Spokane River and Lake Spokane Dissolved Oxygen Total Maximum Daily Load

10-Year Effectiveness Study

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Cover Photo: Spokane River at Nine Mile Dam. ***Cover Photo Credit:*** Tighe Stuart.

[1] https://www.ecology.wa.gov/Research-Data/Data-resources/Environmental-Information-Management-database

Spokane River and Lake Spokane Dissolved Oxygen Total Maximum Daily Load 10-Year Effectiveness Study

by

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Abstract

Ecology adopted the *Spokane River and Lake Spokane Dissolved Oxygen Total Maximum Daily Load* (TMDL) in 2010 to address low dissolved oxygen (DO) levels in the Spokane River and Lake Spokane, as well as harmful algal blooms in Lake Spokane. The TMDL identified that Ecology would conduct an interim assessment of conditions approximately 10 years into the TMDL implementation period.

Ecology assessed dissolved oxygen and nutrients in the Spokane River and Lake Spokane using data we collected during an October 2021 – October 2022 field study, along with a variety of other data collected by Ecology and partner organizations.

In recent years, point source dischargers have substantially reduced their phosphorus discharges to the Spokane River. As a result, since 2021, summertime total phosphorus (TP) levels entering Lake Spokane have typically been less than 0.01 mg/L. Although tributary and nonpoint sources have also decreased over recent decades, nonpoint sources, particularly Hangman Creek, remain as the largest sources of phosphorus. For example, during March – May 2022, Hangman Creek contributed 74% of the total load entering the Spokane River.

As of 2022, DO levels in Lake Spokane had not yet responded to recent phosphorus reductions. In the past, when a large phosphorus reduction occurred during the 1970s, Lake Spokane DO took at least five years to fully respond. Furthermore, during 2022, large Hangman Creek phosphorus loads during June may have complicated conditions in Lake Spokane for that year. Therefore, it is likely too soon to draw conclusions about Lake Spokane DO response.

We recommend continued monitoring of Lake Spokane over the next several years to assess the lake response. We also recommend continued efforts to reduce nonpoint phosphorus pollution in the tributaries, especially Hangman Creek.

Introduction

Ecology adopted the *Spokane River and Lake Spokane Dissolved Oxygen Total Maximum Daily Load Water Quality Improvement Plan* (Moore and Ross 2010; henceforth referred to as the *Spokane DO TMDL*, or simply **"**the TMDL**"**) to address ongoing low dissolved oxygen (DO) levels in the Spokane River and Lake Spokane, as well as harmful algal blooms in Lake Spokane. The TMDL established allocations for point and nonpoint total phosphorus (TP), carbonaceous biochemical oxygen demand (CBOD), and ammonia to meet DO standards in Lake Spokane. Since that time, point source dischargers have made improvements to effluent treatment, resulting in substantial reductions in pollutant loading, and various organizations have worked to reduce nonpoint pollution.

The TMDL identified that Ecology would conduct an interim assessment of conditions in Spokane River and Lake Spokane approximately 10 years after the adoption of the TMDL in 2010. During October 2021 – October 2022, Ecology collected field data in the Spokane River and Lake Spokane. We used this data in combination with a variety of other data collected by Ecology and several other organizations to assess phosphorus loading and dissolved oxygen response in the Spokane River system.

Background — Dissolved Oxygen TMDL

Algae blooms and low dissolved oxygen levels in the lower depths of Lake Spokane (Long Lake) have existed for decades. Patmont et al. (1987) described water quality problems that occurred in the lake during the 1930s, 1960s, and beyond. During the 1970s, Eastern Washington University and others completed multiple studies on the lake. These studies indicated that removing phosphorus, particularly from the city of Spokane's wastewater treatment plant, would help improve the lake's water quality (Patmont et al. 1987).

These toxic algae blooms resulted in the court-ordered establishment of a phosphorus TMDL because phosphorus was identified as the limiting nutrient causing eutrophication. This resulted in the development of the 1992 total phosphorus TMDL, which was originally adopted as a Phosphorus Management Plan in 1989. This total phosphorus TMDL focused on preventing toxic blue-green algae blooms by requiring the city of Spokane, and other local entities that discharge to the river, to reduce the levels of phosphorus in their effluent at the time by 85 percent to meet a total phosphorus concentration in Lake Spokane of 25 µg/L.

In December 1977, the city of Spokane completed an upgrade to their wastewater treatment plant to remove 85 percent of the phosphorus coming into the plant. Over the next several years, the lake's minimum dissolved oxygen concentrations showed significant improvement (Patmont et al. 1987; Cusimano 2004).

However, subsequent years of excessive algae blooms in Lake Spokane and continued violations of water quality standards for dissolved oxygen (DO) and phosphorus demonstrated that the total phosphorus TMDL did not adequately protect water quality (Cusimano 2004). As a result, several water body segments of the Spokane River were included on the Department of Ecology's 1996, 1998 and 2004 303(d) lists of impaired water bodies, which required that the *Spokane DO TMDL* be developed.

The goal of the *Spokane DO TMDL* is to achieve the dissolved oxygen water quality standard in the Spokane River and Lake Spokane. The TMDL includes allocations for the following nutrient sources within Washington State:

- Point sources such as municipal wastewater treatment plants or industrial facilities that discharge treated water into the river. There are five point source discharger facilities in Washington on the Spokane River, as well as stormwater sources.
- Nonpoint source pollution that enters our waters from everyday activities such as over-application of fertilizer, poor management of livestock and pet waste, bare stream banks that erode, and failing septic systems. Most of the nonpoint source pollution comes from the tributaries (Hangman Creek, Coulee Creek, and the Little Spokane River).
- Avista received a portion of the responsibility for DO improvement because Long Lake Dam created the reservoir conditions, such as longer residence times and thermal stratification, that contributed to low DO levels.

There are also three point source dischargers to the Spokane River in Idaho. Ecology does not have authority to require reductions in Idaho, but we worked with the Environmental Protection Agency (EPA) which was responsible for issuing National Pollutant Discharge Elimination System (NPDES) wastewater discharge permits in Idaho at that time (EPA 2013). (Idaho Department of Environmental Quality (IDEQ) is now the permitting agency.) The permits contain conditions that ensure compliance with Washington water quality standards.

Since 2010, Ecology and its partners have been implementing the TMDL through point and nonpoint source reductions. We describe these activities in more detail in later in this report.

Watershed description

The Spokane River watershed drains over 6,700 square miles of land in Washington and Idaho. The watershed stretches from the Idaho-Montana border to Lake Roosevelt and includes the St. Joe and Coeur d'Alene River basins upstream of Lake Coeur d'Alene in Idaho. Most of the people in the watershed live in the Spokane – Coeur d'Alene metropolitan area. The *Spokane DO TMDL* covers the portion of the watershed upstream of Long Lake Dam within Washington (Figure 1).

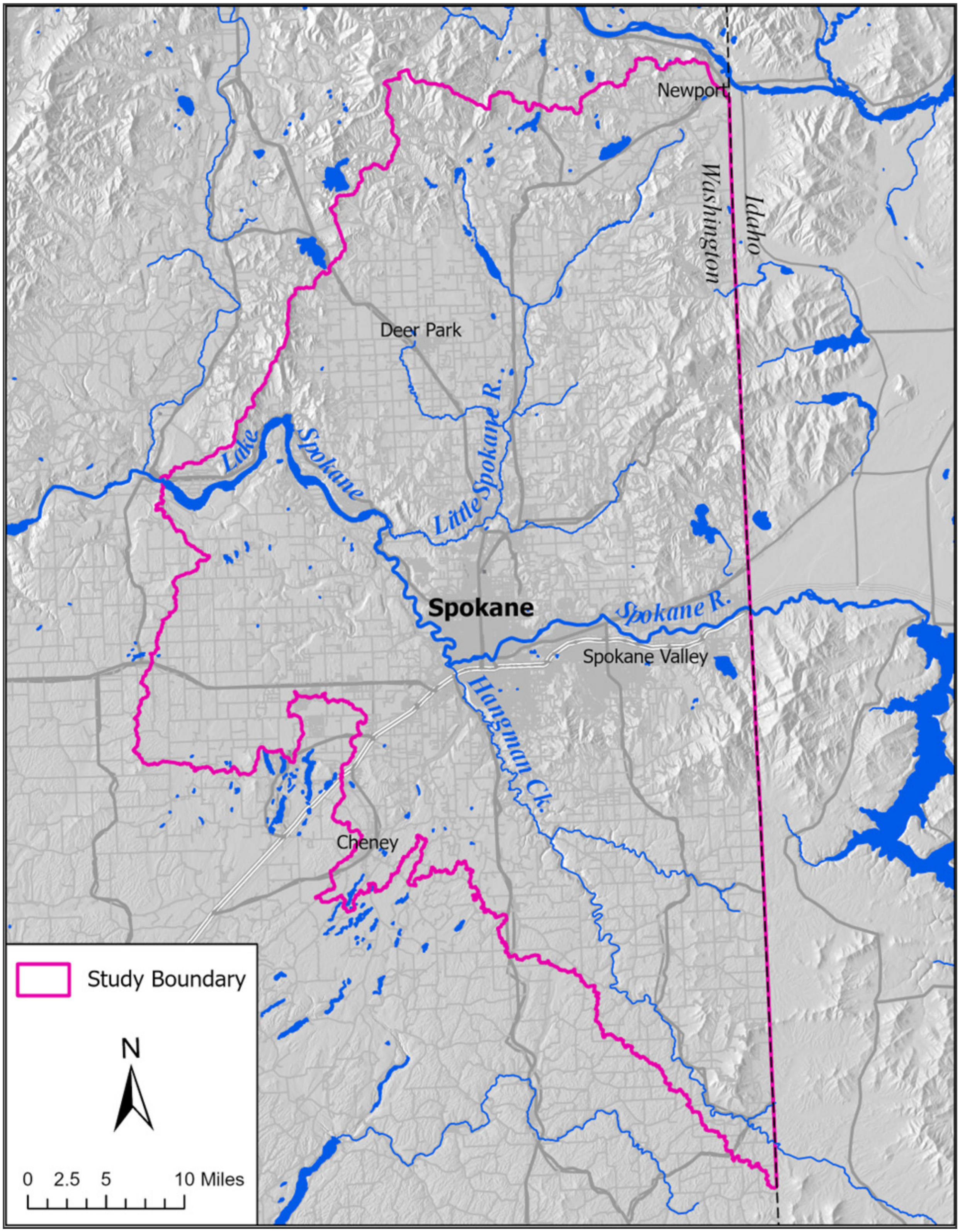

Figure 1. The Spokane River watershed in Washington upstream of Long Lake Dam.

The Spokane River flows through a transition area between the scablands of the Columbia basin to the west, coniferous forests and mountainous regions to the north and east, and prairie lands to the south (Hsieh et al. 2007).

Spokane receives an average of 16.5 inches of precipitation annually. It is affected by the rain shadow from the Cascade Mountains and thus receives roughly half of what Seattle gets annually (36.2 inches). Temperatures in Spokane also tend to be more extreme with warm summers and cold winters. Much of the winter precipitation can fall as snow, particularly at higher elevations.

The Spokane River sits atop the western portion of the Spokane Valley-Rathdrum Prairie Aquifer (Figure 2) (Kahle and Bartolino 2007). There is significant interchange between the river and the aquifer (Bartolino 2007), with the river losing flow to the aquifer in some areas and gaining flow from the aquifer in other areas. Spring snowmelt and rainfall dominate flows in the Spokane River from April through June, whereas July through September baseflows mostly come from the aquifer.

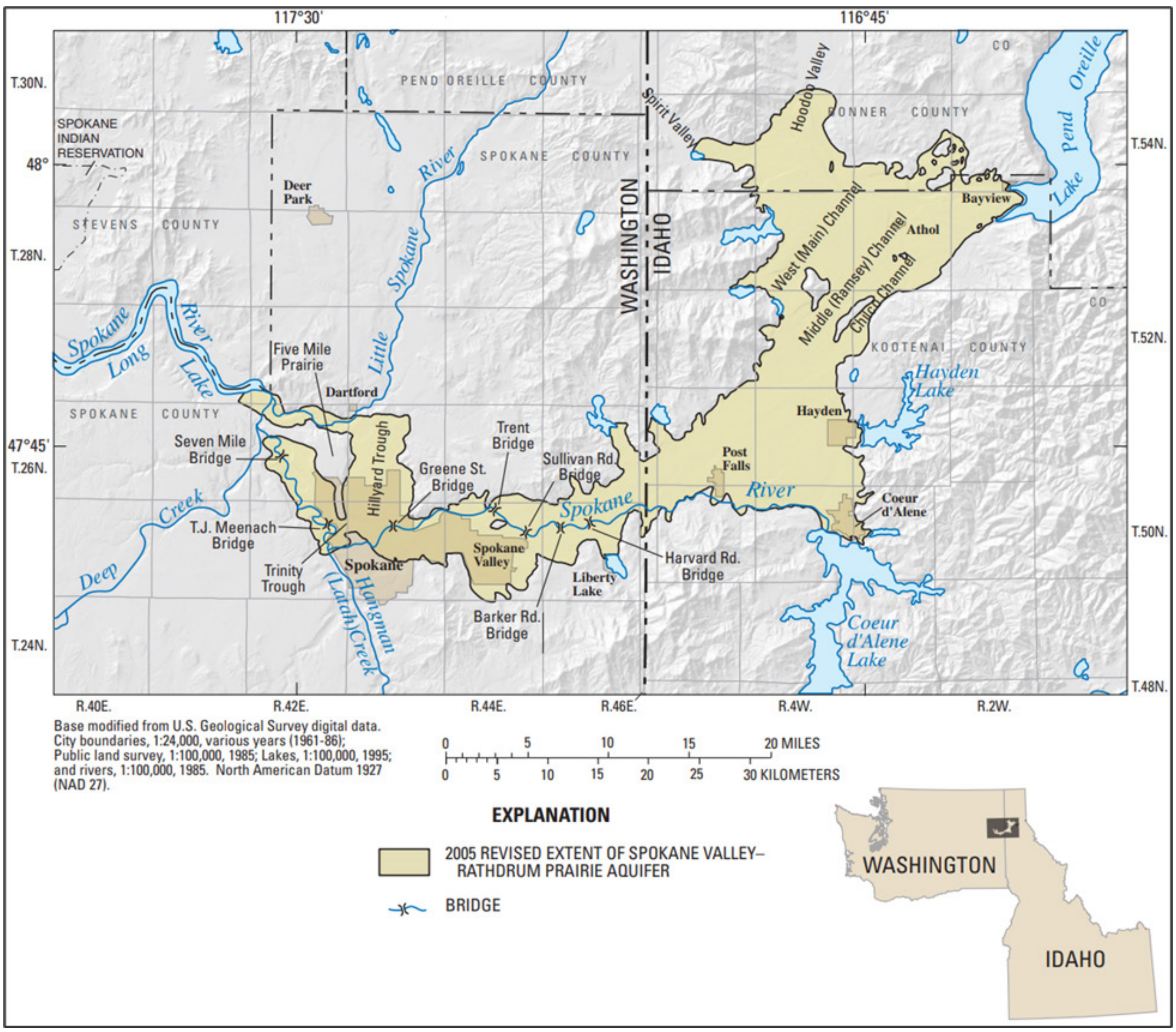

Figure 2. Spokane Valley Rathdrum Prairie Aquifer Map (from Kahle et al. 2005)

There are five major dams located along the Spokane River in Washington (Figure 3): Upriver Dam, Upper Falls Dam, Monroe Street Dam, Nine Mile Dam, and Long Lake Dam. There is also a dam at Post Falls, Idaho that influences the hydrodynamics of the river. All the Washington dams are run-of-the river types except Long Lake Dam, which creates Long Lake (Lake Spokane), a 24-mile-long reservoir (Figure 4).

Historically, anadromous salmonids were present in much of the study area. However, today several dams, including Grand Coulee Dam, eliminate fish passage and connectivity to the ocean. The Upper Columbia United Tribes (UCUT), which includes several regional tribes including the Spokane Tribe of Indians and the Coeur d'Alene Tribe of Indians, has initiated an effort to reintroduce salmon to the region (UCUT 2019; UCUT 2022).

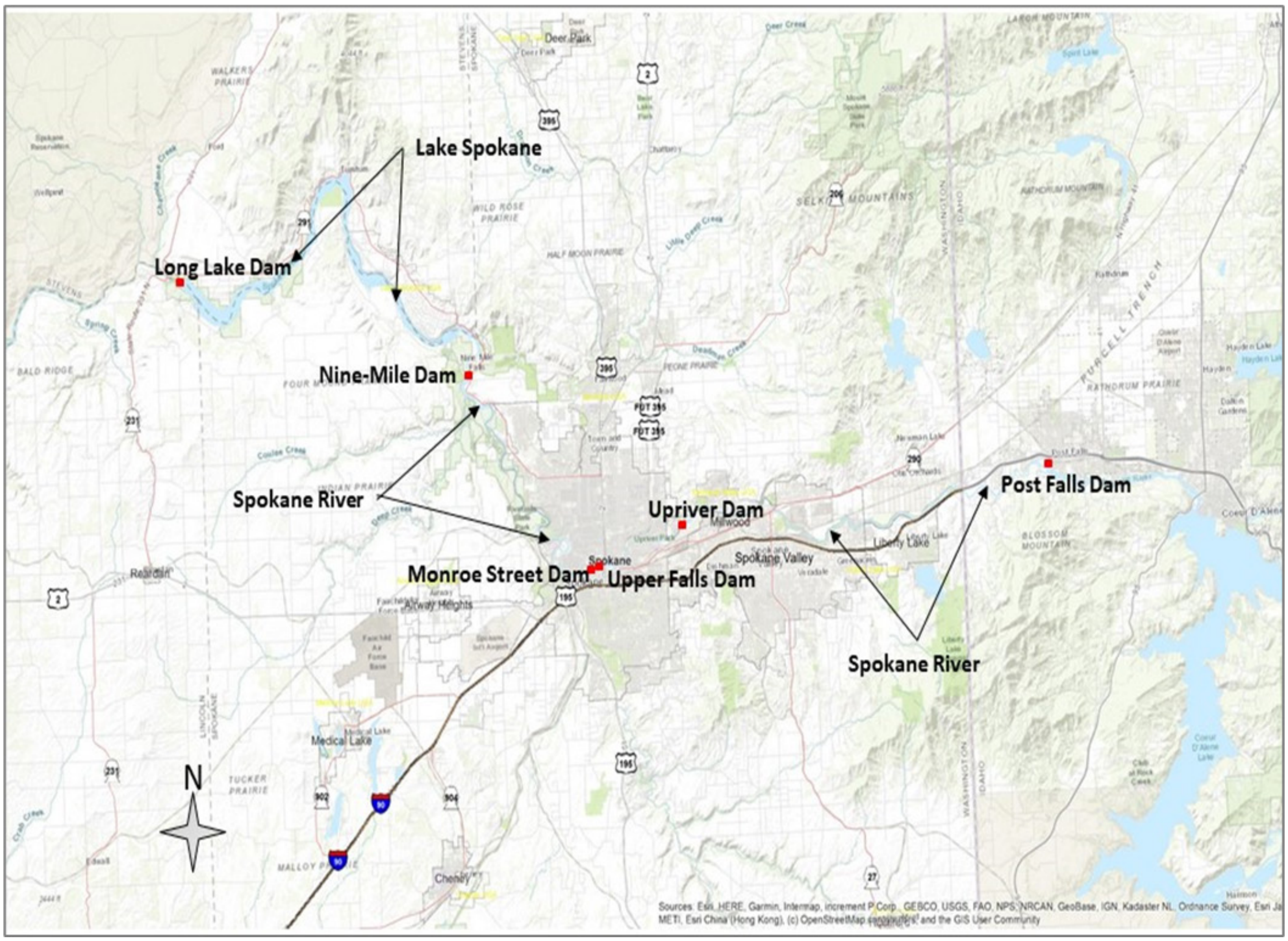

Figure 3. Dams on the Spokane River in Washington and Idaho.

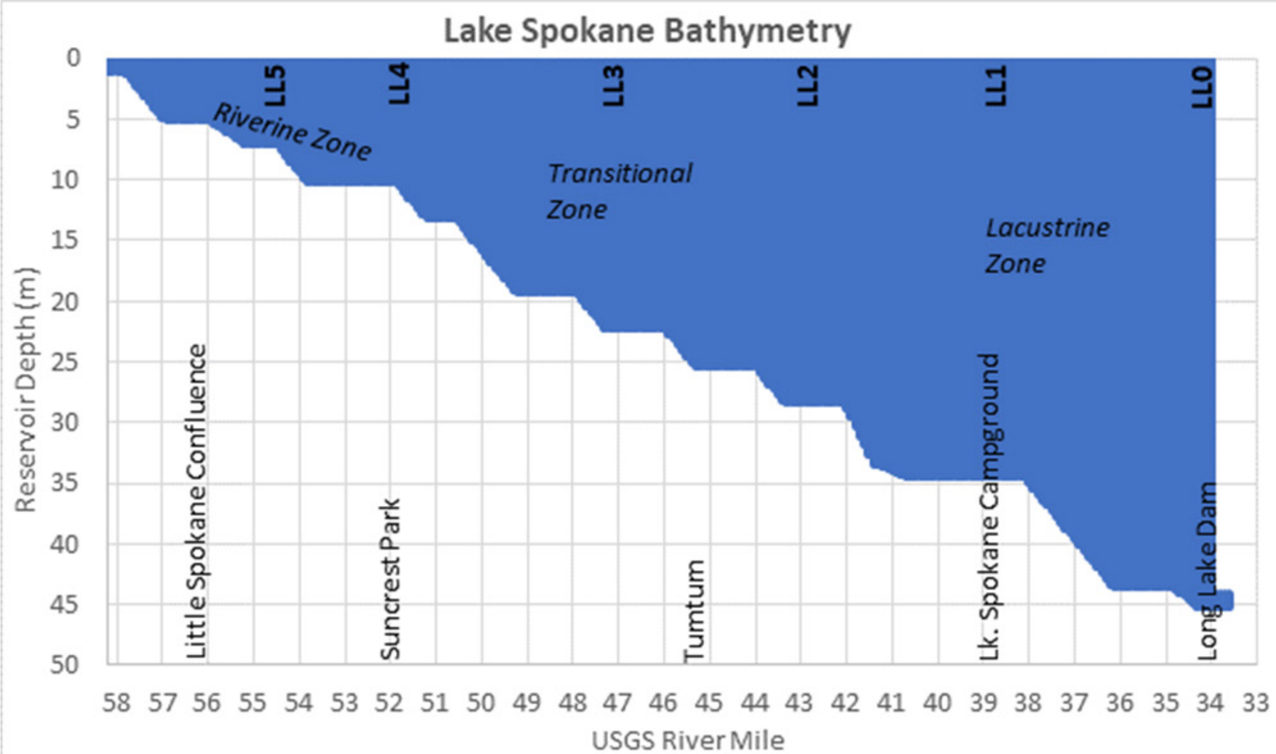

Figure 4. Bathymetric diagram of Lake Spokane, showing sampling locations and geographic references.

See Figure A-1 in Appendix A for a more detailed map showing these sampling locations.

Regulatory criteria and water quality standards

Dissolved oxygen (DO) and pH

In the Washington state water quality standards, freshwater aquatic life use categories are described using key species (salmonid versus warm-water species) and life-stage conditions (spawning versus rearing). Minimum concentrations of dissolved oxygen are used as criteria to protect different categories of aquatic communities [Washington Administrative Code (WAC) 173-201A-200].

The standards treat lakes differently from rivers for protecting dissolved oxygen conditions. Therefore, there are two dissolved oxygen standards for the TMDL, one for the main stem of the Spokane River from the state line to Nine Mile Dam, and one for Lake Spokane from Nine Mile Dam to Long Lake Dam. For lakes, and for reservoirs with a mean annual retention time of greater than 15 days, human actions considered cumulatively may not decrease the one-day minimum oxygen concentration by more than 0.2 mg/L below estimated natural conditions.

The *Spokane DO TMDL* was developed using the 2006 edition of the water quality standards. Table 1 presents the 2006 standards.[2]

Table 1. Designated aquatic life uses and criteria protected by the *Spokane DO TMDL*.

Portion of Study Area	Aquatic Life Uses	Dissolved Oxygen Criterion
Spokane River (from Nine Mile Bridge to the Idaho border)	Migration/Rearing/ Spawning	Dissolved oxygen shall exceed 8.0 mg/L. If natural conditions are less than the criteria, the natural conditions shall constitute the water quality criteria. [a]
Lake Spokane (from Long Lake Dam to Nine Mile Bridge)	Core Summer Habitat	No measurable (0.2 mg/L) decrease from natural conditions.
Spokane Arm of Lake Roosevelt (from confluence of Columbia River and Spokane River to Little Falls Dam — outside of TMDL compliance point)	N/A	Dissolved oxygen shall not be less than 8.0 mg/L. [b]

[a] For riverine reaches, the 2022 updated DO criteria are 10 mg/L or 90% saturation. These criteria have not yet been approved by the EPA and cannot be used for Clean Water Act-related purposes.
[b] Spokane Tribe of Indians Surface Water Quality Standards (Resolution 2003-259).

Phosphorus, ammonia, and CBOD

The *Spokane DO TMDL* established wasteload allocations (WLAs) for point source dischargers, as well as load allocations (LAs) for non-point sources. The TMDL also assigned a DO responsibility for Avista. Avista does not discharge pollutants to the Spokane River/Lake Spokane system, but owns and operates Long Lake Dam, which creates Lake Spokane. The goal of the TMDL is to achieve the dissolved oxygen water quality standards in the Spokane River and Lake Spokane.

Wasteload allocations

Table 2 shows the wasteload allocations for Washington State point sources. These are based on meeting a monthly average TP concentration of 50 µg/L. The seasonal average concentrations reflected in the table are less than 50 µg/L because effluent concentrations are not constant over time.

Dischargers had the opportunity to exchange some of their phosphorus removal for the additional removal of ammonia and/or CBOD as part of their Delta Elimination Plan. Dischargers had to demonstrate through modeling that the proposed combination of TP, ammonia, and

[2] Note that Ecology updated the DO criteria pertaining to riverine reaches during 2022. As of 2024 the updated DO criteria are pending EPA approval. However, the *Spokane DO TMDL* mainly depends on the criteria for Lake Spokane (as opposed to the Spokane River), which have not changed.

CBOD would result in equal or less impact to Lake Spokane than the original WLA combination. Therefore, some dischargers have effluent limits that differ from the original WLAs shown in Table 2.

Ecology does not have authority to require reductions in Idaho, but Ecology worked with the Environmental Protection Agency (EPA), which was responsible at that time for issuing permits in Idaho. The permits contain conditions that ensure compliance with Washington water quality standards. The TMDL assumed the following total loads from Idaho wastewater treatment plants and stormwater:

- 7.2 lbs/day phosphorus
- 497 lbs/day CBOD
- 94.4 lbs/day ammonia

Table 2. Wasteload allocations for WA State point sources (Moore and Ross 2010)

Point Source Discharge	2027 Projected Flow Rates (MGD) [a]	NH_3-N (mg/L)	NH_3-N WLA (lbs/day)	TP (mg/L)	TP WLA (lbs/day)	$CBOD_5$ [b] (mg/L)	$CBOD_5$ [b] WLA (lbs/day)
Liberty Lake	1.5	variable [c]	variable [c]	0.036	0.45	3.6	45.1
Kaiser [d]	15.4	0.07	9.0	0.025	3.21	3.6	462.7
Inland Empire Paper Company	4.1	0.71	24.29	0.036	1.23	3.6	123.2
City of Spokane	50.8	variable [c]	variable [c]	0.042	17.81	4.2	1780.6
Spokane County (new plant)	8	variable [c]	variable [c]	0.042	2.80	4.2	280.4
Stormwater [e]	2.36	0.05	0.98	0.310	6.1	3.0	59.1
CSO	0.12	1.0	1.0	0.95	0.95	30.0	30.0

[a] Actual, not projected flows, will determine compliance with wasteload allocations (WLA) in NPDES permits.
[b] NPDES permit limits will use $CBOD_5$ (as shown) rather than $CBOD_{ult}$ (as modeled).
[c] Ammonia wasteload allocations vary depending on the season based on the following effluent concentrations (loading limits use these concentrations and the design flow):
· Liberty Lake: March – May, October: 0.71 mg/L; June – September: 0.18 mg/L
· City of Spokane and Spokane County: March – May, October: 0.83 mg/L; June – September: 0.21 mg/L
[d] Wasteload allocations for Kaiser are lower than other dischargers due to non-contact groundwater, which is low in nutrients and comprises a significant portion of the facility's discharge.
[e] Stormwater wasteload allocation is for Washington sources only and is based on average existing flows, not 2027 projected flows.

Load allocations

The TMDL assigned load allocations to nonpoint sources of pollution (Table 3). The three tributaries (Hangman Creek, Coulee Creek, and the Little Spokane River) and the area surrounding Lake Spokane are the primary sources of nonpoint pollution to the river and lake.

The TMDL established three seasons for assigning load allocations. These seasons are based on hydrological patterns at different times of year. The March – May season represents springtime high-flow conditions, the June season represents a "receding hydrograph" transitional period, and the July – October season represents summertime low-flow conditions.

For Hangman and Coulee creeks, the allocations translate to the following reductions:

- 20%: March – May
- 40%: June
- 50%: July – October

In the Little Spokane River, the allocation represents a 36% decrease in phosphorus during the entire March through October critical season.

Table 3. Tributary and groundwater TMDL allocations (Moore and Ross 2010)

Water Body	Season	2001 Flow (cfs)	TP Allocation Concentration (mg/L) [a]	TP 2001 Load Allocation (lbs/day)	NH_3-N Allocation Concentration (mg/L)	NH_3-N 2001 Load Allocation (lbs/day	CBOD Allocation Concentration (mg/L)	CBOD 2001 Load Allocation (lbs/day)
Hangman Creek	March – May Average	229	0.113	140.2	0.034	42.1	3.3	4102.1
Hangman Creek	June	31	0.044	7.5	0.012	2.1	2.8	479.0
Hangman Creek	July – October Average	9	0.030	1.4	0.009	0.4	2.3	107.9
Coulee Creek	March – May Average	30	0.113	18.2	0.034	5.5	3.3	533.7
Coulee Creek	June	8	0.044	1.8	0.012	0.5	2.8	116.5
Coulee Creek	July – October Average	2	0.030	0.4	0.009	0.1	2.3	28.6
Little Spokane River	March – May Average	565	0.034	102.5	0.035	106.2	2.1	6409.3
Little Spokane River	June	426	0.023	53.9	0.005	11.5	2.1	4828.2
Little Spokane River	July – October Average	364	0.016	32.2	0.006	11.0	1.5	2867.8
GW – US of Lake Spokane	March – May Average	1946	0.0081	87	N/A	N/A	N/A	N/A
GW – US of Lake Spokane	June	1583	0.0078	66	N/A	N/A	N/A	N/A
GW – US of Lake Spokane	July – October Average	1165	0.0076	48	N/A	N/A	N/A	N/A

Water Body	Season	2001 Flow (cfs)	TP Allocation Concentration (mg/L) [a]	TP 2001 Load Allocation (lbs/day)	NH_3-N Allocation Concentration (mg/L)	NH_3-N 2001 Load Allocation (lbs/day	CBOD Allocation Concentration (mg/L)	CBOD 2001 Load Allocation (lbs/day)
GW / Surf. Water Runoff – Lake Spokane Watershed	March – May Average	588 [b]	0.025	79	N/A	N/A	N/A	N/A
GW / Surf. Water Runoff – Lake Spokane Watershed	June	225 [b]	0.025	30	N/A	N/A	N/A	N/A
GW / Surf. Water Runoff – Lake Spokane Watershed	July – October Average	180 [b]	0.025	24	N/A	N/A	N/A	N/A

[a] Allocation concentrations are based on critical low flow conditions.
[b] Reservoir correction flows in the water quality model. Flows are both positive and negative. The listed value is the average of positive inflows to the reservoir.

In the TMDL, Avista received a “DO responsibility” because they do not discharge nutrients, but their Long Lake Dam created the lake and conditions that contribute to the reservoir’s impairment. Avista’s task is to increase dissolved oxygen in the deeper parts of Lake Spokane from July 1 through October 31. The level of dissolved oxygen improvement required depends on the location and depth of the lake, as well as time of the year, but the required increase ranges from 0.1 to 1.0 mg/L.

Progress made during the last decade

Point Sources (including stormwater and CSO’s)

Point source dischargers have made significant progress in implementing the WLAs specified by the TMDL. Municipal and industrial point source dischargers in Washington have largely implemented tertiary treatment technology. This has substantially reduced discharges of phosphorus, as well as ammonia and CBOD. The following sections provide a high-level overview of improvements at each Washington point source. These overviews cannot capture the full complexity and scale of the work that has gone into these improvements. Rather, the purpose here is to briefly describe the approach that each permittee has taken to meet their WLAs. Also, although the focus of this report is on Washington sources, Idaho dischargers have also implemented, or are implementing, similar upgrades.

Liberty Lake Sewer and Water District

Liberty Lake Sewer and Water District’s (LLSWD) wastewater treatment facility was constructed in 1982 to eliminate septic systems that were contributing to water quality issues in Liberty Lake. The facility discharges to the Spokane River near river mile (RM) 92, just downstream of Harvard Road. The facility originally provided secondary treatment. LLSWD implemented a variety of improvements between 2004 – 2006 to accommodate population growth and reduce nutrient loads. A second set of upgrades, including chemically enhanced solids removal and membrane ultra-filtration (UF), came online in 2018.

Kaiser Aluminum Trentwood

Kaiser Aluminum Washington, LLC, owns an aluminum rolling mill and metal finishing plant at Trentwood, in Spokane Valley. The facility discharges to the Spokane River near RM 86, between Sullivan Rd. and Trent Ave. The primary issue of concern at this facility involves groundwater contamination by polychlorinated biphenyls (PCBs). To comply with the *Spokane DO TMDL,* Kaiser upgraded their wastewater treatment facility to include chemical precipitation for phosphorus removal. Installation of this upgrade was completed in 2018.

Inland Empire Paper Company

Inland Empire Paper Company (IEP) is a manufacturer of newsprint and specialty paper products. The facility discharges to the Spokane River near RM 83, just upstream of Argonne Rd. IEP has been on the technological "cutting edge" of pulp and paper industry wastewater treatment. Over 20 years of experimentation and optimization have led to a multi-stage treatment process including (but not limited to) heat exchange, Speece Cone super oxygenation, multiple clarifiers, moving bed biofilm reactors (MBBF) with nutrient feed and control, activated sludge, and membrane ultra-filtration (UF). IEP's treatment optimization efforts are ongoing.

Spokane County Regional Water Reclamation Facility

The Spokane County Regional Water Reclamation Facility (SCRWRF) began operation in 2011. The facility treats wastewater from the City of Spokane Valley, as well as from portions of the City of Spokane, Millwood, City of Liberty Lake, and unincorporated Spokane County. Prior to the completion of the SCRWRF, wastewater from these areas was delivered to the City of Spokane for treatment at the Riverside Park Water Reclamation Facility. The SCRWRF was designed to comply with the TMDL. The facility uses preliminary treatment, chemically enhanced primary treatment (CEPT) and membrane bioreactor treatment to remove phosphorous and other oxygen demanding wastes from the effluent. The facility also reuses a portion of their effluent for landscape watering.

City of Spokane Riverside Park Water Reclamation Facility

The Riverside Park Water Reclamation Facility (RPWRF), previously known as the Spokane Advanced Wastewater Treatment Plant (SAWTP), discharges to the Spokane River near RM 67, downstream of Hangman Creek, between T.J. Meenach bridge and the Bowl and Pitcher pedestrian bridge. This facility treats wastewater from the City of Spokane and was historically the largest point source contributor of phosphorus to the Spokane River. The first treatment plant was constructed in 1958 and was upgraded to advanced secondary treatment in 1977. Construction on Next Level of Treatment (NLT) began in 2015 and was completed in 2020. The NLT system included use of CEPT and membrane ultra-filtration (UF) technology and began operating in 2021.

Stormwater

The cities of Spokane and Spokane Valley, along with Spokane County, are working to redirect stormwater runoff so it can infiltrate into the ground rather than flowing directly into the Spokane River. A major project in northwest Spokane will infiltrate stormwater from the Cochran Basin, the

City of Spokane's largest MS4 collection basin, in the vicinity of Downriver Golf Course. Construction on this project began in 2021 and is mostly complete as of 2024. (This project was not yet online during our 2022 study period.) The Washington State Department of Transportation is also an active partner in reducing stormwater from the highways by performing maintenance and working with adjacent landowners to eliminate pollution sources entering the ditches and drains.

CSOs

A portion of Spokane still relies on a combined sewer system, where stormwater uses the same sewer system as wastewater and travels to the Riverside Park Water Reclamation Facility. During major runoff events, this system can overflow, causing raw sewage to enter the Spokane River and/or Hangman Creek via combined sewer overflow (CSO) outfalls. Since the mid 1990's, the City of Spokane has been installing CSO control facilities (CH2M Hill 2014) to reduce overflow volumes. As of 2020, all but three outfalls had achieved a "controlled state." The average number of CSO events has declined from 268/yr during 2008 – 2010 to 13/yr during 2020 – 2022 (City of Spokane 2023).

Nonpoint Sources

Various organizations including the Spokane, Pine Creek, Pend Oreille, and Whitman Conservation Districts, The Spokane and Coeur d'Alene Tribes, Avista, Spokane Riverkeeper, Natural Resources Conservation Services, The Lands Council, Spokane Falls Trout Unlimited, and many others have been working to reduce nonpoint pollution through riparian restoration, implementation of best management practices (BMPs) for agricultural, residential, and forest land, outreach and education, and a variety of other actions.

To date, these groups have completed hundreds of projects to reduce nonpoint source pollution. Many of these projects are in the Hangman Creek and Little Spokane watersheds. The types of projects completed include connecting homes historically on septic systems to a municipal sewer system; improving forest roads and forest practices to reduce erosion; installing livestock best management practices such as fencing off waterways and off-stream watering; improving tillage practices such as installation buffers along waterways and converting fields from high disturbance (conventional tillage) to lower disturbance (mulch tillage or direct seed/no-till); planting degraded riparian (stream bank) areas previously in crop production, with trees and shrubs; and using various bioengineered streambank stabilization methods to mitigate streambank erosion.

10-Year Effectiveness Study

Effectiveness monitoring studies

TMDL effectiveness monitoring is a fundamental component of any TMDL implementation activity. It is an essential part of the TMDL adaptive management process. Effectiveness monitoring measures to what extent management activities have resulted in progress toward meeting state water quality standards. Effectiveness monitoring takes a holistic look at TMDL implementation, watershed management plan implementation, and other watershed-based cleanup efforts. Rather than monitoring the effectiveness of any specific implementation action, effectiveness monitoring studies generally measure the cumulative effect of all activities in the watershed. Success may be measured against TMDL load allocations or targets, correlated with baseline conditions or desired future conditions.

The TMDL effectiveness evaluation benefits by providing:

- A measure of progress toward implementation of recommendations - how much watershed restoration has been achieved and how much more effort is required.
- More efficient allocation of funding and optimization in planning and decision-making.
- Identification of restoration activities that worked and those that were most successful for the money spent.
- Technical feedback to refine the initial TMDL model, best management practices, nonpoint source plans, and permits.

Spokane TMDL 10-year assessment

The *Spokane DO TMDL* defined a twenty-year timeline for achieving water quality improvement goals (Moore and Ross 2010). The concept of a Spokane River/Lake Spokane ten-year assessment emerged while working with the TMDL advisory group. However, the TMDL did not set specific ten-year water quality objectives. Rather, the purpose of the ten-year assessment is to provide a midway check to determine whether substantial progress is being made toward meeting the twenty-year goals.

The TMDL report characterized the ten-year assessment as a data-based, objective review conducted to determine:

- The amount of phosphorus removed from the river compared to the phosphorus reduction requirements.
- The Spokane River and Lake Spokane’s response to the reductions and associated changes in dissolved oxygen.
- The likelihood of further phosphorus reductions occurring in the second ten years if the actions already taken are continued.

- A set of actions that could be initiated in the second ten years that would likely result in further phosphorus reductions.
- The reasonableness of pursuing other strategies if the dissolved oxygen standard has not been met and continuing existing or implementing additional phosphorus removal strategies will likely achieve the dissolved oxygen standard.
- The progress on implementation of Avista's dissolved oxygen responsibility.
- Whether the hypolimnion has met the dissolved oxygen standard with technology improvements and target pursuit actions or Avista's dissolved oxygen responsibility, or if modified water quality standards for this layer are appropriate.
- Whether the wasteload allocations, load allocations and dissolved oxygen responsibility are being met and whether they should be lowered or raised (or redistributed) while still being protective of water quality.

The ten-year assessment will consider factors such as how long the treatment technology has been in operation and whether sufficient data are available to determine river conditions and dissolved oxygen response.

The ten-year assessment concept included utilization of CE-QUAL-W2, a mechanistic water quality model commonly used for long, narrow lakes and reservoirs, and currently maintained by Portland State University (PSU), in Portland, OR. The concept did not specify how the model would be used to determine progress towards the twenty-year water quality objectives. Our analysis of the available data, presented in this report, provides a good picture of the status and progress toward meeting the TMDL. It is not clear that using the CE-QUAL-W2 model would provide additional insight at this time.

Data Sources

This Spokane River and Lake Spokane DO TMDL 10-Year Effectiveness Study depends on data collected over many years by multiple organizations. These data span many data types, locations, and time periods. This section summarizes the data sources that we used for our analysis.

Ecology ambient river monitoring

Ecology collects samples and measurements monthly at a variety of rivers and streams around the state. In the Spokane River watershed, this includes four long-term monitoring stations, as well as two rotating "basin stations" that we sampled during Water Year 2022. These ambient river data form the backbone of our river analysis. These data also provide the primary basis for detecting trends in the river over time. These data are available in Ecology's EIM Database,[3] search Study ID's AMS001, AMS001B, AMS001C, AMS001D, AMS001E.

Ecology project data collection (this study)

Ecology collected field data in the Spokane River watershed during October 2021 – October 2022. This data collection effort followed a project-specific Quality Assurance Project Plan (QAPP; Stuart et al. 2021) as well as Ecology's *Programmatic QAPP for Water Quality Impairment Studies* (McCarthy and Mathieu 2017). The data are available in EIM, search Study ID tist0003. Appendix B of this report presents a quality assessment of this dataset. This data collection included the following elements:

- **River monitoring** — We collected water samples and measurements monthly at selected locations along the Spokane River and tributaries to fill gaps in data collected by Ecology's Ambient Monitoring program. These data included six additional parameters, and three additional locations not included in the Ambient program routine monitoring.
- **Lake monitoring** — We collected water samples and measurements at six locations in Lake Spokane. We collected samples monthly from April through October 2022. We collected measurements during one additional visit each month, about halfway between sampling events.
- **Continuous turbidity monitoring** — We collected continuous turbidity at three locations, one each on the Spokane River, Hangman Creek, and the Little Spokane River. Turbidity tends to be strongly correlated with sediment and phosphorus (Stuart 2022). We also collected total suspended solids and total phosphorus samples at these locations to determine the relationship between turbidity, sediment, and phosphorus. An attempt to monitor one additional location on Hangman Creek failed due to vandalism of equipment.

[3] https://apps.ecology.wa.gov/eim/search/default.aspx

- **Little Spokane River source tracking** — We collected samples and measurements along the lower 14 miles of the Little Spokane River during one synoptic survey during high flow conditions in April 2022. We collected these data to improve our understanding of an apparent sediment and phosphorus load of unknown origin identified in the *Little Spokane River DO, pH, & TP TMDL* (Johnson et al. 2020).

Past Ecology studies

We used data from several past Ecology studies, as applicable to our analysis. These include the following. All these data are available in EIM.

- **Spokane TMDL study 1999 – 2000** (EIM Study ID: BCUS0005) — Ecology collected samples and measurements along the Spokane River, in Lake Spokane, tributaries, and groundwater sources. These data formed the basis of the modeling and analysis that led to the *Spokane DO TMDL* (Moore and Ross 2010). A data summary report (Cusimano 2003) summarizes and assesses these data in detail.
- **Lake Spokane monitoring 2010 – 2011** (EIM Study ID: JROS0020) — Ecology worked in partnership with Tetra Tech, under contract from Avista Corporation. Both organizations collected samples and measurements from Lake Spokane, as well as the Spokane River and Little Spokane River locations just upstream from the lake. A data summary report (Ross 2013) summarizes and assesses these data.
- **Little Spokane TMDL study 2010, 2013, 2015 – 16** (EIM Study ID: JJOY0007) — Ecology collected samples and measurements throughout the Little Spokane River watershed. These data supported the *Little Spokane River DO, pH, & TP TMDL* (Johnson et al. 2020). A data summary report (Stuart 2012) summarizes and assesses the 2010 data. The 2013 and 2015 – 16 data summary and assessment are found in Appendices D and E of the TMDL report (Johnson et al. 2020). For purposes of this Spokane 10-Year Effectiveness Study, we only used data collected near the mouth of the Little Spokane River.
- **Hangman Creek studies 2008 – 09, 2016, 2017 – 2018** (EIM Study IDs: JJOY0005, TIST0002) — Ecology collected samples and measurements throughout the Hangman Creek watershed. These data supported the *Tekoa WWTP DO, pH, & Nutrients Receiving Water Study* (Stuart 2020) and the *Hangman Creek Nutrients & Sediment Pollutant Source Assessment* (Stuart 2022). A data summary report (Ross 2011) summarizes and assesses the 2008 – 09 data. The 2016 and 2017 – 2018 data summary and assessment are found in appendices of the study reports (Stuart 2020; Stuart 2022). For purposes of this Spokane 10-Year Effectiveness Study, we only used data collected near the mouth of Hangman Creek.
- **Deep Creek groundwater study 2016** (EIM Study ID: KSIN0009) — We collected samples and measurements from instream piezometers at the mouth of Deep Creek, to evaluate nutrient fluxes to the Spokane River. A study report (Sinclair and Gallagher 2019) summarizes, assesses, and interprets these data.

Avista/Tetra Tech Lake Spokane monitoring

Tetra Tech, under contract from Avista Corporation, collected samples and measurements in Lake Spokane during 2012 – 2018 (Avista et al. 2014). Avista collected this data as a part of their Water Quality Attainment Plan pursuant to their Federal Energy Regulatory Commission (FERC) relicensing water quality certification under section 401 of the Clean Water Act (Avista and Four Peaks 2022a). These data provide a key window into conditions in Lake Spokane during the decade after the *Spokane DO TMDL* was adopted in 2010. The data are available in EIM, search Study ID LKSpokaneNutrient_WQ. Tetra Tech published annual data summaries during this time which present the data in detail (Avista et al. 2014; Avista et al. 2015; Avista and Tetra Tech 2017; Avista and Tetra Tech 2018; Avista and Tetra Tech 2019). These documents are available on the Avista website.[4]

During 2020, Tetra Tech collected additional data, this time looking at diel fluctuations in dissolved oxygen and temperature in Lake Spokane (Avista and Tetra Tech 2020). These data are available in EIM, search Study ID AVLSWQCON20. Tetra Tech published an annual data summary that presents detailed graphs of this data (Avista and Tetra Tech 2021).

Spokane County groundwater data

Spokane County maintains an extensive groundwater monitoring program. This program routinely collects and publishes water quality data for the Spokane Valley-Rathdrum Prairie Aquifer (SVRPA; Spokane County 2007). The monitoring program includes a host of toxics and other parameters, including nitrate and phosphorus. These data provide the best basis for estimating groundwater nutrient loads entering the Spokane River. Spokane County publishes annual monitoring reports (e.g., Spokane County 2022), which present and summarize the data. The data and reports are available on the Spokane County website.[5]

City of Spokane stormwater and CSO data

The City of Spokane has collected a variety of data on its stormwater and combined sewer overflow (CSO) discharges over the past decade. The Cochran Basin stormwater monitoring report (City of Spokane 2020; City of Spokane 2016) presents stormwater quality sampling results from 2012 – 2019, as well as monthly discharge volume data from 2016 – 2019. We obtained unpublished Cochran Basin discharge volume data from city staff for 2020 – 2022 (Donovan 2023, pers. comm.). The City of Spokane Integrated Clean Water Plan (CH2M Hill, 2014) summarizes some additional stormwater quality monitoring data, including for the Washington Basin. This document also provides key data including catchment area and impervious fraction for six major stormwater basins

[4] https://www.myavista.com/about-us/celebrate-our-rivers/our-environment-documents
[5] https://www.spokanecounty.org/1285/Groundwater-Monitoring

including Cochran, Hollywood, Rifle Club, Washington, Kiernan, and Union. These six basins comprise about 75% of the total area covered by the separated stormwater (MS4) system.

The City of Spokane also collects discharge volume data for overflow events from its CSO system. These data are summarized in CSO reports published monthly and yearly (e.g., City of Spokane 2023). These reports are available on the City's CSO webpage.[6]

Discharger monitoring data

Point source dischargers to the Spokane River routinely monitor their effluent for a variety of parameters, as part of the requirements of their National Pollutant Discharge Elimination System (NPDES) permits. These dischargers report the results of this monitoring to Ecology in monthly Discharge Monitoring Reports (DMRs). All the Spokane dischargers monitor TP, ammonia, and CBOD (or BOD), the parameters for which the 2010 *Spokane DO TMDL* set wasteload allocations. Most of the dischargers also collect other nutrient parameters and other parameters relevant to this study. These DMR effluent data provide the basis for estimating point source loads to the Spokane River.

USGS streamflow data

The U.S. Geological Survey (USGS) currently operates three stream gages on the Spokane River at Post Falls, Spokane, and just below Nine Mile Dam. Additionally, they operate gages on Hangman Creek and the Little Spokane River. Historically, the USGS has also operated several additional gages at intermediate locations on the Spokane River. USGS gages provide the principal source of streamflow data for this analysis. Gage data are available in near real-time on the USGS website.[7]

USGS groundwater studies

The USGS conducted studies between 2014 and 2019 examining nearshore groundwater along both the north and south shores of Lake Spokane (Gendaszek et al. 2016; Sheibley and Foreman 2021). These studies characterized groundwater nutrient concentrations and seepage rates, and made estimates of groundwater nutrient loading to Lake Spokane. These studies provide our current best estimate of groundwater nitrogen and phosphorus loading directly to Lake Spokane (as opposed to loading to riverine portions of the system).

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[6] https://my.spokanecity.org/publicworks/wastewater/cso/
[7] https://waterdata.usgs.gov/nwis

Data Quality

We assessed the quality of all data used in this analysis. Appendix B presents a detailed analysis of the quality of data collected during this study (EIM Study ID tist0003). Appendix C presents a detailed analysis of the quality of data collected outside of this study, including Ecology ambient monitoring data as well as data collected by organizations other than Ecology. For past Ecology studies used in this analysis, each study resulted in either a data summary report, or another project report (Cusimano 2003; Ross 2013; Stuart 2012; Johnson et al. 2020; Ross 2011; Stuart 2020; Stuart 2022; Sinclair and Gallagher 2019). These individual reports each provide a detailed quality assessment of data collected during that study.

We found all data to be of adequate quality to their use in this analysis, with the following exception: We observed evidence that total phosphorus (TP) data analyzed by a contract lab during summer and fall of 2022 were biased high relative to data analyzed by Manchester Environmental Lab (MEL). This bias affected some TP data collected as part of this project, as well as some Ecology ambient monitoring data. Appendix B provides more details. We did not use the potentially biased contract lab TP data for our analysis.

Results and Discussion

Hydrologic representativeness of 2022 study year

Ecology's field study ran from October 2021 – October 2022, approximately corresponding to Water Year (WY) 2022. (Water years run from October of one year to September of the next.) We evaluated the representativeness of hydrologic conditions during this time by comparing WY 2022 streamflows to flows from other years.

Table 4 presents seasonal mean streamflows for the Spokane River at Spokane USGS gage[8] for 1980 – 2022. The table also presents these seasonal streamflows relative to the median seasonal flow for the 1980 – 2022 period. For 2022, both the March – May season, representing springtime high-flow conditions, and the July – October season, representing summertime low-flow conditions were near normal (median).

Streamflows during the June season were well above normal, over twice the median value for that season. In fact, the peak streamflow during 2022 occurred on June 18th, a month and a half later than normal. This was due in part to abnormally high rainfall. The National Weather Service station at Spokane Airport[9] recorded 2.5 in of precipitation during June 2022, compared to a typical June value of 1.2 in. June 2022 was also abnormal in that the abundant rainfall caused high flows and extreme sediment/turbidity events in Hangman Creek, which impacted the Spokane River and Lake Spokane as well.

In sum, March – May and July – October 2022 were representative of normal streamflow conditions for those seasons. June 2022 was higher than normal.

Note that the allocations in the *Spokane DO TMDL* are based on 2001 conditions. 2001 was an extremely dry year, representing critical low-flow conditions. Therefore, although the March – May and July – October 2022 periods represent near-normal conditions, data from 2022 are still not directly comparable to the 2001 TMDL year.

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[8]USGS station #12422500. This station is located just upstream of the Hangman Creek confluence, not far from Sandifur Bridge.
[9]Station KGEG.

Table 4. TMDL seasonal mean Spokane River (at Spokane) streamflows, 1980 – 2022.

Year	Flow (cfs) Mar – May	Flow (cfs) June	Flow (cfs) July – Oct	% of median Mar – May	% of median June	% of median July – Oct
1980	9583	9569	2076	73%	119%	108%
1981	9796	10152	2214	75%	126%	115%
1982	17518	12834	2317	134%	160%	121%
1983	13100	8159	2621	100%	102%	137%
1984	13078	14388	2372	100%	179%	124%
1985	12840	10870	1993	98%	135%	104%
1986	13783	4334	1602	105%	54%	84%
1987	9595	2532	1276	73%	32%	67%
1988	8662	3925	1215	66%	49%	63%
1989	14485	6905	1797	111%	86%	94%
1990	13388	15100	2114	102%	188%	110%
1991	14146	10914	2247	108%	136%	117%
1992	6669	2342	1363	51%	29%	71%
1993	13278	4901	2360	101%	61%	123%
1994	6355	2666	1039	49%	33%	54%
1995	12247	4925	1962	93%	61%	102%
1996	14958	8263	2023	114%	103%	105%
1997	21748	19634	3177	166%	244%	166%
1998	10245	7061	1808	78%	88%	94%
1999	13879	15960	2423	106%	199%	126%
2000	15853	7717	1959	121%	96%	102%
2001	6154	3800	1259	47%	47%	66%
2002	15981	19772	2216	122%	246%	116%
2003	9799	4779	1210	75%	59%	63%
2004	9955	6787	1920	76%	84%	100%
2005	7091	3680	1396	54%	46%	73%
2006	13268	8279	1462	101%	103%	76%
2007	13131	3787	1200	100%	47%	63%
2008	13471	24753	2513	103%	308%	131%
2009	14048	8574	1556	107%	107%	81%
2010	6449	12575	1985	49%	156%	103%
2011	17396	23907	3175	133%	298%	166%
2012	19065	16667	2384	146%	207%	124%
2013	11741	5585	1772	90%	69%	92%
2014	17014	8036	1809	130%	100%	94%
2015	7813	1697	852	60%	21%	44%
2016	12324	3366	1625	94%	42%	85%
2017	22701	8138	1918	173%	101%	100%
2018	16241	6094	1636	124%	76%	85%
2019	10698	4684	1585	82%	58%	83%
2020	10466	8170	1617	80%	102%	84%
2021	8274	4583	1151	63%	57%	60%
2022	**13531**	**18251**	**1961**	103%	227%	102%
Median	13100	8036	1918			

2022 source loads, riverine assessment point, and Avista responsibility

We estimated loading for phosphorus and other pollutants as applicable, for point source, nonpoint sources, and the riverine assessment point based on data from 2022. We also discuss Avista's DO responsibility. The purpose of this evaluation is to provide a "snapshot" of how the system as a whole is progressing toward meeting TMDL requirements a decade into TMDL implementation.

We evaluated all sources on the basis of the three TMDL seasons: March – May, June, and July – October. For some sources, such as facility point sources, the effluent flow and concentration do not vary much between seasons. Other sources, such as stormwater and tributary nonpoint, are seasonal in nature, with higher loads during the springtime than during the summer.

Point Sources

Tables 5 – 7 present 2022 observed seasonal point source loads, along with their respective wasteload allocations (WLAs) established in the *Spokane DO TMDL*.

It needs to be emphasized that *these comparisons do not constitute an evaluation of permit compliance*. Ecology's Water Quality Program permit unit evalutes National Pollutant Discharge Elimination System (NPDES) permit compliance based on effluent limits, sampling frequencies, and time periods that may differ from what is presented here. Furthermore, dischargers may participate in bubble allocations, compliance schedules, and some have exchanged a portion of their TP reduction for additional reductions of CBOD and phosphorus, by demonstrating that the proposed combination of pollutants would result in equal or less impact to Lake Spokane than the orginal WLA. These nuances can affect the way compliance is evaluated. The purpose of the comparison presented here, as with all comparisons presented in this report, is to provide a big-picture sense of how the system as a whole is progressing toward meeting the requirements of the TMDL.

Point source dischargers have made significant reductions. Point source TP loads, not including stormwater and combined sewer overflows (CSOs),[10] averaged 23 lbs/day during Mar – Oct 2022. This compares with 239 lbs/day during Mar – Oct 2001[11], the time period used to develop the TMDL. This represents a more than 90% reduction. Point source CBOD and ammonia loads are substantially lower as well.

[10] The 2001 CE-QUAL-W2 current conditions model run used to calculate point source loads for the TMDL report did not explicitly include stormwater or CSOs. Ecology estimated stormwater loads using the simple method (Schueler 1987; Lubliner 2007), as stormwater data were not available at that time. Therefore, to make an "apples-to-apples" comparison between 2022 and 2001, it is necessary to omit these sources.
[11] As represented in the 2001 CE-QUAL-W2 model input files.

Table 5. Point source TP loads during 2022 compared with WLAs.

Point Source Discharge	Season, 2022	Effluent flow (mgd)	TP concentration (mg/L)	TP load (lbs/day)	Anticipated 2027 flow (mgd) [a]	TP WLA concentration (mg/L) [a]	TP WLA (lbs/day) [a]
Liberty Lake	Mar – May	0.84	0.014	0.099	1.5	0.036	0.45
Liberty Lake	June	0.86	0.014	0.10	1.5	0.036	0.45
Liberty Lake	Jul – Oct	0.82	0.022	0.15	1.5	0.036	0.45
Kaiser Aluminum	Mar – May	5.1	0.006	0.27	15.4	0.025	3.21
Kaiser Aluminum	June	5.3	0.008	0.37	15.4	0.025	3.21
Kaiser Aluminum	Jul – Oct	5.0	0.008	0.34	15.4	0.025	3.21
Inland Empire Paper	Mar – May	5.5	0.387 [b]	18 [b]	4.1	0.036	1.23
Inland Empire Paper	June	5.5	0.329 [b]	15 [b]	4.1	0.036	1.23
Inland Empire Paper	Jul – Oct	6.3	0.224 [b]	12 [b]	4.1	0.036	1.23
Spokane County	Mar – May	7.6	0.042	2.7	8.0	0.042	2.80
Spokane County	June	7.0	0.056	3.3	8.0	0.042	2.80
Spokane County	Jul – Oct	6.9	0.052	3.0	8.0	0.042	2.80
City of Spokane	Mar – May	31	0.016	4.2	50.8	0.042	17.81
City of Spokane	June	40	0.018	6.0	50.8	0.042	17.81
City of Spokane	Jul – Oct	27	0.021	4.8	50.8	0.042	17.81
Stormwater	Mar – May	1.3 [c]	1.02 [c]	11 [c]	2.36	0.310	6.1
Stormwater	June	4.4 [c]	0.54 [c]	20 [c]	2.36	0.310	6.1
Stormwater	Jul – Oct	0.22 [c]	0.39 [c]	0.71 [c]	2.36	0.310	6.1
CSO	Mar – May	0.0034	unknown [d]	unknown [d]	0.12	0.95	0.95 [f]
CSO	June	0.091	unknown [d]	unknown [d]	0.12	0.95	0.95 [f]
CSO	Jul – Oct	0	unknown [d]	0	0.12	0.95	0.95 [f]
Total Point Sources	**Mar – May**	**51**	**(N/A)**	**36** [e]	**82**	**(N/A)**	**32**
Total Point Sources	**June**	**63**	**(N/A)**	**45** [e]	**82**	**(N/A)**	**32**
Total Point Sources	**Jul – Oct**	**46**	**(N/A)**	**21** [e]	**82**	**(N/A)**	**32**

[a] These WLA values, including the 2027 projected flow rates, concentrations, and loads, are found in the *Spokane DO TMDL* (Moore and Ross 2010), Table 5. Care should be taken when comparing actual loads with these original WLA values, because some dischargers exchanged a portion of their total phosphorus (TP) reduction for additional CBOD and/or ammonia reduction as part of their Delta Elimination Plans. Loads shown in this table in excess of the original WLA do not necessarily constitute a violation of the TMDL or of NPDES permit requirements.
[b] Inland Empire Paper received a compliance schedule to optimize operations of its wastewater treatment system. The due date to meet final effluent limits for TP and $CBOD_5$ is November 1, 2024.
[c] Stormwater values based on City of Spokane data and reports. See Appendix G for calculation of the estimates.
[d] Concentration data are not available for CSOs.
[e] These values do not include CSO loads, which are unknown due to the lack of concentration data. However, given the small flow volumes involved, CSO loads likely constitute a small fraction of the total.
[f] The apparently identical concentration and load values are not a typo. By coincidence, given 0.12 mgd flow volume, concentrations in mg/L and loads in lbs/day work out to be almost exactly the same numeric value.

Table 6. Point source $CBOD_5$ loads during 2022 compared with WLAs.

Point Source Discharge	Season, 2022	Effluent flow (mgd)	$CBOD_5$ concentration (mg/L)	$CBOD_5$ load (lbs/day)	Anticipated 2027 flow (mgd) [a]	$CBOD_5$ WLA concentration (mg/L) [a]	$CBOD_5$ WLA (lbs/day) [a]
Liberty Lake	Mar – May	0.84	1.98	14	1.5	3.6	45.1
Liberty Lake	June	0.86	1.95	14	1.5	3.6	45.1
Liberty Lake	Jul – Oct	0.82	2.08	14	1.5	3.6	45.1
Kaiser Aluminum	Mar – May	5.1	3.62	150	15.4	3.6	462.7
Kaiser Aluminum	June	5.3	4.57	200	15.4	3.6	462.7
Kaiser Aluminum	Jul – Oct	5.0	5.52	230	15.4	3.6	462.7
Inland Empire Paper	Mar – May	5.5	8.37 [b]	380 [b]	4.1	3.6	123.2
Inland Empire Paper	June	5.5	15.1 [b]	690 [b]	4.1	3.6	123.2
Inland Empire Paper	Jul – Oct	6.3	7.88 [b]	420 [b]	4.1	3.6	123.2
Spokane County	Mar – May	7.6	0.37	23	8.0	4.2	280.4
Spokane County	June	7.0	1.10	65	8.0	4.2	280.4
Spokane County	Jul – Oct	6.9	1.15	66	8.0	4.2	280.4
City of Spokane	Mar – May	31	1.98	510	50.8	4.2	1780.6
City of Spokane	June	40	2.00	670	50.8	4.2	1780.6
City of Spokane	Jul – Oct	27	1.92	440	50.8	4.2	1780.6
Stormwater	Mar – May	1.3 [c]	12.0 [c]	130 [c]	2.36	3.0	59.1
Stormwater	June	4.4 [c]	12.0 [c]	440 [c]	2.36	3.0	59.1
Stormwater	Jul – Oct	0.22 [c]	7.25 [c]	13 [c]	2.36	3.0	59.1
CSO	Mar – May	0.0034	unknown [d]	unknown [d]	0.12	30.0	30.0 [f]
CSO	June	0.091	unknown [d]	unknown [d]	0.12	30.0	30.0 [f]
CSO	Jul – Oct	0	unknown [d]	0	0.12	30.0	30.0 [f]
Total Point Sources	**Mar – May**	**51**	**(N/A)**	**1210 [e]**	**82**	**(N/A)**	**2781.1**
Total Point Sources	**June**	**63**	**(N/A)**	**2070 [e]**	**82**	**(N/A)**	**2781.1**
Total Point Sources	**Jul – Oct**	**46**	**(N/A)**	**1180 [e]**	**82**	**(N/A)**	**2781.1**

[a] These WLA values, including the 2027 projected flow rates, concentrations, and loads, are found in the *Spokane DO TMDL* (Moore and Ross 2010), Table 5.
[b] Inland Empire Paper received a compliance schedule to optimize operations of its wastewater treatment system. The due date to meet final effluent limits for total phosphorus (TP) and $CBOD_5$ is November 1, 2024.
[c] Stormwater values based on City of Spokane data and reports. See Appendix G for the calculation of these estimates.
[d] Concentration data are not available for CSOs.
[e] These values do not include CSO loads, which are unknown due to the lack of concentration data. However, given the small flow volumes involved, CSO loads likely constitute a small fraction of the total.
[f] The apparently identical concentration and load values are not a typo. By coincidence, given 0.12 mgd flow volume, concentrations in mg/L and loads in lbs/day work out to be almost exactly the same numeric value.

Table 7. Point source NH_3-N loads during 2022 compared with WLAs.

Point Source Discharge	Season, 2022	Effluent flow (mgd)	NH_3-N concentration (mg/L)	NH_3-N load (lbs/day)	Anticipated 2027 flow (mgd) [a]	NH_3-N WLA concentration (mg/L) [a]	NH_3-N WLA (lbs/day) [a]
Liberty Lake	Mar – May	0.84	0.028	0.20	1.5	0.71	8.9
Liberty Lake	June	0.86	0.032	0.23	1.5	0.18	2.3
Liberty Lake	Jul – Oct	0.82	0.054	0.37	1.5	0.18 (Oct: 0.71) [b]	2.3 (Oct: 8.9 [b])
Kaiser Aluminum	Mar – May	5.1	0.064	2.7	15.4	0.07	9.0
Kaiser Aluminum	June	5.3	0.031	1.4	15.4	0.07	9.0
Kaiser Aluminum	Jul – Oct	5.0	0.051	2.1	15.4	0.07	9.0
Inland Empire Paper	Mar – May	5.5	0.245	11	4.1	0.71	24.29
Inland Empire Paper	June	5.5	0.159	7.3	4.1	0.71	24.29
Inland Empire Paper	Jul-Oct	6.3	0.138	7.3	4.1	0.71	24.29
Spokane County	Mar – May	7.6	0.947	60	8.0	0.83	55.4
Spokane County	June	7.0	0.030	1.8	8.0	0.21	14.0
Spokane County	Jul – Oct	6.9	0.025	1.4	8.0	0.21 (Oct: 0.83) [b]	14.0 (Oct: 55.4) [b]
City of Spokane	Mar – May	31	0.245	63	50.8	0.83	352
City of Spokane	June	40	0.048	16	50.8	0.21	89.0
City of Spokane	Jul – Oct	27	0.069	16	50.8	0.21 (Oct: 0.83) [b]	89.0 (Oct: 352) [b]
Stormwater	Mar – May	1.3 [c]	0.625 [c]	6.7 [c]	2.36	0.05	0.98
Stormwater	June	4.4 [c]	0.371 [c]	13 [c]	2.36	0.05	0.98
Stormwater	Jul – Oct	0.22 [c]	0.119 [c]	0.22 [c]	2.36	0.05	0.98
CSO	Mar – May	0.0034	unknown [d]	unknown [d]	0.12	1.0	1.0 [f]
CSO	June	0.091	unknown [d]	unknown [d]	0.12	1.0	1.0 [f]
CSO	Jul – Oct	0	unknown [d]	0	0.12	1.0	1.0 [f]
Total Point Sources	**Mar – May**	**51**	**(N/A)**	**144** [e]	**82**	**(N/A)**	**451.6**
Total Point Sources	**June**	**63**	**(N/A)**	**40** [e]	**82**	**(N/A)**	**140.6**
Total Point Sources	**Jul – Oct**	**46**	**(N/A)**	**27** [e]	**82**	**(N/A)**	**140.6**

[a] These WLA values, including the 2027 projected flow rates, concentrations, and loads, are found in the *Spokane DO TMDL* (Moore and Ross 2010), Table 5.

[b] For municipal wastewater facilities, the *Spokane DO TMDL* specified NH_3-N WLAs for three seasons: March – May, June – September, and October. The October WLAs are the same as March – May WLAs.

[c] Stormwater values based on City of Spokane data and reports. See Appendix G for the calculation of these estimates.
[d] Concentration data are not available for CSOs.
[e] These values do not include CSO loads, which are unknown due to the lack of concentration data. However, given the small flow volumes involved, CSO loads likely constitute a small fraction of the total.
[f] The apparently identical concentration and load values are not a typo. By coincidence, given 0.12 mgd flow volume, concentrations in mg/L and loads in lbs/day work out to be almost exactly the same numeric value.

Nonpoint sources including tributaries and groundwater

Nonpoint pollution occurs in the Spokane River, Lake Spokane, and tributary streams. The *Spokane DO TMDL* established load allocations (LA's) for tributaries and groundwater. Each of these tributary and groundwater sources potentially contains both natural and anthropogenic sources.

Table 8 compares 2022 observed tributary and groundwater TP loads with their respective LA's. We did not evaluate tributary and groundwater loads for $CBOD_5$ and NH_3-N, as concentrations of these parameters in ambient surface water and groundwater tend to be too low to detect.

Table 8. Tributary and groundwater TP loads during 2022 compared with LAs.

Tributary/groundwater source	Season, 2022	Mean flow (cfs)	TP conc. (mg/L)	TP load (lbs/day)	2001 flow (cfs) [a]	TP LA conc. (mg/L) [a]	TP LA (lbs/day) [a]
Hangman Ck.	Mar – May	435 [b]	0.246 [g]	578 [g]	229	0.113	140.2
Hangman Ck.	June	649 [b]	0.517 [g]	1810 [g]	31	0.044	7.5
Hangman Ck.	Jul – Oct	19 [b]	0.0273 [h]	2.8 [h]	9	0.030	1.4
Indian Canyon Ck.	Mar – May	0.66 [c]	0.070 [c]	0.25 [c]	unknown [k]	N/A [k]	N/A [k]
Indian Canyon Ck.	June	0.59 [c]	0.090 [c]	0.29 [c]	unknown [k]	N/A [k]	N/A [k]
Indian Canyon Ck.	Jul – Oct	0.36 [c]	0.087 [c]	0.17 [c]	unknown [k]	N/A [k]	N/A [k]
Deep/Coulee Ck. (groundwater)	Mar – May	2.3 [d]	0.093 [d]	1.2 [d]	30	0.113	18.2
Deep/Coulee Ck. (groundwater)	June	1.6 [d]	0.093 [d]	0.79 [d]	8	0.044	1.8
Deep/Coulee Ck. (groundwater)	Jul – Oct	0.86 [d]	0.093 [d]	0.43 [d]	2	0.030	0.4
Little Spokane R.	Mar – May	640 [b]	0.040 [g]	140 [g]	565	0.034	102.5
Little Spokane R.	June	672 [b]	0.047 [g]	170 [g]	426	0.023	53.9
Little Spokane R.	Jul – Oct	370 [b]	0.011 [i]	22 [i]	364	0.016	32.2
Groundwater – US Lk. Spokane	Mar – May	839 [e]	0.0054 [j]	24 [j]	1946	0.0081	87
Groundwater – US Lk. Spokane	June	505 [e]	0.0053 [j]	15 [j]	1583	0.0078	66
Groundwater – US Lk. Spokane	Jul – Oct	825 [e]	0.0055 [j]	24 [j]	1165	0.0076	48
GW – Lk. Spokane watershed	Mar – May	2.0 [f]	0.068 [f]	0.073 [f]	588	0.025	79
GW – Lk. Spokane watershed	June	2.0 [f]	0.068 [f]	0.073 [f]	225	0.025	30
GW – Lk. Spokane watershed	Jul – Oct	2.0 [f]	0.068 [f]	0.073 [f]	180	0.025	24
Total Nonpoint Sources	**Mar – May**	**1920**	**(N/A)**	**740**	**3358**	**(N/A)**	**426.9**
Total Nonpoint Sources	**June**	**1830**	**(N/A)**	**2000**	**2273**	**(N/A)**	**159.2**
Total Nonpoint Sources	**Jul – Oct**	**1220**	**(N/A)**	**52**	**1720**	**(N/A)**	**106.0**

[a] These LA values, including the 2001 flow rates, concentrations, and loads, are found in the *Spokane DO TMDL* (Moore and Ross 2010), Table 6a.
[b] Seasonal mean flows calculated from USGS stream gage data.
[c] Seasonal mean flows calculated as mean of monthly flow measurements. Seasonal concentrations calculated as mean of monthly sample results. Loads forward calculated from seasonal flows and concentrations. There is no correllation between flow and total phosphorus (TP) at this location.
[d] Sinclair and Gallagher (2019) estimated groundwater inflow volumes and TP loads for each sampling event. They estimated groundwater discharge using instream piezometer measurements, and calculated loads using the geometric mean piezometer sample concentration. Seasonal flows and loads here are the mean of sampling event inflows and loads within each season. No sampling events occurred during June, therefore we estimated June seasonal inflows and loads as being halfway between the March – May and July – October values.
[e] Groundwater inflows estimated from flow balace. See **2022 mass balance and source contributions** section below. Seasonal flows are calculated as the sum of inflows in all gaining reaches.
[f] Median inflow and load estimates estimated by Sheibley and Foreman (2021). The authors gave loads in terms of orthophosphate (also known as soluble reactive phosphorus), and presented evidence that orthophosphate comprises substantially all of the groundwater total phosphorus inflows.
[g] For Hangman Creek and the Little Spokane River, wet season phosphorus is highly variable, subject to storm events, and strongly correlated with suspended sediment and turbidity. We calculated continuous loads for March – May and June based on continuous turbidity data (see Appendix D). The concentrations given here are back-calculated from seasonal mean flow and load.
[h] July – October TP sample results at the mouth of Hangman Creek (56A070) were impacted by the contract lab sample bias issue (see Appendix B). We therefore calculated the seasonal mean concentrations and loads using unimpacted data from shortly upstream at Hangman Creek at 11th Ave. (56HAN-01.5).
[i] July – October TP sample results at the mouth of the Little Spokane River (55B070) were also impacted by the contract lab sample bias issue. However, unlike with Hangman Creek, we didn't have a nearby alternate sample location. We used the LSR multiple linear regression (MLR) model to estimate July – October loads (see Appendix E).
[j] We used Spokane County SVRPA groundwater sampling data to estimate groundwater concentrations and loads to the Spokane River. See **2022 mass balance and source contributions** section below, footnotes to Tables 9 –11, for details about which wells we used for which reaches.
[k] Indian Canyon Creek is a small tributary that discharges to Hangman Creek 0.3 mi upstream of the Spokane River confluence. It is located downstream of the sampling site used to characterize Hangman Creek at the mouth, and therefore is not included in Hangman flow and load estimates. The *Spokane DO TMDL* did not set load allocations for this waterbody.

Tributaries

Following the substantial reductions in point source loads that have occurred over the last decade, the tributaries now remain as the largest contributors of phosphorus to the Spokane River and Lake Spokane during the springtime runoff season. In total, the tributaries contributed over 90% of the total phosporus (TP) load during March – May and June 2022.[12] Hangman Creek in particular contributed more than all other point and nonpoint sources combined, constituting 74% of the total phosphorus load during March – May and 89% during June. However, these proportions are substantially lower during the July – October low flow season.

Tributary TP loads for Hangman Creek and the Little Spokane River generally exceeded their wet season load allocations (LA), both in terms of concentration and load. Hangman Creek in particular greatly exceeded its LA during the March – May high flow season. During the unusually rainy June 2022, TP in Hangman Creek was 12 times the allocated concentration and 240 times the allocated load. During July – October low flow season, however, Hangman Creek met its LA in terms of concentration but not load, and the Little Spokane River met its LA both in terms of concentration and load.

[12] These values only include loads entering the Spokane River system in Washington. This does not include the load already carried by the river when it crosses the state line from Idaho.

The *Little Spokane River Dissolved Oxyen, pH, and Total Phosphorus TMDL* (Johnson et al. 2020) and the *Hangman Creek Watershed Nutrients and Sediment Pollutant Source Assessment* (Stuart 2022) found that it will not always be possible to meet these tributary LAs in terms of load. *The Spokane DO TMDL* set load allocations based on conditions during 2001, a low-flow year. Because load is the product of concentration and flow, and because phosphorus concentrations themselves increase with flow, loads tend to rise exponentially with increasing flow. This means that meeting low-flow loads during higher-flow years presents a mathematical near-impossibility. Ecology has chosen to focus on meeting these tributary LA's in terms of concentration.

These studies found that springtime phosphorus loading linked to suspended sediment is a significant problem for both the Little Spokane River and Hangman Creek. In order to meet TP LA concentrations at least 90% of the time, the Little Spokane River will need to reduce 80 – 90% of anthropogenic nonpoint TP (Johnson et al. 2020), and Hangman Creek will need to reduce overall March – May TP by 76%, equating to a suspended sediment reduction of 95% (Stuart 2022).

Our 2022 results provide yet another demonstration of this issue. Springtime tributary TP loads are the single biggest remaining factor preventing the Spokane River and Lake Spokane from meeting the *Spokane DO TMDL*. This is also an important water quality issue in the tributaries themselves. More work to reduce nonpoint TP in the tributaries is needed, especially in Hangman Creek.

Groundwater

Estimated groundwater phosphorus loads for 2022 were substantially less than their load allocations for both the areas upstream of Lake Spokane, and for the Lake Spokane watershed. This does not mean that groundwater phosphorus loads have actually decreased since the 2001 condition used to develop the TMDL. Rather, this reflects the availability of better information since that time, as well as differences in calculation approach.

For the areas upstream of Lake Spokane, the TMDL used groundwater phosphorus concentration values from 0.0078 – 0.0081 mg/L. More recent monitoring of the Spokane Valley-Rathdrum Prairie Aquifer (SVRPA) by Spokane County (e.g., Spokane County 2022) suggests values from 0.0053 – 0.0055 mg/L. Estimated groundwater inflow volumes for 2022 were less than those used in the TMDL as well. This discrepancy may be the result of the longer reaches we used to estimate flow gains and losses as compared to those in the CE-QUAL-W2 model. (See the **2022 mass balance and source contributions** section below.)

The Lake Spokane watershed (or subbasin), which is a 112 mi^2 area that drains directly to Lake Spokane, rather than via the Spokane River or tributaries, is located in a rural, outlying part of the TMDL area. Little was known about groundwater inflows from the Lake Spokane subbasin at the time the TMDL was developed. The TMDL estimates of groundwater inflows come from the residual differences between inflows to Lake Spokane and measured outflows at Long Lake Dam. Only the positive residuals were averaged to calculate the flow volumes for the groundwater load allocation. This resulted in a large estimated inflow volume from 180 cfs (July – October) to 588 cfs (March – May). More recently, the U.S. Geological Survey (USGS) undertook two detailed investigations of groundwater inflows to Lake Spokane. The first study investigated differences in groundwater nutrients between developed areas with on-site septic systems (OSSs) and undeveloped areas (Gendaszek et al. 2016). The second study provided an overall characterization of groundwater nutrient concentrations and inflow volumes for the lake as a whole (Sheibley and Foreman 2021). Sheibley and Foreman provide a range of possible concentrations and inflow volumes. The 2022 load estimates shown in Table 8 are based on the median concentration and inflow values provided by Sheibley and Foreman. This resulted in estimated loads as much as two orders of magnitude lower than the TMDL load allocations.

Riverine Assessment Point

The *Spokane DO TMDL* established the concept of a "riverine assessment point" (Moore and Ross 2010). This concept primarily pertains to Avista's dissolved oxygen responsibility, and more generally represents a way of summarizing all of the upstream phosphorus sources at the point where the Spokane and Little Spokane Rivers flow into Lake Spokane.

The riverine assessment point is defined as the flow-weighted average of conditions in the Spokane River below Nine Mile Dam (e.g., 54A090, 54SPK-57.2) and the Little Spokane River at the mouth (55B070). The TMDL set a benchmark TP concentration of 10 ug/L (or 0.010 mg/L) based a regional survey of nearby rivers with minimal human impact. This benchmark does not constitute a water quality standard or a TMDL allocation. Rather, it provides a way to gauge phosphorus levels entering Lake Spokane. The CE-QUAL-W2 water quality model simulation used to develop the TMDL predicted that if all load and wasteload allocations were being met, the TP concentration at the riverine assessment point would be near this 10 µg/L benchmark during the June and July – October seasons. TP concentrations during the March – May season would, however, still exceed the benchmark.

Figure 5 presents estimated TP concentrations at the riverine assessment point during March – October, 2022. Figure 5 also presents the component (Spokane River at Nine Mile and Little Spokane River) concentrations. The flow-weighted average is mostly driven by the Spokane River concentrations, due to the higher flows in the Spokane River relative to the Little Spokane River.

Flow-weighted average TP concentrations at the riverine assessment point generally exceeded the 10 µg/L benchmark during the March – May and June seasons. This is mainly the result of sediment-linked nonpoint phosphorus from Hangman Creek and the Little Spokane River. The "spikes" visible in the blue Nine Mile line in Figure 5 result from high flow/high turbidity events in Hangman Creek discharging phosphorus down the Spokane River. High flow/high turbidity events also occur in the Little Spokane River, though at a smaller scale. Flow-weighted average TP concentrations during these tributary events often exceeded 100 µg/L (0.1 mg/L), an order of magnitude higher than the benchmark.

During the July – October low-flow season, flow-weighted TP concentrations met the 10 µg/L benchmark by a wide margin. Concentrations appeared to gradually decline throughout the low-flow period. During October, the TP lab result for the Spokane River at Nine Mile[13] was a non-detect at 5 µg/L. The true value is therefore even less than what is shown during October in Figure 5. As discussed later in this report, these low summer – fall TP concentrations in the Spokane River at Nine Mile are a new phenomenon, first observed in 2021, resulting primarily from upstream point source phosphorus reductions.

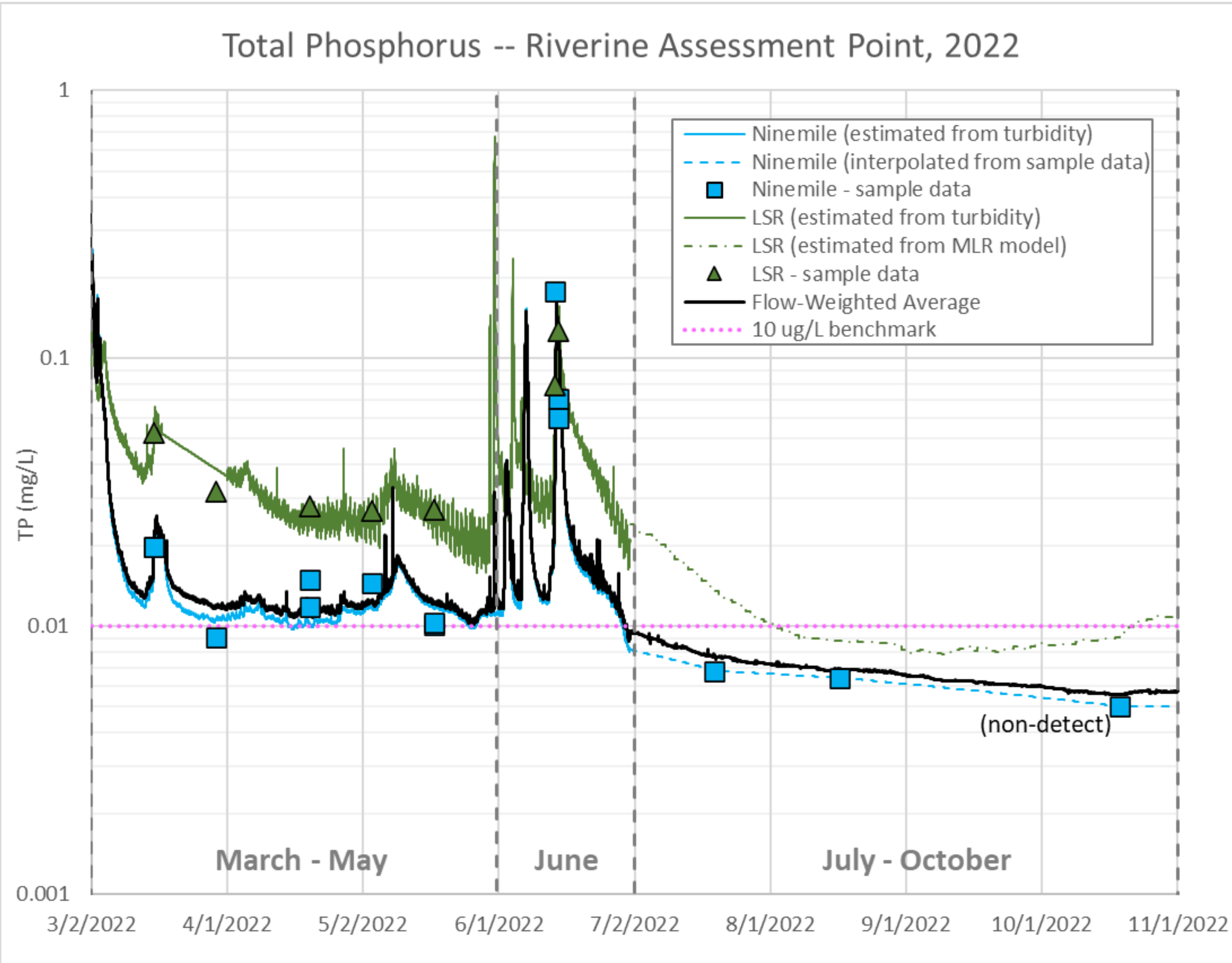


Figure 5. Total phosphorus concentrations at the riverine assessment point during 2022.

[13] This sample, along with several of the other Nine Mile sample results shown in Figure 5, was collected at 54SPK-57.2, located 0.4 mi downstream of the ambient monitoring station at Charles Rd. bridge (54A090). The two locations are functionally equivalent from a water quality monitoring standpoint.

Avista's DO responsibility

The *Spokane DO TMDL* assigned Avista a responsibility to improve dissolved oxygen in the lower levels of Lake Spokane during July – October. Avista does not discharge nutrients, but this responsibility reflects the effect of Long Lake Dam in creating the reservoir conditions where low DO can occur.

The TMDL used a "riverine assessment" approach to determining Avista's DO responsibility. This approach assumes that if total phosphorus concentrations entering Lake Spokane are less than 10 µg/L, a level typical of regional high-quality rivers with minimal human impact as discussed above, that remaining DO impairments are the responsibility of the dam operator. Therefore, Avista's responsibility was calculated as the difference between the hypolimnion DO predicted by the TMDL model scenario and that predicted by the natural or "no source" scenario, while allowing for a 0.2 mg/L total human impact.

Avista developed and Ecology approved a DO Water Quality Attainment Plan (WQAP) according to WAC 173-201A-510(5) *Compliance Schedule for Dams* (Avista and Golder Associates 2012). This plan lists potential measures to improve DO in Lake Spokane. Avista prioritized TP reduction measures to achieve a nutrient reduction goal calculated by using a known TP to oxygen ratio developed for the Brownlee Reservoir in Hells Canyon, Idaho (Idaho Power Company 2007). Since that time, Avista implemented measures including (Avista and Four Peaks 2022a):

- Carp removal
- Floating wetlands
- Acquisition and restoration of wetlands at Sacheen Springs in the upper Little Spokane River
- Conversion of grazing land along Lake Spokane
- Lawn fertilizer reduction and native vegetation buffers at Avista and private property locations
- Education and outreach

Currently, Avista is pursuing a modeling approach using a modified and recalibrated Lake Spokane-only version of the CE-QUAL-W2 model used to develop the TMDL. Avista used this model to assess the impact of some past measures, as well as to assess the impact of potential future measures. The modeling analysis found that:

> The nutrient load reduction actions implemented by Avista have produced only small improvements in DO when evaluating each action individually. Considering the magnitude of the DO changes, and the very conservative assumptions used to evaluate the maximum potential DO improvements from these actions, it is evident that each of these actions either individually or collectively are unlikely to result in ameasurable change in DO if implemented at the levels from the past. (Avista and Four Peaks 2022b).

Avista is evaluating potential DO improvement options, including:

- Nutrient reduction in-lake and from upstream nonpoint sources, including Hangman Creek
- Operational changes such as altered drawdown and fill timing
- Artificial oxygenation and destratification techniques in Lake Spokane
- Structural changes to the withdrawal point at Long Lake Dam

Avista's work toward achieving their DO responsibility is ongoing. A new DO WQAP will describe Avista's approach and proposed reasonable and feasible DO improvement measures to be implemented over the next decade.

2022 mass balance and relative source contributions

To better understand the present-day sources and sinks of phosphorus in the Spokane River and Lake Spokane, we constructed a simple TP mass balance for 2022, for each TMDL season. Figure 6 summarizes 2022 TP loads by season. Tables 9 – 11 present the mass balance.

Sources

During the 2001 conditions that the *Spokane DO TMDL* was based on, point sources were the most important source of phosphorus loading. At that time, point sources contributed around 2/3 of the anthropogenic phosphorus load during March – May and June, and over ¾ of the anthropogenic load during July – October. The TMDL report calculated that under full compliance with all wasteload and load allocations, the proportion of phosphorus contributed by point sources would decrease. Tributaries and groundwater would become the most important contributors (Moore and Ross 2010).

As predicted, the implementation of point source phosphorus controls has changed the situation. Point sources, including stormwater, now contribute a smaller fraction of the total TP load entering the Spokane River system. During 2022, point source contributions constituted about 5% of the total during March – May, 2% during June, and 29% during July – October.

In contrast, tributaries contributed about 92% of the total load during March – May, 97% during June, and 36% during July – October. As mentioned previously, Hangman Creek was the biggest wet season contributor by far, contributing 74% of the total load during March – May and 89% during June, with the Little Spokane River constituting most of the remaining tributary load. During the July – October low flow season, phosphorus loads were an approximate three-way split between point sources (29%), tributaries (36%), and groundwater (35%).

It is beyond the scope of this report to precisely differentiate between anthropogenic and natural tributary and groundwater loads. It is likely that much of the groundwater phosphorus load is natural. Johnson et al. (2020) found that phosphorus loads in the Little Spokane River are a mix of human and natural. In Hangman Creek, most of the wet season sediment-associated phosphorus loads are likely human in origin (SCD 2022; Stuart 2022). However, it is not known whether that is the case for Hangman summertime loads.

Sinks

The TP load residuals in Tables 9 – 11 can indicate unaccounted sources or sinks. Note that because mainstem TP concentrations are very low, often less than 10 µg/L (0.01 mg/L), there is significant uncertainty in the residuals. Residuals less than +/- 10 – 15% are likely the result of measurement uncertainty and may not signify any real-world sources or sinks. However, larger negative load residuals during July – October 2022 may in fact signify sinks. One possible mechanism for phosphorus loss is uptake by attached bottom algae, also known as periphyton.

Another potential sink both for flow and for phosphorus is surface water withdrawals. As of 2023, water rights for surface withdrawal found in Ecology's Water Rights Search[14] tool total 76 cfs from the Spokane River and 54 cfs from Lake Spokane. However, a large majority of these rights are no longer active, and actual surface withdrawals are likely a fraction of these amounts (Tolleson 2023, pers. comm.).

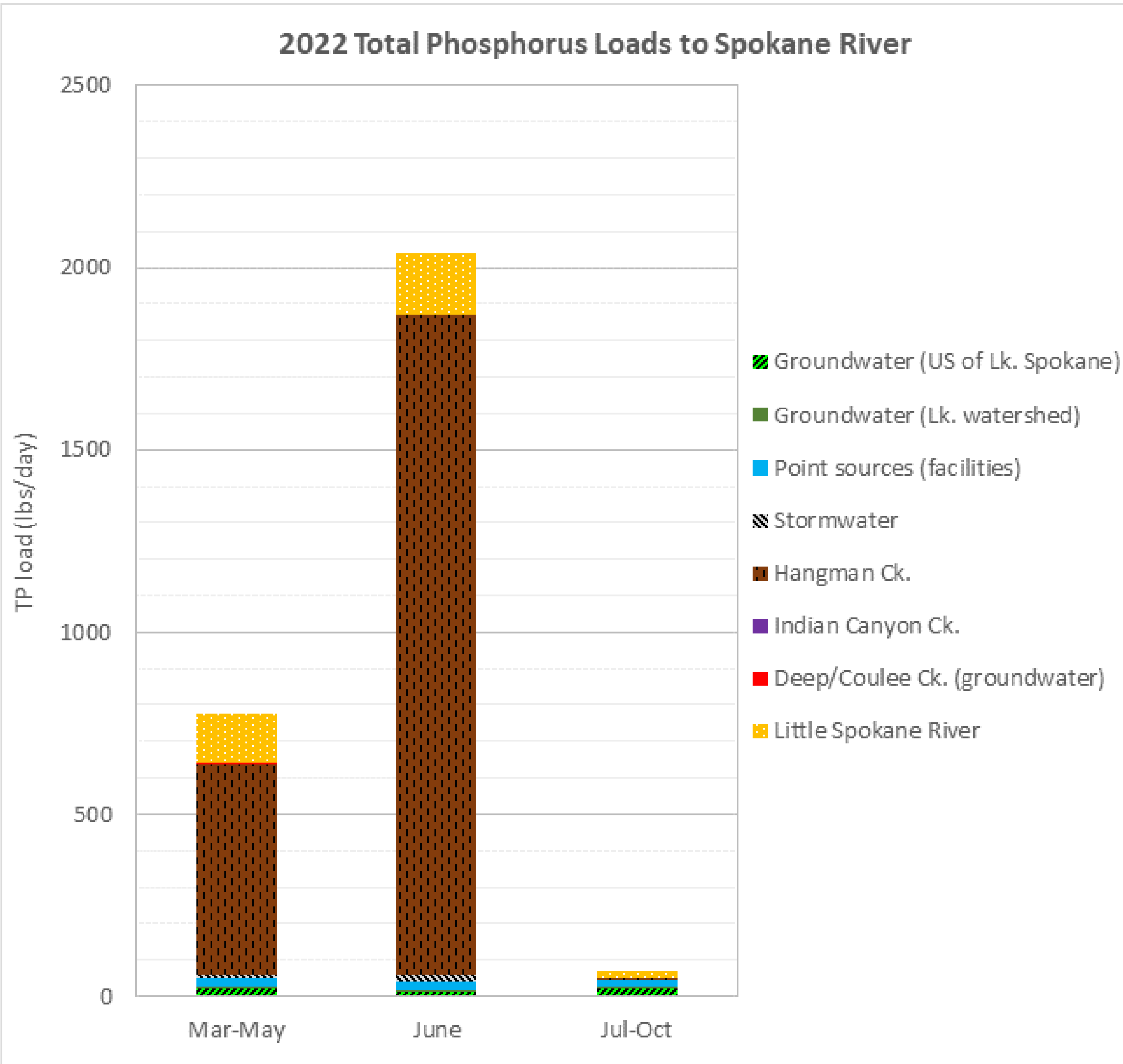


Figure 6. Total phosphorus loads entering the Spokane River and Lake Spokane between the WA/ID state line and Long Lake Dam.

[14] https://appswr.ecology.wa.gov/waterrighttrackingsystem/WaterRights/default.aspx

Table 9. Estimated seasonal average TP mass balance for March – May 2022.

Location or Source	River Mile	Flow (cfs) [a]	TP conc. (mg/L)	TP load (lbs/day)	TP load residual (lbs/day) [a]	TP load residual (%) [a]
Spokane R. at State Line	**96.0**	**13400**	**0.0085**	**620**	**—**	**—**
Liberty Lake WRF	92.4	1.3	0.0142	0.099		
Kaiser Aluminum	86.1	7.8	0.0064	0.27		
Groundwater gain/loss [b]	—	*+700*	*0.0053 [d]*	*+20*		
Spokane R. at Plantes Ferry	**84.2**	**14200**	**0.0083**	**630**	**-10**	**-1%**
Inland Empire Paper	82.7	8.5	0.387	18		
Spokane Co. Regional WRF	78.9	12	0.0423	2.7		
Groundwater gain/loss [b]	—	*-500*	*(N/A)*	*-23*		
Spokane R. at Greene St.	**78.0**	**13700**	**0.0097**	**710**	**+80**	**+10%**
Stormwater — Greene to Sandifur	—	0.76	1.07	4.4		
Groundwater gain/loss [b]	—	*-100*	*(N/A)*	*-10*		
Spokane R. at Sandifur Bridge	**72.4**	**13500**	**0.0093**	**680**	**-30**	**-4%**
Hangman Ck.	72.2	435	0.246	580		
Indian Canyon Ck.	72.2	0.66	0.0701	0.25		
City of Spokane WRF	67.5	48	0.0162	4.2		
Stormwater — Sandifur to Nine Mile	—	1.2	0.980	6.5		
Deep/Coulee Ck. (groundwater)	59.0	2.3	0.0928	1.2		
Groundwater gain/loss [b]	—	*+100*	*0.0060 [e]*	*0*		
Spokane R. at Nine Mile	**57.5**	**14200**	**0.0167**	**1300**	**0**	**0%**
Little Spokane River	56.3	640	0.0398	140		
Groundwater to Lk. Spokane [c]	—	+2.0	0.068	0.73		

key:

Mainstem Spokane River locations

Point sources

Tributaries

Groundwater

[a] We rounded the values shown in this table to the correct number of significant digits after performing all calculations. Therefore, the numbers presented here may not precisely add up. This particularly affects the groundwater gain/loss and load residual values.

[b] Groundwater gain/loss flow values are the residuals between flow at each monitoring station, accounting for all inflows between monitoring stations. Positive groundwater loads are calculated from this estimated inflow volume and concentrations derived from groundwater monitoring data. Negative groundwater loads (losses) are calculated from the estimated outflow volume and the instream concentration at the upstream monitoring station.

[c] USGS Lake Spokane groundwater study (Sheibley and Foreman 2021), median flow and concentration values.

[d] Spokane County SVRPA groundwater monitoring data. Average of Sullivan Park South MW and Sullivan Spring, 2018 – 2022, mean total phosphorus (TP) values.

[e] Spokane County SVRPA groundwater monitoring data. Average of Trinity School Adams & Carlisle City MW and Three Springs, 2018 – 2022, mean TP values.

Table 10. Estimated seasonal average TP mass balance for June 2022.

Location or Source	River Mile	Flow (cfs) [a]	TP conc. (mg/L)	TP load (lbs/day)	TP load residual (lbs/day) [a]	TP load residual (%) [a]
Spokane R. at State Line	**96.0**	**18000**	**0.0092**	**900**	**—**	**—**
Liberty Lake WRF	92.4	1.3	0.0142	0.10		
Kaiser Aluminum	86.1	8.2	0.0084	0.37		
Groundwater gain/loss [b]	—	*+400*	*0.0053* [d]	*12*		
Spokane R. at Plantes Ferry	**84.2**	**18500**	**0.0080**	**800**	**-110**	**-12%**
Inland Empire Paper	82.7	8.5	0.329	15		
Spokane Co. Regional WRF	78.9	11	0.0560	3.3		
Groundwater gain/loss [b]	—	*0*	*0.0055* [e]	*0.76*		
Spokane R. at Greene St.	**78.0**	**18500**	**0.0086**	**860**	**+40**	**+5.4%**
Stormwater — Greene to Sandifur	—	2.6	0.572	7.9		
Groundwater gain/loss [b]	—	*-300*	*(N/A)*	*-12*		
Spokane R. at Sandifur Bridge	**72.4**	**18300**	**0.0098**	**960**	**+110**	**+13%**
Hangman Ck.	72.2	649	0.517	1800		
Indian Canyon Ck.	72.2	0.59	0.0897	0.29		
City of Spokane WRF	67.5	62	0.0179	6.0		
Stormwater — Sandifur to Nine Mile	—	4.2	0.521	12		
Deep/Coulee Ck. (groundwater)	59.0	1.6	0.0927	0.79		
Groundwater gain/loss [b]	—	*+100*	*0.0060* [f]	*2.0*		
Spokane R. at Nine Mile	**57.5**	**19000**	**0.0260**	**2700**	**-130**	**-13%**
Little Spokane River	56.3	672	0.0465	170		
Groundwater to Lk. Spokane [c]	—	+2.0	0.068	0.73		

key:

Mainstem Spokane River locations

Point sources

Tributaries

Groundwater

[a] We rounded the values shown in this table to the correct number of significant digits after performing all calculations. Therefore, the numbers presented here may not precisely add up. This particularly affects the groundwater gain/loss and load residual values.

[b] Groundwater gain/loss flow values are the residuals between flow at each monitoring station, accounting for all inflows between monitoring stations. Positive groundwater loads are calculated from this estimated inflow volume and concentrations derived from groundwater monitoring data. Negative groundwater loads (losses) are calculated from the estimated outflow volume and the instream concentration at the upstream monitoring station.

[c] USGS Lake Spokane groundwater study (Sheibley and Foreman 2021), median flow and concentration values.

[d] Spokane County SVRPA groundwater monitoring data. Average of Sullivan Park South MW and Sullivan Spring, 2018 – 2022, mean total phosphorus (TP) values.

[e] Spokane County SVRPA groundwater monitoring data. Average of Hale's Ale nested site east MW and Hale's Ale nested site mid MW, mean TP values.

[f] Spokane County SVRPA groundwater monitoring data. Average of Trinity School Adams & Carlisle City MW and Three Springs, 2018 – 2022, mean TP values.

Table 11. Estimated seasonal average TP mass balance for July – October 2022.

Location or Source	River Mile	Flow (cfs) [a]	TP conc. (mg/L)	TP load (lbs/day)	TP load residual (lbs/day) [a]	TP load residual (%) [a]
Spokane R. at State Line	**96.0**	**1400**	**0.0077**	**58**	**—**	**—**
Liberty Lake WRF	92.4	1.3	0.0218	0.15		
Kaiser Aluminum	86.1	7.8	0.0081	0.34		
Groundwater gain/loss [b]	—	*+530*	*0.0053 [d]*	*15*		
Spokane R. at Plantes Ferry	**84.2**	**1940**	**0.0060**	**63**	**-11**	**-19%**
Inland Empire Paper	82.7	9.8	0.224	12		
Spokane Co. Regional WRF	78.9	11	0.0518	3.0		
Groundwater gain/loss [b]	—	*+80*	*0.0055 [e]*	*2.4*		
Spokane R. at Greene St.	**78.0**	**2040**	**0.0067**	**73**	**-7**	**-11%**
Stormwater — Greene to Sandifur	—	0.13	0.416	0.29		
Groundwater gain/loss [b]	—	*-80*	*(N/A)*	*-2.8*		
Spokane R. at Sandifur Bridge	**72.4**	**1960**	**0.0070**	**74**	**+3**	**+4%**
Hangman Ck.	72.2	19	0.0273	2.8		
Indian Canyon Ck.	72.2	0.36	0.0874	0.17		
City of Spokane WRF	67.5	42	0.0210	4.8		
Stormwater — Sandifur to Nine Mile		0.21	0.379	0.43		
Deep/Coulee Ck. (groundwater)	59.0	0.86	0.0925	0.43		
Groundwater gain/loss [b]	—	*+220*	*0.0060 [f]*	*6.9*		
Spokane R. at Nine Mile	**57.5**	**2240**	**0.0052**	**63**	**-26**	**-35%**
Little Spokane River	56.3	370	0.0112	22		
Groundwater to Lk. Spokane [c]	—	+2.0	0.068	0.73		

key:

Mainstem Spokane River locations

Point sources

Tributaries

Groundwater

[a] We rounded the values shown in this table to the correct number of significant digits after performing all calculations. Therefore, the numbers presented here may not precisely add up. This particularly affects the groundwater gain/loss and load residual values.

[b] Groundwater gain/loss flow values are the residuals between flow at each monitoring station, accounting for all inflows between monitoring stations. Positive groundwater loads are calculated from this estimated inflow volume and concentrations derived from groundwater monitoring data. Negative groundwater loads (losses) are calculated from the estimated outflow volume and the instream concentration at the upstream monitoring station.

[c] USGS Lake Spokane groundwater study (Sheibley and Foreman 2021), median flow and concentration values.

[d] Spokane County SVRPA groundwater monitoring data. Average of Sullivan Park South MW and Sullivan Spring, 2018 – 2022, mean total phosphorus (TP) values.

[e] Spokane County SVRPA groundwater monitoring data. Average of Hale's Ale nested site east MW and Hale's Ale nested site mid MW, mean TP values.

[f] Spokane County SVRPA groundwater monitoring data. Average of Trinity School Adams & Carlisle City MW and Three Springs, 2018 – 2022, mean TP values.

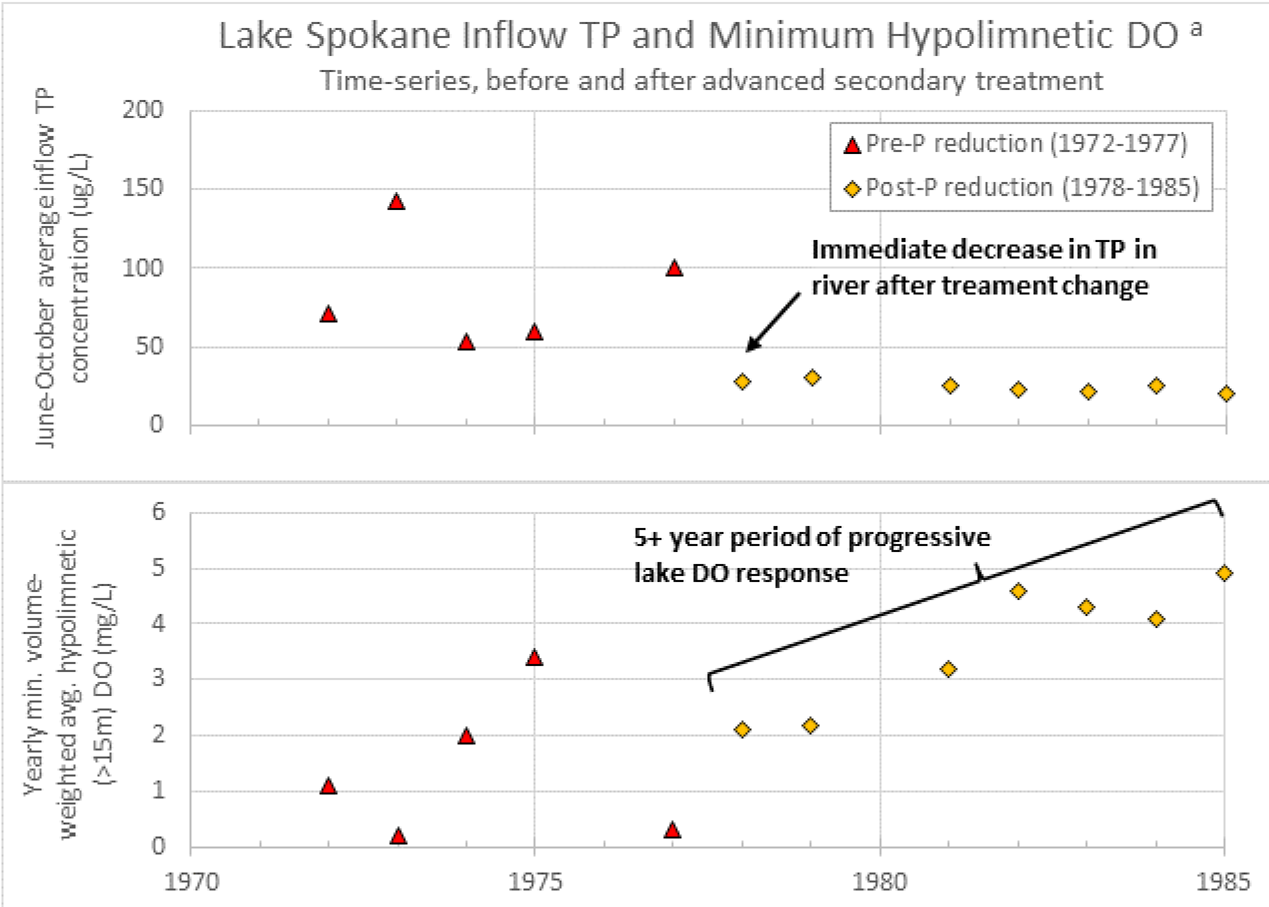
Trends over time in the Spokane River and Lake Spokane

Improvements during the 1970 – 1980s

Phosphorus concentrations in the Spokane River have declined substantially over the last several decades. This has resulted both from point, as well as nonpoint source load reductions. In particular, treatment improvements at the City of Spokane's wastewater treament facility, which has historically been the largest point source contrubutor of phosphorus to the Spokane River, have had an important impact.

Patmont et al. (1987) found that phosphorus concentrations in the Spokane River decreased and dissolved oxgyen in the hypolimnion of Lake Spokane increased following the City of Spokane's construction of an advanced secondary wastewater treatment facility, which began operating in December 1977. These data reveal that, although the reduction in phosphorus occurred immediately once the improved treatment was brought online, the resulting improvement in hypolimnetic dissolved oxygen (DO) in Lake Spokane occurred gradually over at least the next five years (Figure 7). Welch et al. (2015) suggests that gradual improvements may have continued after this period due to gradual reduction of internal phosphorus loading.

Reservoir nutrient cycling is complex. Multiple external sources of nutrients exist, such as upstream boundary inflows and groundwater inflows. Internal loading can also be important (Kennedy et al. 1986, Cooke et al. 2011). Within the reservoir system, lakebed sediments can act as both a source and a sink for phosphorus (Wetzel 2001). When upstream boundary inflow phosphorus is substantially reduced, as occurred in 1977, it may take a number of years for the reservoir nutrient cycle to reach a new equilibrium state. This pattern has been observed in other lakes as well. For example, it took about 10 years for for lake transparency to fully adjust following sewage effluent diversion from Lake Washington in the late 1960s (Edmondson and Litt 1982).



a Data from Patmont et al. (1987) and Welch et al. (2015).

Figure 7. Time-series of Spokane River total phosphorus (TP) and Lake Spokane dissolved oxygen (DO) before and after City of Spokane's advanced secondary wastewater treatment. (Two charts, one each for TP and DO)

Long-term trends in the Spokane River

Ecology has maintained a long-term ambient monitoring station on the Spokane River at the Bowl and Pitcher pedestrian swinging bridge at Riverside State Park since 1972.[15] Data have been collected routinely (typically monthly) since the early 1970s. This location is downstream of all point source discharges and tributary sources except for Deep/Coulee Creek and the Little Spokane River. Figure 8 presents the time-series of all total phosphorus data collected at this location from 1972 – 2022. Figure 9 presents box-plots showing these same data grouped by decade.

We applied two separate statistical analysis tests for monotonic trends at the long term monitoring site: 1) simple linear regression, and 2) Seasonal Mann-Kendall test (Meals et al. 2011). We then pooled the data by decade, calculated the percent phosphorus reduction, and conducted a one-factor analysis of variance on the decadal data.

[15] EIM Location ID 54A120

A strong declining trend is apparent in the data. Overall, median phosphorus concentration has declined by 84% from the 1970s compared to the 2020s. Linear regression slope estimates shows a significant downward trend during the same timespan. Slope interpretation indicates that an average 3% annual phosphorus reduction has occurred in the Spokane River since sampling began at the long term monitoring location. The Seasonal Mann-Kendall statistical test corroborated the regression analysis and found a comparable rate of change in the riverine phosphorus concentration (Table 12). The trend is also apparent in the grouped decadal data (Figure 9), and analysis of variance detected significant differences between decades ($F_{5, 632} = 50.5$, $P < 0.001$). This improvement is a result both of upgraded point source treatment technologies, as well as nonpoint source phosphorus reduction activities that have been ongoing in the watershed for the past several decades.

Table 12. Seasonal Mann-Kendall Test Statistics.

Location	N	Tau (τ)	Score	P-Value	Thiel-Sen's Slope
Spokane River @ Riverside State Park	562	-0.449	-5794	< 0.001 [a]	-0.00093
Hangman Creek @ Mouth	497	-0.247	-2774 [c]	< 0.001 [b]	-0.00769
Little Spokane River @ Mouth	511	-0.203	-684 [c]	< 0.001 [b]	-0.00881
Riverine Assessment Point	178	-0.375	-462	< 0.001 [b]	-0.00073

[a] Two-sided p-value corrected for intra-block correlation (month).
[b] Two-sided p-value of the partial test MK test, after correction for intra-block correlation (month) with the presence of covariate (streamflow).
[c] Partial Kendall's score with the presence of a covariate (streamflow).

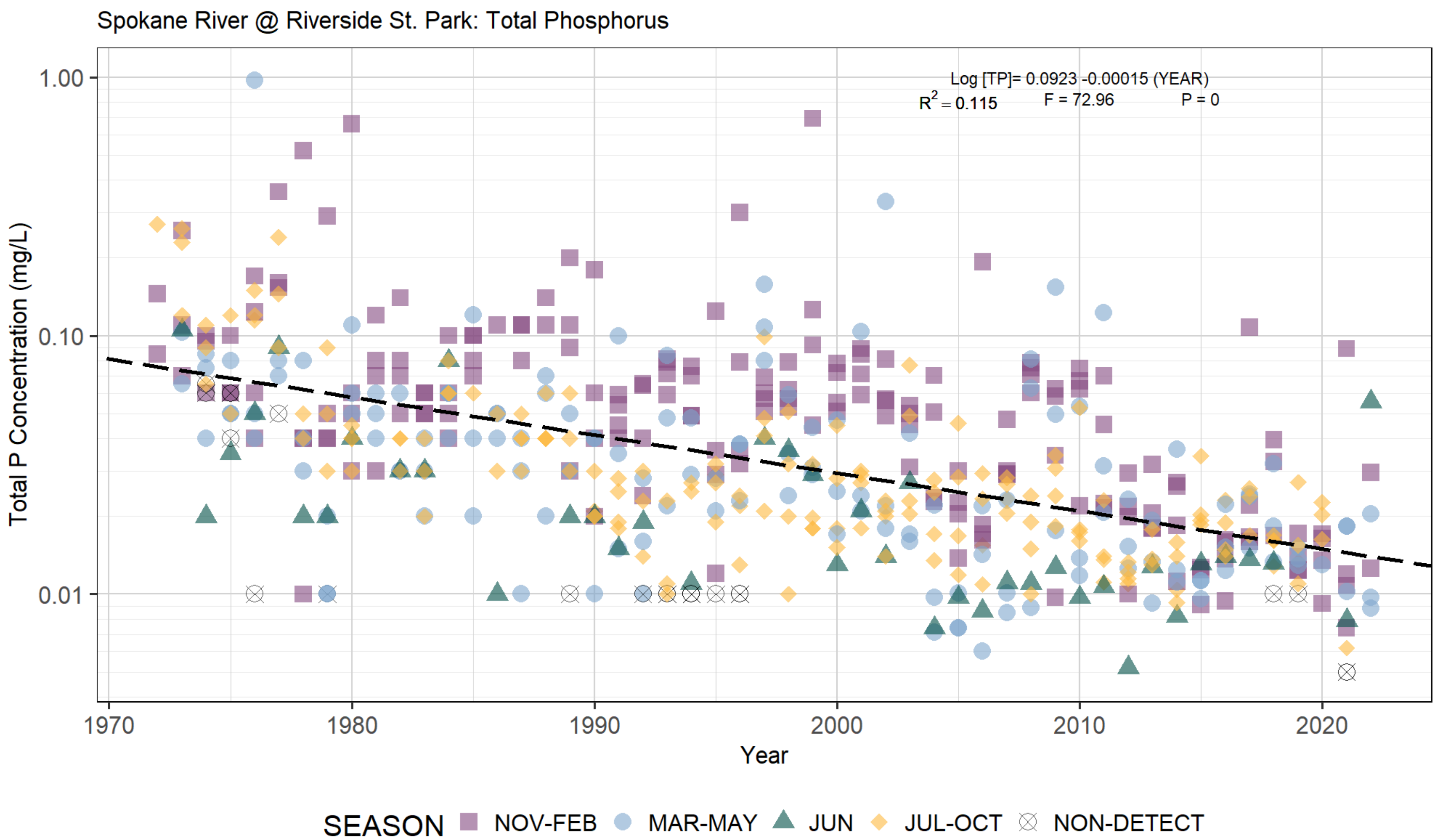
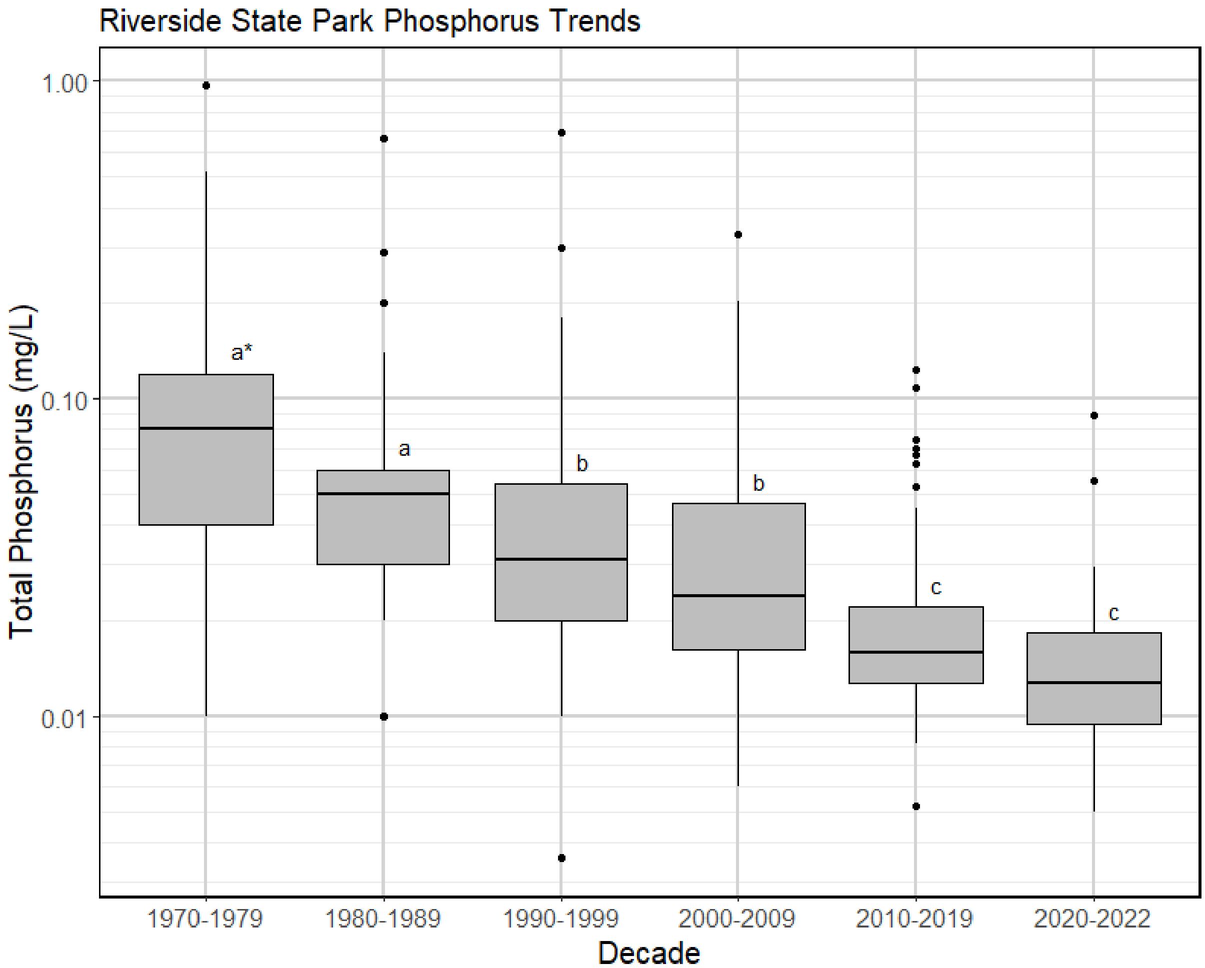


Figure 8. Total phosphorus data from the Spokane River at Riverside State Park (Bowl and Pitcher), 1972 – 2022.

[a] Linear regression coefficients calculated using cumulative month (Time) as predictor of total phosphorus.



* Letters reflect significant differences using Tukey's Honest Significant Difference (HSD) post-hoc test at the $\alpha = 0.01$ level of significance.

Figure 9. Box-plot showing total phosphorus data from the Spokane River at Riverside State Park (Bowl and Pitcher) by decade.

Long-term trends in the tributaries

Hangman Creek and the Little Spokane River are important tributaries that have major impacts on the nutrient dynamics of the Spokane River and Lake Spokane. Hangman Creek in particular is known to be a primary source of phosphorus to the system. Long-term ambient water quality monitoring has been ongoing at both locations since the early 1970s and trend analysis shows phosphorus conditions have improved since monitoring began.

Median phosphorus concentration in Hangman Creek[16] has declined by 67% since the 1970s (Figure 10). and we detected significant downward monotonic trends in both regression analysis and the Partial Mann-Kendall tests (Table 12). Similar phosphorus reductions occurred in the Little Spokane River[17], though the overall magnitude of the phosphorus concentration

[16] EIM Location ID 56A070
[17] EIM Location ID 55B070

and the rate of change have been lower than what is observed in Hangman Creek. Overall, median total phosphorus concentrations the Little Spokane have decreased by 46% from their peak concentrations in the 1980s, and the monotonic trends analysis detected significant reductions during the monitoring period (Figure 10). The observed reductions in both Hangman Creek and the Little Spokane River are likely due to the nonpoint source reduction efforts that have taken place in the respective watersheds over the past several decades.

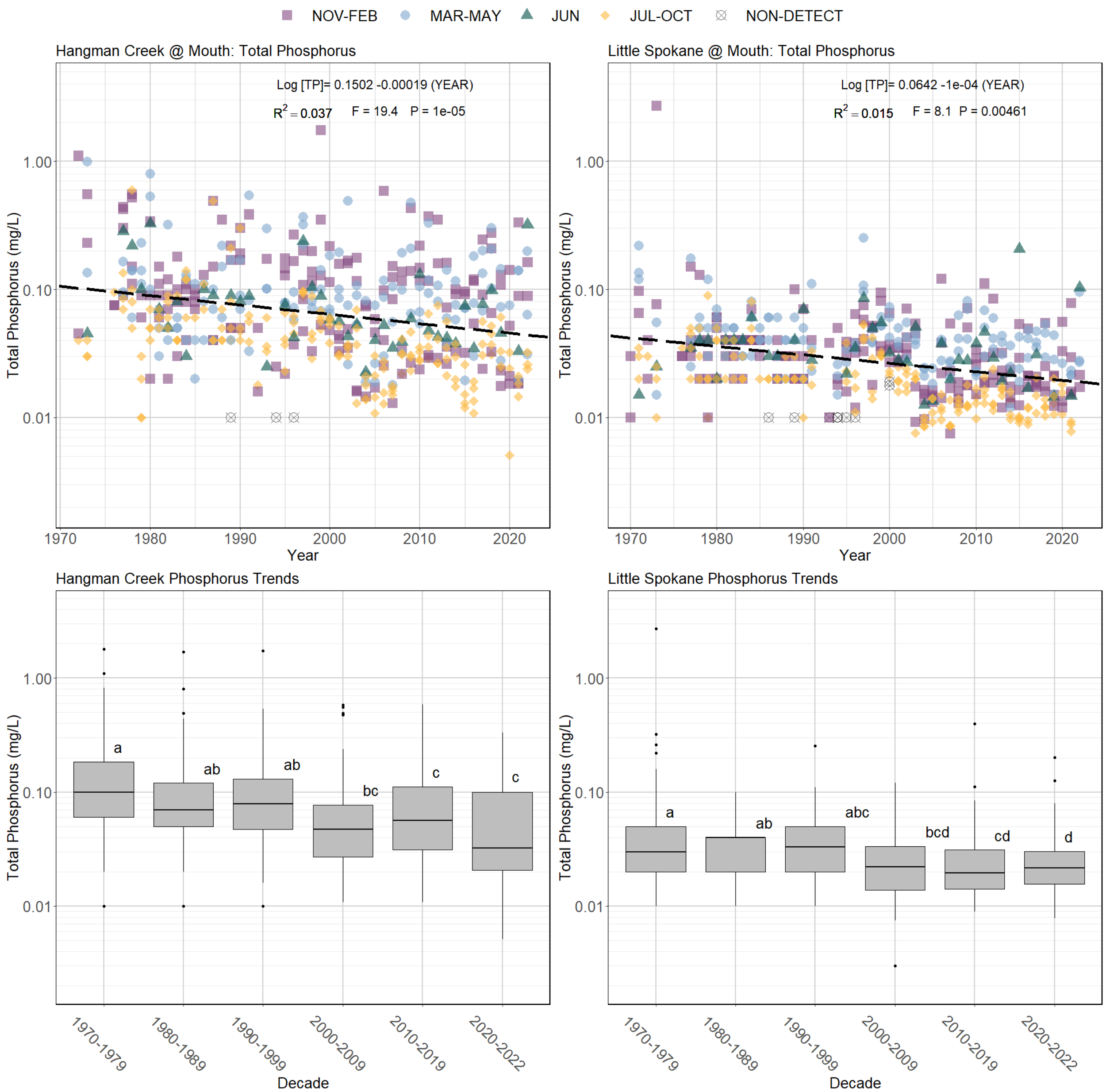


Figure 10. Total Phosphorus data from Hangman Creek (left) and the Little Spokane River (right), 1972 – 2022.

[a] Linear regression coefficients calculated using cumulative month (Time) as predictor of total phosphorus.

Riverine Assesment Point

We estimated the daily total phosphorus concentration for 2008 – 2020 at the riverine assessment point using a method that accounts for short-lived event “spikes” at Hangman Creek and the Little Spokane River (Figure 11). Appendix F provides the details of this analysis.

The original CE-QUAL-W2 modeling efforts predicted that if the TMDL wasteload allocations were met, TP concentrations at the riverine assessment point would fall below 0.01 mg/L during the June and July – October seasons. TP was predicted to still exceed the 0.01 mg/L benchmark during March – May (Moore and Ross, 2010).

Our trends assessment focused on the July through October timeframe. This lower flow period is less variable from year to year, as it tends not to be affected by event-driven spikes in Hangman Creek and the Little Spokane River.

Consistent with the trends that we observed on the Spokane River at Riverside State Park, at Hangman Creek, and at the Little Spokane River, the phosphorus concentration at the riverine assessment point also shows a significant downward trend overall (Table 12). From 2008 through 2020, the trend was characterized by a low and relatively constant rate of decrease. However, after the City of Spokane’s tertiary wastewater treatment facility came online in 2021, a noticeable step trend reduction occurred (Figure 11). The mean total phosphorus concentration decreased by approximately 55% at the riverine assessment point during the July – October season after tertiary treatment became operational. Further, after tertiary treatment was activated, the total phosphorus concentration dropped below the 0.01 mg/L target during the entirety of the July through October period in 2021 and 2022.

Further reductions to nonpoint/tributary sources will further reduce TP concentrations during March – May and June. Although March – May TP concentrations at the riverine assessment point are still expected to exceed 0.01 mg/L, compliance with tributary load allocations will result in springtime concentrations substantially lower than what currently occur.

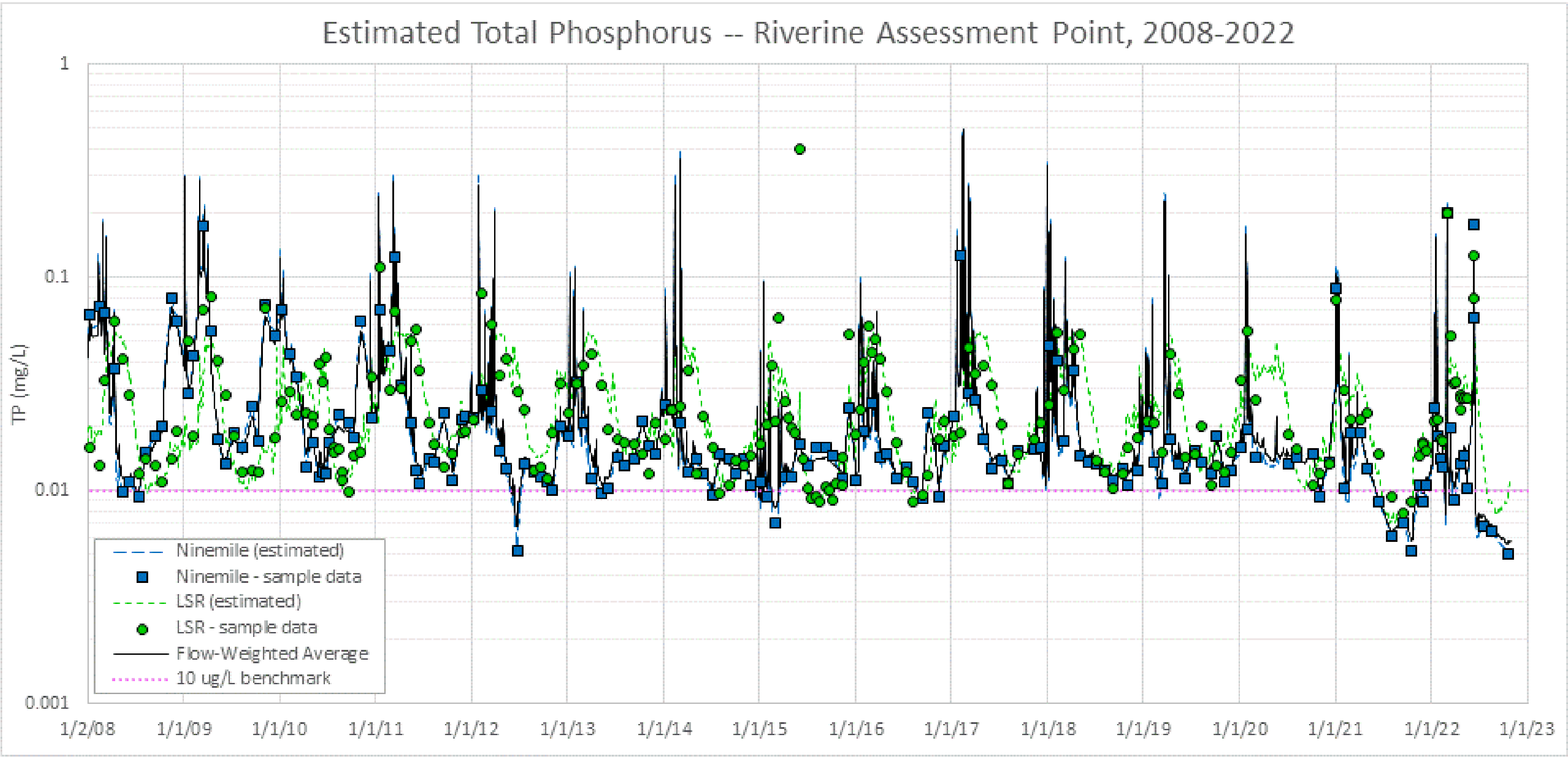


Figure 11. Estimated daily total phosphorus concentration at the riverine assessment point, 2008 – 2022.

Nine Mile sample data shown on this graph also include some data from Spokane River at Riverside State Park (54A120) for gaps in the Nine Mile (54A090) dataset, mainly during 2011 – 2012.

Trends in Lake Spokane

As discussed above, phosphorus levels in the Spokane River and its tributaries have decreased substantially over the last several decades. Following recent point source load reductions, summertime phosphorus levels entering Lake Spokane are now typically less than 0.01 mg/L. We assessed whether DO, phosphorus, and chlorophyll in Lake Spokane have yet responded to these inflow phosphorus reductions.

Dissolved oxygen (DO)

Figure 12 presents Lake Spokane dissolved oxygen profiles from July – August 2022. These plots also show gray shading indicating the statistical ranges of observed July – August dissolved oxygen for 2010 – 2018. As these plots make clear, dissolved oxygen conditions have not improved in 2022 since 2010 – 2018. If anything, dissolved oxygen levels during 2022 may have been a bit lower than during the previous decade.

To provide a bit of long-term historical context, Figure 13 presents time-series plots of June – October average inflow TP concentration alongside yearly minimum volume-weighted average hypolimnetic DO. This includes the data from the 1970 – 1980s shown previously in Figure 7, as well as more recent data from 2010 – 2022. These data demonstrate that, since the 1970 – 1980s, Lake Spokane phosphorus levels have continued to decrease and dissolved oxygen has continued to increase.

The year 2022, when we collected detailed data for this ten-year effectiveness study, appears to be a bit of an anomaly. June – October inflow phosphorus levels were a bit higher, and minimum hypolimnetic DO levels a bit lower, than typical values during the 2010s. At first, this seems surprising, given the recent implementation of tertiary treatment technology at major point sources. After all, late summer phosphorus concentrations in the Spokane River reached new lows well below 10 µg/L during 2021 and 2022 (see Figure 11). However, during 2022, the large phosphorus loads originating from Hangman Creek during June 2022 more than outweighed the point source reductions, even when considered for the entire June – October period.[18]

Figure 14 presents the same data as Figure 13, shown in terms of the correllation between inflow TP and hypolimnetic DO. Patmont et al. (1987), Welch et al. (2015), and Avista and Tetra Tech (2020) have used this type of plot to demonstrate the relationship between TP and DO, and to show the response of Lake Spokane DO to ongoing reductions in inflow TP. As Figure 14 demonstrates, there is a strong, nonlinear relationship between inflow TP and hypolimnetic DO.

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[18] One might ask whether the June – October period is the best season to consider for average TP inflows. Might minimum hypolimnetic DO correlate better to TP averaged over some other period, for example, August extreme low-flow conditions? Appendix I presents a cursory look at this question. Our findings, though not statistically conclusive, appear to support the wisdom of Patmont's selection of the June – October period.

Hypolimnetic DO during 2022 was exactly what one might have expected given the TP inflow conditions during that year.

As discussed above, the last time that a major reduction of inflow phosphorus occurred during the 1970s, it took several years for dissolved oxygen in Lake Spokane to fully respond. Following major point source phosphorus reductions, 2022 was only the second year when widespread summertime sub-10 µg/L TP levels occurred in the Spokane River entering Lake Spokane. Furthermore, large phosphorus loads from Hangman Creek during June 2022 may have impacted conditions in Lake Spokane during 2022. It is therefore too soon to draw conclusions about what the long-term effect of recent phosphorus reductions on DO in Lake Spokane will be.

We recommend continued monitoring of Lake Spokane DO over the next several years, particularly during the late summer critical period when yearly minimum hypolimnetic DO generally occurs. This will provide the information necessary to track Lake Spokane's DO response to reduced inflow phosphorus over the medium to long term.

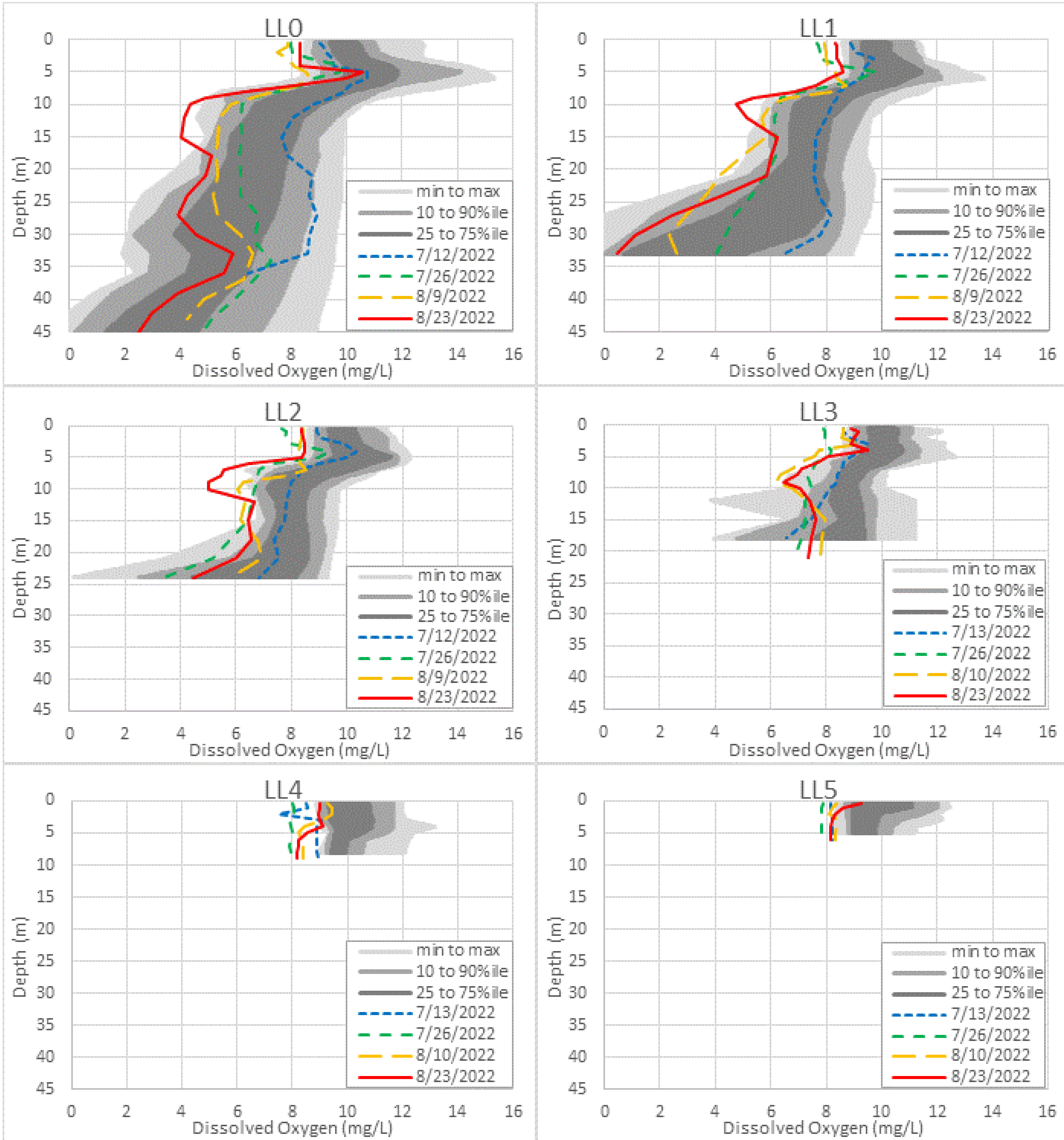
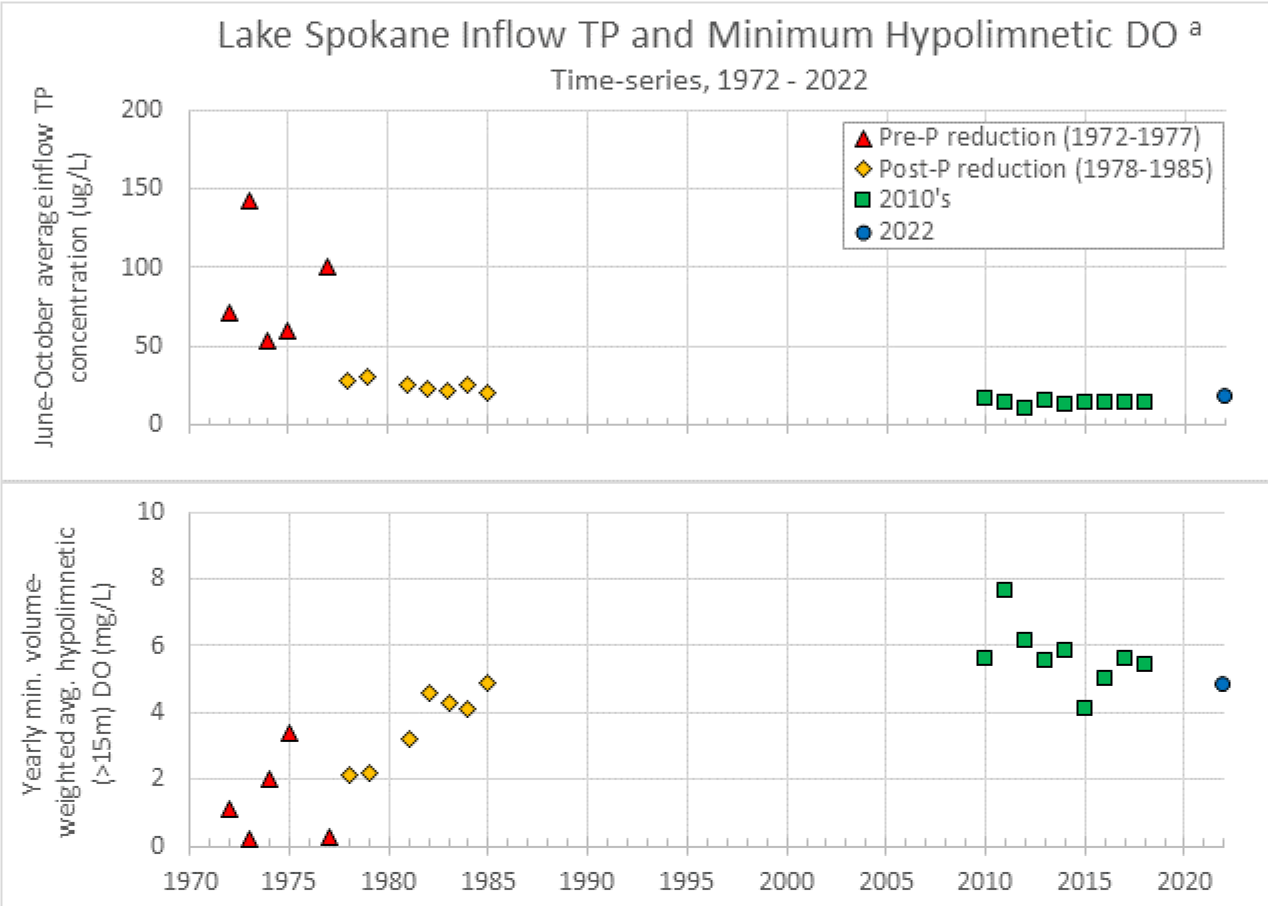


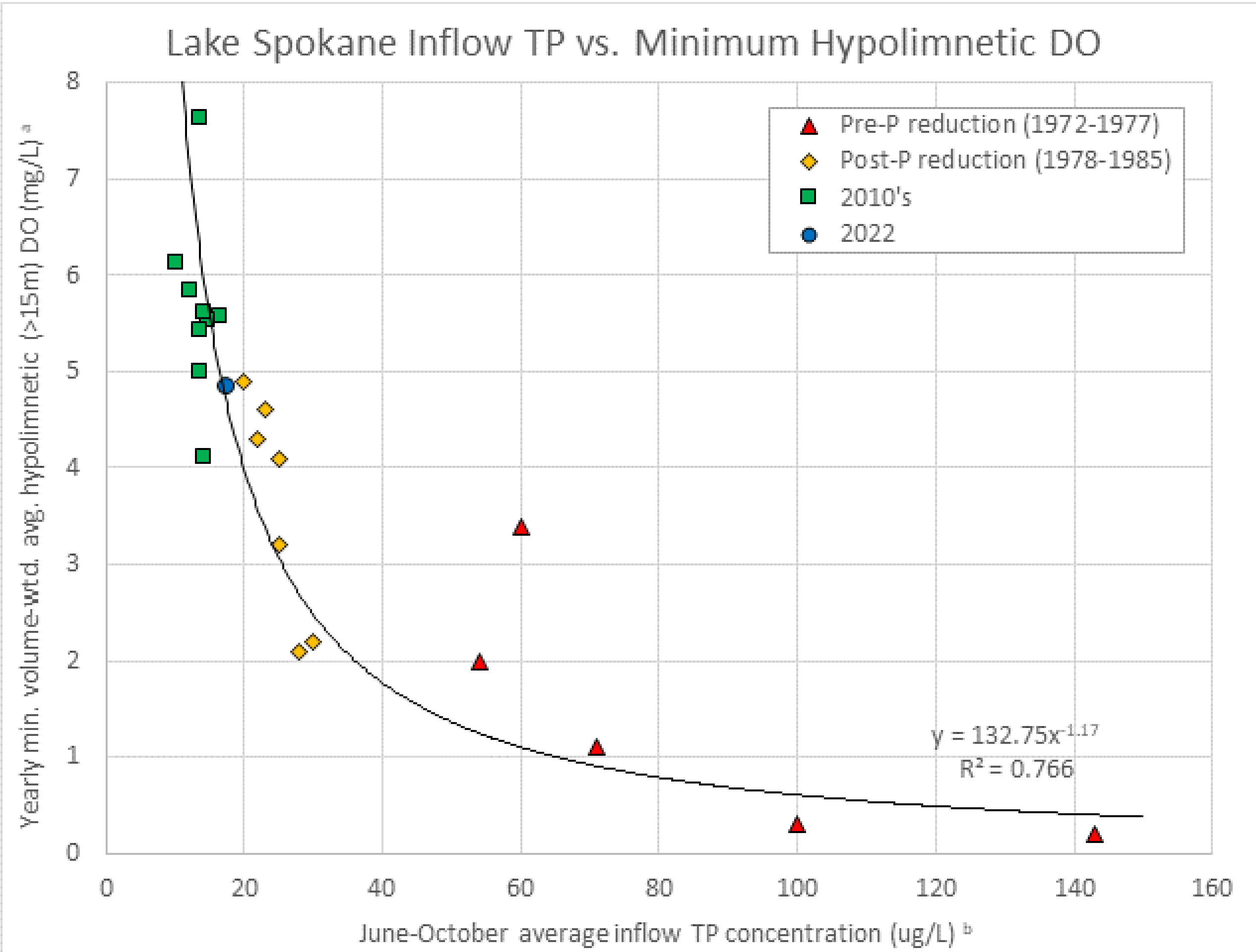
Figure 12. Lake Spokane dissolved oxygen profiles for July – August 2022, along with statistical ranges of July – August DO from 2010 – 2018 (six charts, LL0 – LL5).

See Appendix A, Figure A-1 for a map of these locations.



[a] 1972 – 1985 data from Patmont et al. (1987) and Welch et al. (2015).

Figure 13. Time-series of Spokane River total phosphorus (TP) and Lake Spokane dissolved oxygen (DO), 1972 – 2022. (Two charts, one each for TP and DO)



[a] See Appendix H for the computation of volume-weighted average hypolimnetic DO for 2010 – 2022. 1972 – 1985 values from Patmont et al. (1987).
[b] June – October average inflow TP concentrations for 2010 – 2022 calculated from daily average estimated concentrations at the riverine assessment point (Appendix F). 1972 – 1985 values from Patmont et al. (1987) and Welch, et al. (2015).

Figure 14. Lake Spokane June – October average inflow TP concentration vs. yearly minimum volume-weighted average hypolimnetic DO, after Patmont et al. (1987), Welch et al. (2015), and Avista and Tetra Tech (2020).

In-lake phosphorus

As noted, phosphorus concentrations entering Lake Spokane have decreased substantially over the last few decades. One might expect that this would result in a decrease in phosphorus within Lake Spokane itself. Given the strong relationship between inflow TP and lake DO (Figure 14), this probably has been the case historically. Ecology does not have in-lake TP data from before 2000, so it was not possible to assess this over the long term. However, we did assess whether the sudden decrease in summertime inflow TP during 2021 – 2022, following the City of Spokane's tertiary treatment coming online, influenced TP levels in the lake.

Figure 15 presents a time-series graph comparing TP concentrations in the Spokane River flowing into Lake Spokane, along with concentrations in Lake Spokane at LL4. LL4 is located in the upstream "riverine"[19] reach of Lake Spokane, near Suncrest. The lake is only ~9m deep at this location. There is not significant stratification at LL4. The water column at LL4 stays fully oxygenated, and light often penetrates to the bottom.

Figure 15 shows that during the 2010s, TP concentrations in Lake Spokane at LL4 were typically in the same range as that found in the inflow to the lake. This suggests that the upstream portion of Lake Spokane may have reached a near-equilibrium with inflowing water, with internal processes neither acting as a large source or sink of phosphorus.

During 2022, a different pattern emerged. As previously discussed, since 2021 inflow TP concentrations during the summer/fall period were substantially lower than during the 2010s. However, TP concentrations at LL4 continued at levels similar to what was observed during the 2010s. During July – October 2022, mean inflow TP, represented by the riverine assessment point, was about 0.007 mg/L. However, mean TP at LL4 during this time was about 0.016 mg/L. Thus, phosphorus loads more than doubled as the water passed through the upper ("riverine") section of Lake Spokane. This suggests that the upstream portion of Lake Spokane is no longer at equilibrium, with internal processes now acting as source of phosphorus to the water.

Again, nutrient cycling in lakes and reservoirs is complex. The phosphorus cycle includes processes that occur in the water column, processes that occur in the sediments, and processes that move phosphorus in either direction across the sediment-water interface (Wetzel 2001). Traditionally, phosphorus releases from sediments have been considered to be most likely under low-dissolved oxygen, reducing conditions (Einsele 1936; Einsele 1938; Mortimer 1941; Mortimer 1971). More recently, multiple studies have shown substantial releases to well-aerated water as well (Ryding and Forsberg 1977; Stevens and Gibson 1977; Lee et al. 1976), resulting in a paradigm shift among limnologists (Hupfer and Lewandowski 2008).

Welch et al. (2015) provide an excellent discussion of reservoir internal loading as it relates to Lake Spokane. Cooke et al. (2011) observed summer average riverine zone TP double the inflow concentration in Tenkiller Reservoir, in Oklahoma. This is similar to our Lake Spokane (LL4) pattern during 2022, although overall levels in Tenkiller Reservoir were an order of magnitude higher. Welch et al. (2015) discuss internal loading equilibrium dynamics in Lake Spokane and posit a multiple-year or even decades-long timeframe for complete lake response to inflow phosphorus load reductions.

It is possible that, over time, phosphorus levels in the riverine section of Lake Spokane (LL4) may come into a new equilibrium with the newly reduced inflow levels.

[19] The upstream portion of Lake Spokane, represented by monitoring stations LL5 and LL4, is sometimes referred to as the "riverine" section of the reservoir (see Figure 4). This is not to be confused with the "riverine assessment point" which represents the river inflow to Lake Spokane.

A spatial view of phosphorus data can provide additional insights. Figure 16 presents a panel of longitudinal graphs showing TP throughout the Spokane River and Lake Spokane system for each sampling month during 2022.[20] During early-season high-flow conditions, TP levels in Lake Spokane are similarly low to those in the Spokane River (<20 µg/L), representing system flushing. The June plot represents rapidly changing runoff event concentrations from Hangman Creek.

The July, August, and October plots provide the best snapshot of summer-fall low-flow conditions where internal processes become important. As already seen in Figure 15, TP levels increased from Nine Mile to the riverine section of Lake Spokane (LL5 and LL4) during 2022, likely reflecting internal loading. Levels then decrease through the transitional section (LL3).

In the lacustrine section of Lake Spokane (LL2, LL1, LL0), TP levels in the euphotic zone (epilimnion) remain low. However, levels in the hypolimnion increase throughout the summer to as much as ~40 – 50 µg/L during August. This could represent a more "classical" case of hypolimnion internal loading under low-dissolved oxygen conditions.[21] Elevated phosphorus levels in the summertime hypolimnion are a long-known feature in Lake Spokane; data from 2000, 2001, and 2010 – 2017 also clearly showed this pattern. The CE-QUAL-W2 model used to develop the TMDL included a sediment phosphorus release process, which was needed to capture this pattern (Berger et al. 2002; Berger et al. 2003).

These data underscore the complexity of internal loading and nutrient cycling process in Lake Spokane. This further supports the conclusion that lake response to reduced inflow phosphorus will be a matter of equilibrium shift, which could take years.

[20] We discarded all TP data collected during September 2022 due to a contract laboratory data quality issue. See Appendix B for details.

[21] We observed a range of near-bottom July-August DO levels in the lacustrine zone, from less than 1 mg/L to over 6 mg/L (see the bottoms of the colored lines in Figure 12). We collected these measurements at regular 3-meter intervals, so actual DO levels in the near-sediment boundary layer may have been lower.

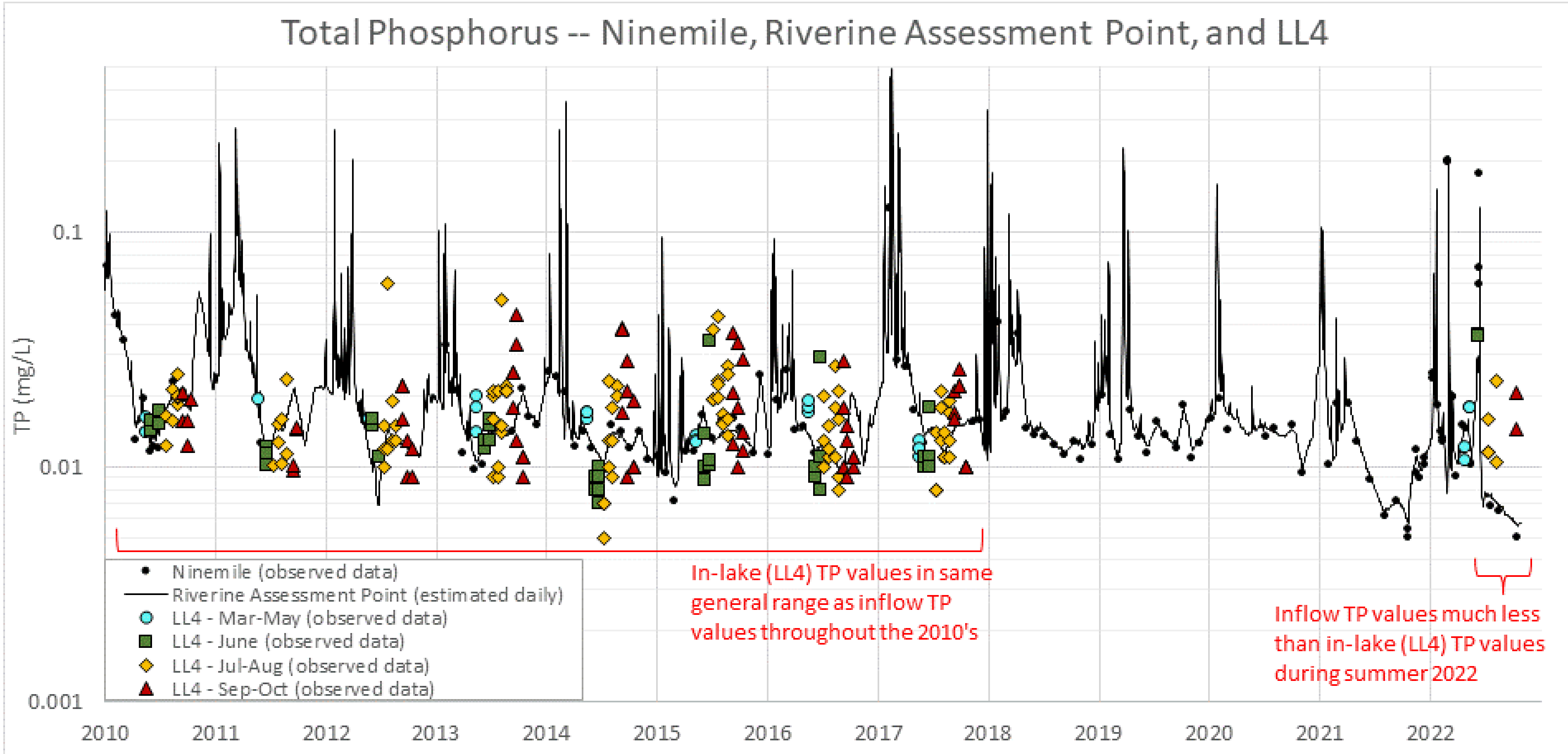


Figure 15. Time-series graph of total phosphorus in the Spokane River at Nine Mile, the Riverine Assessment Point, and in Lake Spokane at LL4.

The Riverine Assessment Point is calculated as the flow-weighted average of the Spokane River at Nine Mile and the Little Spokane River, which represents the inflow to Lake Spokane.

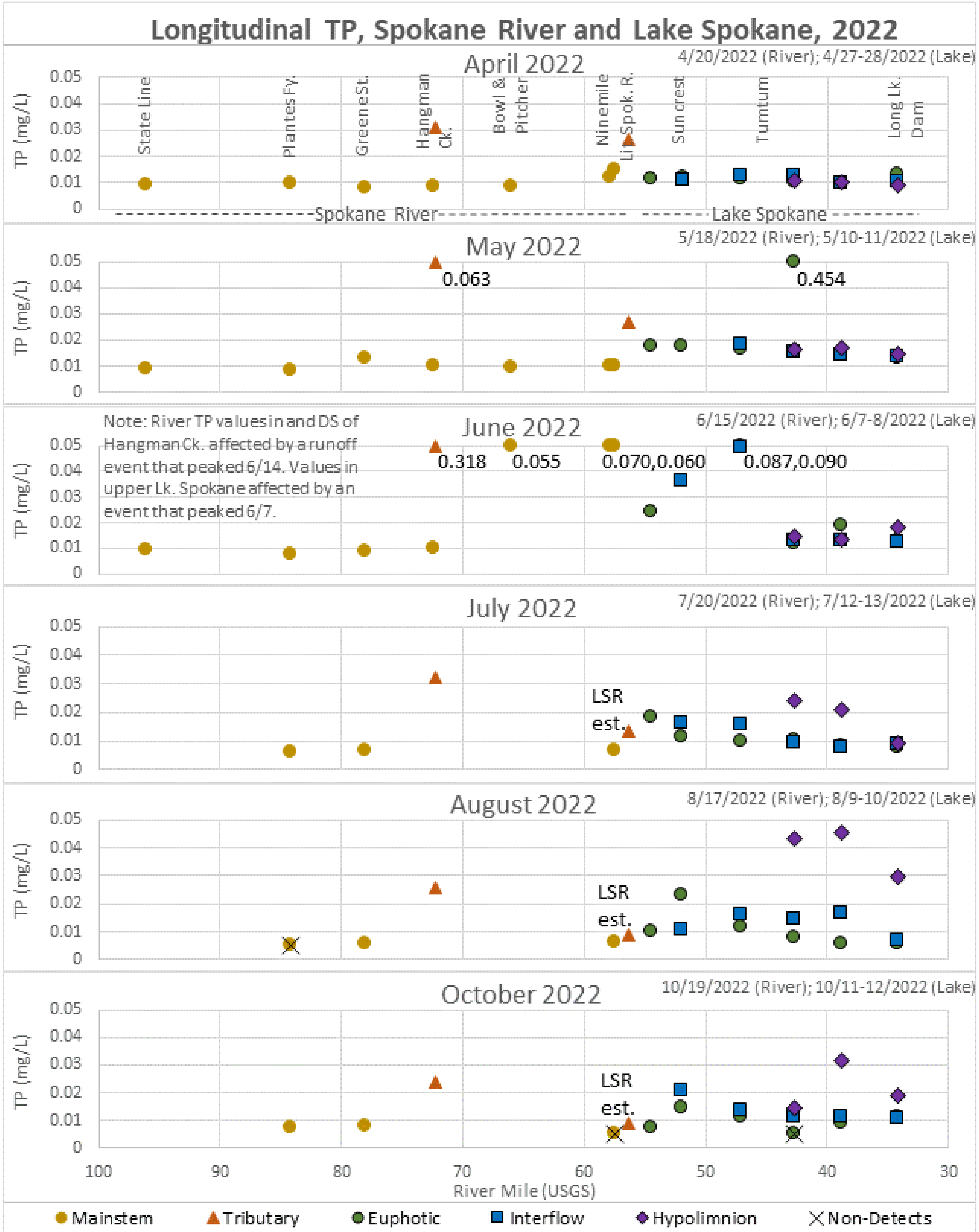


Figure 16. Longitudinal plots of total phosphorus (TP) in the Spokane River and Lake Spokane, April – October 2022 (six charts).

Chlorophyll

Figure 17 presents trends in chlorophyll-*a* concentration at each of the six Lake Spokane sampling locations from 2000 through 2022. Because Lake Spokane chlorophyll data from before 2000 was not available, we were not able to include earlier decades in the analysis. Overall, there were generally not significant trends during the 2000 – 2022 timeframe. Regression analysis did identify potentially significant negative trends ($p = 0.0002$) at two locations (LL2, LL3). In the case of LL2, this appears to have been driven by some high values during 2000. For LL3, although the p-value is low, the magnitude of the trend is small. Therefore, the potential trends at these two locations may not be very meaningful.

This is not surprising. As previously discussed, in-lake dissolved oxygen and phosphorus have not changed substantially during the 2010 – 2022 period. Epilimnetic chlorophyll is largely driven by nutrient (in the case of Lake Spokane, phosphorus) availability. Therefore, internal phosphorus loading, and lake equilibrium dynamics will have a strong effect on chlorophyll concentrations. Further changes in chlorophyll in Lake Spokane, as is the case with phosphorus and dissolved oxygen, will be a matter of equilibrium shift.

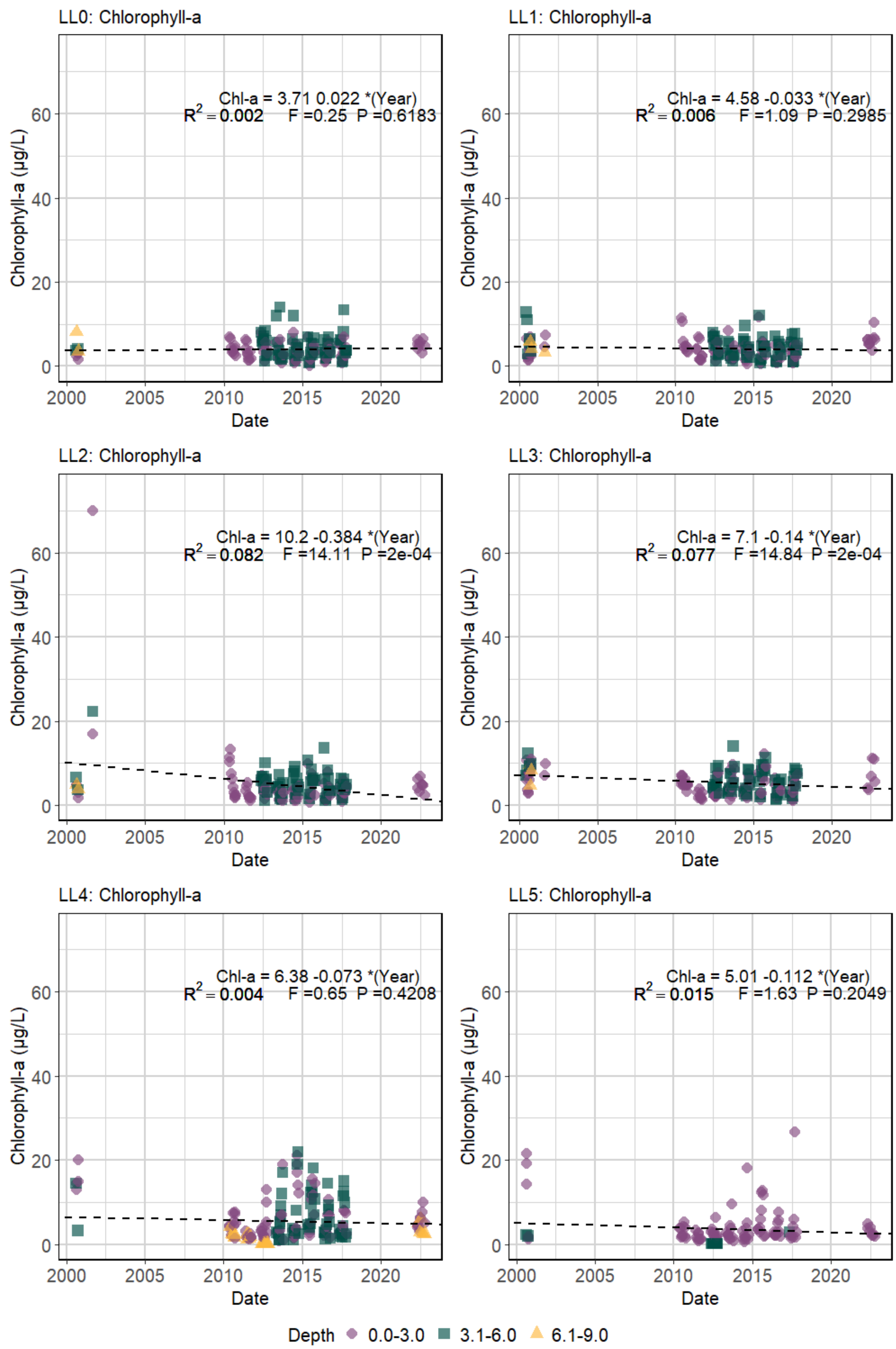


Figure 17. Lake Spokane chlorophyll *a* trends 2000 – 2022.

Effects of tributary nonpoint pollution

As previously noted, the successful implementation of tertiary treatment technology by point source facility dischargers has resulted in an over 90% reduction in point source phosphorus contribution between 2001 and 2022. This reduction has left the tributaries as the largest remaining source of phosphorus to the Spokane River system. During March – May 2022, which was a hydrologically near-typical (median) March – May period, Hangman Creek alone contributed 74% of the total source load. Put another way, Hangman Creek (Figure 18) contributed nearly three times as much phosphorus as all other point and nonpoint loads combined. Tributaries in total contributed 92% of the overall source load during March – May 2022.

Figure 18. Turbid water from Hangman Creek meeting clear water from the Spokane River, at their confluence.

Photo credit: Cutboard Studios/Spokane Riverkeeper

Despite substantial improvements over the last several decades, high sediment and phosphorus conditions persist. Hangman Creek has experienced suspended sediment concentrations (SSC) over 1000 mg/L and TP over 1 mg/L during recent years (Stuart 2022). High-sediment events during June 2022 underscore this ongoing problem, with observed turbidity values in Hangman Creek in excess of 1000 NTU on three separate occasions during that month (Figure 19).

The effects of this tributary phosphorus load on the Spokane River and Lake Spokane are not entirely understood. The springtime phosphorus loads carried by Hangman Creek, and to a lesser extent, the Little Spokane River, are strongly associated with turbidity and suspended sediment. This association is so strong that we were able to use the waterbody-specific correlations ($R^2 > 0.97$) between turbidity and total phosphorus to estimate continuous TP using continuous turbidity data (Stuart 2022; Appendix D in this study).

The majority of Hangman Creek springtime phosphorus is not soluble reactive phosphorus (SRP). That is, much of this phosphorus is bound up in larger, more complex molecules likely associated with soil particles. These more complex forms of phosphorus are not immediately available for uptake by algae. However, this phosphorus may enter the lake's phosphorus cycle and contribute to bioavailable SRP (Wetzel 2001).

Furthermore, because Hangman Creek and Little Spokane springtime phosphorus loads are strongly associated with sediment, they are potentially subject to settling. The sediment particles containing much of the phosphorus are suspended, rather than dissolved. Given sufficiently still water and enough time, they can come out of suspension and settle to the stream or lakebed. The sediment particles associated with Palouse loess are very fine and apparently do not settle easily in a flowing stream environment. The *Hangman Creek Watershed Nutrients and Sediment Pollutant Source Assessment* (Stuart 2022) did not find evidence of significant suspended sediment losses in the Hangman Creek watershed during the springtime months.[22] However, in a still water environment such as Nine Mile Reservoir or Lake Spokane, the situation may be different.

Fate and transport of tributary sediment and phosphorus – upstream of Lake Spokane

Figure 19 shows the continuous turbidity record from the Spokane River just below Nine Mile Dam, along with the records for Hangman Creek and the Little Spokane River. Comparing the turbidity records for the Spokane River and Hangman Creek, the turbidity values in the Spokane River are lower due to dilution of the Hangman Creek sediment load by the larger volume of Spokane River mixing with Hangman Creek. However, the patterns of turbidity in both water bodies are nearly identical, apart from a small timing delay due to the travel time from the Hangman Creek confluence through Nine Mile Reservoir. This "fingerprint" match between the two records demonstrates that sediment loads from Hangman Creek are driving downstream sediment and turbidity patterns in the Spokane River as well.

[22] Table 9 and Figures 14-15 in Stuart (2022) do show a net negative contribution, or sink, for two subbasins in lower Hangman Creek. However, these values resulted from subtracting one or more large upstream load estimates from a large downstream estimate to find the relatively small subbasin contribution. This resulted in a large degree of estimate uncertainty for these lower watershed subbasins. The subbasin loss estimates for total phosphorus, which had the best accuracy of the parameters analyzed, never exceeded 7% of the total downstream load. The subbasin loss estimates for suspended sediment, which were less accurate, never exceeded 15% of the total downstream load. Furthermore, the substrate in lower Hangman Creek typically consists of cobbles, rather than layers of sediment/fines, even in deep pools. This would not be expected if significant net deposition were occurring.

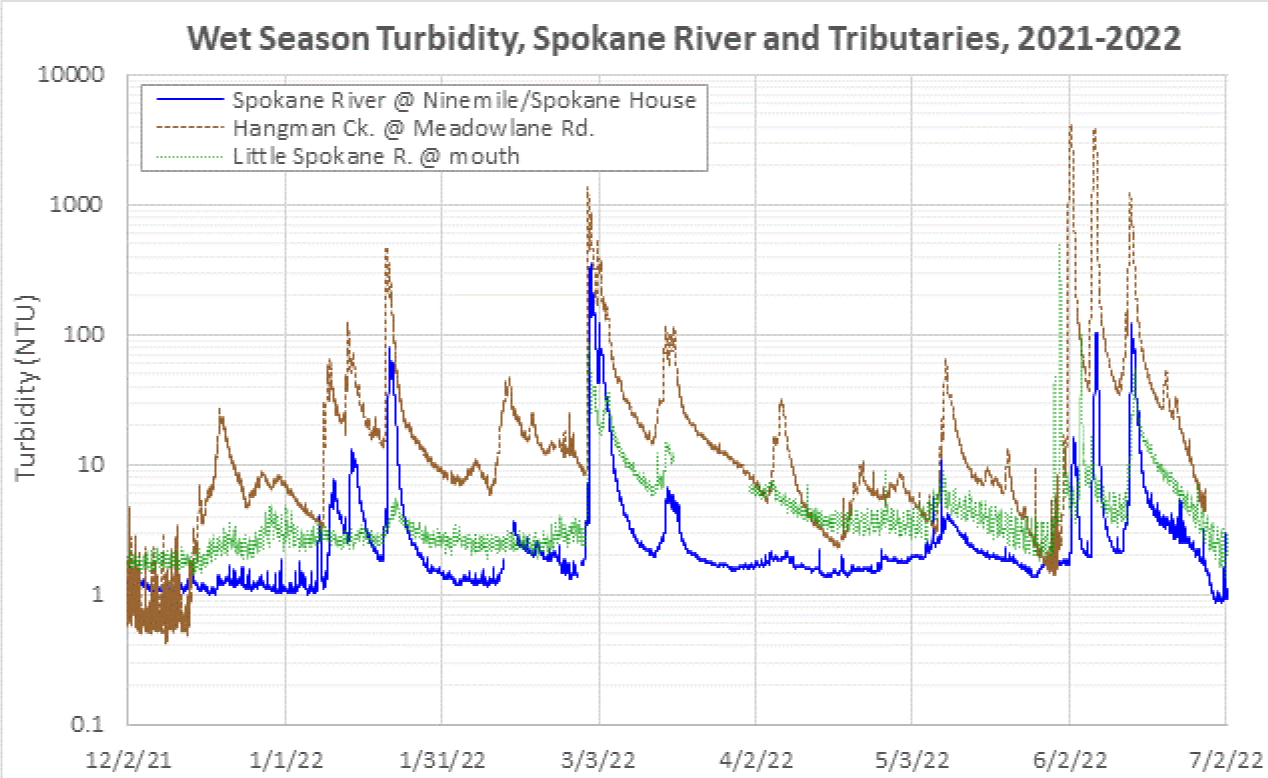


Figure 19. Continuous turbidity in the Spokane River, Hangman Creek, and the Little Spokane River, December 2021 – June 2022.

The total phosphorus mass balance for March – May 2022 (Table 9) indicates no net gain or loss in the Sandifur bridge – Spokane House/Nine Mile reach. In other words, the phosphorus load in the Spokane River upstream of Hangman Creek, plus the loads from Hangman Creek, City of Spokane WRF, and all other sources in that reach, added up to the observed load at Spokane House/Nine Mile almost exactly. The mass balance for June 2022 (Table 10) shows a small negative residual in this reach, equivalent to -4.9% of the Spokane/House Nine Mile load (-13% of the Sandifur Bridge load). This residual is within the range of load estimate uncertainty and probably is not meaningful.

These mass balance results suggest that there is no significant net springtime phosphorus settling or attenuation in Nine Mile Reservoir, and that sediment-linked phosphorus from Hangman Creek passes through Nine Mile Reservoir nearly in its entirety. These results agree with Avista's finding that Nine Mile Reservoir has reached "dynamic equilibrium" with respect to sediment. Avista notes that deposition and scouring do occur:

> …equilibrium conditions in the Nine Mile reservoir do not mean that the reservoir bed does not change from year to year, simply that on a long-term basis the reservoir cannot capture significant additional sediment (Avista and Watershed Science & Engineering 2013).

After passing through Nine Mile Reservoir, sediment and phosphorus from Hangman Creek enter Lake Spokane.

The Little Spokane River also experiences high-turbidity sediment transport events during the springtime, although not on the same scale as Hangman Creek. Figure 19 shows that the turbidity record for the Little Spokane River follows a somewhat different pattern than Hangman Creek and the Spokane River do. Sediment and phosphorus from the Little Spokane River enter Lake Spokane at the Little Spokane River confluence, located at the far upper end of the lake.

These data demonstrate that most of the suspended sediment and phosphorus entering the Spokane River system from the tributaries enters the upstream end of Lake Spokane.

Fate and transport of tributary sediment and phosphorus — within Lake Spokane

An estimated 220 tons/day of sediment (total suspended solids) and 1400 lbs/day of phosphorus, from all sources, entered the upstream end of Lake Spokane during March – May 2022. It is not entirely clear what happens to this material once it enters Lake Spokane. Neither Ecology nor any of our partner organizations has monitored continuous turbidity downstream of Long Lake Dam. Therefore, it is currently unknown how much sediment and phosphorus passes through Lake Spokane, versus how much deposits on the lakebed.

Unlike Nine Mile Reservoir, which is a run-of-the-river reservoir with a residence time of a just few hours during springtime high flows, Lake Spokane is a 243,000-acre-foot reservoir (Scheibley and Foreman 2021) with an average residence time ranging from around a week during springtime high flows to well over a month during summertime low flows. (See Appendix J for residence time estimates.) The still-water conditions and volumetric capacity of Lake Spokane may allow significant sediment deposition. Avista concluded that:

> Sediment deposition in [Lake Spokane] is primarily occurring in the upper third of the reservoir…Future sedimentation in [Nine Mile Reservoir] and [Lake Spokane] is expected to follow current trends with Nine Mile maintaining a dynamic equilibrium and Lake Spokane capturing most of the sediment input into it (Avista and Watershed Science and Engineering, 2013).

Golder Associates (2005) provided the following estimates:

> Lake Spokane…captures the majority of sediments…entering this reservoir. …Course materials…will most likely accumulate within the first one to three miles of the lake downstream of the Nine Mile HED. Finer grained materials will most likely deposit within the upper one to eight miles of the lake.

Additional investigation is needed to quantify the deposition of sediment and sediment-linked phosphorus in Lake Spokane.

Possible effects of tributary sediment and phosphorus on the Spokane River and Lake Spokane

Spokane River

It is unlikely that phosphorus associated with Hangman Creek sediment contributes much to eutrophication in free-flowing portions of the Spokane River. As discussed above, event phosphorus loads pass through the Spokane River and Nine Mile Reservoir into Lake Spokane in a short amount of time. (The following section discusses the possible effects of this material in Lake Spokane.) The cold temperatures and high flows during the winter and springtime likely keep algae growth in the river to a minimum during this period.

However, the sediment itself has the potential for deleterious effects in the Spokane River. Turbidity in the water column and sediment that has settled out on the river bottom can affect fish and other aquatic life. The effects of turbidity, sediment, and solids on fish and other aquatic life can be divided into four categories: (1) acting directly on the fish swimming in the water and either killing them or reducing their growth rate, resistance to disease, etc.; (2) preventing the successful development of fish eggs and larvae; (3) modifying behavior, natural movements, and migrations; and (4) reducing the abundance of available food (Joy et al. 2009).

Fish and benthic macroinvertebrate populations are especially sensitive to the direct and indirect effects of sedimentation and turbidity. While in the water column, suspended sediments can damage the health of fish and sweep out benthic macroinvertebrates. When suspended sediments settle, they can suffocate salmonid eggs in redds (fish nests) and smother macroinvertebrates. High turbidities can cause behavioral changes in fish communities. Some toxic and oxygen-demanding chemicals are adsorbed to settled sediment where they are available to harm organisms. The effects of sediment on aquatic life tend to be a function of both concentration and duration (Newcombe and McDonald 1991).

Sediment discharged from Hangman Creek to the Spokane River could be a matter of concern for native Redband Trout (Muhlfeld et al. 2015) populations. Lee (2013) estimated a population of about 1000 individuals >25cm in the Spokane River between Peaceful Valley and T.J. Meenach Bridge. Addley and Peterson (2011) found substantial Redband spawning activity in the reach just downstream of Hangman Creek, with a particular concentration in the vicinity of T.J. Meenach Bridge. Redband Trout generally spawn in April, with emergence during May – June. This is during the period when high sediment events in Hangman Creek often occur. Addley and Peterson (2011) also found that survival in artificial redds was negatively related to fine sediment intrusion.

Sediment could also be matter of concern for ongoing efforts to re-introduce salmon and steelhead to the upper Columbia basin. After a cultural/educational release of 147 adult Chinook at Sandifur Bridge during August 2022, Spokane Tribal staff observed spawning behavior in the Spokane River reach downstream of the Hangman Creek confluence. Staff observed 32 new redds during October 2022 (Giorgi 2023). It is unknown what the potential effects of high-sediment events on eggs and/or alevins in this reach might be.

Lake Spokane

The ongoing deposition of phosphorus-laden sediments, assuming that is occurring, could have various implications. For one thing, there is the potential for lake aggradation. Golder Associates (2005) estimated that "Lake Spokane…channel/reservoir thalweg elevations in some areas will fill in by as much as 5 feet in the next 50 years."

Deposition could also affect the phosphorus cycle. As previously discussed, phosphorus cycling in lakes and reservoirs is complex, and internal loading can be important. In Lake Spokane, our data suggest that internal loading occurred in the riverine section (represented by LL5 and LL4) during summer – fall 2022. Our data also suggest summertime internal loading to the hypolimnion in the lacustrine section (represented by LL2, LL1, and LL0). Sediment storage of phosphorus and long-term equilibrium dynamics between internal and external loading may be of key importance. If a fresh layer of sediment from Hangman Creek and other tributary sources is depositing in Lake Spokane during the winter-spring each year, that could potentially affect these nutrient equilibriums by continually replenishing the lake's internal phosphorus supply.

Ultimately, the actual importance of this potential effect is not known. The effects of winter – springtime deposition of phosphorus-laden sediment from Hangman Creek and other tributary sources on summertime nutrient cycling, algae growth, and dissolved oxygen in Lake Spokane are not well understood. This is clearly a potential cause for concern. However, further research on this topic is needed.

We recommend a continuation of efforts to reduce nonpoint sediment and phosphorus runoff in Hangman Creek as well as the Little Spokane River. These efforts will benefit water quality and aquatic life in the tributary watersheds themselves, as well as protecting downstream conditions in the Spokane River and Lake Spokane.

Conclusions

Results of this study support the following conclusions:

- Point sources in the Washington portion Spokane River watershed have made substantial reductions to their phosphorus discharges. Point source TP loads, not including stormwater and CSOs, averaged 23 lbs/day during March – October 2022. This compares with 239 lbs/day during March – October 2001, representing over a 90% reduction.
- Hangman Creek and the Little Spokane River exceeded their wet season (March – May and June) LAs during 2022. Hangman Creek contributed more than all other point and nonpoint sources combined, constituting 74% of the total TP load during March – May and 89% during June. Tributary sources generally met their LAs, at least in terms of concentration, during the dry season (July – October).
- TP concentrations in the Spokane River and its tributaries have displayed a significant declining trend over the last several decades. TP in the Spokane River at Riverside State Park has decreased by 82% since the 1970's. TP in Hangman Creek has decreased by 61% since the 1970's. TP in the Little Spokane River has decreased by 58% since the 1970's.
- TP concentrations at the Riverine Assessment Point, which represents water flowing into the upstream end of Lake Spokane, stayed below 10 µg/L during July – October 2022, but not during March – May or June. Sub-10 µg/L summertime levels began in 2021, after tertiary treatment came online at City of Spokane's Riverside Park Water Reclamation Facility.
- TP and DO conditions in Lake Spokane have improved substantially since the 1970's. Summertime hypolimnetic DO in Lake Spokane is strongly related to inflow TP, as others have observed (Patmont et al. 1987; Welch et al. 2015).
- Nutrient cycling, internal loading, and equilibrium processes are important in Lake Spokane. After a large-scale point source TP reduction during the 1970s, DO conditions in Lake Spokane took at least five years to fully respond (Patmont et al. 1987; Welch et al. 2015).
- As of 2022, TP and DO conditions in Lake Spokane had not yet responded to reduced summertime inflow TP levels. Given the multi-year timeframe required for Lake Spokane DO to respond to past inflow TP reductions and given the confounding factor of unusually large sediment and phosphorus inputs from Hangman Creek during June 2022, it is too soon to draw conclusions about what the ultimate lake DO response will be.
- The greatest remaining obstacle to meeting the requirements of the *Spokane DO TMDL* is sediment and phosphorus delivered in the winter and springtime by tributary nonpoint sources, especially Hangman Creek. Despite substantial improvements over the last several decades, high sediment and phosphorus conditions persist. Hangman Creek has experienced suspended sediment concentrations (SSC) over 1000 mg/L and TP over 1 mg/L during recent years (Stuart, 2022). High-sediment events during June 2022 underscore this ongoing problem, with observed turbidity values in Hangman Creek exceeding 1000 NTU on three separate occasions during that month.

Recommendations

Results of this study support the following recommendations.

- Conservation districts, local and tribal governments, nonprofit organizations, farm associations, families, and other stakeholders should continue efforts to reduce nonpoint pollution. These efforts should particularly focus on sediment-laden runoff in the Hangman Creek and Little Spokane River watersheds. Addressing nonpoint sources should be the highest priority during the next 10 years of TMDL implementation.
- Local governments should continue efforts to reduce and mitigate stormwater flow.
- Avista should continue measures toward achieving their DO responsibility.
- Monitoring of Lake Spokane should continue, to capture the multi-year lake response to recent point source phosphorus reductions.
- Research should be conducted into the fate, transport, and impacts of sediment and phosphorus in Lake Spokane. This includes investigating how much of the Hangman/Little Spokane sediment and phosphorus load deposits in Lake Spokane vs. passing through. This should also include investigating the effects of ongoing sediment and phosphorus deposition on nutrient cycling, internal loading, algae growth, and dissolved oxygen in Lake Spokane.

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Glossary, Acronyms, and Abbreviations

Glossary

Anthropogenic: Human-caused.

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

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Diel: Of, or pertaining to, a 24-hour period.

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

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

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

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

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 waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare; (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses; or (3) livestock, wild animals, birds, fish, or other aquatic life.

Redd: A depression (or nest) in the stream/river bed where salmon deposit their eggs. A female salmon creates the redd by using her body and tail to suck up gravel and allow it to drift downstream. She then deposits eggs in the redd and covers the red with gravel, generally by creating another redd directly upstream and allowing the gravel from that new redd to drift downstream and cover the previous one. Redds are visible in a stream as areas of clean exposed gravel.

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 waterbody designed to protect it from not meeting water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a Margin of Safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector, such as a stream, river, or lake at a lower elevation.

Water Year: A year-long period used for assessing and describing hydrologic conditions. Each water year lasts from October through the following September. For example, Water Year 2022 lasted from October 2021 through September 2022.

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

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

Acronyms and Abbreviations

BMP	best management practice
BOD	biochemical oxygen demand
CBOD	carbonaceous biochemical oxygen demand
CEPT	chemically enhanced primary treatment
CSO	combined sewer overflow
CV	coefficient of variation
DI	deionized water
DMR	discharge monitoring report
DO	dissolved oxygen
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
ERO	Ecology's Eastern Regional Office
FERC	Federal Energy Regulatory Commission
HSD	Honest Significant Difference
HUC	Hydrologic Unit Code
IDEQ	Idaho Department of Environmental Quality
IEP	Inland Empire Paper Company
KCEL	King County Environmental Laboratory
LA	load allocation
LLSWD	Liberty Lake Sewer and Water District
LSR	Little Spokane River
MBBF	moving bed biofilm reactor
ME	mean error
MEL	Manchester Environmental Laboratory
MK	Mann-Kendall test
MLR	multiple linear regression
MQO	measurement quality objective
MS4	municipal separated storm sewer system
MW	monitoring well
N/A	not applicable
ND	non-detect
NH_3-N	ammonia nitrogen
NLT	next level of treatment
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System (see glossary)
OSS	on-site septic system
PCB	polychlorinated biphenyl
PSU	Portland State University
QA	quality assurance
QAMP	quality assurance monitoring plan
QAPP	quality assurance project plan
QC	quality control

RAP	riverine assessment point
RL	reporting limit
RM	river mile
RMSE	root mean squared error
RPD	relative percent difference
RPWRF	City of Spokane's Riverside Park Water Reclamation Facility
RSD	relative standard deviation
SAWTP	Spokane Advanced Wastewater Treatment Plant
SCD	Spokane Conservation District
SCRWRF	Spokane County Regional Water Reclamation Facility
SM	Standard Methods
SRP	soluble reactive phosphorus
SSC	suspended sediment concentration
SVRPA	Spokane Valley-Rathdrum Prairie Aquifer
TDS	total dissolved solids
TMDL	Total Maximum Daily Load (see glossary)
TP	total phosphorus
TSS	total suspended solids
UCUT	Upper Columbia United Tribes
UF	ultrafiltration
USGS	U.S. Geological Survey
V-W DO	volume-weighted dissolved oxygen
WAC	Washington Administrative Code
WLA	wasteload allocation
WQAP	water quality attainment plan
WRIA	Water Resource Inventory Area
WY	Water Year

Units of Measurement

af	acre-feet
°C	degrees centigrade
cfs	cubic feet per second
cfu/100mL	colony forming units per 100 milliliters, a unit of bacteria concentration
d	days
gal	gallons
in	inches
lbs/day	pounds per day, a unit of loading
m	meter
m^3	cubic meters
MGD	millions of gallons per day
mg/L	milligrams per liter (parts per million)
MG/yr	millions of gallons per year
mi	miles
mi^2	square miles

NTU	nephelometric turbidity units
s.u.	standard units
tons/day	tons per day, a unit of loading
µg/L	micrograms per liter (parts per billion)
µS/cm	microsiemens per centimeter, a unit of conductivity
W/cm^2	Watts per square centimeter, a unit of solar radiation intensity

Appendices

Appendix A. Monitoring locations and data types collected

This appendix details the monitoring locations and types of data collected by Ecology during our 2021 – 2022 field study. Tables A-1 through A-5 and Figure A-1 present the monitoring locations along with frequency and timing. Tables A-6 and A-7 detail the laboratory and field parameters.

The project QAPP (Stuart et al. 2021) indicated that this field study would include a groundwater monitoring component. Upon further review, we determined that the proposed groundwater monitoring would not add value to the existing Spokane County groundwater monitoring program and was therefore not worth pursuing.

Table A-1. Ambient river monitoring locations (October 2021 – October 2022)

Location ID	Location Description	Approx. Frequency	Stream samples	Lake samples	Groundwater samples (temporary drive point)	Field measurements (Hydrolab or other meters)	Continuous turbidity	Instantaneous flow
57A150	Spokane River @ State Line	1x/month	X	—	—	X	—	—
57A140 a	Spokane River @ Centennial Trail bridge	1x/month	X	—	—	X	—	—
57A133 a	Spokane River @ Greene Street	1x/month	X	—	—	X	—	—
57A123	Spokane River @ Sandifur Bridge	1x/month	X	—	—	X	—	—
56IND-00.0 [a]	Indian Canyon Creek @ Mouth	1x/month	X	—	—	X	—	X
56A070	Hangman Creek @ Mouth	1x/month	X	—	—	X	—	—
54A120	Spokane River @ Riverside State Park	1x/month	X	—	—	X	—	—
54A090	Spokane River @ Nine Mile Bridge	1x/month	X	—	—	X	—	—
55B070	Little Spokane River @ Mouth	1x/month	X	—	—	X	—	—

[a] These locations are not included in the regular Environmental Assessment Program (EAP) ambient monitoring network and were sampled by TMDL staff.

Table A-2. Lake monitoring locations (April – October 2022)

Location ID	Location Description	Approx. Frequency	Stream samples	Lake samples	Groundwater samples (temporary drive point)	Field measurements (Hydrolab or other meters)	Continuous turbidity	Instantaneous flow
LL5	Lake Spokane near Nine Mile campground	1x/month	—	X	—	X	—	—
LL4	Lake Spokane near Suncrest Park	1x/month	—	X	—	X	—	—
LL3	Lake Spokane upstream of Willow Bay	1x/month	—	X	—	X	—	—
LL2	Lake Spokane downstream of TumTum	1x/month	—	X	—	X	—	—
LL1	Lake Spokane near Lake. Spokane Campground	1x/month	—	X	—	X	—	—
LL0	Lake Spokane near Long Lake Dam	1x/month	—	X	—	X	—	—

Table A-3. Continuous turbidity monitoring locations (October 2021 – October 2022)

Location ID	Location Description	Approx. Frequency	Stream samples	Lake samples	Groundwater samples (temporary drive point)	Field measurements (Hydrolab or other meters)	Continuous turbidity	Instantaneous flow
56HAN-06.2	Hangman Creek @ Meadowlane Road	Continuous	X	—	—	—	X	—
56HAN-01.5	Hangman Creek @ 11th Ave.	Continuous	X	—	—	—	[a]	—
55B070	Little Spokane River @ Mouth	Continuous	X	—	—	—	X	—
54SPK-57.2	Spokane River @ Spokane House	Continuous	X	—	—	—	X	—

[a] Our continuous turbidity monitoring equipment at Hangman Creek at 11th Ave. was vandalized a short time after deployment. After this occurred, we continued to collect samples at this location, but did not collect continuous turbidity.

Table A-4. Continuous DO, pH, conductivity, and temperature monitoring locations (March – October 2022)

Location ID	Location Description	Approx. Frequency	Stream samples	Lake samples	Groundwater samples (temporary drive point)	Field measurements (Hydrolab or other meters)	Continuous turbidity	Instantaneous flow
57A150	Spokane River @ State Line	Continuous	—	—	—	X	—	—
56A070	Hangman Creek @ Mouth	Continuous	—	—	—	[a]	—	—
54SPK-57.2	Spokane River @ Spokane House	Continuous	—	—	—	X	—	—
55B070	Little Spokane River @ Mouth	Continuous	—	—	—	X	—	—

[a] We decided against deployment of continuous monitoring equipment at Hangman Creek at mouth (55B070) due to the high risk of vandalism. We elected instead to deploy the equipment at Hangman Creek at 11th Avenue (56HAN-01.5), but this equipment was vandalized soon after deployment.

Table A-5. Little Spokane River source tracking locations (March 2022)

Location ID	Location Description	Approx. Frequency	Stream samples	Lake samples	Groundwater samples (temporary drive point)	Field measurements (Hydrolab or other meters)	Continuous turbidity	Instantaneous flow
55LSR-13.5	Little Spokane River @ North LSR Drive	1x total [a]	X	—	—	X	—	X
55LDP-00.1	Little Deep Creek at Shady Slope Road	1x total [a]	X	—	—	X	—	X
55DEA-00.2	Deadman Creek below Little Deep Creek	1x total [a]	X	—	—	X	—	X
55LSR-11.7	Little Spokane River @ Pine River Park	1x total [a]	X	—	—	X	—	X
55WAN-00.0	Wandermere Springs @ mouth	1x total [a]	X	—	—	X	—	X
55LSR-10.3	Little Spokane River @ North Dartford Drive	1x total [a]	X	—	—	X	—	X
55DAR-00.2	Dartford Creek @ Mouth	1x total [a]	X	—	—	X	—	X
55WAK-00.0	Waikiki Springs main branch @ Mouth	1x total [a]	X	—	—	X	—	X
55WAK-PND	Waikiki Springs pond branch @ Mouth	1x total [a]	X	—	—	X	—	X
55LSR-09.4	Little Spokane River below Waikiki Springs	1x total [a]	X	—	—	X	—	X
55WAK-VIS	Waikiki Springs Vistawood branch above pond	1x total [a]	X	—	—	X	—	X
55LSR-07.5	Little Spokane River @ West Waikiki Road	1x total [a]	X	—	—	X	—	X
55GRI-00.0	Griffith Springs @ Mouth	1x total [a]	X	—	—	X	—	X
55LSR-05.5	Little Spokane River below Saint George's School	1x total [a]	X	—	—	X	—	X
55LSR-03.9	Little Spokane River @ Painted Rocks	1x total [a]	X	—	—	X	—	X
55B070	Little Spokane River @ Mouth	1x total [a]	X	—	—	X	—	X

[a] After our first lower Little Spokane River (LSR) source tracking survey failed to show any evidence of the "mystery load," we elected not to continue these surveys. See Appendix K for details.

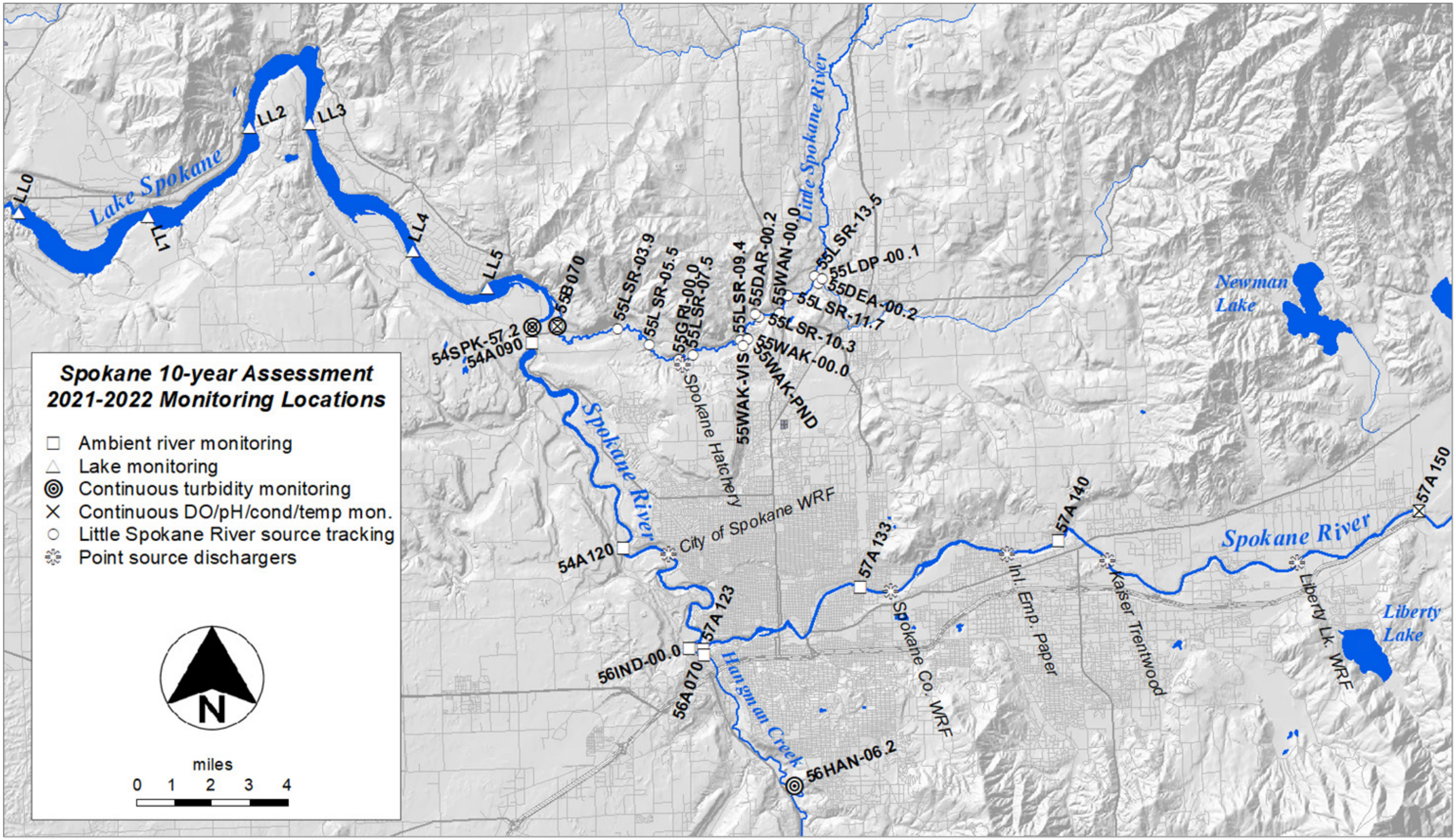

Figure A-1. Map of sampling locations for the Spokane River 10-yr assessment 2021 – 2022 field study.

Table A-6. Laboratory sample parameters.

Parameter	Lab Method(s)	Unit of Measure	Ambient river monitoring	Lake monitoring	Continuous turbidity monitoring	Continuous DO, pH, cond, temp monitoring	Groundwater monitoring	Little Spokane River source tracking
Total suspended solids	SM 2540 D [c]	mg/L	X	X	X	—	—	X
Total non-volatile suspended solids	EPA 160.4 [c]	mg/L	X [n]	X	—	—	—	—
Total dissolved solids	SM 2540 C [c]	mg/L	X [n b]	X	—	—	X	—
Turbidity (lab)	SM 2130 [c]	NTU	X [a]		—	—	—	—
Total persulfate nitrogen	SM 4500 NB [c] SM 4500 NC	mg/L	X	X	—	—	X	X
Nitrate-Nitrite	SM 4500 NO3 I [c] EPA 353.2 [d]	mg/L	X	X	—	—	X	X
Ammonium	SM 4500 NH3 H [c] SM 4500 NH3 D [d]	mg/L	X	X	—	—	X	X
Total phosphorus, low level	SM 4500 PH [c] SM 4500 PF [d]	mg/L	X	X	X	—	—	X
Orthophosphate (soluble reactive phosphorus)	SM 4500 PG [c] SM 4500 PE [d]	mg/L	X	X	—	—	X	X
Total organic carbon	SM 5310 B [c]	mg/L	X [n]	X	—	—	—	X
Dissolved organic carbon	SM 5310 B [c]	mg/L	X [n]	X	—	—	X	X
Alkalinity	SM 2320 B [c d]	mg/L	X [n]	X	—	—	X	—
Chlorophyll *a*	SM 10200 H3 [c]	µg/L	X [n b]	X	—	—	—	—
E. coli	SM 9222 G1 [c]	cfu/100mL	X [a]	—	—	—	—	—
Fecal Coliform	SM 9222 D [c]	cfu/100mL	X [a]	—	—	—	—	—

SM: standard methods
EPA: U.S. Environmental Protection Agency methods
[n] These sample parameters are not normally part of the ambient monitoring suite. We added them to these sites for this study.
[a] These sample parameters were not needed for this study but were collected as part of the normal ambient monitoring suite.
[b] We collected these parameters during regular stream sampling at four sites: 57A150 (Spokane R. @ State Line), 56A070 (Hangman Ck. @ mouth), 54A090 (Spokane R. @ Nine Mile Bridge), and 55B070 (Little Spokane R. @ mouth).
[c] Manchester Environmental Lab (MEL) method
[d] Contract lab method (see Appendix B).

Table A-7. Field measurement parameters.

Parameter	Unit of Measure	Ambient river monitoring	Lake monitoring	Continuous turbidity monitoring	Continuous DO, pH, conductivity, temperature monitoring	Groundwater monitoring	Little Spokane River source tracking
Temperature	°C	D+C	P	—	C	D	—
Conductivity	uS/cm	D	P	—	C	D	—
pH	S.U.	D	P	—	C	D	—
Dissolved oxygen	mg/L	D	P	—	C	D	—
Turbidity (field)	NTU	D	—	D+C	—	—	D
Streamflow	cfs	D [a]	—	—	—	—	D
Secchi depth	m	—	D	—	—	—	—
Light	W/cm^2	—	P	—	—	—	—

[a] We monitored streamflow at 56IND-00.0 (Indian Canyon Creek), but not the other river monitoring sites.

D = discrete measurements, C = continuous measurements, P = vertical profile measurements

References — Appendix A

Stuart, T., A. Albrecht, and J. Stevens, 2021. Quality Assurance Project Plan: Spokane River and Lake Spokane Dissolved Oxygen Total Maximum Daily Load 10-Year Effectiveness Monitoring Study. Washington State Department of Ecology, Olympia, WA. Publication 21-03-112. https://apps.ecology.wa.gov/publications/SummaryPages/2103112.html

Appendix B. Data quality — this study

This appendix describes the quality of the data that Ecology collected during 2021 – 2022 for the *Spokane DO 10-year* study (EIM Study ID tist0003). Appendix C describes the quality of data obtained from other programs, organizations, and agencies that we used in our analysis.

Typically, we assessed data by comparing quality metrics such as replicate precision statistics or instrument calibration end checks to a target Measurement Quality Objective (MQO). EAP's programmatic QAPP for water quality impairment studies (McCarthy and Mathieu 2017) and the QAPP for the *Spokane DO TMDL 10-Year Study* (Stuart et al. 2021) define the MQOs for this study. We found all data to be acceptable for use in this study, except for some total phosphorus sample results affected by a contract laboratory bias issue, described below.

Sample data quality

Ecology's Manchester Environmental Laboratory (MEL) analyzed the majority of samples for this project. However, MEL was unable to analyze all of the samples due to laboratory equipment failures and staffing shortages. MEL subcontracted the remainder of the samples to OnSite Environmental Inc. in Redmond, WA, King County Environmental Laboratory in Seattle, WA, and ALS Lab Group in Kelso, WA. Table B-1 summarizes the sample parameters and time periods analyzed by the contract labs.

There were two primary impacts of the change in analytical laboratories to our data quality. First, some of the contract labs were not able to achieve reporting limits (RL) as low as MEL. Table B-2 lists MEL and contract lab reporting limits for the affected parameters, and summarizes the impact to our dataset. Second, there was an apparent bias between total phosphorus (TP) results between King County Environmental Laboratory (KCEL) and MEL.

Table B-1. Sample parameters and time periods analyzed by contract laboratories.

Laboratory	Parameter(s)	Time period
OnSite Environmental Inc.	Alkalinity	Nov 2021 – Aug 2022
OnSite Environmental Inc.	Nitrate-Nitrite, Ammonia	Jun 2022 – Oct 2022
King County Environmental Lab	Total Persulfate Nitrogen	Jun 2022 – Oct 2022
King County Environmental Lab	Total Phosphorus	Sep 2022
ALS Lab Group	Orthophosphate	Sep 2022

MEL analyzed all other parameters and time periods not listed here.

Table B-2. Reporting limits (RL) affected by contract laboratories.

Parameter	MEL RL (mg/L)	Contract Lab RL (mg/L)	Impact to study
Alkalinity	5	2	none
Nitrate-Nitrite	0.01	0.05	minimal — all but three results were above the RL anyway
Ammonia	0.01	0.05	minimal — most results were non-detects anyway
Total Persulfate N	0.025	0.1	none — there were no non-detects
Total Phosphorus	0.005 [a]	0.005 [b]	No RL impact, but bias impact — see below [c]
Orthophosphate	0.003	0.05	Loss of September 2022 orthophosphate results for both lake and river samples. Nearly all results were non-detects, which would have been detectable at the lower RL.

RL: reporting limit

[a] This is MEL's low-level option for total phosphorus analysis

[b] King County Environmental Lab (KCEL) has a RL of 0.01 mg/L for TP. However, they reported values down to their method detection limit (MDL) of 0.005 mg/L. KCEL marked result values above the MDL but below the RL with the JT qualifier.

[c] The RL difference didn't cause a problem in itself but see **Total phosphorus KCEL vs. MEL bias issue** section in this appendix, below.

Total phosphorus KCEL vs. MEL bias issue

We observed evidence suggesting that total phosphorus (TP) results analyzed by King County Environmental Lab (KCEL) were biased high as compared to results analyzed by Ecology's Manchester Environmental Laboratory (MEL). This was especially true for results near the reporting limit. However, the pattern also included samples with higher results. The reasons for this apparent bias are unknown. For the sake of comparability to past data, we only used MEL TP results for our analysis.

Figures B-1 through B-3 present time-series TP datasets showing the evidence of this bias. This pattern is also apparent at most other locations in the study, including lake locations.

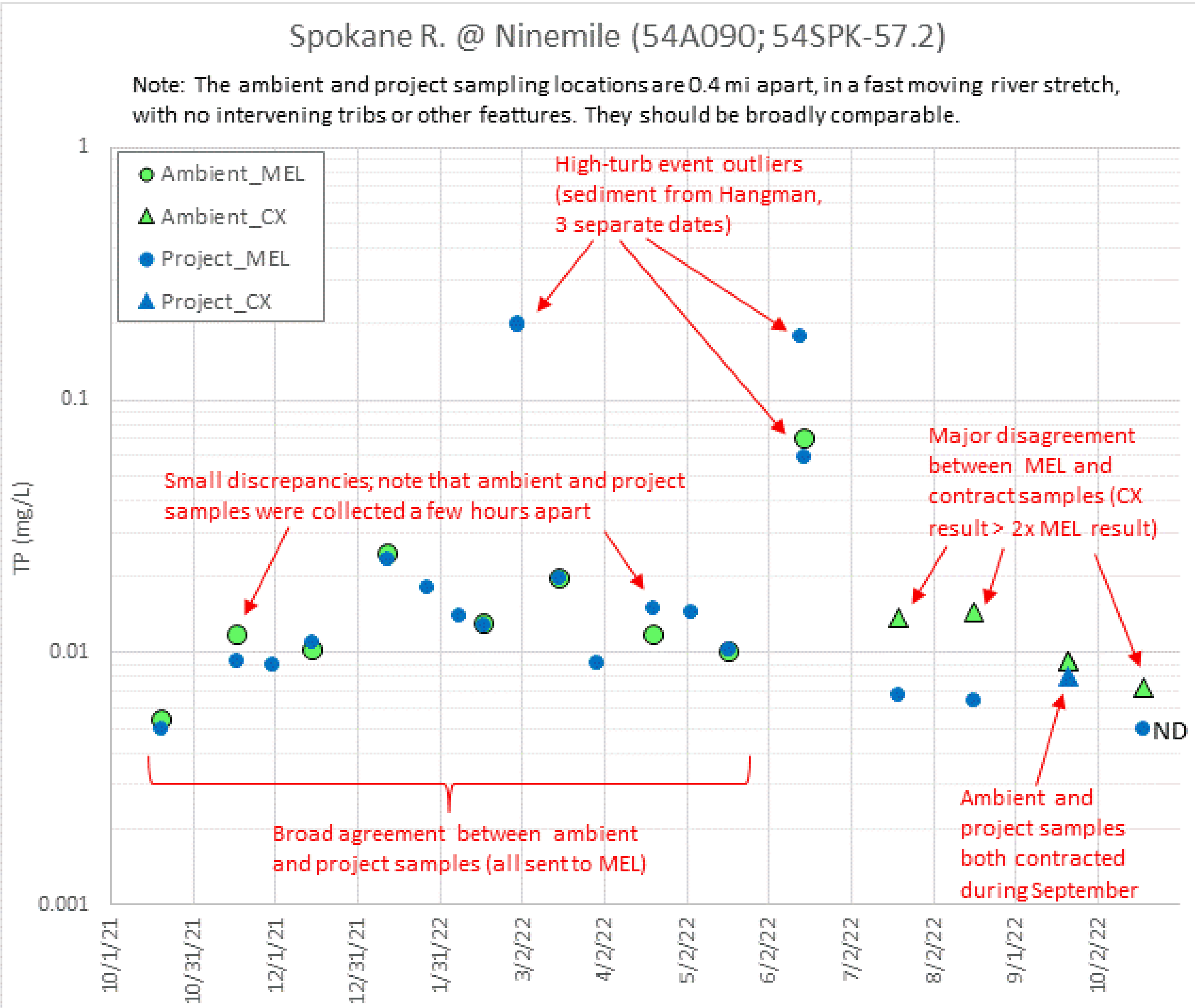

Figure B-1. Time-series plot of TP for Spokane River at Nine Mile, showing both ambient and project sample results.

Ambient results were contracted to KCEL from July 2022 onward, while project results were only contracted during September 2022.

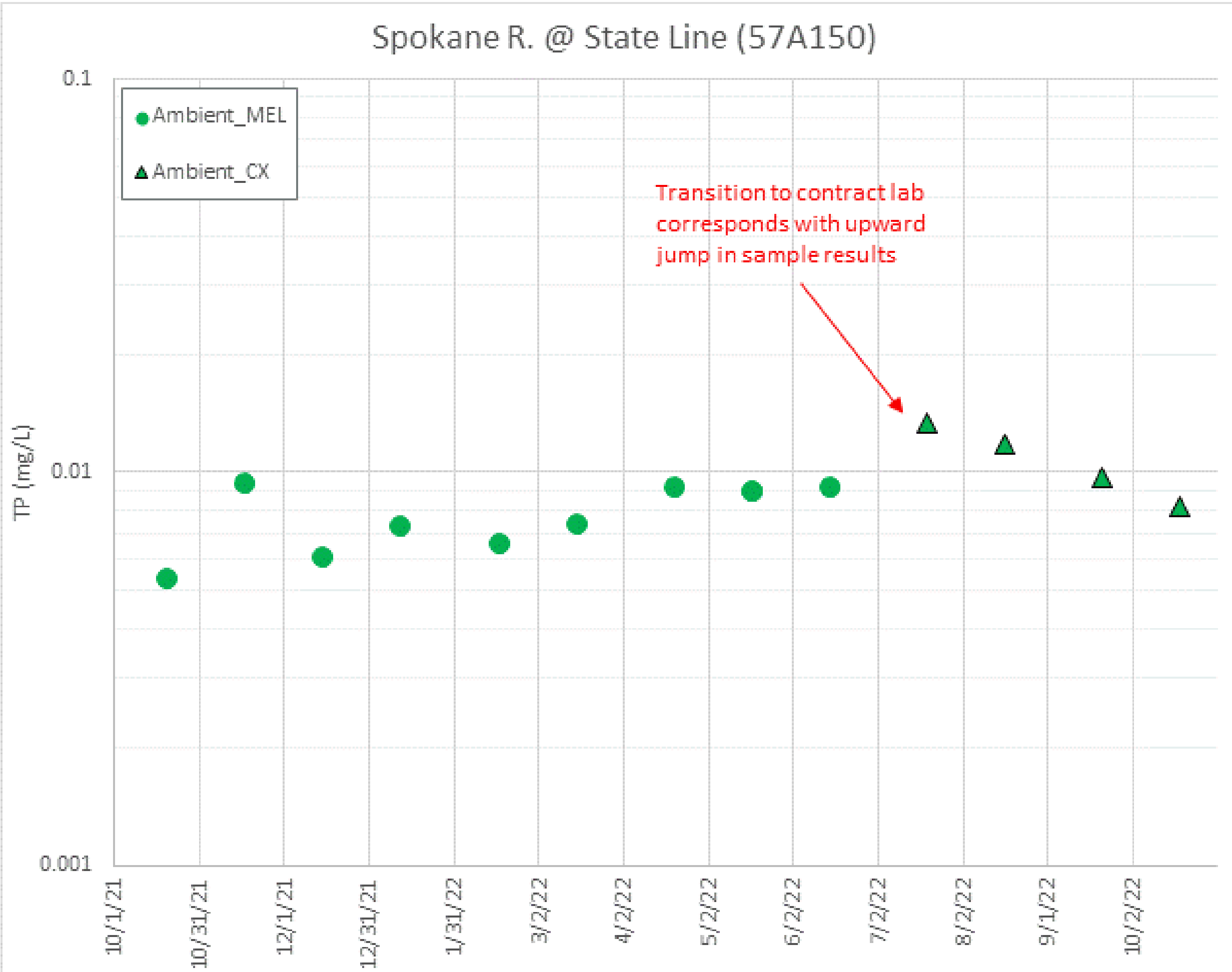

Figure B-2. Time-series plot of TP for Spokane River at State Line.

Ambient results were contracted to KCEL from July 2022 onward.

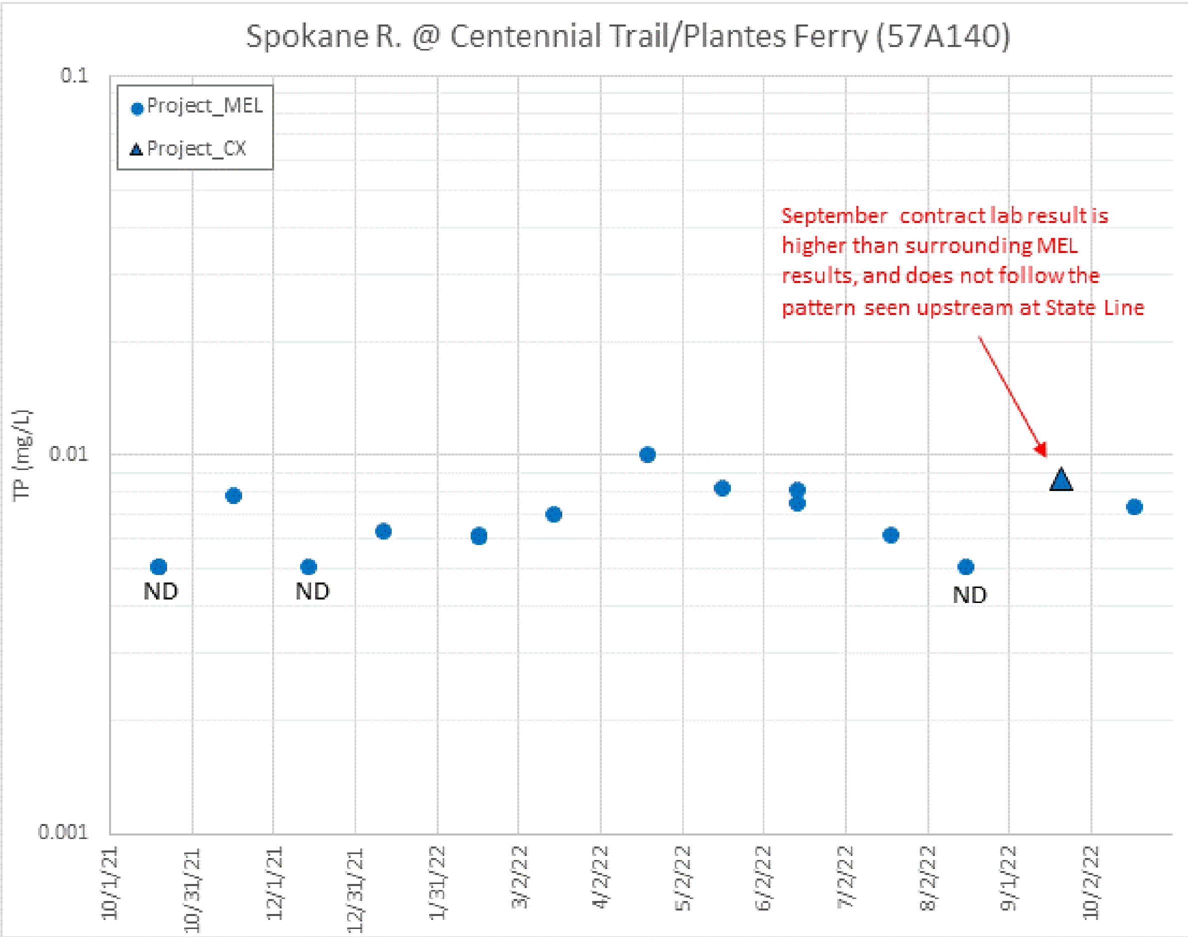

Figure B-3. Time-series plot of TP for Spokane River at Centennial Trail/Plantes Ferry.

Project results were contracted to KCEL during September 2022 only.

Duplicates, replicates, and matrix spikes

Ecology uses laboratory duplicates and field replicates to assess sample precision. Laboratory duplicates consist of two subsamples taken from the same sample container and analyzed separately. These serve as a check on the precision of the lab analysis. Tables A-3 through A-6 present lab precision calculated from these duplicates, for MEL and each of the contract labs.

Ecology's Manchester Environmental Laboratory (MEL) standard operating procedure (SOP) calls for duplicating a minimum of 5% of all samples (1/20 samples or 1/analytical batch). However, MEL and the contract labs often combine samples from different projects in lab batches, and the duplicates may come from other projects. Tables A-3 through A-6 only include lab duplicates from this project. This is why the duplication rate is less than 5% for some parameters. MEL did not duplicate samples for chlorophyll *a*.

Field replicates consist of two samples collected from the same location and as close to the same time as possible. Ecology collects field replicates to check the precision of the entire process of sampling and analysis. Table B-7 presents the total (field + lab) precision calculated from field replicates. Both the frequency of field replicates and the precision of the replicated samples generally fell within the target levels set in the QAPP. This indicates a high level of precision suitable for our analysis.

MEL, along with each of the contract labs, assesses bias for certain parameters using matrix spikes. Tables B-3 through B-6 present these results alongside lab precision. As was the case with lab duplicates, we only included matrix spikes taken from this project's samples. Matrix spike recoveries were within targets for all parameters.

Table B-3. Lab precision and bias results for Ecology's Manchester Environmental Laboratory (MEL).

Parameter	Number Samples	Number Dups	% duplicated	Target Precision	Median %RSD < 5x RL [a]	Median %RSD >= 5x RL	Matrix Spike % recovery Target range	Matrix Spike % recovery Actual range	Matrix Spike % recovery Avg %rec
Total Suspended Solids	242	37	15.3%	<20% RPD	0.0%	0.5%	—	—	—
Total Non-Volatile Suspended Solids	238	29	12.2%	<20% RPD	11.1%	3.7%	—	—	—
Total Dissolved Solids	152	22	14.5%	<20% RPD	7.2%	2.5%	—	—	—
Total Phosphorus	220	20	9.1%	<20% RPD	2.4%	2.7%	75% - 125%	91% - 101%	96.2%
Ortho-Phosphate	149	9	6.0%	<20% RPD	4.2%	1.8%	75% - 125%	95% - 111%	101.9%
Total Persulfate Nitrogen	72	1	1.4%	<20% RPD	—	4.1%	75% - 125%	101% - 103%	102.0%
Nitrate-Nitrite as N	72	2	2.8%	<20% RPD	—	0.0%	75% - 125%	95% - 99%	97.0%
Ammonia	72	2	2.8%	<20% RPD	0.0%	—	75% - 125%	98% - 110%	102.0%
Total Organic Carbon	238	15	6.3%	<20% RPD	3.2%	4.5%	75% - 125%	88% - 114%	97.7%
Dissolved Organic Carbon	238	3	1.3%	<20% RPD	3.0%	5.2%	75% - 125%	93% [b]	93.0%
Chlorophyll *a*	184	0 [c]	0.0%	<20% RPD	—	—	—	—	—
Total Alkalinity	51	1	2.0%	<20% RPD	—	0.8%	—	—	—

RSD: relative standard deviation; RPD: relative percent difference; RL: reporting limit

[a] Results at the detection limit (i.e., if either the primary or the duplicate sample result was a non-detect) are excluded from consideration.

[b] There was only one matrix spike for dissolved organic carbon.

[c] MEL does not perform lab duplicates for Chlorophyll *a*.

Table B-4. Lab precision and bias results for OnSite Environmental, Inc.

Parameter	Number Samples	Number Dups	% duplicated	Target Precision	Median %RSD < 5x RL [a]	Median %RSD >= 5x RL	Matrix Spike % recovery Target range	Matrix Spike % recovery Actual range	Matrix Spike % recovery Avg %rec
Nitrate-Nitrite as N	79	5	6.3%	<20% RPD	7.1%	1.6%	75% - 125%	93% - 114%	104.2%
Ammonia	79	4	5.1%	<20% RPD	1.5%	—	75% - 125%	90% - 110%	101.0%
Total Alkalinity	177	7	4.0%	<20% RPD	—	2.2%	—	—	—

RSD: relative standard deviation; RPD: relative percent difference; RL: reporting limit
[a] Results at the detection limit (i.e., if either the primary or the duplicate sample result was a non-detect) are excluded from consideration.

Table B-5. Lab precision and bias results for King County Environmental Laboratory (KCEL).

Parameter	Number Samples	Number Dups	% duplicated	Target Precision	Median %RSD < 5x RL [a]	Median %RSD >= 5x RL	Matrix Spike % recovery Target range	Matrix Spike % recovery Actual range	Matrix Spike % recovery Avg %rec
Total Phosphorus	22	1	4.5%	<20% RPD	16.2%	—	75% – 125%	96% [b]	96.0%
Total Persulfate Nitrogen	81	4	4.9%	<20% RPD	—	0.4%	75% – 125%	101% – 108%	106.0%

RSD: relative standard deviation; RPD: relative percent difference; RL: reporting limit
[a] Results at the detection limit (i.e., if either the primary or the duplicate sample result was a non-detect) are excluded from consideration.
[b] There was only one matrix spike for total phosphorus.

Table B-6. Lab precision and bias results for ALS Laboratory.

Parameter	Number Samples	Number Dups	% duplicated	Target Precision	Median %RSD < 5x RL [a]	Median %RSD >= 5x RL	Matrix Spike % recovery Target range	Matrix Spike % recovery Actual range	Matrix Spike % recovery Avg %rec
Ortho-Phosphate	26	1	3.8%	<20% RPD	— [b]	—	75% – 125%	104% [c]	104.0%

RSD: relative standard deviation; RPD: relative percent difference; RL: reporting limit
[a] Results at the detection limit (i.e., if either the primary or the duplicate sample result was a non-detect) are excluded from consideration.
[b] The only duplicate was a non-detect.
[c] There was only one matrix spike for orthophosphate.

Table B-7. Total precision (field + lab) results, calculated from field replicates.

Parameter	Number Samples [a]	Number Replicates	% replicated	Target Precision	Median %RSD < 5x RL [b]	Median %RSD >= 5x RL
Total Suspended Solids	218	24	11.0%	<15% RSD	0.0%	0.0%
Total Non-Volatile Susp. Solids	214	24	11.2%	<15% RSD	28.3%	2.9%
Total Dissolved Solids	135	16	11.9%	<15% RSD	7.9%	4.5%
Total Phosphorus	218	24	11.0%	<10% RSD	5.5%	1.8%
Ortho-Phosphate	157	18	11.5%	<10% RSD	6.0%	1.0%
Total Persulfate Nitrogen	139	14	10.1%	<10% RSD	—	1.2%
Nitrate-Nitrite as N	136	15	11.0%	<10% RSD	—	1.2%
Ammonia	136	15	11.0%	<10% RSD	— [c]	—
Total Organic Carbon	214	24	11.2%	<10% RSD	4.7%	2.8%
Dissolved Organic Carbon	214	24	11.2%	<10% RSD	5.0%	4.0%
Chlorophyll a	165	17	10.3%	<20% RSD	—	5.9%
Total Alkalinity	205	23	11.2%	<10% RSD	6.7%	1.5%

RSD: relative standard deviation
RPD: relative percent difference
RL: reporting limit
[a] Number of samples only includes primary samples. This does not include field replicates or blanks. That is why the numbers quoted here are sometimes less than the corresponding number of samples in Tables B-3 through B-6, which include all samples submitted to the laboratory, regardless of type.
[b] Results at the detection limit (i.e., if either the primary or the replicate sample result was a non-detect) are excluded from consideration.
[c] All field replicates for ammonia were non-detects.

Blanks

MEL and the contract labs routinely ran lab method blanks along with each analytical batch. Tables B-8 through B-11 present the lab blank results. In addition, Ecology submitted field blanks for analysis regularly throughout the project. Table B-12 presents the field blank results.

Field blank results during early 2022 were impacted by a failure in Ecology's Eastern Regional Office (ERO) Annex Deionized Water (DI) system. The primary ion exchanger column was used up (color change had reached the far end of the column). We replaced the defective cartridges on June 27, 2022. Field blanks submitted before that date had significant detections, likely resulting from failure to adequately filter the blank water before sampling. Field blanks submitted after this date were generally non-detects.

Blank detections caused some potential concern about sample data quality for two parameters. There were multiple lab method blank detections for total dissolved solids (TDS), and multiple field blank detections (even after the DI system was fixed) for chlorophyll *a*. We qualified all TDS sample results less than 2x the highest blank detection as "JL" (possible high biased estimate). There were no chlorophyll *a* results less than 2x the highest blank detection, so no qualifications were applied. (Chlorophyll *a* sample results throughout the project were generally many times the reporting limit.)

Table B-8. Lab method blank results for Ecology's Manchester Environmental Laboratory.

Parameter	Number Samples	Number lab blanks	Number results >RL	Highest blank result >RL
Total Suspended Solids	242	88	0	—
Total Non-Volatile Susp. Solids	238	58	0	—
Total Dissolved Solids	152	40	4	27 mg/L
Total Phosphorus	220	24	0	—
Ortho-Phosphate	149	25	0	—
Total Persulfate Nitrogen	72	13	0	—
Nitrate-Nitrite as N	72	13	0	—
Ammonia	72	13	0	—
Total Organic Carbon	238	32	0	—
Dissolved Organic Carbon	238	30	0	—
Chlorophyll *a*	184	0	—	—
Total Alkalinity	51	8	0	—

RL: reporting limit

Table B-9. Lab method blank results for OnSite Environmental, Inc.

Parameter	Number Samples	Number lab blanks	Number results >RL	Highest blank result >RL
Nitrate-Nitrite as N	79	9	0	—
Ammonia	79	9	0	—
Total Alkalinity	177	18	0	—

RL: reporting limit

Table B-10. Lab method blank results for King County Environmental Laboratory (KCEL).

Parameter	Number Samples	Number lab blanks	Number results >RL	Highest blank result >RL
Total Phosphorus	22	8	0 [a]	—
Total Persulfate Nitrogen	81	31	0	—

RL: reporting limit
[a] KCEL's RL for total phosphorus was 0.01 mg/L. However they reported results down to the MDL, which was 0.005 mg/L. All of KCEL's lab method blanks for total phosphorus were less than the 0.005 mg/L MDL.

Table B-11. Lab method blank results for ALS Laboratory.

Parameter	Number Samples	Number lab blanks	Number results >RL	Highest blank result >RL
Ortho-Phosphate	26	3	0	—

RL: reporting limit

Table B-12. Field blank results.

Parameter [a]	Number Samples [b]	11/30/21	2/16/22	6/8/22	6/15/22	8/10/22	10/12/22
Status of ERO DI system		**Uncertain**	**Bad**	**Bad**	**Bad**	**OK**	**OK**
Total Suspended Solids	218	1 U	—	1 U	1 U	1 U	1 U
Total Non-Volatile Susp. Solids	214	—	1 U	1 U	1 U	1 U	1 U
Total Dissolved Solids	135	—	—	**60**	**29**	—	19 U
Total Phosphorus	218	0.005 U	—	**0.0088**	0.005 U	0.005 U	0.005 U
Ortho-Phosphate	157	—	—	**0.0109**	**0.0071**	0.003 U	0.003 U
Total Persulfate Nitrogen	139	—	—	**0.05**	**0.09 JT**	0.05 U	0.05 U
Nitrate-Nitrite as N	136	—	—	0.01 U	0.05 U	0.05 U	0.05 U
Ammonia	136	—	—	0.01 U	0.05 U	0.05 U	0.05 U
Total Organic Carbon	214	—	**1.31**	0.5 U	0.5 U	0.5 U	0.5 U
Dissolved Organic Carbon	214	—	**1.51**	**0.54**	**0.53**	0.5 U	0.5 U
Chlorophyll *a* (µg/L)	165	—	—	**0.02 J**	**0.02**	**0.01**	**0.04**
Total Alkalinity	205	—	**50**	**2**	2 U	2 U	5 U

[a] All results in this table are in mg/L, except for Chlorophyll, which is in µg/L.
[b] Number of samples only includes primary samples. This does not include field replicates or blanks. That is why the numbers quoted here are sometimes less than the corresponding number of samples in Tables B-8 through B-11, which include all samples submitted to the laboratory, regardless of type.

Turbidity data quality

During this project, we collected turbidity data using three different methods:

- Discrete turbidity field measurements using Hach® 2100Q and 2100P portable meters, at 25 sampling locations during the study and at continuous turbidity stations
- Continuous turbidity logging using FTS® DTS-12 sensors, at three locations during study
- Water samples, analyzed for turbidity by Manchester Environmental Laboratory (MEL).

Discrete turbidity field measurement quality

We collected all discrete turbidity field measurements in triplicate throughout the study. Table B-13 presents replicate precision based on these triplicate measurements. Median %RSD were well within the MQO of 15% (McCarthy and Mathieu, 2017). To minimize error, we averaged all three results for each measurement to get the final measurement values. The values in EIM are these averaged results.

We checked meter calibration regularly throughout the project using a 4-point check against StablCal® turbidity standards. All end checks were well within the ±10% MQO.

Table B-13. Replicate precision for Hach® meter discrete turbidity measurements

Result Value Range (NTU)	# of sample sets	# of duplicate pairs	Median %RSD	90th percentile %RSD
0 – 1	39	117	11.7%	38.50%
1 – 10	124	372	7.30%	25.70%
10 – 100	26	78	2.40%	6.20%
100 +	9	27	0.90%	2.70%

RSD: relative standard deviation

Comparison of turbidity methods

Continuous turbidity data collected with the FTS® DTS-12 probes are critical to this analysis. We developed simple mathematical relationships that use turbidity to predict total phosphorus and total suspended sediment with a high degree of accuracy. Previous studies conducted by Ecology have given us insight into the variability between different turbidity meters and their respective relationships to total phosphorus (TP) and total suspended solids (TSS) (Stuart 2022). Our data suggest that the Hach® 2100Q/2100P turbidity meter results have the best correlation to TP, and therefore we adopted the Hach® meter results as the standard for this project. We adjusted the raw data collected by the FTS® probes using site-specific relationships with the Hach® 2100Q/2100P discrete measurements taken in the field (Figure B-4).

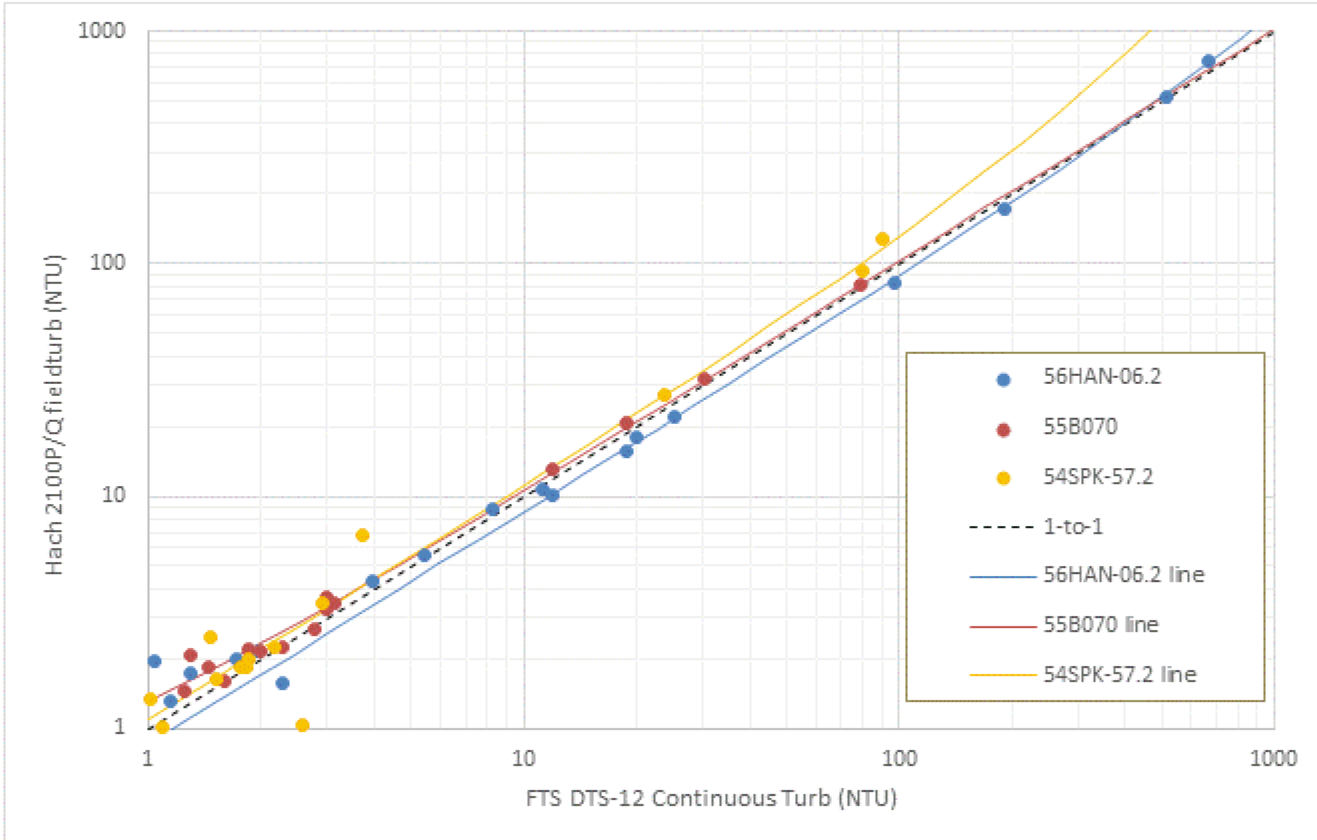

Figure B-4. Site-specific relationships between continuous and discrete field turbidity.

Adjusted continuous turbidity data quality

Table B-14 presents quality metrics for the continuous turbidity data, which was collected with FTS® DTS-12 probes and adjusted using the site-specific relationships with Hach® 2100Q/2100P meter results, as described previously. Median %RSDs were all well within the MQO of 15%. We qualified periods of data within the record as estimates (EIM data qualifier "EST") for any of the following reasons:

- Data spikes, defined as any value greater than 1.5 times the 2-hour rolling average value.
- Probe range exceeded, any time the raw (uncorrected) probe value exceeded 1600 NTU, the top of the DTS-12 probe's rated capability.
- Adjustment extrapolation, defined as any time the final (adjusted) result value was greater than 1.5 times the highest Hach® meter result used to define the adjustment.
- Data replacement, mostly when we removed obvious spikes and replaced with linear interpolation.

Table B-14. Continuous turbidity data quality summary

Location ID	FMU Gage ID	Gage location	# of check measurements	% RSD Median	%RSD 90th percentile
54SPK-57.2	56A250	Spokane River at Spokane House	20	8.9%	38.4%
55B070	56C070	Little Spokane River near Mouth	20	6.3%	29.5%
56HAN-06.2	56A200	Hangman Creek at Meadowlane Road	20	12.1%	31.4%

FMU: Ecology Environmental Assessment Program's Freshwater Monitoring Unit
RSD: relative standard deviation

Flow data quality

We assessed the quality of all flow measurement data. If a flow measurement contained issues likely to result in a measurement error ≥ ±10%, then we qualified the measurement as an estimate (EIM quality code "EST"). We qualified 0 out of 13 flow measurements taken (0%).

Multiprobe sonde data quality

Ecology calibrated Hydrolab® MiniSonde multiprobe meters according to manufacturer's specifications using certified standards. For meters that collected data continuously throughout the study period, we compared their in-situ readings weekly to a recently calibrated check instrument and/or to certified standards to check for biofouling and calibration drift. We cleaned biofouling from the continuous instrument probes and recalibrated to certified standards if excessive drift occurred.

We used spot check measurements, calibration standard post-checks, and Winkler dissolved oxygen (DO) titration results to evaluate continuous instrument data. If indicated by the weight of evidence, we adjusted raw instrument data as follows:

- "Stable drift" bias adjustment to correct for moderate levels of miscalibration.
- "Sliding drift" bias adjustment to correct for slipping calibration or buildup of biofouling.
- Proportional bias adjustment, for instances where bias appeared to be proportional rather than arithmetic.

After applying any adjustments, we assessed the final data record according to the MQOs in Table B-15 (McCarthy and Mathieu 2017). Table B-16 lists all instances where we qualified or rejected data, or where we lost data, for long-term continuous deployments. Table B-17 lists such instances for discrete measurements. Table B-18 lists such instances for lake profiles. Adjusted data are flagged "IA" and qualified data are flagged "EST" in the EIM database.

Table B-15. Accuracy targets for water quality multiprobe sondes.

Parameter	Accept	Qualify	Reject
Temperature	≤ 0.2°C	> 0.2 and ≤ 0.8°C	> 0.8°C
Conductivity	≤ 10%	> 10% and ≤ 20%	> 20%
pH	≤ 0.2 S.U.	> 0.2 and ≤ 0.8 S.U.	> 0.8 S.U.
Dissolved oxygen	≤ 0.5 mg/L	> 0.5 and ≤ 0.1 mg/L	> 0.8 mg/L

Table B-16. Qualified, rejected, and lost data for long-term continuous deployments.

All dates refer to 2022.

Location	Temperature	Conductivity	pH	DO
57A170 (Spokane River at State Line)	**April 18 – 29:** Lost due to vandalism **August 16 – 17:** Rejected due to probe becoming unwatered at low stage **Aug 31 – Sept 7:** No data. Removed probe from deep water location prior to Labor Day flow bump but couldn't return to slant pipe until after flow increase.	**April 18 – 29:** Lost due to vandalism **August 16 – 17:** Rejected due to probe becoming unwatered at low stage **Aug 31 – Sept 7:** No data. Removed probe from deep water location prior to Labor Day flow bump but couldn't return to slant pipe until after flow increase.	**April 2 – 17:** Qualified due to poor agreement with spot checks **April 18 – 29:** Lost due to vandalism **August 16 – 17:** Rejected due to probe becoming unwatered at low stage **Aug 31 – Sept 7:** No data. Removed probe from deep water location prior to Labor Day flow bump but couldn't return to slant pipe until after flow increase.	**April 2 – 5:** Lost due to LDO probe power failure **April 18 – 29:** Lost due to vandalism **August 16 – 17:** Rejected due to probe becoming unwatered at low stage **Aug 31 – Sept 7:** No data. Removed probe from deep water location prior to Labor Day flow bump but couldn't return to slant pipe until after flow increase.
54SPK-57.2 (Spokane River at Spokane House)	**May 14 – 18:** Lost due to power failure **June 19 – 22:** Lost due to power failure **July 4 – 7:** Lost due to power failure **Oct 26 – Nov 3:** Lost due to power failure	**May 14 – 18:** Lost due to power failure **June 15 – 19:** Qualified due to noisy signal **June 19 – July 7:** Rejected bad data caused by deployment configuration issues and biofouling. This period also includes some power losses. **July 13 – 14:** Rejected period of noisy/spiky bad data **Oct 26 – Nov 3:** Lost due to power failure	**March 2 – 3:** Rejected due to probe equilibration problems **March 4 – 19:** Qualified due to poor agreement with spot checks **March 7:** Rejected period of noisy/spiky bad data **April 14 – 15:** Qualified due to calibration shifts and noise **May 12 – 14:** Qualified due to poor agreement with spot checks **May 14 – 18:** Lost due to power failure **May 18 – 25:** Rejected due to poor agreement with spot checks **June 2:** Rejected period of noisy/spiky bad data **June 5 – July 7:** Rejected bad data caused by deployment configuration issues and biofouling. This period also includes some power losses. **Oct 26 – Nov 3:** Lost due to power failure	**May 10 – 14:** Qualified due to noisy signal. This period also includes some power losses. **May 14 – 18:** Lost due to power failure **May 18 – Jun 2:** Qualified due to noisy signal **June 3 – July 7:** Rejected bad data caused by deployment configuration issues and biofouling. This period also includes some power losses. **July 14 – 15:** Lost due to LDO probe power failure **Oct 26 – Nov 3:** Lost due to power failure

Location	Temperature	Conductivity	pH	DO
55B070 (Little Spokane River at mouth)	**April 12 – 14:** Lost due to power failure **April 18 – 20:** Series of losses due to partial power failures **April 26 – 29:** Lost due to power failure	**April 12 – 14:** Lost due to power failure **April 18 – 20:** Series of losses due to partial power failures **April 26 – 29:** Lost due to power failure	**April 12 – 14:** Lost due to power failure **April 18 – 20:** Series of losses due to partial power failures **April 26 – 29:** Lost due to power failure	**April 10:** Lost due to power failure **April 10 – 11:** Qualified due to noisy signal. **April 12 – 14:** Lost due to power failure **April 17 – 20:** Lost due to power failure **April 25 – 29:** Lost due to power failure **Oct 19 – Nov 3:** Qualified due to poor agreement with spot checks
56HAN-01.5 (Hangman Creek at 11th Ave.)	**All data lost. Station hardware destroyed by vandalism during second month of deployment. Continuous deployment at this location discontinued.**	No data due to vandalism.	No data due to vandalism.	No data due to vandalism.

Table B-17. Qualified, rejected, and lost data for discrete stream/river measurements.

Date/Event [a]	Temperature	Conductivity	pH	DO
12/15/2021 River sampling run	(N/A)	(N/A)	(N/A)	Qualified all measurements due to only having one Winkler value to compare
3/14/2022 Continuous hydrolab maintenance run	(N/A)	(N/A)	(N/A)	Qualified all (2) measurements due to only having one Winkler value to compare
3/16/2022 River sampling run	(N/A)	(N/A)	(N/A)	Qualified 2 of 7 measurements due to poor agreement with Winklers
5/18/2022 River sampling run	(N/A)	(N/A)	(N/A)	Qualified 2 of 8 measurements due to poor agreement with Winklers
6/15/2022 River sampling run	(N/A)	(N/A)	(N/A)	Qualified 2 of 8 measurements due to poor agreement with Winklers
7/20/2022 River sampling run	(N/A)	(N/A)	Qualified 2 of 11 measurements due to probe equilibration problems	Qualified 2 of 11 measurements due to poor agreement with Winklers
9/21/2022 River sampling run	(N/A)	(N/A)	(N/A)	Qualified 2 of 11 measurements due to poor agreement with Winklers

[a] This list does not include all field dates, only those for which some of the sonde data was rejected or qualified.

Table B-18. Qualified, rejected, and lost data for Lake Spokane profiles.

Date/Event [a]	Temperature	Conductivity	pH	DO
4/27 – 28/2022 Lake sampling run	(N/A)	(N/A)	Qualified all measurements due to probe post-check result outside the MQO value	(N/A)
5/10 – 11/2022 Lake sampling run	Qualified 1m reading at LL2 due to questionable value	(N/A)	Qualified 5m reading at LL3 due to questionable value. Qualified all readings at LL4 due to noisy data.	(N/A)
6/7 – 8/2022 Lake sampling run	(N/A)	Qualified all measurements due to probe post-check result outside the MQO value	Qualified all measurements due to probe equilibration problems	(N/A)
7/26/2022 Profiles-only run	(N/A)	Rejected 3m reading at LL1 due to clearly bad value	(N/A)	(N/A)
8/23/2022 Profiles-only run	(N/A)	(N/A)	(N/A)	Rejected 1m reading at LL4 due to clearly bad value

[a] This list does not include all field dates, only those for which some of the sonde data was rejected or qualified.

Continuous temperature data quality

We compared spot measurements of temperature taken with either a Hydrolab® or with an Oakton® long-line electronic thermistor to the continuous Hobo® TidbiT® v2 data, and we post checked temperature loggers in calibration baths. We verified field check results and removed outliers using Rosner's generalized extreme studentized deviate test. The validated data was used to calculate bias statistics. Table B-19 presents field check results and bias.

Table B-19. Continuous water temperature logger calibration and field check results.

Location ID	Check Instrument type	Calibration bath results	Number of field checks	Field check result (Mean absolute error °C)	Field check result (Bias °C)
54SPK-57.2	HL	Outside criteria	62	0.29	-0.29[a]
55B070	HL	OK	55	0.03	0.02
56A070	LLT	OK	9	0.23	0.20
57A150	HL	OK	51	0.04	0.02

[a] Instrument result adjusted; reported result meets study objectives

Secchi data quality

One location was selected for replicate secchi disk measurements during each field collection event. A total of nine replicate measurements were taken during the study. Median %RSDs were well within the MQO of 10% (Table B-20).

Table B-20. Replicate precision for secchi disk water clarity measurements

# of check measurements	% RSD Median	%RSD 90^{th} percentile
9	4.6%	13.5%

RSD: relative standard deviation

References — Appendix B

McCarthy, S. and N. Mathieu, 2017. Programmatic Quality Assurance Project Plan: Water Quality Impairment Studies. Department of Ecology, Olympia, WA. Publication 17-03-107. https://apps.ecology.wa.gov/publications/SummaryPages/1703107.html

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Stuart, T., A. Albrecht, and J. Stevens, 2021. Quality Assurance Project Plan: Spokane River and Lake Spokane Dissolved Oxygen Total Maximum Daily Load 10-Year Effectiveness Monitoring Study. Washington State Department of Ecology, Olympia, WA. Publication 21-03-112. https://apps.ecology.wa.gov/publications/SummaryPages/2103112.html

Appendix C. Data quality — data sources outside this study

This appendix describes the quality of the data obtained from sources *other than* this 2021 – 2022 Ecology field study. We found all of these data to be of appropriate quality for use in our analysis, except as otherwise noted below.

Ecology directed studies

We used data from several past Ecology studies, as applicable to our analysis. Each of these studies resulted in either a data summary report, or another project report (Cusimano 2003; Ross 2013; Stuart 2012; Johnson et al. 2020; Ross 2011; Stuart 2020; Stuart 2022; Sinclair and Gallagher 2019). These individual reports each provide a detailed quality assessment of data collected during that particular study. We found all applicable data collected during those studies to be appropriate for use in our analysis.

Ecology ambient monitoring data

Ecology collects ambient water quality monitoring data monthly at a large variety of locations statewide, on an ongoing basis. Ambient sample data formed a key part of our analysis. A Quality Assurance Monitoring Plan (QAMP; Von Prause 2021) describes the ambient monitoring program, its data quality requirements, and quality assurance/quality control (QA/QC) procedures. Ambient staff calculate statewide data quality statistics on a yearly basis to assess data quality in an ongoing, adaptive process. Historically, ambient data quality were summarized in published water quality monitoring reports.[23]

As part of our analysis, we also calculated total precision statistics for field replicates collected at the Spokane River watershed sites, during our study period, for parameters of interest (Table C-1). Replicate precision was generally good for nitrogen and phosphorus parameters. For total suspended solids (TSS), there were multiple replicate pairs with poor precision in excess of the MQO. The reasons for this are unknown. Ambient TSS data were not important to our analysis or findings.

Ambient monitoring total phosphorus (TP) data were also affected by the same contract lab vs. MEL bias issue as project TP data, described above in Appendix A. This issue affected more of the ambient monitoring TP data than project data, as the contract lab analyzed multiple months worth of ambient samples. We determined that we could not use these data. For the sake of comparability to past data, we only used MEL TP results for our analysis.

23 https://apps.ecology.wa.gov/publications/UIPages/PublicationList.aspx?IndexTypeName=Topic&NameValue=Rivers+and+Streams+%E2%80%93+Annual+Water+Quality+Reports&DocumentTypeName=Publication

Table C-1. Ambient monitoring total precision (field + lab) results, calculated from field replicates.

Parameter	Number Samples [a]	Number Replicates	% replicated	Target Precision	Median %RSD < 5x RL [b]	Median %RSD >= 5x RL
Total Suspended Solids	78	5	6.4%	<10% RSD [c]	23.6%	60.2%
Total Phosphorus	78	15	19.2%	<10% RSD	6.8%	2.9%
Ortho-Phosphate	72	12	16.7%	<10% RSD	1.6%	2.1%
Total Persulfate Nitrogen	72	15	20.8%	<10% RSD	—	0.7%
Nitrate – Nitrite as N	78	9	11.5%	<10% RSD	—	0.2%
Ammonia	78	9	11.5%	<10% RSD	3.0%	—

RSD: relative standard deviation
RL: reporting limit
[a] Number of samples only includes primary samples. This does not include field replicates or blanks.
[b] Results at the detection limit (i.e., if either the primary or the replicate sample result was a non-detect) are excluded from consideration.
[c] Note that the ambient monitoring MQO for total suspended solids is <10% RSD (Von Prause 2021), as opposed to <15% RSD for water quality impairment studies (McCarthy and Mathieu, 2017).

Avista/Tetra Tech Lake Spokane Data

Tetra Tech, under contract from Avista Corporation, collected samples and measurements in Lake Spokane during 2012 – 2018 (Avista et al. 2014). Avista contracted this data collection as a part of their Water Quality Attainment Plan pursuant to their Federal Energy Regulatory Commission (FERC) relicensing water quality certification under section 401 of the Clean Water Act (Avista and Four Peaks 2022a). These data were collected under an Ecology-approved QAPP (Avista et al. 2014).

Table C-2 presents total precision statistics calculated from sample field replicates. Replicate precision was generally good. The one exception to this was Pheophytin a, which typically had replicate pairs with somewhat higher variation. We did not use Pheophytin a as part of our analysis.

Tetra Tech collected Winkler samples as a QC check on dissolved oxygen measured with a multiprobe sonde. Figure C-1 presents a scatter plot of Winkler vs. optical DO results. Winkler and optical DO results generally agreed well, with a calculated optical DO bias of -0.25 mg/L. The results do show some variability. However, it is difficult to collect accurate Winkler samples in a lake environment, especially from greater depths. It is likely that the outliers represent bad Winkler QC check results, rather than bad optical DO results.

Table C-2. Avista/Tetra Tech 2012 – 2018 total precision (field + lab) results, calculated from field replicates.

Parameter	Number Samples [a]	Number Replicates	% replicated	Target Precision [b]	Median %RSD < 5x RL [c]	Median %RSD >= 5x RL
Total Phosphorus	1306	70	5.4%	<14.1% RSD	9.4%	5.0%
Ortho-Phosphate	1306	70	5.4%	<14.1% RSD	0.0%	1.2%
Total Kjeldahl Nitrogen as N	210	20	9.5%	<14.1% RSD	—	1.5%
Total Persulfate Nitrogen	1096	50	4.6%	<14.1% RSD	—	3.9%
Nitrate + Nitrite as N	1306	70	5.4%	<14.1% RSD	—	1.2%
Chlorophyll *a*	957	55	5.7%	<14.1% RSD	—	8.3%
Pheophytin *a*	957	55	5.7%	(N/A)	24.9%	24.9%

RSD: relative standard deviation
RL: reporting limit
[a] Number of samples only includes primary samples. This does not include field replicates or blanks.
[b] Avista et al. (2014) specified the target precision for all parameters as <20% RPD. This equivalent to <14.1% RSD. We calculated replicate precision in terms of %RSD for comparability to other data sources.
[c] Results at the detection limit (i.e., if either the primary or the replicate sample result was a non-detect) are excluded from consideration.

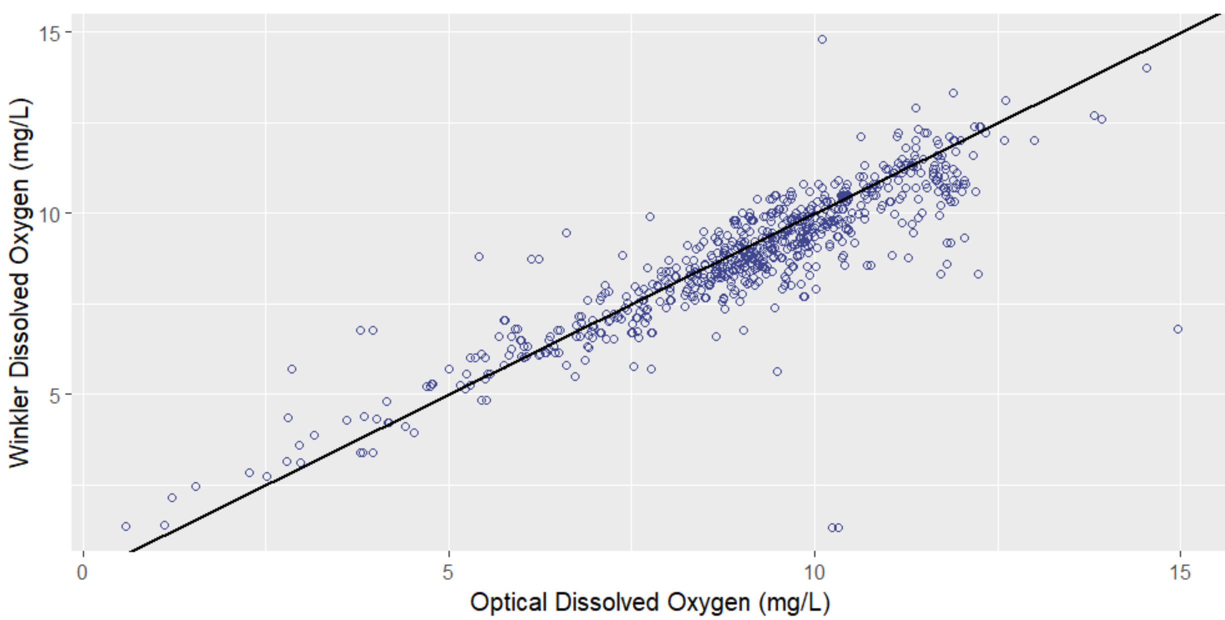

Figure C-1. Avista/Tetra Tech Winkler and optical dissolved oxygen results.

Spokane County groundwater data

Spokane County collects routine groundwater samples from a variety of monitoring wells, production wells, and springs representing the Spokane Valley-Rathdrum Prairie Aquifer (SVRPA). A QAPP (Spokane County 2007) describes the monitoring program and its QA/QC procedures. The County regularly collects replicates and blanks as part of their sampling procedure. Table C-3 presents total precision statistics calculated from sample field replicates for nutrient parameters. This table also presents frequencies of blank detections. These calculations only apply to the 8 locations used in this analysis, for 2018 – 2022.

Replicate precision was generally good for all parameters. However, for nitrate-nitrite, there were a significant number of blank detections. The maximum value detected in a blank sample was 0.958 mg/L. Therefore, it is possible that nitrate-nitrite sample results could be biased high due to sample contamination. We used County nitrate-nitrite results with caution. Nitrate-nitrite was a parameter of secondary importance in this analysis and is not regulated by the *Spokane DO TMDL*.

Table C-3. Spokane County total precision (field + lab) results, calculated from field replicates, and blank detections, 2018 – 2022, selected locations [a].

Parameter	Number Samples [b]	Number Replicates	% replicated	Target Precision [c]	Median %RSD < 5x RL [d]	Median %RSD >= 5x RL	Blank Detections
Total Phosphorus	77	6	7.8%	<15.6%	5.4%	—	0 / 20
Soluble Reactive P	77	6	7.8%	<12.0%	0.0%	—	1 / 20; max 0.003
Nitrate + Nitrite as N	77	6	7.8%	<14.1%	—	1.9%	9 / 20; max 0.958

RSD: relative standard deviation

RL: reporting limit

[a] These locations are 5411R03 (Sullivan Park South MW); 5411R05s (Sullivan Spring); 5404A01 (Plantes Ferry Park MW); 5312C01 (Felts Field City MW); 5311J05 (Hale's Ale Nested Site east); 5311J07 (Hale's Ale Nested Site mid); 5307M01 (Trinity School, Adams & Carlisle City MW); 5212F01s (Three Springs).

[b] Number of samples only includes primary samples. This does not include field replicates or blanks.

[c] Spokane County (2007) specified target precisions in terms of %RPD as <22% for TP, <17% for SRP, and <20% for NO2-3. We present these here as the equivalent %RSD values for comparability to other data sources.

[d] Results at the detection limit (i.e., if either the primary or the replicate sample result was a non-detect) are excluded from consideration.

City of Spokane stormwater data

The City of Spokane has collected stormwater volume and quality data in the Cochran Basin over several years. A QAPP (City of Spokane 2016) details this monitoring effort and the data quality procedures used. The City of Spokane Riverside Park Water Reclamation Facility (RPWRF) laboratory analyzed all the nutrient samples. The RPWRF laboratory is fully accredited for these sample parameters.

Discharge Monitoring Report (DMR) data

Municipal and industrial facilities that discharge effluent to water bodies are required to routinely monitor their effluent streams for a variety of parameters. The National Pollutant Discharge Elimination System (NPDES) permit for each facility establishes that facility's monitoring requirements. Permitted facilities report their monitoring results to Ecology in Discharge Monitoring Reports (DMRs).

Permittees follow standardized sampling and testing procedures, which are listed in each NPDES permit. All samples must be analyzed by an Ecology-accredited lab (Jenkins 2023, pers. comm.). Regional staff in Ecology's Water Quality Program routinely screen and review DMR data. There are also some automated validation tools that screen for obviously wrong values (Klimek, pers. comm.).

USGS Streamflow data

The U.S. Geological Survey (USGS) collects continuous streamflow data at gaging stations across the nation. USGS follows published standard protocols (Rantz 1982; Turnipseed and Sauer 2010) and is the nationwide authority on streamflow gaging.

USGS Groundwater study data

The USGS Lake Spokane groundwater studies both included rigorous sample QC including replicates and blanks. Both study reports (Gendaszek et al. 2016; Sheibley and Foreman 2021) present analyses of their sample data quality. The quality of data collected in these studies is appropriate for use in our analysis.

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Appendix D. Estimation of TP and TSS loads from continuous turbidity data

By leveraging the adjusted 15-minute interval continuous turbidity data, publicly available streamflow data, and bi-weekly grab samples, we estimated seasonal TP and TSS loads by using a simple numerical integration technique. The core of this estimation method relies on a tight-fitting regression between turbidity and TP and turbidity and TSS grab sample data (Figure D-1, Table D-1). We used a common power function to fit the regressions for this analysis: $Y = aX^b + c$; Where a is a scaling factor, b is an exponent determining the rate of growth, and c is a y-intercept.

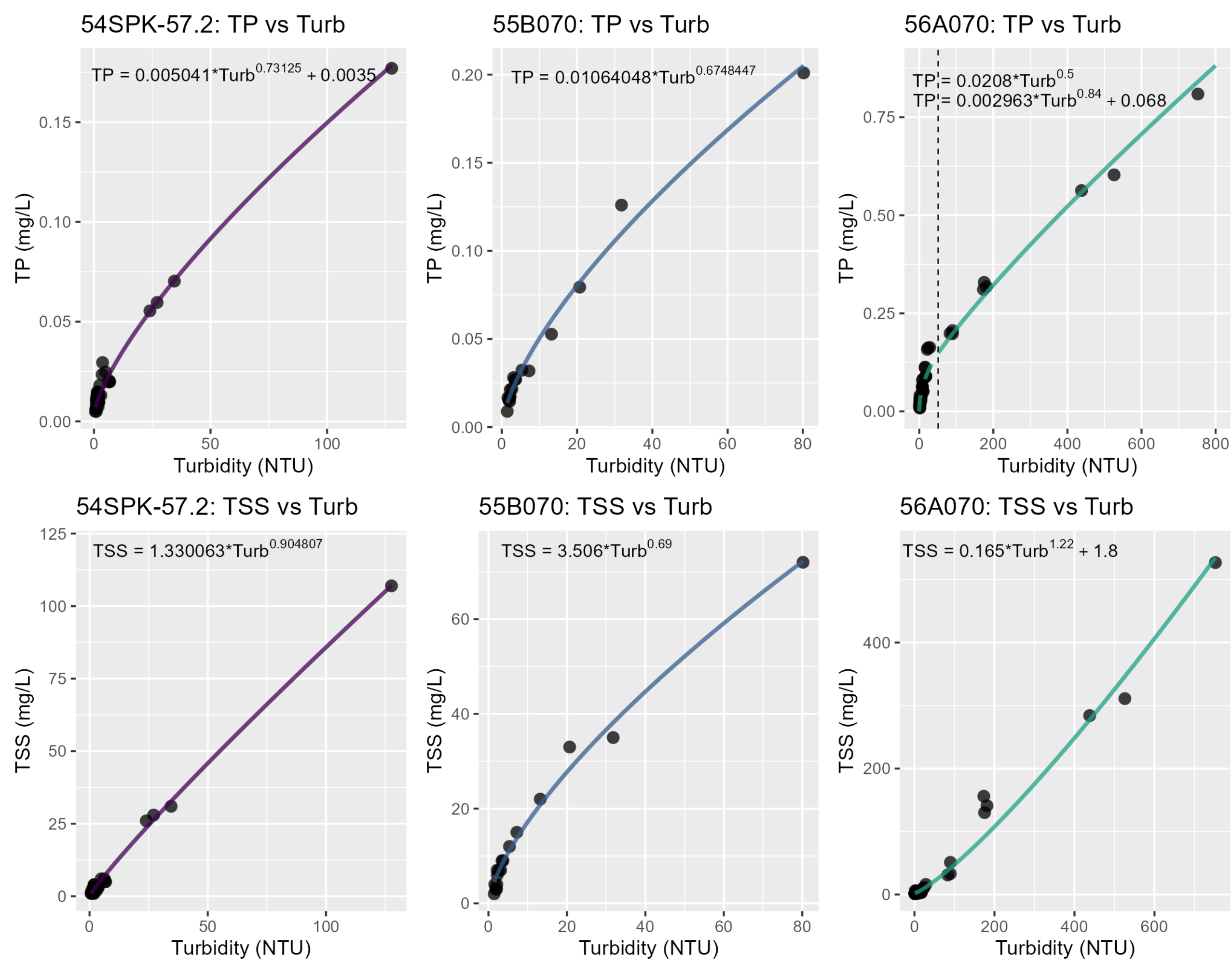

Figure D-1. Relationship between turbidity and total phosphorus (top) and turbidity and total suspended solids (bottom) at the three continuous turbidity monitoring stations. Equations are shown on the top of each panel.

Table D-1. Goodness-of-fit statistics for turbidity vs. TP and turbidity vs. TSS

Location	TP n	TP RMSE	TP R^2	TSS n	TSS RMSE	TSS R^2
54SPK-57.2	34	1.13	0.996	34	0.0036	0.986
55B070	17	1.90	0.988	17	0.0056	0.986
56A070	44	14.65	0.978	44	0.0211	0.984

RMSE: root mean squared error

$$\text{RMSE} = \sqrt{\sum_{i=0}^{n} \frac{(predicted - observed)^2}{n}} \qquad R^2 = 1 - \frac{Residual\ Sum\ of\ Squares}{Total\ Sum\ of\ Squares}$$

FTS® DTS-12 turbidity sensors were deployed at the beginning of the study period in October 2021 at three locations within the Spokane River watershed, i) 54SPK-57.2, ii) 55B070, and iii) 56HAN-06.2. The continuous turbidity sensors and USGS streamflow gages were active and logging data for the duration of WY22 at each site (Figure D-2).

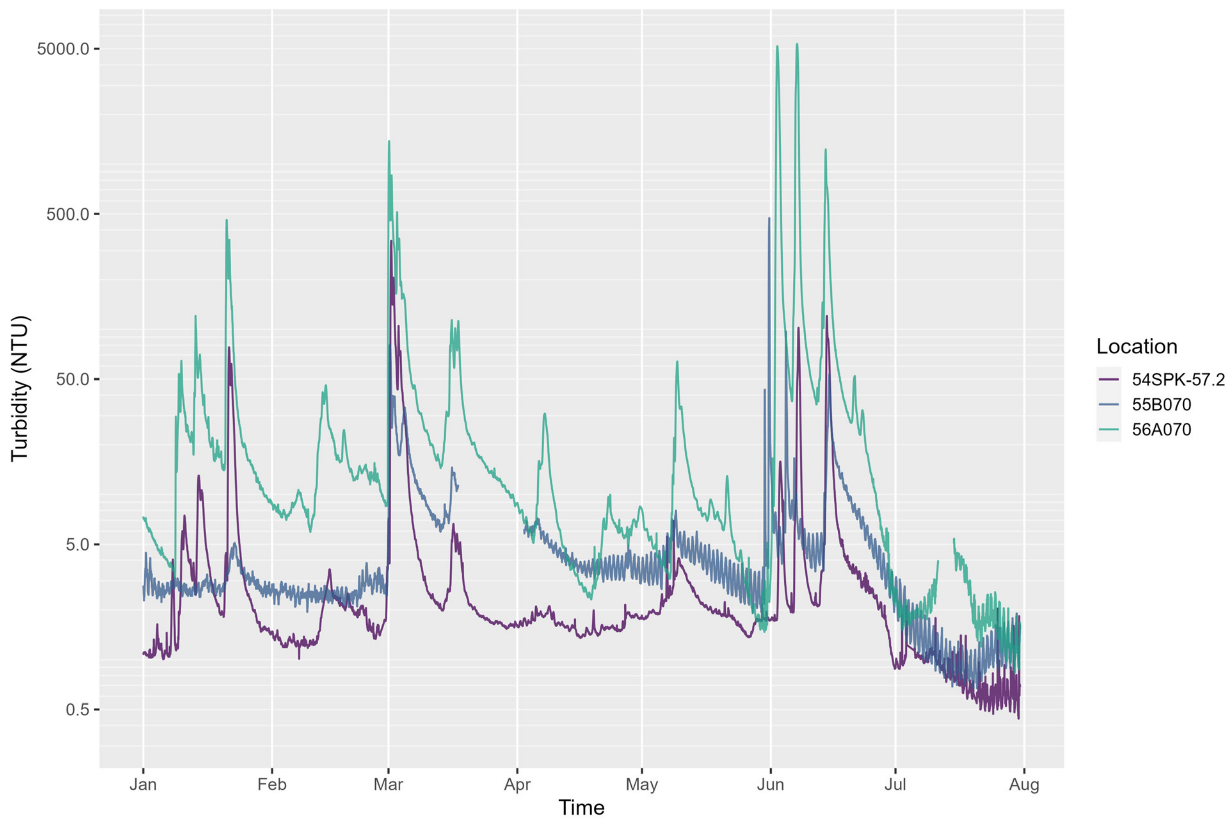

Figure D-2. Continuous turbidity records Jan – Jul 2022.

At the three locations with continuous turbidity data, we used the continuous turbidity record along with the regression parameters to predict TP and TSS concentration at every 15-minute interval. We then multiplied the estimated TP and TSS concentrations by the respective continuous flow records and applied appropriate unit conversions to estimate nutrient and suspended solid load at each time interval. From this, we calculated seasonal average loads.

Appendix E. Estimation of daily TP at Hangman Creek and the Little Spokane River, 2008 – 2022

Our best continuous TP estimates for 2022 are those calculated using continuous turbidity data, as described above in Appendix D. However, it is also helpful to have near-continuous estimates over a medium-long term record. Because TP concentrations in Hangman Creek and the Little Spokane River are driven by short-term runoff events during the late winter and springtime, simply using a monthly ambient monitoring result to represent conditions for that entire month is inadequate.

We estimated daily TP concentrations in Hangman Creek and the Little Spokane River from 2008 – 2022 using multiple-linear regression modeling (MLR; Cohn et al. 1989). We selected the 2008 – 2022 period because that is the period of the most reliable TP data, following a method change at MEL in fall 2007. This period also includes the time when all the more recent Lake Spokane monitoring data was collected, starting in 2010, which enables high-quality comparisons between inflow TP and DO in the lake.

The MLR models followed the form:

$$\log[(K-d)/c] = \beta_0 + \beta_1 \log(Q/A) + \beta_2 \log(Q/A)^2 + \beta_3 \sin(2\pi f_y) + \beta_4 \cos(2\pi f_y) + \alpha_1 {f_y}^3 + \alpha_2 {f_y}^2 + \alpha_3 f_y + \alpha_4$$

Where:

K = constituent concentration (mg/L)
Q = flow (cms)
A = contributing watershed area (km^2)
f_y = year fraction (e.g., July 1, 2018 = 2018.50)
β_0 = intercept parameter
$\beta_{1,2}$ = parameters relating to flow dependence
$\beta_{3,4}$ = parameters relating to seasonal variation
$\alpha_{1,2,3,4}$ = parameters relating to long-term trend
c = slope adjuster applied after back-transform
d = intercept applied after back-transform

Table E-1 presents the parameterization for the MLR models, and Table E-2 presents goodness of fit statistics for each model. Figures E-1 and E-2 present time-series plots of predicted and observed TP concentrations for Hangman Creek and the Little Spokane River.

Table E-1. Parameterization for multiple linear regression models for Hangman Creek and the Little Spokane River.

Water Body	β_0 intcpt.	β_1 log (Q/A)	β_2 log $(Q/A)^2$	β_3 sin $(2\pi f_y)$	β_4 cos $(2\pi f_y)$	α_1 trend	α_2 trend	α_3 trend	α_4 trend	*c* slope post	*d* intcpt. post
Hangman Creek	0.5975	0.8129	0.0579	-0.0249	0.0016	8.085E-5	-0.4902	990.9	-667616	1.155	-0.0075
Little Spokane River	-8.5657	-8.4881	-2.4718	0.0162	0.00120	0	0	0	0	1	0

Table E-2. Goodness-of-fit for multiple linear regression models for Hangman Creek and the Little Spokane River.

Water Body	RMSE CV [a]	%ME [b]	M%E [c]	Slope [d]	R^2 [e]
Hangman Ck.	56.4%	-3.4%	+8.1%	0.9997	0.8576
Little Spokane R.	107.8%	-11.6%	+5.0%	1.1379	0.5326
Little Spokane R. (excluding 4 outliers) [f]	38.7%	-0.1%	+6.5%	0.9927	0.8944

[a] RMSE CV is the Root Mean Squared Error coefficient of variation (CV), or the RMSE divided by the average observed value:

$$RMSE\ CV = \frac{\sqrt{[\sum(K_{modeled} - K_{observed})^2]/n}}{\overline{K_{observed}}}$$

[b] %Mean Error (also known as %Bias) is the ME divided by the average observed value:

$$\%ME = \frac{[\sum(K_{modeled} - K_{observed})]/n}{\overline{K_{observed}}}$$

[c] The Mean %Error takes the average of relative error at each data point:

$$M\%E = \frac{\sum(K_{modeled} - K_{observed})/K_{observed}}{n}$$

[d] The slope of the best fit line through the back-transformed predicted vs. observed scatter plot, with a specified zero intercept. The ideal value is 1.

[e] The R^2 value of the best fit line through the back-transformed predicted vs. observed scatter plot, with a specified zero intercept.

[f] The goodness-of-fit for the Little Spokane River MLR model was heavily impacted by four extreme outliers. These may represent occasional high-sediment events in one or more of the Little Spokane River tributaries, such as Deadman Creek. Excluding these four outliers still retains 198 of 202, or 98% of the total records.

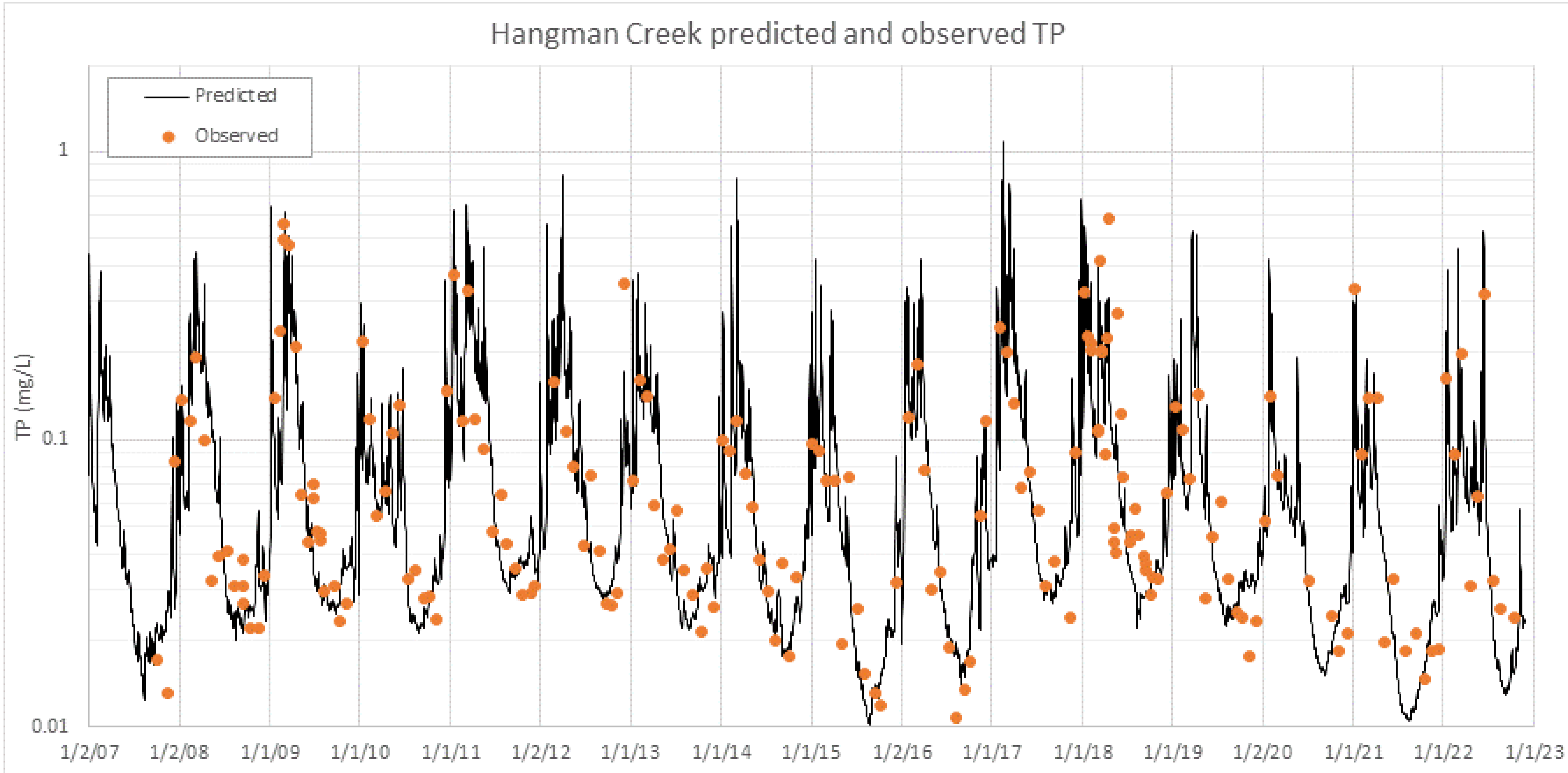

Figure E-1. Predicted and observed total phosphorus in Hangman Creek, using the multiple linear regression (MLR) model.

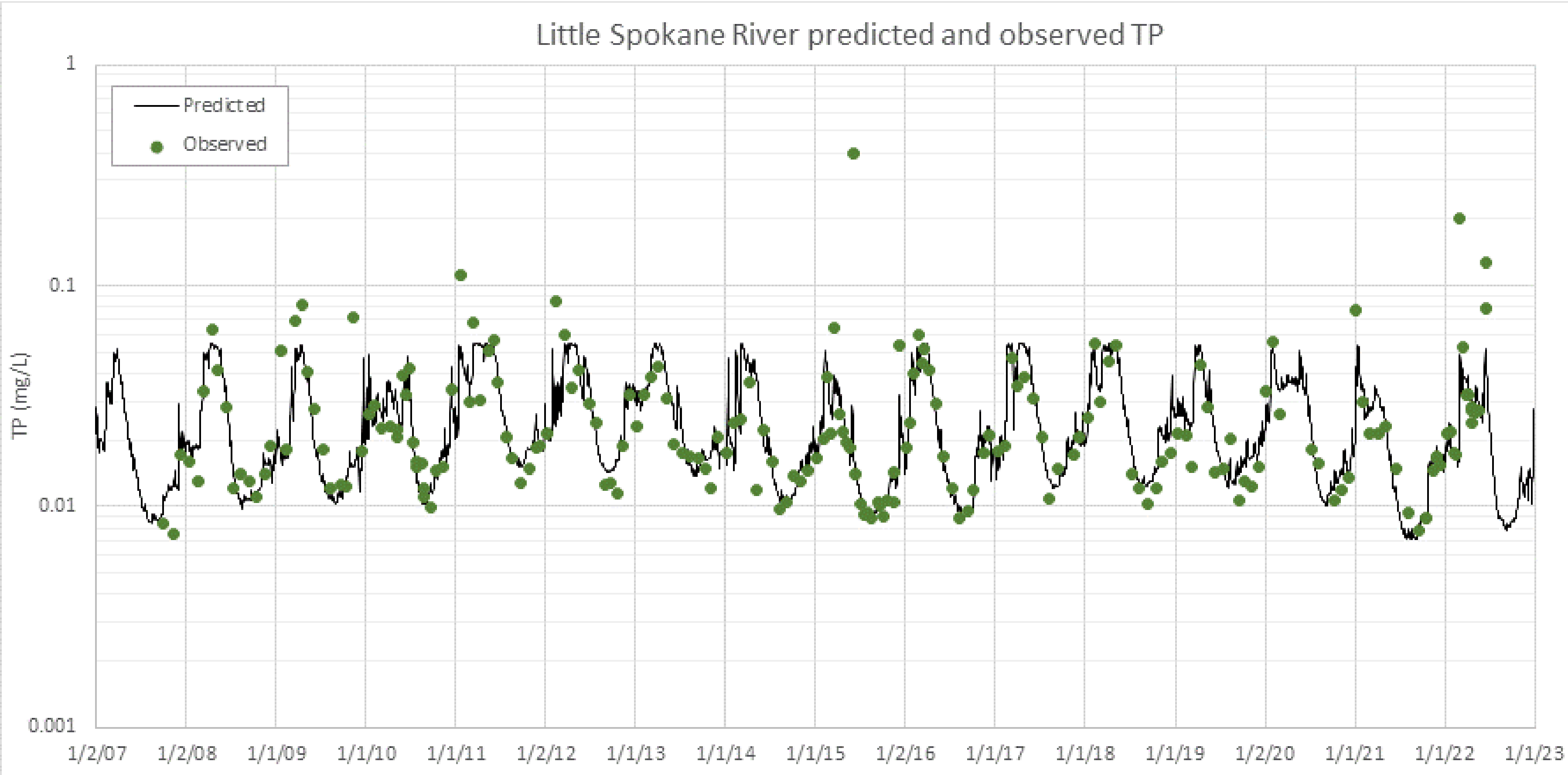

Figure E-2. Predicted and observed total phosphorus in the Little Spokane River, using the multiple linear regression (MLR) model.

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Appendix F. Estimation of daily TP at the Riverine Assessment Point, 2008 – 2022

The Riverine Assessment Point (RAP) represents the inflow to Lake Spokane. It is calculated as the flow-weighted average of the Spokane River at Nine Mile and the Little Spokane River. TP concentrations at the RAP cannot be accurately predicted using a simple MLR approach. This is because conditions at the RAP are driven by event-driven fluctuations in Hangman Creek and the Little Spokane River, bulk concentrations in the Spokane River, and point source contributions.

To estimate daily TP at the RAP, we used an approach that accounts for all these factors. There is some complexity to this exercise. One cannot simply use the ambient results from Nine Mile and simultaneously account for event-driven fluctuations in Hangman Creek, since concentrations in Nine Mile already include loads from Hangman Creek. However, it is also not practical to simply add Hangman values to Spokane River above Hangman (Sandifur Bridge) values, since this would miss both a key point source (City of Spokane) as well as groundwater effects downstream of Hangman Creek. Therefore, we followed these steps:

Steps performed on monthly dataset

1. First, we assembled all records of TP data for the Spokane River at Nine Mile (54A090, 54SPK-57.2), starting in October 2007 after the method change at MEL. Sample frequency for most of this period was monthly. During periods when data were not collected at Nine Mile (Oct 2010 – Jan 2013, Aug 2013, Oct 2016 – Jan 2017, Dec 2020 – Jan 2021), we used data from Spokane River at Riverside State Park (54A120). TP values at Riverside State Park and at Nine Mile are generally similar (Figure F-1).
2. For each day where Nine Mile (or Riverside State Park) data was available, we used the Hangman MLR model (see Appendix E) to estimate Hangman Creek TP.
3. Using flow and measured or estimated TP concentration, we calculated Hangman and Nine Mile TP loads for each of these days.
4. We then subtracted the Hangman load from the Nine Mile load, and the Hangman flow from the Nine Mile flow, to obtain a theoretical Nine Mile load and flow that would be expected if Hangman Creek did not exist.
5. From this, we then calculated the theoretical Nine Mile concentration that would be expected if Hangman Creek did not exist. We set a “floor” of 5 µg/L, near the lowest concentrations ever observed in the Spokane River. We also set a “ceiling” of 2x the yearly 90^{th} percentile of raw “Nine Mile without Hangman” values. The floor and ceiling served to avoid gross under- or over-estimates resulting from imprecision in the Hangman MLR model. We set the floor and ceiling cautiously, so as to affect only a minimum number of extreme cases. The floor and ceiling together only affected 4 of 184 data points.

Steps performed for every day 2008 – 2022

6. For each day, we found the daily "Nine Mile if Hangman didn't exist" by using linear interpolation between the monthly points found in step 5.
7. We used the Hangman MLR model to estimate Hangman TP concentration for each day.
8. Using Hangman and "Nine Mile without Hangman" flows, we calculated daily loads for Hangman and "Nine Mile without Hangman."
9. We then "added back" Hangman by adding the Hangman and "Nine Mile without Hangman" daily loads. This provides an estimate of Nine Mile TP loads that fully accounts for event-driven fluctuations in Hangman Creek.
10. Using the original Nine Mile flows, we then back-calculated the daily estimated Nine Mile TP concentration.
11. We used the Little Spokane MLR model to estimate Little Spokane TP concentration for each day.
12. Finally, we calculated the flow-weighted average of the estimated daily Nine Mile and Little Spokane TP concentrations to obtain the daily estimate for the RAP.

The daily estimates are presented in Figure 11 in the main body of this report.

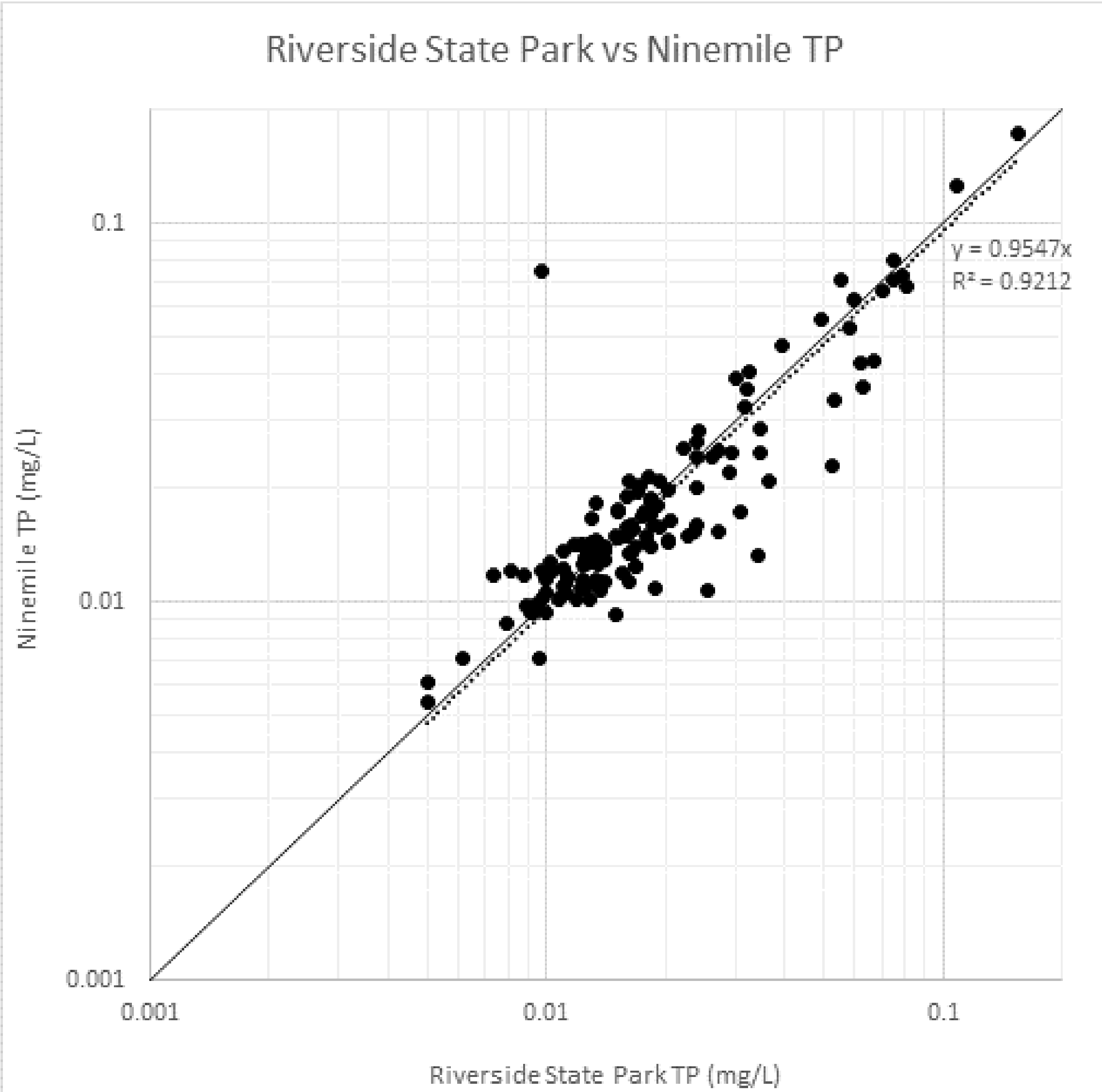

Figure F-1. Comparison of TP values in the Spokane River at Riverside State Park (54A120) and Nine Mile (54A090; 54SPK-57.2).

Appendix G. Estimation of stormwater loads

The City of Spokane has a complex stormwater system. Many portions of the city, including much of Downtown, the South Hill, West Central, and other areas use a Combined Sewer Overflow (CSO) system. Stormwater in these areas drains through the same "combined" sewer system as municipal sewage and is treated at the city's Riverside Park Water Reclamation Facility. In contrast, much of the city north of the river and in other areas uses a Municipal Separated Storm Sewer System (MS4). Stormwater in these areas drains through a separate sewer system from municipal sewage and discharges to the Spokane River, or in a few cases, Hangman Creek. Still other areas, particularly in outlying parts of the city, use infiltration and/or evaporation basins (CH2M Hill, 2014).

The *Spokane DO TMDL* set separate wasteload allocations (WLAs) for stormwater and for CSOs[24]. The stormwater WLAs apply to stormwater that discharges to the Spokane River from MS4 outfalls or other routes. To estimate stormwater flows, we assumed that stormwater in infiltration/evaporation areas generally does not reach the river. For purposes of this estimate we also ignored the City of Spokane Valley, because many of Spokane Valley's MS4 systems infiltrate stormwater; only a small fraction of Spokane Valley's MS4 area discharges directly to the Spokane River. Therefore, we only estimated stormwater discharge from the City of Spokane MS4 areas (Figure G-1).

We estimated stormwater loads using the following sources of data and information:

- City of Spokane Integrated Clean Water Plan, which includes summary data on six major stormwater basins, as well as some stormwater quality data for 2012 – 2014 (CH2M Hill 2014)
- Cochran Basin stormwater monitoring report, which includes discharge volume data for 2016 – 2019 and stormwater quality data for 2012 – 2019 (City of Spokane 2020; City of Spokane 2016)
- Cochran Basin discharge volume data for 2020 – 2022, obtained from city staff (Donovan, 2023 pers. comm.)

The Spokane Integrated Clean Water Plan notes that:

> ...the City has approximately 130 stormwater basins, including 100 draining to the Spokane River and 30 draining to Latah Creek, the majority of which are less than 10 acres in size. Six of the City's stormwater basins (the Cochran, Kiernan, Hollywood, Rifle Club, Washington, and Union basins) make up approximately 75 percent of the total area served by a separated stormwater system (CH2M Hill 2014).

[24] Note that the WLAs for CSOs only apply to overflows directly to the river. These WLAs do not apply to stormwater which reaches the Riverside WRF as intended.

Note that during 2023, the City of Spokane is in the construction phase of a major project to reduce stormwater flows in the Cochran Basin. This project will divert the majority of Cochran Basin stormwater flow into natural bioretention facilities for infiltration to ground (City of Spokane 2018). This infrastructure was not in place during 2022 and does not affect the analyses here. However, future stormwater flow volumes from the Cochran Basin will likely be much lower.

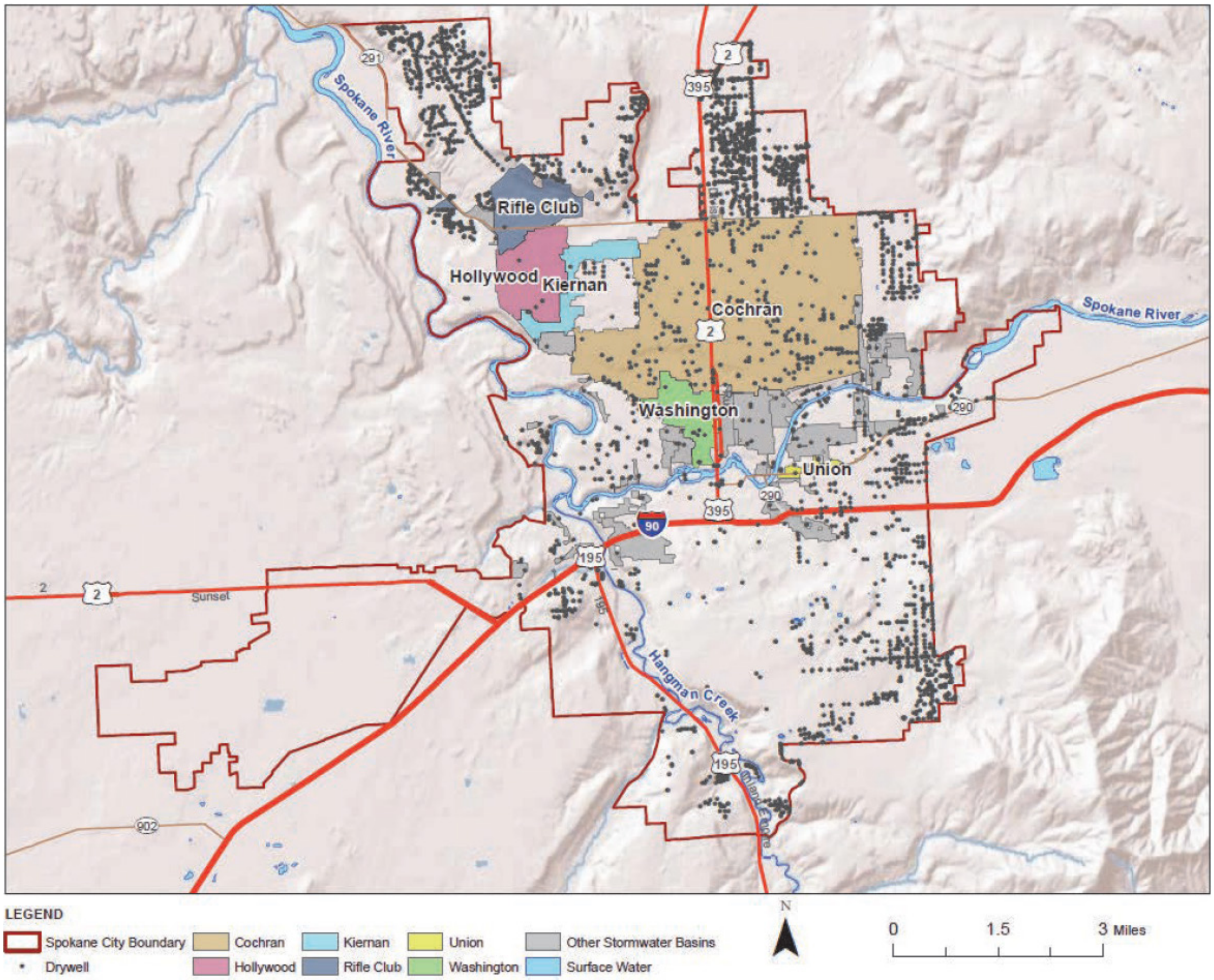

Figure G-1. Overview of City of Spokane's MS4 system (reproduced from CH2M Hill 2014)

To estimate stormwater flow volumes, we started with Cochran Basin monthly discharge volume data from 2016 – 2022. We then used basin-specific data from the Spokane Integrated Clean Water Plan to estimate the flow volumes for the other major basins and for the remaining 25% of the MS4 area not included in one of the six major basins, based on a ratio to measured Cochran Basin flow. Table G-1 summarizes Cochran Basin flow volumes. Table G-2 summarizes basin-specific values used to estimate flow volumes for areas other than the Cochran Basin.

To estimate loads, we then used basin-specific flow volume estimates along with stormwater quality data collected by the City of Spokane. Tables G-3 through G-5 summarize stormwater loads for 2022. Tables G-6 through G-8 summarize average stormwater loads for 2016 – 2022.

Table G-1. Cochran Basin stormwater flow volumes (millions of gallons per month), summarized by TMDL season.

TMDL Season	Average 2016 – 2022	Water Year 2022 (Nov 2021 – Oct 2022)
Nov – Feb [a]	19.2	14.7
Mar – May	18.7	18.0
June	13.2	60.1 [b]
Jul – Oct	7.66	3.08

[a] The November – February season is not included in the *Spokane DO TMDL*. These data are shared here for general reference.
[b] This value reflects the fact that June 2022 was an abnormally wet month, with unusually high precipitation amounts.

Table G-2. Stormwater basin-specific data.

Basin Characteristic	Cochran	Hollywood	Rifle Club	Washington	Kiernan	Union	Other basins
Basin area (acres) [a]	5328	711	647	453	397	82	~2539 [c]
Basin impervious area (acres) [a]	1665	183	147	203	120	39	not given
Basin impervious % [a]	26%	26%	23%	45%	30%	31%	~38% [d]
Approx. avg. annual runoff volume (MG/year) [a]	251	35	29	34	22	7	not given
Approx. impervious yield (gal/year/impervious acre) [b]	151,000	191,000	197,000	167,000	183,000	179,000	not given
Impervious yield ratio to Cochran [b]	1	1.27	1.31	1.11	1.22	1.19	~1.15 [d]

[a] Values taken from City of Spokane Integrated Clean Water Plan (CH2M Hill 2014); Table 2-6.
[b] Calculated by Ecology from City of Spokane values
[c] Value estimated given that the six major subbasins constitute about 75% of the total MS4 area, the other basins compose about 25%.
[d] Ecology does not have data for the other basins. Given where these other basins are located (generally near downtown; see Figure G-1), we assumed that the average characteristics of this area fall somewhere between those of the Washington and Union basins.

Table G-3. Estimated stormwater loads for March – May 2022.

Basin	Spokane River Reach [a]	Est flow (mgd) [c]	Est TP (mg/L) [d]	Est TSS (mg/L) [d]	Est NH4 (mg/L) [e]	Est CBOD5 (mg/L) [e]	Est TP (lbs/day)	Est TSS (tons/day)	Est NH4 (lbs/day)	Est CBOD5 (lbs/day)
Other Basins	Greene-Sandifur [b]	0.39	0.980	442	0.625	12	3.2	0.72	2.0	39
Union	Greene-Sandifur	0.016	0.980	442	0.625	12	0.13	0.030	0.085	1.6
Washington	Greene-Sandifur	0.080	1.561	535	0.625	12	1.0	0.18	0.42	8.0
Cochran	Sandifur-Nine Mile	0.59	0.980	442	0.625	12	4.8	1.1	3.1	59
Kiernan	Sandifur-Nine Mile	0.052	0.980	442	0.625	12	0.42	0.095	0.27	5.2
Hollywood	Sandifur-Nine Mile	0.082	0.980	442	0.625	12	0.67	0.15	0.43	8.2
Rifle Club	Sandifur-Nine Mile	0.068	0.980	442	0.625	12	0.56	0.13	0.35	6.8
Total	Greene-Sandifur	0.49	—	—	—	—	4.4	0.9	2.5	49
Total	Sandifur-Nine Mile	0.79	—	—	—	—	6.5	1.5	4.1	79
Total	**All**	**1.28**	**—**	**—**	**—**	**—**	**10.8**	**2.4**	**6.7**	**128**

[a] These reaches pertain to the mass balance analysis presented in Tables 9 – 11 in the main body of this report.
[b] This reach assignment is not exact. Some of these other basins discharge above Greene Street, below Sandifur bridge, or even to Hangman Creek. However, most are in the near-downtown area, so this is an adequate approximation.
[c] Flow values for Cochran Basin come from City of Spokane continuous measurement data. We estimated flow values for other basins using the Cochran data alongside the basin impervious areas and the impervious yield ratios shown in Table G-2.
[d] Concentration values for all basins except Washington come from the seasonal mean value observed for Cochran Basin, 2012 – 2020 (City of Spokane 2020). Values for the Washington basin are modified from the Cochran value by using the ratio of Washington/Cochran median values given in CH2M Hill (2014), Table 2-7.
[e] Concentration values for all basins come from the seasonal mean value observed for Cochran Basin, 2012 – 2020 (City of Spokane 2020). CH2M Hill (2014) did not provide data for ammonium or CBOD.

Table G-4. Estimated stormwater loads for June 2022.

Basin	Spokane River Reach [a]	Est flow (mgd) [c]	Est TP (mg/L) [d]	Est TSS (mg/L) [d]	Est NH4 (mg/L) [e]	Est CBOD5 (mg/L) [e]	Est TP (lbs/day)	Est TSS (tons/day)	Est NH4 (lbs/day)	Est CBOD5 (lbs/day)
Other Basins	Greene-Sandifur [b]	1.3	0.521	145	0.371	12	5.8	0.81	4.1	134
Union	Greene-Sandifur	0.056	0.521	145	0.371	12	0.24	0.034	0.17	5.6
Washington	Greene-Sandifur	0.27	0.831	175	0.371	12	1.9	0.20	0.84	27
Cochran	Sandifur-Nine Mile	2.0	0.521	145	0.371	12	8.7	1.2	6.2	201
Kiernan	Sandifur-Nine Mile	0.18	0.521	145	0.371	12	0.76	0.11	0.54	18
Hollywood	Sandifur-Nine Mile	0.28	0.521	145	0.371	12	1.2	0.17	0.86	28
Rifle Club	Sandifur-Nine Mile	0.23	0.521	145	0.371	12	1.0	0.14	0.72	23
Total	Greene-Sandifur	1.7	—	—	—	—	7.9	1.0	5.1	167
Total	Sandifur-Nine Mile	2.7	—	—	—	—	11.7	1.6	8.3	270
Total	**All**	**4.4**	**—**	**—**	**—**	**—**	**19.7**	**2.7**	**13.5**	**436**

See Table G-3 for explanation of all footnotes.

Table G-5. Estimated stormwater loads for July – October 2022.

Basin	Spokane River Reach [a]	Est flow (mgd) [c]	Est TP (mg/L) [d]	Est TSS (mg/L) [d]	Est NH4 (mg/L) [e]	Est CBOD5 (mg/L) [e]	Est TP (lbs/day)	Est TSS (tons/day)	Est NH4 (lbs/day)	Est CBOD5 (lbs/day)
Other Basins	Greene-Sandifur [b]	0.067	0.379	147	0.119	7.25	0.21	0.041	0.067	4.0
Union	Greene-Sandifur	0.0028	0.379	147	0.119	7.25	0.0088	0.0017	0.0028	0.17
Washington	Greene-Sandifur	0.014	0.604	179	0.119	7.25	0.068	0.010	0.014	0.82
Cochran	Sandifur-Nine Mile	0.10	0.379	147	0.119	7.25	0.32	0.062	0.10	6.1
Kiernan	Sandifur-Nine Mile	0.0088	0.379	147	0.119	7.25	0.028	0.0054	0.009	0.53
Hollywood	Sandifur-Nine Mile	0.014	0.379	147	0.119	7.25	0.044	0.0086	0.014	0.85
Rifle Club	Sandifur-Nine Mile	0.012	0.379	147	0.119	7.25	0.037	0.0071	0.012	0.70
Total	Greene-Sandifur	0.083	—	—	—	—	0.29	0.053	0.08	5.0
Total	Sandifur-Nine Mile	0.13	—	—	—	—	0.43	0.083	0.13	8.1
Total	**All**	**0.22**	**—**	**—**	**—**	**—**	**0.71**	**0.136**	**0.22**	**13.2**

See Table G-3 for explanation of all footnotes.

Table G-6. Estimated stormwater loads for March – May, average 2016 – 2022.

Basin	Spokane River Reach [a]	Est flow (mgd) [c]	Est TP (mg/L) [d]	Est TSS (mg/L) [d]	Est NH4 (mg/L) [e]	Est CBOD5 (mg/L) [e]	Est TP (lbs/day)	Est TSS (tons/day)	Est NH4 (lbs/day)	Est CBOD5 (lbs/day)
Other Basins	Greene-Sandifur [b]	0.41	0.980	442	0.625	12	3.3	0.75	2.1	41
Union	Greene-Sandifur	0.017	0.980	442	0.625	12	0.14	0.031	0.088	1.7
Washington	Greene-Sandifur	0.082	1.561	535	0.625	12	1.1	0.18	0.43	8.3
Cochran	Sandifur-Nine Mile	0.61	0.980	442	0.625	12	5.0	1.1	3.2	61
Kiernan	Sandifur-Nine Mile	0.053	0.980	442	0.625	12	0.44	0.098	0.28	5.3
Hollywood	Sandifur-Nine Mile	0.085	0.980	442	0.625	12	0.69	0.16	0.44	8.5
Rifle Club	Sandifur-Nine Mile	0.070	0.980	442	0.625	12	0.57	0.13	0.37	7.0
Total	Greene-Sandifur	0.51	—	—	—	—	4.5	1.0	2.6	51
Total	Sandifur-Nine Mile	0.82	—	—	—	—	6.7	1.5	4.3	82
Total	**All**	**1.32**	**—**	**—**	**—**	**—**	**11.2**	**2.5**	**6.9**	**132**

See Table G-3 for explanation of all footnotes.

Table G-7. Estimated stormwater loads for June, average 2016 – 2022.

Basin	Spokane River Reach [a]	Est flow (mgd) [c]	Est TP (mg/L) [d]	Est TSS (mg/L) [d]	Est NH4 (mg/L) [e]	Est CBOD5 (mg/L) [e]	Est TP (lbs/day)	Est TSS (tons/day)	Est NH4 (lbs/day)	Est CBOD5 (lbs/day)
Other Basins	Greene-Sandifur [b]	0.29	0.521	145	0.371	12	1.3	0.18	0.91	29
Union	Greene-Sandifur	0.012	0.521	145	0.371	12	0.053	0.0074	0.038	1.2
Washington	Greene-Sandifur	0.059	0.831	175	0.371	12	0.4	0.043	0.18	6.0
Cochran	Sandifur-Nine Mile	0.44	0.521	145	0.371	12	1.9	0.26	1.4	44
Kiernan	Sandifur-Nine Mile	0.038	0.521	145	0.371	12	0.17	0.023	0.12	3.9
Hollywood	Sandifur-Nine Mile	0.061	0.521	145	0.371	12	0.27	0.037	0.19	6.1
Rifle Club	Sandifur-Nine Mile	0.051	0.521	145	0.371	12	0.22	0.031	0.16	5.1
Total	Greene-Sandifur	0.36	—	—	—	—	1.7	0.23	1.1	37
Total	Sandifur-Nine Mile	0.59	—	—	—	—	2.6	0.36	1.8	59
Total	**All**	**0.95**	**—**	**—**	**—**	**—**	**4.3**	**0.58**	**2.9**	**96**

See Table G-3 for explanation of all footnotes.

Table G-8. Estimated stormwater loads for July – October, average 2016 – 2022.

Basin	Spokane River Reach [a]	Est flow (mgd) [c]	Est TP (mg/L) [d]	Est TSS (mg/L) [d]	Est NH4 (mg/L) [e]	Est CBOD5 (mg/L) [e]	Est TP (lbs/day)	Est TSS (tons/day)	Est NH4 (lbs/day)	Est CBOD5 (lbs/day)
Other Basins	Greene-Sandifur [b]	0.17	0.379	147	0.119	7.3	0.53	0.10	0.17	10
Union	Greene-Sandifur	0.007	0.379	147	0.119	7.3	0.022	0.0043	0.0069	0.42
Washington	Greene-Sandifur	0.034	0.604	179	0.119	7.3	0.17	0.025	0.034	2.0
Cochran	Sandifur-Nine Mile	0.25	0.379	147	0.119	7.3	0.79	0.15	0.25	15
Kiernan	Sandifur-Nine Mile	0.022	0.379	147	0.119	7.3	0.069	0.013	0.022	1.3
Hollywood	Sandifur-Nine Mile	0.035	0.379	147	0.119	7.3	0.11	0.021	0.035	2.1
Rifle Club	Sandifur-Nine Mile	0.029	0.379	147	0.119	7.3	0.091	0.018	0.029	1.7
Total	Greene-Sandifur	0.21	—	—	—	—	0.72	0.13	0.21	13
Total	Sandifur-Nine Mile	0.33	—	—	—	—	1.06	0.21	0.33	20
Total	**All**	**0.54**	**—**	**—**	**—**	**—**	**1.77**	**0.34**	**0.54**	**33**

See Table G-3 for explanation of all footnotes.

References — Appendix G

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Appendix H. Computation of Lake Spokane volume-weighted average hypolimnetic DO for 2010 – 2022

Patmont et al. (1987), Welch et al. (2015), Avista and Tetra Tech (2020), and possibly others have used the concept of volume-weighted average hypolimnetic dissolved oxygen in Lake Spokane. Taking the volume-weighted average of hypolimnetic DO provides a useful and relevant way to boil down the complexity of DO patterns in a large, deep reservoir to a single value that can be easily compared to other variables. In particular, these authors have successfully compared volume-weighted average hypolimnetic DO with seasonal average inflow TP concentrations.

We calculated the volume-weighted average hypolimnetic DO for all Lake Spokane profile data available. This includes data from 2000 – 2022. Ecology does not have the datasets from the 1970 – 1980s. For these older datasets we relied on calculations performed by Patmont et al. (1987). Welch et al. (2015) and Avista and Tetra Tech (2020) have also performed this calculation on the 2010 – 2018 datasets. Ecology does not currently possess the exact bathymetry and computational methodology used by previous authors. Our motivations for recalculating volume-weighted DO for as many datasets as possible were two:

- We wanted to make a true apples-to-apples comparison between Lake Spokane DO conditions in 2022 and, at least, other recent years.
- We wanted to evaluate volume-weighted DO over various portions of the depth profile, including:
    - Full lake (surface to bottom)
    - Depths >8m. This is the depth range that the *Spokane DO TMDL* used to define Avista's DO responsibility.
    - Depths >15m. This is the depth range defined as the hypolimnion by Patmont et al. (1987) and other authors mentioned.
    - Depths > 20m. This is the depth range corresponding to hypolimnion composite lab samples collected by Ecology during 2010 – 2011 and 2022.

We calculated volume-weighted average hypolimnetic DO using the bathymetry from the 2001 CE-QUAL-W2 model (Annear et al. 2001; Slominski et al. 2002). This bathymetry divided the lake into 36 horizontal segments generally 1.07km long and 46 depth layers each 1m thick. Although our method may differ slightly from that used by others, it produced very similar results. Our version of the "Patmont Curve" graph, shown above as Figure 14 in the main body of this report, looks very similar to that shown in Avista and Tetra Tech (2020).

Our computation for each sampling event followed these steps:

1. First, for the six segments corresponding to the six sampling stations (LL0 – LL5), we calculated the DO for each layer by linear interpolation from the DO profile data. For this, we used the depth at the middle of each layer.

2. For layers representing depths below the lake bottom, we defined the DO as that at the deepest point measured. Although this may seem nonsensical at first, it is important for the lateral interpolation step that comes next.
3. For the segments in between the sampling locations, we estimated the DO by interpolating laterally from one sampling location to the next, for each layer. For segments upstream of LL5, we used the values from LL5.
4. For each cell (segment x layer), we calculated "Volume DO" as DO (mg/L) * cell volume (m^3).
5. To calculate whole-lake volume-weighted average DO (mg/L), we summed all of the cell Volume DO (m^3 * mg/L) values, and divided that by the entire lake volume, i.e., the sum of all the cell volumes (m^3).
6. We then repeated step 5 for each depth range of interest (depths >15m, etc.) by summing the Volume DO values for that depth range, and then dividing by the sum of the cell volumes for that range.

Table H-1 (next 11 pages) presents the calculated volume-weighted average DO values for each sampling event from 2000 – 2022. For partial sampling runs where not all six locations were profiled, we present volume-weighted average DO for each sampling location that was profiled, but not for the whole lake.

Table H-1 (includes 11 tables on pages 138 – 159).
Volume-weighted (V-W) average dissolved oxygen (DO) for sampling events, 2000 – 2022.

Sampling event #	1	2	3	4	5	6	7	8	9	10
Month	6	6	7	8	8	9	5	6	6	7
Year	2000	2000	2000	2000	2000	2000	2010	2010	2010	2010
LL0 date	no profile	no profile	no profile	8/16/2000	no profile	9/27/2000	5/17/2010	6/1/2010	6/29/2010	7/20/2010
LL0 max dep sampled	no profile	no profile	no profile	36	no profile	36	43.7	39	45	48
LL0 all-dep V-W DO (mg/L)	no profile	no profile	no profile	7.07	no profile	7.15	11.78	10.22	9.12	8.26
LL0 hypo >8m V-W DO (mg/L)	no profile	no profile	no profile	5.40	no profile	6.63	11.22	9.86	8.72	7.55
LL0 hypo >15m V-W DO (mg/L)	no profile	no profile	no profile	4.28	no profile	6.06	11.00	9.64	8.52	7.09
LL0 hypo >20m V-W DO (mg/L)	no profile	no profile	no profile	3.76	no profile	6.01	10.91	9.50	8.35	6.78
LL1 date	6/6/2000	6/27/2000	7/18/2000	8/16/2000	8/29/2000	9/27/2000	5/17/2010	6/1/2010	6/29/2010	7/20/2010
LL1 max dep sampled	30	27	27	30	30	30	33.8	33	32	33
LL1 all-dep V-W DO (mg/L)	10.38	8.78	8.04	6.71	6.73	8.50	11.46	10.24	9.15	8.55
LL1 hypo >8m V-W DO (mg/L)	9.94	8.31	7.32	5.13	5.52	8.43	10.90	9.81	8.73	7.85
LL1 hypo >15m V-W DO (mg/L)	9.77	8.23	6.80	4.13	5.69	8.33	10.90	9.58	8.59	7.40
LL1 hypo >20m V-W DO (mg/L)	9.67	8.12	6.52	3.14	6.05	8.54	10.93	9.48	8.42	7.00
LL2 date	no profile	no profile	no profile	8/16/2000	no profile	9/27/2000	5/18/2010	6/1/2010	6/29/2010	7/20/2010
LL2 max dep sampled	no profile	no profile	no profile	24	no profile	24	24	24	25	26
LL2 all-dep V-W DO (mg/L)	no profile	no profile	no profile	7.66	no profile	8.85	11.12	10.63	9.23	8.97
LL2 hypo >8m V-W DO (mg/L)	no profile	no profile	no profile	6.15	no profile	8.94	10.65	10.10	8.54	7.72
LL2 hypo >15m V-W DO (mg/L)	no profile	no profile	no profile	5.25	no profile	9.22	10.72	9.93	8.45	6.97
LL2 hypo >20m V-W DO (mg/L)	no profile	no profile	no profile	4.30	no profile	9.40	10.77	9.83	8.34	6.01

LL3 date	6/6/2000	6/27/2000	7/18/2000	8/16/2000	8/29/2000	9/26/2000	5/17/2010	6/1/2010	6/30/2010	7/21/2010
LL3 max dep sampled	15	15	15	15	15	15	21.6	21	21	21
LL3 all-dep V-W DO (mg/L)	10.24	9.67	8.75	8.70	8.54	9.47	10.56	10.65	8.80	9.23
LL3 hypo >8m V-W DO (mg/L)	9.85	8.75	8.37	8.36	7.84	9.48	10.19	10.32	8.45	7.83
LL3 hypo >15m V-W DO (mg/L)	9.70	8.60	8.10	8.50	8.00	9.90	9.86	10.12	8.21	6.82
LL3 hypo >20m V-W DO (mg/L)	9.70	8.60	8.10	8.50	8.00	9.90	9.36	10.02	7.76	4.71
LL4 date	no profile	no profile	no profile	8/16/2000	no profile	9/26/2000	5/18/2010	6/2/2010	6/30/2010	7/21/2010
LL4 max dep sampled	no profile	no profile	no profile	6	no profile	6	9	9	9	9
LL4 all-dep V-W DO (mg/L)	no profile	no profile	no profile	9.95	no profile	11.27	10.24	10.61	8.51	9.37
LL4 hypo >8m V-W DO (mg/L)	no profile	no profile	no profile	9.90	no profile	10.50	10.20	10.53	8.37	9.27
LL4 hypo >15m V-W DO (mg/L)	no profile	no profile	no profile	N/A	no profile	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	no profile	no profile	no profile	N/A	no profile	N/A	N/A	N/A	N/A	N/A
LL5 date	no profile	no profile	no profile	8/16/2000	no profile	9/26/2000	5/18/2010	6/2/2010	6/30/2010	7/21/2010
LL5 max dep sampled	no profile	no profile	no profile	5.5	no profile	6	7	7	6	5
LL5 all-dep V-W DO (mg/L)	no profile	no profile	no profile	10.30	no profile	9.96	10.38	10.64	9.01	8.32
LL5 hypo >8m V-W DO (mg/L)	no profile	no profile	no profile	N/A	no profile	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	no profile	no profile	no profile	N/A	no profile	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	no profile	no profile	no profile	N/A	no profile	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	—	—	—	7.62	—	8.59	11.27	10.42	9.08	8.73
Ovl hypo >8m V-W DO (mg/L)	—	—	—	5.82	—	8.13	10.88	9.95	8.66	7.76
Ovl hypo >15m V-W DO (mg/L)	—	—	—	4.54	—	7.73	10.86	9.68	8.52	7.18
Ovl hypo >20m V-W DO (mg/L)	—	—	—	3.58	—	7.61	10.87	9.53	8.36	6.73

Sampling event #	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Month	8	8	9	9	10	5	6	6	7	7
Year	2010	2010	2010	2010	2010	2011	2011	2011	2011	2011
LL0 date	8/9/2010	8/30/2010	9/13/2010	9/27/2010	10/12/2010	5/23/2011	6/6/2011	6/20/2011	7/11/2011	7/25/2011
LL0 max dep sampled	46.5	45	45	45	51	54	51	44	54	44
LL0 all-dep V-W DO (mg/L)	7.39	5.17	6.82	7.73	7.46	11.97	11.55	11.52	10.06	8.95
LL0 hypo >8m V-W DO (mg/L)	5.85	3.75	5.70	6.85	6.87	11.84	11.39	11.49	9.72	8.60
LL0 hypo >15m V-W DO (mg/L)	5.18	3.14	5.47	6.84	6.75	11.76	11.31	11.50	9.58	8.47
LL0 hypo >20m V-W DO (mg/L)	4.76	2.63	5.53	6.70	6.55	11.71	11.25	11.50	9.50	8.33
LL1 date	8/9/2010	8/30/2010	9/13/2010	9/27/2010	10/12/2010	5/23/2011	no profile	6/20/2011	7/11/2011	7/25/2011
LL1 max dep sampled	30	33	32	33	30	33	no profile	32	33	32
LL1 all-dep V-W DO (mg/L)	7.51	7.34	7.85	8.60	8.50	11.78	no profile	11.68	9.95	8.95
LL1 hypo >8m V-W DO (mg/L)	6.21	6.56	7.18	8.23	8.22	11.69	no profile	11.53	9.53	8.62
LL1 hypo >15m V-W DO (mg/L)	5.59	6.65	7.42	8.26	8.13	11.63	no profile	11.52	9.47	8.48
LL1 hypo >20m V-W DO (mg/L)	4.95	6.99	8.01	8.50	8.16	11.60	no profile	11.51	9.50	8.31
LL2 date	8/10/2010	8/30/2010	9/13/2010	9/27/2010	10/12/2010	5/23/2011	no profile	6/20/2011	7/11/2011	7/25/2011
LL2 max dep sampled	25	25	25	24	24	24	no profile	26	24	24
LL2 all-dep V-W DO (mg/L)	8.34	8.06	8.22	8.93	8.80	11.91	no profile	11.41	10.16	9.58
LL2 hypo >8m V-W DO (mg/L)	7.03	7.53	7.67	8.83	8.68	11.83	no profile	11.35	9.51	9.28
LL2 hypo >15m V-W DO (mg/L)	6.30	7.94	8.51	9.07	8.57	11.75	no profile	11.31	9.31	9.28
LL2 hypo >20m V-W DO (mg/L)	5.39	8.11	8.83	9.04	8.55	11.71	no profile	11.31	9.04	9.25

LL3 date	8/10/2010	8/31/2010	9/14/2010	9/28/2010	10/13/2010	5/24/2011	no profile	6/21/2011	7/12/2011	7/26/2011
LL3 max dep sampled	21	21	21	18	21	21	no profile	18	21	20
LL3 all-dep V-W DO (mg/L)	8.99	8.70	9.26	9.76	9.22	11.82	no profile	11.53	10.17	9.77
LL3 hypo >8m V-W DO (mg/L)	7.60	8.65	9.26	9.74	9.26	11.74	no profile	11.54	9.85	9.61
LL3 hypo >15m V-W DO (mg/L)	6.48	9.03	9.44	9.66	9.26	11.67	no profile	11.54	9.68	9.59
LL3 hypo >20m V-W DO (mg/L)	6.00	8.97	9.34	9.65	9.20	11.62	no profile	11.54	9.61	9.44
LL4 date	8/10/2010	8/31/2010	9/14/2010	9/28/2010	10/13/2010	5/24/2011	no profile	6/21/2011	7/12/2011	7/26/2011
LL4 max dep sampled	9	9	9	9	9	9	no profile	9	9	9
LL4 all-dep V-W DO (mg/L)	10.00	9.24	9.75	11.28	10.10	12.09	no profile	11.55	9.91	9.85
LL4 hypo >8m V-W DO (mg/L)	9.29	9.66	9.81	9.86	9.93	12.01	no profile	11.58	9.74	9.75
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	no profile	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	no profile	N/A	N/A	N/A
LL5 date	8/10/2010	8/31/2010	9/14/2010	9/28/2010	10/13/2010	5/24/2011	no profile	6/21/2011	7/12/2011	7/26/2011
LL5 max dep sampled	7	5	6	8	8	5.5	no profile	5	7	6.8
LL5 all-dep V-W DO (mg/L)	9.58	10.04	9.66	9.74	9.85	12.06	no profile	11.66	10.14	9.42
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	no profile	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	no profile	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	no profile	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	8.11	7.37	8.08	8.83	8.54	11.89	—	11.56	10.06	9.26
Ovl hypo >8m V-W DO (mg/L)	6.46	6.18	7.11	8.11	8.03	11.78	—	11.48	9.63	8.85
Ovl hypo >15m V-W DO (mg/L)	5.58	5.76	7.04	7.97	7.77	11.70	—	11.48	9.50	8.65
Ovl hypo >20m V-W DO (mg/L)	4.92	5.39	7.17	7.86	7.56	11.67	—	11.48	9.44	8.43

Sampling event #	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Month	8	8	9	9	5	6	6	7	7	8
Year	2011	2011	2011	2011	2012	2012	2012	2012	2012	2012
LL0 date	no profile	8/22/2011	9/12/2011	9/26/2011	5/23/2012	6/5/2012	6/25/2012	7/10/2012	7/24/2012	8/6/2012
LL0 max dep sampled	no profile	44	45	45	49.5	48	48	48	50	49.3
LL0 all-dep V-W DO (mg/L)	no profile	7.44	7.87	7.47	11.40	10.94	10.93	10.01	8.35	7.42
LL0 hypo >8m V-W DO (mg/L)	no profile	6.57	7.02	7.12	11.35	10.79	10.84	9.60	8.25	6.62
LL0 hypo >15m V-W DO (mg/L)	no profile	6.05	7.13	7.24	11.33	10.71	10.83	9.43	8.16	6.45
LL0 hypo >20m V-W DO (mg/L)	no profile	5.91	7.36	7.23	11.35	10.66	10.82	9.42	7.87	6.33
LL1 date	no profile	8/22/2011	9/12/2011	9/26/2011	5/23/2012	6/5/2012	6/25/2012	7/10/2012	7/24/2012	8/6/2012
LL1 max dep sampled	no profile	32	33	27	34	33	34	34	33	33
LL1 all-dep V-W DO (mg/L)	no profile	8.60	8.11	8.23	11.22	10.70	10.68	9.88	8.13	7.43
LL1 hypo >8m V-W DO (mg/L)	no profile	8.04	7.46	7.86	11.18	10.54	10.59	9.24	7.68	6.64
LL1 hypo >15m V-W DO (mg/L)	no profile	8.16	7.76	7.98	11.17	10.44	10.66	8.96	7.47	6.31
LL1 hypo >20m V-W DO (mg/L)	no profile	8.52	8.17	8.16	11.15	10.43	10.75	8.86	7.04	5.32
LL2 date	8/9/2011	8/22/2011	9/12/2011	9/26/2011	5/23/2012	6/5/2012	6/25/2012	7/10/2012	7/24/2012	8/6/2012
LL2 max dep sampled	9	26	25	24	25	24	25	25	25	25
LL2 all-dep V-W DO (mg/L)	incomplete	8.79	8.39	8.46	11.11	10.60	10.56	9.90	7.95	8.60
LL2 hypo >8m V-W DO (mg/L)	incomplete	8.42	8.04	8.30	11.04	10.52	10.42	9.10	7.10	8.18
LL2 hypo >15m V-W DO (mg/L)	incomplete	8.97	8.64	8.59	11.00	10.46	10.31	8.63	6.23	8.70
LL2 hypo >20m V-W DO (mg/L)	incomplete	9.08	8.79	8.83	10.98	10.47	10.23	8.47	5.24	8.67

LL3 date	8/9/2011	8/23/2011	9/13/2011	9/26/2011	5/24/2012	6/6/2012	6/26/2012	7/11/2012	7/25/2012	8/7/2012
LL3 max dep sampled	9	20	20	21	17	17	17	18	18	18
LL3 all-dep V-W DO (mg/L)	incomplete	8.46	8.65	8.73	11.27	10.88	10.35	9.43	8.65	9.01
LL3 hypo >8m V-W DO (mg/L)	incomplete	8.29	8.72	8.58	11.21	10.91	10.33	8.79	7.90	9.00
LL3 hypo >15m V-W DO (mg/L)	incomplete	9.01	8.96	9.02	11.06	11.02	10.33	7.98	5.32	9.41
LL3 hypo >20m V-W DO (mg/L)	incomplete	8.99	8.87	9.05	11.03	11.04	10.33	7.69	4.01	9.38
LL4 date	8/9/2011	8/23/2011	9/13/2011	9/27/2011	5/24/2012	6/6/2012	6/26/2012	7/11/2012	7/25/2012	8/7/2012
LL4 max dep sampled	9	9	9	9	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	9.64	9.25	9.03	9.12	11.62	11.30	10.00	9.64	9.58	9.45
LL4 hypo >8m V-W DO (mg/L)	9.38	9.58	9.43	9.37	11.44	11.37	9.97	9.80	9.64	9.67
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/9/2011	8/23/2011	9/13/2011	9/27/2011	5/24/2012	6/6/2012	6/26/2012	7/11/2012	7/25/2012	8/7/2012
LL5 max dep sampled	7	6	7	7	5	5	5	5	5	5
LL5 all-dep V-W DO (mg/L)	9.01	9.18	9.17	9.29	11.74	11.61	9.90	8.92	9.00	incomplete
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	incomplete
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	incomplete
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	incomplete
Ovl all-dep V-W DO (mg/L)	—	8.44	8.29	8.24	11.30	10.84	10.61	9.84	8.35	—
Ovl hypo >8m V-W DO (mg/L)	—	7.76	7.59	7.80	11.22	10.67	10.60	9.30	7.80	—
Ovl hypo >15m V-W DO (mg/L)	—	7.63	7.73	7.84	11.21	10.57	10.65	9.03	7.40	—
Ovl hypo >20m V-W DO (mg/L)	—	7.58	7.91	7.82	11.23	10.54	10.70	9.02	7.07	—

Sampling event #	31	32	33	34	35	36	37	38	39	40
Month	8	9	9	10	5	6	6	7	7	8
Year	2012	2012	2012	2012	2013	2013	2013	2013	2013	2013
LL0 date	8/20/2012	9/10/2012	9/25/2012	10/15/2012	5/13/2013	6/11/2013	6/25/2013	7/9/2013	7/24/2013	8/5/2013
LL0 max dep sampled	48	49.5	49.5	48	49	48	47	47	47	47
LL0 all-dep V-W DO (mg/L)	7.69	5.85	7.55	8.24	11.51	10.29	8.74	8.87	8.28	7.15
LL0 hypo >8m V-W DO (mg/L)	6.16	5.00	6.86	8.01	11.20	9.93	8.31	8.13	6.75	5.95
LL0 hypo >15m V-W DO (mg/L)	5.97	5.05	7.33	8.55	11.12	9.45	8.08	7.34	6.20	5.43
LL0 hypo >20m V-W DO (mg/L)	5.55	4.97	7.56	8.67	11.11	9.29	7.91	6.98	5.81	5.07
LL1 date	8/20/2012	9/10/2012	9/25/2012	10/15/2012	5/13/2013	6/11/2013	6/25/2013	7/9/2013	7/24/2013	8/5/2013
LL1 max dep sampled	33	33	33	33	33	33	34	33	33	33
LL1 all-dep V-W DO (mg/L)	7.76	7.59	8.21	8.86	11.06	10.06	8.86	9.11	7.74	7.40
LL1 hypo >8m V-W DO (mg/L)	6.47	7.02	7.45	8.91	10.93	9.74	8.59	8.61	6.87	6.26
LL1 hypo >15m V-W DO (mg/L)	6.00	7.37	8.04	9.10	10.91	9.53	8.48	8.04	6.09	5.16
LL1 hypo >20m V-W DO (mg/L)	5.15	7.69	8.31	9.24	10.94	9.26	8.20	7.71	5.28	3.86
LL2 date	8/20/2012	9/10/2012	9/25/2012	10/15/2012	5/13/2013	6/11/2013	6/25/2013	7/9/2013	7/24/2013	8/5/2013
LL2 max dep sampled	25	25	25	25.5	26	25	25	25	25	25
LL2 all-dep V-W DO (mg/L)	8.24	8.27	8.38	8.79	10.48	9.80	9.54	9.07	8.58	8.95
LL2 hypo >8m V-W DO (mg/L)	6.98	7.93	7.74	8.92	10.50	9.37	9.24	8.06	7.37	8.33
LL2 hypo >15m V-W DO (mg/L)	6.68	7.88	8.81	9.24	10.51	9.12	8.97	7.38	6.00	8.44
LL2 hypo >20m V-W DO (mg/L)	5.88	8.64	8.80	9.42	10.14	8.75	8.76	6.34	4.52	8.50

LL3 date	8/21/2012	9/11/2012	9/26/2012	10/16/2012	5/14/2013	6/12/2013	6/26/2013	7/10/2013	7/25/2013	8/6/2013
LL3 max dep sampled	19	18	18	18	19	19	19	18	19	18
LL3 all-dep V-W DO (mg/L)	9.17	9.19	9.71	9.04	10.39	10.17	9.93	8.55	9.20	9.28
LL3 hypo >8m V-W DO (mg/L)	8.74	9.00	9.27	9.20	10.40	9.96	9.17	7.43	8.22	8.82
LL3 hypo >15m V-W DO (mg/L)	8.87	9.11	9.14	9.51	10.37	9.43	9.10	5.63	6.54	9.08
LL3 hypo >20m V-W DO (mg/L)	8.87	9.10	9.12	9.53	10.36	8.84	9.10	5.01	3.86	9.03
LL4 date	8/21/2012	9/11/2012	9/26/2012	10/16/2012	5/14/2013	6/12/2013	6/26/2013	7/10/2013	7/25/2013	8/6/2013
LL4 max dep sampled	8	8	8	8	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	9.90	10.03	10.27	9.85	10.90	9.93	9.42	9.33	9.95	10.05
LL4 hypo >8m V-W DO (mg/L)	9.74	9.63	9.93	9.81	10.86	9.87	9.44	9.28	9.93	9.21
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/21/2012	9/11/2012	9/26/2012	10/16/2012	5/14/2013	6/12/2013	6/26/2013	7/10/2013	7/25/2013	8/6/2013
LL5 max dep sampled	5	5	5	5	5	5	5	5	5	6
LL5 all-dep V-W DO (mg/L)	9.20	9.48	9.46	9.51	11.07	9.78	9.37	8.86	9.46	8.76
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	8.21	7.74	8.45	8.78	10.97	10.08	9.17	9.02	8.48	8.11
Ovl hypo >8m V-W DO (mg/L)	6.69	6.83	7.52	8.65	10.88	9.76	8.69	8.30	7.13	6.83
Ovl hypo >15m V-W DO (mg/L)	6.13	6.77	7.93	8.94	10.89	9.40	8.41	7.57	6.14	5.92
Ovl hypo >20m V-W DO (mg/L)	5.30	6.79	8.02	9.02	10.89	9.16	8.12	7.21	5.40	4.97

Sampling event #	41	42	43	44	45	46	47	48	49	50
Month	8	9	9	10	5	6	6	7	7	8
Year	2013	2013	2013	2013	2014	2014	2014	2014	2014	2014
LL0 date	8/20/2013	9/9/2013	9/24/2013	10/14/2013	5/14/2014	6/10/2014	6/24/2014	7/8/2014	7/23/2014	8/5/2014
LL0 max dep sampled	47	47	47	47	48	47	46	46	46	47
LL0 all-dep V-W DO (mg/L)	6.62	5.64	5.72	9.34	11.86	10.57	9.68	9.44	7.86	7.01
LL0 hypo >8m V-W DO (mg/L)	5.02	4.53	5.01	9.24	11.68	10.05	9.28	8.80	7.19	5.36
LL0 hypo >15m V-W DO (mg/L)	4.28	4.07	4.58	9.18	11.64	9.83	9.33	8.33	6.68	4.87
LL0 hypo >20m V-W DO (mg/L)	3.82	3.41	3.99	9.35	11.63	9.88	9.36	8.25	6.41	4.73
LL1 date	8/20/2013	9/9/2013	9/24/2013	10/14/2013	5/14/2014	6/11/2014	6/24/2014	7/8/2014	7/23/2014	8/5/2014
LL1 max dep sampled	33	33	33	33	33	30	30	33	33	33
LL1 all-dep V-W DO (mg/L)	7.72	7.24	7.41	9.25	12.11	9.90	9.98	9.16	7.57	7.84
LL1 hypo >8m V-W DO (mg/L)	6.36	6.50	6.95	9.17	12.02	9.57	9.78	8.48	6.65	6.56
LL1 hypo >15m V-W DO (mg/L)	5.79	6.83	6.94	9.03	11.93	9.46	9.71	8.16	5.81	6.14
LL1 hypo >20m V-W DO (mg/L)	5.35	6.91	7.11	9.04	11.87	9.45	9.64	7.92	5.06	5.51
LL2 date	8/20/2013	9/9/2013	9/24/2013	10/14/2013	5/14/2014	6/11/2014	6/24/2014	7/8/2014	7/23/2014	8/5/2014
LL2 max dep sampled	25	25	25	25	25	25	25	25	25	25
LL2 all-dep V-W DO (mg/L)	9.21	7.92	8.22	9.62	11.98	10.08	10.41	9.28	7.65	8.59
LL2 hypo >8m V-W DO (mg/L)	7.58	7.12	8.19	9.64	11.92	9.54	9.98	8.25	6.43	7.36
LL2 hypo >15m V-W DO (mg/L)	7.00	7.86	8.49	9.86	11.95	9.32	9.64	7.76	5.42	6.95
LL2 hypo >20m V-W DO (mg/L)	5.47	7.75	8.63	9.89	11.92	9.12	9.42	7.08	4.34	6.02

LL3 date	8/21/2013	9/10/2013	9/25/2013	10/15/2013	5/15/2014	6/11/2014	6/25/2014	7/9/2014	7/24/2014	8/6/2014
LL3 max dep sampled	18	18	18	18	19	19	19	19	19	19
LL3 all-dep V-W DO (mg/L)	10.00	8.76	8.71	10.31	10.23	10.38	10.21	9.65	8.71	8.85
LL3 hypo >8m V-W DO (mg/L)	9.00	8.15	9.02	10.20	10.27	10.37	10.08	9.19	8.05	7.81
LL3 hypo >15m V-W DO (mg/L)	8.73	8.83	9.25	10.19	10.35	10.36	10.78	9.34	9.62	9.34
LL3 hypo >20m V-W DO (mg/L)	8.63	8.80	9.27	10.18	10.40	10.35	11.48	9.41	9.61	9.34
LL4 date	8/21/2013	9/10/2013	9/25/2013	10/15/2013	5/15/2014	6/11/2014	6/25/2014	7/9/2014	7/24/2014	8/6/2014
LL4 max dep sampled	8	8	8	8	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	11.40	10.06	9.83	10.66	11.67	9.77	9.70	9.48	9.16	10.48
LL4 hypo >8m V-W DO (mg/L)	9.96	9.60	9.66	10.55	11.67	9.76	9.54	9.33	8.99	9.91
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/21/2013	9/12/2013	9/25/2013	10/15/2013	5/15/2014	6/11/2014	6/25/2014	7/9/2014	7/24/2014	8/6/2014
LL5 max dep sampled	5	5	5	5	5	5	5	5	5	5
LL5 all-dep V-W DO (mg/L)	10.56	10.10	9.84	10.55	11.97	9.94	9.73	8.70	9.06	9.67
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	8.38	7.45	7.60	9.62	11.73	10.19	9.99	9.36	7.99	8.13
Ovl hypo >8m V-W DO (mg/L)	6.49	6.21	6.93	9.40	11.71	9.81	9.67	8.64	6.97	6.46
Ovl hypo >15m V-W DO (mg/L)	5.54	6.05	6.61	9.26	11.74	9.64	9.60	8.21	6.26	5.83
Ovl hypo >20m V-W DO (mg/L)	4.71	5.47	6.25	9.29	11.74	9.63	9.51	7.97	5.63	5.12

Sampling event #	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**
Month	8	9	9	10	5	6	6	7	7	8
Year	2014	2014	2014	2014	2015	2015	2015	2015	2015	2015
LL0 date	8/20/2014	9/9/2014	9/23/2014	10/14/2014	5/13/2015	6/9/2015	6/23/2015	7/7/2015	7/21/2015	8/4/2015
LL0 max dep sampled	47	47	47	47	47.5	47.5	47.5	47.5	47	47.5
LL0 all-dep V-W DO (mg/L)	6.82	5.72	7.59	8.19	10.99	8.59	7.68	7.61	7.60	6.62
LL0 hypo >8m V-W DO (mg/L)	5.06	4.16	6.81	7.84	10.67	7.98	6.95	6.37	5.85	4.87
LL0 hypo >15m V-W DO (mg/L)	4.64	3.41	7.05	7.45	10.11	7.79	6.61	5.54	5.07	4.26
LL0 hypo >20m V-W DO (mg/L)	4.08	2.68	7.39	7.72	9.97	7.53	6.39	5.43	4.71	3.89
LL1 date	8/20/2014	9/9/2014	9/23/2014	10/14/2014	5/13/2015	6/9/2015	6/23/2015	7/7/2015	7/21/2015	8/4/2015
LL1 max dep sampled	33	33	33	33	33	33	33	33	33	33
LL1 all-dep V-W DO (mg/L)	7.93	7.83	8.12	8.61	10.70	8.47	7.43	7.45	6.72	6.64
LL1 hypo >8m V-W DO (mg/L)	6.55	6.89	7.43	8.40	10.28	7.60	6.57	6.17	5.23	4.72
LL1 hypo >15m V-W DO (mg/L)	6.48	7.34	8.04	8.14	9.75	7.17	5.69	4.80	4.18	3.81
LL1 hypo >20m V-W DO (mg/L)	6.07	7.85	8.47	8.33	9.63	6.60	4.66	3.36	2.93	2.53
LL2 date	8/20/2014	9/9/2014	9/23/2014	10/14/2014	5/13/2015	6/9/2015	6/23/2015	7/7/2015	7/21/2015	8/4/2015
LL2 max dep sampled	25	25	25	25	25.5	25.5	25	25	25	25
LL2 all-dep V-W DO (mg/L)	8.71	8.56	8.95	9.20	10.43	8.77	8.65	8.75	7.71	8.71
LL2 hypo >8m V-W DO (mg/L)	7.47	7.40	8.40	8.96	9.88	7.53	7.85	7.14	5.64	7.38
LL2 hypo >15m V-W DO (mg/L)	7.98	8.35	8.80	8.93	9.17	6.52	6.22	5.41	3.71	7.19
LL2 hypo >20m V-W DO (mg/L)	7.90	8.81	8.59	8.83	8.72	5.26	3.82	3.03	1.37	4.73

LL3 date	8/21/2014	9/10/2014	9/24/2014	10/15/2014	5/14/2015	6/10/2015	6/24/2015	7/8/2015	7/22/2015	8/5/2015
LL3 max dep sampled	19	19	19	19	18	18.5	19	18.5	19	19.5
LL3 all-dep V-W DO (mg/L)	9.73	9.99	7.79	9.33	9.99	8.49	9.67	9.01	9.86	10.39
LL3 hypo >8m V-W DO (mg/L)	10.41	10.34	8.54	10.26	9.37	7.07	9.64	7.11	9.14	9.93
LL3 hypo >15m V-W DO (mg/L)	11.19	11.09	8.48	10.48	8.64	5.30	9.52	5.22	8.62	10.24
LL3 hypo >20m V-W DO (mg/L)	11.20	10.97	8.49	10.46	8.48	4.33	9.42	4.60	8.19	10.16
LL4 date	8/21/2014	9/10/2014	9/24/2014	10/15/2014	5/14/2015	6/10/2015	6/24/2015	7/8/2015	7/22/2015	8/5/2015
LL4 max dep sampled	8	8	8	8	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	10.80	11.35	11.26	10.11	10.24	9.67	10.11	11.06	11.53	12.18
LL4 hypo >8m V-W DO (mg/L)	9.56	10.39	9.89	9.65	10.22	9.12	9.97	9.74	11.04	12.04
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/21/2014	9/10/2014	9/24/2014	10/15/2014	5/14/2015	6/10/2015	6/24/2015	7/8/2015	7/22/2015	8/5/2015
LL5 max dep sampled	5	5	5	5	5	5	5	5	5	5
LL5 all-dep V-W DO (mg/L)	10.26	10.05	9.65	9.67	10.13	8.87	9.85	10.62	11.53	11.84
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	8.28	8.08	8.32	8.82	10.61	8.65	8.27	8.29	8.04	8.06
Ovl hypo >8m V-W DO (mg/L)	6.64	6.62	7.54	8.51	10.26	7.65	7.25	6.54	5.97	5.84
Ovl hypo >15m V-W DO (mg/L)	6.18	6.36	7.77	8.08	9.73	7.13	6.24	5.09	4.57	4.68
Ovl hypo >20m V-W DO (mg/L)	5.36	5.94	7.96	8.09	9.63	6.68	5.31	4.12	3.48	3.31

Sampling event #	61	62	63	64	65	66	67	68	69	70
Month	8	9	9	10	5	6	6	7	7	8
Year	2015	2015	2015	2015	2016	2016	2016	2016	2016	2016
LL0 date	8/24/2015	9/8/2015	9/23/2015	10/13/2015	5/17/2016	6/7/2016	6/21/2016	7/5/2016	7/19/2016	8/10/2016
LL0 max dep sampled	47.5	47	47	47.5	47	47	47	47	46.5	47
LL0 all-dep V-W DO (mg/L)	5.80	5.21	5.46	6.42	9.70	9.55	8.52	8.22	7.33	7.22
LL0 hypo >8m V-W DO (mg/L)	3.93	3.61	3.77	5.37	9.49	9.25	8.00	7.42	6.41	5.48
LL0 hypo >15m V-W DO (mg/L)	3.40	2.61	3.29	4.37	9.33	8.95	7.70	6.58	5.77	4.78
LL0 hypo >20m V-W DO (mg/L)	2.89	2.20	2.65	3.91	9.17	8.78	7.52	6.13	5.30	4.15
LL1 date	8/24/2015	9/8/2015	9/23/2015	10/13/2015	5/17/2016	6/7/2016	6/21/2016	7/5/2016	7/19/2016	8/10/2016
LL1 max dep sampled	33	33.5	33	33.5	33	33	33	33	33	33
LL1 all-dep V-W DO (mg/L)	6.66	7.35	7.96	8.11	10.13	9.74	8.51	8.18	7.62	7.28
LL1 hypo >8m V-W DO (mg/L)	4.74	6.47	7.18	7.65	9.77	9.49	8.20	7.80	6.76	5.47
LL1 hypo >15m V-W DO (mg/L)	3.73	5.85	6.94	7.23	9.44	8.99	8.03	7.24	6.17	4.53
LL1 hypo >20m V-W DO (mg/L)	2.02	5.45	7.01	7.43	9.13	8.77	7.91	6.59	5.28	3.91
LL2 date	8/24/2015	9/8/2015	9/23/2015	10/13/2015	5/17/2016	6/7/2016	6/21/2016	7/5/2016	7/19/2016	8/10/2016
LL2 max dep sampled	25	25.5	25	25	25	25	25	25	25	25
LL2 all-dep V-W DO (mg/L)	8.24	7.89	8.86	9.03	10.61	9.89	8.99	8.49	8.76	8.66
LL2 hypo >8m V-W DO (mg/L)	6.65	6.95	8.39	8.80	9.91	9.44	9.05	8.03	8.18	6.91
LL2 hypo >15m V-W DO (mg/L)	5.96	8.16	8.53	8.43	9.73	8.84	9.13	7.26	7.88	6.47
LL2 hypo >20m V-W DO (mg/L)	3.73	8.43	8.76	8.24	9.86	8.42	8.95	6.49	7.57	4.39

LL3 date	8/25/2015	9/9/2015	9/24/2015	10/14/2015	5/18/2016	6/8/2016	6/22/2016	7/6/2016	7/20/2016	8/11/2016
LL3 max dep sampled	19	19.5	19	19.5	18.5	18.5	18.5	18.5	19.5	19.5
LL3 all-dep V-W DO (mg/L)	9.51	8.48	9.93	9.89	11.20	9.58	9.26	8.49	9.14	9.81
LL3 hypo >8m V-W DO (mg/L)	8.89	8.01	9.70	9.88	10.63	9.23	9.51	7.68	8.25	8.80
LL3 hypo >15m V-W DO (mg/L)	9.22	9.09	9.55	9.79	10.50	8.29	9.56	6.99	7.36	8.94
LL3 hypo >20m V-W DO (mg/L)	9.20	9.11	9.54	9.66	10.45	7.93	9.51	6.92	6.90	8.92
LL4 date	8/25/2015	9/9/2015	9/24/2015	10/14/2015	5/18/2016	6/8/2016	6/22/2016	7/6/2016	7/20/2016	8/11/2016
LL4 max dep sampled	8	8	8	8	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	11.29	10.84	11.84	11.12	10.29	9.39	9.60	9.35	10.32	10.54
LL4 hypo >8m V-W DO (mg/L)	10.85	9.98	10.09	10.09	10.24	9.26	9.64	9.65	9.43	9.78
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/25/2015	9/9/2015	9/24/2015	10/14/2015	5/18/2016	6/8/2016	6/22/2016	7/6/2016	7/20/2016	8/11/2016
LL5 max dep sampled	5	5	5	5	5	5	5	5	5	5
LL5 all-dep V-W DO (mg/L)	11.60	11.32	10.29	10.45	10.25	8.84	9.68	8.99	10.05	10.28
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	7.57	7.38	8.07	8.41	10.28	9.66	8.83	8.44	8.24	8.22
Ovl hypo >8m V-W DO (mg/L)	5.29	5.81	6.60	7.50	9.80	9.38	8.46	7.78	7.11	6.17
Ovl hypo >15m V-W DO (mg/L)	4.10	4.98	5.90	6.61	9.48	8.91	8.16	6.99	6.32	5.16
Ovl hypo >20m V-W DO (mg/L)	2.56	4.16	5.23	6.22	9.24	8.70	7.90	6.39	5.56	4.16

Sampling event #	71	72	73	74	75	76	77	78	79	80
Month	8	9	9	10	5	6	6	7	7	8
Year	2016	2016	2016	2016	2017	2017	2017	2017	2017	2017
LL0 date	8/24/2016	9/6/2016	9/19/2016	10/12/2016	5/15/2017	6/5/2017	6/20/2017	7/11/2017	7/25/2017	8/8/2017
LL0 max dep sampled	47	47	47	45	46	46.5	47	47	47	47
LL0 all-dep V-W DO (mg/L)	6.16	5.54	5.47	8.46	11.69	10.12	9.41	8.46	7.28	7.54
LL0 hypo >8m V-W DO (mg/L)	4.33	3.87	4.25	8.27	11.68	9.79	8.96	7.95	6.55	5.81
LL0 hypo >15m V-W DO (mg/L)	3.47	3.14	4.08	8.09	11.68	9.81	9.01	7.42	6.15	5.21
LL0 hypo >20m V-W DO (mg/L)	2.84	2.48	4.17	8.33	11.68	9.88	9.04	7.13	5.89	4.80
LL1 date	8/24/2016	9/6/2016	9/19/2016	10/12/2016	5/15/2017	6/5/2017	6/20/2017	7/11/2017	7/25/2017	8/8/2017
LL1 max dep sampled	33	33	33	31	33	33	33	33	33	33
LL1 all-dep V-W DO (mg/L)	7.24	7.42	8.30	8.73	11.79	10.10	9.59	8.10	7.31	7.73
LL1 hypo >8m V-W DO (mg/L)	6.01	6.33	7.89	8.58	11.80	9.85	9.28	7.64	6.63	6.36
LL1 hypo >15m V-W DO (mg/L)	5.41	6.30	7.97	8.65	11.80	9.76	9.44	7.26	6.00	5.44
LL1 hypo >20m V-W DO (mg/L)	4.64	5.78	8.41	8.88	11.79	9.79	9.46	6.88	5.24	4.15
LL2 date	8/24/2016	9/6/2016	9/19/2016	10/12/2016	5/15/2017	6/5/2017	6/20/2017	7/11/2017	7/25/2017	8/8/2017
LL2 max dep sampled	25	25	25	24.5	25.5	25	25	25	25	25
LL2 all-dep V-W DO (mg/L)	8.16	8.56	8.86	9.28	12.05	10.24	9.95	8.01	7.87	8.69
LL2 hypo >8m V-W DO (mg/L)	7.03	7.73	8.95	9.18	12.05	10.01	9.73	7.35	7.23	7.28
LL2 hypo >15m V-W DO (mg/L)	6.41	8.40	9.34	9.04	12.06	9.85	9.63	6.58	6.13	6.40
LL2 hypo >20m V-W DO (mg/L)	6.00	8.59	9.51	8.93	12.06	9.70	9.60	5.78	4.61	4.70

LL3 date	8/25/2016	9/7/2016	9/20/2016	10/13/2016	5/16/2017	6/6/2017	6/21/2017	7/12/2017	7/26/2017	8/9/2017
LL3 max dep sampled	19.5	19.5	19.5	18.5	19.5	19	18.5	18.5	18.5	19.5
LL3 all-dep V-W DO (mg/L)	9.58	9.21	9.23	9.59	11.93	10.39	9.91	8.00	8.95	9.81
LL3 hypo >8m V-W DO (mg/L)	8.94	9.04	9.35	9.69	11.92	10.34	10.01	6.80	8.70	9.00
LL3 hypo >15m V-W DO (mg/L)	9.09	9.44	9.62	9.72	11.92	10.25	9.91	4.58	8.46	9.19
LL3 hypo >20m V-W DO (mg/L)	9.08	9.44	9.63	9.74	11.94	10.23	9.84	3.64	8.34	9.14
LL4 date	8/25/2016	9/7/2016	9/20/2016	10/13/2016	5/16/2017	6/6/2017	6/21/2017	7/12/2017	7/26/2017	8/9/2017
LL4 max dep sampled	8	8	8	7.5	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	11.26	10.09	10.52	10.73	11.81	10.10	9.80	9.14	9.34	10.09
LL4 hypo >8m V-W DO (mg/L)	10.01	9.66	9.91	10.86	11.79	10.11	9.84	9.27	9.76	9.94
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/25/2016	9/7/2016	9/20/2016	10/13/2016	5/16/2017	6/6/2017	6/21/2017	7/12/2017	7/26/2017	8/9/2017
LL5 max dep sampled	5	5	5	4	5	5	5	5	5	5
LL5 all-dep V-W DO (mg/L)	10.55	10.00	10.19	10.01	11.84	10.47	9.43	8.72	8.89	9.67
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	7.84	7.66	8.04	9.05	11.83	10.18	9.67	8.29	7.84	8.38
Ovl hypo >8m V-W DO (mg/L)	6.03	6.11	7.17	8.74	11.82	9.90	9.34	7.65	6.98	6.65
Ovl hypo >15m V-W DO (mg/L)	4.99	5.53	6.93	8.54	11.80	9.79	9.32	7.06	6.19	5.61
Ovl hypo >20m V-W DO (mg/L)	4.03	4.61	6.93	8.64	11.78	9.79	9.29	6.77	5.51	4.49

Sampling event #	81	82	83	84	85	86	87	88	89	90
Month	8	9	9	10	5	6	6	7	7	8
Year	2017	2017	2017	2017	2018	2018	2018	2018	2018	2018
LL0 date	8/22/2017	9/12/2017	9/26/2017	10/18/2017	5/16/2018	6/6/2018	6/19/2018	7/10/2018	7/23/2018	8/7/2018
LL0 max dep sampled	47	47	47	47	47	47	47	47	47	47
LL0 all-dep V-W DO (mg/L)	6.95	6.24	8.10	9.15	12.12	10.29	9.11	8.54	8.85	7.35
LL0 hypo >8m V-W DO (mg/L)	4.74	5.06	7.69	9.12	11.92	10.08	8.69	7.72	7.15	5.73
LL0 hypo >15m V-W DO (mg/L)	4.18	4.52	7.97	9.18	11.87	10.01	8.60	7.37	6.30	5.14
LL0 hypo >20m V-W DO (mg/L)	3.77	3.79	8.28	9.29	11.84	9.96	8.63	7.19	6.08	4.81
LL1 date	8/22/2017	9/12/2017	9/26/2017	10/18/2017	5/16/2018	6/6/2018	6/19/2018	7/10/2018	7/23/2018	8/7/2018
LL1 max dep sampled	33	33	33	33	33	33	33	33	33	33
LL1 all-dep V-W DO (mg/L)	8.27	7.88	8.30	9.68	11.87	10.23	9.48	9.00	8.86	7.74
LL1 hypo >8m V-W DO (mg/L)	7.04	7.24	8.04	9.69	11.83	9.94	9.21	8.23	7.65	6.33
LL1 hypo >15m V-W DO (mg/L)	7.38	7.75	8.51	9.74	11.79	9.86	9.14	8.12	6.85	5.34
LL1 hypo >20m V-W DO (mg/L)	7.66	8.07	8.97	9.80	11.71	9.86	9.07	8.24	6.57	4.31
LL2 date	8/22/2017	9/12/2017	9/26/2017	10/18/2017	5/16/2018	6/6/2018	6/19/2018	7/10/2018	7/23/2018	8/7/2018
LL2 max dep sampled	25	25	25	25.5	25	25	25	25	25	25
LL2 all-dep V-W DO (mg/L)	8.64	8.04	8.63	9.97	11.74	10.34	9.73	9.68	8.63	8.66
LL2 hypo >8m V-W DO (mg/L)	7.57	7.58	8.66	10.04	11.70	9.84	9.36	8.79	7.29	7.28
LL2 hypo >15m V-W DO (mg/L)	8.31	8.34	9.42	10.08	11.67	9.56	9.18	8.49	6.44	5.35
LL2 hypo >20m V-W DO (mg/L)	8.25	8.66	9.43	10.10	11.66	9.45	9.09	8.24	5.55	3.14

LL3 date	8/23/2017	9/13/2017	9/27/2017	10/19/2017	5/17/2018	6/7/2018	6/20/2018	7/11/2018	7/24/2018	8/8/2018
LL3 max dep sampled	19	18.5	18.5	18.5	18.5	18.5	19	18.5	19.5	18.5
LL3 all-dep V-W DO (mg/L)	9.36	9.27	9.48	10.12	11.67	9.82	9.93	9.73	8.68	9.74
LL3 hypo >8m V-W DO (mg/L)	8.41	8.85	9.65	10.11	11.67	9.55	9.60	9.00	7.19	9.22
LL3 hypo >15m V-W DO (mg/L)	9.36	9.21	9.62	10.09	11.66	9.48	9.49	8.41	4.74	9.15
LL3 hypo >20m V-W DO (mg/L)	9.33	9.20	9.61	10.10	11.65	9.44	9.48	8.24	2.97	9.12
LL4 date	8/23/2017	9/13/2017	9/27/2017	10/19/2017	5/17/2018	6/7/2018	6/20/2018	7/11/2018	7/24/2018	8/8/2018
LL4 max dep sampled	8	8	8	8	8	8	8	8	8	8
LL4 all-dep V-W DO (mg/L)	10.71	10.35	10.11	9.66	11.85	9.64	10.38	9.70	10.02	10.14
LL4 hypo >8m V-W DO (mg/L)	9.92	9.65	9.91	9.67	11.88	9.56	10.25	9.37	9.74	10.20
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/23/2017	9/13/2017	9/27/2017	10/19/2017	5/17/2018	6/7/2018	6/20/2018	7/11/2018	7/24/2018	8/8/2018
LL5 max dep sampled	5	5	5	5	5	5	5	5	5	5
LL5 all-dep V-W DO (mg/L)	10.21	10.02	9.43	9.82	11.91	9.67	9.51	9.03	9.39	9.88
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	8.41	7.98	8.63	9.65	11.88	10.17	9.56	9.20	8.96	8.34
Ovl hypo >8m V-W DO (mg/L)	6.59	6.93	8.23	9.61	11.81	9.93	9.13	8.30	7.47	6.66
Ovl hypo >15m V-W DO (mg/L)	6.39	6.88	8.50	9.59	11.77	9.86	8.96	7.95	6.50	5.43
Ovl hypo >20m V-W DO (mg/L)	5.96	6.53	8.73	9.61	11.73	9.86	8.88	7.83	6.21	4.44

Sampling event #	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**100**
Month	8	9	9	10	4	5	6	6	7	7
Year	2018	2018	2018	2018	2022	2022	2022	2022	2022	2022
LL0 date	8/28/2018	9/13/2018	9/25/2018	10/16/2018	4/27/2022	5/10/2022	6/7/2022	6/29/2022	7/12/2022	7/26/2022
LL0 max dep sampled	47	47	47	47	49	48	45	54	36	45
LL0 all-dep V-W DO (mg/L)	5.81	6.68	7.88	9.25	11.40	10.82	10.17	10.42	8.67	7.05
LL0 hypo >8m V-W DO (mg/L)	4.00	5.65	7.36	9.10	11.28	10.72	10.08	10.26	8.18	6.34
LL0 hypo >15m V-W DO (mg/L)	3.19	6.13	7.69	8.96	11.25	10.70	10.09	10.28	8.05	6.33
LL0 hypo >20m V-W DO (mg/L)	2.61	6.48	7.87	9.05	11.28	10.67	10.09	10.31	8.09	6.40
LL1 date	8/28/2018	9/13/2018	9/25/2018	10/16/2018	4/27/2022	5/10/2022	6/7/2022	6/29/2022	7/12/2022	7/26/2022
LL1 max dep sampled	33	33	33	33	30	30	33	24	33	33
LL1 all-dep V-W DO (mg/L)	7.94	7.65	8.66	9.76	11.12	11.15	10.16	incomplete	8.26	6.66
LL1 hypo >8m V-W DO (mg/L)	6.99	6.94	8.31	9.72	11.00	11.14	10.09	incomplete	7.81	5.83
LL1 hypo >15m V-W DO (mg/L)	7.33	7.45	8.45	9.69	10.96	11.16	10.02	incomplete	7.67	5.53
LL1 hypo >20m V-W DO (mg/L)	7.87	7.91	8.97	9.78	11.00	11.15	9.94	incomplete	7.72	5.11
LL2 date	8/28/2018	9/12/2018	9/25/2018	10/16/2018	4/27/2022	5/10/2022	6/7/2022	6/29/2022	7/12/2022	7/26/2022
LL2 max dep sampled	25	25	25	25	24	24	24	24	24	24
LL2 all-dep V-W DO (mg/L)	8.47	8.47	8.92	10.22	10.89	11.52	10.36	9.81	8.39	6.84
LL2 hypo >8m V-W DO (mg/L)	7.65	8.03	8.80	10.21	10.67	11.53	10.28	9.67	7.62	5.90
LL2 hypo >15m V-W DO (mg/L)	8.41	8.62	9.49	10.30	10.51	11.53	10.27	9.59	7.31	5.07
LL2 hypo >20m V-W DO (mg/L)	8.58	8.62	9.63	10.35	10.43	11.53	10.26	9.52	7.08	4.05

LL3 date	8/29/2018	9/13/2018	9/26/2018	10/17/2018	4/28/2022	5/11/2022	6/8/2022	6/29/2022	7/13/2022	7/26/2022
LL3 max dep sampled	19	18.5	18.5	19	21	18	21	21	18	21
LL3 all-dep V-W DO (mg/L)	9.08	9.29	9.34	10.35	10.90	12.00	10.23	9.34	8.33	7.60
LL3 hypo >8m V-W DO (mg/L)	8.66	9.28	9.63	10.29	10.92	11.98	10.24	9.19	7.62	7.25
LL3 hypo >15m V-W DO (mg/L)	9.14	9.25	9.77	10.43	10.91	11.99	10.26	8.93	6.82	7.09
LL3 hypo >20m V-W DO (mg/L)	9.10	9.21	9.75	10.44	10.90	12.00	10.26	8.45	6.60	6.87
LL4 date	8/29/2018	9/13/2018	9/26/2018	10/17/2018	4/28/2022	5/11/2022	6/8/2022	6/29/2022	7/13/2022	7/26/2022
LL4 max dep sampled	8	8	8	8	9	9	8	9	9	8
LL4 all-dep V-W DO (mg/L)	9.99	10.18	10.27	10.82	11.42	12.29	10.40	8.95	8.60	7.98
LL4 hypo >8m V-W DO (mg/L)	9.83	9.60	10.32	10.98	11.39	12.23	10.46	8.84	8.92	7.93
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/29/2018	9/13/2018	9/26/2018	10/17/2018	4/28/2022	5/11/2022	6/8/2022	6/29/2022	7/13/2022	7/26/2022
LL5 max dep sampled	5	5	5	5	5	5	5	4	6	5
LL5 all-dep V-W DO (mg/L)	10.18	9.68	9.68	10.38	11.73	12.30	10.48	9.12	8.20	7.85
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	7.92	8.01	8.74	9.89	11.16	11.36	10.23	—	8.46	7.06
Ovl hypo >8m V-W DO (mg/L)	6.46	7.00	8.27	9.69	11.03	11.18	10.14	—	7.93	6.17
Ovl hypo >15m V-W DO (mg/L)	6.14	7.26	8.41	9.55	11.00	11.09	10.09	—	7.75	5.81
Ovl hypo >20m V-W DO (mg/L)	5.80	7.44	8.60	9.54	11.05	11.01	10.04	—	7.84	5.55

Sampling event #	101	102	103	104	105	106
Month	8	8	9	9	10	10
Year	2022	2022	2022	2022	2022	2022
LL0 date	8/9/2022	8/23/2022	9/13/2022	9/27/2022	10/11/2022	10/25/2022
LL0 max dep sampled	43	45	45	45	48	48
LL0 all-dep V-W DO (mg/L)	6.35	5.79	5.55	6.26	7.03	8.24
LL0 hypo >8m V-W DO (mg/L)	5.59	4.51	4.40	5.16	6.42	8.17
LL0 hypo >15m V-W DO (mg/L)	5.49	4.55	4.25	5.16	6.49	8.06
LL0 hypo >20m V-W DO (mg/L)	5.55	4.47	3.89	4.75	6.35	8.03
LL1 date	8/9/2022	8/23/2022	9/13/2022	9/27/2022	10/11/2022	10/25/2022
LL1 max dep sampled	33	33	33	33	33	33
LL1 all-dep V-W DO (mg/L)	6.01	6.07	6.99	7.13	8.19	8.43
LL1 hypo >8m V-W DO (mg/L)	4.90	4.98	6.24	6.60	7.46	8.38
LL1 hypo >15m V-W DO (mg/L)	4.12	4.66	6.90	7.02	7.97	8.35
LL1 hypo >20m V-W DO (mg/L)	3.43	3.68	7.21	7.20	8.12	8.40
LL2 date	8/9/2022	8/23/2022	9/13/2022	9/27/2022	10/11/2022	10/25/2022
LL2 max dep sampled	24	24	24	24	24	24
LL2 all-dep V-W DO (mg/L)	7.30	6.71	7.62	7.63	8.65	8.54
LL2 hypo >8m V-W DO (mg/L)	6.39	5.85	6.60	7.20	8.20	8.48
LL2 hypo >15m V-W DO (mg/L)	6.44	5.81	7.81	7.79	8.49	8.40
LL2 hypo >20m V-W DO (mg/L)	6.21	5.04	8.28	8.01	8.48	8.36

LL3 date	8/10/2022	8/23/2022	9/14/2022	9/27/2022	10/12/2022	10/25/2022
LL3 max dep sampled	21	21	21	21	21	21
LL3 all-dep V-W DO (mg/L)	7.66	7.94	8.89	8.03	9.08	8.72
LL3 hypo >8m V-W DO (mg/L)	7.29	7.25	8.56	8.15	8.92	8.69
LL3 hypo >15m V-W DO (mg/L)	7.84	7.47	8.78	8.51	8.78	8.78
LL3 hypo >20m V-W DO (mg/L)	7.77	7.35	8.81	8.49	8.80	8.81
LL4 date	8/10/2022	8/23/2022	9/14/2022	9/27/2022	10/12/2022	10/25/2022
LL4 max dep sampled	9	9	8	8	9	9
LL4 all-dep V-W DO (mg/L)	8.91	8.80	9.96	8.85	9.15	9.23
LL4 hypo >8m V-W DO (mg/L)	8.37	8.18	9.17	8.69	9.09	9.29
LL4 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A
LL4 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A
LL5 date	8/10/2022	8/23/2022	9/14/2022	9/27/2022	10/12/2022	10/25/2022
LL5 max dep sampled	6	6	5	5	6	6
LL5 all-dep V-W DO (mg/L)	8.32	8.56	8.94	8.52	8.83	9.22
LL5 hypo >8m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >15m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A
LL5 hypo >20m V-W DO (mg/L)	N/A	N/A	N/A	N/A	N/A	N/A
Ovl all-dep V-W DO (mg/L)	6.83	6.61	7.28	7.34	8.22	8.52
Ovl hypo >8m V-W DO (mg/L)	5.67	5.20	6.04	6.52	7.49	8.38
Ovl hypo >15m V-W DO (mg/L)	5.13	4.82	6.19	6.67	7.64	8.27
Ovl hypo >20m V-W DO (mg/L)	4.70	4.09	5.96	6.46	7.56	8.24

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Appendix I. Cursory evaluation of June – October averaging period for Lake Spokane inflow TP

Patmont et al. (1987) identified the strong nonlinear relationship between inflow TP concentration and hypolimnetic DO in Lake Spokane. (See Figure 14 in this report.) Patmont used the June – October period for calculating a seasonal average TP concentration for purposes of this comparison. More recent analyses such as Welch et al. (2015) and Avista and Tetra Tech (2020) have followed this precedent.

We performed a cursory evaluation of this season selection by comparing seasonal average inflow TP concentration with hypolimnetic DO, using four different averaging season options. This analysis is somewhat limited by the fact that we only have enough data to estimate these values for all season options for 2010 – 2018 and 2022. The range of TP and DO conditions during this set of years is limited, with variation mainly resulting from different hydrological conditions during different years. If it were possible to include conditions from earlier decades, the results might be clearer.

Figure I-1 presents the comparison. March – May TP does correlate with summertime minimum hypolimnetic DO, but in the opposite direction expected, with higher TP relating to higher DO. This is likely because in the high flow season, higher flows mean higher TP concentrations, especially considering Hangman Ck. and the Little Spokane River. However, the hydrologic consideration is more important. Higher DO occurs during high-flow years in spite of higher springtime TP levels, because of better dilution and hydrologic flushing later in the season. July – October TP does not have a statistically significant correlation with hypolimnetic DO. June and June – October TP do correlate with DO in the expected direction, although the correlation is weak (R^2 = 0.12 – 0.20) and not strongly significant (P = 0.20 – 0.33).

Although not conclusive, the results of this evaluation seem to support the wisdom of using Patmont's June – October averaging period for evaluating Lake Spokane inflow TP.

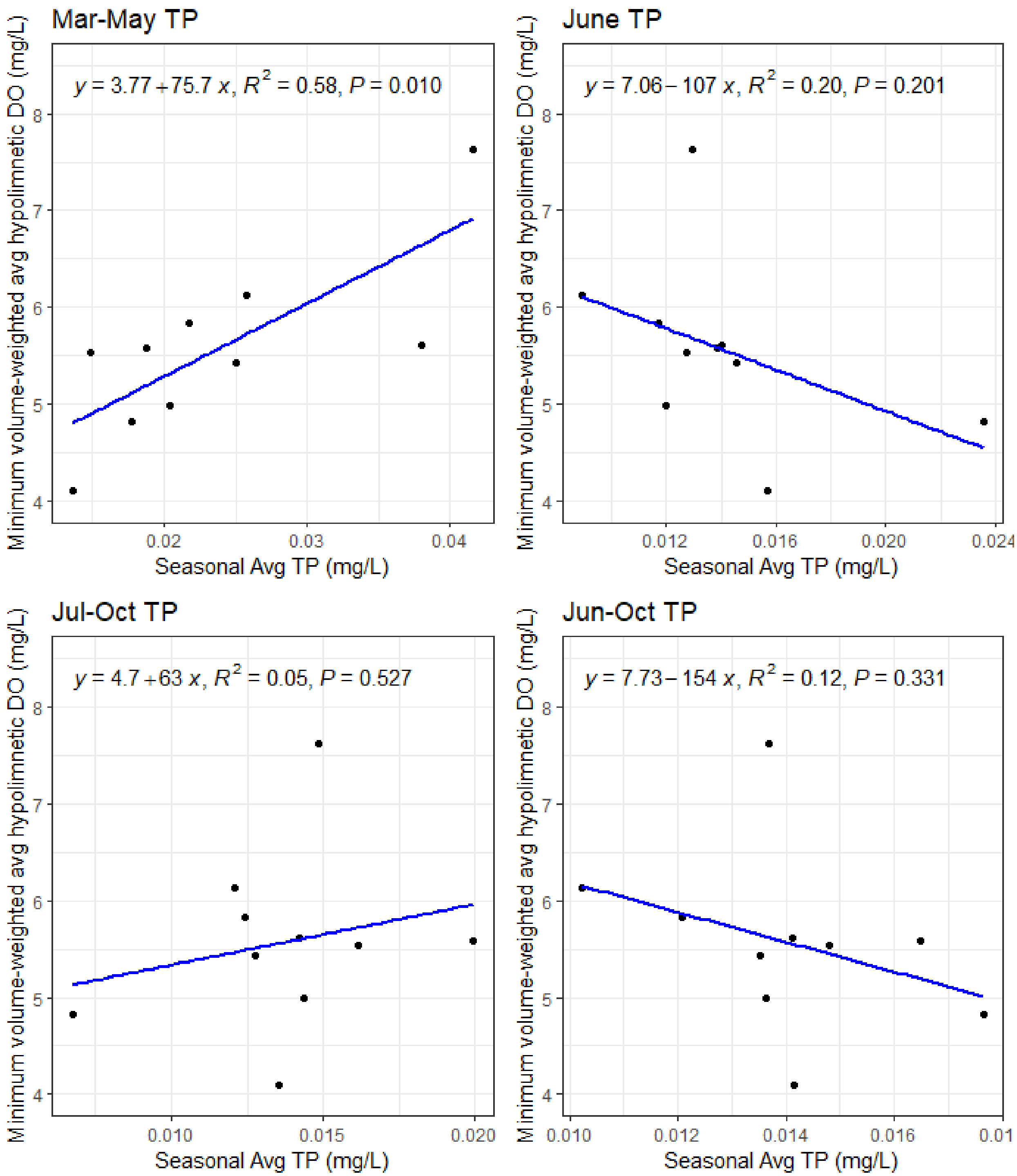

Figure I-1. Yearly minimum volume-weighted average hypolimnetic DO vs. seasonal average TP entering Lake Spokane, for each year 2010 – 2018 and 2022.

References — Appendix I

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Appendix J. Estimated hydraulic travel times for the Spokane River system

We estimated hydraulic travel times for the Spokane River system for different flow conditions. These estimates did not form a numeric piece of our analyses in this report, but a general feel for travel time is very helpful in understanding the dynamics of a river system.

For free-flowing stretches of river, we estimated time-of-travel based on estimated velocity and reach distance. We estimated velocity based on the relationship between measured streamflow and channel average velocity at USGS gage stations in or similar to each reach. This method must be treated with caution — it is only accurate to the degree that gage stations are located in locations representative of the reach as a whole. In smaller streams that display section-control (pool-riffle) hydraulics, this method is unreliable and should not be used. In larger rivers that display channel-control hydraulics, it should be less prone to error. We use this approach here nevertheless recognizing the potential for inaccuracy. These estimates are not as reliable as, for example, time-of-travel dye tracking study data would be.

For reservoirs, we estimated time-of-travel, or residence time, from streamflow and reservoir volume. This is a generally reliable approach. However, in Lake Spokane, these average residence time values gloss over an important nuance of large reservoir hydrodynamics. During the summer, cooler water entering the lake tends to "plunge" beneath the epilimnion and forms an "interflow zone" between the epilimnion and the hypolimnion, along the approximate depth of the Long Lake Dam penstocks. Furthermore, water in the hypolimnion gets trapped there by temperature stratification, a condition which persists each year until fall turnover. Therefore, the actual residence time of water in Lake Spokane varies greatly with depth.

Table J-1 presents time-of-travel estimates for March – May 2022. Table J-2 presents estimates for July – October 2022. We present March – May 2022 and July – October 2022 because these two periods were both hydraulically typical (near median streamflow) for their season. These represent typical high-flow and low-flow conditions.

Table J-1. Estimated time-of-travel for the Spokane River system from Washington/Idaho state line to Long Lake Dam, March– May 2022 mean flow condition.

Reach	Upper RM	Lower RM	Reach length (mi)	Approx flow (cfs)	Flow basis [a b]	Estimated velocity (ft/s) [c]	Reservoir Volume (acre-ft)	Estimated travel time (d)
State Line – Plante's Ferry	96.0	84.2	11.8	14019	Post Falls	5.4 [d]	—	0.13
Plante's Ferry – Upriver pool	84.2	83.1	1.1	14159	Plantes Ferry	5.1	—	0.013
Upriver Dam pool	83.1	80.2	2.9	14159	Plantes Ferry	—	3,000 [g]	0.11
Upriver Dam – Greene Street	80.2	78.0	2.2	13660	Greene St.	5.9	—	0.023
Greene Street – Upper Falls pool	78.0	76.8	1.2	13660	Greene St.	5.9	—	0.012
Upper Falls Dam pool	76.8	74.5	2.3	13531	Sandifur Bridge	—	800 [g]	0.030
Spokane Falls	74.5	74.1	0.4	13531	Sandifur Bridge	5.9 [e]	—	0.0042
Monroe Street Dam pool	74.1	73.95	0.1	13531	Sandifur Bridge	—	30 [g]	0.0011
Monroe Street Dam – Sandifur Bridge	73.95	72.4	1.6	13531	Sandifur Bridge	5.0	—	0.019
Sandifur Bridge – Nine Mile Reservoir	72.4	63.9	8.5	14157	Nine Mile	5.0 [f]	—	0.10
Nine Mile Reservoir	63.9	58.1	5.8	14157	Nine Mile	—	4,600 [g]	0.16
Nine Mile Dam – Lake Spokane	58.1	57.1	1.0	14157	Nine Mile	4.7	—	0.013
Lake Spokane	57.1	34.0	23.1	14797	Nine Mile + LSR	—	243,000 [h]	8.3
Total State Line to Lake Spokane	—	—	**38.9**	—	—	—	—	**0.62**
Total State Line to Long Lake Dam	—	—	**62.0**	—	—	—	—	**8.9**

Light pink = free-flowing riverine reaches
Dark pink = reservoir reaches

RM: River Mile, LSR: Lower Spokane River
[a] Flow bases are all USGS stream gages. The labels used here are chosen to clearly indicate the near-exact location of the gage station, rather than using the official USGS gage name. For example, “Plantes Ferry” refers to USGS 12421500 “Spokane River below Trent Bridge near Spokane, WA”, which is actually near Plantes Ferry park.
[b] For gages that were not active during 2022, we estimated flows at that location based on the regression between flows at that gage and flows at a nearby gage, for a time period when both were active.
[c] Unless otherwise noted, we estimated free-flowing river velocities from the gage indicated as the flow basis.
[d] We estimated velocities for the long State Line – Plante’s Ferry reach as the average of velocity estimates from four USGS locations: Post Falls, State Line, Barker Road, and Plante’s Ferry.
[e] The Spokane Falls move very quickly. We do not have data for this reach. We used the highest value from any other reach. This may still be an underestimate. However, this is such a small reach that it doesn’t affect the total estimates much.
[f] For March– May, we estimated velocities for the Sandifur Bridge – Nine Mile reach using Sandifur Bridge (USGS Spokane River at Spokane) rather than Nine Mile. This reach contains significant rapids, and Sandifur Bridge produced a slightly higher estimate.
[g] Bauer, 2023, pers. comm.
[h] Gendaszek et al. 2016

Table J-2. Estimated time-of-travel for the Spokane River system from Washington/Idaho state line to Long Lake Dam, July – October 2022 mean flow condition.

Reach	Upper RM	Lower RM	Reach length (mi)	Approx flow (cfs)	Flow basis [a b]	Estimated velocity (ft/s) [c]	Reservoir Volume (acre-ft)	Estimated travel time (d)
State Line – Plante's Ferry	96.0	84.2	11.8	1643	Post Falls	1.4 [d]	—	0.50
Plante's Ferry – Upriver pool	84.2	83.1	1.1	1936	Plantes Ferry	1.4	—	0.048
Upriver Dam pool	83.1	80.2	2.9	1936	Plantes Ferry	—	3,000 [g]	0.78
Upriver Dam – Greene Street	80.2	78.0	2.2	2038	Greene St.	1.4	—	0.094
Greene St. – Upper Falls pool	78.0	76.8	1.2	2038	Greene St.	1.4	—	0.051
Upper Falls Dam pool	76.8	74.5	2.3	1961	Sandifur Bridge	—	800 [g]	0.21
Spokane Falls	74.5	74.1	0.4	1961	Sandifur Bridge	1.8 [e]	—	0.013
Monroe Street Dam pool	74.1	73.95	0.1	1961	Sandifur Bridge	—	30 [g]	0.0077
Monroe St. Dam – Sandifur Bridge	73.95	72.4	1.6	1961	Sandifur Bridge	1.3	—	0.070
Sandifur Bridge – Nine Mile Reservoir	72.4	63.9	8.5	2240	Nine Mile	1.8 [f]	—	0.28
Nine Mile Reservoir	63.9	58.1	5.8	2240	Nine Mile	—	4,600 [g]	1.0
Nine Mile Dam – Lake Spokane	58.1	57.1	1.0	2240	Nine Mile	1.8	—	0.033
Lake Spokane	57.1	34.0	23.1	2610	Nine Mile + LSR	—	243,000 [h]	47
Total State Line to Lake Spokane	—	—	**38.9**	—	—	—	—	**3.1**
Total State Line to Long Lake Dam	—	—	**62.0**	—	—	—	—	**50**

Light pink = free-flowing riverine reaches
Dark pink = reservoir reaches

RM: River Mile, LSR: Lower Spokane River
[a] Flow bases are all USGS stream gages. The labels used here are chosen to clearly indicate the near-exact location of the gage station, rather than using the official USGS gage name. For example, "Plantes Ferry" refers to USGS 12421500 "Spokane River below Trent Bridge near Spokane, WA", which is near Plantes Ferry park.
[b] For gages that were not active during 2022, we estimated flows at that location based on the regression between flows at that gage and flows at a nearby gage, for a time period when both were active.
[c] Unless otherwise noted, we estimated free-flowing river velocities from the gage indicated as the flow basis.
[d] We estimated velocities for the long State Line — Plante's Ferry reach as the average of velocity estimates from four USGS locations: Post Falls, State Line, Barker Road, and Plante's Ferry.
[e] The Spokane Falls move very quickly. We do not have data for this reach. We used the highest value from any other reach. This may still be an underestimate. However, this is such a small reach that it doesn't affect the total estimates much.
[f] For July – October, we estimated velocities for the Sandifur Bridge — Nine Mile reach using Nine Mile estimates. This reach contains significant rapids, and Nine Mile produced a higher estimate than Sandifur Bridge.
[g] Bauer 2023, pers. comm.
[h] Gendaszek et al. 2016

References — Appendix J

Bauer, J., 2003. Personal communication. Email June 8, 2023. Washington State Department of Ecology Water Quality Program.

Gendaszek, A., S. Cox, and A. Spanjer, 2016. Preliminary Characterization of Nitrogen and Phosphorus in Groundwater Discharging to Lake Spokane, Northeastern Washington, Using Stable Nitrogen Isotopes. U.S. Geological SurveyOpen-File Report 2016-1029. https://pubs.usgs.gov/publication/ofr20161029

Appendix K. Lower Little Spokane River high-flow source tracking survey

2015 – 2016 monitoring for the *Little Spokane River DO, pH, and TP TMDL* (Johnson et al. 2020) found a large TP and sediment load of unknown origin entering the river somewhere in the lower 13 miles. This load occurred consistently during the high-flow springtime period but not during other seasons.

To narrow down the source of this load, Ecology conducted a high-flow period synoptic survey on the lower Little Spokane River on April 6, 2022. Flow conditions during this survey were about 450 cfs at the USGS at Dartford gage, and about 709 cfs at the USGS near Dartford (painted rocks) gage. These flows are similar to the conditions where we observed the "mystery load" during 2015 – 2016.

Table K-1 presents the flow balance for this source tracking survey. Tables K-2 and K-3 present the TP and TSS balances. The total TP residual from N. LSR Dr. (55LSR-13.5) to the mouth (55B070) was +26.0 lbs/day, of which about +11 lbs/day are accounted for as Spokane Valley-Rathdrum Prairie Aquifer (SVRPA) inflows, leaving about +15 lbs/day unaccounted. This contrasts with about +51 lbs/day human load [25] for March – May during 2015 – 2016. The total TSS residual over this reach was +5.9 tons/day, as compared to values ranging from +5 to +49 tons/day during spring 2015.

Overall, the TP and TSS load increases observed during our April 2022 survey were much less than those observed during 2015 – 2016. Furthermore, we observed substantial variation or "noise" in our survey data, with a large negative residual in one reach sometimes being balanced out by a large positive residual in the next. This likely is a result of dynamic instability, i.e., the system not being at "steady state," inherent to high-flow conditions.

To further illustrate this, we can look at TP in the reaches between Dartford (55LSR-10.3) and Painted Rocks (55LSR-03.9), which is where nearly all the SVRPA aquifer inflows occur. The expected residual in this reach would be about +11.0 lbs/day, given known SVRPA loads *not* accounted in the surface springs. The measured residual was +17.9 lbs/day. The discrepancy, therefore, is +7.9 lbs/day, or only +5.5% of the total downstream load, well within the range of measurement error.

Therefore, we concluded that we did not find evidence of the 2015 – 2016 "mystery load."

[25] Table 25 in Johnson et al. 2020. This value is given as 23 kg/day, converted here to 51 lbs/day.

Table K-1. Flow balance for the April 6, 2022 lower Little Spokane River source tracking survey.

Site ID	Location	Rkm [a]	Mainstem flow (cfs)	Trib flow (cfs)	Flow residual (cfs)	Flow residual %
55LSR-13.5	LSR @ North LSR Drive	23.5	364.8	—	—	—
55LDP-00.1	Little Deep Creek @ SS Road	22.9	—	9.5	—	—
55DEA-00.6	Deadman Creek @ SS Road	22.9	—	50.5	—	—
55LSR-11.7	LSR @ Pine River Park	21.2	461.0	—	+36.1	+7.8%
55WAN-00.0	Wandermere Springs	20.3	—	7.9	—	—
55LSR-10.3	LSR @ North Dartford Drive	19.3	463.5	—	-5.5	-1.2%
55DAR-00.2	Dartford Creek	19.2	—	2.9	—	—
55WAK-00.0	Waikiki Springs Main branch	17.8	—	12.6	—	—
55WAK-PND	Waikiki Springs Pond branch.	17.7	—	2.0	—	—
55LSR-09.4	LSR below Waikiki Springs	17.5	466.9	—	-14.0	-3.0%
55WAK-VIS	Waikiki Springs Vistawood branch	17.0	—	1.5	—	—
55WAK-KCC	Waikiki Springs KCC branch	17.0	—	2.2 [b]	—	—
55LSR-07.5	LSR @ West Waikiki Road	13.9	661.5	—	+191.0	+28.9%
55GRI-00.0	Griffith Springs @ mouth	12.6	—	32.5	—	—
55LSR-05.5	LSR below Saint George's	10.0	729.8	—	+35.8	+4.9%
55LSR-03.9	LSR @ Painted Rocks	7.4	740.1	—	+10.3	+1.4%
55B070	LSR @ Mouth	1.8	731.3	—	-8.8	-1.2%
Total	**Top-to-Bottom**	—	—	—	**+244.9**	**+33.5%**
Total	**Dartford-to-Painted Rocks**	—	—	—	**+223.1**	**+30.1%**

Blue = mainstem Little Spokane River (LSR) locations

Purple = tributary and surface spring locations

[a] River distances in km, from high-resolution digitized stream centerline. This captures true stream distance through the present-day configuration of the meandering lower river.

[b] We did not sample the Kalispel Country Club (KCC) branch of Waikiki Springs during 2022. We used the average of four measurements taken during July – August 2010. Based on flow patterns at the two USGS gages on the lower Little Spokane River, it is unlikely that any of these springs exhibit much seasonal flow variation.

Table K-2. Total phosphorus mass balance for the April 6, 2022 lower Little Spokane River source tracking survey.

Site ID	Location	Rkm [a]	Mainstem TP (mg/L)	Trib TP (mg/L)	Mainstem TP load (lbs/day)	Trib TP load (lbs/day)	TP load residual (lbs/day)	TP load residual %
55LSR-13.5	LSR @ North LSR Drive	23.5	0.0398	—	78.3	—	—	—
55LDP-00.1	Little Deep Creek @ SS Road	22.9	—	0.0644	—	3.3	—	—
55DEA-00.6	Deadman Creek @ SS Road	22.9	—	0.0531	—	14.5	—	—
55LSR-11.7	LSR @ Pine River Park	21.2	0.0441	—	109.7	—	+13.6	+12.4%
55WAN-00.0	Wandermere Springs	20.3	—	0.0105	—	0.45	—	—
55LSR-10.3	LSR @ North Dartford Drive	19.3	0.0415	—	103.7	—	-6.4	-6.1%
55DAR-00.2	Dartford Creek	19.2	—	0.0369	—	0.57	—	—
55WAK-00.0	Waikiki Springs Main branch	17.8	—	0.0050 [b]	—	0.34	—	—
55WAK-PND	Waikiki Springs Pond branch	17.7	—	0.0074	—	0.078	—	—
55LSR-09.4	LSR below Waikiki Springs	17.5	0.0341	—	85.9		-18.9	-22.0%
55WAK-VIS	Waikiki Springs Vistawood branch	17.0	—	0.0050 [b]	—	0.039	—	—
55WAK-KCC	Waikiki Springs KCC branch	17.0	—	0.0050	—	0.059	—	—
55LSR-07.5	LSR @ West Waikiki Road	13.9	0.0324	—	115.6	—	+29.6	+25.6%
55GRI-00.0	Griffith Springs @ mouth	12.6	—	0.0215	—	3.8	—	—
55LSR-05.5	LSR below Saint George's	10.0	0.0315	—	124.0	—	+4.6	+3.7%
55LSR-03.9	LSR @ Painted Rocks	7.4	0.0317	—	126.5	—	+2.5	+2.0%
55B070	LSR @ Mouth	1.8	0.0323	—	127.4	—	+0.9	+0.7%
Total	**Top-to-Bottom**	—	—	—	—	—	**+26.0**	**+20.4%**
Total	**Dartford-to-Painted Rocks**	—	—	—	—	—	**+17.9**	**+14.2%**

Blue = mainstem Little Spokane River (LSR) locations

Purple = tributary and surface spring locations

[a] River distances in km, from high-resolution digitized stream centerline. This captures true stream distance through the present-day configuration of the meandering lower river.

[b] These values were non-detects at 0.005 mg/L. Given concentrations in other springs, including the Waikiki Springs pond branch, and subsurface inflows, we estimate that the reporting limit is likely closer to the true value than half the reporting limit. Therefore, we estimated 0.005 mg/L.

[c] We did not sample the Kalispel Country Club (KCC) branch of Waikiki Springs during 2022. Of four samples taken during July – August 2010, three were non-detects at 0.005, and one was a detection at just slightly over 0.005. Therefore, we estimated a value of 0.005 mg/L.

Table K-3. Total suspended solids mass balance for the April 6, 2022 lower Little Spokane River source tracking survey.

Site ID	Location	Rkm [a]	Mainstem TSS (mg/L)	Trib TSS (mg/L)	Mainstem TSS load (tons/day)	Trib TSS load (tons/day)	TSS load residual (tons/day)	TSS load residual %
55LSR-13.5	LSR @ North LSR Drive	23.5	17	—	16.7	—	—	—
55LDP-00.1	Little Deep Creek @ SS Road	22.9	—	5	—	0.13	—	—
55DEA-00.6	Deadman Creek @ SS Road	22.9	—	4	—	0.54	—	—
55LSR-11.7	LSR @ Pine River Park	21.2	14	—	17.4	—	+0.0	+0.0%
55WAN-00.0	Wandermere Springs.	20.3	—	0 [b]	—	0	—	—
55LSR-10.3	LSR @ North Dartford Drive	19.3	13	—	16.2	—	-1.2	-7.1%
55DAR-00.2	Dartford Creek	19.2	—	10	—	0.077	—	—
55WAK-00.0	Waikiki Springs Main branch.	17.8	—	0 [b]	—	0	—	—
55WAK-PND	Waikiki Springs Pond branch.	17.7	—	0 [b]	—	0	—	—
55LSR-09.4	LSR below Waikiki Springs	17.5	13	—	16.4	—	+0.0	+0.3%
55WAK-VIS	Waikiki Springs Vistawood branch	17.0	—	0 [b]	—	0.0	—	—
55WAK-KCC	Waikiki Springs KCC branch	17.0	—	0 [b]	—	0.0	—	—
55LSR-07.5	LSR @ West Waikiki Road	13.9	10	—	17.8	—	+1.5	+8.3%
55GRI-00.0	Griffith Springs @ mouth	12.6	—	3	—	0.26	—	—
55LSR-05.5	LSR below Saint George's	10.0	9.5	—	18.7	—	+0.6	+3.2%
55LSR-03.9	LSR @ Painted Rocks	7.4	10	—	20.0	—	+1.3	+6.3%
55B070	LSR @ Mouth	1.8	12	—	23.7	—	+3.7	+15.7%
Total	**Top-to-Bottom**	—	—	—	—	—	**+5.9**	**+25.0%**
Total	**Dartford-to-Painted Rocks**	—	—	—	—	—	**+3.4**	**+16.9%**

Blue = mainstem Little Spokane River (LSR) locations

Purple = tributary and surface spring locations

[a] River distances in km, from high-resolution digitized stream centerline. This captures true stream distance through the present-day configuration of the meandering lower river.

[b] The total suspended solids (TSS) result for all springs were non-detects, including 55WAK-KCC data from 2010. These springs all produce very clear water, with measured turbidity ≤ 1 NTU. Therefore, we are estimating TSS concentration of zero for these inflows.

References — Appendix K

Johnson, C., T. Stuart, and P. Pickett, 2020. Little Spokane River Dissolved oxygen, pH, and Total Phosphorus Total Maximum Daily Load. Washington State Department of Ecology, Olympia, WA. Publication 20-10-033. https://apps.ecology.wa.gov/publications/SummaryPages/2010033.html

Appendix L. Selected longitudinal data plots

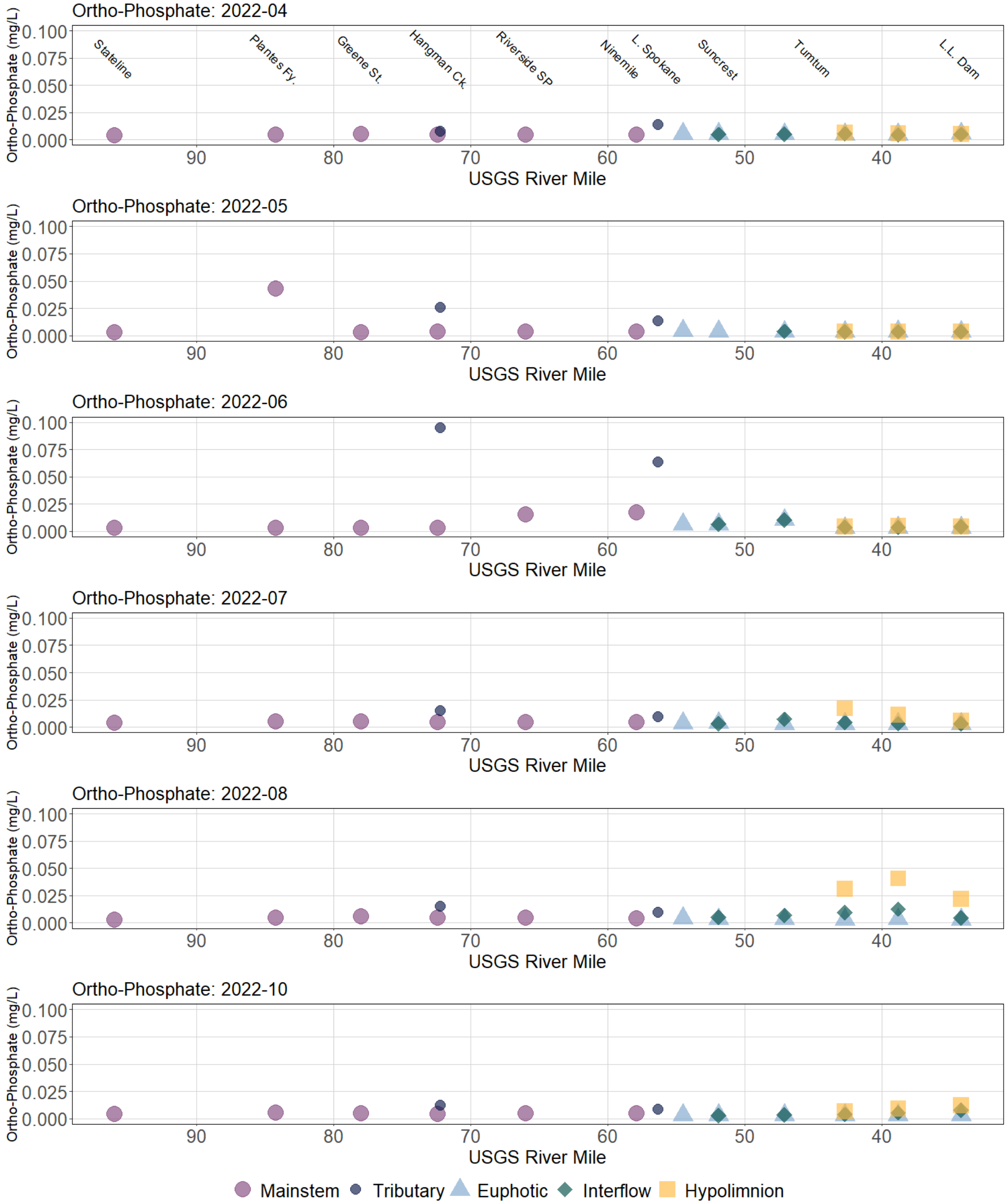

Figure L-1. Longitudinal plots of ortho-phosphate concentration in the Spokane River in 2022.

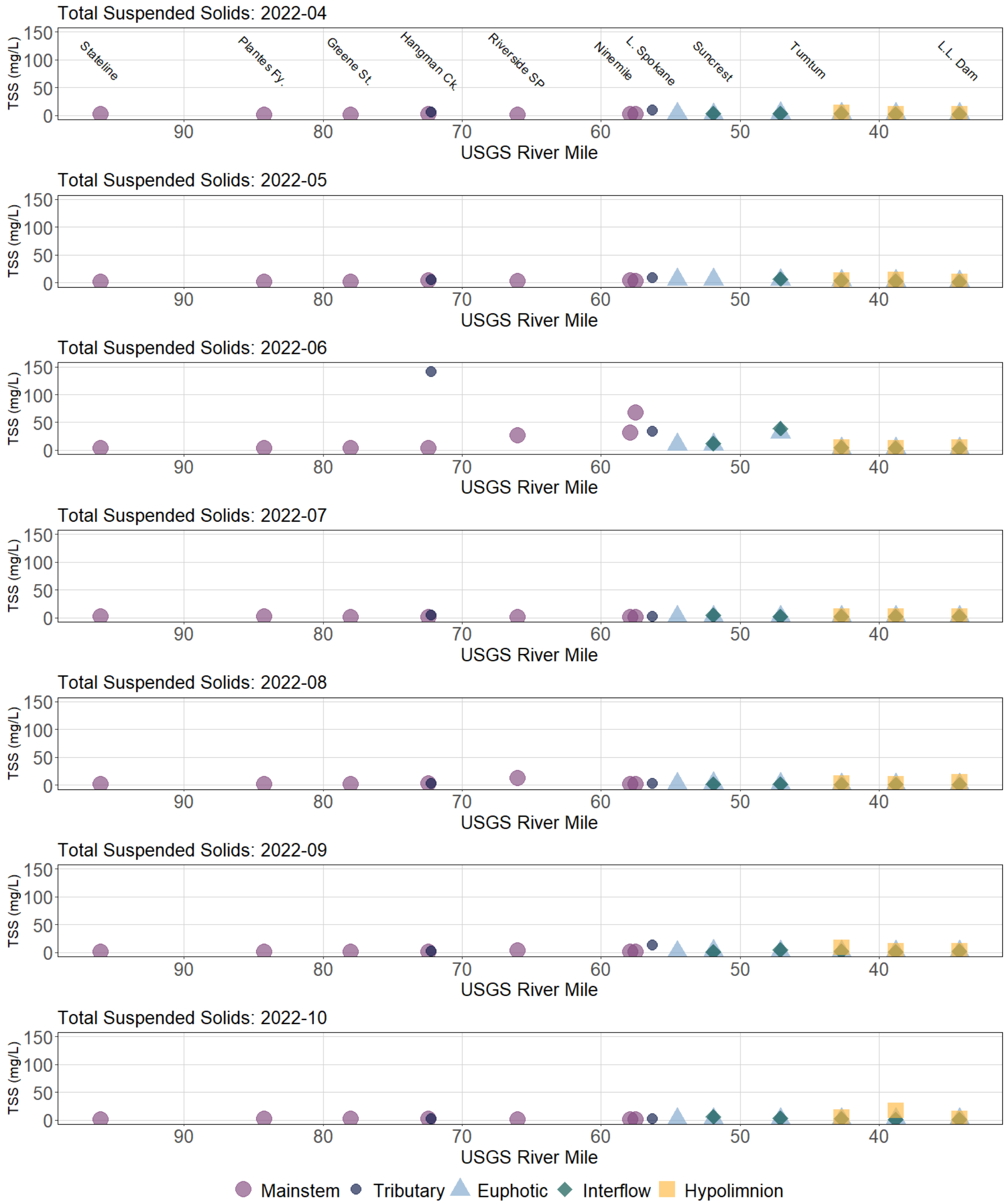

Figure L-2. Longitudinal plots of total suspended solid concentration in the Spokane River in 2022.

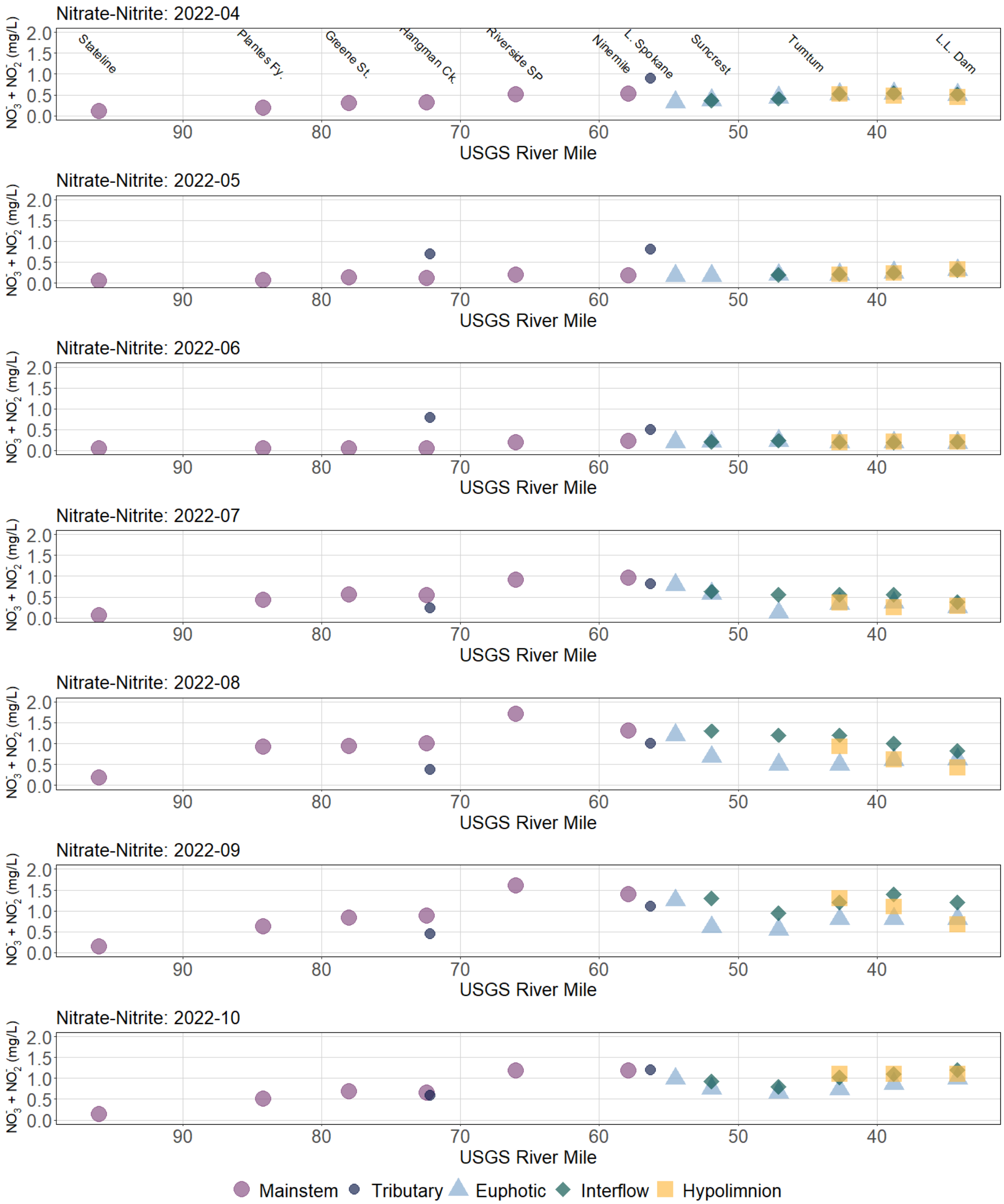

Figure L-3. Longitudinal plots of nitrate-nitrite as N concentration in the Spokane River 2022.

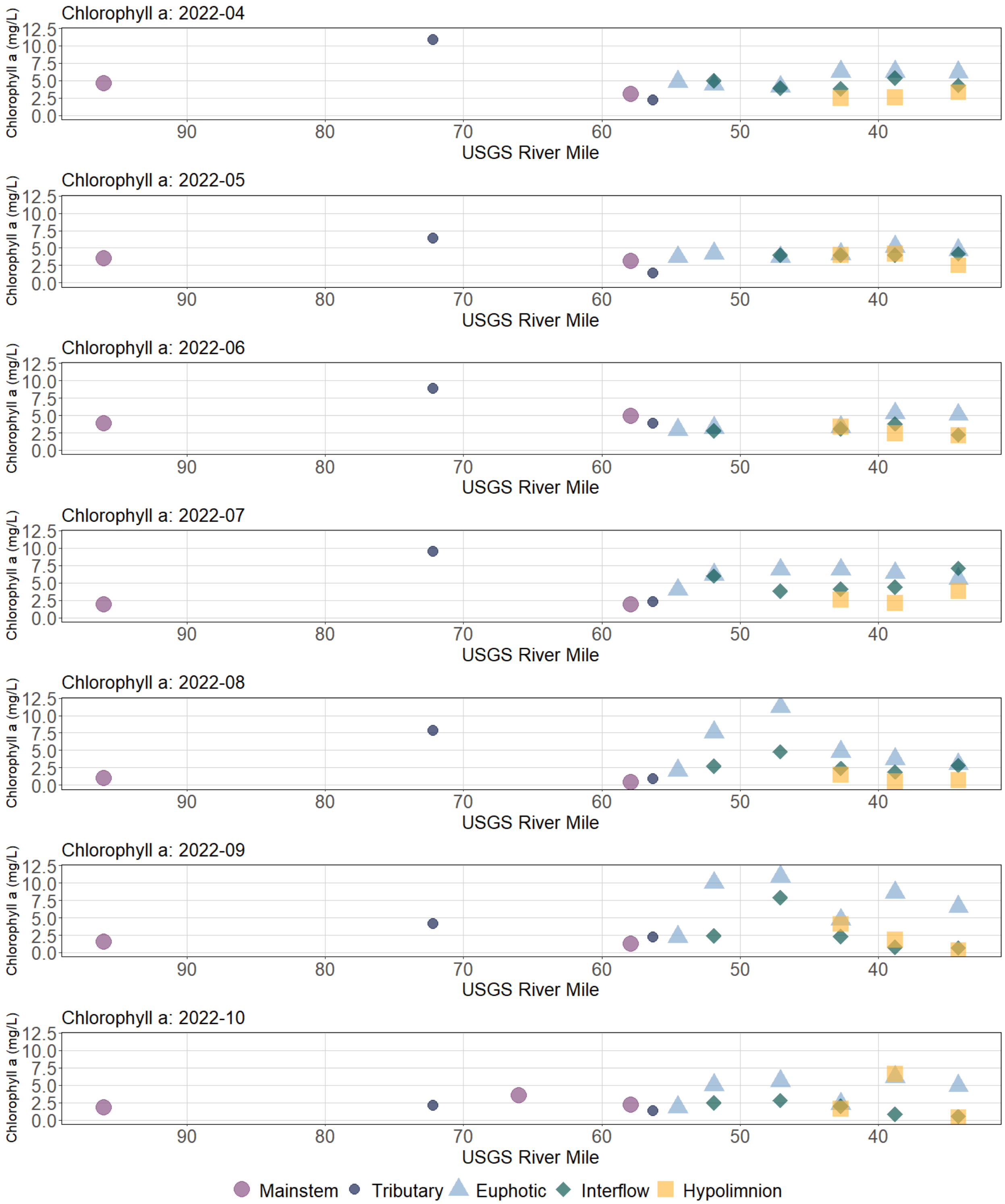

Figure L-4. Longitudinal plots of chlorophyll *a* concentration in the Spokane River in 2022.

Appendix M. Selected time-series data plots for the Spokane River

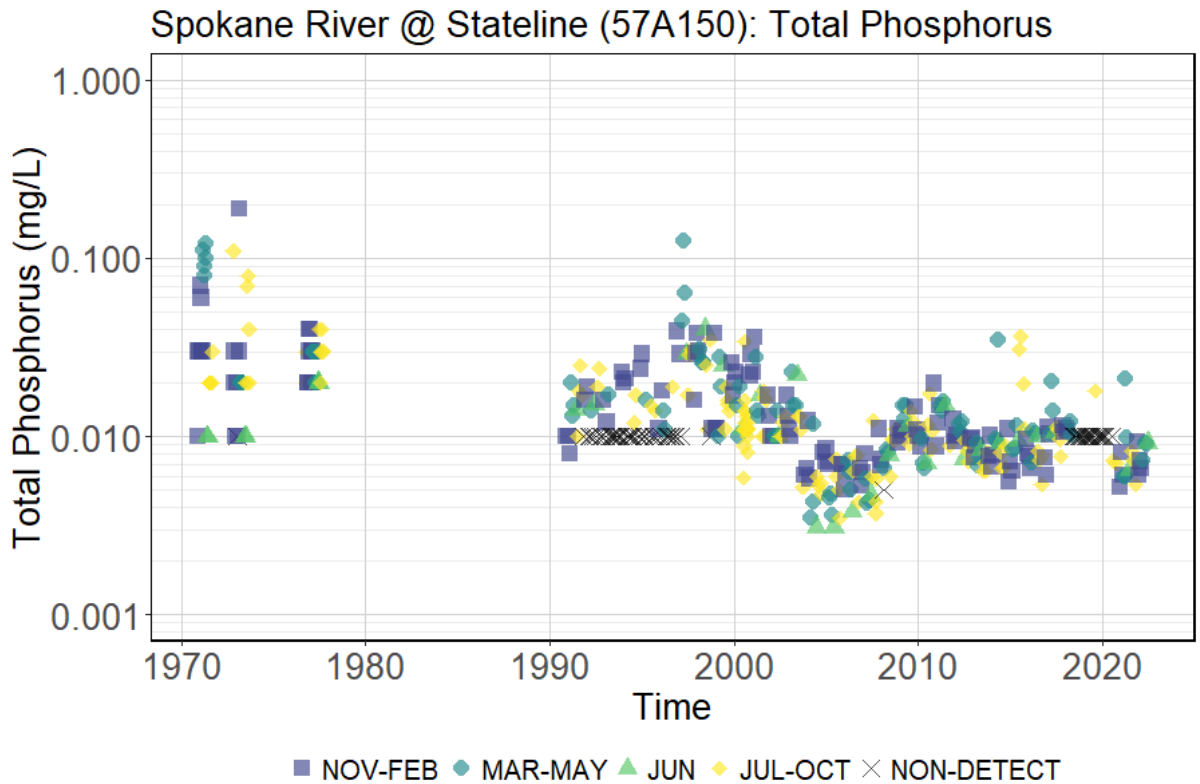

Figure M-1. Time-series data of total phosphorus concentration in the Spokane River at the WA/ID state line (57A150).

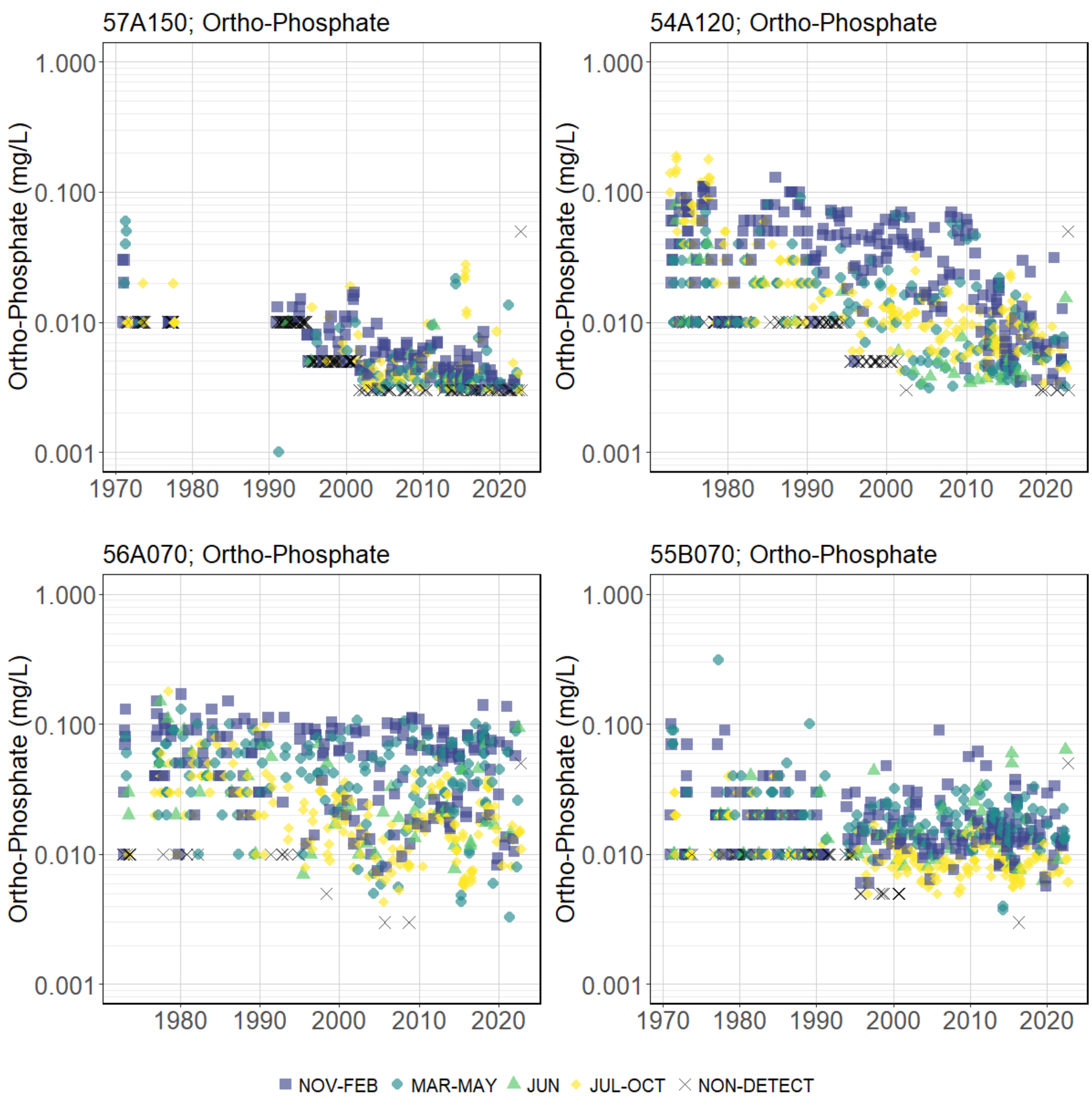

Figure M-2. Time-series plots of ortho-phosphate concentration in the Spokane River at the WA/ID state line (57A150; top left), the Spokane River at Riverside State Park (54A120; top right), Hangman Creek near the mouth (56A070; bottom left), and the Little Spokane River near the mouth (55B070; bottom right).

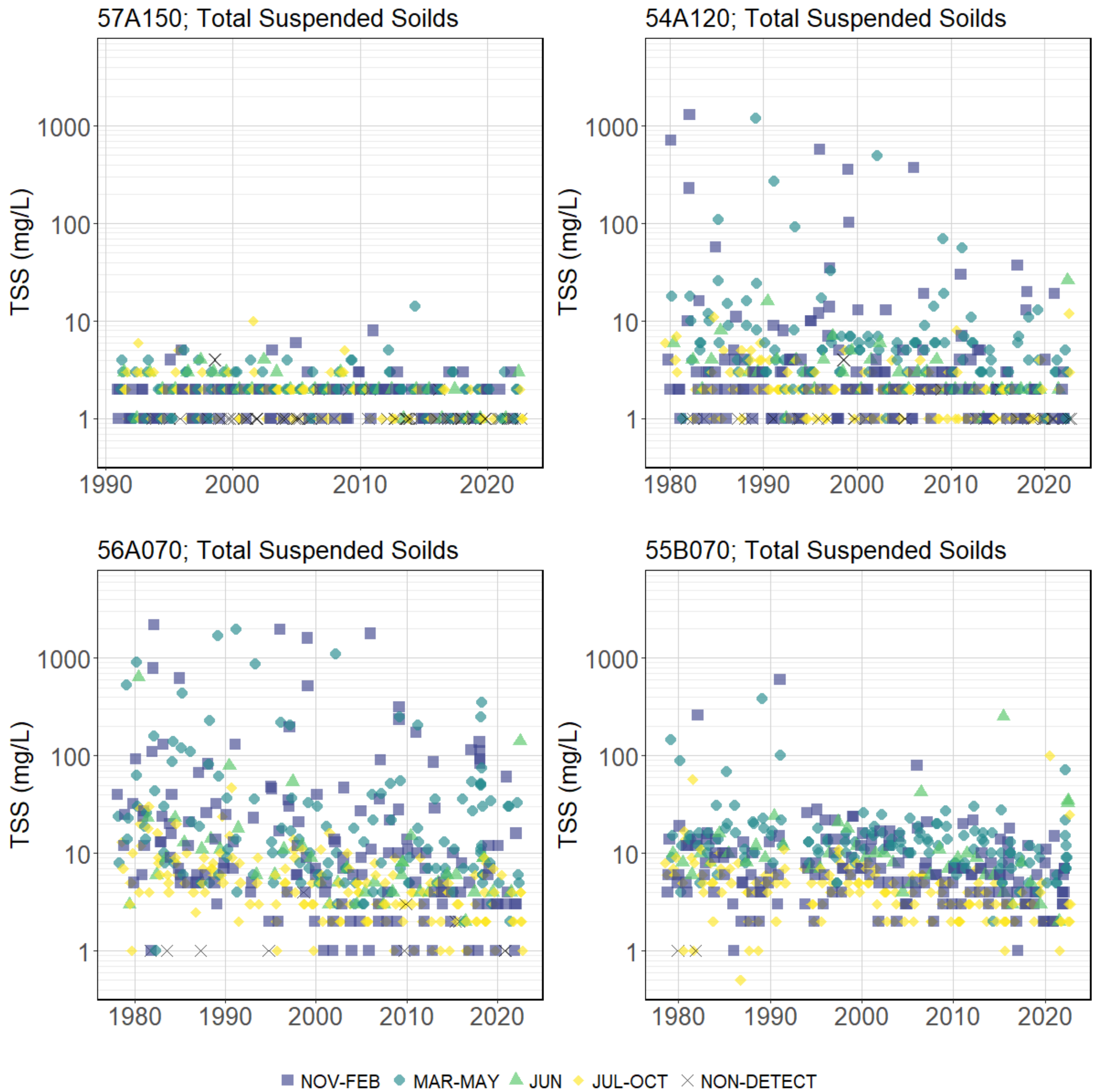

Figure M-3. Time-series plots of total suspended solid concentration in the Spokane River at the WA/ID state line (57A150; top left), the Spokane River at Riverside State Park (54A120; top right), Hangman Creek near the mouth (56A070; bottom left), and the Little Spokane River near the mouth (55B070; bottom right).

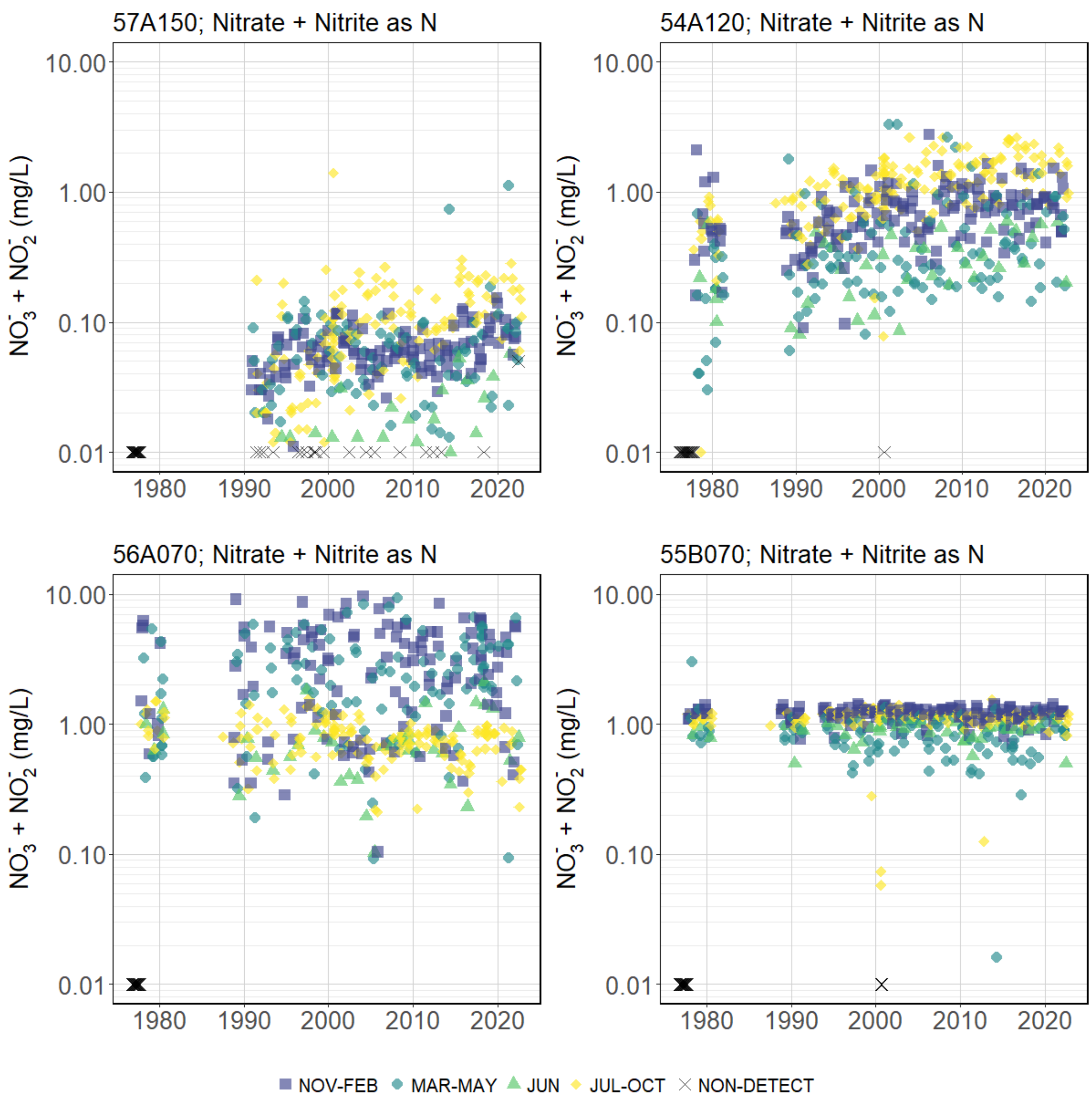

Figure M-4. Time-series plots of nitrate-nitrite nitrogen concentration in the Spokane River at the WA/ID state line (57A150; top left), the Spokane River at Riverside State Park (54A120; top right), Hangman Creek near the mouth (56A070; bottom left), and the Little Spokane River near the mouth (55B070; bottom right).

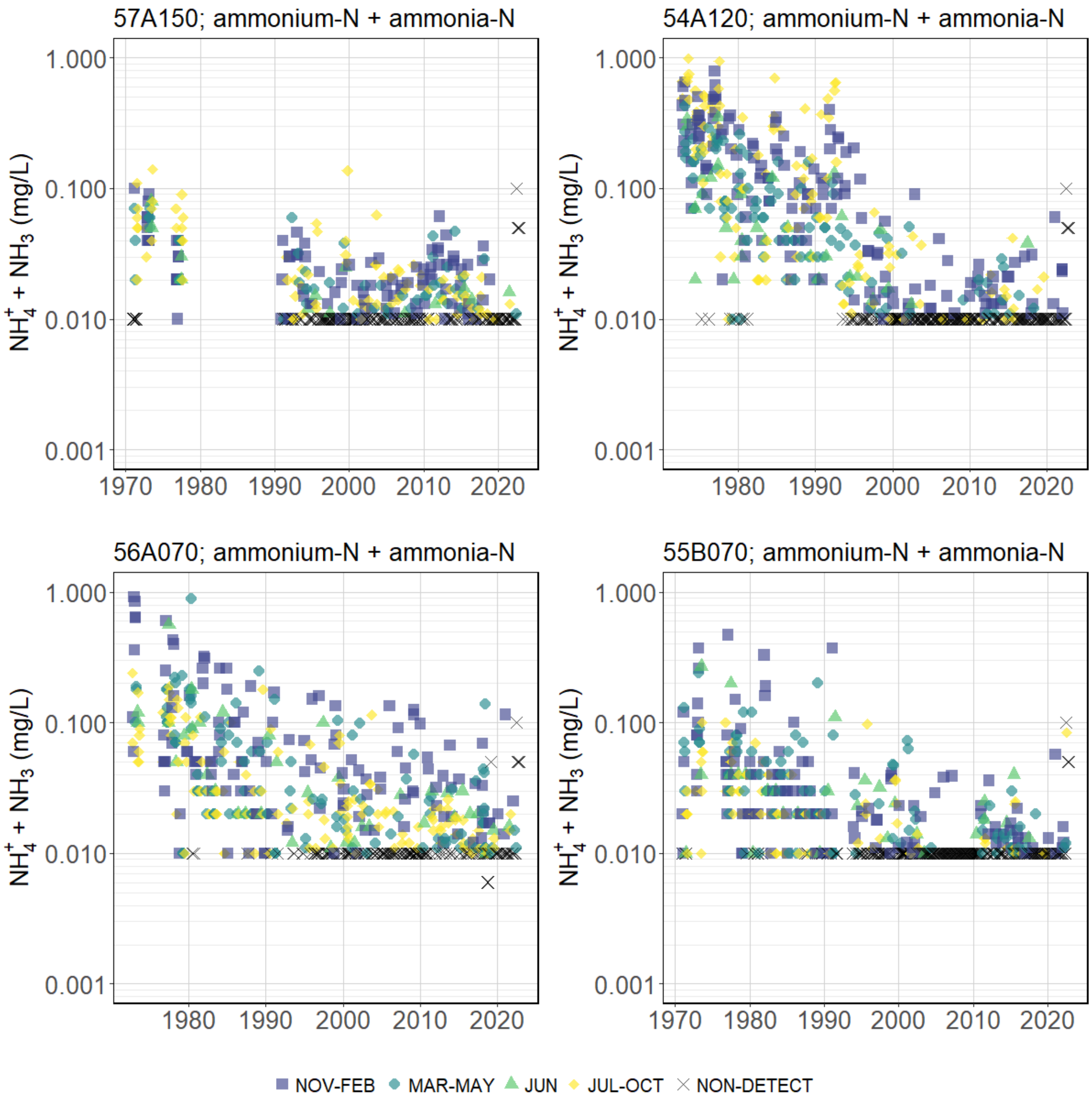

Figure M-5. Time-series plots of ammonia concentration in the Spokane River at the WA/ID state line (57A150: top left), the Spokane River at Riverside State Park (54A120; top right), Hangman Creek near the mouth (56A070; bottom left), and the Little Spokane River near the mouth (55B070; bottom right).

Appendix N. Selected time-series data plots for Lake Spokane

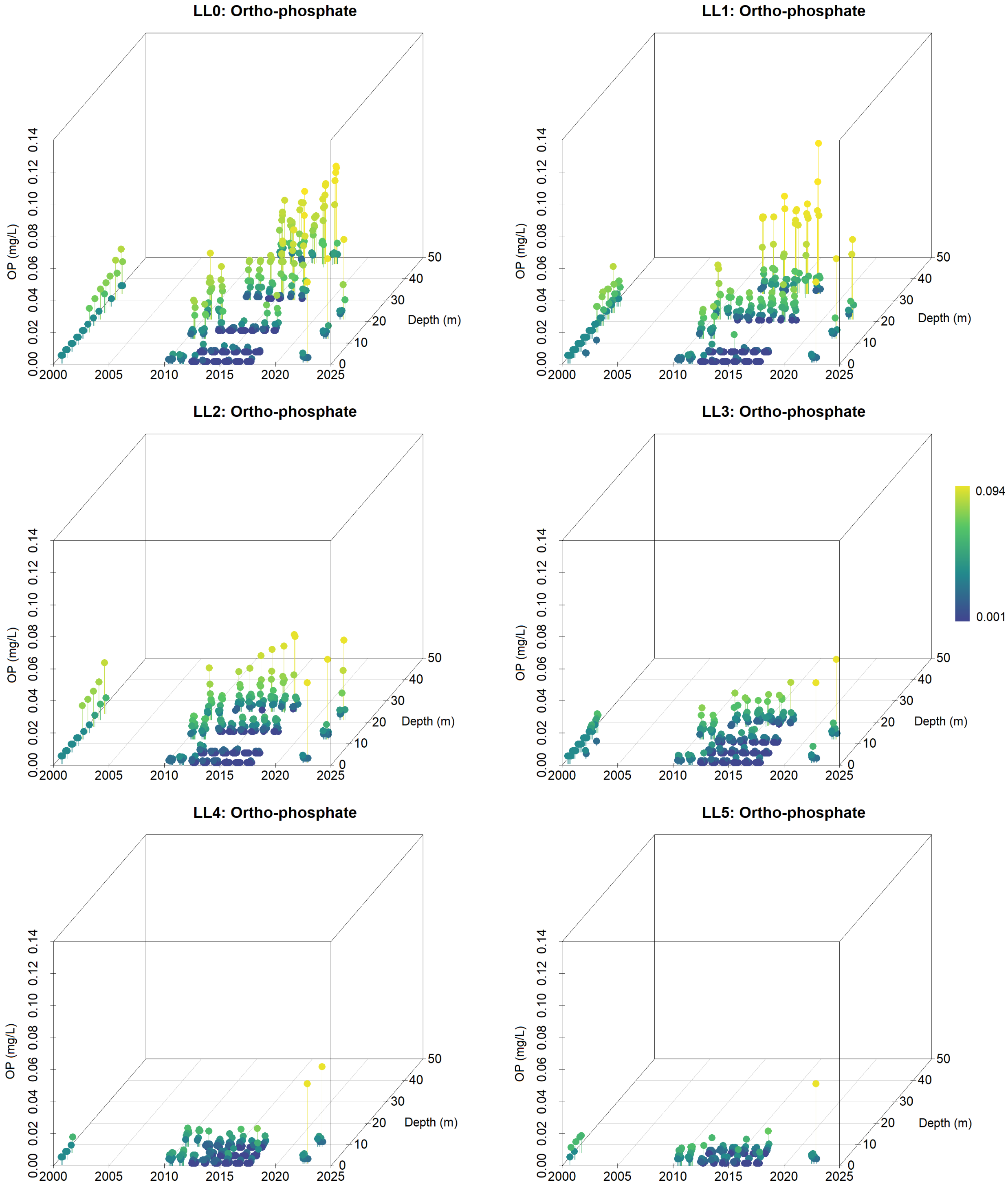

Figure N-1. Time-series data of ortho-phosphate concentrations in Lake Spokane at LL0, LL1, LL2, LL3, LL4, and LL5.

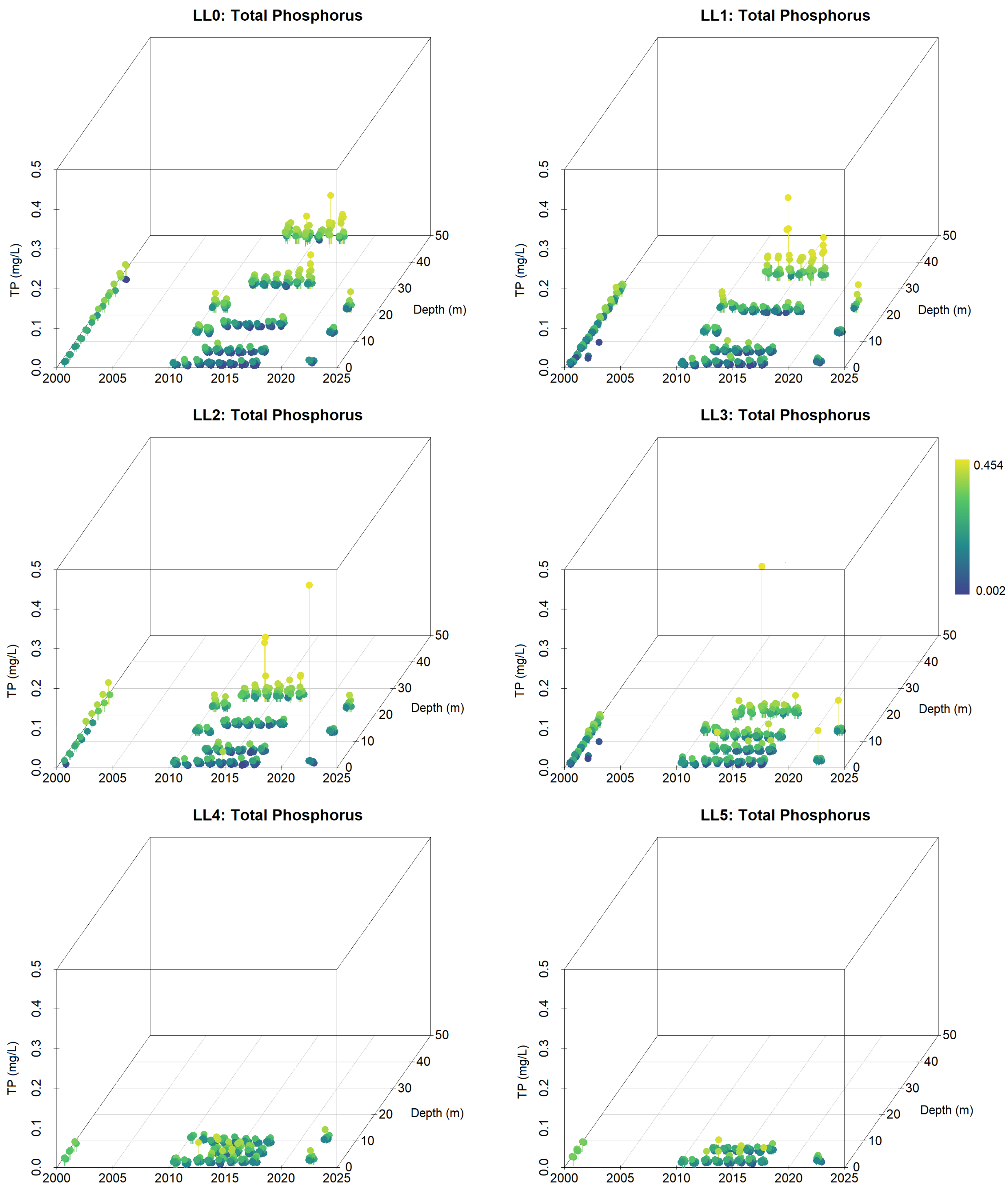

Figure N-2. Time-series data of total phosphorus concentrations in Lake Spokane at LL0, LL1, LL2, LL3, LL4, and LL5.

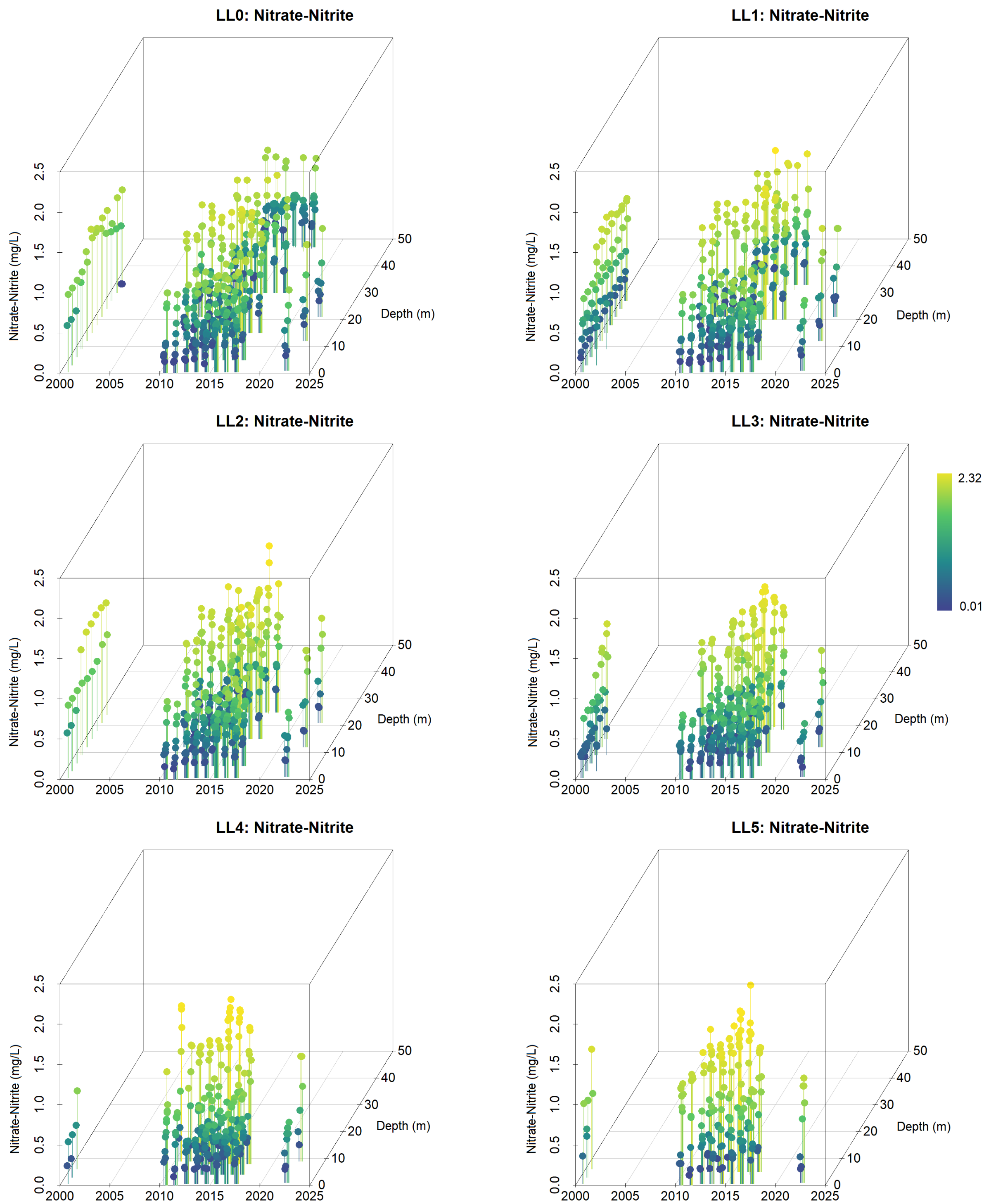

Figure N-3. Time-series data of nitrate-nitrite concentrations in Lake Spokane at LL0, LL1, LL2, LL3, LL4, and LL5.

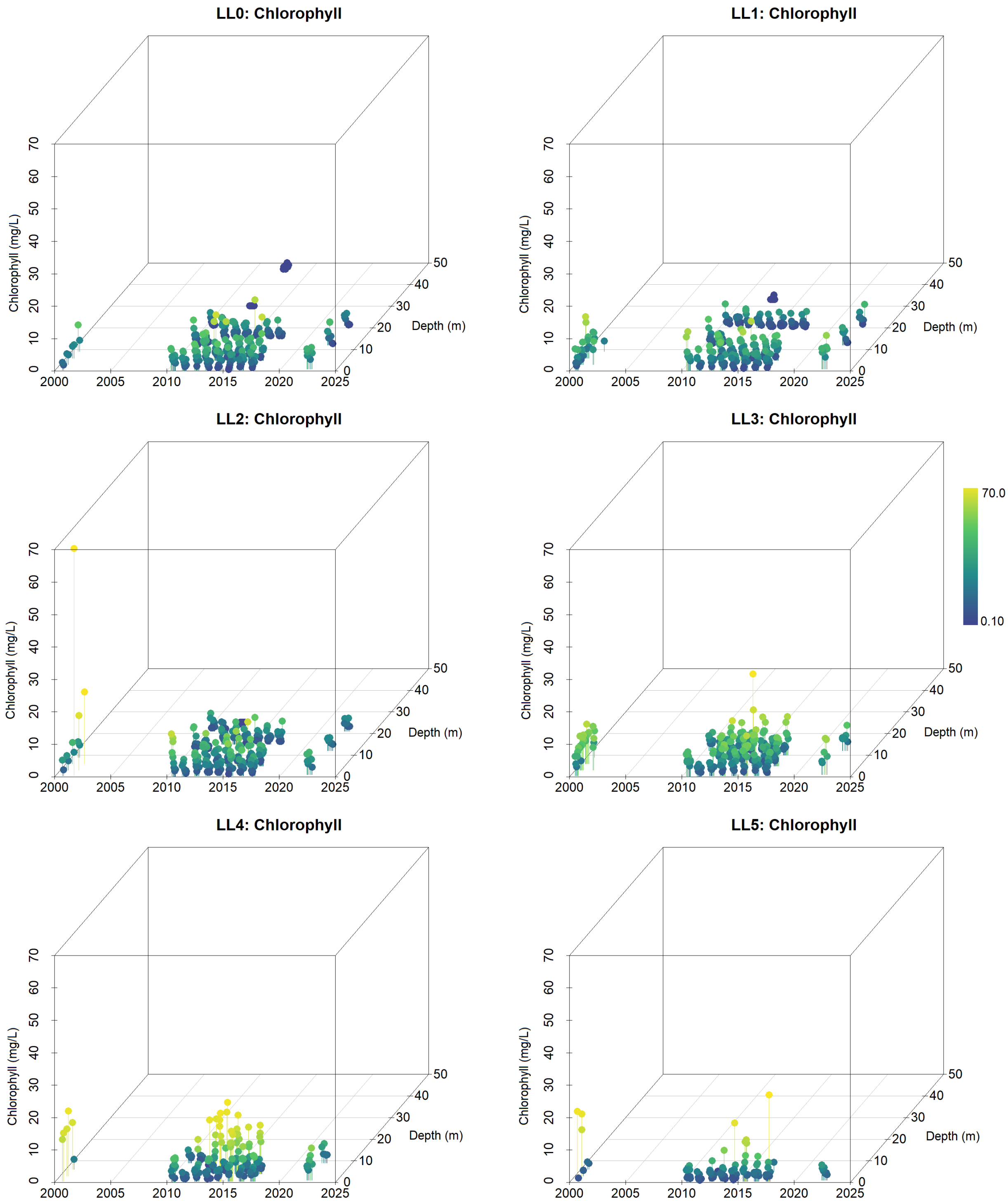

Figure N-4. Time-series data of chlorophyll *a* concentrations in Lake Spokane at LL0, LL1, LL2, LL3, LL4, and LL5.