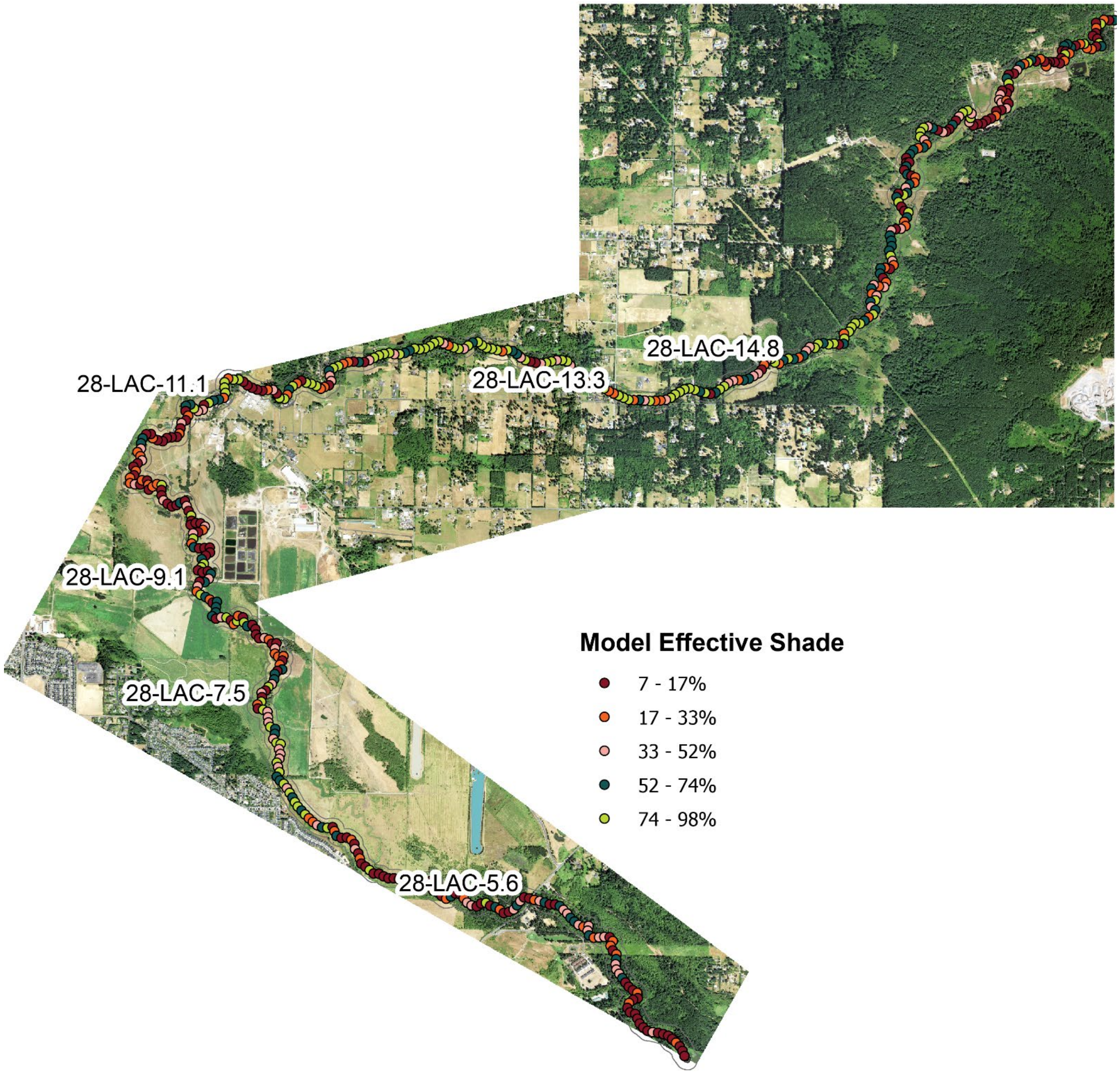


Figure C16. Model effective shade conditions for 2013 along the Lacamas Creek watershed.

Potential Changes in Effective Shade

In this study, we determined a shade deficit of approximately 28% in the upper watershed during the summertime critical period for the year 2013. There is interest in whether there has been an improvement in shade conditions for Lacamas Creek since the initial study by (Swanson 2011). Under ideal circumstances, we would have tried to answer this question by creating a shade model for a recent year (between 2020 and 2023) and comparing it with the 2013 model. Unfortunately, however, the LIDAR data used in the 2013 model is the most recent data available, and therefore, we were unable to quantify changes in shade conditions using this approach. Instead, we have attempted to answer the question of whether shade conditions have improved in Lacamas Creek qualitatively by using tree canopy cover data from the National Land Cover Dataset (NLCD) and Rangeland Condition Monitoring Assessment and Projection (RCMAP) and additionally by comparing new hemispherical photos taken in 2023 with the photos from 2011. Both NLCD and RCMAP datasets were retrieved from the Multi-Resolution Land Characteristics Consortium (MLRC[8]) and offer tree canopy cover at 30 meter resolution based on Landsat imagery.

The most recent NLCD dataset for tree canopy cover was available for 2021 and was compared with NLCD canopy cover conditions for 2011. RCMAP, like NLCD, also uses Landsat-based imagery. However, RCMAP, unlike NLCD, relates certain climate drivers to Landsat imagery as a means to predict future changes in a number of land use categories, including the percentage of tree canopy cover (Shi et al. 2022). RCMAP tree canopy cover conditions for the year 2021 were compared with conditions in 2011. Both the RCMAP and NLCD datasets were assessed within the riparian zone of Lacamas Creek (approximately 200 feet from the stream channel). Canopy cover changes estimated by both NLCD and RCMAP were very minor.

NLCD showed changes in canopy cover between 2021 and 2011 throughout the watershed, with the exception of the agricultural area between LAC-9.1 and slightly upstream of LAC-5.6 exhibiting almost no change at all (Figure C17). RCMAP results were very different from NLCD and estimated essentially no change in canopy cover, with the exception of a few areas near the headwaters predicted to have a decrease in canopy cover from 2011 to 2021 (Figure C17). RCMAP had limited or no data between LAC-11.1 and LAC-13.3 and similarly near the mouth of the watershed. NLCD predicted there to be a 4% average increase in canopy cover between 2011 and 2021, while RCMAP predicted essentially no change. The results of RCMAP and NLCD analyses indicate that there has been little to no change in canopy cover; however, the numerous discrepancies between NLCD and RCMAP prompted us to look further.

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[8] https://www.mrlc.gov/

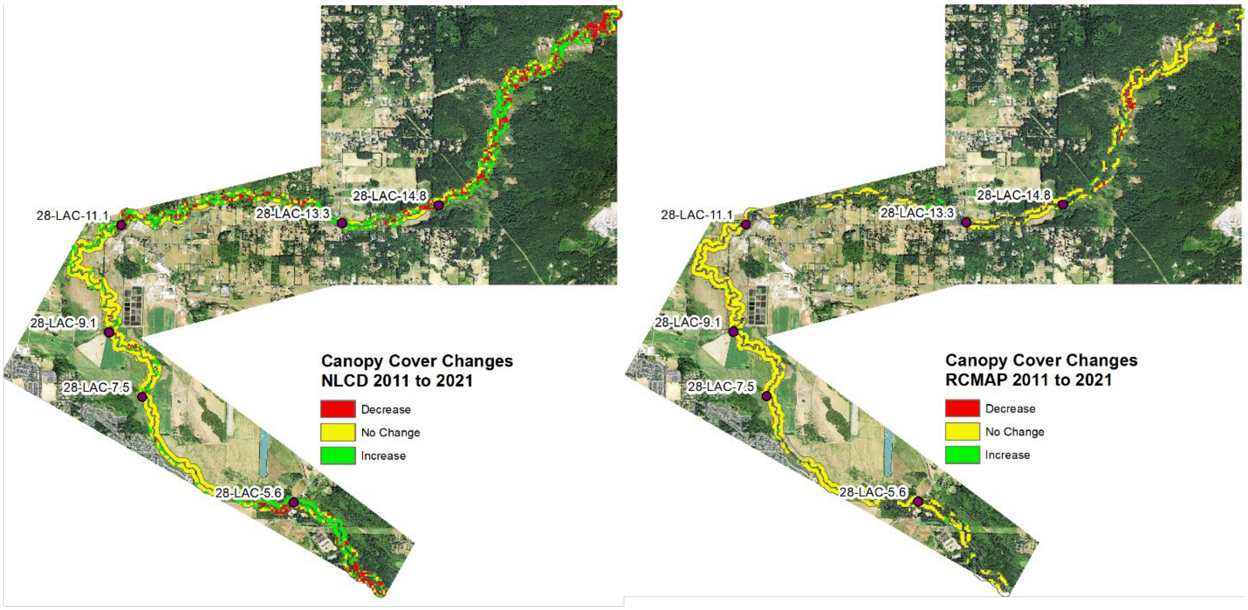

Figure C17. Changes in tree canopy cover in Lacamas Creek riparian zone from the beginning of the study (2011) to the latest available year.
Left: for the National Land Cover Dataset (2021); Right: Rangeland Condition Monitoring Assessment and Projection (2021).

To get a better understanding of current conditions in Lacamas Creek, hemispherical photos were taken at 4 of the 6 original hemiview sites from 2011, including LAC-5.6, LAC-7.5, LAC-13.3, and LAC-14.8. Visual inspection of photos from 2011 and 2023 showed almost no differences in canopy cover (Figure C18), with the exception of LAC-7.5 (Figure C19), which appeared to have a slight decrease in the canopy, which we believe to be the result of a few downed trees found at the site (Figure C20). Gap Light Analysis of 2023 hemispherical photos showed an average decline in canopy cover of 2.5% (Table C2). GLA results were compared with NLCD and RCMAP for canopy cover. RCMAP had greater congruence with GLA than did NLCD for 2 out of 4 sites. However, RCMAP did not have coverage for LAC-14.8, and at LAC-7.5 both RCMAP and NLCD were significantly underpredicting the amount of canopy cover (Table C2). Interestingly, despite little evidence to indicate improvements in shade conditions, GLA results showed 20% – 25% increases in effective shade for LAC-13.3 and LAC-14.8 and little to no changes in LAC-5.6 and LAC-7.5 (Figure C21). Using the Gap Light Analyzer software, we found that although there was a minor decrease in canopy cover on average, the distribution of canopy cover had changed in such a way that there was slightly more coverage along the solar path for August 1st than there was before. Although there were improvements in effective shade for the typical hottest day of the year, the slight decline in canopy cover for 3 out of 4 of the 2023 hemiview sites may indicate that Lacamas is currently not on track to reaching system potential shade.

LAC-5.6 2011 LAC-5.6 2023

Figure C18. Comparison of Hemiview photographs at LAC-5.6 used to calculate canopy cover and effective shade.

LAC-7.5 2011 LAC-7.5 2023

Figure C19. Comparison of Hemiview photographs at LAC-7.5 used to calculate canopy cover and effective shade.

Figure C20. Downed trees found in the stream channel right next to the LAC-7.5 hemiview site in September 2023.

Table C2. Vegetative canopy cover measurements comparison between NLCD and RCMAP using GLA for validation. Effective Shade calculations are only relevant for GLA.

Site	Year	Data Source	Effective Shade	Canopy Cover
LAC-5.6	2011	GLA	16	67.5
LAC-5.6	2011	NLCD	N/A	47
LAC-5.6	2011	RCMAP	N/A	83
LAC-5.6	2023	GLA	13	65
LAC-5.6	2021	NLCD	N/A	67
LAC-5.6	2021	RCMAP	N/A	83
LAC-7.5	2011	GLA	82	88
LAC-7.5	2011	NLCD	N/A	0
LAC-7.5	2011	RCMAP	N/A	0
LAC-7.5	2023	GLA	82	85
LAC-7.5	2021	NLCD	N/A	34
LAC-7.5	2021	RCMAP	N/A	0
LAC-13.3	2011	GLA	60	85
LAC-13.3	2011	NLCD	N/A	34
LAC-13.3	2011	RCMAP	N/A	67
LAC-13.3	2023	GLA	84	82
LAC-13.3	2021	NLCD	N/A	64
LAC-13.3	2021	RCMAP	N/A	76
LAC-14.8	2011	GLA	23	70
LAC-14.8	2011	NLCD	N/A	77
LAC-14.8	2011	RCMAP	N/A	N/A
LAC-14.8	2023	GLA	44	72
LAC-14.8	2021	NLCD	N/A	74
LAC-14.8	2021	RCMAP	N/A	N/A

GLA = gap light analysis; N/A = not applicable; NLCD = National Land Cover Dataset ;RCMAP = Rangeland Condition Monitoring Assessment and Projection.

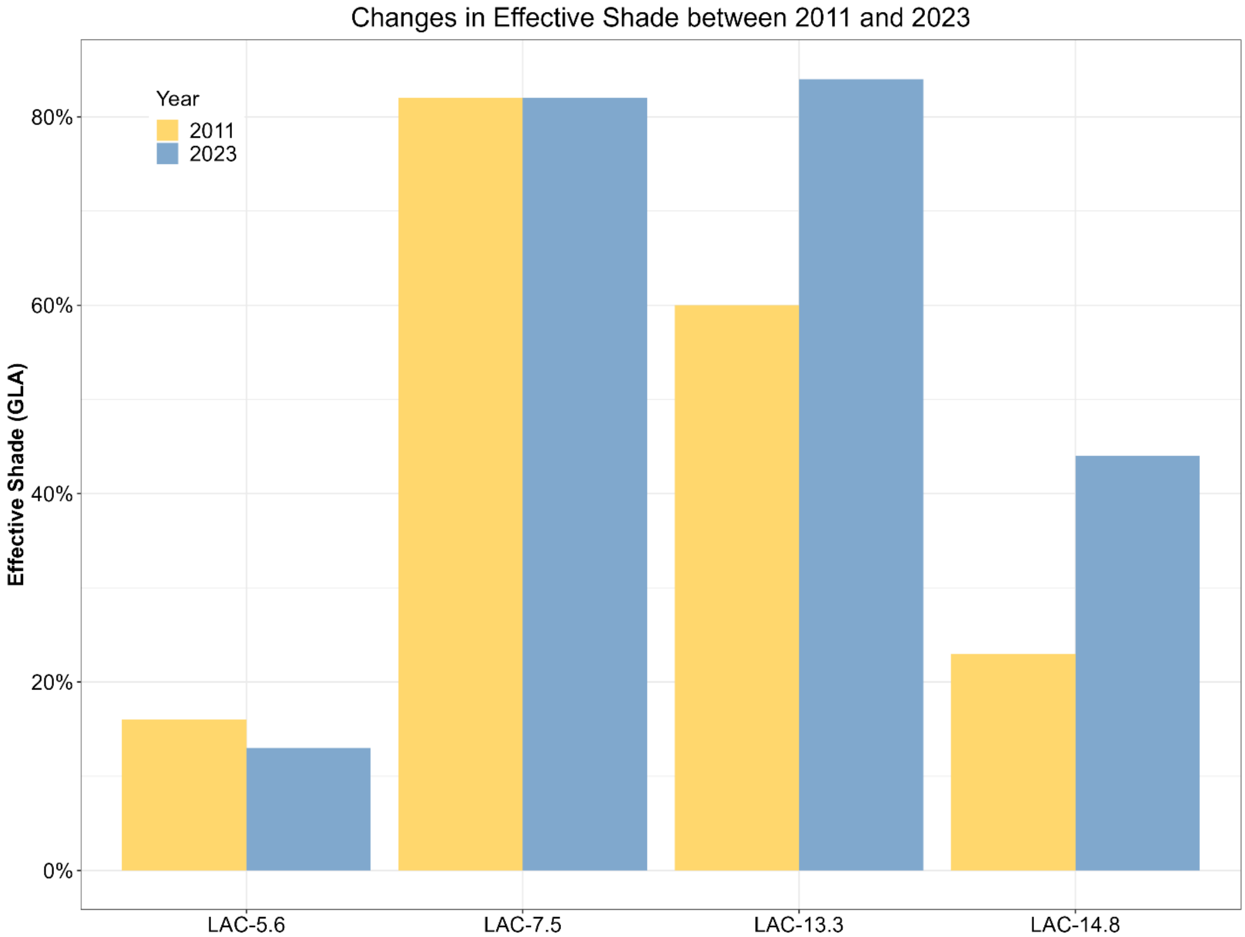

Figure C21. Comparison of 2011 and 2023 effective shade between four different hemiview stations.

Two additional stations, LAC-9.1 and LAC-11.1, from the original study were not sampled in 2023.

Appendix C References

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Appendix D. Data Quality

This Appendix contains information regarding the data quality for the following parameters:

- Fecal coliform (FC) bacteria results collected during the 2010 – 2011 and 2021 sampling efforts.
- *E. coli* results collected in 2021.
- Nutrient results from samples collected in 2011.
- Dissolved oxygen (DO) and pH results from short-term deployments of multi-parameter sondes deployed during the summer of 2011.
- Continuous temperature measurements collected in 2011.

Table D1 contains the Measurement Quality Objectives (MQOs) for lab procedures, and Tables D2 and D3 contain the MQOs and acceptance criteria for field procedures. These MQOs were applied to data from both the 2010 – 2011 and 2021 field efforts and are discussed further in the 2021 Quality Assurance Project Plan (QAPP; Gleason and McCarthy 2021).

Following the 2010 – 2011 field collection, sample and measurement results were reviewed and finalized before being entered into EIM. During this study, the results from the 2010 – 2011 collection were reviewed for quality, and a data quality assessment was completed for the 2010 – 2011 data. This assessment also involved a review of laboratory case narrative reports and QC reports delivered by MEL.

Table D1. Measurement Quality Objectives (MQOs) for lab procedures.

Parameter	Method Detection Limit (MDL)[a]	Method Blank Limit	Calibration Standards/ Blanks	Lab Control Samples (% Recovery Limits)	Matrix Spikes or SRMs (% Recovery Limits)	Precision — Field Duplicate (RSD)[b]	Precision — Laboratory Duplicate (RPD)
Fecal coliform (MF)	1 cfu/100 mL	<MDL	N/A	N/A	N/A	50% of replicate pairs < 20% RSD 90% of replicate pairs <50% RSD	40%
E. coil (MF)	1 cfu/100 mL	<MDL	N/A	N/A	N/A	50% of replicate pairs < 20% RSD 90% of replicate pairs <50% RSD	40%
Dissolved Oxygen — Winkler	0.1 mg/L	N/A	N/A	N/A	N/A	±0.2 mg/L	± 0.2 mg/L
Alkalinity	5.0 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	N/A	10%	20%
Chloride	0.1 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	90%–110%	75%–125%	5%	20%
Ammonia/Ammonium	0.01 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%
Dissolved Organic Carbon	1.0 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%
Nitrate/Nitrite	0.01 mg/L	<1/2 RL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%

Parameter	Method Detection Limit (MDL)[a]	Method Blank Limit	Calibration Standards/ Blanks	Lab Control Samples (% Recovery Limits)	Matrix Spikes or SRMs (% Recovery Limits)	Precision — Field Duplicate (RSD)[b]	Precision — Laboratory Duplicate (RPD)
Total Persulfate Nitrogen	0.025 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%
Orthophosphate	0.003 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%
Total Phosphorous	0.005 mg/L	<2.2x MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%
Total Organic Carbon	1.0 mg/L	<MDL[c]	ICV/CCV: 90%–110% ICB/CCB: <MDL	80%–120%	75%–125%	10%	20%
Chlorophyll-a	0.05 ug/L	<1/2 RL[c]	N/A	N/A	N/A	20%	20%
Total Suspended Solids	1.0 mg/L	±0.3 mg/L[d]	N/A	80%–120%	N/A	15%	5%

CCB = continuing calibration blank; CCV = continuing calibration verification; ICB = initial calibration blank; ICV = initial calibration verification; MDL = method detection limit; MF = membrane filtration ; N/A = not applicable; RPD = relative percent difference ; RL = reporting limit; RSD = relative standard deviation; SRM = standard reference material.

[a]Reporting limit may vary depending on dilutions. MDL listed in the table represents the lowest possible RL.

[b]Field duplicate results with a mean of less than or equal to 5x the reporting limit will be evaluated separately.

[c]Or less than 10% of the lowest sample concentration for all samples in the batch (i.e., 20 samples or fewer).

[d]Filter blank.

Table D2. Measurement Quality Objectives (MQOs) for field procedures.

Parameter	Precision — Field Duplicates	Bias	Equipment Accuracy	Equipment Resolution	Equipment Range	Estimated Range
Stream Velocity	10%	±0.05 ft/s	0.01 ft/s	0.01 ft/s	-0.5–20 ft/s	0.01–10 ft/s
Water Temperature	±0.2°C	See Table 12	0.01°C	0.01°C	-5°C–50°C	0–30° C
Specific Conductivity	5% RSD	See Table 12	±0.5% + 1 uS/cm	1 uS/cm	0–100,000 uS/cm	20–1000 umhos/cm
pH	±0.2 s.u.	See Table 12	±0.2 s.u.	0.01 s.u.	0–14 s.u.	6–10 s.u.
Dissolved Oxygen	5% RSD	See Table 12	±0.1 mg/L; at <8 mg/L; ±0.2 mg/L; at 8 – <20 mg/L[a]	0.01 mg/L	0–60 mg/L	0.1–15 mg/L
Continuous Water Temperature	N/A	N/A	±0.21°C at 0°C–50°C	N/A	0–50°C	0–30°C

N/A = not applicable.

Table D3. Acceptance criteria for instrument calibrations and post-checks.

Parameter	Unit	Accept	Qualify	Reject
Dissolved Oxygen	% saturation	≤ ± 5%	> ± 5% and ≤ ± 15%	> ± 15%
Dissolved Oxygen	mg/L	≤ ± 0.5	> ± 0.5 and ≤ ± 1.0	> ± 1.0
pH	standard unit	≤ ± 0.2	> ± 0.2 and ≤ ± 0.8	> ± 0.8
Specific Conductivity	uS/cm	≤ ± 10%	> ± 10% and ≤ ± 20%	> ± 20%
Water Temperature	°C	≤ ± 0.2	> ± 0.2 and ≤ ± 0.8	> ± 0.8
Turbidity	NTU	≤ ± 10%	> ± 10% and ≤ ± 20%	> ± 20%

Bacteria

All FC and *E. coli* samples were analyzed at the Manchester Environmental Laboratory (MEL) for the 2010 – 2011 and 2021 sampling efforts. All sampling procedures and protocols for FC and *E. coli* sampling complied with procedures from the QAPPs (Swanson 2011; Gleason and McCarthy 2021).

Precision for Field Replicates

The precision for field sampling and laboratory analysis was assessed by analyzing field replicate samples. Field replicate samples are collected at the same time and place as the original sample, using identical protocols to the original sample. The 2021 QAPP requires that 10% of samples have associated field replicates (Gleason and McCarthy 2021). Both the 2010 – 2011 and 2021 field collections met these targets.

The precision for field replicates is defined as the percent relative standard deviation (%RSD). The %RSD is calculated by first calculating the RSD, also referred to as the coefficient of variation (CV), by calculating the standard deviation of the original and replicate samples and then dividing this value by the average. The RSD is converted to %RSD by multiplying by 100.

As noted in the QAPP, both the 2010 – 2011 and 2021 results were assessed based on MQOs for FC and *E. coli* defined in the 2021 QAPP, where at least 50% of replicate pairs are less than 20% RSD and at least 90% of replicate pairs are less than 50% RSD (Gleason and McCarthy 2021).

Table D4 shows that, on the whole, the 2010 – 2011 data met the MQO for precision.

Table D4. Fecal coliform data quality results for 2010 – 2011 field collection.

MQO	Result	Meets MQO?
50% of replicate pairs <20% RSD	57%	Yes
90% of replicate pairs <50% RSD	90%	Yes
Samples with replicates count	172	—
Sample count	819	—
% samples with replicates	21%	Yes
Median RSD	16%	Yes

MQO = measurement quality objective; RSD = relative standard deviation.

Both the FC and *E. coli* samples collected in 2021 met the MQOs for precision defined in the 2021 QAPP (Tables D5 and D6, Gleason and McCarthy 2021).

Table D5. Fecal coliform data quality results for 2021 field collection.

MQO	Result	Meets MQO?
50% of replicate pairs < 20% RSD	55%	Yes
90% of replicate pairs <50% RSD	95%	Yes
Samples with replicates count	20	—
Sample count	205	—
% samples with replicates	10%	—
Median RSD	16%	Yes

MQO = measurement quality objective; RSD = relative standard deviation.

Table D6. E. coli data quality results for 2021 field collection.

MQO	Result	Meets MQO?
50% of replicate pairs <20% RSD	70%	Yes
90% of replicate pairs <50% RSD	90%	Yes
Samples with replicates count	20	—
Sample count	205	—
% samples with replicates	10%	—
Median RSD	14%	Yes

MQO = measurement quality objective; RSD = relative standard deviation.

Nutrients

Table D7 includes the nutrient parameters, the %RSD required by the 2021 QAPP (Gleason and McCarthy 2021), and the % of samples meeting the MQO for each parameter. Only one sample, an ammonia sample from location 28-LAC-5.6 collected on 7/26/2011, did not meet the 10% RSD criteria for ammonia.

Table D7. Nutrient data quality results for 2011 field collection.

Parameter	% RSD	% Samples that meet MQO	Samples that do not meet MQO
Ammonia	10%	88%	28-LAC-5.6 (7/26/2011)
Nitrite + Nitrate as N	10%	100%	—
Total Persulfate Nitrogen	10%	100%	—
Ortho-Phosphate	10%	100%	—
Total Phosphorus	10%	100%	—
Dissolved Organic Carbon	10%	100%	—
Total Organic Carbon	10%	100%	—

MQO = measurement quality objective; RSD = relative standard deviation

Temperature, DO, and pH

The Relative Percent Difference (RPD) was used to determine agreement between in-situ loggers and spot checks performed by Ecology staff using Hydrolabs. In cases where the differences exceeded the precision requirements, the data were investigated further and either adjusted or qualified in EIM.

The following corrections and/or qualifications were added to the data from the July 2011 synoptic survey:

- Spot checks for one hydrolab were corrected for pH (0.52 units) and conductivity (5.2 uS/cm). This was because the hydrolab was consistently high on all pH spot checks during the synoptic, and a post-check conductivity showed a bias of 5.2 uS/cm.
- Conductivity at 28-LAC-13.3 and 28-FIF-3.4 were corrected for the average of the difference between the spot checks and the results. These two sites used the same in-situ hydrolab and had a consistent offset between the continuous measurements and spot checks.
- pH data from 28-LAC-9.1 were qualified but not adjusted because the measured pH was similar to values upstream and downstream.
- pH data from 28-SHA-1.3 were qualified but not adjusted because Ecology staff could not determine if the in-situ or spot-checking hydrolab was correct.

The following corrections and/or qualifiers were added to the data from the August to September 2011 synoptic survey:

- At 28-SPR-0.3, continuous DO measurements were corrected to match the spot-checked hydrolab because the spot-checking DO measurements closely matched Winkler DO samples.
- All conductivity measurements were corrected to a single spot-check hydrolab. The two other hydrolabs had inconsistencies during post-synoptic calibration checks.
- Temperature results at 28-LAC-9.1 were corrected to the spot check hydrolab, which matched those of other deployed hydrolabs.
- pH data at 28-LAC-9.1 were qualified because even after adjusting for a pH "jump" that occurred in both measured pH and offset of deployed and spot-checked pH in the middle of deployment, data did not meet MQOs.

Thermistors deployed for long-term temperature modeling met equipment accuracy targets in both pre- and post-deployment water bath tests.

Appendix D References

Gleason, M.G., and S. McCarthy. 2021. Lacamas Creek Bacteria, Temperature, and Nutrients Source Assessment (Quality Assurance Project Plan). Publication No. 21-10-017. Washington State Department of Ecology, Olympia, WA. https://apps.ecology.wa.gov/publications/summarypages/2110017.html

Swanson, T. 2011. Lacamas Creek Fecal Coliform, Temperature, Dissolved Oxygen, and pH Total Maximum Daily Load: Water Quality Study Design (Quality Assurance Project Plan). Publication No. 11-03-102. Washington State Department of Ecology, Olympia, WA. https://apps.ecology.wa.gov/publications/SummaryPages/1103102.html

Appendix E. Supplemental Figures

Additional Maps of Nutrient Concentrations

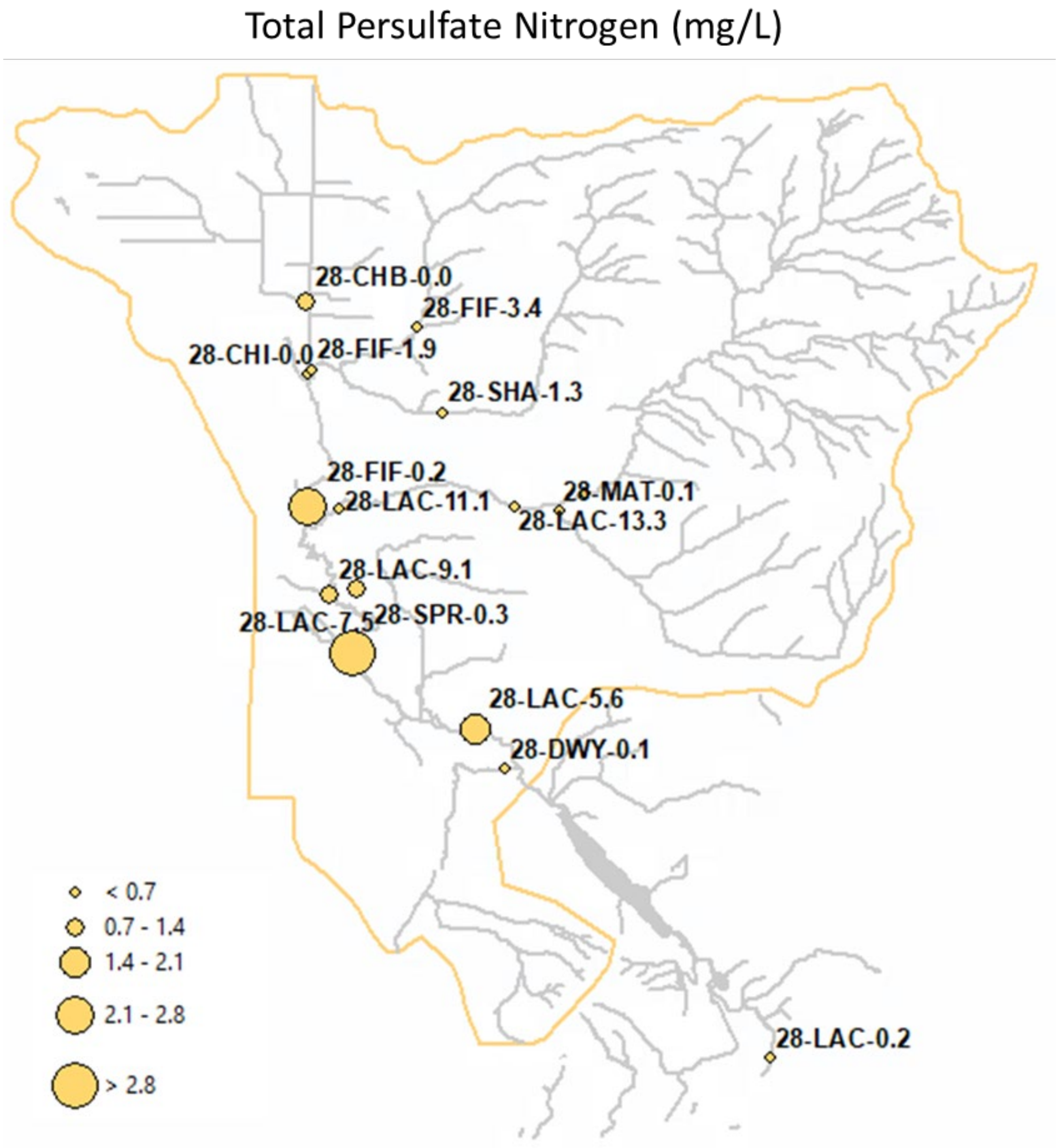

Figure E1. Average total persulfate nitrogen concentrations in the study area from 2011 synoptic surveys.

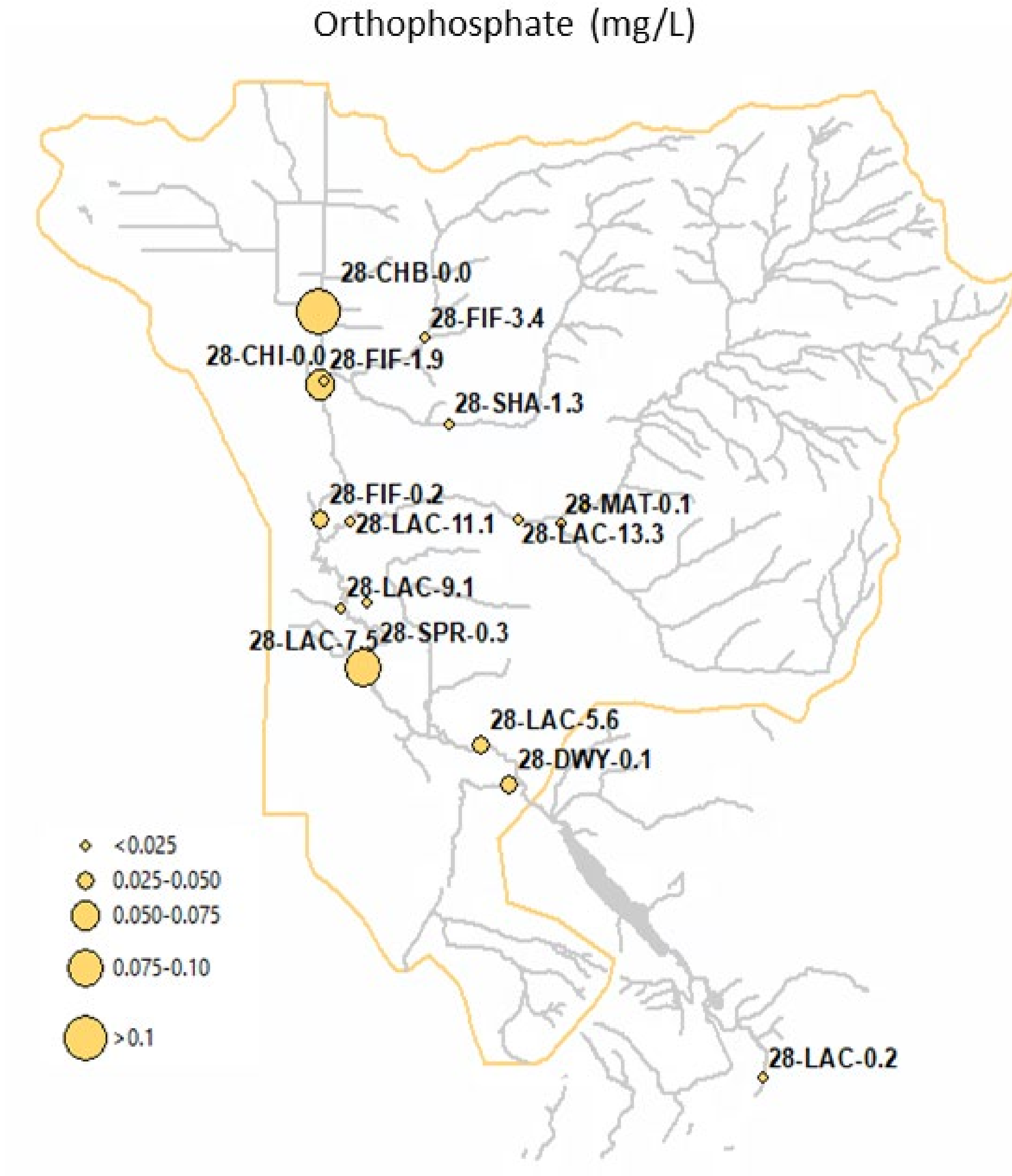

Figure E2. Average orthophosphate concentrations in the study area from 2011 synoptic surveys.

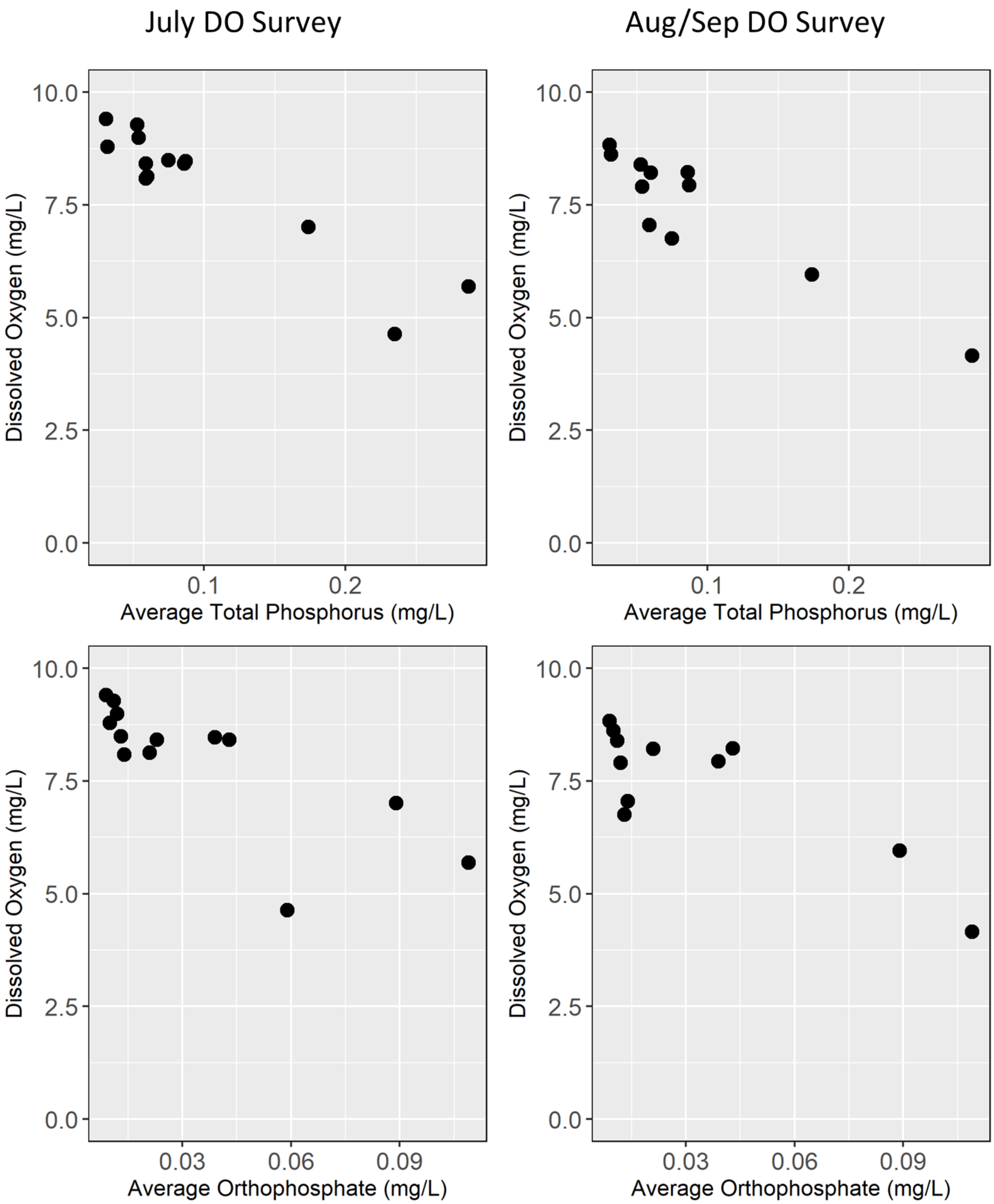

Figure E3. Dissolved oxygen (DO) measurements compared with phosphorus concentrations in the study area.

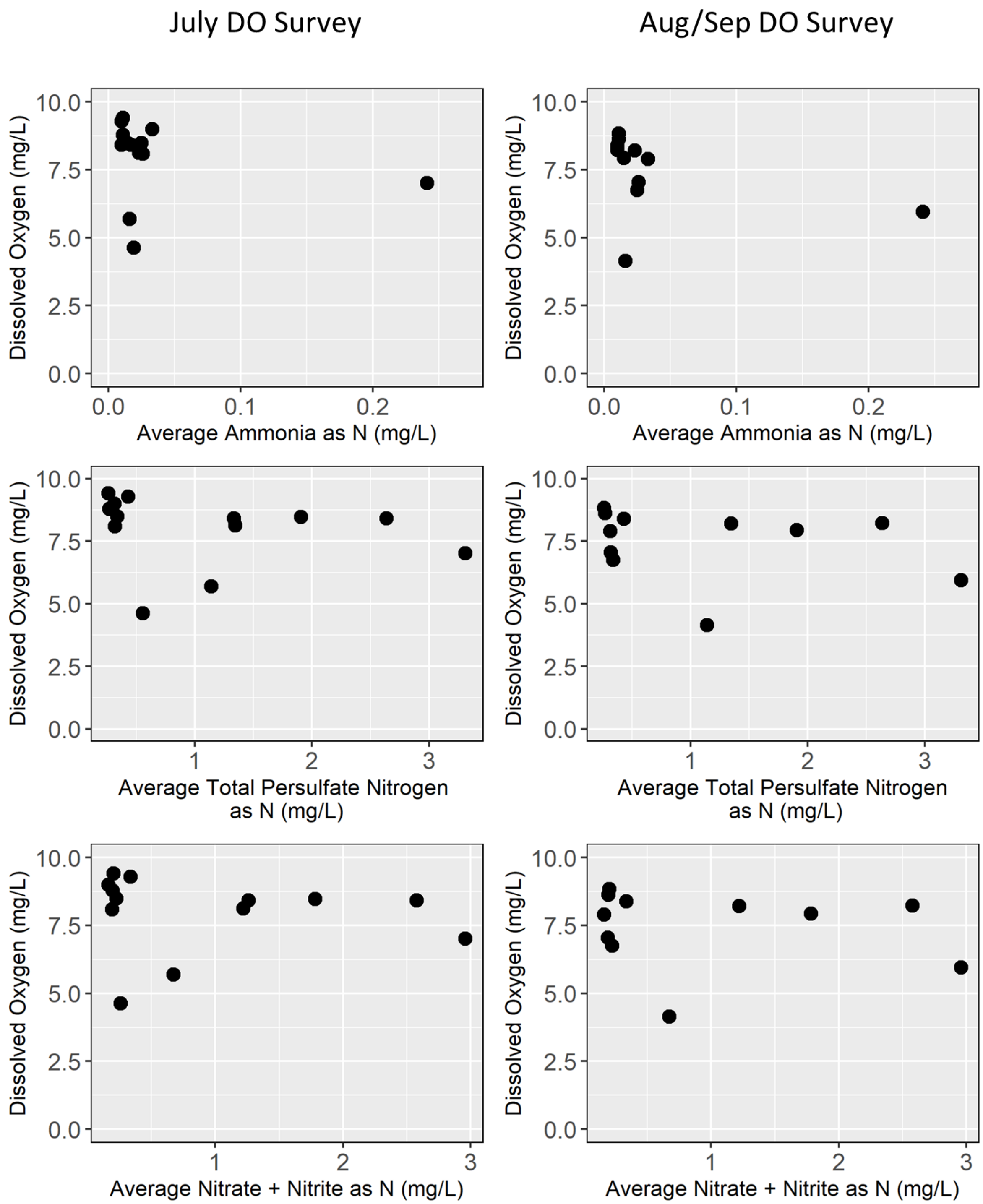

Figure E4. Dissolved oxygen (DO) measurements compared with nitrogen concentrations in the study area.

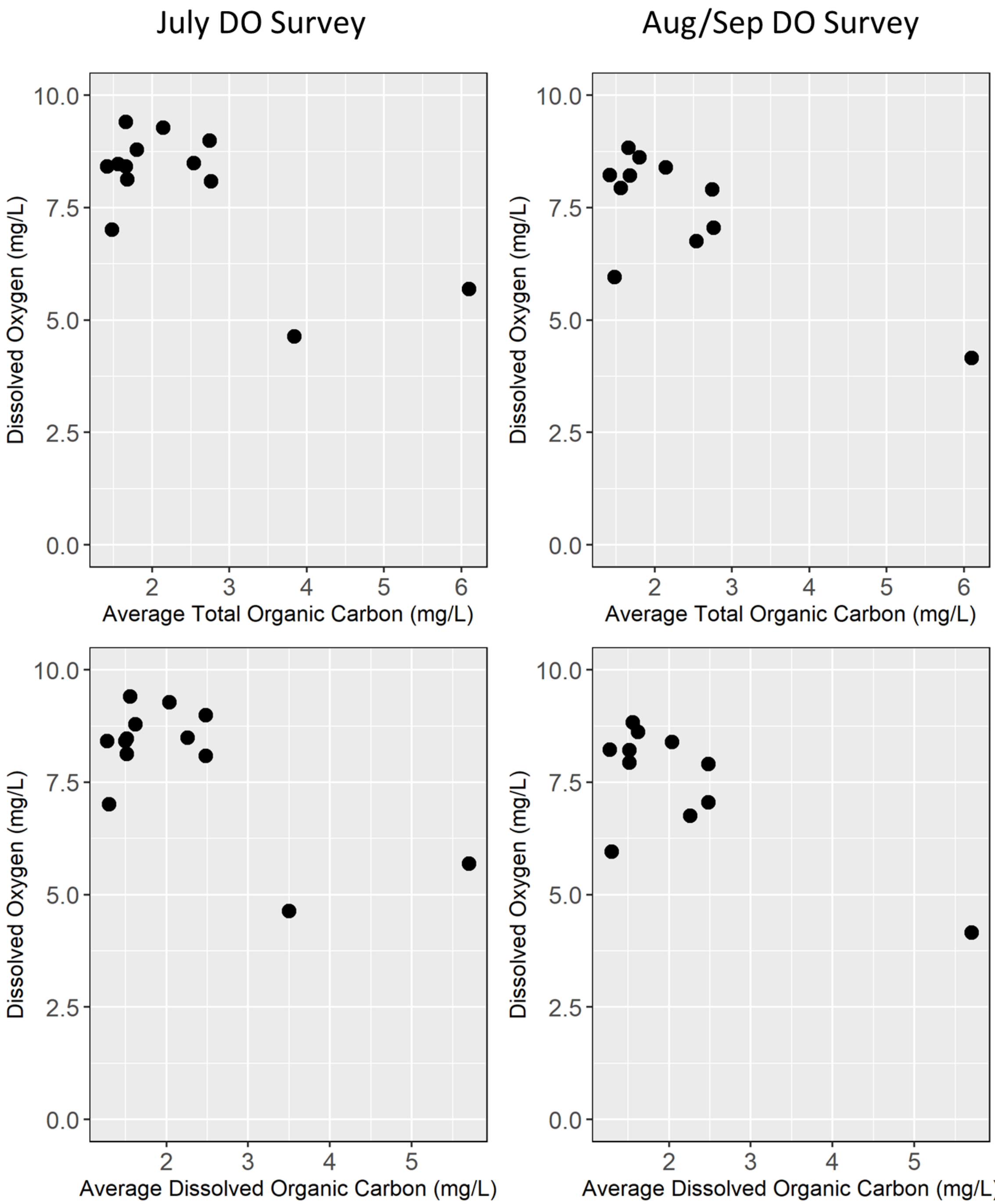

Figure E5. Dissolved oxygen (DO) measurements compared with organic carbon concentrations in the study area.

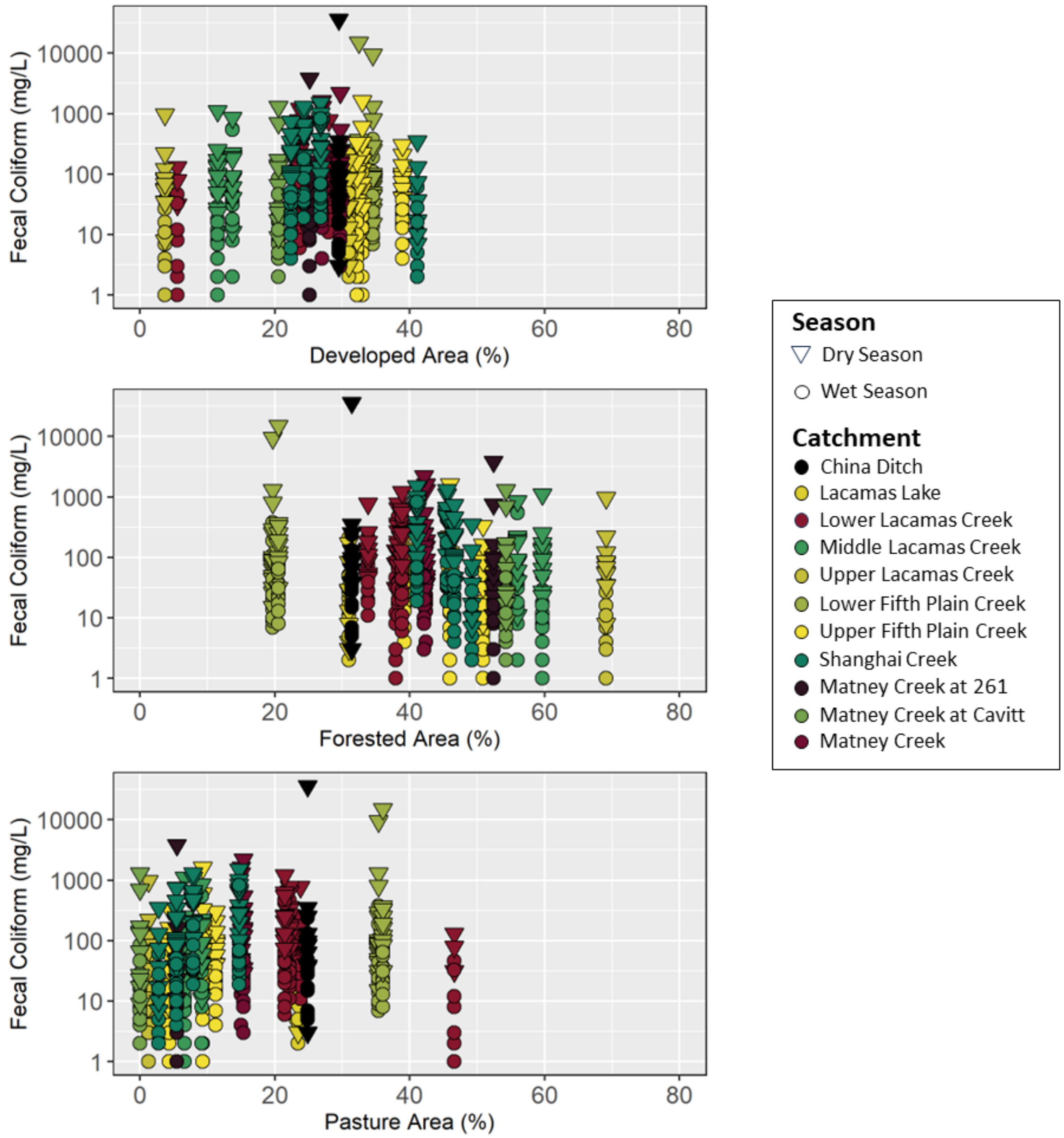

Figure E6. Relationship between 2010 – 2011 fecal coliform concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (top: developed area; middle: forested area; bottom: pasture area).

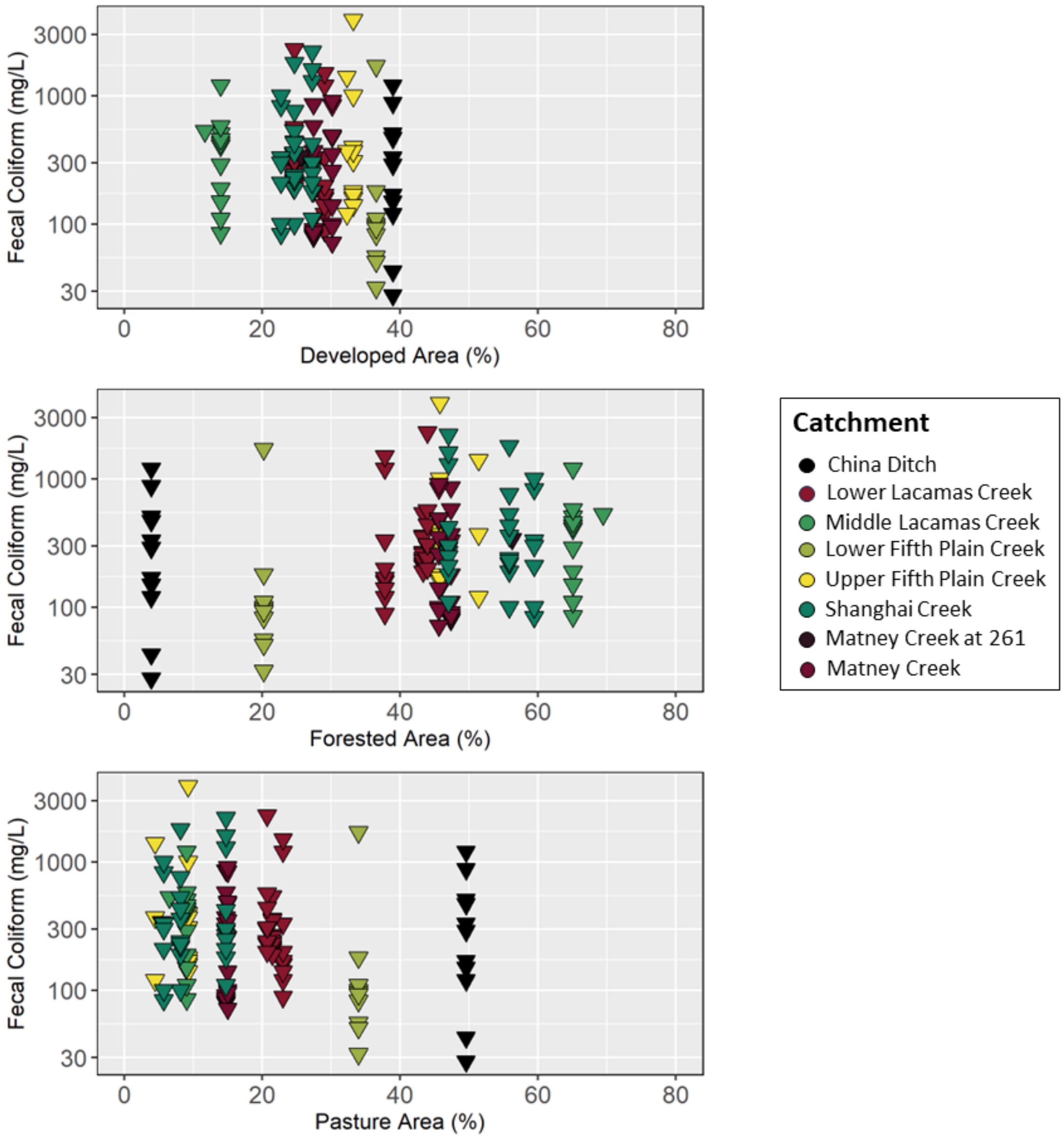

Figure E7. Relationship between 2021 fecal coliform concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (top: developed area; middle: forested area; bottom: pasture area).

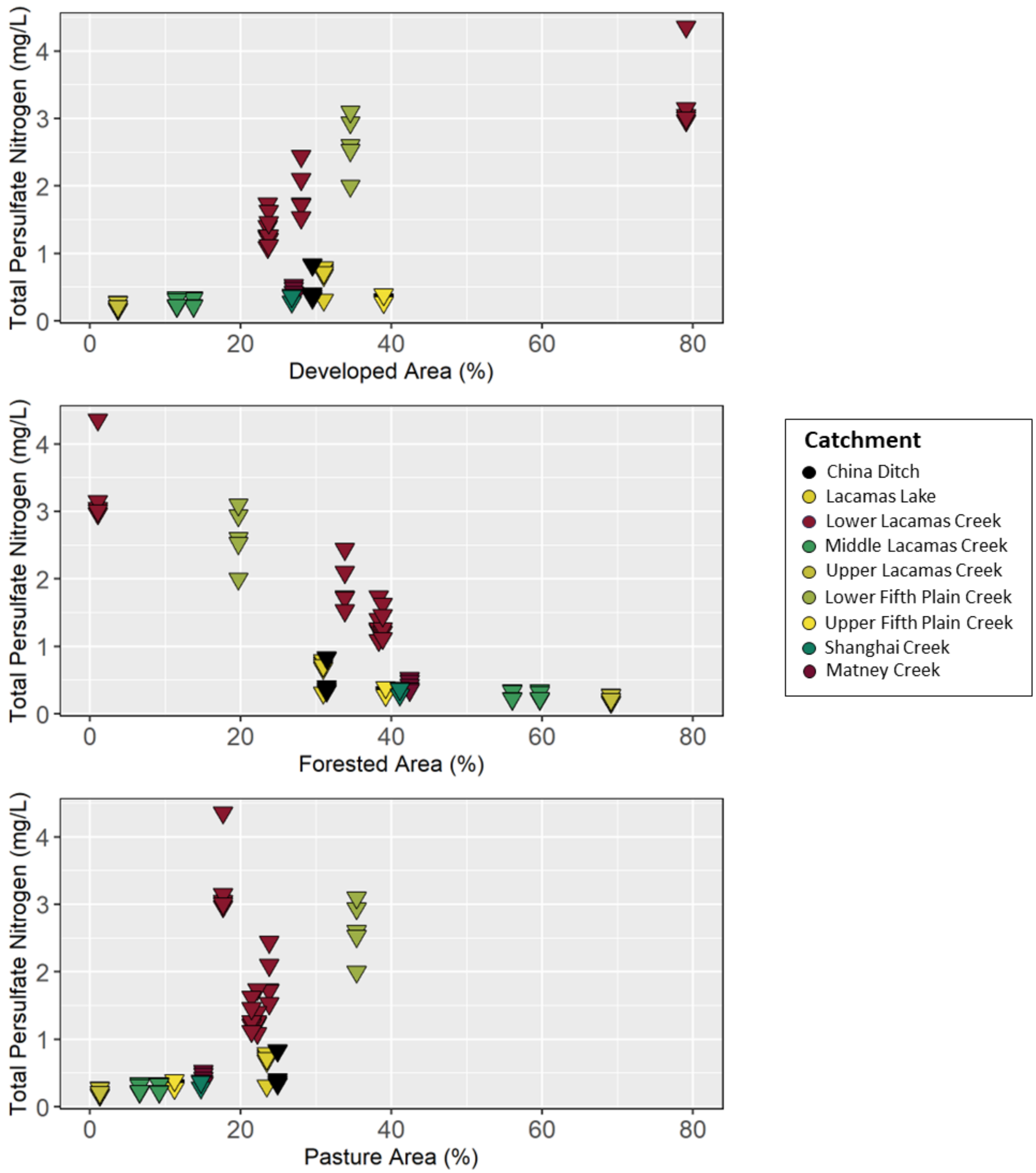

Figure E8. Relationship between persulfate nitrogen concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (top: developed area; middle: forested area; bottom: pasture area).

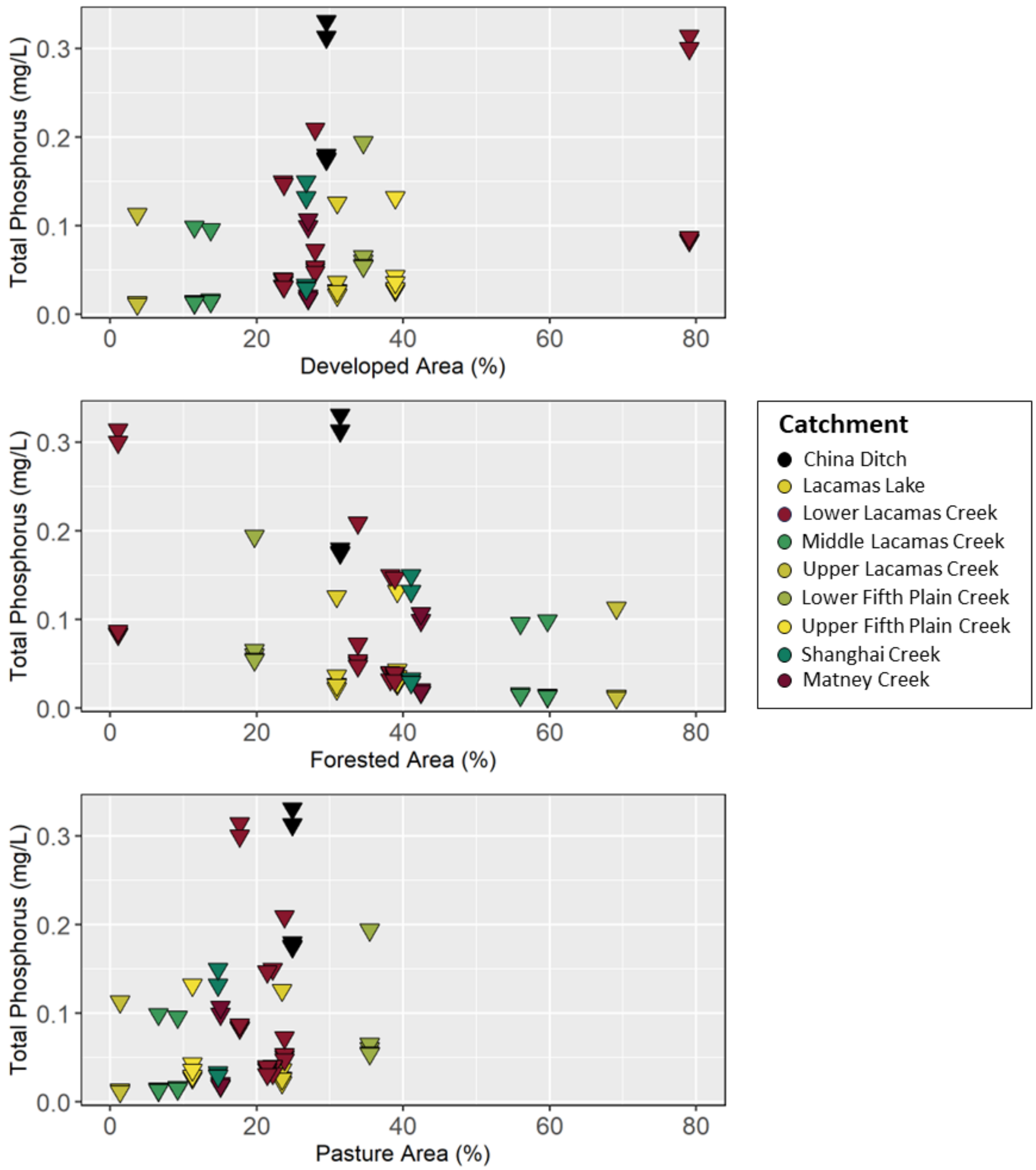

Figure E9. Relationship between total phosphorus concentrations and land use in each sample's drainage area.

Y-axis shows sample concentration, X-axis shows the percentage of that sample's drainage area in the given land use category (top: developed area; middle: forested area; bottom: pasture area).