Geosyntec consultants

engineers | scientists | innovators

LACAMAS, ROUND, AND FALLEN LEAF LAKES MANAGEMENT PLAN AND LAKE CYANOBACTERIA MANAGEMENT PLAN

LACAMAS, ROUND, AND FALLEN LEAF LAKES, CLARK COUNTY, WASHINGTON

Prepared for

The City of Camas

Prepared by

Geosyntec Consultants
MacKay Sposito
JLA Public Involvement
Annear Water Resources

September 2023

Lacamas, Round, and Fallen Leaf Lakes Management Plan and Lake Cyanobacteria Management Plan

Lacamas, Round, and Fallen Leaf Lakes, Clark County, Washington

Prepared for

The City of Camas

Prepared by

Geosyntec Consultants
MacKay Sposito
JLA Public Involvement
Annear Water Resources

The following individuals have reviewed this Lake Management Plan and approved it for use.

City of Camas	**Washington State Department of Ecology**
______________________________	______________________________
(Type name here), P.E., etc. Title	(Type name here), P.E., etc. Title

Date

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

APPENDICES

LIST OF ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
µS/cm	microsiemens per centimeter
APAM	Aquatic Plant and Algae Management
Beak and SRI	Beak Consultants, Inc. and Scientific Resources, Inc.
BMP	best management practices
CCD	Clark Conservation District
CCH	Clark County Health
Chl-a	chlorophyll-a
DDE	dichlorodiphenyldichloroethylene
DDT	dichlorodiphenyltrichloroethane
DO	dissolved oxygen
Ecology	Washington Department of Ecology
g/m2	grams per square meter
Geosyntec	Geosyntec Consultants, Inc.
GIS	geographic information system
HABs	harmful algal blooms
HDPE	high density polyethylene
IRC	Intergovernmental Resource Center
LCFEG	Lower Columbia Fish Enhancement Group
LMP	Lake Management Plan
LWC	Lacamas Watershed Council
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mg/m2/day	milligrams per square meter per day
NALMS	North American Lake Management Society
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrite and nitrate
NWS	National Weather Service
OP	orthophosphate
ORP	oxidation-reduction potential
PDUs	precision dose units

PDX	Portland International Airport
PMN	Phytoplankton Monitoring Network
QAPP	Quality Assurance Project Plan
SC	specific conductivity
TKN	total Kjeldahl nitrogen
TMDLs	total maximum daily loads
TSI	trophic state index
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WDFW	Washington Department of Fish and Wildlife
WQA	water quality assessment

EXECUTIVE SUMMARY

This comprehensive Lake Management Plan (Lake Cyanobacteria Management Plan) was developed for Lacamas, Round, and Fallen Leaf Lakes, located in Clark County in southwest Washington. Following increased Harmful Algal Blooms (HABs) in recent years, the City of Camas received a grant from the Washington Freshwater Algae Control Program to support the development of this plan. Additional funds were received from a State Capital Budget allocation, and the City committed $300,000 of stormwater funds for the effort.

Water quality data from both the Lakes and inflows from major tributaries near their discharge to the Lakes were collected for one year. The number and location of sampling locations were identified through and iterative process between the City and the Project Team based on balancing the requirements of Ecology's Lake Cyanobacterial Management Plan template, information available from past studies, value of the data collected to the overall Plan, and the City's available funding for the Project. Water temperature, dissolved oxygen, chlorophyll-a, phosphorus, and nitrogen were measured in the lakes over a period of one year, and this data was used to develop water and nutrient budgets for the lakes.

Key findings from the data included:

- Lacamas Creek is the dominant source of water and phosphorus loading to Lacamas and Round Lakes, representing approximately 90% of the water and 72% of the phosphorus loading to Lacamas and Round Lakes.
- The most elevated total phosphorus concentrations were near the bottom of Lacamas and Round Lakes, and these concentrations were higher than measured in studies and measurements taken in the past 30 years.
- While phosphorus loading from the lake sediments is a meaningful component (approximately 19%) of the phosphorus budget for Lacamas and Round Lakes; it is a substantially smaller component than loading from inflowing creeks, primarily Lacamas Creek.
- Fallen Leaf Lake has similar levels of phosphorus to Lacamas and Round Lakes and should continue to be monitored. However, there have been no cyanotoxin measurements above state recreational guidelines as taken from the state database.

Based on these findings and considering community outreach, recommendations for management actions were developed to improve water quality in the near-term. It is recommended that treatment initially focus on Lacamas Lake only, as Round Lake is located downstream of Lacamas Lake and may see benefits from treatment of Lacamas Lake. Fallen Leaf Lake is not currently recommended for treatment, though it should continue to be monitored and a focus on stormwater discharges should be included in the City's stormwater management program.

Management alternatives recommended for in-lake treatment are outlined below. Detail for how these recommendations were developed is in the body of this Lake Management Plan. In-Lake treatment as described will likely be needed both in the near-term and into the foreseeable future while efforts continue on the full Lacamas Creek Watershed management and water quality improvements.

- Chemical treatment (with alum or Eutrosorb WC) to remove phosphorus from the water column.
- In-lake treatment chemical treatment (with alum or Eutrosorb G) to inactivate the phosphorus in the lake sediments and make it unavailable for algae growth. This additional treatment is recommended only for the deepest areas of Lacamas Lake over a period of 5-10 years.

Other likely options considered but not recommended due to lower expected benefit or higher costs included:

- Injection of alum or Eutrosorb WC to remove phosphorus from Lacamas Creek before it enters Lacamas Lake.
- Aeration or oxygenation of the hypolimnion (near-bottom portion of the lake) to reduce loading of phosphorus from the sediments to the lake. Nanobubblers were also considered but not recommended as part of the larger aeration category.

In addition to in-lake treatments, continuing existing programs to reduce loading of phosphorus from the watershed to the lakes is strongly recommended. Reduction of the loading of phosphorus to the lakes is necessary for long-term improvements, and to reduce or eliminate the long-term need for in-lake treatment.

It is recommended that the City of Camas prioritize stormwater facilities draining to Fallen Leaf Lake for monitoring, maintenance, and retrofits since the watershed for this lake is fully within the City, meaning that the City has more control over loading to Fallen Leaf Lake relative to Lacamas and Round Lakes. Facilities draining to Lacamas and Round Lakes could also be prioritized, but due to the large size of the watershed for these lakes, and the relatively small portion within the City of Camas, the expected benefit would be smaller.

Collaboration with agency and non-profit partners as important Stakeholders was critical to completion of this Plan. Clark County and the Department of Ecology both played vital roles not only in sharing of data collected within the watershed amongst the various efforts of each agency, but also their role in providing technical input and review of the process from beginning to end. Continued partnership and collaboration will be critical to achieving long-term reductions in watershed phosphorus loading. In particular, Clark County has stated that it will continue to fund existing programs, in particular stormwater programs, agricultural management, and septic system management. The Washington State Department of Ecology is developing an Alternative Restoration Plan for Lacamas Creek, expected to be available January 2025. The Alternative Restoration Plan will identify priority areas for improvements and will identify specific targeted programs and areas within the watershed for management projects. The Alternative Restoration Plan will be a primary source of guidance for long-term management strategies for the watershed.

The Public at large also played a vital stakeholder role in the process of developing this Plan and ongoing public education efforts will need to continue if any real progress is to be made outside of the larger public agency projects and programs. Collaboration with Clark Conservation

District and organizations such as the Lacamas Watershed Council, Watershed Alliance of Southwest Washington, City of Vancouver Water Resource Education Center, and Lower Columbia Fish Enhancement Group will be critical to successfully implementing the recommendations of this plan.

This plan is intended to be used by the City of Camas, partner agencies and non-profit organizations to guide management decisions and to seek funding for implementation. Additionally, this plan is not intended to be a one-time, static effort; to bring the watershed and the Lakes back to a condition that existed prior to the creation of the Lacamas Lake dams, this will need to be a living document that adapts through time to meet the changing conditions. It will take everyone working together to achieve the ideal conditions desired.

1. BACKGROUND

1.1 Introduction and Problem Statement

Lacamas, Round, and Fallen Leaf Lakes are located in Clark County in southwest Washington State. These lakes have been classified as eutrophic since at least the 1980s, based on several previous studies (Table 1). Each lake has experienced algae blooms in recent years, with the blooms of most concern being harmful algal blooms (HABs), which are distinguished by the presence of cyanotoxin-producing cyanobacteria. Lacamas and Round Lakes have had more frequent algae blooms in recent years.

The primary inflow to Lacamas Lake is Lacamas Creek, which enters the lake in its northern portion. Round Lake is downstream of Lacamas Lake, and the two lakes are connected by a short channel. Fallen Leaf Lake is located to the west of Lacamas and Round Lakes. Fallen Leaf Lake is higher in elevation, and outflow from Fallen Leaf Lake reaches the downstream end of Lacamas Lake through a pipe when the water level in Fallen Leaf Lake is high enough (Clark County, 2021). Lacamas and Round Lakes are drawn down annually for dam inspections, typically in early September, with the lake typically returning to full volume in October or November.

Lacamas Lake has had cyanotoxin measurements exceeding state guidelines in each year since 2018, including near-continuous exceedances of the guideline for the cyanotoxin microcystin in summer 2020. Round Lake has also seen increases in HABs in recent years and Fallen Leaf Lake had its first recorded algae bloom in 2020—though state guidelines for cyanotoxins were not exceeded—the lake was found to be eutrophic in a recent study from Clark County (2021).

The City of Camas received a grant through the Washington State Department of Ecology (Ecology) Freshwater Algae Control Program to assist with the preparation of this plan. To develop evidence-based recommendations for lake management, and as part of the grant requirements, collection of water quality data sufficient for developing water and nutrient budgets was necessary. As described in Section 1.1.4, the lakes have been studied since the 1980s, but relatively little data has been collected since the mid-2000s. As such, a robust data collection effort was needed to identify science-based management recommendations.

This document describes results from a year-long water quality study of the lakes and their inflows, focusing on parameters relevant to understanding HABs. This information is then analyzed and interpreted to inform the selection of management alternatives to achieve reductions in HABs and public health notices and to improve overall lake water quality.

1.1.1 Lake and Watershed

The Lacamas, Round, and Fallen Leaf Lake watershed includes agricultural, residential, commercial, and industrial land uses. The watershed extends from Hockinson, Washington, in the northern part of the watershed, to Camas, Washington, in the southern part of the watershed. The watershed area is reported as 67 square miles (Gleason and McCarthy, 2021), though as delineated by United States Geological Survey (USGS) StreamStats, the area is 59.7 square miles (38,184 acres). Lacamas Creek flows 18 miles from forested areas through both agricultural and residential areas prior to discharging into Lacamas Lake. There are five major tributaries to Lacamas Creek: Matney Creek, Shanghai Creek, Fifth Plain Creek, China Ditch, and Dwyer Creek (Figure 1).

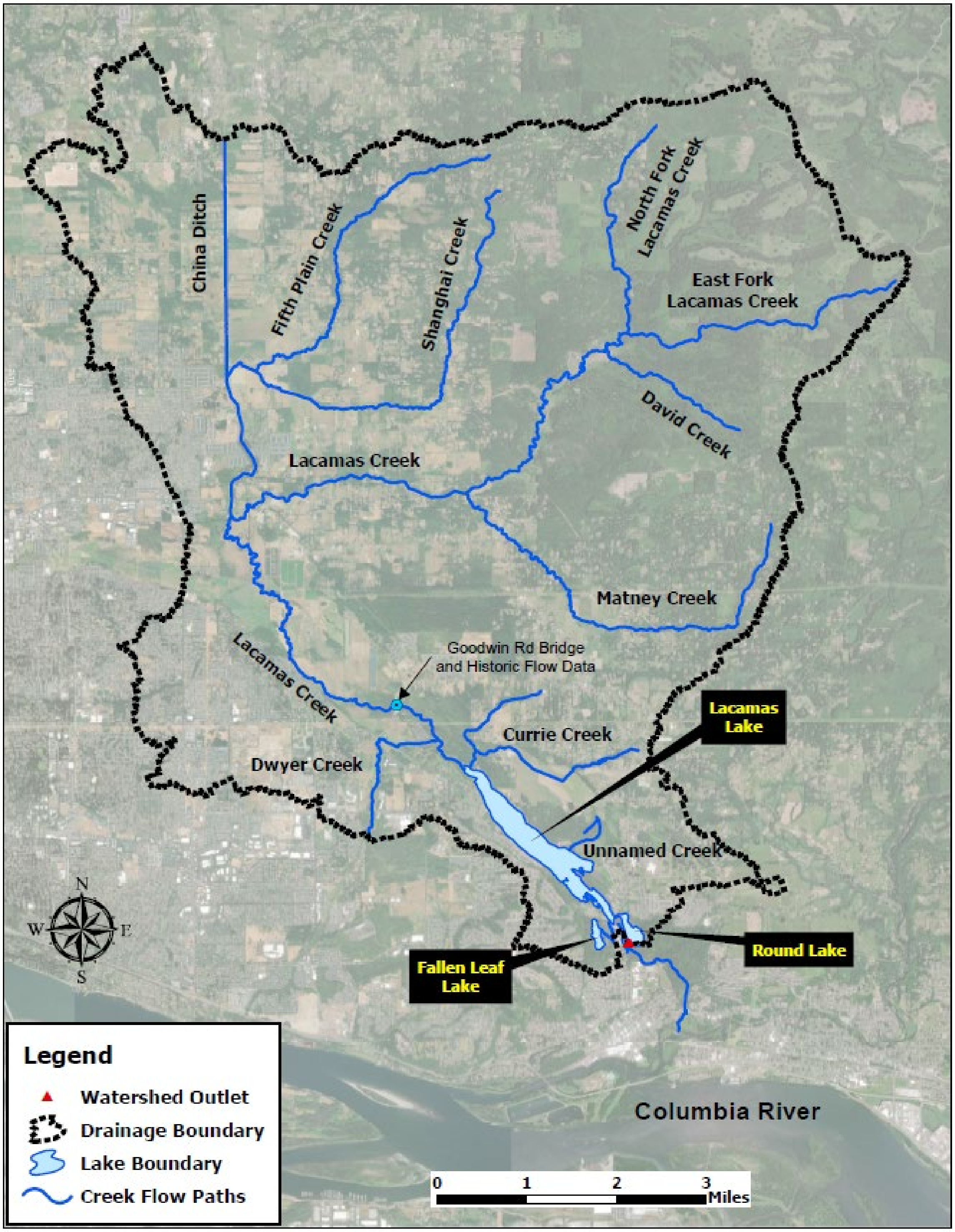

Figure 1. Lacamas/Round Lake watershed as delineated by USGS StreamStats

The largest of the three lakes, Lacamas Lake, is approximately 300 acres with a maximum depth of approximately 60 feet. Lacamas Lake is long and narrow, approximately 2.5 miles long and approximately 0.3 miles wide. The vast majority of inflow to Lacamas Lake is from Lacamas Creek—the historically gaged flow measured at Lacamas Creek at Goodwin Road accounted for approximately 95% of the flow to the lake in the early 1980s as estimated by Beak Consultants, Inc. and Scientific Resources, Inc. (Beak and SRI, 1985). Dwyer Creek enters Lacamas Creek below this gage location, and there is additional limited inflow from Currie Creek, which is a small tributary to Lacamas Lake at its northeast end, and an unnamed creek at its southeast end, both of which drain directly into Lacamas Lake (Figure 1). There are also some direct inflows from stormwater and likely from groundwater. However, direct groundwater inflow is not believed to be a major source of nutrients to the lakes, based on a 1985 study which concluded that groundwater flux was small relative to other portions of the water budget (Beak and SRI, 1985).

Based on 2023 land zoning data from Clark County, the Lacamas Lake watershed is approximately 28% forestland, 14% agriculture, and 51% residential (97% of this being rural and low-density residential), with the remaining 7% made up of commercial and industrial lands, schools, and water (Clark County, 2023). Figure **2** shows a comparison of land use from 1974, based on analysis of aerial photographs performed for a later USGS study (Price et al., 2006), and 2023, based on Clark County zoning data. While exact comparisons in land use changes between the two figures is not recommended due to differences in how the data were created (i.e., historic photographs versus zoning data), a general comparison is still useful in that it shows how much change has occurred in the watershed over the past 50 years, with a clear decrease in forest and agricultural land uses, as well as a clear increase in residential use.

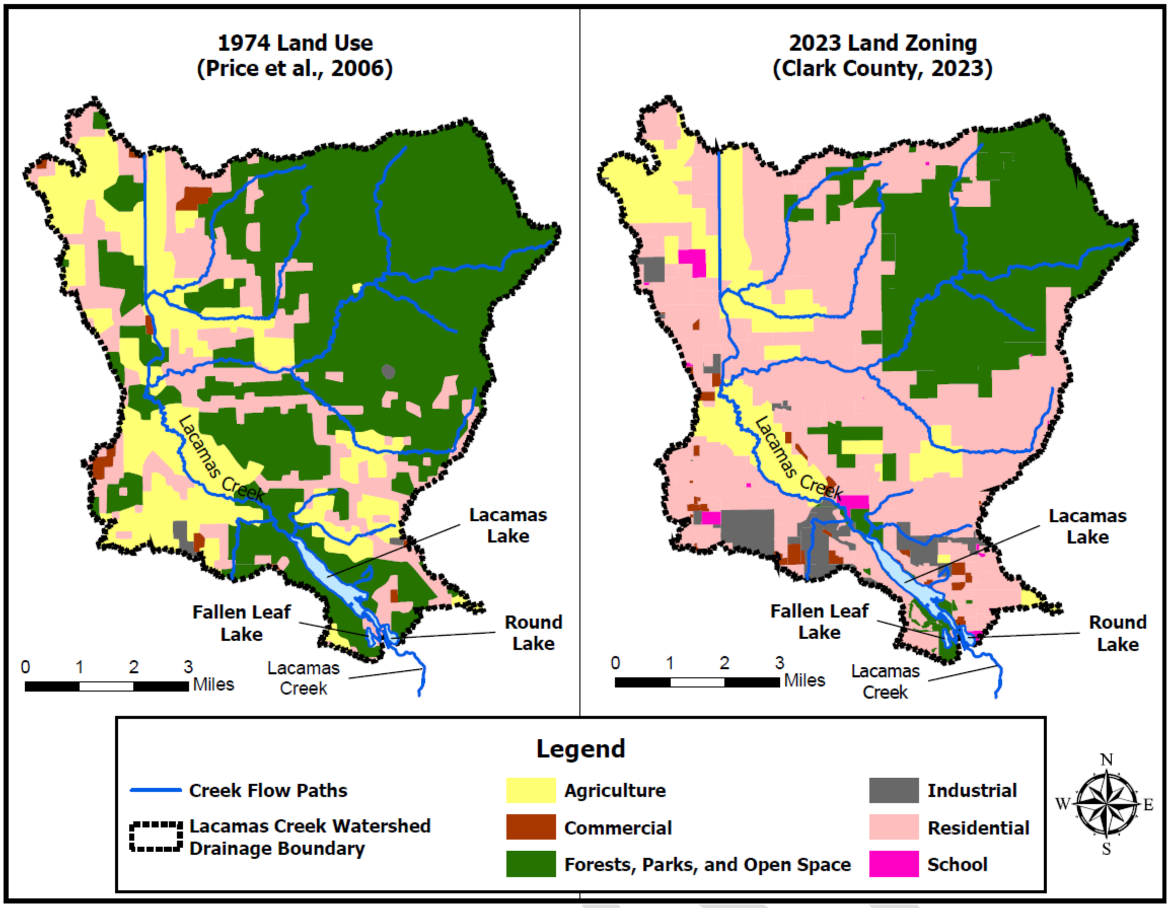

Figure 2. Map of land use in Lacamas Creek Watershed in 1974 (left) and 2023 (right).

Round Lake lies downstream of Lacamas Lake. The channel connecting Lacamas and Round Lakes is the dominant inflow to Round Lake. The Channel is approximately 100 feet wide and 10 feet deep. Round Lake is much smaller than Lacamas Lake, approximately 26 acres, and is also relatively deep, with a maximum depth of approximately 55 feet. Water exits Round Lake either through the upper dam, where it discharges into lower Lacamas Creek, or through Mill Pond and the lower dam, where it discharges to a short, approximately 100-foot side stream that then discharges into lower Lacamas Creek.

Both Lacamas and Round Lakes are natural but were enlarged after the construction of two dams on Lacamas Creek downstream of Round Lake during the 1880s (Beak and SRI, 1985). Historically, the dams were used to control discharge to the Mill Ditch, which provided flow to a paper mill now operated by Georgia Pacific, and to Lacamas Creek downstream of the Lakes, which flows into the Washougal River (Figure 3). The dams were gifted to the City of Camas by Georgia Pacific in 2018 (Green, 2018). The Mill Ditch is no longer used, and flow below the dams is now directed only into Lacamas Creek (personal communication, Steve Wall, City of Camas, 2021).

Fallen Leaf Lake is located just west of the downstream end of Lacamas Lake. Fallen Leaf Lake is a natural lake, approximately 21 acres, and has a maximum depth of approximately 30 feet. Fallen Leaf Lake is higher in elevation than the other two lakes, and its outlet flows into

Lacamas Lake near Lacamas Lake Lodge during periods of high water (Figure 3). During periods of low water, the flows from Fallen Leaf to Lacamas Lake are negligible (Clark County, 2021). Fallen Leaf Lake has three small tributary streams, with a direct drainage area of approximately 0.55 square miles (350 acres), which is largely residential (Figure 4).

There are 3,518 septic systems within the Lacamas Lake watershed in the Clark County geographic information system (GIS) database (2021), with the majority of those being part of older developments on the east and north sides of the lakes. The Fallen Leaf Lake watershed is entirely within the City of Camas, and Clark County septic system data indicate only two properties with septic system documents (Clark County, n.d.).

All three lakes are designated as core summer salmonid habitat and primary contact recreation sites, with additional uses for water supply (domestic, industrial, agricultural, stock), and miscellaneous uses (wildlife habitat, harvesting, commerce/navigation, boating, aesthetics). However, there are no known water supply uses for the water within the lake themselves, other than occasional use for fire suppression. Lacamas Lake's fishery is currently dominated by common carp, though various species of sunfish, bass, perch, suckers, crappie, and sturgeon are also present (Patrick Cooney, Smith Root, and Washington Department of Fish and Wildlife [WDFW], personal communication with author, 2023). Lacamas Lake is stocked primarily with brown and rainbow trout (WDFW, 2023). Both native and invasive aquatic plants are known to exist in Lacamas Lake, with Washington State Noxious Weed Class B Brazilian elodea and Class C fragrant waterlily and curly leaf pondweed being the most concerning. No endangered or threatened species are known to use the area as critical habitat.

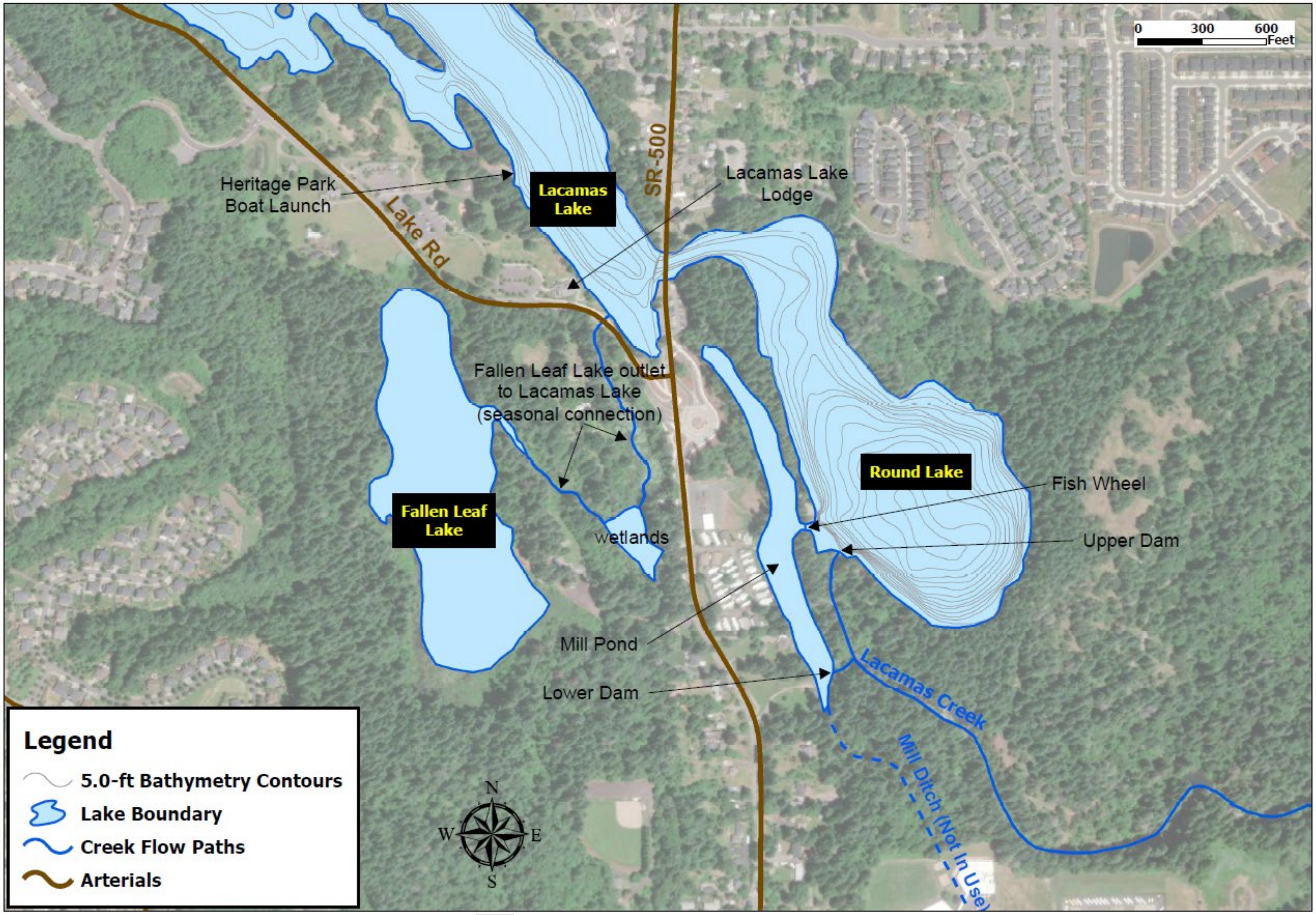

Figure 3. Detail of Hydraulic Connections Between Lacamas, Round, and Fallen Leaf Lakes

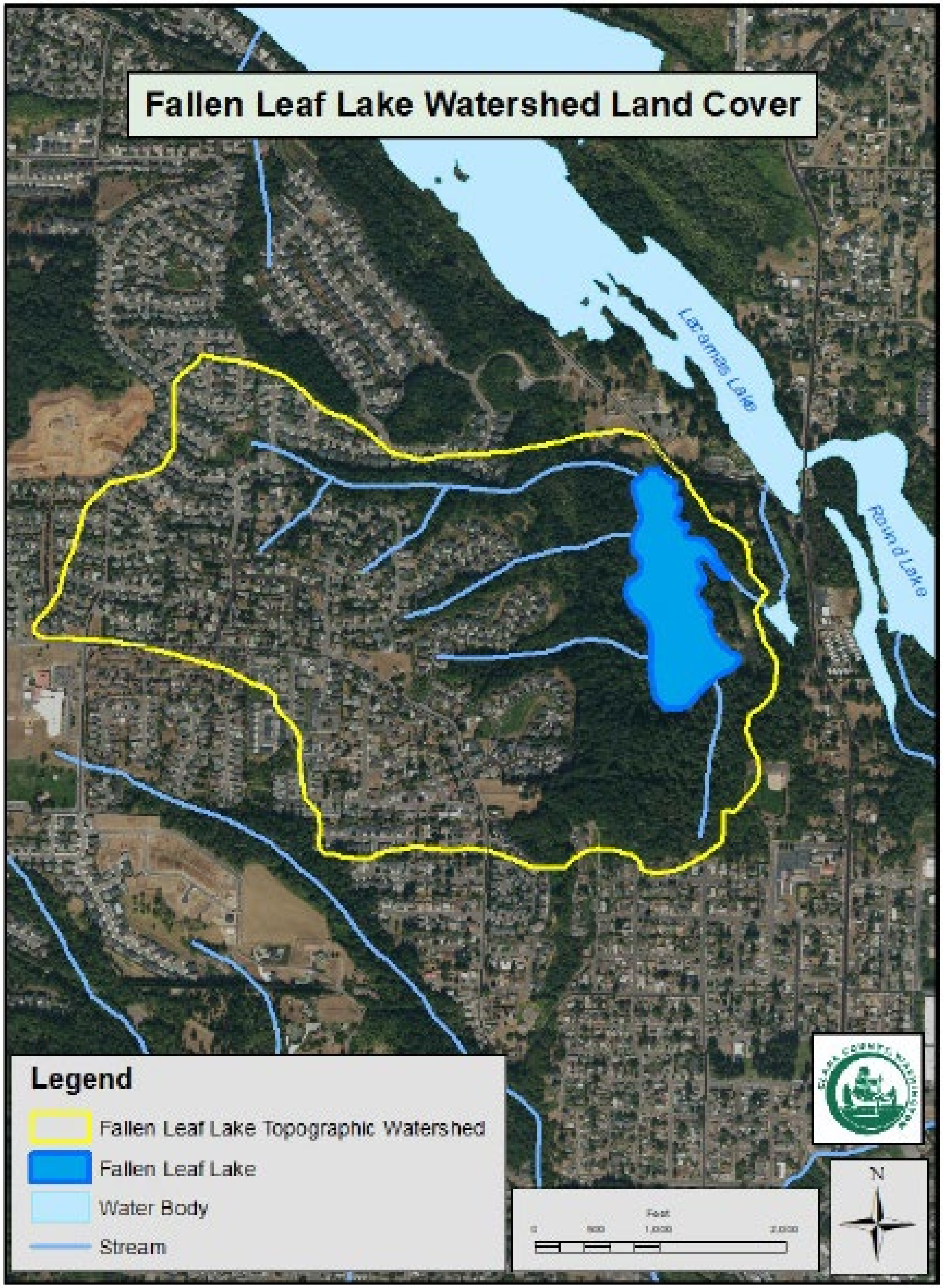

Figure 4. Fallen Leaf Lake watershed (Clark County, 2021)

1.1.2 History of the Study Area

Development within the Lacamas/Round Lake watershed largely began in the 1880s. In 1883, La Camas Colony Company was created and the town of La Camas, later changed to Camas, was formed (Beak and SRI, 1985). Also in 1883, work began on the dams used to provide water for the newly constructed paper mill. During this time, significant population growth in the area occurred and farms were formed. Beginning in the 1890s, drainage channels were built to drain the wetlands for farmland and to increase the flow of water delivered to the Camas paper mill; these channels led to altered watershed hydrology, which caused erosion of stream banks and increased flooding (Gleason and McCarthy, 2021). The current concrete dams were constructed in 1936 to replace the log dams constructed in the 1880s. The mill discontinued use of lake water for paper manufacturing in 2015 (Georgia-Pacific Consumer Operations LLC, 2018).

From 1900 to 1960, dairy cattle operations increased in the pasture areas of the watershed, in part due to improved roadways allowing for easier transportation of milk products to Vancouver, Washington, and Portland, Oregon (Beak and SRI, 1985). Subsequently, the land was divided into smaller plots as the size of farms decreased and some became no longer economically feasible. As a result, the watershed includes both large farms and small 5-acre parcels of residential land (Beak and SRI, 1985).

In recent years, the population of Clark County has increased substantially, from approximately 238,000 in 1990 to an estimated 527,400 people in 2023 (Washington Office of Financial Management, 2023). The increased population growth has led to increased residential development in the watershed and increased use of the lakes for recreation, but somewhat decreased agricultural use of the watershed.

1.1.3 Lake Usage

Lacamas, Round, and Fallen Leaf Lakes are all used for recreation, including stand-up paddleboarding, kayaking, fishing, and swimming. A lake usage survey was conducted in August 2022, in which 13 surveys were conducted by six volunteers on two days—Thursday, August 25 and Sunday, August 28, 2022. A total of 151 stand-up paddleboarders, 100 kayakers or canoers, 54 swimmers or inner-tubers, 36 jet-boats or wakeboats, and 30 anglers were observed at Lacamas Lake. One survey was conducted at Round Lake from Heritage Park, where 17 stand-up paddleboarders, 5 kayakers or canoers, 18 swimmers or inner-tubers, and 2 anglers were observed. Relative to July 2022, anecdotally, fewer motorized boats were on the lake (Steve Wall, personal communication with author, 2022). However, the data are sufficient to demonstrate active usage of the lake for a variety of recreational activities.

1.1.4 Water Quality History

This section describes the water quality history of Lacamas, Round, and Fallen Leaf Lakes, including previous studies, data collection, and past efforts to improve water quality.

1.1.4.1 Past water quality conditions

Table 1 provides a summary of previous studies regarding water quality in Lacamas, Round, and Fallen Leaf Lakes. Table 2 provides a summary of the relevant available data from those studies.

Table 1. Previous studies pertaining to water quality at Lacamas, Round, and Fallen Leaf Lakes

Year	Author(s)	Title
1985	Beak Consultants, Inc. and Scientific Resources, Inc.	Lacamas - Round Lake Diagnostic and Restoration Analysis
1989–1999	Washington State Department of Ecology	Environmental Information Management System Data (accessed 2023)
1993	Recker, J., Hallock, D.	Lake Water Quality Assessment Project, 1990
1991	Conin, S. for USEPA Region 10	Characteristics of Successful Riparian Restoration Projects in the Pacific Northwest
1996	Eilers, J.M., Raymond, R.B., Vache, K.B., Sweet, J.W., Gubala, C.P., Sweets, P.R.	Lacamas Lake Watershed 1995 Water Quality Monitoring Program
1997	Raymond, R.B., Eilers, J.M., Vache, K.B., Sweet, J.W., Sweets, P.R., Gubula, C.P.	Lacamas Lake Watershed 1996 Water Quality Monitoring Program
1998	Raymond, R.	Dye Tracer Mixing Study at Lacamas Lake, 1996 and 1997
1998	Raymond, R.B., Eilers, J.M., Bernert, J.A., Vache, K.B.	Lacamas Lake Watershed Restoration Project Program Review
1999	Mueller, K.W., Downen, M.R.	1997 Lacamas Lake Survey: The Warmwater Fish Community of a Highly Eutrophic Lowland Lake
1999	Parsons, J.	Aquatic Plants Technical Assistance Program. 1998 Activity Report.
2000	Schnabel, J.D.	Lacamas Lake Restoration Program: WY1998 and WY1999 Water Quality Monitoring.
2002	Schnabel, J.D.	Lacamas Lake Restoration Program: WY2000 and WY2001 Water Quality Monitoring
2004	Schnabel, J.D.	Lacamas Lake Nutrient Loading and In-Lake Conditions
2005	Schnabel, J.D.	Monitoring Report - Lacamas Lake Annual Data Summary for 2005
2006	Schnabel, J.D.	Monitoring Report - Lacamas Lake Annual Data Summary for 2006
2007	Schnabel, J.D.	Monitoring Report - Lacamas Lake Annual Data Summary for 2007
2011	Deemer, B.R., Harrison, J.A., Whitling, E.W.	Microbial dinitrogen and nitrous oxide production in a small eutrophic reservoir: An in,situ approach to quantifying hypolimnetic process rates
2012	Henderson, S.M., Deemer, B.R.	Vertical propagation of lake wide internal waves
2015	Deemer, B.R., Henderson, S.M., Harrison, J.A.	Chemical mixing in the bottom boundary layer of a eutrophic reservoir: The effects of internal seiching on nitrogen dynamics
2017	Perkins, K.R.	Influence of environmental factors on the vertical distribution of phytoplankton in Lacamas Lake, Washington
2017	Harrison, J.A., Deemer, B.R., Birchfield, M.K., O'Malley, M.T.	Reservoir water-level drawdowns accelerate and amplify methane emission
2019	Deemer, B.R. and Harrison, J.A.	Summer redox dynamics in a eutrophic reservoir and sensitivity to a summer's end drawdown event.
2019	Nolan, S., Bollens, S.M., and Rollwagen-Bollens, G.	Diverse taxa of zooplankton inhabit hypoxic waters during both day and night in a temperate eutrophic lake
2019	Perkins, K.R., Rollwagen-Bollens, G., Bollens, S.M., Harrison, J.A.	Variability in the vertical distribution of chlorophyll in a spill-managed temperate reservoir
2021	Rose, V., Rollwagen-Bollens, G., Bollens, S.M., Zimmerman, J.	Effects of Grazing and Nutrients on Phytoplankton Blooms and Microplankton Assemblage Structure in Four Temperate Lakes Spanning a Eutrophication Gradient
2021	Clark County Public Works, Clean Water Division	Fallen Leaf Lake Baseline Monitoring Report

Table 2. Summary of existing water and sediment quality data for Lacamas, Round, and Fallen Leaf Lakes

Sample Type	Years Sampled	Locations	Measured Parameters
Lacamas Lake			
Water Quality	Various, 1984–2017	Deepest location; SR500 bridge; field profiles throughout lake	Temperature, DO, conductivity, pH, turbidity, Secchi, alkalinity, total phosphorus, orthophosphate, TSS, TKN, nitrate, nitrite, ammonia, Chl-a, phytoplankton
Sediment	1984, 1995, 1996	Deepest location; three other locations	Total phosphorus, available phosphorus, total iron, total aluminum, TKN, ammonia, Paleolimnological parameters (1995)
Sediment Flux[1]	1984, 1996	Deepest location, three other locations	Temperature, DO, conductivity, pH, total phosphorus, soluble reactive phosphorus, dissolved phosphorus, TKN, ammonia, dissolved iron, metals, DDT, DDE
Stormwater	1985	Lacamas Creek at Goodwin Road, during storm	Temperature, DO, conductivity, pH, turbidity, total phosphorus, TSS, TKN, nitrate, nitrite, ammonia, fecal coliform
Inflow (Lacamas Creek at Goodwin Road)	1995, 1996, 2003	Goodwin Road	Temperature, DO, conductivity, pH, turbidity, total phosphorus, TSS, TKN, nitrate, nitrite, ammonia, fecal coliform
Round Lake			
Water Quality	1984–1985	Deepest location	Temperature, DO, conductivity, pH, turbidity, Secchi, alkalinity, total phosphorus, soluble reactive phosphorus, TSS, TKN, nitrate, nitrite, ammonia, Chl-a, phytoplankton
Water Quality	1990	Deepest Location	Secchi, temperature, DO, total phosphorus, total nitrate
Sediment	1984	Deepest location; near inlet	Total phosphorus, available phosphorus, total iron, total aluminum, TKN, ammonia
Sediment Flux	1984	Deepest location; near inlet	Temperature, DO, conductivity, pH, total phosphorus, soluble reactive phosphorus, dissolved phosphorus, TKN, ammonia, dissolved iron, metals, DDT, DDE
Stormwater	*None*	*None*	*None*
Outflow (Lacamas Creek downstream of dams)	*None*	*None*	*None*
Fallen Leaf Lake			
Water Quality	2020	Deepest location	Temperature, DO, conductivity, pH, Secchi, total phosphorus, TKN, nitrate, Chl-a, *E. coli*
Sediment	*None*	*None*	*None*
Sediment Flux	*None*	*None*	*None*
Stormwater	2020	Tributaries (storm-dominated)	Temperature, DO, conductivity, pH, turbidity, total phosphorus, TSS, *E. coli*

Notes: Chl-a - chlorophyll-a; DDE - dichlorodiphenyldichloroethylene; DDT - dichlorodiphenyltrichloroethane; DO - dissolved oxygen; TKN - total Kjeldahl nitrogen; TSS - total suspended solids

[1] Beak and SRI (1985) conducted elutriate testing to understand potential impacts of dredging and/or wind disturbance. Beak and SRI (1985) also used dissolved oxygen data and literature to estimate phosphorus release under anoxic conditions. Raymond et al. (1998) discussed an evaluation of a 1996 sediment core and found that phosphorus release was small relative to watershed loading.

Key insights from Washington State University-Vancouver research of Lacamas Lake have included the following observations:

- Internal waves were observed at Lacamas Lake, causing mixing within the lake lagging wind events (Henderson and Deemer, 2012); these internal waves play a role in the nitrogen cycling within the reservoir (Deemer et al., 2015).
- Chl-a was concentrated above the thermocline; though the depth at which concentrations were highest varied between 2-5 meters (6.6-16.4 feet) deep, no evidence of downward movement of Chl-a concentrations during the summer season was observed (Perkins et al., 2019). There was minimal evidence of impacts of seasonal drawdowns of the lake on Chl-a distribution (Perkins et al., 2019).
- Zooplankton were broadly distributed within the water column, both in the hypolimnion and epilimnion (Nolan et al., 2019). Comparisons to other lakes showed that zooplankton concentrations impacted growth rate of phytoplankton more in lakes that were oligotrophic, but less in eutrophic lakes such as Lacamas Lake (Rose et al., 2021).

Clark County Public Works found eutrophic conditions in Lacamas Lake based on Chl-a, phosphorus, and Secchi depth measurements during monitoring in 2005, 2006, and 2007. There have been fewer studies of Round Lake, but it was determined to be eutrophic to hypereutrophic by Beak and SRI (Beak and SRI, 1985). Fallen Leaf Lake was assessed in 2020 by Clark County and was also found to be generally eutrophic.

Following several years of seasonal HABs (two noted in 2018 and three to four noted in 2019), Lacamas Lake experienced near-continuous HABs from April through October 2020. Round Lake has also seen increases in HABs in recent years; one sample tested above toxicity levels for microcystin in April 2019, compared to six such samples in 2020. An HAB was reported on July 28, 2021, for both Lacamas and Round Lakes, with the advisory level reduced to a warning on September 30, 2021, despite the blooms remaining present, and warnings lifted in November 2021. Fallen Leaf Lake had its first recorded bloom in 2020, though it is not routinely sampled for cyanotoxin levels. In 2022, samples from Lacamas Lake exceeded state guideline levels for microcystin in July, August, and September. Samples from Round Lake exceeded state guidelines for microcystin multiple times in August, but not in July or September.

1.1.4.2 Efforts to Improve Water Quality

There have been attempts to improve water quality in the lakes since the 1980s. Following the study by Beak and SRI (1985), recommendations were made to reduce the quantity of phosphorus and nitrogen entering Lacamas Lake from Lacamas Creek through a range of best management practices (BMPs) on agricultural land and reductions in septic system use. A range of in-lake treatments were also recommended for consideration but were not implemented.

A 1991 report from the United States Environmental Protection Agency (USEPA) included a case study description of the restoration efforts focused on Lacamas Lake (Conin, 1991). The report described efforts by the Intergovernmental Resource Center (IRC) following the Beak and SRI (1985) study (which was commissioned by the IRC) to reduce phosphorus loading to

Lacamas Lake by at least 84% through community outreach, development of pasture management plans for individual farms, riparian fencing, installation of off-site watering facilities, and tree planting in riparian zones (Conin, 1991). The report stated that water quality in several headwater drainages had improved but water quality measurements in Lacamas and Round Lakes did not demonstrate improvement.

In 1998, a report by E&S Environmental Chemistry to Clark County Department of Public Works described a similar range of agricultural BMPs and a range of recommended management actions for septic systems, including the following:

- A 1986–1987 septic system survey, leading to recommendations to install sewers in the Prune Hill, Lacamas Heights, and Hockinson subbasins
- Repair failing septic systems in other areas
- Education regarding septic system maintenance

The 1998 report (Raymond, 1998) also described the results of the Lacamas Lake Restoration Program recommended as a result of the Beak and SRI work and funded through the Washington Department of Ecology (Ecology), from 1988–1995. During that time, 101 BMPs were installed for 42 landowners (66 riparian BMPs and 35 waste management BMPs). Nearly 90% of the BMPs were classified as effective (Raymond, 1998). The 1998 report documented lower summer phosphorus concentrations in the lakes and creeks in 1992 compared with 1984, but still described eutrophic conditions with similar levels of algae productivity.

Reports in 2000 and 2002 by Clark County documented monitoring conducted between 1998 and 2001. The major findings included that loading of phosphorus from Lacamas Creek to Lacamas Lake had decreased by approximately 50% since 1983, and that concentrations of total phosphorus near the surface (epilimnion) of Lacamas Lake had been reduced since 1983. However, the reports noted that there had been no observed improvement in summertime DO concentrations at the bottom of Lacamas Lake. Likewise, no improvement in water clarity or hypolimnetic nutrient concentrations were observed. Continued monitoring between 2004 and 2007 showed similar levels of nutrients and other water quality characteristics in the lakes.

Overall, while there is evidence that the concentration of total phosphorus entering Lacamas Lake from Lacamas Creek was reduced in the late 1980s and 1990s, the change was not sufficient to change the lake's trophic state, and improvements in water quality appear to have stalled since the 1990s. Internal recycling of nutrients from lake sediments likely also contribute to the continued algae blooms.

1.1.5 Current Conditions

The recent water quality data prior to this project was summarized in Section 1.1.4. This section focuses on contaminants of concern, regulatory status, and existing total maximum daily loads (TMDLs).

1.1.5.1 Contaminants of Concern

1.1.5.1.1 Cyanotoxins

Lacamas Lake has had cyanotoxin measurements exceeding state guidelines in every year since 2018 except for 2019 (where there were three detections but none exceeding state guidelines), including frequent exceedances of the guideline for the cyanotoxin microcystin in summer 2020 (King County, 2023). Round Lake has also seen increases in HABs in recent years: one sample tested above toxicity levels for the cyanotoxin microcystin in April 2019, six samples were above the state guidelines for microcystin in 2020, five in 2021, and three in 2022 (King County, 2023). Fallen Leaf Lake had its first recorded algae bloom in 2020, though state guidelines for cyanotoxins were not exceeded, and was found to be eutrophic in a recent study from Clark County (2021). Table 3 shows a summary of exceedances of state cyanotoxin guidelines based on data from King County (2023). The state guideline for microcystin is 6 micrograms per liter (µg/L) and the guideline for anatoxin-a is 1 µg/L (Washington State Department of Health, 2008).

Table 3. Summary of cyanotoxin exceedances of state guidelines (King County, 2023)

Year	Number of Samples Exceeding Stage Guidelines for Cyanotoxins	Cyanotoxin(s) Exceeding State Guideline
2018	Lacamas Lake: 2	Microcystin (2), maximum concentration: 47.1 µg/L
	Round Lake: 0	
	Fallen Leaf Lake: 0	
2019	Lacamas Lake: 0	
	Round Lake: 1	Microcystin (1), maximum concentration 25.8 µg/L
	Fallen Leaf Lake: 0	
2020	Lacamas Lake: 14	Microcystin (13), maximum concentration 76.0 µg/L Anatoxin-a (1), maximum concentration 1.46 µg/L
	Round Lake: 6	Microcystin (6), maximum concentration 81.9 µg/L
	Fallen Leaf Lake: 0	
2021	Lacamas Lake: 5	Microcystin (5), maximum concentration 270 µg/L
	Round Lake: 5	Microcystin (5), maximum concentration 19.7 µg/L
	Fallen Leaf Lake: 0	
2022	Lacamas Lake: 5	Microcystin (5), maximum concentration 2750 µg/L
	Round Lake: 3	Microcystin (3), maximum concentration 488 µg/L
	Fallen Leaf Lake: 0	
2023	Lacamas Lake: 3	Microcystin (3), maximum concentration 71.0 µg/L
	Round Lake: 0	
	Fallen Leaf Lake: 0	

1.1.5.1.2 303(d) List Status

In accordance with the Clean Water Act, Ecology conducts a water quality assessment of Washington state waters every two years. The result of these assessments is a database of categorical rankings for each applicable standard in each assessment unit. Those assessment units classified as Category 5 make up the 303(d) list of impaired water bodies of the state. Lacamas Lake is currently listed as impaired for phosphorus in the water column, while Round Lake is impaired for pH and DO in the water column. Fallen Leaf Lake has not been assessed by the state for water quality impairment. Lacamas Creek, which feeds Lacamas Lake, is impaired for DO, bacteria, and temperature within the assessment unit just upstream of Lacamas Lake. The 303(d) listings are summarized in Table 4.

Table 4. Impaired water quality parameters in Lacamas, Round, and Fallen Leaf Lake, as well as nearby tributaries

Waterbody	Parameter	Listing ID[1]
Lacamas Lake	Total phosphorus	6346
Round Lake	DO	7936
	pH	**7935**
Fallen Leaf Lake	*not assessed*	
Lacamas Creek	Bacteria - fecal coliform	7913
	DO	7912, 7915
	pH	7916
	Temperature	7914, 7917
Dwyer Creek	DO	7894
Currie Creek	*not assessed*	

Note:
[1] Bolded listing IDs are listings that appear in the 2014 water quality assessment (WQA; approved by USEPA on July 22, 2016) but are not brought forth in the draft 2018 WQA (submitted to USEPA, but not yet approved).

1.1.5.1.3 TMDLs

A source assessment is currently being developed by Ecology for Lacamas Creek for Fecal Coliform, temperature, DO, and bacteria. Currently no approved TMDLs exist for the lakes or tributaries (Gleason and McCarthy, 2021).

1.1.5.1.4 Regulatory Criteria

Lacamas and Round Lakes' designated uses include core summer salmonid habitat; primary contact recreation; domestic, industrial, agricultural, stock and wildlife habitat water supply; harvesting; commerce and navigation; boating; and aesthetics. Fallen Leaf Lake is separately designated and has the same designated uses. Algae blooms impair each of these uses. Regulatory criteria presented in Table 5 apply for conventional pollutants as defined in Washington Administrative Code (WAC) 173-201A-600 (1)(a)(ii).

Table 5. Lacamas, Round, and Fallen Leaf Lakes regulatory criteria

Criterion	Value	Units
Temperature	16[1]	°C
DO	9.5[2]	mg/L
Total dissolved gas	≤ 110	%
pH	6.5–8.5[3]	-
Turbidity	5 over background when background < 50 10% increase when background > 50	NTU
E. coli	100[4] No more than 10% < 320	CFU or MPN per 100 mL

Notes: CFU – Colony Forming Units; mg/L - milligrams per liter; MPN – Most Probable Number; NTU - Nephelometric turbidity units

[1] Applies as seven-day average of the daily maximum temperature (7DADMax).
[2] Applies as daily minimum.
[3] Human-caused variation must be less than 0.2 units.
[4] Applies to geometric mean of at least three samples.

1.1.6 Community Involvement

This section describes community engagement efforts, including interested agencies and stakeholders, and summaries of meetings, interviews, workshops, and open houses.

1.1.6.1 Public Participation

The City of Camas conducted community outreach in two phases. Phase 1 occurred in the summer and fall of 2021, and Phase 2 occurred between the fall of 2021 and summer of 2023. Water quality sampling took place from spring 2022 until spring 2023. Phase 1 outreach focused on sharing information about the Lake Management Plan (LMP), understanding how the community uses the lakes, and what their expectations are for how the City of Camas should work to improve the lakes' water quality. Phase 2 built on Phase 1 engagement, keeping the public informed about how development of the LMP progressed, sharing information about water sampling efforts, and asking for input on potential lake management strategies. Engagement with the public and key stakeholders conducted in both phases is outlined in the following section.

The Camas community is engaged and interested in finding solutions to improve the water quality of the lakes. The "Lacamas Watershed Council (LWC)" is a local non-profit group focused on monitoring the lake and finding solutions to improve lake water quality. The LWC recently became a 501(c)(3) group. The LWC conducts monitoring for algae, macroinvertebrates, and other water quality parameters. Its algae data is submitted to the National Oceanic and Atmospheric Administration (NOAA) as part of its Phytoplankton Monitoring Network (PMN). Other public engagement efforts included two Camas Middle School students developing a device to filter algae (Moyer, 2021). Camas school district students have conducted watershed and lake surveys and worked with the LWC to sample the lake.

1.1.6.2 Key Agencies and Interested Stakeholders

The project team has regularly engaged with two primary groups of interested parties: a group of local and state agencies and a group of non-profit organizations.

1.1.6.2.1 State and Local Agencies

The project team has engaged with the following state and local agencies:

- Ecology. Ecology provided a grant that has helped fund this project and the development of this report. Ecology has also conducted sampling at Lacamas Creek as part of its bacteria, temperature, and nutrients source assessment. Additionally, Ecology reviewed the Quality Assurance Project Plan (QAPP; Geosyntec Consultants, Inc. [Geosyntec], 2022) and provided valuable comments.
- WDFW. WDFW has regularly attended update calls with the project team and has provided key insights on the presence of common carp, a non-native fish that can

influence the availability of phosphorus in the water column and contribute to algal blooms.

- Clark County Public Works. Staff from the Clark County Public Works department have been a critical resource to the project team. The County has conducted sampling of Lacamas Creek, and all three lakes, and has shared data and resources with the project team. The County will be a key partner in the future in terms of identifying and implementing actions within the Lacamas Creek watershed to improve water quality.
- Clark County Public Health. Staff from Clark County Public Health sample for cyanotoxins and provides information to the public regarding safely using the lakes for recreation. County public health staff have attended open houses and provided information to the public and have remained engaged with the project team.
- Washington Department of Agriculture. The Washington Department of Agriculture is an interested stakeholder due to the agricultural land within the Lacamas Lake watershed. The agency has regularly attended updates with the project team.
- Clark Conservation District (CCD). CCD is a non-regulatory subdivision of state government. CCD administers a range of programs which contribute to improved water quality within the Lacamas Lake watershed. CCD has regularly engaged with the project team and will be a key partner for efforts to improve water quality within the watershed going forward.

1.1.6.2.2 Non-Profit Organizations

The project team has regularly engaged with the following non-profit agencies:

- Lacamas Watershed Council (LWC). As described above, the LWC is a citizen-based group involved in multiple efforts focused on understanding and improving the water quality of the Watershed and Lakes. The LWC conducts monitoring as part of NOAA's PMN program. The LWC is also involved in public education and advocacy for improved water quality practices. The LWC has been engaged collaboratively with the project team and will be an important group moving forward in implementing recommended actions.
- Watershed Alliance of Southwest Washington. The Watershed Alliance of Southwest Watershed was founded as the Vancouver Watershed Alliance in 2008 focused on the restoration of Burnt Bridge Creek in Vancouver. The organization changed its name in 2017 to reflect its broader focus. The Watershed Alliance organizes an annual Lacamas Lake clean-up event and is interested in collaborating on future efforts to improve the creek and lake water quality.
- City of Vancouver Water Resource Education Center. The City of Vancouver Water Resource Education Center is involved in county-wide public education focused on watershed science. As such, the group plays an important role in public education and in building support for improving lake water quality.
- Lower Columbia Fish Enhancement Group (LCFEG) is a group that promotes recovery of self-sustaining, naturally spawning salmon populations and healthy

streams through restoration projects and public education. The LCFEG is a partner for a range of restoration activities in the watershed and has engaged with the project team in stakeholder updates.

1.1.6.3 Stakeholder and Public Outreach

1.1.6.3.1 Stakeholder Outreach

The project team conducted the following stakeholder engagement activities:

- **Summer 2021 Stakeholder Interviews.** In summer 2021, during Phase 1 of the project, the City of Camas hosted stakeholder interviews with representatives from state, local, and county agencies, the Camas Parks and Recreation Commission, Camas Meadows Golf Course, Sweetwater SUP Rentals, the Lacamas Watershed Council, and the Johnston property (formerly a dairy operation). Key takeaways from the events included a widespread desire for collaborative efforts to improve lake water quality and build community awareness.
- **February 2022 "Non-profit Organizations" Meeting.** An update meeting was held with educational and volunteer groups (Section 1.1.6.1) to share project information and current or upcoming work efforts in the Watershed and to discuss opportunities for collaboration and future funding and partnership opportunities. Feedback included discussion of future sampling efforts, how to help the community understand the complexity of what is affecting the lakes' water quality, and timelines for restoring natural habitat on the Rose and Leadbetter properties. The group also discussed potential collaboration and joint volunteer efforts, as well as funding and grant opportunities.
- **October 2022 Agency Meeting.** An update meeting was held with the agency stakeholder group (Section 1.1.6.2) to provide an update on the sampling program, high level potential management alternatives at Lacamas and Round Lakes, and a potential demonstration project at Fallen Leaf Lake. Feedback included discussion of managing areas of very dense yellow pond-lily at Fallen Leaf Lake while not eliminating it since it is not an invasive plant, influence of Carp in Lacamas Lake and potential for bioturbation increasing phosphorus in the water column, and why management is needed at Fallen Leaf Lake given the limited history of HABs.
- **March 2023 Agency Meeting.** An update meeting was held with the agency stakeholder group (Section 1.1.6.2) to share information about initial sampling results. Participants were given the opportunity to ask questions. The group discussed what is meant by the "middle" of the lake, how the shape and size of the lakes may affect phosphorus levels, the connection between Round and Lacamas Lakes, and where toxic algae bloom samples are taken in the lake.
- **March 2023 Non-profit Organizations Meeting.** An update meeting was held with the non-profit stakeholder group (Section 1.1.6.2) to share information about initial sampling results. Participants were given the opportunity to ask questions. Questions included whether there would be another vegetation species analysis, how the dam

affects phosphorous levels in the lake, and whether the county's toxic algae bloom warning system will change.

- **June 2023 Workshop.** A workshop was held with lake and watershed stakeholders to provide an overview of the work completed as a result of the Lake Management Plan effort, including the results of water sampling activities. A presentation provided an overview of what was learned from the research, sampling, and community engagement efforts. In addition, participants were invited to review and brainstorm solutions for the lakes and the watershed based upon the research, sampling, and community expectations. Over a dozen community members participated in this meeting.

1.1.6.3.2 Public Outreach

- **Summer 2021 Online Survey.** An online survey was conducted on the Engage Camas website, and 55 individuals participated. Responses included a widespread desire for the ability to swim without being concerned with water quality and a desire for improvements in water quality to be sustainable. The survey was open from July 29 through September 25, 2021.
- **Tabling Events.** Four tabling events were held between summer 2021 and summer 2023 to build awareness about the LMP project and solicit feedback. Feedback included concerns regarding prevalence of algae blooms, appreciation of signage regarding the algae blooms, and concern regarding the Lacamas Shores biofilter. The tabling events were held in July 2021, August 2021, September 2021, and October 2022.
- **Open House #1 was held June 15, 2022.** A total of 49 people participated, 45 during the in-person open house and an additional four on the online survey. Overall, participants expressed a desire to see a plan with clear actions and an identifiable budget that will help improve lake water quality within the next few years. Many people said that they would like to use the lakes for recreation (swimming, fishing, kayaking, etc.) and were interested in both in-lake and watershed-wide improvements.
- **Open House #2 was held October 6, 2022**. There were 69 attendees at the open house and one additional participant for the online survey. Overall, participants said public outreach and education, agricultural BMPs, and stream restoration were the most appropriate lake management solutions. The majority also believed not taking any action was not a very appropriate solution. Several participants specifically asked for natural options as opposed to chemical treatments or costly technologies, and others mentioned they would like to see the City of Camas act quickly to improve lake water quality.
- **Open House #3 was held July 12, 2023**. Overall, 464 people were engaged in this phase of outreach. 122 people participated in the open house, 12 participated in the online survey and 330 people visited the project page on Engage Camas while the online survey was open. The purpose of the open house and online survey were to share information with the community about the Lake Management Plan, including:

- What has been learned about the water in Lacamas, Round, and Fallen Leaf Lakes through sampling and other research.
- The proposed management strategies being considered in the near-term and longer term to improve lake water quality as well as improve the overall watershed health.
- The open house was supplemented by an online survey hosted on Engage Camas that was available from July 12 to July 26, 2023. Poster boards that were displayed at the open house were made available on Engage Camas as well.

1.1.6.4 Public Support

As described in Section 1.1.5.1, the Camas and Clark County communities are engaged and committed to seeking solutions to improve lake water quality. This is evidenced by attendance at public meetings and engagement from community groups such as the LWC, Watershed Alliance, and Water Resource Education Center. The Camas City Council has committed substantial funding to the project, and the Mayor and Council members have attended open house events, demonstrating great interest in the effort to reduce HABs and improve water quality.

2. PROJECT DESCRIPTION

2.1 Project Goals and Objectives

The goal of the LCMP is to produce a document that can be used to guide management decisions aimed at reducing the occurrence and duration of HABs in Lacamas, Round, and Fallen Leaf Lakes. The goals and objectives of the data collection effort are described in the QAPP (Geosyntec, 2022). In summary, the goal of the water quality sampling effort was to collect data of sufficient quality and quantity to support development of this LCMP. To accomplish this, data collection was aimed at the following goals:

- Tracking changes in the water quality characteristics of Lacamas, Round, and Fallen Leaf Lakes throughout a year
- Quantifying the nutrient loading of different sources and inputs of nutrients to Lacamas, Round, and Fallen Leaf Lakes
- Developing hydrologic and nutrient budgets for Lacamas and Round Lakes
- Obtaining a rough picture of lake macroecology through collection of data related to aquatic vegetation and human use
- Provide science-based guidance on the types of management alternatives that could improve lake water quality

3. MONITORING METHODS AND RESULTS

3.1 Monitoring Methods

Monitoring methods used to collect data for this LCMP effort are described in the QAPP (Geosyntec, 2022). Lake and creek water quality data and samples were obtained in accordance with the QAPP between May 2022 and April 2023 (Table 6). Fallen Leaf Lake was sampled fewer times because of the recent sampling effort by Clark County (2021), and lake sampling efforts focused on the summer and fall season, with quarterly sampling in winter and spring.

Table 6. Water quality sample collection dates

Monday of Data Collection Week	Creeks	Lacamas Lake	Round Lake	Fallen Leaf Lake
May 30, 2022	X	X	X	
June 20, 2022	X	X	X	X
July 18, 2022	X	X	X	
August 15, 2022*	X	X	X	X
September 19, 2022	X	X	X	
October 17, 2022	X			
October 24, 2022		X	X	X
November 14, 2022	X			
December 12, 2022	X			
January 16, 2023		X	X	
January 23, 2023	X			
February 27, 2023	X			
March 20, 2023	X			
April 17, 2023	X	X	X	

Note: *included algae speciation sampling

Other data were collected as follows:

- Lake use surveys were conducted on August 25 and 28, 2022.
- Thermistor chains (HOBO TidbiT MX2203s in Lacamas Lake, and HOBO Pendant MX2201s in Round Lake) were installed in the lakes on September 15, 2022, and are still in place.
- The water level gage (HOBO MX2001) in Lacamas Creek at Goodwin Road was installed on October 18, 2022, and is still in place.
- Channel cross sections from Lacamas Creek at Goodwin Road were obtained on October 20, 2022, November 17, 2022, and March 22, 2023.
- Stormwater grab samples were obtained on December 8, 2022, February 7, 2023, and March 23, 2023.
- Sediment samples were obtained on March 23 and 24, 2023.
- The Lacamas and Round Lakes aquatic vegetation survey was performed on May 9 and 10, 2023 with follow up observations on June 27, 2023.

Instrumentation used to collect field data primarily consisted of a YSI ProDSS, but a YSI ProSeries Professional Plus, an Aquaread Aquaprobe, and a Horiba U-52 were each used on at least one occasion. Channel cross section velocity measurements were taken using a Hach FH950 flow meter and a Rickly top set wading rod.

Water chemistry and most sediment samples were analyzed by ALS Environmental in Kelso, Washington. Algae speciation was performed by EcoAnalysts, Inc. in Moscow, Idaho. Sediment samples were obtained with the assistance of Gravity Marine. Sediment phosphorus speciation extractions were performed by SiREM Laboratories in Knoxville, Tennessee, with extracts analyzed by ALS Environmental. The aquatic vegetation survey was performed by Environmental Science Associates.

3.1.1 Lake Surface Water Sampling

Surface water sampling locations were identified to characterize water quality in each of Lacamas, Round, and Fallen Leaf Lakes (Figure 5). Two types of lake sample locations were used—complete and limited. Both field and laboratory data were collected at the complete sampling locations, while only field parameters were collected at limited sampling locations (Table 7). Eight lake sampling events occurred on Round and Lacamas Lakes (May–October, January, and April), and three occurred on Fallen Leaf Lake (June, August, October; Table 6).

Table 7. Complete versus limited lake sample locations

Complete Lake Sample Locations	Limited Lake Sample Locations
• Field parameters collected during every lake sampling event • Samples for laboratory analysis collected during every lake sampling event	• Field parameters collected during every lake sampling event • No samples for laboratory analysis collected

Samples for laboratory analysis were collected using a 4.2-liter clear Van Dorn sampler. Sampling depths were 0.5 meters (1.6 feet) below the surface, 0.5 meters (1.6 feet) above the bottom, and 0.5–1.0 meters (1.6-3.3 feet) below the bottom of the oxycline (the part of the water column where DO rapidly changes with increasing depth). Chl-a samples were only collected at depths of less than 10 meters (33 feet). Samples submitted to the laboratory were analyzed for TSS, hardness, ammonia, TKN, nitrite and nitrate, orthophosphate, total phosphorus, and Chl-a.

Field parameters were measured using either a YSI ProDSS or an Aquaread Aquaprobe. Samples were taken at depth intervals of 1 meter (3.3 feet). When possible, depths were measured by the instrument; when not possible, a depth-calibrated rope was used to hand measure depth. Instrument readings were required to remain relatively stable for at least 30 seconds before being hand-recorded and moved to the next depth. Water quality instruments were calibrated by the rental company prior to every sampling event, and as necessary during the sampling period. Collected field parameters consisted of apparent depth, Secchi disk depth, temperature, specific conductivity (SC), DO, oxidation-reduction potential (ORP), and pH.

Algae samples were taken from each of the four complete lake sampling locations during the August sampling events. Samples were collected from 0.5 meters (1.6 feet) below the surface using the Van Dorn bottle, and were transferred into brown high-density polyethylene (HDPE) bottles provided by the analytical laboratory and were preserved in the field with Lugol's solution prior to shipping to the laboratory.

Thermistor chains were also deployed in Lacamas Lake at LL1 and Round Lake at RL1 (Figure 5). Thermistor chains were constructed using a 10-pound mushroom anchor, lead-core rope, a submerged tension buoy located approximately 10 feet below surface during high water to accommodate annual drawdowns, and a surface marker buoy. Individual thermistors were added every 0.75 meters (2.5 feet), starting 0.5 meters (1.6 feet) from the bottom of the lake, and ending at the tension buoy, with a final thermistor attached to the bottom of the surface buoy. A total of 21 HOBO TidbiT MX2203s were used in Lacamas Lake, and 17 HOBO Pendant MX2201s were used in Round Lake. Thermistor chains were installed in the lakes on September 15, 2022, and are still in place. Thermistor data were downloaded and location verified during each subsequent lake sampling event, plus during one additional trip in March.

Sample results are provided in Appendices A and B and are described in Section 3.2.

3.1.2 Creek Sampling

Creek sampling was conducted monthly at Lacamas Creek at Goodwin Road, Dwyer Creek, Currie Creek, an unnamed creek discharging into the southeast end of Lacamas Lake, and Lacamas Creek below the Upper Round Lake dam (Figure 3; Geosyntec, 2022).

Laboratory samples were collected using either a metal bucket and rope, or a fiberglass sample pole with an HDPE bottle. Equipment was decontaminated before use, and equipment blanks were obtained in accordance with the QAPP. Samples submitted to the laboratory were analyzed for TSS, hardness, ammonia, TKN, nitrite and nitrate, orthophosphate, and total phosphorus.

Field parameters were measured using either a YSI ProDSS, a YSI Pro Series Professional Plus, an Aquaread Aquaprobe, or a Horiba U-52. Instrument readings were required to remain relatively stable for at least 30 seconds before being hand-recorded and moved to the next depth. Water quality instruments were calibrated by the rental company or Geosyntec prior to every sampling event, and as necessary during the sampling period. Collected field parameters consisted of temperature, SC, ORP, DO, and pH.

3.1.3 Sediment Sampling

Sediment sampling was expanded from that described in the QAPP as a result of high observed phosphorus concentrations in lake bottom samples (Section 3.2). Sediment grab samples were obtained at 11 locations (complete, limited, and additional sediment locations in Figure 3) using a Power Grab in Lacamas Lake and a Van Veen Grab Sampler in Round and Fallen Leaf Lakes. Samples were taken from the top 5 centimeters (2.0 inches) of the sediment bed at each location and sent to the laboratory for analysis. Multiple attempts were also made to obtain sediment cores at each of the complete lake sampling locations using a vibracorer in Lacamas Lake and a push corer in Round and Fallen Leaf Lakes; however, this was only successful in some locations. It was not possible to collect a sediment core at LL2 due to the presence of woody debris; a sediment core was collected at LL1, but the recovery was poor; sediment cores were collected near both RL1 and FLL1, though the sampled locations were moved more than 50 feet from the target location as the push corer's maximum reachable depth was 30 feet. As such, only visual observations of the cores were noted, and cores were not analyzed by the laboratory.

Sample results are provided in Appendix B.3 and described in Section 3.2.

3.1.4 Stormwater Sampling

Stormwater sampling was conducted three times at the locations indicated in Figure 3 and as detailed in the QAPP. Only two locations were selected as direct stormwater runoff is anticipated to have limited impact on nutrient loading to the lakes due to the intermittent nature of stormwater as well as the small amount of volume input into the lakes compared to inputs from other sources, such as creeks. These particular locations were selected due to their accessibility, repeatability (i.e. no stagnant water or backwater), and well-sized drainage area. One location drains into Round Lake and one into Fallen Leaf Lake; no stormwater runoff directly flowing into Lacamas Lake was measured due to the inclusion of sampling for small streams flowing directly into Lacamas Lake, and due to the size of Lacamas Lake, which is less likely to be affected by inputs from direct stormwater inflows. Field methods, field parameters, and laboratory parameters were the same as for the creek samples (Section 3.1.2).

Sample results are provided in Appendix B.1 and B.2 and described in Section 3.2.

3.1.5 Aquatic Vegetation Survey

The aquatic vegetation survey was conducted in accordance with the QAPP. Methods are further described in the survey report, provided as Appendix C.

3.1.6 Flow Monitoring

A Hobo MX2001 Water Level Logger was installed at Lacamas Creek at Goodwin Road, near the site of previous flow monitoring conducted from 2003-2012 by Clark County. Previous monitoring efforts used a stilling well that was found to no longer be hydraulically connected to the creek. As such, a length of slotted pipe was attached within the creek under the Goodwin Road bridge to serve as a stilling well. Depths were verified with an existing USGS style staff gage, which was replaced at the same location due to the existing gage's deteriorated condition.

To convert depth measurements to discharge estimates, field measurements made by Clark County (2011) were combined with field measurements collected three times during this study in fall 2022 and spring 2023 to confirm the Clark County rating curve is still valid. Measurements were conducted using a Hach FH950 portable velocity meter and top set wading rod. A modified rating curve using both Clark County and Geosyntec team data points was used to convert depth measurements to flow estimates (Appendix E).

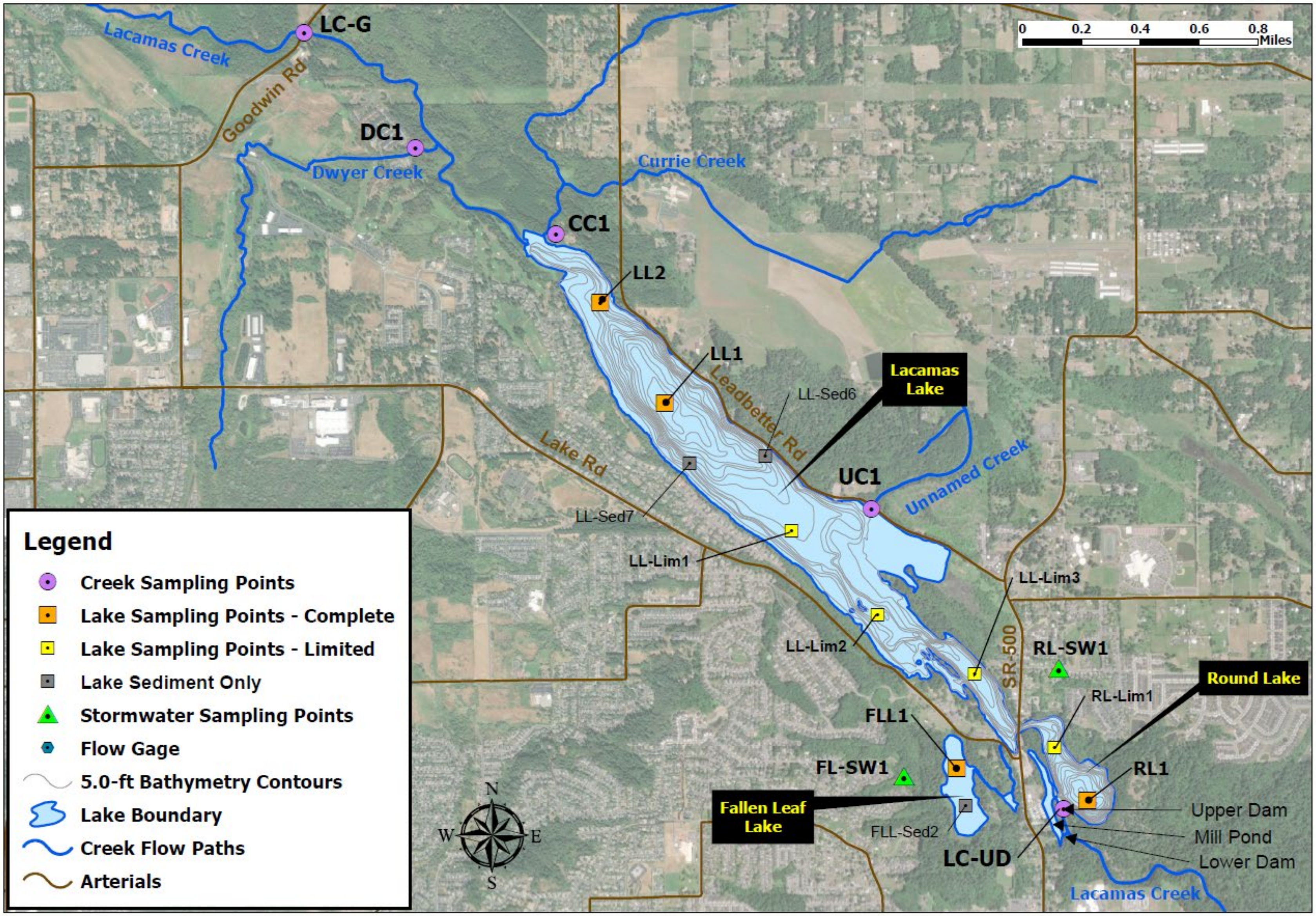

Figure 5. Sampling locations for Lacamas, Round, and Fallen Leaf Lakes

3.2 Monitoring Results

The early portion of the sampling period, May and June 2022, were unusually wet months for the region. The average precipitation for May as measured at Portland International Airport is 2.51 inches and for June it is 1.63 inches (National Weather Service [NWS], 2023). For May and June 2022, the measured values were 3.78 and 3.09 inches, respectively. The overall rainfall for the 12-month period from May 2022–April 2023 was 38.7 inches, which is slightly higher than the average of 36.9 inches, but the higher precipitation in the spring of 2022 may have resulted in different conditions in the lakes relative to an average year.

In addition, the summer and early fall temperatures were above average, with an abrupt drop in temperatures back to normal occurring in late October. September 2022 was unusually dry, as was early October 2022. These conditions may have led to stratification lasting longer than would be typical. However, there is not enough existing data to determine when fall turnover typically occurs. Rainfall was slightly below average for nearly the entire 2023 portion of the sampling year (January–April), with unusually high temperatures at the end of April 2023. While this likely did not affect the data from this study, it may lead to earlier stratification in 2023 than in previous years.

3.2.1 Lake Level

During the sampling period, the level of Lacamas and Round Lakes, as measured by at the Round Lake Dam varied over a range of approximately 5.8 feet, from its maximum level of approximately 11 feet above the Round Lake gage datum to a minimum of 5.2 feet above the datum, the latter of which occurred during the late-summer drawdown period. For a brief period during December 2022, the lake level increased to 12.6 feet above the datum during a rainfall event, however, within a day the lake level had dropped to 11 feet (Figure 6). The range of lake levels was considered when developing the flow (Section 4) and nutrient (Section 5) budgets, since it affects the storage in the lakes. The range of lake levels observed during the sampling period is typical based on a review of data from 2010–2023 (unpublished).

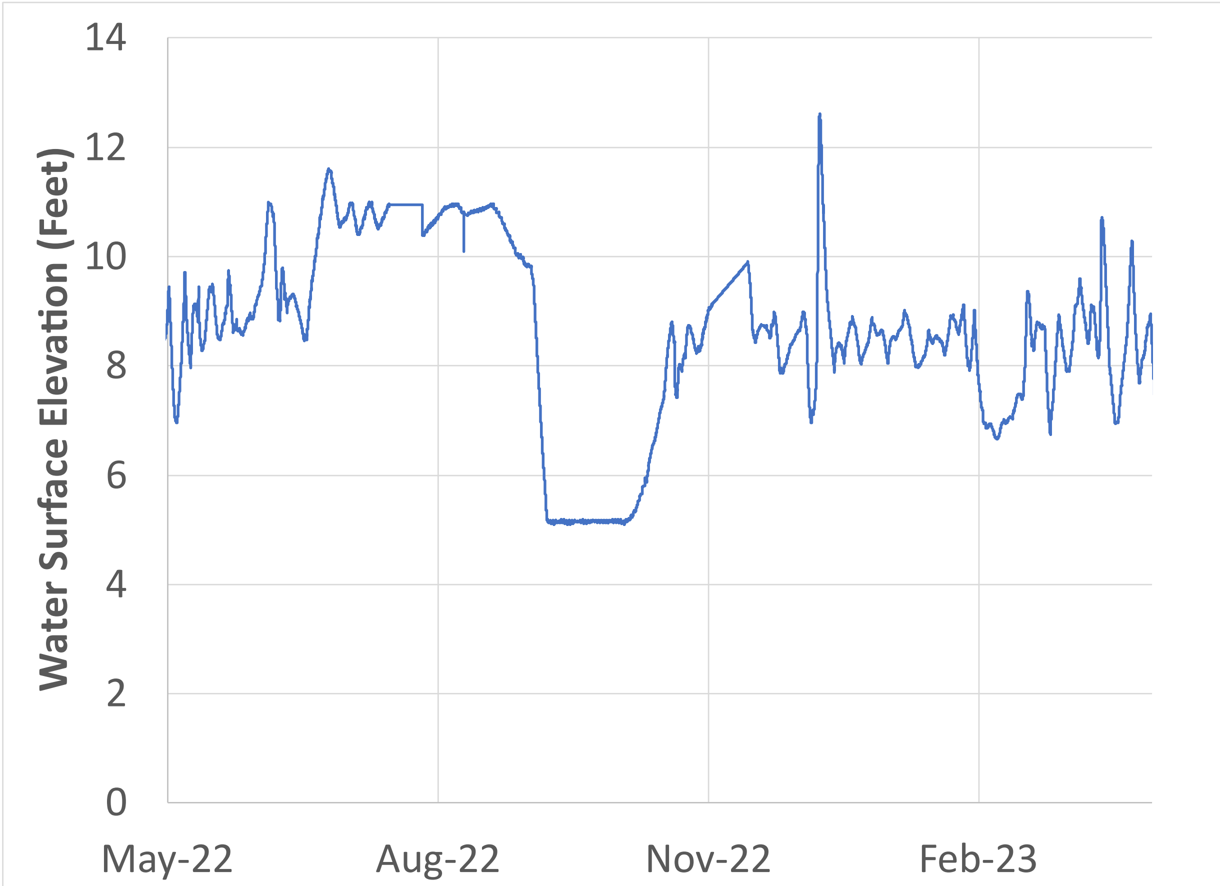

Figure 6. Lake levels as measured at Round Lake Upper Dam relative to Round Lake Gage Datum.

Depth in the largest lake inflow source, Lacamas Creek, was continuously monitored during the wettest portions of the study period using a water level meter (Section 3.1.6). The meter recorded depths in the creek ranging from just under 11 inches to just under 6 feet, with an average depth of about 2 feet (Figure 7). Further detail is provided in Appendix E.

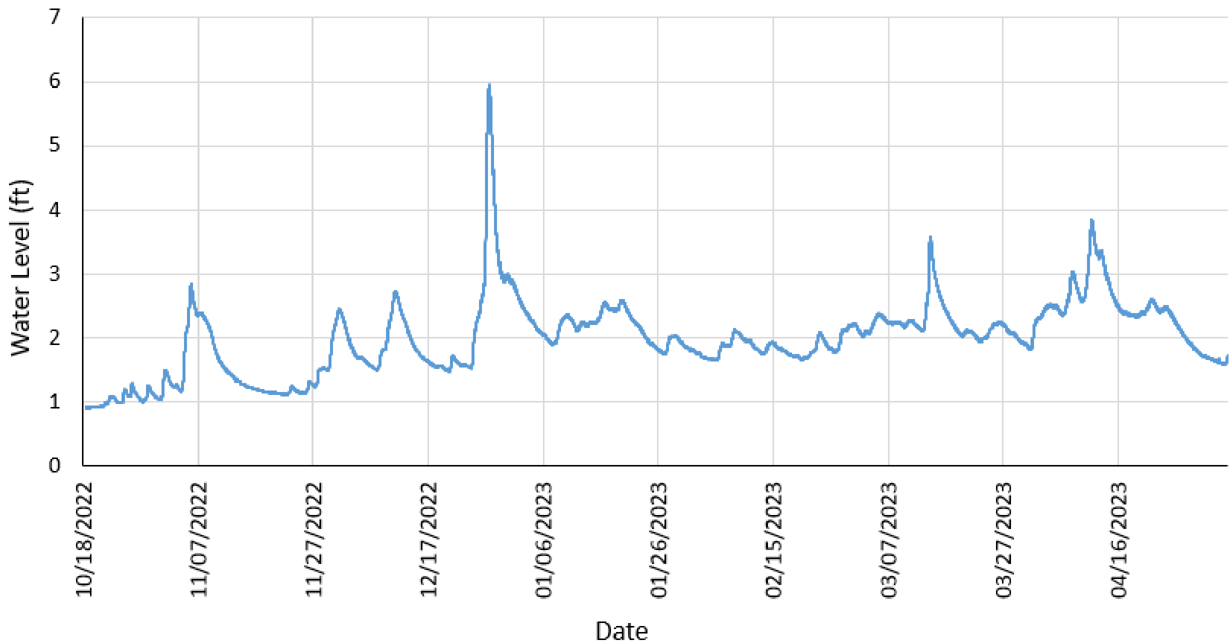

Figure 7. Water level measurements in Lacamas Creek at Goodwin Road

3.2.2 Water Quality Monitoring: Field Measurements

3.2.2.1 Lacamas Lake

Thermistor data showed thermal stratification in Lacamas Lake until early November 2022, when temperatures converged and declined across the entire water column. The presence of thermal stratification indicates the lake is not mixed well across depths, while a lack of thermal stratification may indicate well-mixed conditions across lake depths. The lake began to show weak thermal stratification again in spring 2023, with a period of uniform temperature increase across the entire water column during the first week of March (Figure 8).

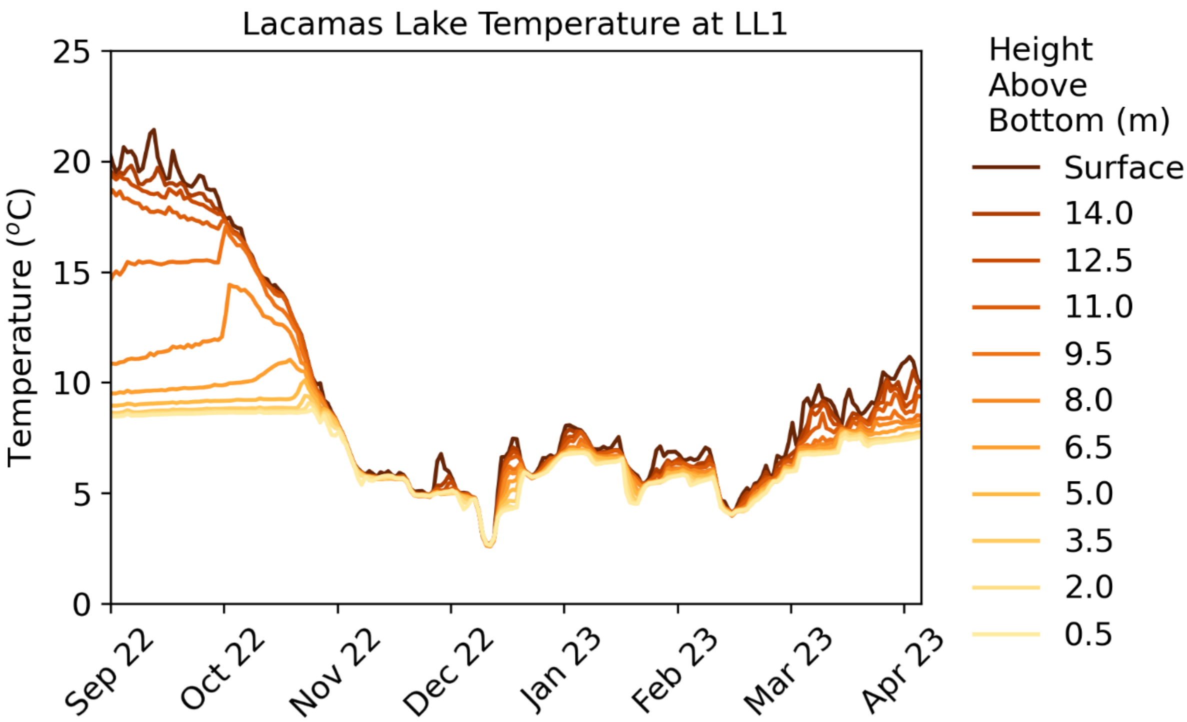

Figure 8. Lacamas Lake temperature at various depths

The first set of field measurements were taken on June 1, 2022. An oxycline was in the process of forming at LL1 during this sampling event (Figure 9) and was fully formed and persistent from the June 21 through the September 20, 2022, sampling events. The DO measurements near the surface on June 1 are higher than the saturation concentration for the water temperature at the time, which may indicate high algal productivity creating supersaturated conditions, or could indicate an issue with the probe. However, the probe did pass calibration checks for DO prior to and following sampling. A sampling event did occur in late October in which an oxycline did appear to be present at LL1, however, total failure of the same water quality probe used that day resulted in all field data from the October 2022 Lacamas Lake sampling event being rejected. Unstratified winter DO levels in Lacamas Lake at LL1 (January 19) averaged 10.3 mg/L for most of the depth of the water column, with somewhat lower levels (6.2 mg/L) near the bottom (Figure 9). Elevations on the figure are provided relative to the maximum water surface elevation measured during the study period (see Figure 6).

At the inlet to Lacamas Lake (LL2), the shallower depth prevented full formation of stratified layers during months where measurements were taken except late June and July 2022 (Figure 10). DO at the lakebed had recovered to 8.4 mg/L by August 16, and the lake profile was uniform by January 19 (Figure 10). As with LL1, the DO measurements near the surface on June 1 are higher than the saturation concentration for the water temperature at the time, The DO measurements near the surface on June 1 are higher than the saturation concentration for the water temperature at the time, which may indicate high algal productivity creating supersaturated conditions, or could indicate an issue with the probe. However, the probe did pass calibration checks for DO prior to and following sampling. All limited sampling locations showed stratification during at least one sampling event, though the timing and duration of stratification varied (Table 8).

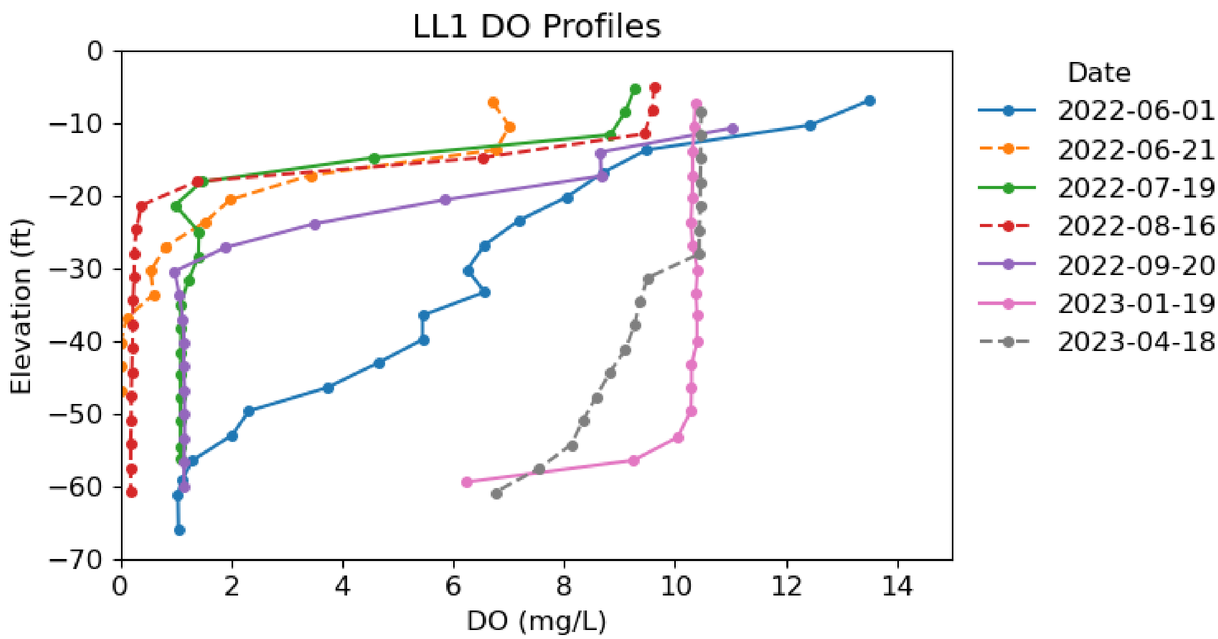

Figure 9. Vertical DO profiles at LL1

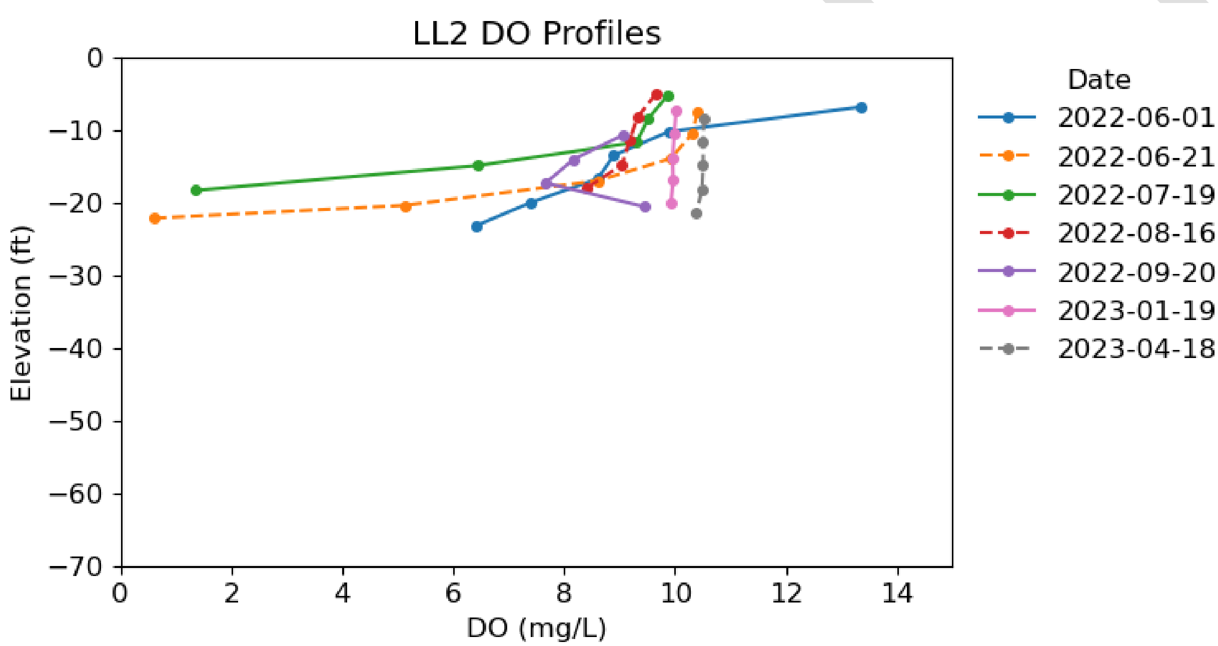

Figure 10. Vertical DO profiles at LL2

Table 8. Approximate depth of oxycline below Lacamas Lake Surface (feet)

Month	LL1	LL2	LL-Lim1	LL-Lim2	LL-Lim3
May 2022	none	none	none	none	none
June 2022	23	18	none (>18)	none (>10)	none (>21)
July 2022	20	15	18	11	13
August 2022	18	none (>16)	18	none (>16)	16
September 2022	23	none (>13)	none (>13)	none (>7)	13
January 2023	none	none	none	none	none
April 2023	none	none	none	none	none

The pH at LL1 was fairly consistent, with most samples falling between approximately 6.0 and 7.5. During summer months, surface pH was occasionally elevated, which is likely a result of phytoplankton productivity. The pH during the unstratified months of January and April did occasionally fall below 6.0 (Figure 11) in the vertical profiles.

The pH at LL2 (Figure 12) was broadly similar to the upper portion of the water column at LL1, with most samples falling between approximately 6.0 and 7.5. As with LL1, during summer months, surface pH was occasionally elevated, which is likely a result of phytoplankton productivity. The pH during the unstratified conditions in January 2023 did drop slightly below 6.0. in the vertical profiles. A similar pattern was seen at the limited lake sampling locations, though no pH values below 6.0 were recorded at those locations.

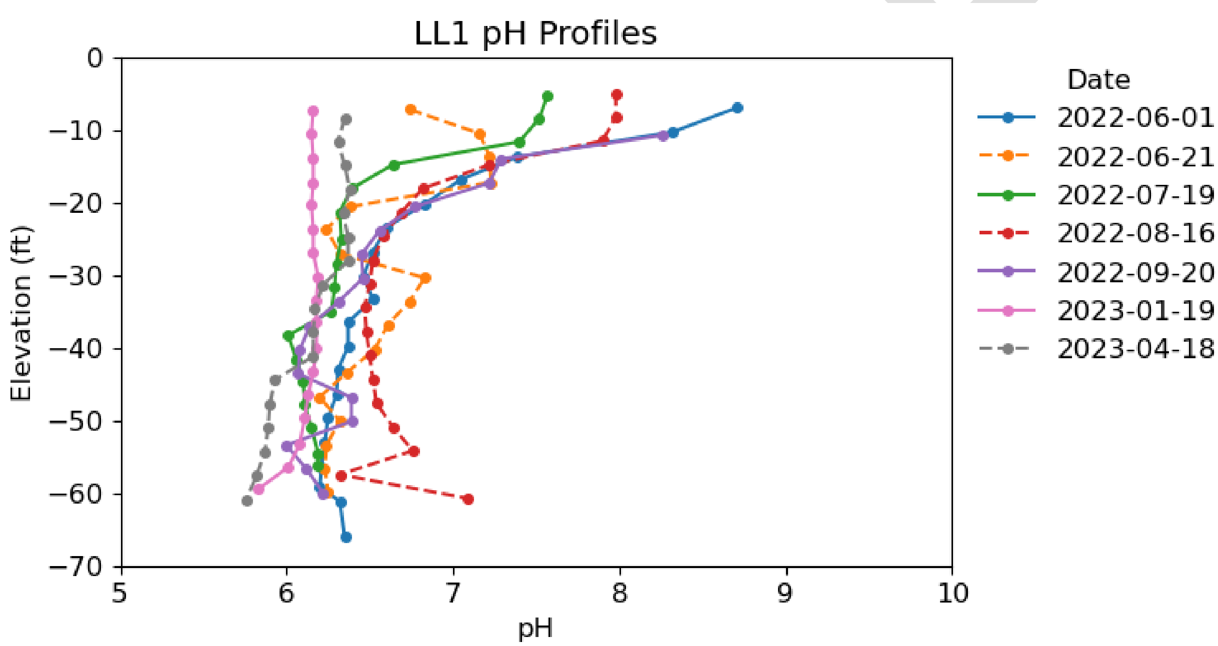

Figure 11. pH vertical profiles as measured at LL1

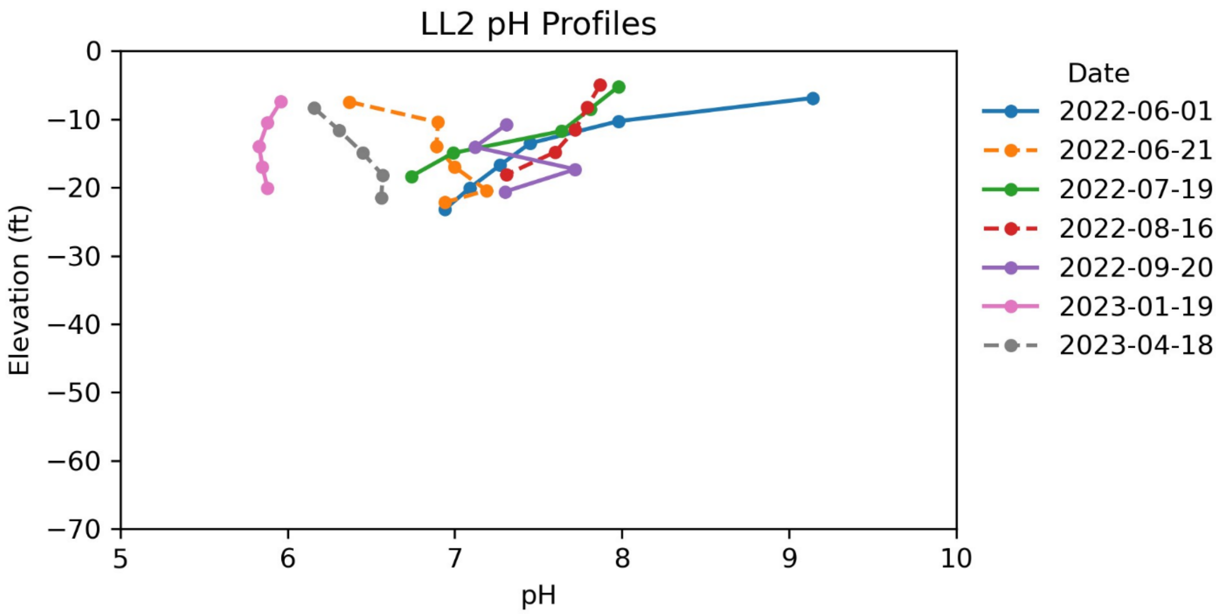

Figure 12. pH vertical profiles as measured at LL2.

SC was lowest during the early June, January, and April sampling events, with values around 50–70 microsiemens per centimeter (µS/cm), while values during the summer months were generally between 80 and 120 µS/cm, with a few measurements up to 150 µS/cm. Figure 13 shows the SC vertical profiles at LL1 and Figure 14 shows the SC vertical profiles at LL2. Both figures indicate increases in SC near the bottom, which could potentially indicate internal loading of nutrients from bottom sediments which release other ions at the same time as bound phosphorus, or could indicate a stronger influence from groundwater, which generally has higher SC.

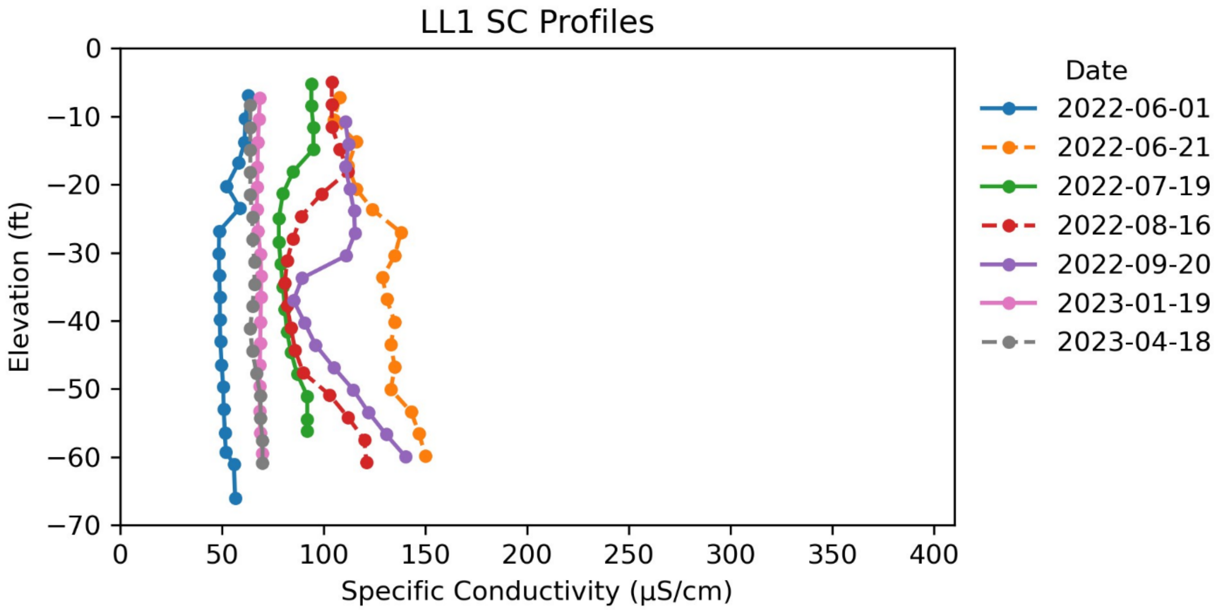

Figure 13. Specific conductivity vertical profiles as measured at LL1

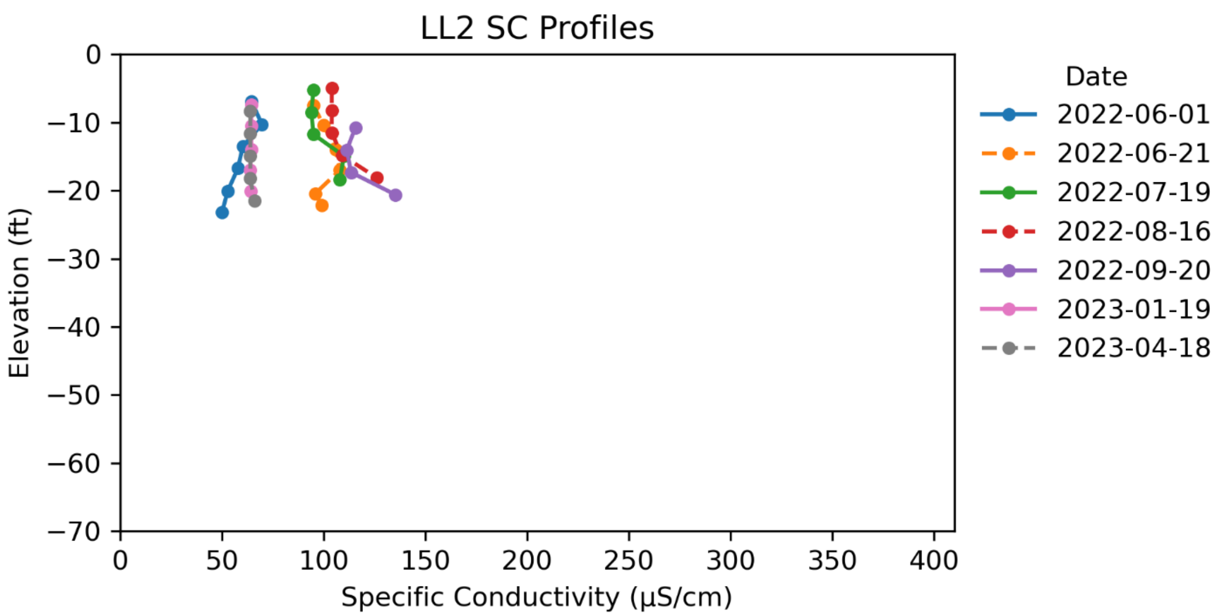

Figure 14. Specific conductivity vertical profiles as measured at LL2

ORP was generally high when DO was high, and vice versa, as is expected. The highest ORP values were measured in April 2023, and the lowest in late June 2022. Figure 15 shows the ORP profiles for LL1 and Figure 16 shows the ORP profiles for LL2. ORP measurements below positive 200 millivolts are indicative of reducing conditions that are more conducive with internal release of phosphorous in the water column resulting in internal loading.

Secchi disk depth at Lacamas Lake locations varied from a minimum of 0.6 meters (2.0 feet) in September to a maximum of 2.3 meters (7.5 feet) in July, with an overall average of 1.2 meters (3.9 feet) (Figure A.1, Appendix B.2).

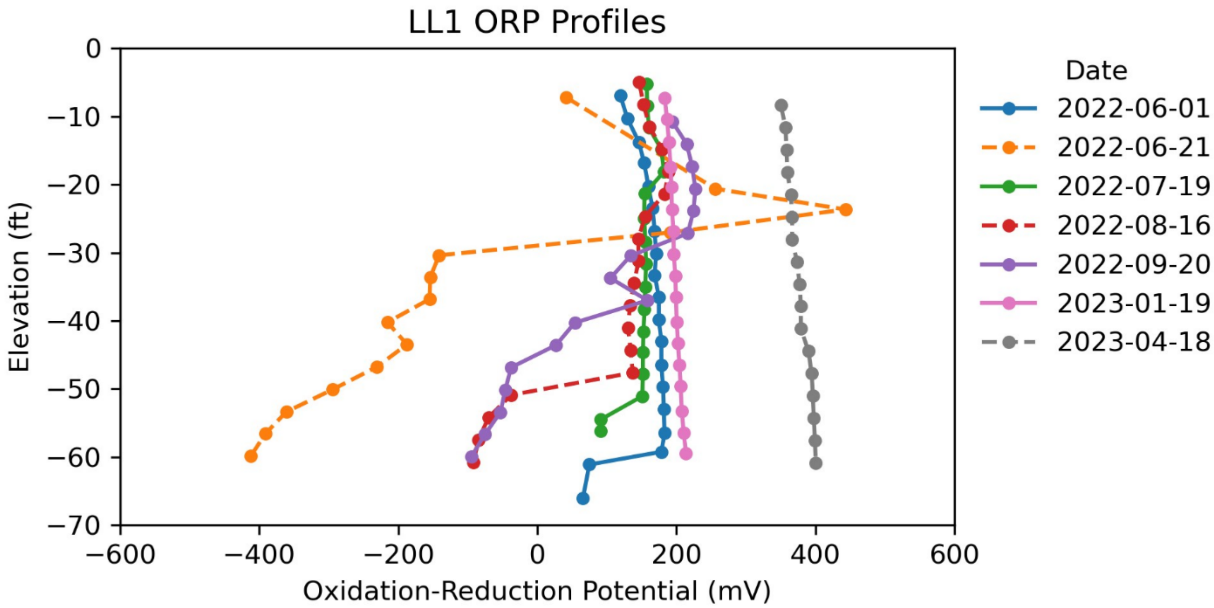

Figure 15. ORP vertical profiles as measured at LL1

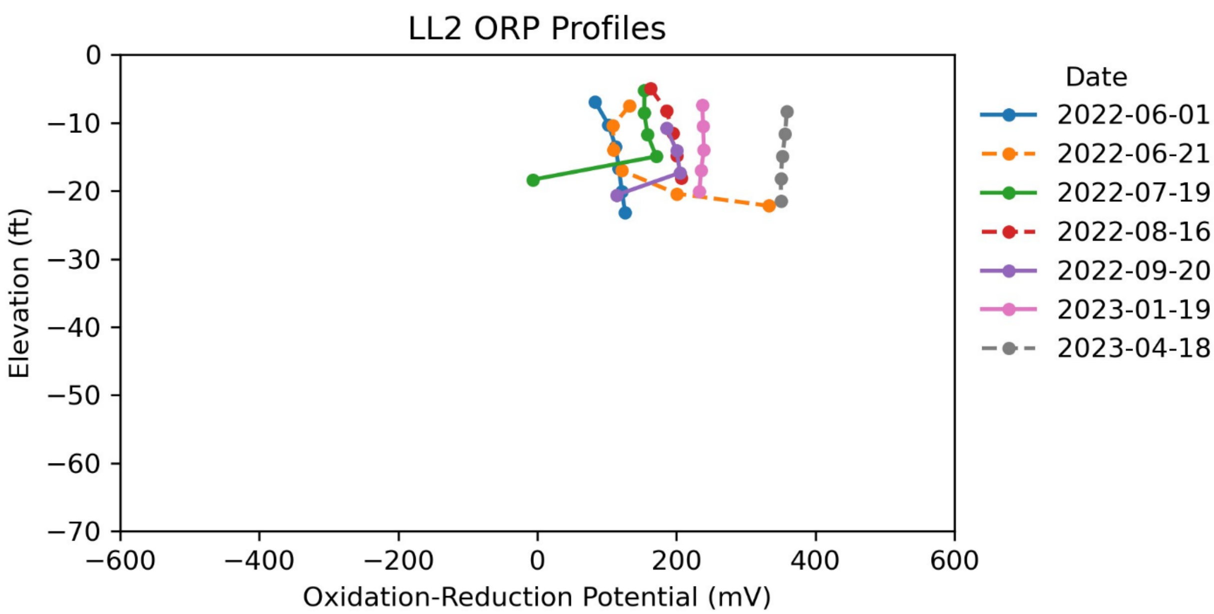

Figure 16. ORP vertical profiles as measured at LL2

3.2.2.2 *Round Lake*

Figure 17 shows thermistor data measured along the vertical profile of RL1 from September 2022 to April 2023. Round Lake stratification was similar to Lacamas Lake in that thermal stratification lasted until early November 2022. Temperatures across depths reconverged abruptly in the second week of November, declined uniformly during the winter, and remained similar across lake depths until late February 2023. Weak thermal stratification began to develop in Round Lake in March 2023, with stronger stratification near the bottom 5–10 feet of the lake.

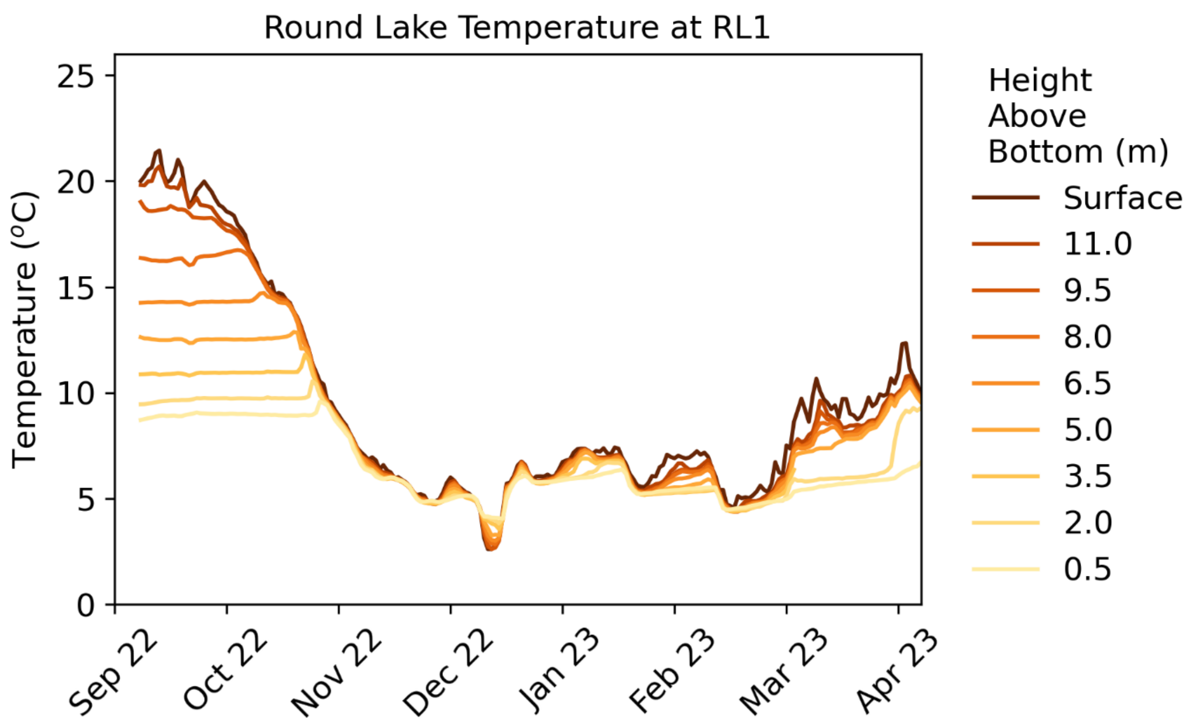

Figure 17. Round Lake temperature at various depths

The DO profiles for Round Lake (Figure 18) shows stratification of DO in the water column was observed during the first sampling event in June 2022, with anoxic (absence of DO) conditions rising upward from the lakebed throughout the summer to an elevation of about 16 feet below the maximum water surface elevation measured during the study period. By the January 18 sampling event, the DO profile was nearly uniform (10.9 mg/L), with a slight decline near the lake bottom (8.8 mg/L). An oxycline was not observed at any point at the limited lake sampling location (RL-Lim1; Table 9). For both June 3 and 22, the two data points nearest the surface are more elevated in DO than expected, which may indicate high algal productivity creating supersaturated conditions, or could indicate an issue with the probe.

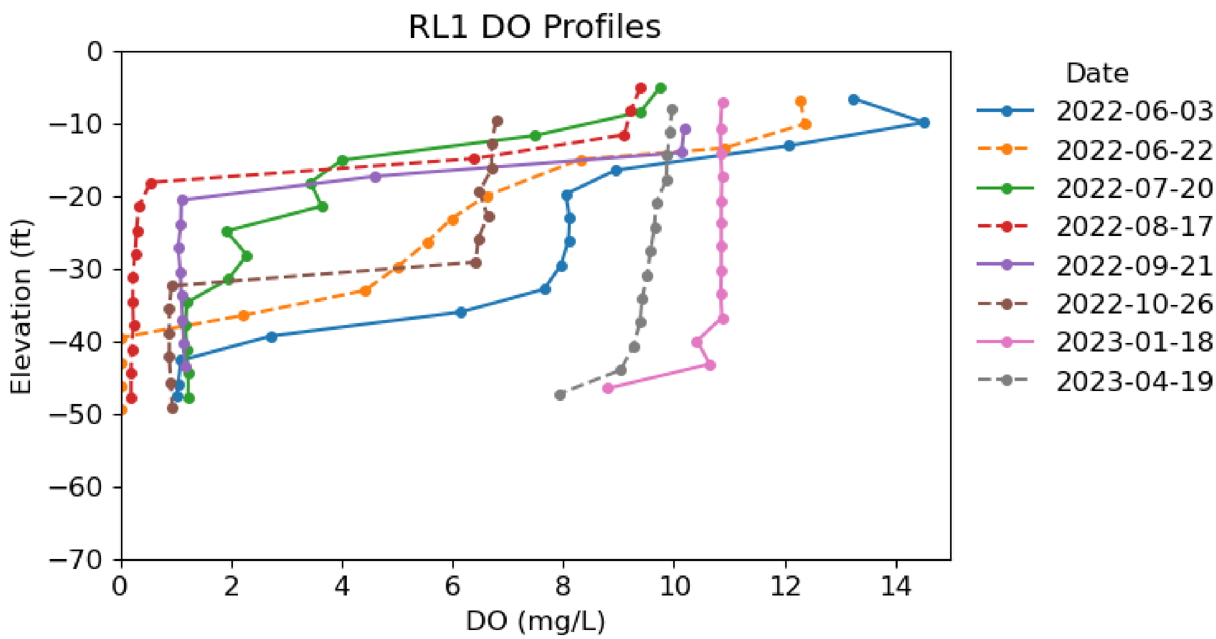

Figure 18. Vertical DO profiles at RL1

Table 9. Approximate depth of oxycline below Round Lake surface (feet)

Month	RL1	RL-Lim1
May 2022	39	none (>11)
June 2022	34	none (>11)
July 2022	33	none (>11)
August 2022	16	none (>13)
September 2022	18	none (>16)
October 2022	26	none (>10)
January 2023	none	none
April 2023	none	none

The pH at RL1 was similar to that in Lacamas Lake, with most samples falling between approximately 6.0 and 7.5, and occasional high pH values near the surface during summer months (Figure 19).

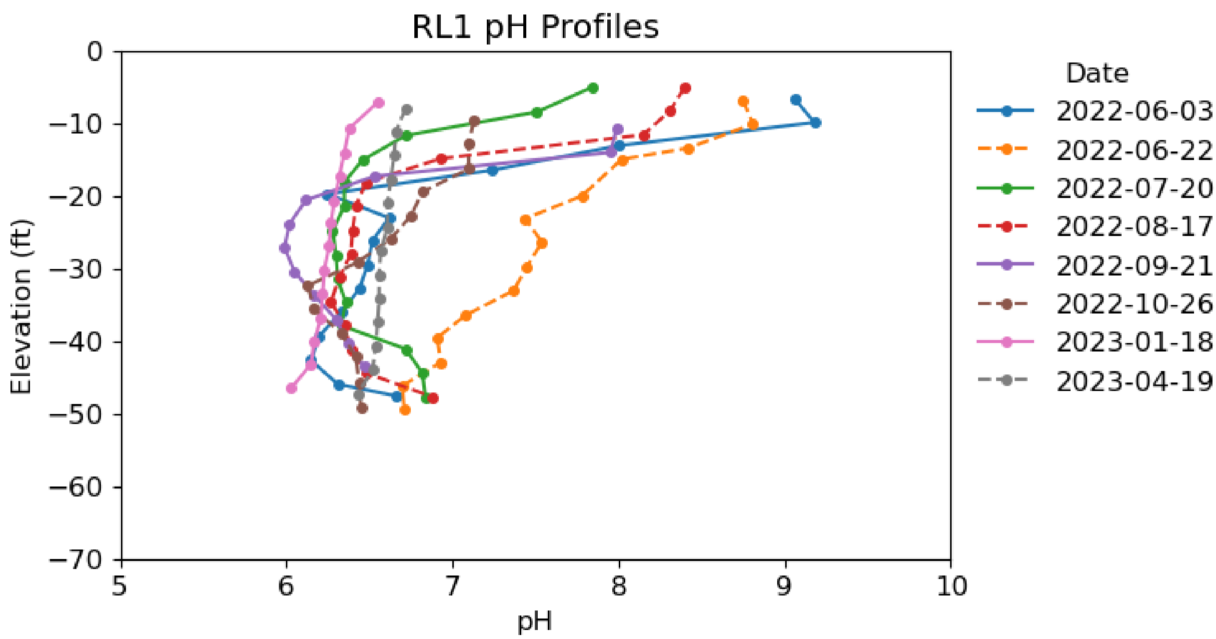

Figure 19. Vertical pH profiles at RL1

SC was similar to Lacamas Lake, with lower values in June, January, and April, and slightly higher values during summer. However, the highest SC values were notably higher than they were in Lacamas Lake, with measurements up to 250 µS/cm during summer months, particularly near the bottom (Figure 20).

ORP was generally high when DO was high, and vice versa, as is expected. The highest ORP values were measured in April 2023, and the lowest in late June 2022 (Figure 21), and are frequently below 200 millivolts, again potentially indicating internal loading of nutrients.

Secchi disk depth at Round Lake locations varied from a minimum of 0.7 meters (2.3 feet) in September to a maximum of 3.7 meters (12.1 feet) in July, with an overall average of 1.5 meters (4.9 feet) (Figure A.1, Appendix B.2).

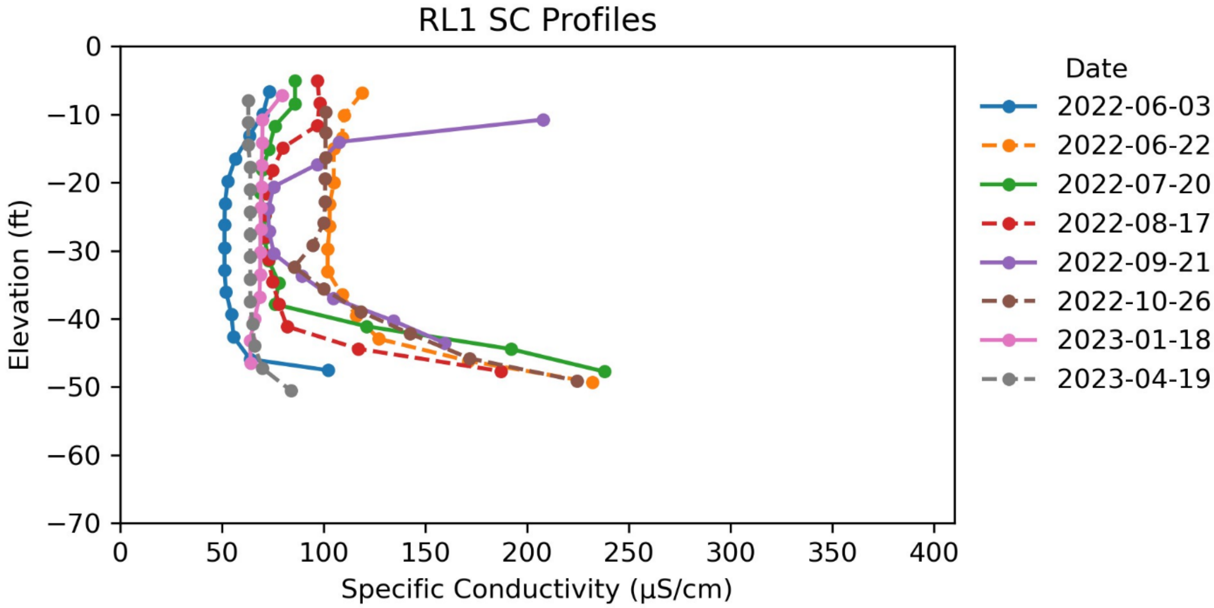

Figure 20. Vertical specific conductivity profiles at RL1

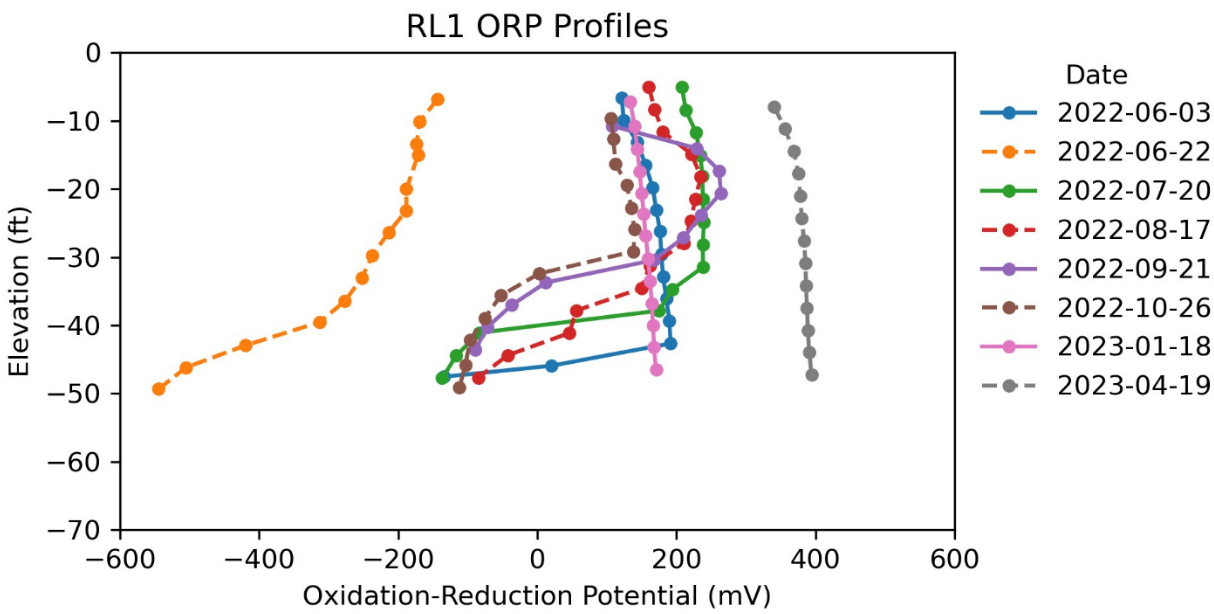

Figure 21. Vertical ORP profiles at RL1

3.2.2.3 Fallen Leaf Lake

Field measurements for Fallen Leaf Lake were taken on three occasions between June and November 2022. Figure 22 shows field-measured vertical profiles of temperature as measured at

FLL1. Thermal stratification was present during each of the three sampling events, with stratification being somewhat weaker during the October sampling event. The temperature vertical profiles observed in 2022 are similar to those observed by Clark County in 2020 (Clark County Public Works, 2021).

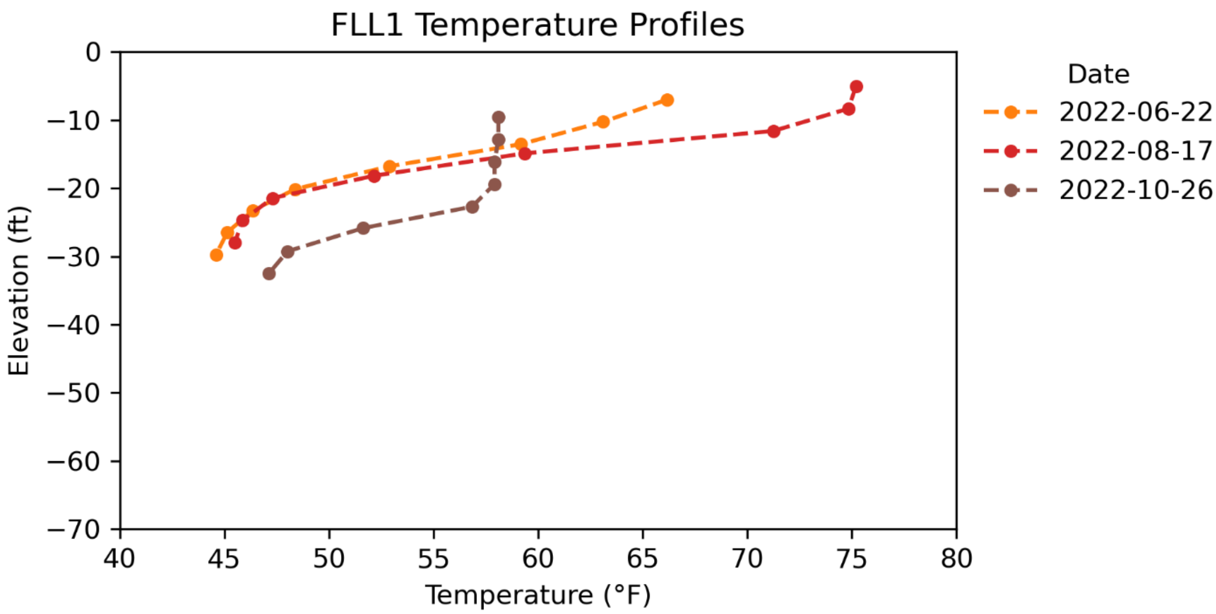

Figure 22. Vertical temperature profiles at FLL1

An oxycline was present during all three events. DO concentrations were higher in the epilimnion during the summer (June) than the fall (October), decreasing from 10.7 to 6.7 mg/L, respectively, at a depth of 1 meter (3.3 feet) below the surface (Figure 23). The elevated DO concentration near the surface in the June measurement may indicate high algal productivity creating supersaturated conditions, or could indicate an issue with the probe. These DO profiles are similar to what Clark County found in 2021, although the oxycline in August 2022 was somewhat closer to the surface than any of the measurements in 2020 (Clark County Public Works, 2021).

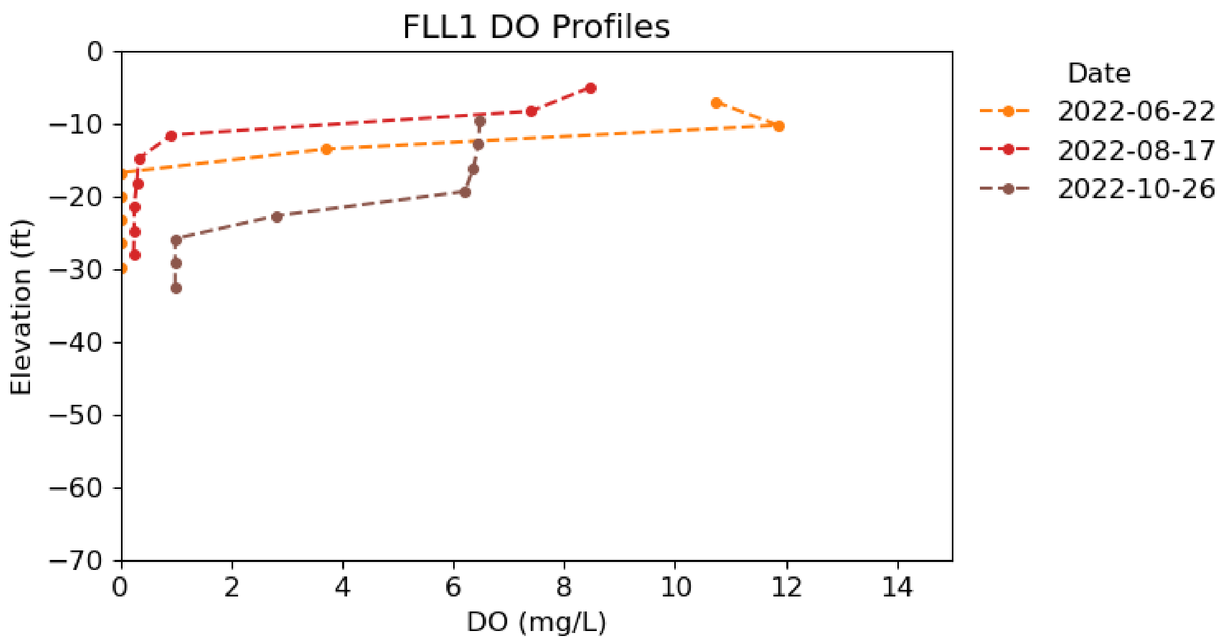

Figure 23. Vertical DO profiles at FLL1

The pH at FLL1 was similar to that in the other lakes, with most samples falling between approximately 6.0 and 7.5, and only one slightly higher pH value was observed near the surface during the first sampling event (Figure 24), potentially indicating increased algal productivity. The pH, as well as the shape of the pH vertical profiles, is similar to what was measured in 2020 (Clark County Public Works, 2021), with the exception that far fewer high pH measurements were noted near the surface of the lake in 2022.

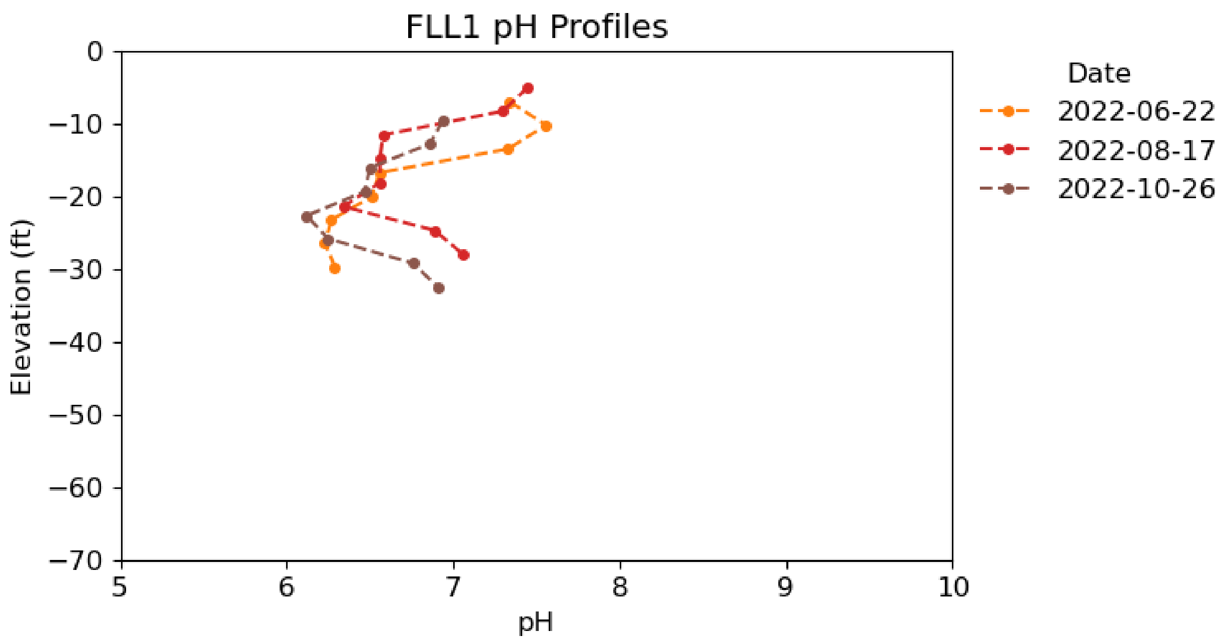

Figure 24. Vertical pH profiles at FLL1

SC was slightly higher than the other two lakes, with epilimnion measurements varying between approximately 80 and 120 µS/cm, and hypolimnion concentrations as high as 400 µS/cm (Figure 25). The increasing SC near the bottom is again indicative of potential internal loading or potential increased influence from groundwater. This is consistent with what was seen by Clark County Public Works in 2020, with the exception of the highest SC measurements in the bottom of the lake in 2022, which were observed to a lesser extent in 2020.

ORP was generally high when DO was high, and vice versa, as is expected (Figure 26). However, ORP values were negative throughout the water column in June, which is unusual given the amount of oxygen in the epilimnion. The ORP values were similar in August and October 2022. Clark County Public Works did not measure ORP in 2020.

Secchi disk depth was consistent throughout the summer, with measurements in the narrow range of 2.0 to 2.1 meters (6.6 to 6.9 feet), which is similar to what was seen by Clark County in 2020 (Figure A.1, Appendix B.2; Clark County Public Works, 2021). This is generally deeper and more consistent than Round or Lacamas Lakes, which may indicate a less dynamic ecosystem and lower algal productivity.

Overall, results in Fallen Leaf Lake confirm what Clark County found in their 2020 study.

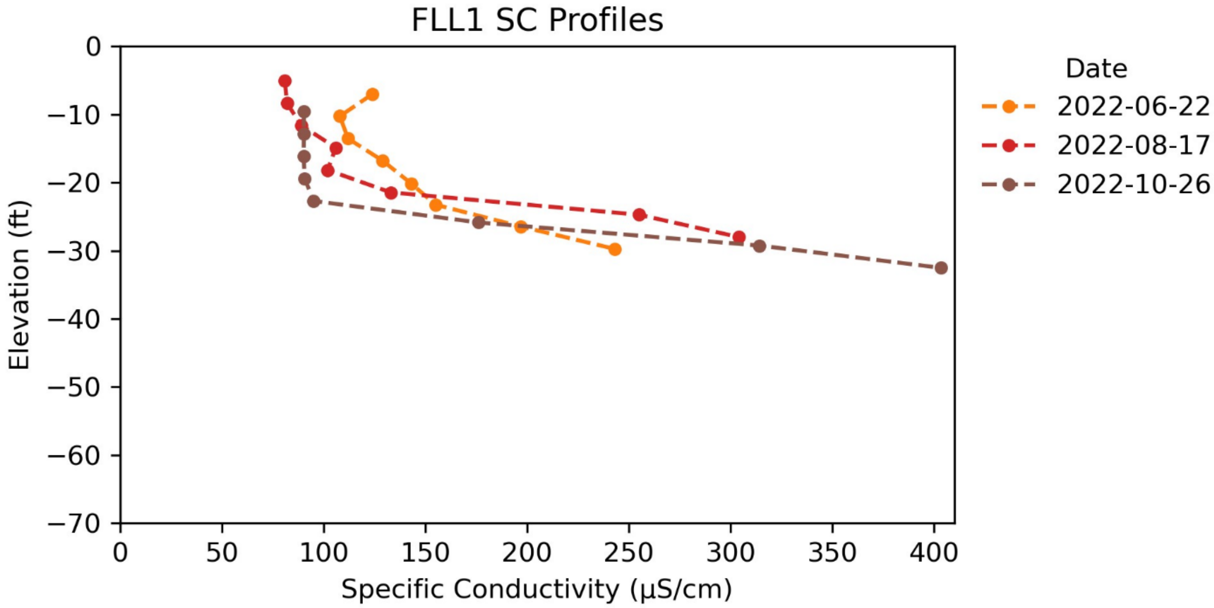

Figure 25. Vertical specific conductivity profiles at FLL1

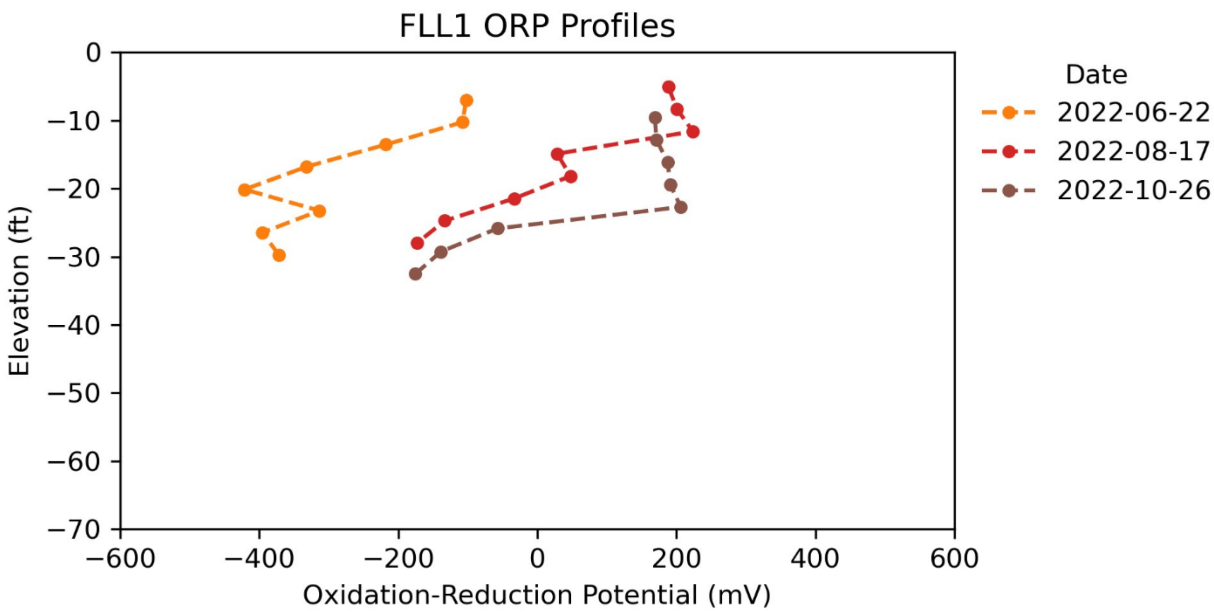

Figure 26. Vertical ORP profiles at FLL1

3.2.2.4 Creeks

Water temperature in the creeks generally varied with air temperature. The highest temperatures were recorded at Round Lake's outlet to Lacamas Creek (LC-UD) in August 2022 (25.1°C), while the lowest temperatures, which approached freezing, were recorded in December 2022. Dwyer Creek (DC1) in particular showed a dichotomous trend in temperature, where all values in June through September were above 16°C and values in other months were no higher than 8.1°C.

DO was generally between 8 and 12 mg/L at all locations, but was unusually low at some locations in late summer through late fall. In particular, Currie Creek fell below 6.0 mg/L DO in August, likely due to low flow. Lacamas Creek fell below 6.0 mg/L DO in October at Goodwin Road (LC-G), and at the Upper Dam in October through December (LC-UD). The low October concentration at LC-G is likely due to the lack of flow out of the lakes during drawdown, with the low November DO likely caused by lake turnover in which the low-DO hypolimnion mixes with the epilimnion prior to draining out of the dam. It is not known why the December DO was so low, however, this sampling event followed a significant snow event, so the low DO could have been caused by high organic loads from sediment runoff or ice management practices, though the SC measurements suggest salt was not an issue.

pH generally fell between 6 and 8, with slightly higher values at LC-UD concurrent with high pH values measured in the lakes. Occasional measurements in fall, winter, and spring also fell just under 6.0, but were never below 5.6. These slightly acidic pH values are likely due to recent rainfall.

SC was fairly consistent, with values ranging from 50–170 µS/cm. The highest SC measurement was one anomalous data point taken in Dwyer Creek in late June at nearly 200 µS/cm. Currie Creek had a somewhat lower SC than the other creeks, with no value exceeding 100 µS/cm (Appendix B.2).

3.2.2.5 Stormwater

Stormwater temperature also varied with air temperature, with values ranging from 4 to 5°C in December to 8 to 9°C in late March. Samples always showed DO above 10 mg/L, with a pH of 6.8 to 7.7, and SC between approximately 70 and 120 µS/cm. These values fall within acceptable ranges for surface water.

3.2.3 Water Quality Monitoring: Lab Measurements

3.2.3.1 Lacamas Lake

3.2.3.1.1 LL1

Total phosphorus measured near the lake bottom of Lacamas Lake at LL1 was elevated compared with previous studies. At LL1, the maximum concentration in the bottom layer was 0.43 mg/L (September 2022) compared to 0.34 and 0.22 mg/L in 1991–1992 and 1984, respectively. Total phosphorus at the bottom of LL1 in January 2023 (0.285 mg/L), after thermal destratification occurred, was 0.22 mg/L higher than the concentration reported in 1991 (0.07 mg/L; Figure 27). On the other hand, phosphorus concentrations near the surface of Lacamas Lake at LL1 were observed to have a similar range compared with data from the 1980s and 1990s (Figure 28). The x-axis of each figure begins in June 2022, with the first sampling event for this study. Data from previous years are shown for comparison.

It is interesting to note there was a small peak in total phosphorus in the bottom of LL1 in late June 2022, with the lowest total phosphorus concentration observed during the study period at the bottom of LL1 in mid-July 2022. Given evidence from other field parameters, such as the deepest Secchi depth at LL1 being recorded during the same July sampling event, as well as the hyper-saturated DO and high pH at the surface of LL1 in early June which were not present in July, evidence suggests there was an early-season algae bloom on Lacamas Lake in June. The algae likely consumed most of the available phosphorus, causing the algae to die off in mid-July. A second algae bloom was then recorded later in summer. It is not known whether the potential June algae bloom was made up of cyanotoxin-producing algae or not. Another possible explanation is the potential that a large storm on June 10, 2022 (2.73 inches in 24 hours based on the Weather Underground KWACAMAS161 station) delivered a very large load of phosphorus to the lake, contributing to the spike in total phosphorus observed in late June.

Orthophosphate (OP) concentrations were similar in magnitude to total phosphorus concentrations; for Lacamas Lake the overall average measured OP concentration was 0.062 mg/L, compared with 0.071 mg/L for total phosphorus, meaning OP accounted for on average 87% of the total phosphorus; in some cases the reported OP concentration were higher than total phosphorus, which indicates uncertainty in the measurement. OP time-series plots can be found in Appendix A and data can be found in Appendix B.1.

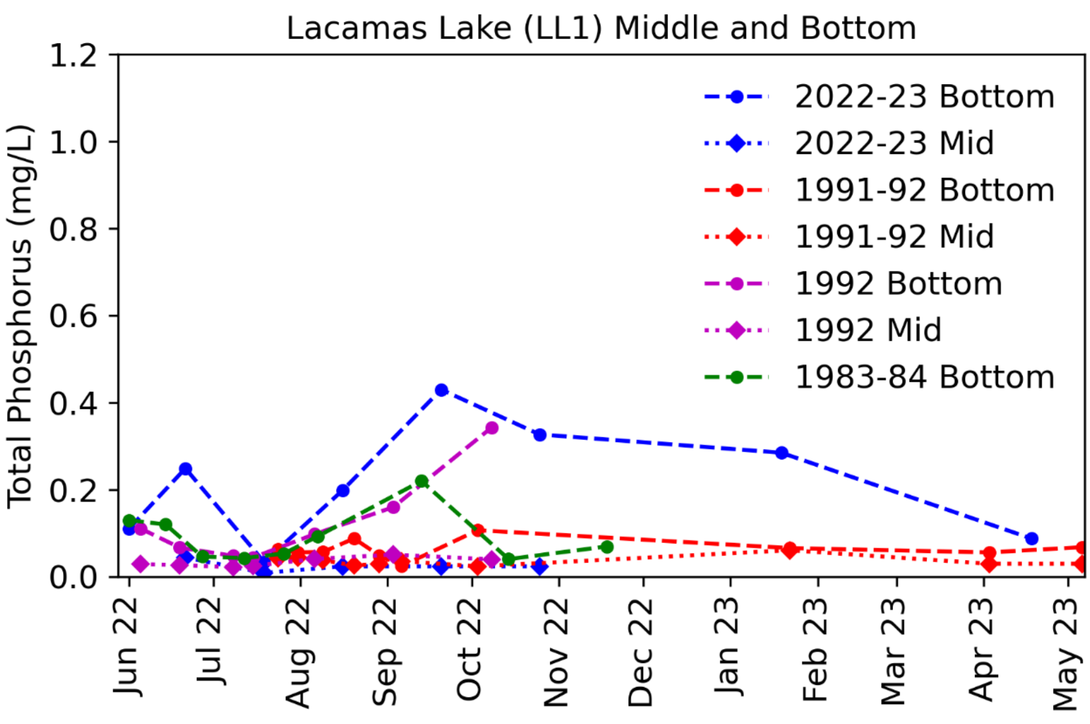

Figure 27. Total phosphorus in the middle and bottom samples of LL1

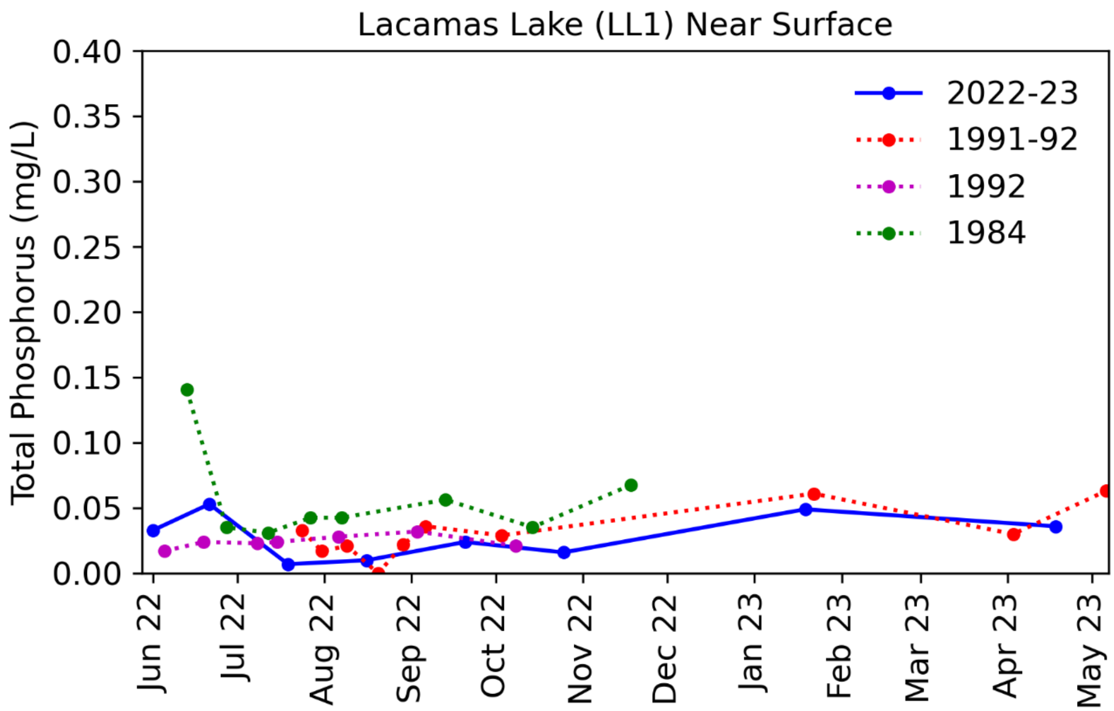

Figure 28. Total phosphorus near the surface of LL1

Total nitrogen was calculated as the sum of TKN and nitrate/nitrite concentrations Where samples were below the detection limit, half the detection limit was assumed. Total nitrogen concentrations near lake bottom were also elevated relative to previous years of study. Total nitrogen in Lacamas Lake at the bottom for sample location LL1 ranged from 0.80 to 2.51 mg/L over the entire 2022-2023 sampling period compared with a range of 0.32 to 1.44 mg/L observed in the previous studies (Figure 29). The species of nitrogen in the lake bottom samples changed over time, with nitrate and nitrite (NOx) being elevated in early summer and spring, when the lake is well-mixed, ammonia in late summer when the lake is stratified and little oxygen is present in the bottom layers, and non-ammonia TKN late fall and winter. Total nitrogen levels near the surface of the lake (Figure 30) fell in the same range as previous study results. Nitrogen in the top layer consisted of mostly non-ammonia TKN, with a spike in NOx in late fall and winter, after the lake turned over. Ammonia, TKN, and nitrate-nitrite plots are available in Appendix A and data is available in Appendix B.1.

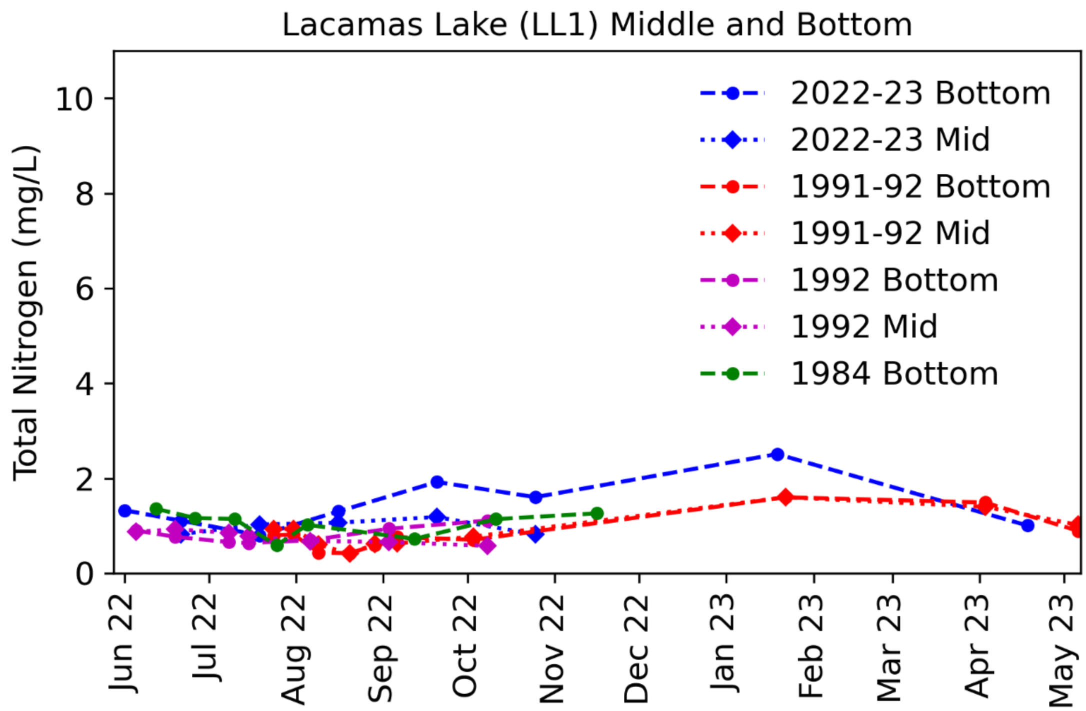

Figure 29. Total nitrogen in the middle and bottom samples at LL1

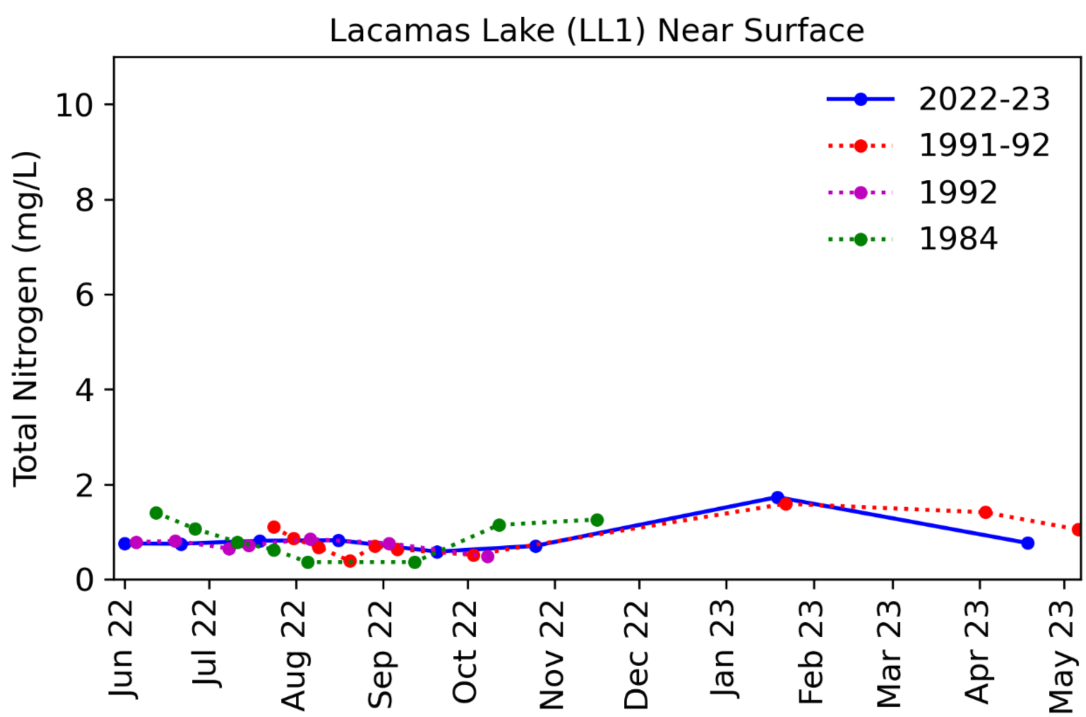

Figure 30. Total nitrogen near the surface of LL1

Concentrations of Chl-a measured near the surface in Lacamas Lake at LL1 were similar in magnitude to previous studies, ranging from 0.65 to 33.3 µg/L. Peak values were recorded in September, which was likely related to the elevated levels of phosphorus in the hypolimnion during the late-summer/fall season. In comparison with data from previous years, the Chl-a concentrations were generally lower, and did not approach the maximum measurement of 64.8 µg/L recorded in previous studies (Figure 31). This indicates that the while significant nitrogen and phosphorus increases were observed, algae growth could have been limited by other environmental factors during the study period.

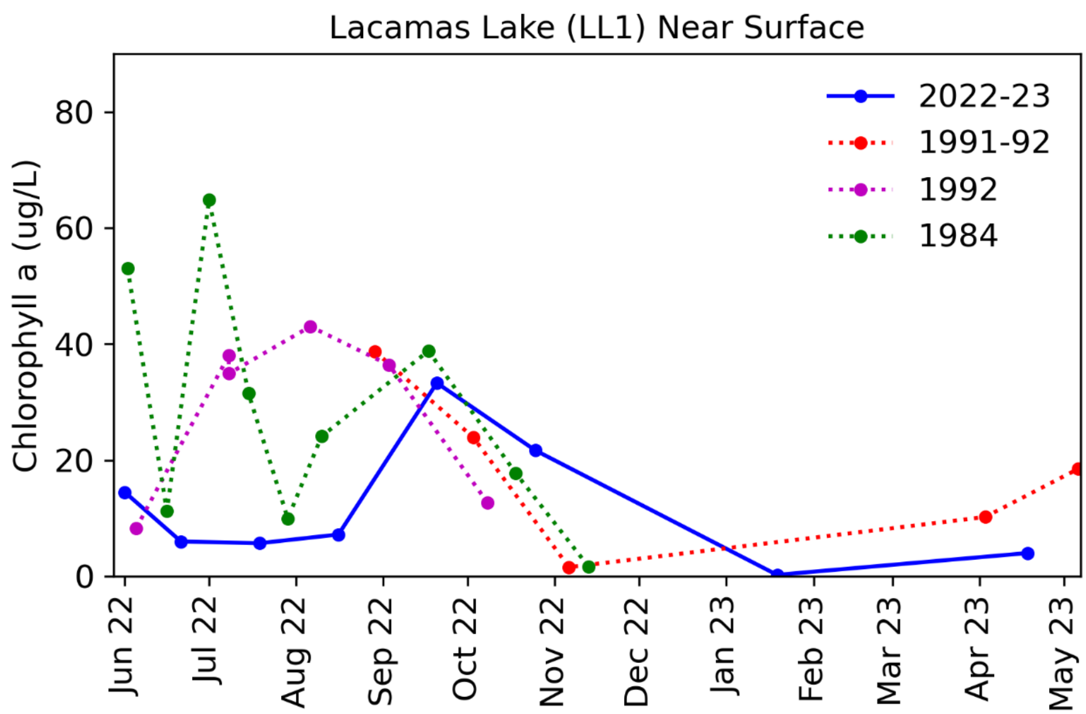

Figure 31. Chlorophyll-a near the surface of LL1

3.2.3.1.2 LL2

Total phosphorus measured in Lacamas Lake at LL2 showed little variation between near-surface and near-bottom measurements (Figure 32). Concentrations were measured below 0.07 mg/L across the duration of the study period, with the highest values occurring in January 2023 following the same temporal pattern as the results at LL1. Total nitrogen values at LL2 (Figure 33) were similar at both lake depths and ranged from 0.61 to 1.57 mg/L. NOx and TKN showed similar seasonal patterns to samples at the top of LL1. Chl-a measured near the lake bottom at LL2 (Figure 34) peaked in September 2022 at 22.5 µg/L. Near the lake surface at LL2, the highest measured value was 27.6 µg/L in September 2022.

These results make sense for LL2 given its shallower and more upstream location in the lake. Based on DO data, an oxycline was only present at LL2 during two of the seven lake sampling events—June and July 2022. This means the top and bottom water at LL2 was likely well mixed for most of the year, leading to more consistent measurements amongst the top and bottom of the water column. Also, with sufficient DO near the bottom of the water column for most of the year, there was little opportunity for any phosphorus in the sediments to be released and contribute via internal loading. Finally, the location's proximity to the mouth of Lacamas Creek means the water there is likely replaced by incoming water more frequently, again signifying more well-mixed conditions at this location.

Additional water quality time series plots are available in Appendix A and data is available in Appendix B.1.

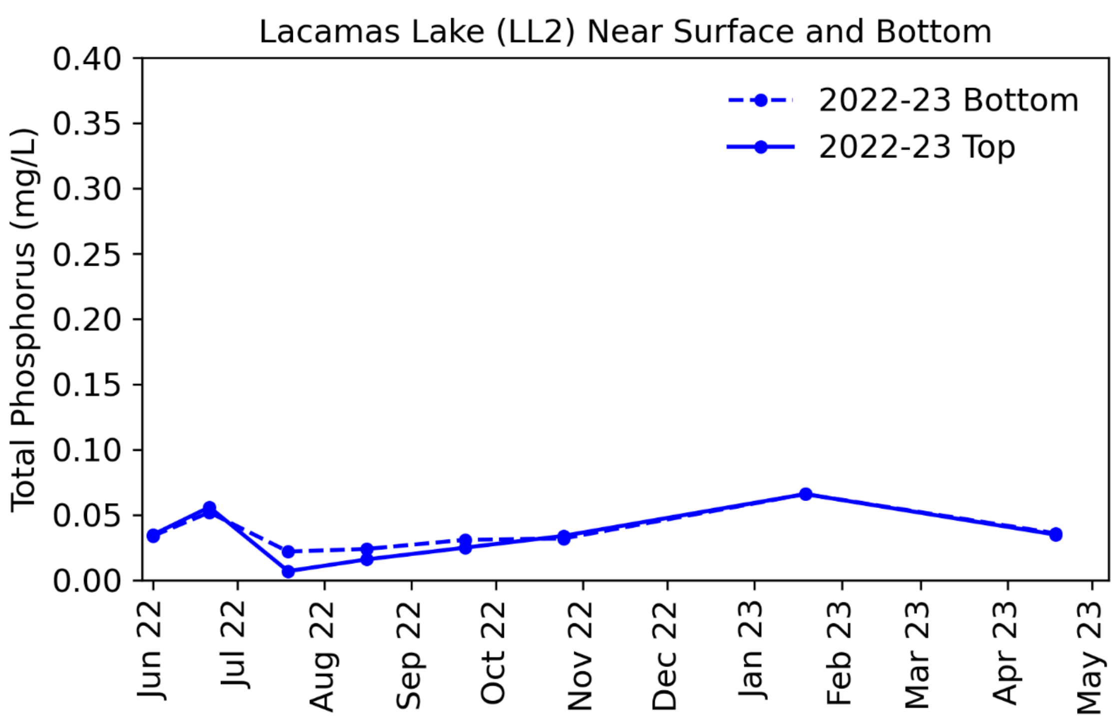

Figure 32. Total phosphorus near the bottom and near the surface of LL2

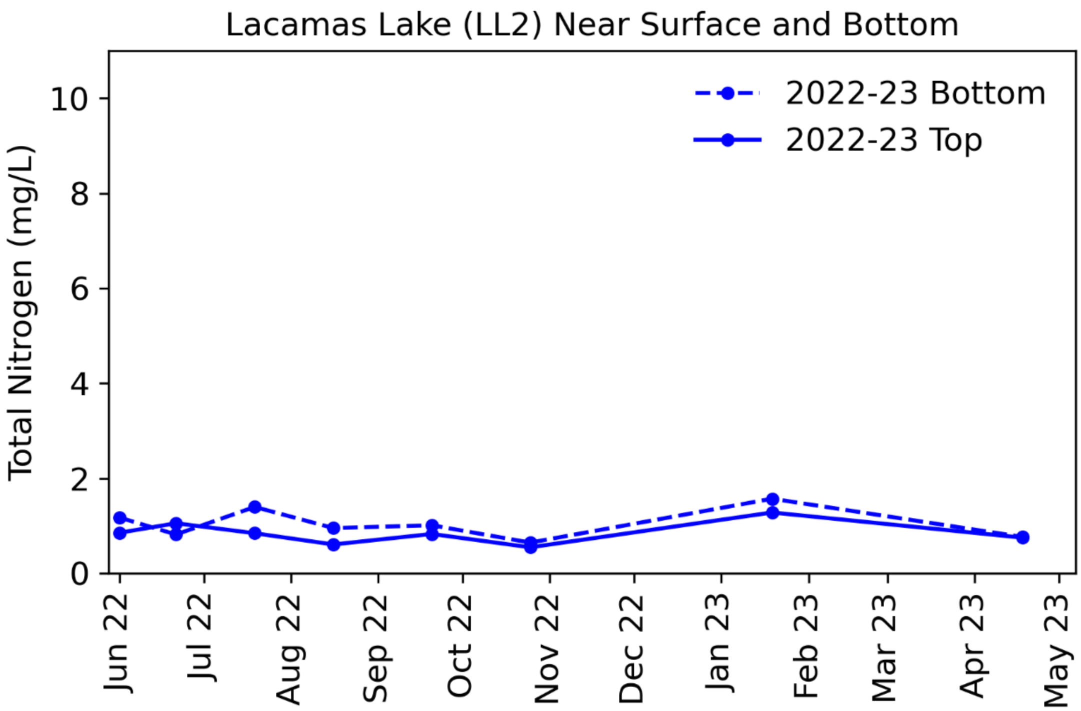

Figure 33. Total nitrogen near the bottom and near the surface of LL2

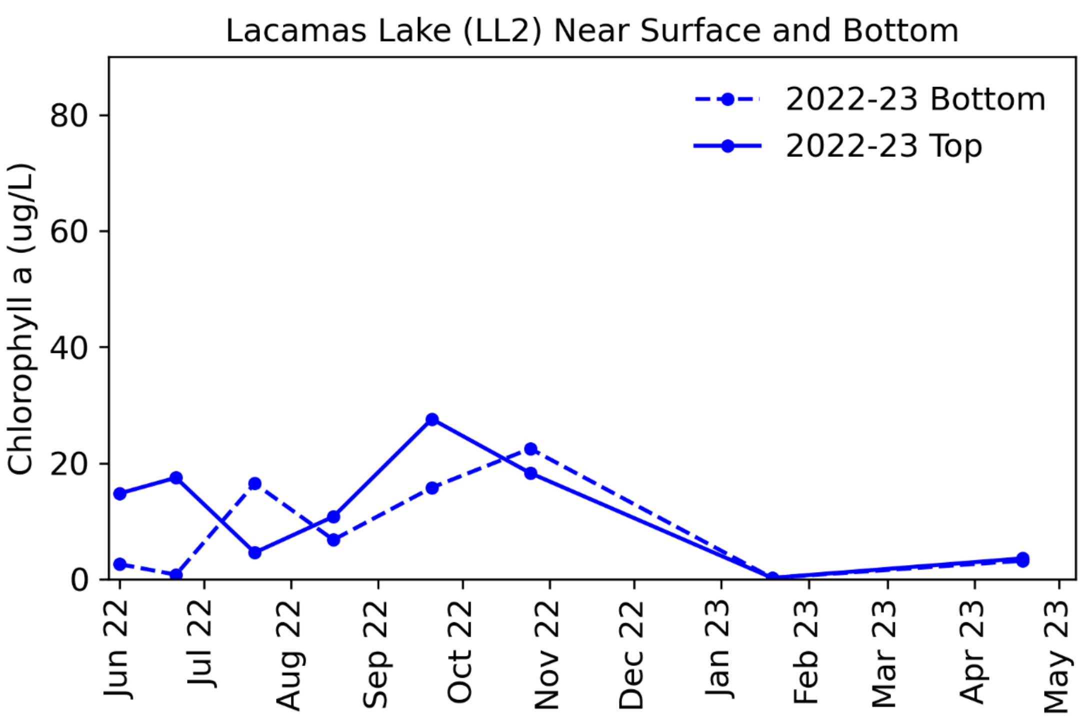

Figure 34. Chlorophyll-a near the bottom and near the surface of LL2

3.2.3.2 Round Lake

Total phosphorus measured near the bottom of Round Lake was greatly elevated compared with previous studies. In Round Lake at RL1, the maximum concentration in the bottom layer was 1.1 mg/L, while the maximum value observed in a 1991–1992 study (Lafer, 1994) was 0.16 mg/L, and was 0.14 mg/L in 1984 (Beak and SRI, 1985). However, the phosphorus sample taken from the bottom of Round Lake in January 2023, after thermal destratification occurred, closely matched with the corresponding 1991 value (Figure 35). The elevated measurements near the bottom of the lake may indicate increased internal loading of nutrients relative to past years. Total phosphorus concentrations near the surface of Round Lake at RL1 were also observed to have a similar range compared with data from the 1980s and 1990s (Figure 36), as well as to concentrations observed at the surface of LL1 during this study. Notably, the highest total phosphorus concentration at RL1 was more than double that at LL1, and occurred earlier in the year. No drop in phosphorus concentrations occurred at RL1 in July as it did at LL1. This similarity in surface concentrations and difference in bottom concentrations supports the theory that the bottom of the water column is fairly stagnant during stratification, with water flowing from Lacamas Creek to Lacamas Lake to Round Lake and out of the dam without mixing with deeper water.

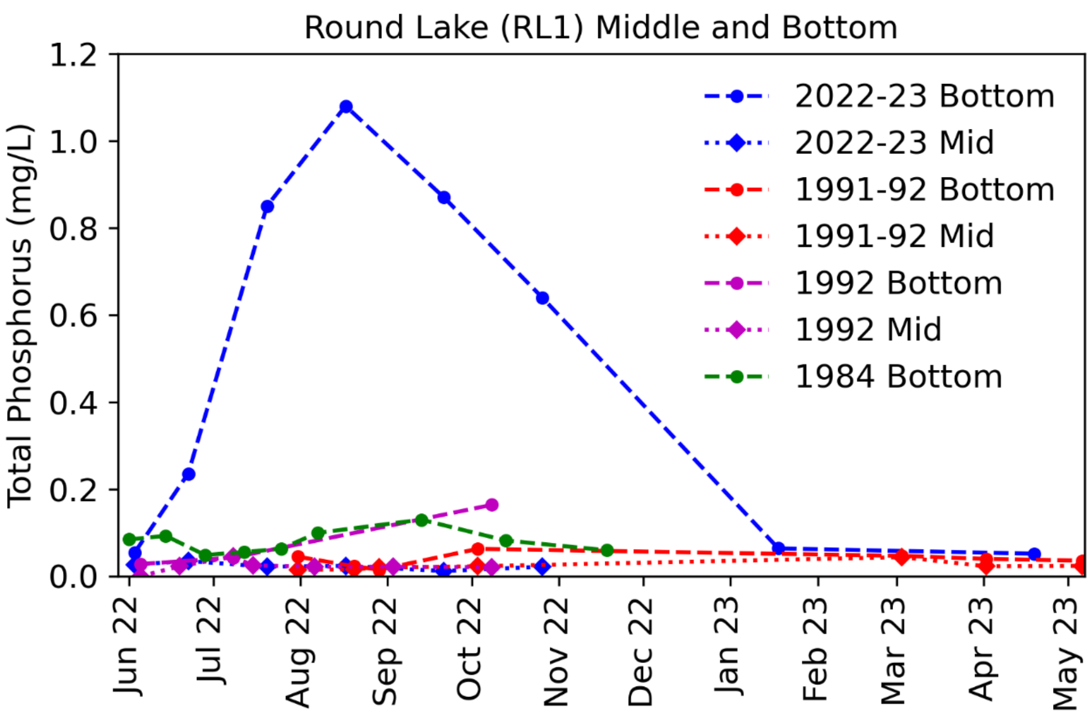

Figure 35. Total phosphorus at the middle and bottom of RL1

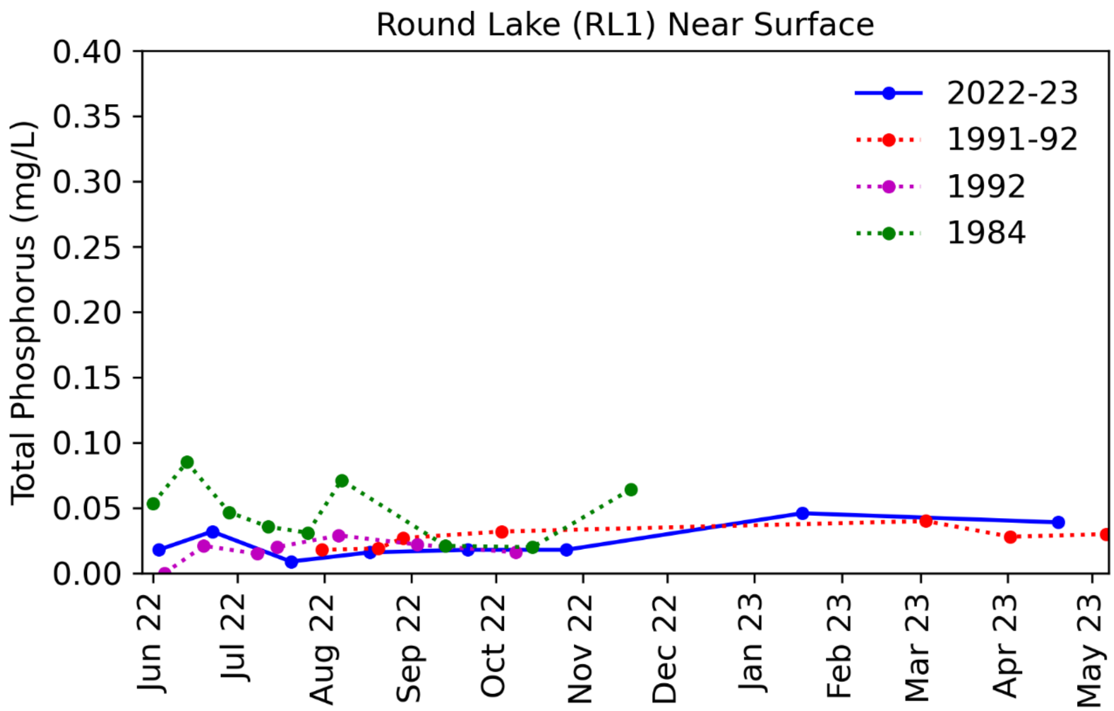

Figure 36. Total phosphorus near the surface of RL1

Total nitrogen concentrations near lake bottom were also elevated relative to previous years of study (Figure 37). The largest difference in concentration was between July and October, during which 2022 sample concentrations ranged from 3.57 to 5.20 mg/L, compared with a previous maximum of 1.22 mg/L measured in 1991. These elevated total nitrogen concentrations were due to increases primarily in ammonia concentrations, with less change shown in nitrate and nitrite concentrations. This is not surprising given the oxygen-poor environment at the bottom of Round Lake during the summer months. Notably, total nitrogen at the bottom or RL1 was greater than that at the bottom of LL1 for the majority of the summer.

Total nitrogen concentrations near the surface of RL1 were generally similar to past years, as well as concentrations observed at LL1. However, a large spike in total nitrogen was observed near the surface of RL1 in January 2023. This spike in total nitrogen was driven by a high concentration of non-ammonia TKN, with a somewhat elevated concentration of nitrate and nitrite. The cause behind this spike in surface total nitrogen in January is unknown.

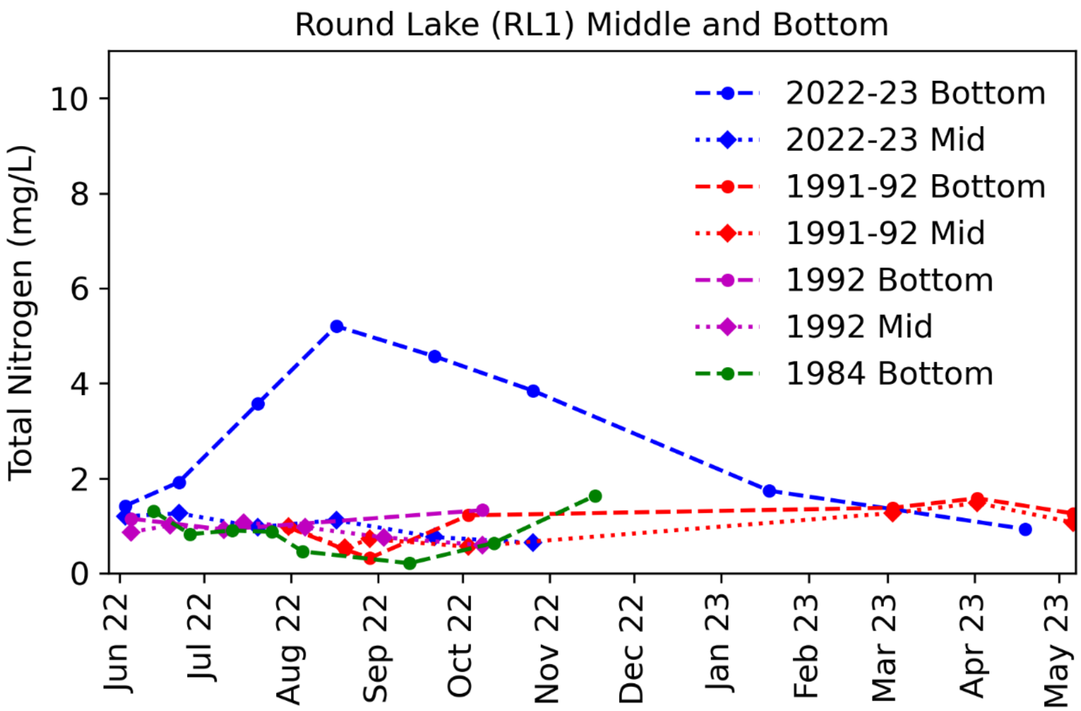

Figure 37. Total nitrogen in the middle and bottom of RL1

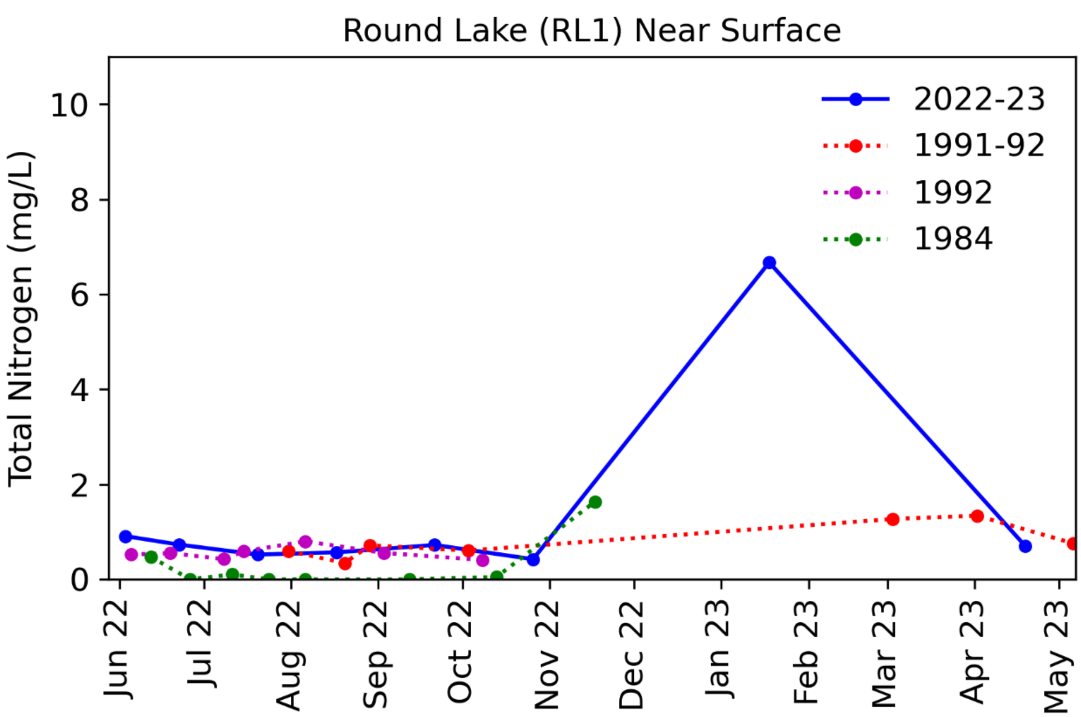

Figure 38. Total nitrogen near the surface of RL1

Concentrations of Chl-a measured near the surface of RL1 were similar in magnitude, ranging from no detection (> 0.5 µg/L) to 27.6 µg/L. Peak values were recorded in September, which was likely related to the elevated levels of total phosphorus in the hypolimnion during the late-summer/fall season. In comparison with data from previous studies, the Chl-a concentrations were generally lower and did not approach the maximum measurement of 85.3 µg/L recorded in prior studies (Figure 39). This indicates that while significant nitrogen and phosphorus increases were observed, algae growth could have been limited by other environmental factors during the study period. Additional water quality time series plots are available in Appendix A and data is available in Appendix B.1.

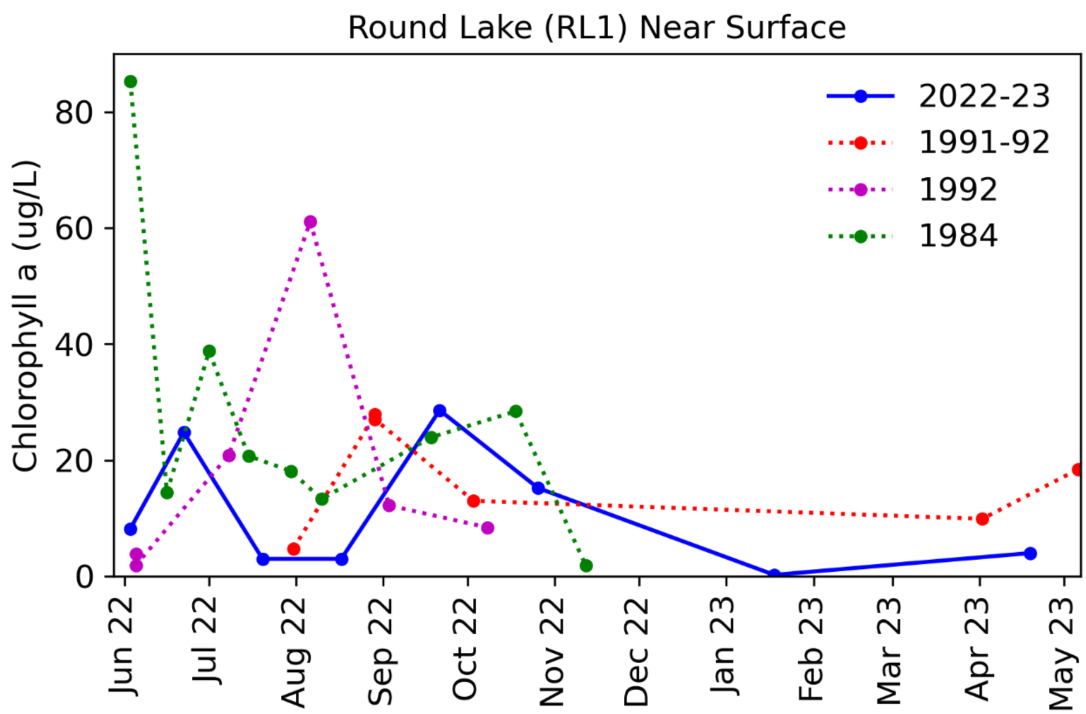

Figure 39. Chlorophyll-a near the surface of RL1

3.2.3.3 Fallen Leaf Lake

Total phosphorus measured in Fallen Leaf Lake (Figure 40) near the lake bottom was between 0.24 and 0.31 mg/L for the three samples taken in June, August, and October of 2022. Near the surface, phosphorus concentrations were less than 0.021 mg/L, while the measurements taken at mid-depth showed a spike in to 0.29 mg/L during August, with lower values in June and October. Clark County only collected near-surface samples from Fallen Leaf Lake in their 2020 study; results were similar to 2022 results with the exception of one unusually high sample seen in July of 2020 which was not observed in 2022 (Clark County Public Works, 2021). The range of total phosphorus concentrations seen at FLL1 in 2022 was similar to that seen at LL1 in 2022.

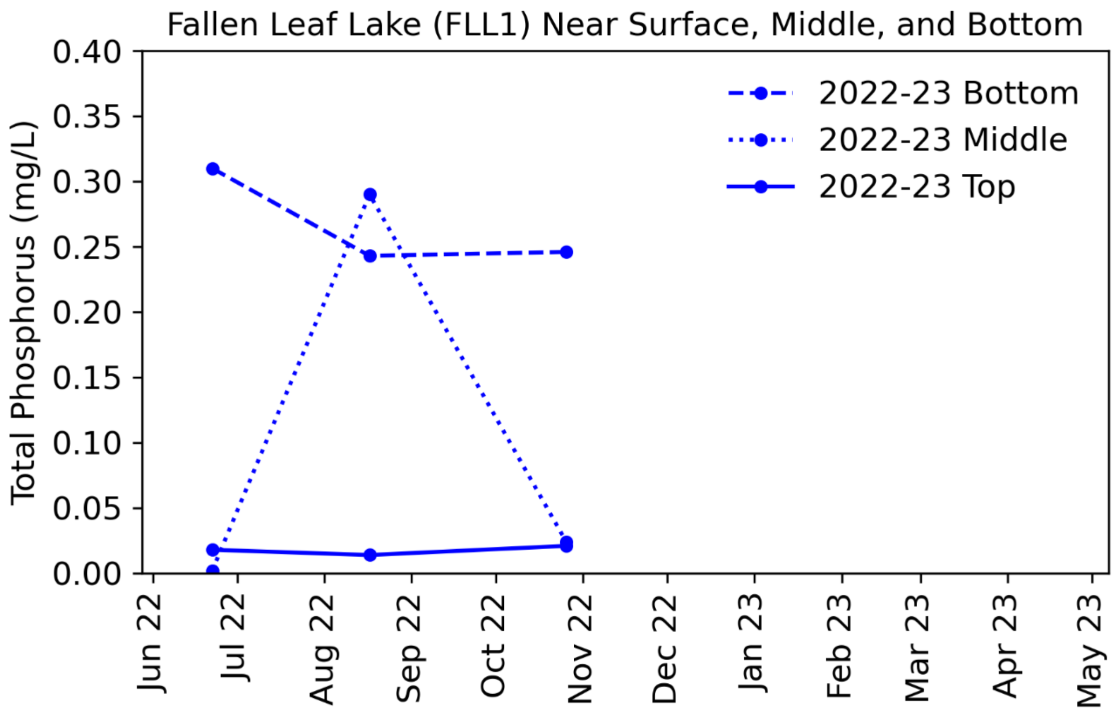

Figure 40. Total phosphorus near the bottom, near the middle, and near the surface of FLL1

Concentrations of total nitrogen in Fallen Leaf Lake peaked in August 2022, measuring 10.7 mg/L near the lake bottom, which was the highest total nitrogen concentration measured among all lake locations. The increase was associated with a higher TKN concentration, which is somewhat but not entirely explained by a higher ammonia concentration (see Appendix A). Clark County only measured surface concentrations in 2020, and did not measure ammonia concentrations specifically, but did observe a spike in TKN concentration at the surface of Fallen Leaf Lake in 2020 (Clark County Public Works, 2021). Concentrations of total nitrogen at mid depth and near the surface at FLL1 in 2022 were between 0.02 and 2 mg/L.

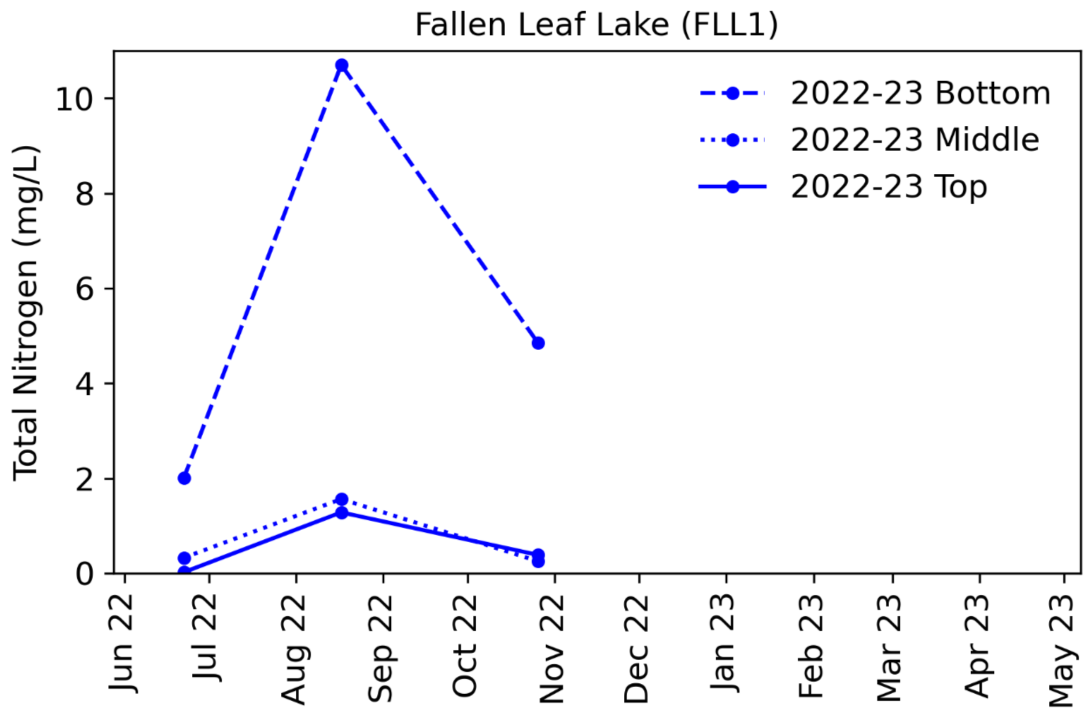

Figure 41. Total nitrogen near the bottom, near the middle, and near the surface of FLL1

Chl-a in Fallen Leaf Lake was highest near the lake bottom, measuring 33.7 and 43.4 µg/L in June and August, decreasing to 5.2 µg/L in October. The reasons for higher chlorophyll in the bottom of FLL1 are not understood, but it is likely a result of different species of algae occupying the water column at FLL1 than at LL1 or RL1 (see Section 3.2.6). Near the lake surface and mid-depth, Chl-a levels were between 4.9 and 19.2 µg/L at FLL1, which is within the range of concentrations observed by Clark County in 2020. The reason for the higher concentrations of chlorophyll at the bottom of FLL1.

Additional water quality time series plots are available in Appendix A and data is available in Appendix B.1.

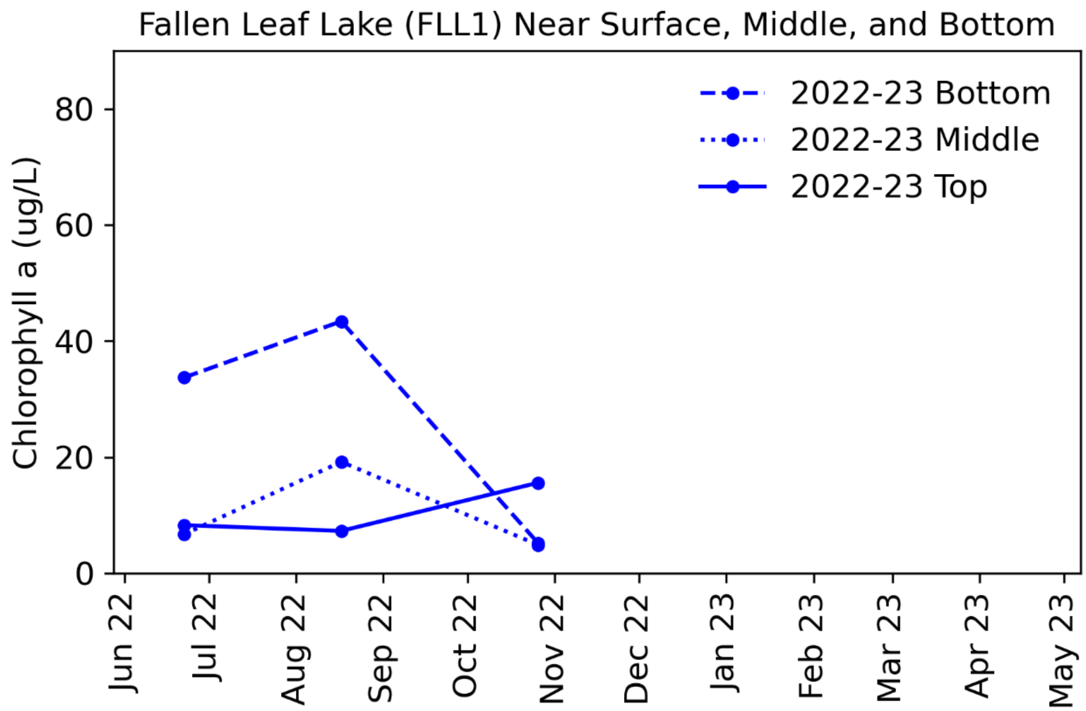

Figure 42. Chlorophyll-a near the bottom, near the middle, and near the surface of FLL1

3.2.3.4 Creeks

Figure 43 shows the results for total phosphorus in Lacamas Creek at Goodwin Road (LC-G), a location upstream of Lacamas Lake that historically has been estimated to account for 95% of the lake's overall inflow. Total phosphorus levels at LC-G were consistent over the course of the study period, with an average of 0.035 mg/L and a maximum of 0.054 mg/L. Excluding the April 2023 sample, orthophosphate concentrations ranged from 75% to 100%, meaning phosphorus was generally in a bioavailable form. In April 2023 orthophosphate made up only 60% of the total phosphorus. Concurrent sampling results from Clark County and Ecology showed some small differences during July of 2022, but overall showed agreement with the results recorded by the Geosyntec team.

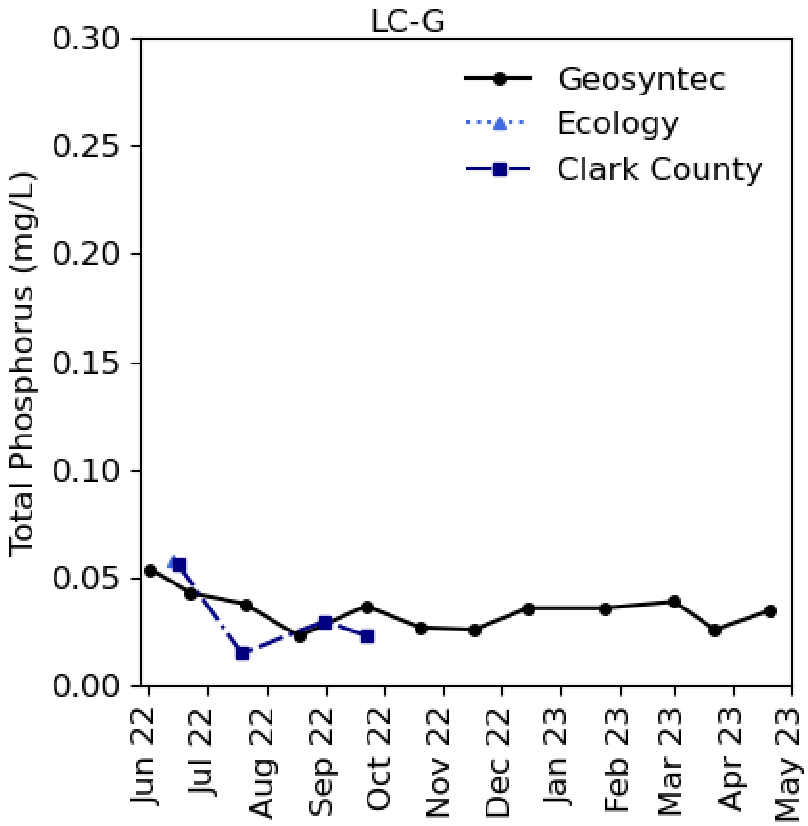

Figure 43. Total phosphorus concentrations in Lacamas Creek at Goodwin Rd (LC-G)

Total phosphorus levels measured in the minor creeks flowing into Lacamas Lake—Currie Creek, Dwyer Creek, and Unnamed Creek—show a mixture of results (Figure 44). The three creeks showed an increase in phosphorus during late summer, which was likely related to lower streamflow before the onset of the wet season. Currie and Dwyer creeks had no flow in September and October 2022. Unnamed Creek in particular had a sharp spike in phosphorus during late summer, reaching a concentration of 0.21 mg/L, and had an average overall level of 0.08 mg/L compared with 0.05 and 0.02 mg/L for Dwyer and Currie Creeks, respectively. One potential explanation for this is the presence of upstream impoundments on this creek, identified using aerial imagery, which may have gone anoxic during the summer. Unnamed Creek also drains a former dairy farm, which may explain the presence of higher concentrations of phosphorus in its drainage area. Unnamed Creek flowed continuously throughout the year. Excluding the April 2023 sampling event, phosphorus in Unnamed Creek was always at least 85% orthophosphate, meaning it was very bioavailable, while orthophosphate in Currie Creek was similarly high in summer but dropped to 57 – 76% of total phosphorus in December 2022 and onward. Dwyer Creek showed a similar pattern to Currie Creek, with the drop in orthophosphate percentage beginning in January 2023.

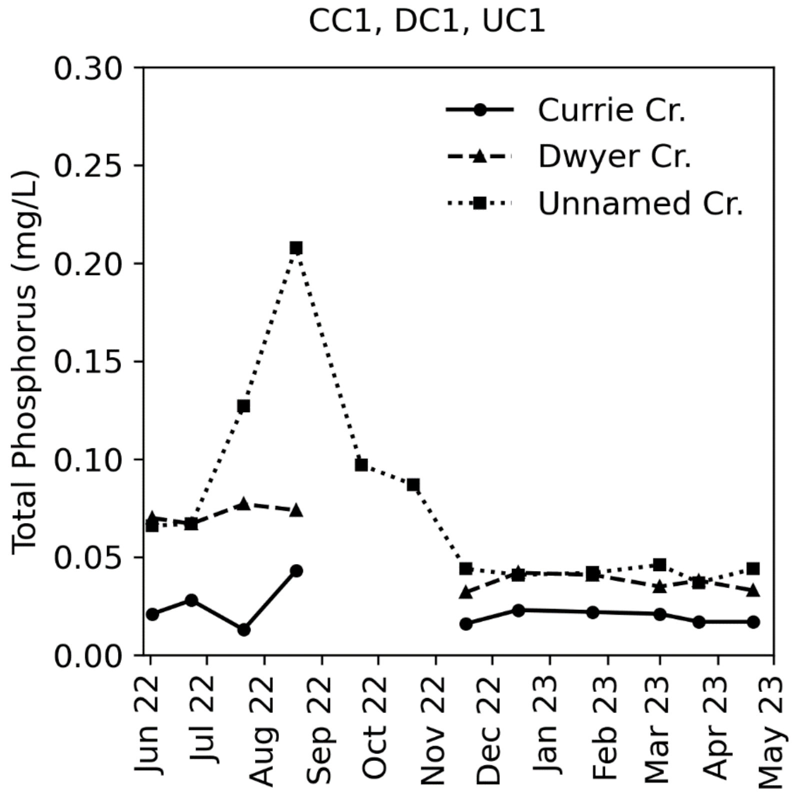

Figure 44. Total phosphorus concentrations in minor tributaries to Lacamas Lake – Currie Creek (CC1), Dwyer Creek (DC1), and Unnamed Creek (UC1)

Lacamas Creek at the outlet from the Round Lake Upper Dam (LC-UD) represents the water quality flowing out of Round Lake. This location showed similar total phosphorus concentrations to Lacamas Creek at Goodwin Rd (LC-G) in summer 2022, but had higher total phosphorus in fall and early winter. Unlike the other creek locations, the outlet samples at LC-UD showed a spike in total phosphorus concentration during the fall (October 2022), reaching a maximum of 0.12 mg/L (Figure 45). However, there was almost no flow out of the dam when this sample was taken as the lakes were still drawn down at this time, suggesting that it may not be representative of lake outflow. The fraction of total phosphorus represented by orthophosphate was similar to that in Lacamas Creek, however, lower percentages of orthophosphate were seen in late June 2022 (60%), November 2022 (75%), February 2023 (77%), and April 2023 (38%). The April 2023 measurement in LC-UD showed the lowest percentage of orthophosphate of any creek or lake sample taken during this study.

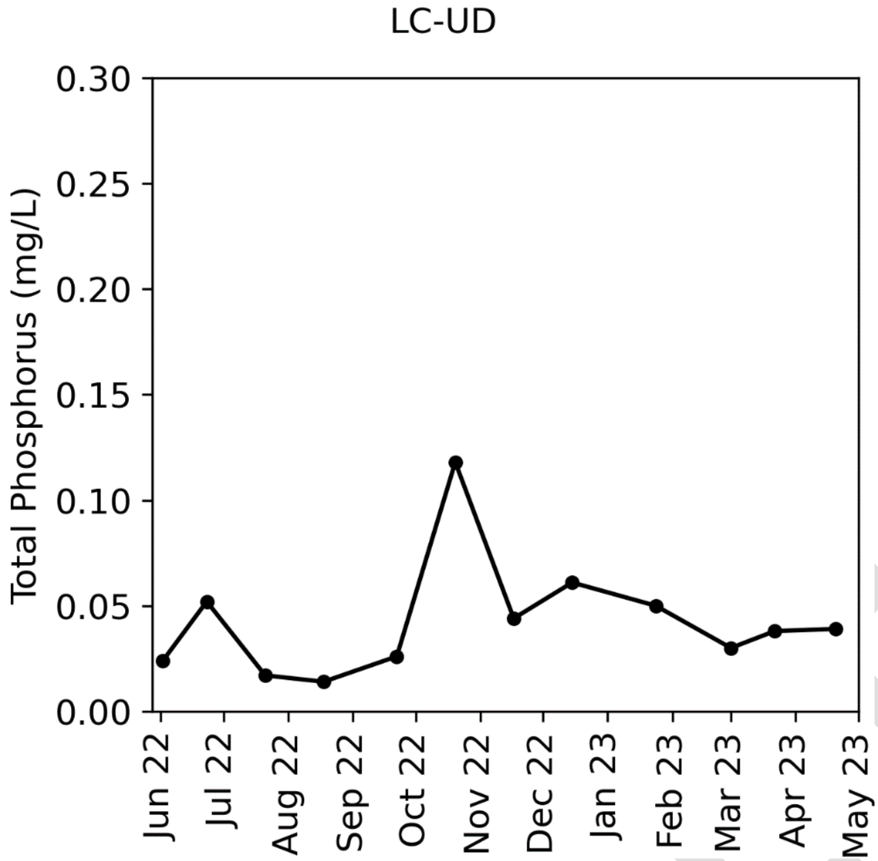

Figure 45. Total phosphorus concentrations in Lacamas Creek at the Outlet From Round Lake Upper Dam (LC-UD)

Total nitrogen concentrations in Lacamas Creek upstream of the lakes (Figure 46) peaked in October 2022, with a concentration of 2.99 mg/L. This uptick in nitrogen in the fall was only observed in the upstream location (LC-G)—other creeks showed a lower range of nitrogen values during the summer and early fall, with an increase in late winter 2023, and an apparent decrease in spring of 2023 (Figure 47 and Figure 48). The uptick in total nitrogen at LC-G is due almost entirely to NOx (see Appendix A), and may be related to agricultural land uses higher up in the watershed, or due to higher nitrogen concentrations in baseflow and a more connected groundwater table higher up in the watershed. Ecology's forthcoming Source Assessment for Lacamas Creek is expected to shed more light on the potential source of these elevated NOx concentrations.

Average nitrogen levels in the creeks were below the concentrations measured in Lacamas Lake and the top and middle of the Round Lake water column, though Round Lake near-bottom samples showed somewhat higher total nitrogen during the summer months. Because the nitrogen species causing the increase in total nitrogen are different for LC-G (NOx) and the bottom of RL1 (primarily ammonia), it is almost certain the nitrogen sources for these two locations are different despite their similar temporal trends.

Additional water quality time series plots are available in Appendix A and data is available in Appendix B.1.

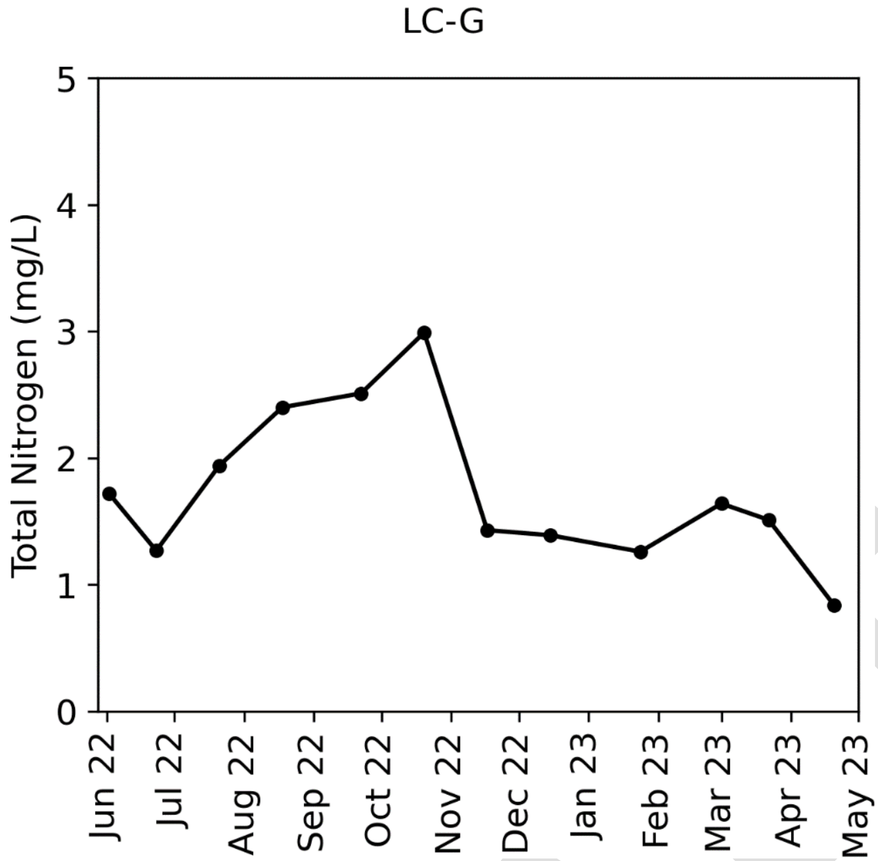

Figure 46. Total nitrogen concentrations in Lacamas Creek at Goodwin Rd (LC-G)

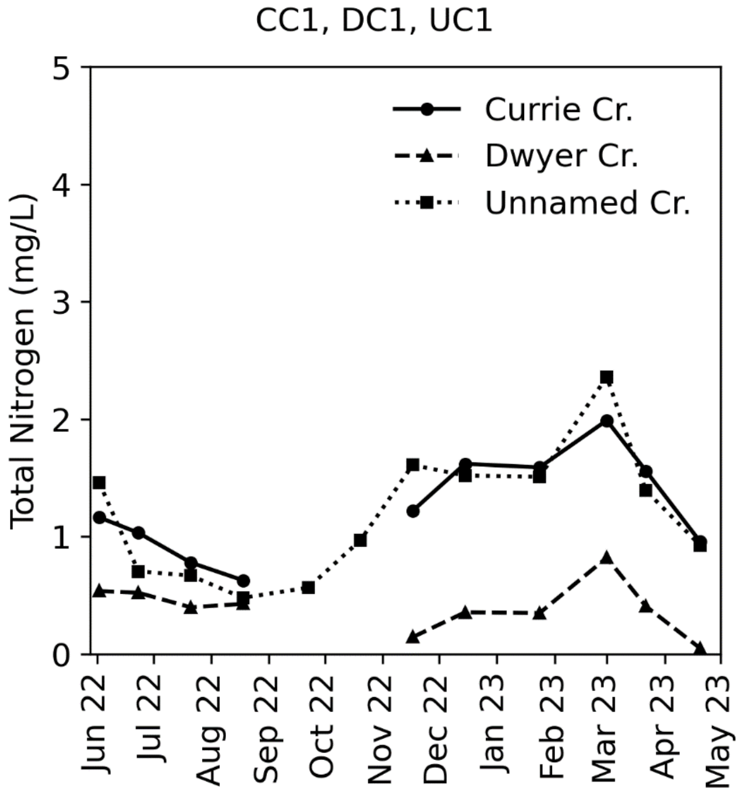

Figure 47. Total nitrogen concentrations in minor tributaries to Lacamas Lake—Currie Creek (CC1), Dwyer Creek (DC1), and Unnamed Creek (UC1)

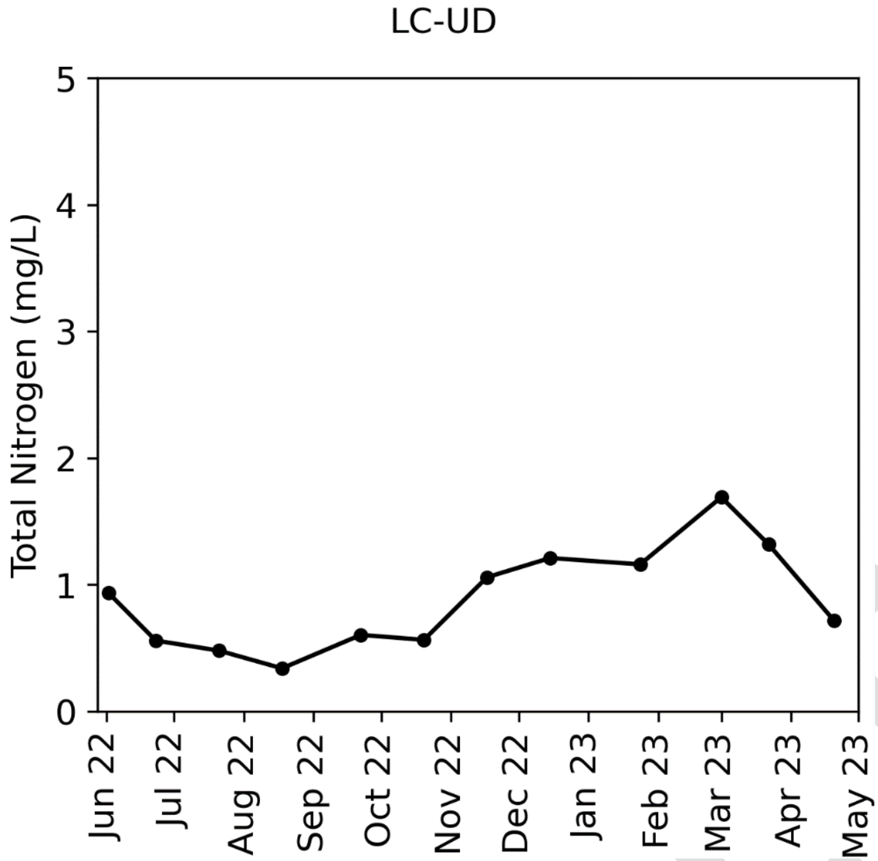

Figure 48. Total nitrogen concentrations in Lacamas Creek at the Outlet From Round Lake Upper Dam (LC-UD)

3.2.3.5 Stormwater

Three stormwater samples were collected from two locations. Although the QAPP called for four samples, the dry late spring conditions coupled with the short hold time for orthophosphate, which prevents sampling from occurring on Friday through Sunday, prevented collection of the final sample.

Total phosphorus in stormwater samples was similar to that measured in the creeks, with FL-SW1 showing somewhat higher concentrations than RL-SW1. Total phosphorus concentrations ranged between 0.02 and 0.06 mg/L. Orthophosphate generally represented 90% or more of this concentration, with the exception of one sample at RL-SW1 and one at FL-SW1 showing 79% and 65% of total phosphorus as orthophosphate, respectively. Total nitrogen is a similar case, where concentrations ranged from 0.26 to 1.7 mg/L, which is similar to what was found in the creeks. Ammonia was not detected in any stormwater sample; NOx was generally the dominant nitrogen species, with TKN completely absent in the December samples but accounting for about a third to half of the total nitrogen in the February and March samples. This increase in TKN may be indicative of a large contribution from the groundwater table, or of increased temperatures resulting in increased microbial activity and breakdown of organics in the watershed. TSS was always below the reporting limit of 5 mg/L.

Stormwater data is available in Appendix B.1 and B.2.

3.2.3.6 Nitrogen/Phosphorus Ratios

The average total nitrogen to total phosphorus mass ratio in Lacamas Lake was approximately 35:1, ranging from a minimum of 4:1 in one data point at LL-1 in the near bottom sample to a maximum of 116:1. Similarly, for Round Lake the average ratio was 35:1 and for Fallen Leaf Lake the average ratio was 40:1.

Koerselman and Meuleman (1996) conducted a review of fertilization studies in the literature on the N:P ratios in plant tissue on a mass ratio basis. Their work showed a N:P mass ratio > 16 indicates P-limitation and N:P mass ratio < 14 indicates N-limitation. Other studies have shown potential for nitrogen limitation at mass ratios higher than 16; for example, Qin et. al (2020) report that ratios above 22.6:1 are consistent with a phosphorus-limited lake.

The data from this study are, on average, well above the N:P mass ratio for Phosphorus limitation, indicating that phosphorus is the limiting nutrient for algal growth and should be focused on for mitigation.

3.2.4 Trophic State Index

The trophic state index (TSI) introduced by Carlson (1977) is used to classify a waterbody's biological condition and its relative productivity for algae plant biomass based on three independent estimates: Chl-a, Secchi depth, and total phosphorus. TSI can range from zero to 100, where lower numbers indicate clearer water with more oxygen and higher numbers indicate deteriorating conditions (i.e., more productive). Table 10 presents the water body trophic state categories based on TSI.

The formulas to calculate the TSI based on Chl-a, total phosphorus, and Secchi depth, respectively, are:

$$TSI(\text{Chl-a}) = 9.81 * \ln(\text{Chl-a}) + 30.6$$

$$TSI(TP) = 14.42 * \ln(TP) + 4.15$$

$$TSI(SD) = 60 - 14.41 * \ln{(SD)}$$

where Secchi depth is in meters and total phosphorus and Chl-a are in mg/L (North American Lake Management Society [NALMS], 2023).

Table 10. Trophic state index categories (NALMS, 2023)

TSI	Category
< 40	**Oligotrophic**: Clear water, oxygen throughout the year in the hypolimnion.
40–50	**Mesotrophic**: Water moderately clear; increasing probability of hypolimnetic anoxia during summer.
50–70	**Eutrophic**: Anoxic hypolimnia, macrophyte problems possible.

> 70	**Hypereutrophic**: (light limited productivity). Dense algae and macrophytes.

The TSIs of the three lakes were calculated using the data collected from the epilimnion. Secchi depth, total phosphorus, and Chl-a were plotted as time series in the sections below to demonstrate the variation in lake conditions from June 2022 to April 2023. The TSI plots focus on the near-surface measurements for total phosphorus and Chl-a.

3.2.4.1 Lacamas Lake

The majority of data points in summer and fall 2022 indicate Lacamas Lake was in a eutrophic condition. The Chl-a data indicate the lake was eutrophic for all but one sampling event in summer and fall 2022. The two data points from January and April 2023 show lower concentrations as expected for the winter and spring. The total phosphorus-based TSI indicates eutrophic conditions except for two sampling events (July and August 2022); during these periods, total phosphorus in the hypolimnion was considerably higher as discussed in Section 3.2.3.1. Following spring turnover, when the water column became uniformly mixed, the total phosphorus concentrations still indicate eutrophic conditions. The Secchi depth data indicates uniformly eutrophic conditions. Overall, the TSI generally indicates eutrophic conditions in Lacamas Lake.

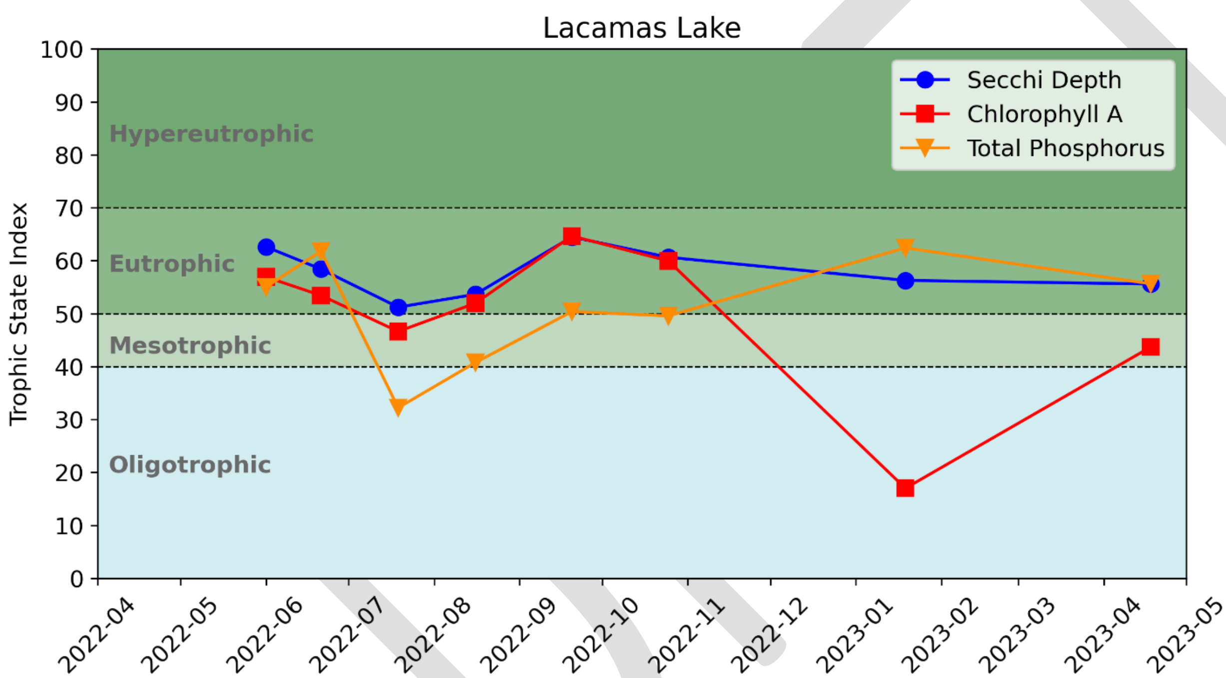

Figure 49. Trophic state index for Lacamas Lake

3.2.4.2 Round Lake

The TSI for Round Lake was generally similar to Lacamas Lake, as expected given their direct connection. The Chl-a based TSI varied between eutrophic and mesotrophic conditions during summer and fall 2022. For total phosphorus, a majority of data points show mesotrophic conditions in the epilimnion. As with Lacamas Lake, hypolimnion total phosphorus concentrations were significantly higher during summer 2022. Following spring turnover, when the water column becomes uniformly mixed, the total phosphorus concentrations indicated eutrophic conditions. The Secchi depth data categorizes the lake condition mostly as eutrophic, except from mid-July and August where the TSI indicates mesotrophic conditions (Figure 50).

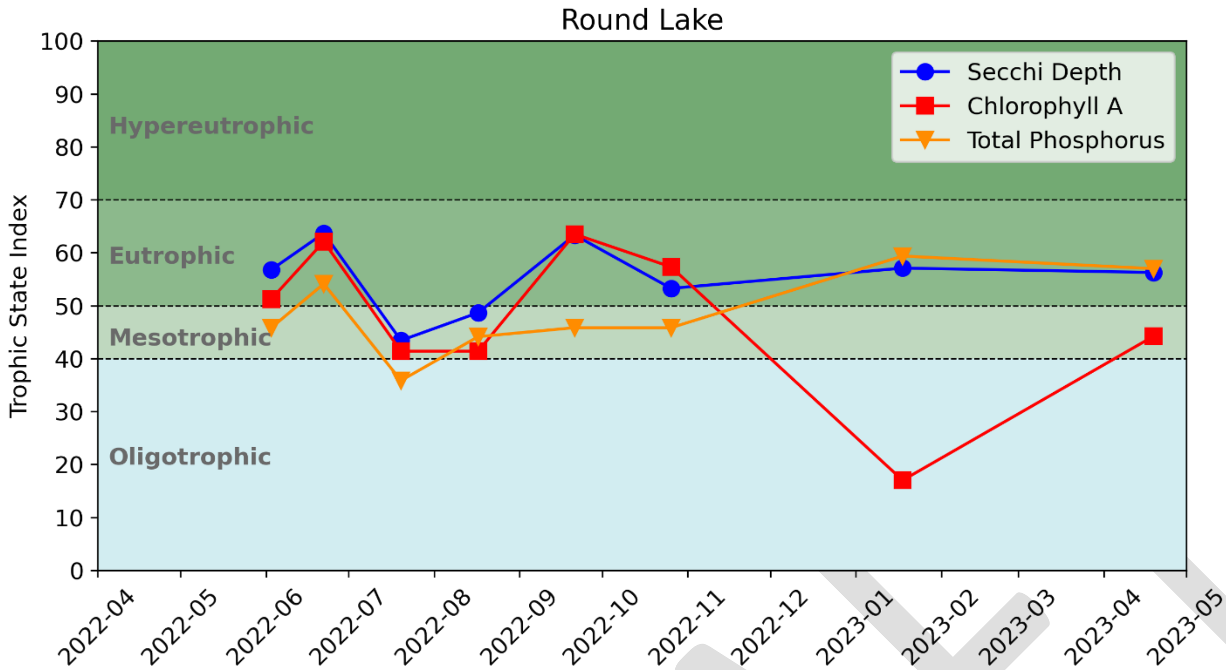

Figure 50. Trophic state index for Round Lake

3.2.4.3 Fallen Leaf Lake

The TSI of Fallen Leaf Lake indicates the lake generally fell into mesotrophic and eutrophic conditions. The near-surface Chl-a data indicate eutrophic conditions, though some Chl-a measurements were significantly higher near the middle of Fallen Leaf Lake than they were near the surface. Total phosphorus measurements categorize the condition of the lake as mesotrophic for all three measurements, though the October 2022 sample indicates near-eutrophic conditions. The TSI calculated based on the Secchi depth remains at the border between mesotrophic and eutrophic conditions. Clark County (2021) found similar results, with data indicating the lake was generally the border between mesotrophic and eutrophic conditions.

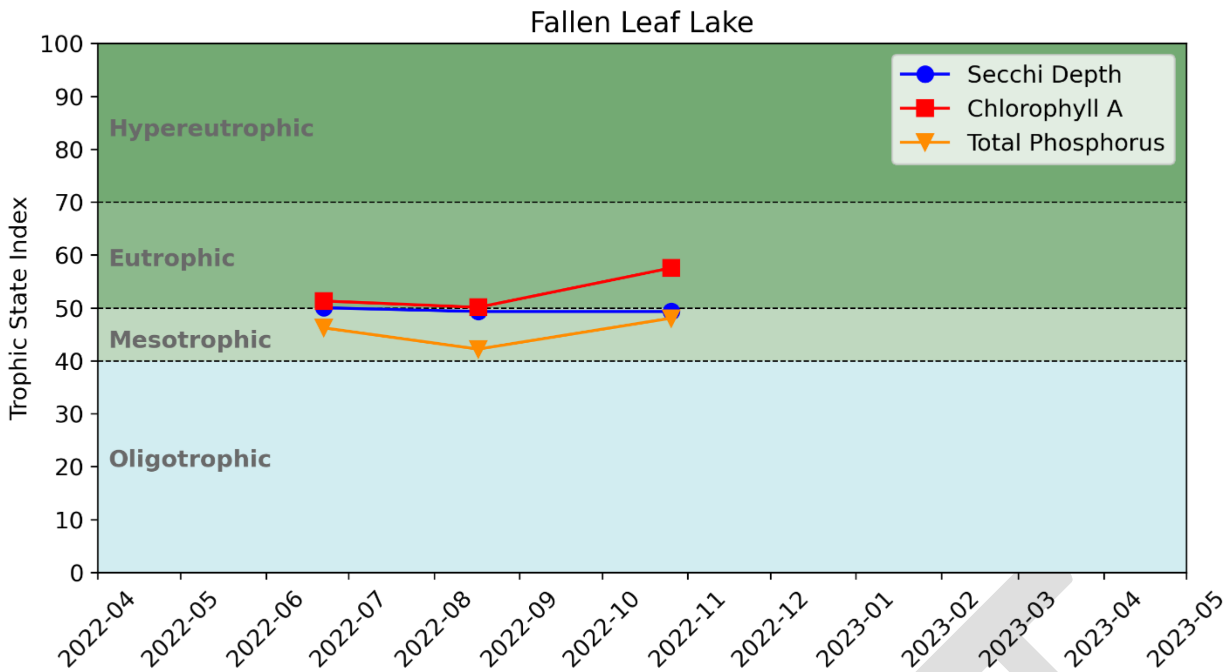

Figure 51. Trophic state index for Fallen Leaf Lake

3.2.5 Sediment

Figure 52 shows the total phosphorus concentration at each sediment sampling location (Figure 5) and Table 11 provides narrative description of the sediment characteristics at each site. The total phosphorus in the sediment samples was highest at the deepest location in each of the three lakes (LL1, RL1, and FLL1). In Lacamas Lake the maximum total phosphorus concentration observed was 1,760 milligrams per kilogram (mg/kg) at LL1, with most of the other locations falling between 1,000 and 1,400 mg/kg. LL-Lim2 showed a slightly lower concentration at 566 mg/kg, which may be due to the large amount of woody debris present in that sample.

In Round Lake the maximum total phosphorus concentration observed was slightly higher than in Lacamas Lake, at 2,080 mg/kg. This slightly higher concentration could be a result of finer particles settling out behind the dams. RL-Lim1 at 665 mg/kg showed a similar concentration to LL-Lim2, which is again likely due to the large amount of woody debris in that sample.

Fallen Leaf Lake showed the highest total phosphorus concentration at 3,040 mg/kg, with FLL-Sed2 showing the highest concentration of total phosphorus of all sample points not at the deepest point of a lake (1,390 mg/kg).

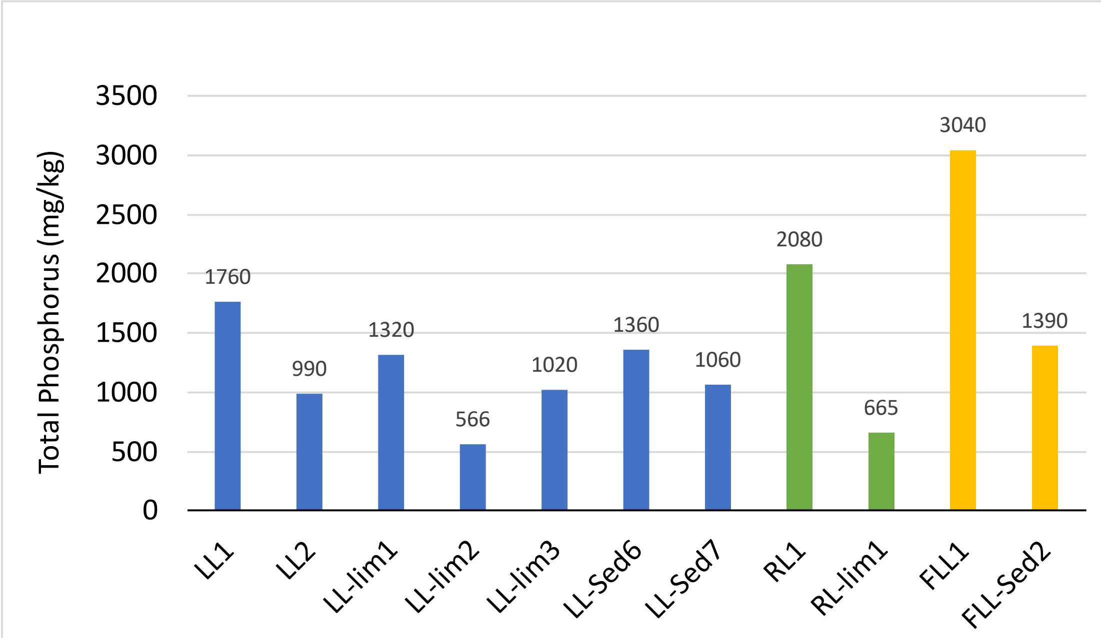

Figure 52. Total phosphorus content in lake sediment samples

Table 11. Description of sediment samples

Sampling Site	Location[1]	Sediment Description
LL1	Surface	Very wet, very soft (soupy) dark brown silt, slight natural organic odor
	0–5 centimeters	Same as above
LL2	Surface	Very wet, very soft, very dark gray silt with 20% plant matter, no odor
	0–5 centimeters	Same as above
LL-Lim1	Surface	Dusting of dark brown silt
	0–5 centimeters	Very wet, very soft (soupy), very dark gray silt, no odor; at 2–5 centimeters trace streaks of tan silt
LL-Lim2	Surface	40% woody debris by area—tan heartwood chunks, twigs, all decomposing
	0–5 centimeters	80% well decomposed wood, sawdust consistency, no odor, 20% very soft, very wet, very dark brown silt
LL-Lim3	Surface	Brown silt
	0–5 centimeters	Very wet, very soft (soupy) dark brown silt, trace fibers (rootlets?), no odor
LL-Sed6	Surface	Dusting of fine dark brown silt
	0–5 centimeters	Very wet, very soft, vert dark gray silt, no odor
LL-Sed7	Surface	Dark brown very fine silt
	0–5 centimeters	Very wet, very soft, very dark gray silt, trace plant matter, no odor
RL1	Surface	Dusting of olive brown silt
	0–5 centimeters	Very wet, very soft (soupy) very dark grayish brown silt with trace fine sand, no odor
RL-Lim1	Surface	30–90% wood debris
	0–5 centimeters	Some wood debris, otherwise wet loose very dark grayish brown well-graded fine-medium sand with silt and trace fine gravel, no odor
FLL1	Surface	Very dark greenish black bottled layer, strong decaying organic odor, fractured into chunks
	0–5 centimeters	Stratified layers alternating tan/black/green, very wet, very soft dark gray silt
FLL-Sed2	Surface	Black/tan/brown streaks, very little odor

Sampling Site	Location [1]	Sediment Description
	0–5 centimeters	Very soft, very wet (soupy), very dark grayish brown silt

Note:
[1] Descriptions were recorded to 30 centimeters, but only the top 5 centimeters were sampled, so only descriptions for the top 5 centimeters are presented here.

Sediment samples taken from the four complete sampling locations (LL1, LL2, RL1, and FLL1) were analyzed for sediment phosphorus fractionation using the modified Chang and Jackson method (Chang and Jackson, 1957) to determine what fraction of the measured total phosphorus is readily available under oxic and anoxic conditions. Specifically, the samples were analyzed for their saloid-bound, iron-bound, and aluminum-bound phosphorus fractions.

The saloid- and iron-bound fractions are considered to be the available fractions: saloid-bound phosphorus is loosely bound and readily available for release into the water column, while iron bound phosphorus is releasable under anoxic conditions. Aluminum-bound phosphorus is more tightly bound and is often assumed to be unavailable (e.g., Welch et al., 2017). Figure 53 and Figure 54 illustrate the fractionation of total phosphorus at each of the four complete sampling locations. Results indicate relative fractionation was similar across the four sites, with slightly more total phosphorus being available in Fallen Leaf Lake than in Lacamas or Round Lakes. The iron-bound fraction accounted for 57–77% of total phosphorus, the saloid-bound fraction accounted for less than 1% of total phosphorus, and the aluminum-bound fraction accounted for 2–12% of total phosphorus. Overall, 57–78% of the sediment phosphorus is available to be released.

These results indicate internal loading of phosphorus to the lake water column from sediment accumulated in the lake bottom is a potentially important source of phosphorus to the lakes during times when an oxycline is present. Deeper portions of the lakes, where the oxycline is the most persistent over the course of the summer, is where the most total and bioavailable phosphorus is located. The relative importance of internal loading is explored further in Section 5.

It is notable that, despite having very few recorded algal blooms, Fallen Leaf Lake has the greatest potential for release of phosphorus due to internal loading of any of the three lakes. It is not known why this is the case. The more diverse array of phytoplankton species and aquatic vegetation in this lake suggest its ecosystem may be more complex than that of Lacamas and Round Lakes.

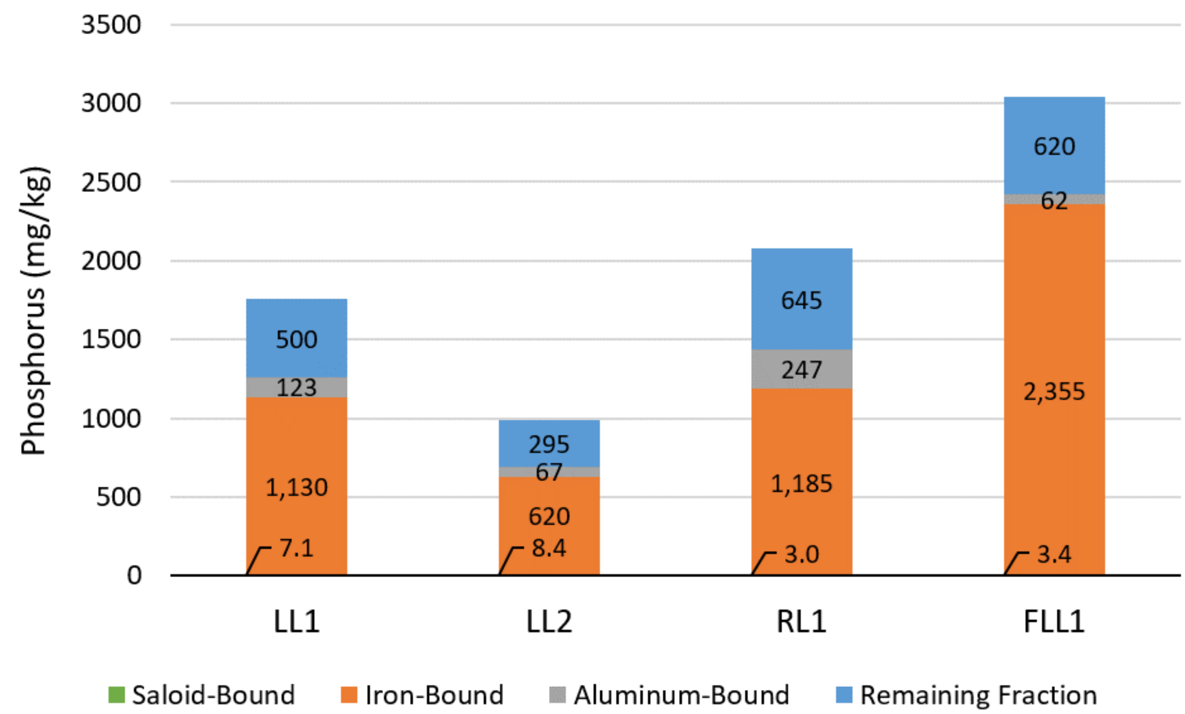

Figure 53. Phosphorus fractionation in lake sediment samples by concentration

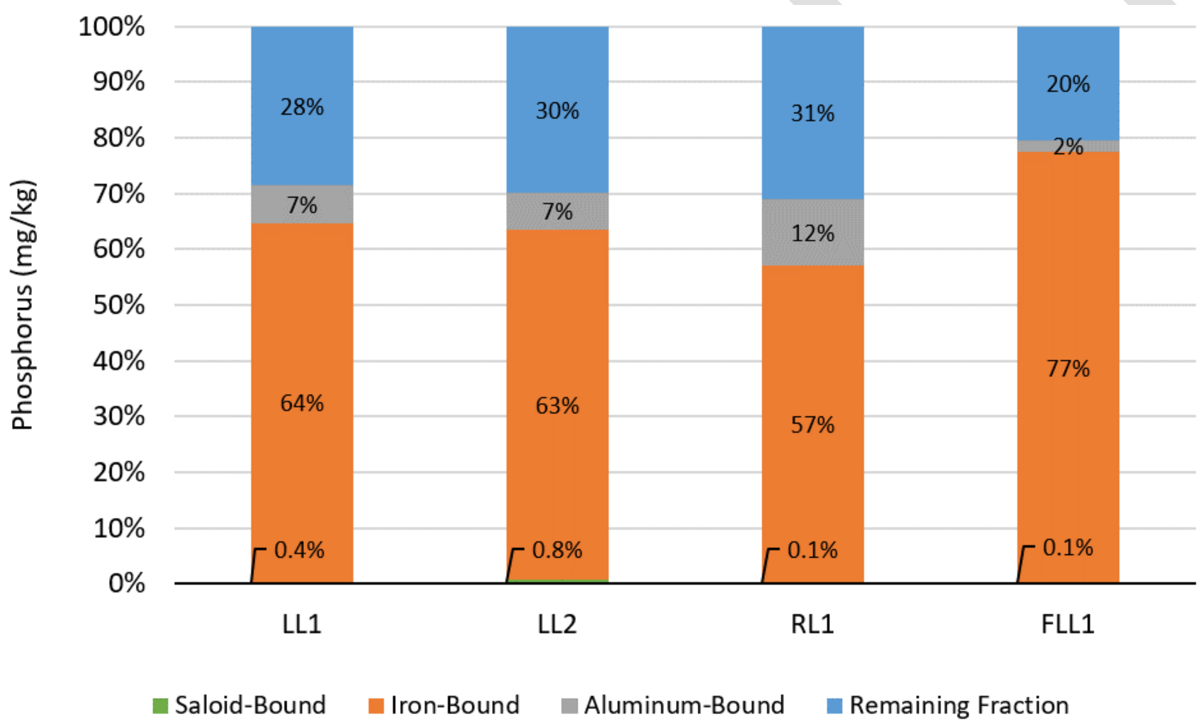

Figure 54. Phosphorus fractionation in lake sediment samples by percentage

3.2.6 Phytoplankton

There are three sources of information regarding phytoplankton for Lacamas, Round, and Fallen Leaf lakes: data collected for this study, data collected by the Lacamas Watershed Council (LWC) volunteer monitoring network, and data gathered by Clark County Health (CCH) for the State of Washington freshwater algae bloom monitoring program are provided in Appendix D. The CCH data indicate exceedances of state guidelines for *Microcystin* in Lacamas and Round Lakes. The LWC data from 2021 and 2022 show regular occurrences of *Dolichospermum* in Lacamas Lake and Round Lakes, with some observations of other species associated with cyanotoxins (*Aphanizomenon, Microcystis, Planktothrix, and Raphidiopsis).*

From the phytoplankton data collected for this study, the breakdown of algae species by lake and algae type is shown in Figure 55. The most common species found in Lacamas and Round Lake were those in the cyanobacteria group, making up 85% and 92% of the cells in each sample, respectively. In both Round Lake and Lacamas Lake the two most dominant cyanobacteria species were *Aphanocapsa elachista* and *Dolichospermum macrosporum.* Along with *Microcystis* species, *Dolichorspermum* is one of the most common cyanobacteria groups associated with toxic algae blooms (Matthews, 2016).

In contrast, in Fallen Leaf Lake, the dominate algae groups were Ochrophyta and Charophyta, with cyanobacteria accounting for about 10% of the cells in the sample, and only one species (*Dolichospermum macrosporum*) present. This species is known to generate cyanotoxins (Matthews, 2016). The class of Ochrophyta found in Fallen Leaf Lake, Chrysophyceae (golden algae) and the class of Charophyta found in Fallen Leaf Lake, Conjugatophyceae (a class of green algae) do not produce cyanotoxins.

The similarity in algae speciation between Lacamas and Round Lakes may be due to the physical connection between the Lakes and the common dominant inflow of Lacamas Lake, while Fallen Leaf Lake has a separate and smaller watershed with distinct land use (forested and residential). Complete phytoplankton sampling results can be found in Appendix B.4.

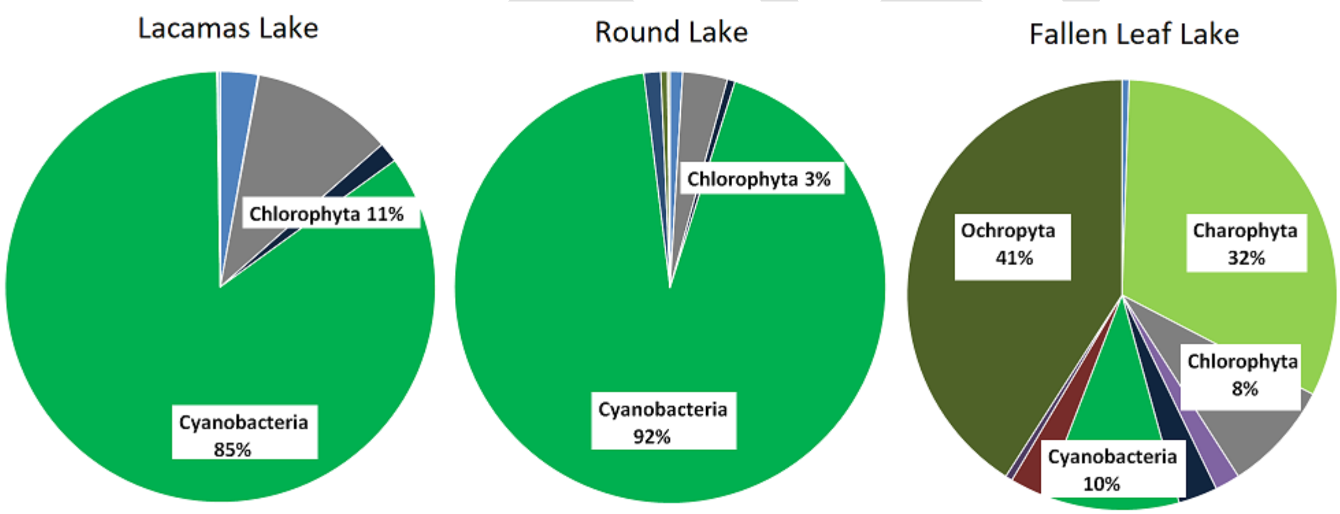

Figure 55. Algae speciation for Lacamas, Round, and Fallen Leaf Lakes

3.2.7 Vegetation Surveys

The aquatic vegetation survey found very little vegetation in both Round and Lacamas Lakes. In Round Lake in particular no aquatic vegetation was found, which was confirmed with side scan sonar. In Lacamas Lake, seven species were found at low density. Of these, three are native (Rocky Mountain pond lily, common hornwart, and Canadian waterweed), two are Class C noxious weeds (fragrant waterlily and curly leaf pondweed), one is a Class B noxious weed (Brazilian elodea), and one is unknown (water starwort). Each of these species have been noted in previous surveys performed by Ecology.

It is thought that the sparse aquatic vegetation is the result of several factors, including annual lake drawdowns, which dewater shallow sediments where aquatic vegetation grows, as well as poor water clarity which limits available light for photosynthesis. In addition, timing may have played a role with the initial survey being conducted early in the year. However, a follow-up survey in late June confirmed the May results. The presence of high levels of cyanotoxins prevented the ability to safely sample for aquatic vegetation later in the summer. The full aquatic vegetation survey report can be found in Appendix C.

4. HYDROLOGIC BUDGET

Per the QAPP, a hydrologic budget was developed for Lacamas and Round Lakes, but not for Fallen Leaf Lake. A combined budget was developed for Lacamas and Round Lakes because the lakes are connected and share a primary common source, and because measurements were made at the primary inflow and outflow locations for the combined lake system.

4.1 Components

The hydrologic budget components evaluated for Lacamas and Round Lakes are described in Equation 1:

$$P + Q_{LC\text{-}G} + \mathrm{Q}_{\mathrm{DC}} + Q_{CC} + Q_{UC} + Q_{SR} + GW = Q_{LC\text{-}UD} + EVAP + \Delta S \qquad (1)$$

where

P is the volume of precipitation falling directly on the lake
$Q_{LC\text{-}G}$ is inflow via Lacamas Creek at Goodwin Road
Q_{DC} is inflow via Dwyer Creek
Q_{CC} is inflow via Currie Creek
Q_{DC} is inflow via Unnamed Creek
Q_{SR} is inflow via surface runoff
GW is net groundwater inflow or outflow volume
$Q_{LC\text{-}UD}$ is flow at Lacamas Creek below the Round Lake Dam
$EVAP$ is evaporation from the lake surface
ΔS is the change in lake storage

The following sections describe how each of these components were measured or estimated.

4.2 Inflows

4.2.1 Precipitation

Precipitation on the lake was estimated using monthly precipitation data at Portland International Airport (PDX) from the NWS, which is the closest long-term precipitation dataset. The average monthly precipitation in feet was multiplied by the average surface area of the lakes for that month.

4.2.2 Lake Storage

The lake storage was determined using lake water level measured at Round Lake and provided by the City of Camas along with the elevation-volume curves in Beak and SRI (1985).

4.2.3 Inflow via Lacamas Creek at Goodwin Road

The flow at Lacamas Creek at Goodwin Road was determined using a Hobo MX2001 water level logger combined with a rating curve developed using seven flow measurements made by

Clark County during 2009 and 2010 and three flow measurements made by the consultant team during 2022 and 2023 (Appendix E). The water level sensor was active from October 13, 2022, through April 30, 2023.

To estimate flow from May through October 2022, a monthly regression was used. Monthly flow at Goodwin Road was predicted using monthly precipitation at PDX for the given month and the two previous months. A best fit equation was developed by comparing the equation's fit to Clark County data from 2002–2012. The r-squared value for this correlation was 0.89. The equation used was:

$$Q_{LC\text{-}Gi} = 26.6 * P_i + 13.2 * P_{i-1} + 9.1 * P_{i-2} \quad (2)$$

where

$Q_{LC\text{-}Gi}$ is the average flow at Goodwin Road for a given month, *i* (cubic feet per second)
P_i is the precipitation at PDX for month *i* (inches)
P_{i-1} is the precipitation for the previous month at PDX (inches)
P_{i-2} is the precipitation at PDX two months prior to month *i* (inches)

Further information is provided in Appendix E.

4.2.4 Inflow via Dwyer Creek

The 1985 report (Beak and SRI, 1985) measured flow at both Lacamas Creek at Goodwin Road and Dwyer Creek. The reported flows correlated well (r-squared of 0.98 based on 17 measurements with Dwyer Creek accounting for on average 0.0465 times the flow at Lacamas Creek at Goodwin Road). Therefore, flows from Dwyer Creek were calculated as 0.0465 times the estimated flow at Lacamas Creek at Goodwin Road. For months where Dwyer Creek was observed to have no surface flow (September and October 2022), values of zero were assigned. While September sampling occurred on September 22, very low flows were observed on August 18, so zero flow for September is a reasonable assumption.

4.2.5 Inflow via Currie and Unnamed Creeks

Velocity and single depth measurements were made at Currie and Unnamed Creek in November 2022. Flow for this period was estimated based on Manning's equation and the 36-inch culvert where depth was measured for Unnamed Creek, assuming a trapezoidal channel for Currie Creek. For other months, the flows at Currie and Unnamed Creeks were estimated by assuming the ratio between these flows and the flow measured at Lacamas Creek at Goodwin Road in November 2022 were consistent throughout the study period. While there is some uncertainty in this estimate, the measurements from November indicated that flows in Currie and Unnamed Creek were small relative to Lacamas Creek, so a significant effect on the water budget is not expected. Currie Creek was dry in September and October 2022, but Unnamed Creek flowed year-round.

4.2.6 Inflow via Surface Runoff

The component of flow from surface runoff was estimated based on the drainage area not accounted for in the previously described creek basins. The estimated drainage areas for Lacamas Creek at the Round Lake outflow is 60.75 square miles (USGS Stream Stats, 2019). The estimated drainage area at Goodwin Road is 51.52 square miles, and the drainage areas for Dwyer, Currie, and Unnamed Creeks are 4.56, 2.36, and 1.41 square miles, respectively. The estimate for Dwyer Creek is based on the City Stormwater Management Action Planning (SMAP) process, while the other estimates are from USGS Stream Stats. Therefore, the unaccounted-for drainage area is 0.90 square miles. The flow from this portion of the watershed was estimated using a drainage area ratio calculation from the Lacamas Creek at Goodwin Road flows (i.e., 0.90/51.52 * Q_{LC-G}).

4.2.7 Inflow via Groundwater

Groundwater was assumed to be negligible for this study, based on previous analysis by Beak and SRI (1985). Notably, groundwater contribution to the measured streamflow would be accounted for in this water budget; only direct groundwater inflow to the lake would be unaccounted for.

4.2.8 Change in Lake Storage

The lake storage at the beginning of each calendar month was estimated using the elevation-volume curves in Beak and SRI (1985) combined with continuous 15-minute lake level data provided by the City of Camas. The change in lake storage for each month was calculated by subtracting the storage at the beginning of the month by the storage at the end of the month.

4.3 Outflows

4.3.1 Evaporation

Monthly evaporation was estimated using the Blaney-Criddle method, using data from PDX. The Blaney-Criddle method calculates reference evaporation based on the monthly average temperature and the percentage of annual daylight hours for that month. A typical coefficient of 0.7 (e.g., Kohler et al., 1955) was applied to estimate the open water evaporation as a percentage of the reference evaporation.

4.3.2 Outflow Past Round Lake Dams

The sum of the total monthly outflow past the two Round Lake dams was assumed to be the values which satisfy Equation 1 based on the above estimates. Because flow was not measured below the dams, an independent check was not possible.

4.4 Results

Figure 56 shows the relative contributions of the various sources of inflows and outflows to the Lacamas and Round Lakes water budget, indicating that Lacamas Creek is the dominant source of flow to the lakes. Figure 56 also indicates the evaporation is relatively insignificant and most lake water leaves via the Round Lake Dam. Table 12 shows the monthly estimated flow budget for the lakes. Lacamas Creek makes up 90% of the inflow, and 99% of the outflow, from Lacamas and Round Lakes.

Notably, the total estimated inflow for the lakes for the year is approximately 157,500 acre-feet, or approximately 21.5 times the maximum combined volume of Lacamas and Round Lakes and 23.1 times the average combined volume of Lacamas and Round Lakes, meaning an annual average residence time of 0.0465 years (17 days).

However, as demonstrated by dye tracer studies (Raymond, 1998) and by the extensive evidence of stratification (Section 3.2), the lakes do not fully mix for much of the year, so this implies that not all the water in the lakes is replaced 23 times per year. Furthermore, the residence time is substantially larger during low flow periods compared with high flow periods; For July, August, and September 2022 the estimated total inflow volume was 8,200 acre-feet, or approximately 1.1 times the storage volume. This corresponds to an average residence time of 83 days. By contrast, for December 2022 through February 2023, the estimated total inflow was 61,500 acre-feet, or approximately 8.4 times the storage volume, indicating an average residence time of 11 days.

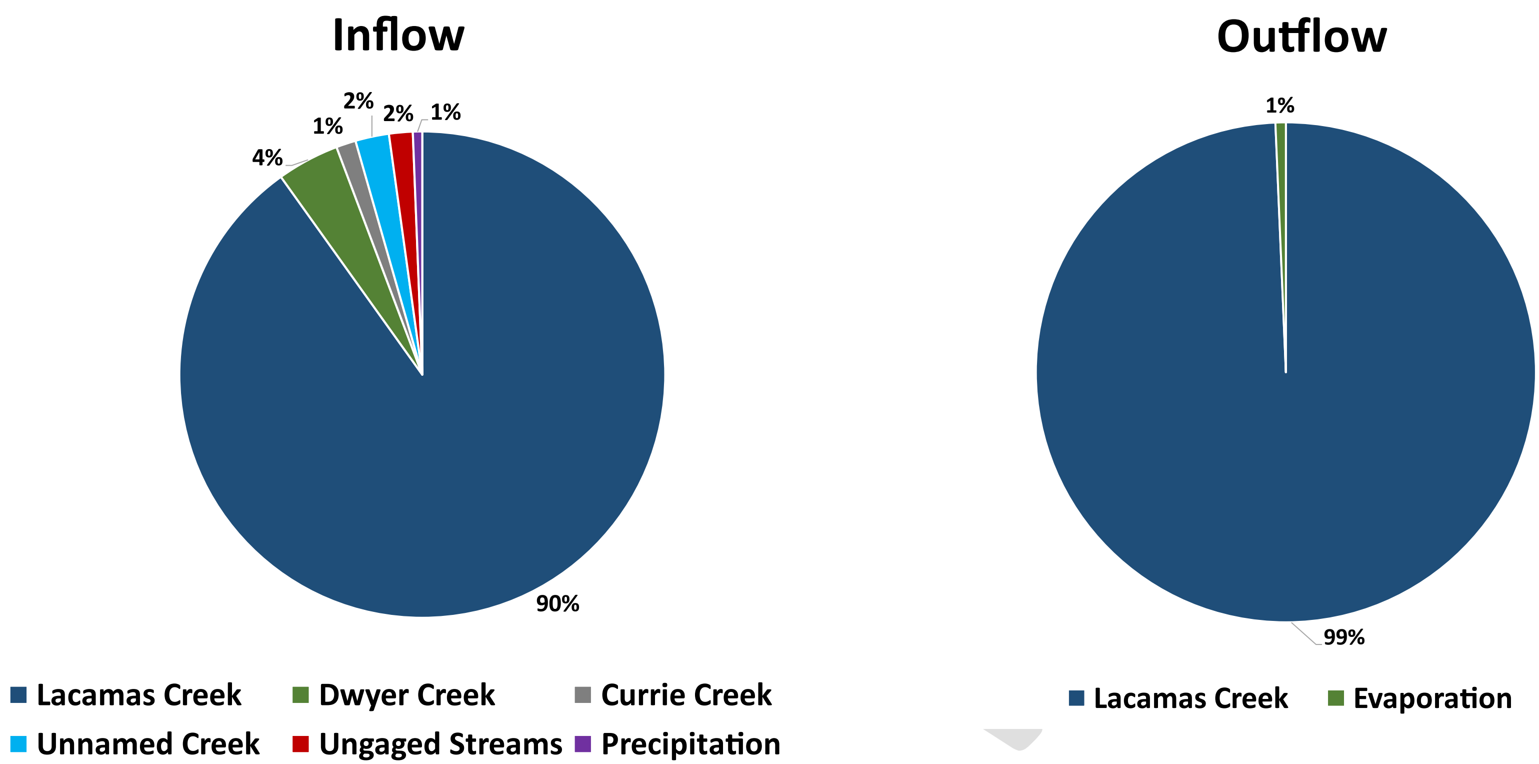

Figure 56. Combined water budget for Lacamas and Round Lakes for May 2022-April 2023

Table 12. Water budget for Lacamas and Round Lakes for May 2022-April 2023 (all values in acre-feet)

Month-Year	Lacamas Creek (acre-feet)	Dwyer (acre-feet)	Currie (acre-feet)	Unnamed (acre-feet)	Ungaged (acre-feet)	Direct Precipitation (acre-feet)	Evaporation Outflow (acre-feet)	Storage Start (acre-feet)	Storage End (acre-feet)	Storage Change (acre-feet)	Lacamas Creek Outflow (acre-feet)
May-22	12,482	580	184	310	218	95	105	6,888	6,888	-	13,764
Jun-22	11,008	512	162	273	192	80	124	6,888	7,325	437	11,667
Jul-22	4,919	229	72	122	86	5	145	7,325	7,271	(54)	5,342
Aug-22	1,906	89	28	47	33	-	139	7,271	7,260	(10)	1,975
Sep-22	595	-	-	15	10	8	99	7,260	5,888	(1,372)	1,901
Oct-22	5,472	-	-	136	96	73	73	5,888	6,514	625	625
Nov-22	6,010	279	88	149	105	128	47	6,514	7,115	602	6,112
Dec-22	31,026	1,443	456	770	542	197	42	7,115	6,708	(408)	34,799
Jan-23	16,227	755	239	403	283	83	46	6,708	6,694	(14)	17,956
Feb-23	8,177	380	120	203	143	59	49	6,694	6,301	(393)	9,426
Mar-23	17,641	820	259	438	308	104	70	6,301	6,708	407	19,093
Apr-23	26,702	1,242	393	663	466	122	87	6,708	6,514	(194)	29,695
TOTAL	**142,165**	**6,329**	**2,001**	**3,529**	**2,483**	**952**	**1,026**	**81,560**	**81,186**	**(375)**	**156,808**

Note:

Parentheses indicate negative numbers.

5. NUTRIENT BUDGET AND PHOSPHORUS MODEL

This section describes a phosphorus model for Lacamas and Round Lakes. A combined nutrient budget was developed because the lakes are connected and share a dominant inflow source and because water quality was measured at the inflow to Lacamas Lake and the outflow from Round Lake.

5.1 External Phosphorus Loading

5.1.1 Atmospheric Deposition

Atmospheric deposition of phosphorus was accounted for by assuming the phosphorus concentration of rainfall falling on the lake was 24 µg/L as was done by Ecology for Lake Loma (Roberts, 2013). While Lake Loma is on Puget Sound, more local data was not found and while there is uncertainty in this measurement, direct precipitation makes up less than 1 % of inflow to Lacamas and Round Lakes, and atmospheric deposition of phosphorus is unlikely to represent a substantial fraction of phosphorus input to the lakes.

5.1.2 Tributary Inflows

The monthly total phosphorus samples taken at each of the creek monitoring stations were used to calculate the monthly phosphorus loading for each creek.

5.1.3 Inflow via Surface Runoff

The stormwater samples were taken to be representative of concentrations in the more urbanized portion of the watershed, and were used to calculate the loading from surface runoff. Because limited data were available, and there was no clear trend in the seasonality of the stormwater samples, the average concentration was used for all months.

5.1.4 Outflow Past Round Lake Dams

The estimated outflow from the hydrologic budget was multiplied by the monthly concentration measurements taken at the LC-UD sampling location to estimate the total phosphorus leaving Round Lake.

5.1.5 Results

Figure 57 shows the relative proportion of external loading from various sources. Lacamas Creek is by far the dominant external source of phosphorus loading to Lacamas and Round Lakes. Dwyer and Unnamed Creek contribute a small but notable amount of phosphorus loading, while the remaining sources contribute a very small percentage of the total phosphorus loading to the lakes. The total external loading is 6,730 kilograms for the study period (May 2022-April 2023), of which 5,935 kilograms are from Lacamas Creek.

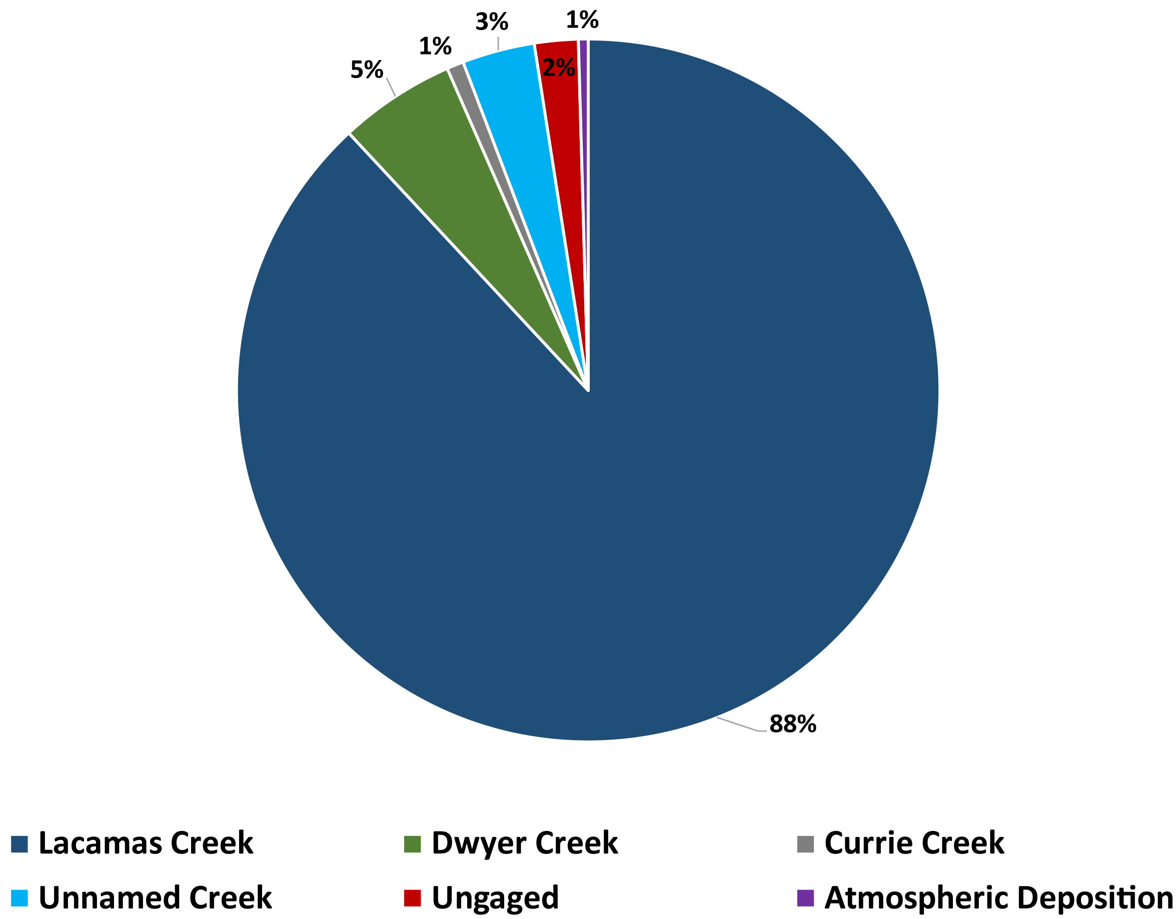

Figure 57. Relative fraction of phosphorus loads from various external sources

5.2 Internal Phosphorus Loading

The range of potential internal total phosphorus loading was evaluated using the regression equations developed by Nürnberg (1998). Figure 58 (reproduced from Nürnberg, 1998) shows a scatter-plot of sediment release rate per unit area per day as a function of sediment bed total phosphorus. The figure indicates a wide range of potential release rates for the range of observed sediment-bed total phosphorus in Lacamas, Round, and Fallen Leaf Lakes.

The average sediment total phosphorus concentration for Lacamas Lake is 1,154 mg/kg. The regression equation in Nurnberg (1988) predicts a release rate of 7.0 milligrams per square meter per day (mg/m^2/day) based on this concentration.

For Round Lake, the average sediment total phosphorus concentration is 1,373 mg/kg, and the regression equation in Nürnberg (1988) predicts a sediment release rate of 8.0 mg/m^2/day.

While 57–78% of the sediment total phosphorus is available, the regression utilized for this calculation is based on total phosphorus rather than available total phosphorus.

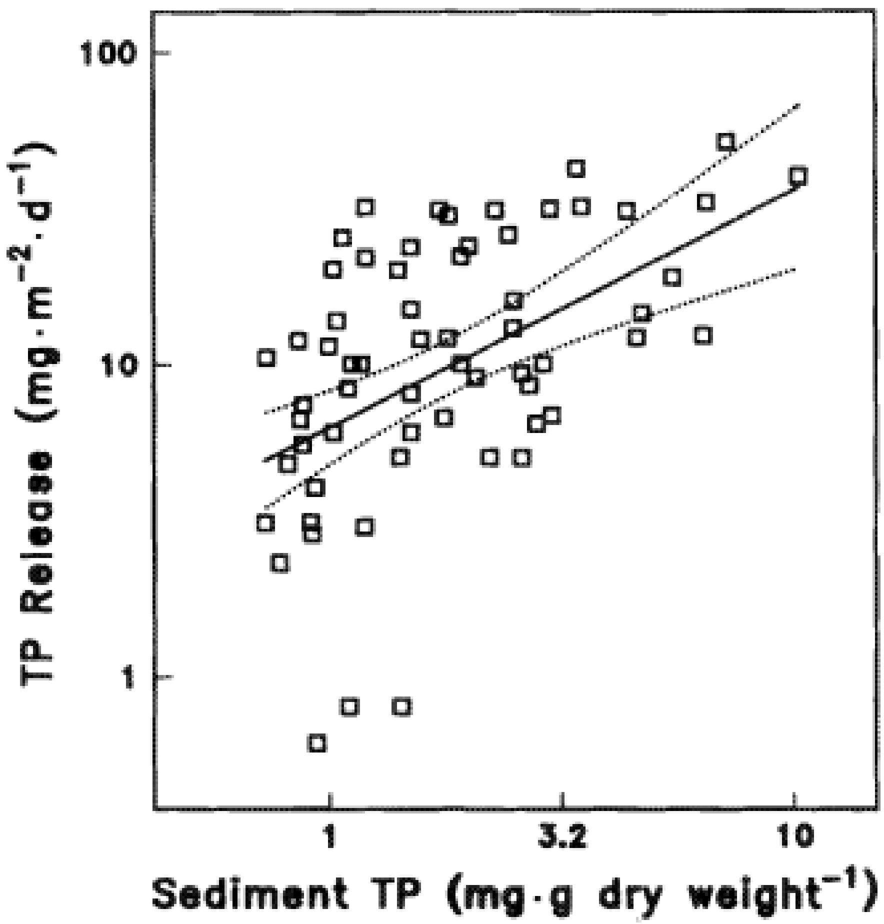

FIG. 3. Regression of TP release rates on sediment TP concentration after logarithmic transformation with literature data on lakes world-wide. The regression line and 95% confidence band are shown (log RR = 0.80 + 0.76 log TP_s, r^2 = 0.21, n = 63).

Figure 58. Scatterplot relationship between sediment total phosphorus and total phosphorus release rate (Nürnberg, 1988)

Assuming 167 days of sediment release (based on anoxic conditions existing from approximately June 1 through November 14), this would mean 1,407 kilograms of sediment phosphorus release for Lacamas Lake and 141 kilograms for Round Lake, for a total of 1,548 kilograms. This represents approximately 19% of the total loading to the lakes. This calculation results in an estimated total (internal and external) phosphorus loading of 8,278 kilograms compared to an estimated total phosphorus outflow of 8,549 kilograms, a difference of 272 kilograms of phosphorus that are not accounted for in the phosphorus budget, approximately 3.3% of the inflow. Because of the uncertainty in measurements for many aspects of the total phosphorus budget, and the simplified calculation of release rate, the specific reasons for the discrepancy cannot be determined, and are minor compared to the overall phosphorous budget.

Figure 59 shows a pie chart of relative sources of total phosphorus to the lake. Table 13 provides the monthly values for the year-long phosphorus budget.

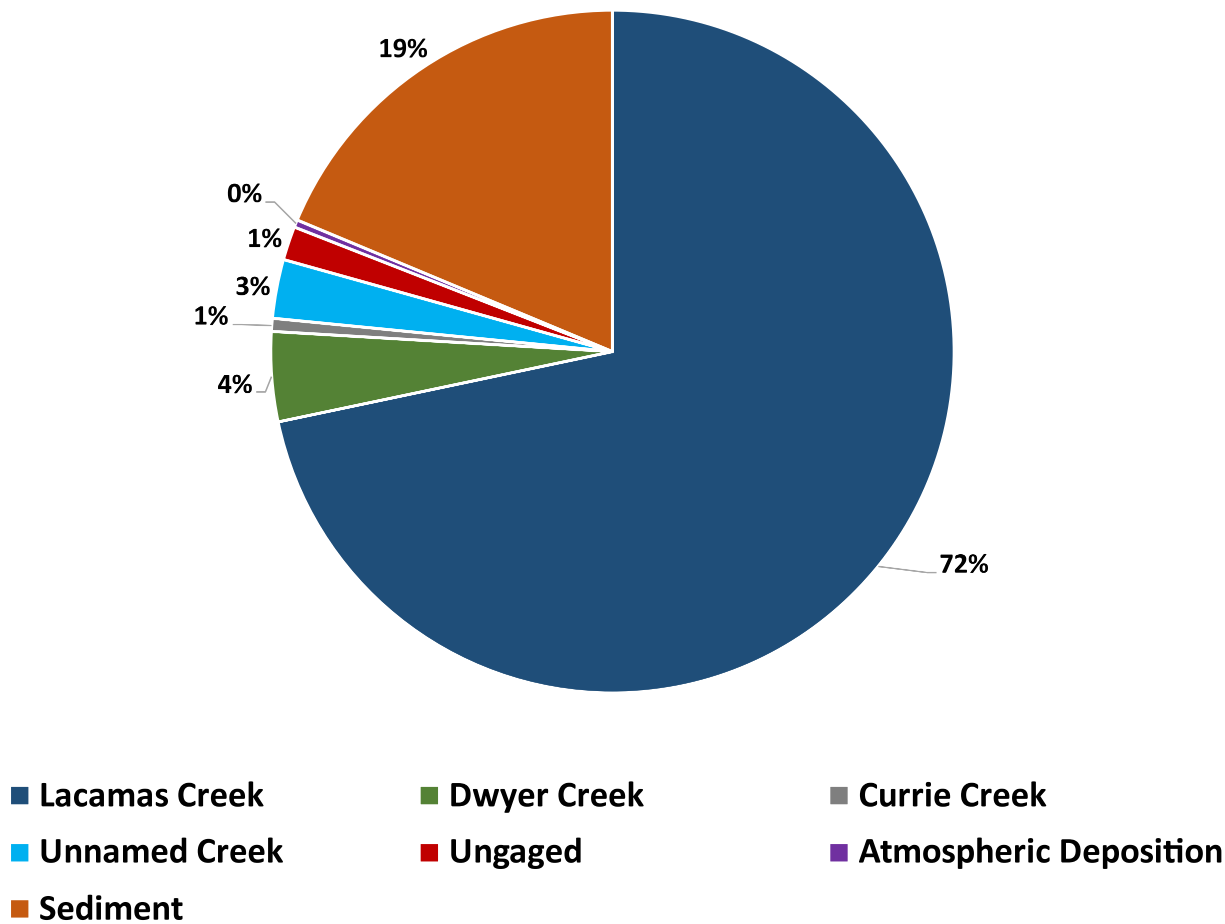

Figure 59. Relative fraction of phosphorus loads to Lacamas and Round Lakes from internal and external sources

Table 13. Phosphorus budget for Lacamas and Round Lakes for May 2022-April 2023 (all values in kilograms)

Month-Year	Lacamas Creek	Dwyer	Currie	Unnamed	Ungaged	Direct Precipitation	Sediment Release[1]	Outflow
May-22	831	50	5	25	19	3	0	407
Jun-22	584	42	6	23	16	2	278	748
Jul-22	231	22	1	19	8	0	287	112
Aug-22	54	8	1	12	3	-	287	34
Sep-22	27	-	-	2	-	0	278	61
Oct-22	182	-	-	15	-	2	287	739
Nov-22	193	11	2	8	4	4	130	332
Dec-22	1,378	75	13	39	28	6	0	2,618
Jan-23	721	38	6	21	14	3	0	1,107
Feb-23	212	16	3	12	6	2	0	349
Mar-23	370	38	5	20	14	3	0	612
Apr-23	1,153	51	8	36	19	4	0	1,428
TOTAL	**5,935**	**352**	**51**	**231**	**132**	**29**	**1,548**	**8,549**

Note:
[1]: Assumed sediment release occurs during anoxic conditions (June 1-November 14); numbers represent release from Lacamas and Round Lakes
[2]: Parentheses indicate negative numbers

5.3 Phosphorus Analytical Model

The Vollenweider (1976) model was used to assess the phosphorus dynamics in the lakes and understand how lake phosphorus concentrations might be impacted by changes in loading. The Vollenweider model predicts concentrations at a time when the lake is uniformly mixed, such as in spring prior to stratification.

The equation for the Vollenweider model can be written as:

$$P = \frac{Lp}{q_S(1 + \sqrt{\tau_W})}$$

where

Lp is the annual phosphorus loading per unit area of the lake (grams per square meter [g/m^2])
q_S is the hydraulic overflow rate, equal to the average depth divided by τ_W (meters per year)
τ_W is the hydraulic residence time, equal to the lake volume divided by the annual inflow (years)
P is the phosphorus concentration in the nonstratified lake (mg/L)

For Lacamas and Round Lakes:

- Lp is calculated as 5.6 g/m^2 based on 6,730 kilograms of external loading, and an average surface area during the study of 297 acres (1.20 million square meters).
- qs is calculated as 6.94 meters (average estimated depth for Lacamas and Round Lakes, based on the average lake volume and surface area during the study period) divided by 0.0465 years, or 149 meters per year.
- τ_W is calculated as the maximum storage divided by the total inflow acre-feet per year, which results in a value of 0.0465 years.

This results in an estimated phosphorus concentration of 0.031 mg/L. This compares with the average measured concentration during non-stratified conditions of 0.073 mg/L for Lacamas Lake (average of samples taken in May 2022, January 2023, and April 2023) and 0.050 mg/L for Round Lake (average of samples taken January 2023 and April 2023). One probable reason for the discrepancy is that the low residence time does not capture the dynamics of Lacamas and Round Lakes. There is evidence from past work (Raymond, 1998) that Lacamas Creek does not mix with the lower levels of the water column, particularly during stratification. Therefore, the effective residence time in Lacamas and Round Lakes may be substantially larger than suggested by a simple calculation. To approximately match the measured concentrations, the residence time in the Vollenweider equation would need to be approximately doubled (for a residence time of 0.1 years, the Vollenweider equation would predict a concentration of 0.061 mg/L).

Figure 60 displays the results of the Vollenweider model graphically.

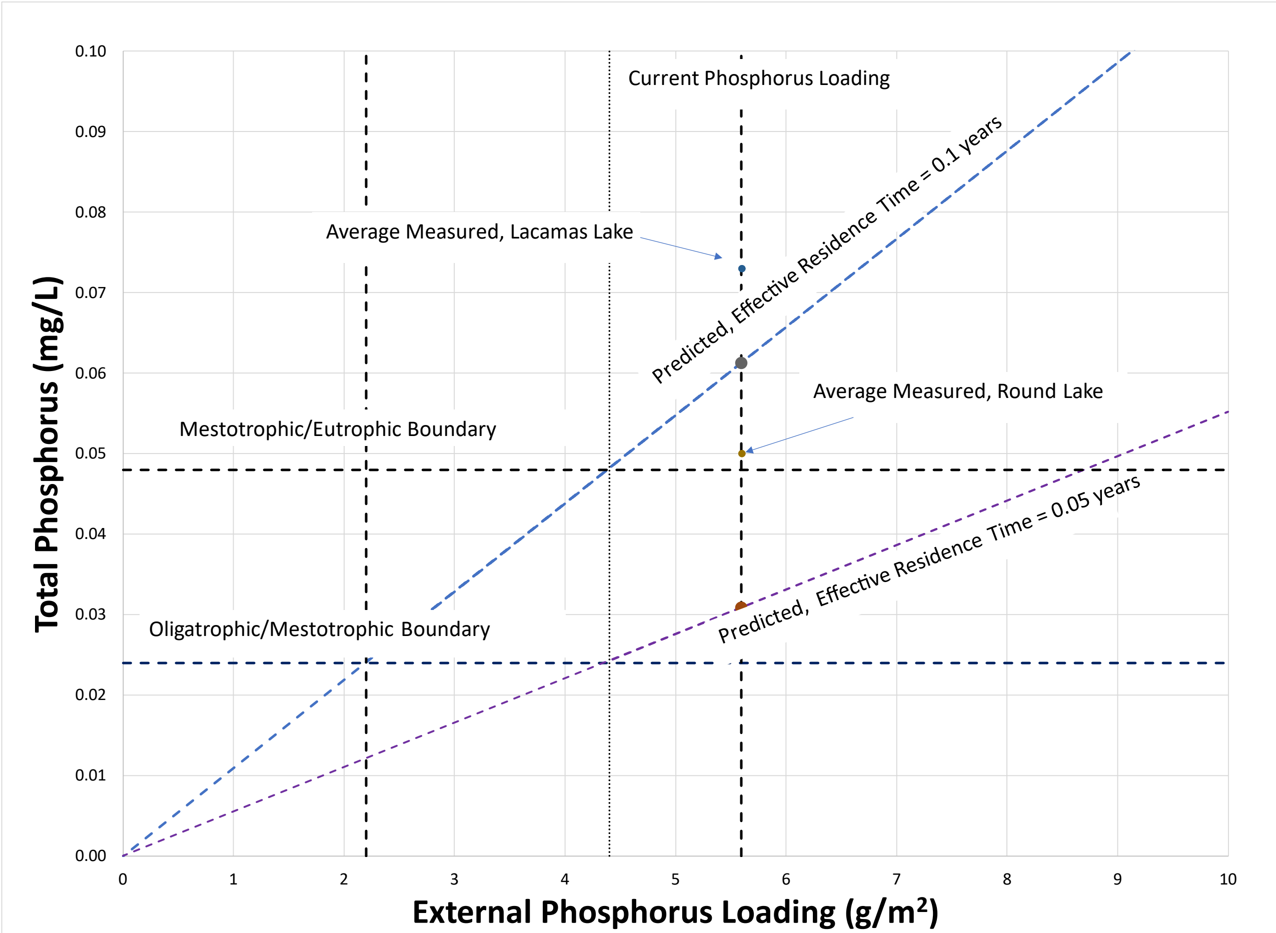

Figure 60. Graphical representation of the Vollenweider phosphorus model and expected reductions in loading required to achieve eutrophic conditions

The figure shows that to reduce the lake concentration to 0.024 mg/L, the benchmark for an oligotrophic lake (NALMS, 2023), a reduction in phosphorus loading of 21% (to 4.4 g/m^2) would be required assuming an annual average residence time of 0.05 years, and a reduction of 61% (to 2.2 g/m^2) would be required assuming an annual average residence time of 0.1 years. Since the effective annual average residence time of 0.1 years more accurately predicts current conditions, it is probable the 61% value more accurately reflects the reduction in loading that would be needed to prevent eutrophic conditions.

5.4 Summary

The phosphorus budget and phosphorus model demonstrate:

- Lacamas Creek accounts for the majority (~72%) of phosphorus entering Lacamas and Round Lakes.
- Other creeks account for approximately 9% of the phosphorus loading.
- While internal loading from the lake sediments is more uncertain, it likely accounts for approximately 19% of phosphorus loading to the surface water.

- The Vollenweider model calculations suggest the effective residence time for the lakes is higher than the overall average residence time of approximately 17 days, due partly to Lacamas Creek not mixing with the bottom of the Lakes during stratified conditions, and partly due to seasonal variation (with longer residence times during the summer). The results of the modeling analysis also indicate that substantial reductions to the nutrient load from the creeks would be needed for the lakes to no longer be eutrophic absent in-lake treatments.

6. MANAGEMENT ALTERNATIVES FOR CYANOBACTERIA CONTROL AND LAKE RESTORATION

There are numerous methods which have been used to reduce the frequency of algal bloom. This section summarizes the methods which were evaluated for Lacamas, Round, and Fallen Leaf Lakes. The methods fall into three categories:

- Direct algae control, where algaecide is used to directly kill algae.
- In-Lake (or near-lake) control, where a management alternative is deployed in the lake, or at the inflow.
- Watershed loading control, which are alternatives focused on reducing the nutrient loading to the lake from the contributing watershed.

The analysis of these methods has been informed by reviews of case studies from around Washington and other locations, conversations with vendors, and discussions with regulators and stakeholders.

6.1 Direct Algae Control

One treatment approach to control cyanobacteria blooms is the use of algaecide. This is a short-term approach to controlling a bloom, and has the potential to impact other non-target species and organisms. The use of algaecides is regulated by Ecology via the Aquatic Plant and Algae Management (APAM) general permit system (Ecology, 2021) as well as by the WDFW.

There are two general classifications of algaecides: systemic and contact. Systemic algaecides are longer-term treatments that can be used proactively to inhibit growth and reactionarily by directly killing existing target species. Contact algaecides are short-term treatments that typically need to be reapplied in a matter of weeks as the ingredients usually dissipate in the environment.

The USEPA maintains a list of chemicals used for cyanobacteria control (USEPA, 2023). Currently, only two types of algaecides are permitted for use in the state of Washington under the APAM general permit: endothall and sodium carbonate peroxy-hydrate. Table 14 provides specific considerations for algaecide use as detailed in the APAM general permit.

Table 14. Specific considerations for algaecide use per the APAM General Permit

Active Ingredient	Restrictions/ Advisories	Treatment Limitations	Other Specific Restrictions
Endothall (mono salt)	Swimming advisory during and for 24 hours after treatment (in the entire waterbody)	Use for control of filamentous algae, cyanobacteria, or harmful algae only (see S1.A.2(b)) Limit concentrations to 0.2 mg/L of active ingredient	Treatment must occur from the shoreline outward into the waterbody Consult Federal Insecticide, Fungicide, and Rodenticide Act product label for water use restrictions

Sodium carbonate peroxyhydrate	None	Do not treat plants growing on the shore	None

Per the APAM general permit, the use of algaecide must not cause further impairment of any 303(d) listed watershed for any listed parameter. Because algaecide application has the potential to reduce DO concentrations, additional monitoring requirements are in place for algaecide use. Another disadvantage of algaecide use is, if applied after a bloom has reached sufficient mass, it can result in a short-duration large increase in toxin concentrations within the water column as cell lyse and the toxins escape (USEPA, 2017).

Any application of algaecide to Lacamas, Round, or Fallen Leaf Lakes should be done as part of a more comprehensive treatment program, and would need to consider the latest information regarding potential toxicity to other organisms and relevant monitoring requirements.

6.2 In-Lake or Near-Lake Control Methods

This section discusses management alternatives which involve treatment either in the lake, or near the lake (at its inflow). These methods are aimed in some way at reducing phosphorus available for algae growth, using a variety of mechanisms.

6.2.1 In-Lake Phosphorus Sequestration

A common approach applied for management of algae blooms in lakes is to reduce the bioavailability of phosphorus in the lake by binding it in an unavailable form in the bottom sediments. The binding of phosphorus in the bottom sediments is thought to be effectively permanent (Rydin and Welch, 1998). The most commonly used agent for this approach is aluminum sulfate (alum), which has been described as a safe and effective option for lake management by NALMS (2004). Alum has been applied to multiple lakes in Washington state, including Lake Ketchum (Burghdoff, Leskiw, and Oden, n.d.), Heart Lake (Herrera, 2018), and Green Lake (Herrera, 2016). Alum is often applied at the lake surface or injected into deeper portions of the lake from a boat using a dose based on the amount of phosphorus in the lake that needs to be sequestered. Because there is potential for alum to cause toxicity to aquatic organisms when the pH drops below approximately 6 (due to potential presence of free aluminum) and above a pH of 9 (due to potential presence of hydroxides) (NALMS, 2004), sodium aluminate is sometimes applied along with alum to maintain a pH within an acceptable range, if a large dose of alum is proposed. Alum could be applied either to strip the water column phosphorus, or (in a much larger dose), to inactivate the phosphorus on the sediment bed.

Another agent used to bind and sequester phosphorus is lanthanum. There are several examples of application of Phoslock, a proprietary lanthanum-modified bentonite (LMB) clay product, in Washington state, including Kitsap Lake (Aquatechnex, 2022a) and Lake Lorene (Aquatechnex, 2022b). In recent years, another LMB product, Eutrosorb G, has been used as a Phoslock replacement, including at Kitsap Lake (Berthiaume, 2023). Phoslock and Eutrosorb G are typically applied as slurries from boats.

The manufacturer of Eutrosorb G, SePRO Corporation, also has a product called Eutrosorb WC, which is designed to strip phosphorus from the water column but not inactivate the phosphorus in the bottom sediments. Eutrosorb WC is an aqueous mix of binding materials, and differs from Eutrosorb G. A Eutrosorb WC application for water column stripping would be a short-term solution since it would not eliminate the potential for internal loading, but would allow for reduction of water column phosphorus concentrations with a substantially smaller dose.

LMB is nontoxic to aquatic life and, as a result, poses a lower risk to aquatic organisms relative to alum. LMB binds with phosphate stably, and effectively permanently and remains nontoxic even under extreme pH conditions. However, there are fewer case studies using Eutrosorb G relative to alum. Eutrosorb WC is a proprietary product that the manufacturer states has no environmental or safety concerns. However, case studies proving this are not yet available.

Two types of in-lake alum or Eutrosorb treatments were considered:

- Water column stripping
- Sediment inactivation

6.2.1.1 Water Column Stripping Treatment with Alum

For water column stripping, a treatment for both Lacamas and Round Lakes was considered; Fallen Leaf Lake was not included in the cost because it has had few HABs and would require a different approach due to inability to use a motorized boat.

Based on phosphorous sampling from May–October 2022, there was an average of approximately 415 kilograms of total phosphorus between the two lakes. Assuming 87% of the total phosphorus is OP (based on sampling results), this is an estimated 361 kilograms of OP to inactivate.

A wide variety of ratios of alum application to total phosphorus have been used, from 10 to 100 kg alum/kg phosphorus (Natarajan and Gulliver, 2020). For this planning level estimate, an application ratio of 20:1 was used, meaning 7,221 kilograms of alum would be needed. Using a conversion of 0.22 kilograms of alum per gallon (Natarajan and Gulliver, 2020), this means 32,800 gallons of alum would be required, at a cost of approximately $2.1 per gallon (Natarajan and Gulliver, 2020), which would mean a materials cost of $70,000. At an application ratio of alum to total phosphorus of 50:1, the equivalent materials cost would be $170,000. Including an increase of 25% to account for planning, monitoring, and contingency, the planning level cost for a water column stripping alum treatment would be $90,000–$215,000. For Lacamas Lake only, the corresponding cost would be $70,000-$180,000. Because of the high external loading of phosphorus, it is expected that this treatment would need to be repeated annually until such time as significant reductions in phosphorus loading from the watershed are achieved. This estimate does not include costs for buffering of alum with sodium aluminate, since it is assumed the relatively small dosage would not move the pH out of an acceptable range. Monitoring during treatment would be required to ensure this.

6.2.1.2 Water Column Stripping Treatment with Eutrosorb WC

Eutrosorb WC is a product designed for water column phosphorus stripping. Eutrosorb WC dosages are calculated on a Prescription Dose Units (PDUs) basis. For 361 kilograms of OP, 9,880 PDUs would be recommended (Ryan van Goethem, personal communication, 2023). Each

275-gallon tote contains 2,200 PDUs; here, 4.5 totes would be required at a materials cost of $173,000 (Ryan van Goethem, personal communication, 2023). Including an estimated cost of implementation of $50,000 (Ryan van Goethem, personal communication, 2023), this results in an overall estimated annual cost of $223,000. For Lacamas Lake only, the estimated corresponding cost is $190,000. Compared with a low dose of alum, Eutrosorb WC is more expensive; however, jar testing may indicate a higher dose of alum would be needed, as well as potential need for buffering with sodium aluminate. Buffering would not be required with Eutrosorb WC. Eutrosorb WC is not currently permitted by Ecology, but could be approved as an experimental product.

6.2.1.3 Sediment Inactivation Treatment with Alum

A sediment inactivation treatment would be intended to make the available phosphorus in the sediments unavailable for release into the water column by binding it as a low solubility aluminum salt, thus making it unavailable for algae growth. The calculation of the required dosage of alum is based on the average concentration of available phosphorus in the sediment, density of the sediments, and a required depth within the sediment for inactivation.

For Lacamas Lake, the average measured sediment phosphorus concentration was 1,152 mg/kg; for Round Lake this value was 1,373 mg/kg. For Lacamas Lake, the phosphorus was 64% available on average compared with 57% for Round Lake. This gives an average available phosphorus concentration in the sediment of 738 mg/kg for Lacamas Lake and 784 mg/kg for Round Lake. Dry density of the sediments was estimated at 0.23 g/cm^3 based on past findings of 1.22 g/cm^3 of wet weight at approximately 80% water content (Beak and SRI, 1985).

It was assumed that the top 5 centimeters would be inactivated using alum, an application ratio of 20:1 would be used, and application would occur over a surface area of 88 acres in Lacamas Lake and 11 acres in Round Lake (based on surface area with a depth of at least 30 feet, since the deepest areas are most likely to go anoxic, and these areas should be prioritized for treatment). Based on these assumptions, it was estimated that there are 3,000 kilograms of available phosphorus in the deepest areas of Lacamas Lake and 400 kilograms in the deepest part of Round Lake, for a total of 3,400 kilograms targeted for inactivation. At a 20:1 ratio, this means 60,400 kilograms (133,000 pounds) of alum would be required for Lacamas Lake and 8,000 kilograms (17,700 pounds) for Round Lake, for a total of 68,500 kilograms (151,000 pounds). Using the estimates of 0.22 kilograms per gallon and $2.1 per gallon, this yields 311,000 gallons of alum at a cost of $650,000. Because of this larger dose, it is assumed sodium aluminate would be required to ensure pH remained in an acceptable range. A ratio of 3 gallons of alum per gallon of sodium aluminate was assumed based on Bartodziej et al. (2017). This means 104,000 gallons at an estimated cost of $8.72 per gallon (Herrera2023) for a cost of $905,000 for sodium aluminate. Combining the cost of alum and sodium aluminate, and adding 25%, this results in a planning level cost for sediment inactivation of $1.95 million for a sediment deactivation with alum. Monitoring would be required during treatment to ensure pH remained at an acceptable level. If applied over a period of 5 years, this would mean a cost of $390,000 per year. For Lacamas Lake alone, the corresponding estimated cost is $1.7 million, or an annual cost of $340,000 for 5 years. Annual partial sediment inactivation could be done at the same time as a water column stripping treatment.

6.2.1.4 Sediment Inactivation Treatment with Eutrosorb G

Eutrosorb G is a lanthanum-modified bentonite produced for phosphorus binding. To deactivate 3,400 kilograms (7,500 pounds) of phosphorus with Eutrosorb G would require 377,000 pounds of Eutrosorb G at a typical ratio of 50:1. At a cost of $3.1 per pound of Eutrosorb G, this would cost $1.17 million. Adding a 25% contingency results in an estimated cost for sediment deactivation of $1.46 million. If applied over a period of five years, this would mean a cost of $290,000 per year. For Lacamas Lake alone, the corresponding estimated cost is $1.3 million, or an annual cost of $260,000 for 5 years.

6.2.1.5 Summary of In-Lake Phosphorus Sequestration Alternatives

Table 15 shows a summary of the in-lake Phosphorus sequestration alternatives discussed in Sections 6.2.1.1 through 6.2.1.4.

Table 15. Comparison of In-Lake Phosphorus Sequestration Alternatives

Option	Planning Level Annual Cost Lacamas Lake Only	Notes
Water column stripping using alum	$70,000-$210,000	• Costs depend on required dosage which would be determined using jar testing. • Costs presented here assume buffering with aluminum sulfate would not be required (would need to be confirmed based on required dosage). • Some risk of toxicity to fish if improper dose used.
Water column stripping using Eutrosorb WC	$190,000	• Estimate is based on prorated quote developed for Lacamas and Round Lakes. Implementation cost included. Phosphorus concentration at the time of application would affect the actual dosage. • Experimental permit would be needed if full approval not granted by Ecology prior to implementation. • New product with few case studies.

Option	Planning Level Annual Cost Lacamas Lake Only	Notes
Sediment inactivation using alum	$340,000 ($1.7 million over 5 years)	• Assumes only deepest areas (>30 feet) would be targeted. • Costs depend on required dosage which would be determined using jar testing. • Estimate assumes 3:1 ratio of alum to sodium aluminate buffer needed. • Some risk of toxicity to fish if improper dose used.
Sediment inactivation using Eutrosorb G	$260,000 ($1.3 million over 5 years)	• Estimate is based on prorated quote developed for Lacamas and Round Lakes. Implementation cost included. • Fewer case studies in Washington relative to alum.

6.2.2 Phosphorus Sequestration at Inflow

Phosphorus sequestration at the lake inflow from Lacamas Creek is a similar concept as sequestration within the lake (Section 6.2.2), with a different application method. Here, alum is injected into an external source, such as a creek, prior to inflow into the lake. The intention is to create flocs to bind and settle out phosphorus prior to it entering the lake. A recent product, Eutrosorb WC, is designed for use in flowing water and could be applied using this methodology. However, dosing application can become complicated due to seasonal flow regimes in creeks, and settling of floc within the stream bed may have ecological implications for fish and other aquatic organisms. The permitting process would be significantly more complex relative to in-lake treatment. A 2016 estimate for Spanaway Lake was that design and construction of the system would cost $175,000 (Brown and Caldwell, 2016). However, design of chemical storage, dosing control, monitoring, permitting, and other considerations, it is expected that design and construction costs could exceed $500,000.

The annual costs for an injection system would be dependent on the required dosage. For alum, a dose of 5 mg/L was assumed based on Churchill (2009). For initial calculation purposes, the total volume from Lacamas Creek for June 2023 was used (under the assumption that the water that would remain in the Lake during the summer would be the most important to treat for phosphorus), which resulted in an estimated volume of 13.6 billion liters. This means a total alum dose of 67,900 kilograms, or 309,000 gallons would be needed, at a cost of $650,000 for alum each year. Smaller doses could also be considered, such as 1–2 mg/L, but this calculation demonstrates that even to treat just one month of inflow would require substantial annual costs for alum alone without considering maintenance or energy costs. For Eutrosorb WC, the required dose would be 1 gallon per kilograms of phosphorus being removed; for removal of 361 kilograms of OP (similar to the in-lake treatment described above), $175,000 of material costs per year is assumed. Including maintenance and energy costs, an annual cost of $220,000 is assumed for the injection system.

Phosphorus sequestration at the Lacamas Creek inflow is likely to be an effective approach given the high fraction of the phosphorus budget that it accounts for. However, compared to in-lake treatments, the annual costs are similar, and a creek injection system would carry additional design, construction, and permitting costs, and would take longer to implement. This may be an strategy to consider in the future should in-lake treatment need to be supplemented or emerging technology make it easier to implement.

6.2.3 Hypolimnetic Oxygenation or Aeration for Internal Loading Control

Increasing DO concentrations near the lake bottom is an option for reducing internal phosphorus loading. As discussed in Sections 3.2.5 and 5.2, sediment phosphorus in Lacamas, Round, and Fallen Leaf Lakes is approximately 60-80% in the iron-bound fraction, which is available for release under anoxic conditions. Therefore, preventing anoxic conditions may meaningfully reduce internal phosphorus loading. Increasing DO concentrations may also provide improved aquatic life habitat. However, importantly, such a system would not address the external loading, which accounts for the majority of phosphorus loading to Lacamas and Round Lakes, and therefore would not be expected to meaningfully reduce HABs as a sole treatment measure.

Hypolimnetic aeration (in which air is used) and hypolimnetic oxygenation (in which pure oxygen is used) have both been used to increase DO near the lake bottom. Oxygenation requires less gas volume than aeration because air is only about 20% oxygen by volume. Hypolimnetic oxygenation has been applied at Newman Lake in Washington since 2001, and is considered effective (e.g., Moore et al., 2015), as well as at Oswego Lake in northwest Oregon (Grund et al., 2022). Hypolimnetic oxygenation or aeration would require ongoing energy costs, and, in the case or oxygenation, costs for the supply of pure oxygen. The Newman Lake Flood Control Zone District received a grant to replace the Newman Lake system in 2022, suggesting a replacement period of approximately 20 years.

Based on costs discussed in Horne and Faisst (2022), a planning level estimate for construction of a hypolimnetic aeration or oxygenation system is $7,800/acre, or $690,000 if targeted for the deepest portion of Lacamas Lake (88 acres), with an annual maintenance cost of approximate $20,000. If a replacement was required in 20 years at a similar cost, $35,000 annualized costs for replacement could be added to the annual maintenance budget.

6.2.4 Nanobubbler

A more recent technology is nanobubblers, which uses small bubbles to achieve a higher efficiency of oxygen transfer. Nanobubblers aerate the entire water column (Herrera, 2020) and increase DO near the sediments, reducing internal loading. Moleaer is a manufacturer of these modular devices. The technology requires power on the shoreline and would carry ongoing energy costs. One of the largest available units costs $80,000 (Clint Hansen, personal communication, 2022). It is assumed that a minimum of 10 units would be needed for Lacamas and Round Lakes, at a minimum cost of $800,000. An annual cost for energy and maintenance is assumed to be $50,000. As with other approaches for oxygenating the bottom of the water column, there is potential for portions of the sediments to remain anoxic even if the hypolimnion of the water column is oxygenated, and this would not address the external loading of phosphorus. As such, nanobubblers alone would not be expected to meaningfully reduce HABs in the lakes.

6.2.5 Floating Treatment Wetlands

Artificial floating islands use plant roots suspended from below the islands to sequester nutrients from the lake. The plant material is then maintained and harvested to achieve a net nutrient removal from the lake. A review by the Interstate Technology Regulatory Council (ITRC, n.d.) found that this approach is most effective for smaller lakes, since the effectiveness depends in part on the size of the floating island relative to the size of the lake and internal loading. Treatment wetlands also reduce the lake surface area available for recreation. An estimated cost per square foot is $40 (Herrera, 2023) and Floating Islands International recommends covering 2% of a lake to improve water quality. For Lacamas Lake, this would mean 6 acres (261,000 square feet) would be required, at a cost of $10.4 million. Furthermore, Lacamas and Round Lakes may require a higher percentage of surface area cover to see water quality improvements than the average lake due to their large depth to size ratio, and therefore small surface area to volume ratio. However, a much smaller demonstration project could be implemented. For example, a project covering 1,000 square feet, would cost an estimated $40,000. While such a project would be unlikely to meaningfully reduce nutrient concentrations, there would be value from a public engagement perspective.

6.2.6 Carp Management

As previously mentioned, Lacamas Lake's fishery is currently dominated by common carp, though various species of sunfish, bass, perch, suckers, and crappie are also present (personal communication with Patrick Cooney, Smith Root and Amaia Smith, WDFW).

Under WDFW permits, Patrick Cooney (Smith-Root) and his team caught 32 common carp on January 18, 2023, 37 on April 19, 2022, 16 on September 19, 2019, 42 on June 3, 2019, and 17 on September 26, 2018 (Patrick Cooney, personal communication, 2023). The common carp were caught from a boat which electrifies down to 8 feet and only along the shoreline (Patrick Cooney, personal communication, 2023).

Carp are known to feed on the lake bottom, uprooting aquatic plants and resulting in higher turbidity. The disturbance of lake sediments can also result in the release of phosphorus stored in the lake bottom into the water column (e.g., Bartodziej, 2017). Increased presence of carp may have contributed to more mobilization of bottom sediments and as a result, the higher levels of phosphorus measured near the bottom of Lacamas and Round Lakes in our study compared with past results.

Removal of common carp would provide multiple benefits. Reduction in mixing of bottom sediments may result in lower concentrations of bioavailable phosphorus near the bottom of the lake. Additionally, carp removal could help establish native aquatic plants along the shoreline in some areas.

Options for removal of common carp include electrofishing and box nets. WDFW has noted that common carp removal can be expensive and further conversations would be needed before implementing a carp removal program (Amaia Smith, personal communication, 2023).

6.3 Watershed Management Methods

While in-lake and/or inflow management methods are needed for short-term improvements in lake water quality, watershed-based programs for limiting total phosphorus loading into the lakes are critical to achieving long-term improvements in lake water quality, and to reducing or eliminating the need for in-lake management. There have been successful efforts to reduce total phosphorus in the Lacamas watershed since 1985 following the Beak and SRI (1985) report. As discussed above, a substantial reduction in loading is still required to reduce the eutrophic state of Lacamas, Round and Fallen Leaf Lakes.

Clark County Public Works collected data in the Lacamas Creek Watershed in Water Year 2022 (October 2021-September 2022), and found that total phosphorous and orthophosphate concentrations in the China Ditch and Lower Fifth Plain Creek portions of the watershed were elevated relative to concentrations at other monitoring locations on tributaries to Lacamas Creek. This data is consistent with past measurements, and identifies one area of potential focus For load reductions. As discussed in Section 3.2.3.4, Unnamed Creek had elevated phosphorus levels relative to other Creeks. Therefore, the sources of nutrients to the Unnamed Creek should also be evaluated.

Ecology is in the process of completing a Source Assessment for Lacamas Creek for bacteria, temperature, and nutrients following its QAPP (Gleason and McCarthy, 2021). Following the completion of this study, which is expected to be completed by the end of 2023 (Molly Gleason, personal communication, 2023), Ecology will complete an Alternative Restoration Plan, which will identify management measures to achieve targets identified in the Source Assessment. The Alternative Restoration Plan is scheduled to be completed in January 2025; this allows time for coordination between the County and City and other partners to begin identifying ways to improve upon ongoing management efforts and work to develop additional funding strategies for implementing the recommendations from the Alternative Restoration Plan.

Because the Lacamas Creek watershed is complex and has numerous landowners and jurisdictions, Clark County and Ecology will be critical partners in implementing management measures within the watershed along with partners such as Clark Conservation District, the Lacamas Watershed Council, and the Watershed Alliance of Southwest Washington. The following sections outline types of management measures that are common in many watersheds throughout the state for reducing external loading and that should be considered for the Lacamas Watershed.

6.3.1 Stormwater BMPs

In some watersheds, stormwater is a major source of phosphorus to lakes. Improved regulations and implementation of stormwater BMPs could reduce external loading to the lakes. Stormwater management for reduced phosphorus export could include additional requirements for new construction, optimization of existing detention ponds to increase removal efficiency, enhanced street sweeping, enhanced catch-basin cleaning, upgrade of existing bioretention facilities, or enhanced maintenance requirements for existing facilities.

Existing City stormwater programs are described in the City Stormwater Management Program (City of Camas, 2023) and Stormwater Sewer System Operations & Maintenance Manual (City of Camas, 2022).

The Stormwater Management Program has been developed in accordance with the City'sPhase II Stormwater National Pollutant Discharge Elimination System (NPDES) permit issued by the Department of Ecology. The program includes planning, public education and outreach, public involvement and planning, mapping and documentation of municipal separate storm sewer systems, illicit discharge detection and elimination, use of BMPs (including low-impact development) to control runoff from development and construction, operations and maintenance, source control for existing discharges, monitoring, and reporting. The City accomplishes these tasks through revenues generated from the City's Stormwater Utility Rates.

The Operations & Maintenance Manual includes descriptions and specifics of maintenance for vegetated BMPs such as biofiltration swales and rain gardens, and for structures such as catch basins and storm sewer pipes.

A 2022 memo (MacKay-Sposito and Geosyntec, 2022) discussed potential methods for optimization of the City's stormwater program, including uniform maintenance and inspection standards, identification of hot spot locations to visit during storms, beaver exclusion devices, and more regular Contech filter cartridge replacement.

Prioritizing stormwater facilities draining to Fallen Leaf Lake for inspection, monitoring, and retrofits is recommended, since the watershed for this lake is within the city limits and reducing stormwater loading is likely to meaningfully impact the lake nutrient budget. Facilities draining to Lacamas and Round Lakes, could also be prioritized, but the impacts to their nutrient budget would be small due to the size of the watershed for Lacamas and Round Lakes.

6.3.2 Septic System Management

Septic systems are a source of nutrients to groundwater. When septic systems are located near lakes, they can be a significant source of external loading of nutrients to those lakes. While direct groundwater inflow to Lacamas and Round Lakes is not believed to be a significant portion of the water balance, groundwater loading to Lacamas Creek would be included in the nutrient budget as measured. There are 3,518 septic systems within the Lacamas Lake watershed in the Clark County GIS database. The County has an existing On-Site Septic System Program, which helps identify and address failing septic systems. The Clark Conservation District's Poop Smart Clark program, with support from Clark County and Washington State University Extension, also funds improvements to septic systems.

6.3.3 Agricultural BMPs

Agriculture, including livestock operations, which contribute nutrients to the watershed via feed, waste, and erosion; and crop cultivating operations, which contribute nutrients to the watershed as a byproduct of fertilization and soil disturbance, can be a major source of external nutrient loading to lakes. Agricultural BMPs to reduce phosphorus export could include source BMPs focused on initial application and BMPs which focus on reducing transport (Sharpley et al., 2006). Source BMPs include the following:

- Fertilizer management and reduced usage
- Management of phosphorus in livestock feed
- Management of phosphorus in manure, including chemical amendments or physical treatment

Transport BMPs include the following:

- Conservation tillage to reduce erosion
- Cover crops
- Conservation buffers
- Streambank protection and restoration

The Clark Conservation District has existing programs supporting education and funding for the installation of agricultural BMPs.

6.3.4 Constructed Treatment Wetlands

Constructed treatment wetlands use substrate and vegetation to improve water quality and provide additional benefits such as flood storage, habitat, and educational opportunities. Constructed wetlands can reduce the influent phosphorus to a lake by mimicking the function of natural wetlands to filter nutrients from water. They can be constructed at the inflow to a lake, or within the lake itself. However, they generally require a large amount of space to provide sufficient treatment.

6.3.5 Stream Restoration

Several types of stream restoration could have benefits for reducing lake nutrient loads. Restoring the connection of creeks to their natural floodplains and allowing for natural channel migration can reduce erosion, as well as reduce water velocities which in turn reduce the potential for sediment transport.

Increasing and restoring riparian buffers with native plants (grasses, shrubs, and trees) can prevent contaminants from entering a creek at the source. BMPs that look similar to agricultural BMPs could also be implemented, and constructed treatment wetlands could be incorporated.

6.3.6 Public Education

Public education is an important element of load reduction. While policy guides commercial and industrial operations, as well as construction and design of new and re-development projects, residential and recreational properties are influenced by how the public chooses to use them. Education can include providing information on how certain behaviors affect the watershed, information on how to alter behaviors to help preserve watershed health, and can promote community vigilance towards these non-preferred activities.

Existing public education programs within the Lacamas Lake watershed include the Clark County Conservation District Poop Smart Clark program, which has existing programs focused on resources for septic system owners, pet waste cleanup, and fishing/hiking/camping waste practices. Other public education programs are being championed by the Lacamas Watershed Council, Watershed Alliance of Southwest Washington, Vancouver Water Resource Education Center, and all of the municipal stormwater programs.

6.4 Policy Considerations

6.4.1 Boat Use

Wakes from boats can result in resuspension of sediments at the bottom of the Lakes. This can result in release of phosphorus from the lake sediments which can contribute to algal blooms (e.g. Harwood, 2017). This possibility could be mitigated by limiting the use of motors in some areas with Lacamas Lake. However, the areas of most-elevated phosphorus in the lake sediments are in deeper areas where boat wakes are unlikely to cause resuspension. Therefore, a boat policy change is not recommended at this time for direct water quality benefits but may still be something the City and agency partners may want to consider for multiple reasons.

6.4.2 Closing Lakes During HABs

Currently, accessing the lakes during algal blooms is permitted, though public health alerts are displayed. Preventing access to certain areas within the lakes when toxins are detected would require a change in policy. This may be difficult to enforce given that the lake has not been closed historically and the area affected by the bloom may vary in size and location.

6.4.3 Fertilizer Policy

Banning of the use of high-nutrient fertilizers during portions of the year can reduce nutrient loading to water bodies and has been adopted by some local governments. As of April 14, 2011, Governor Christine Gregoire signed “Clean Fertilizers, Healthier Lakes and Rivers” (Engrossed Substitute House Bill 1489) into law. This law prohibits retail sales, displays, and the use of fertilizers containing phosphorus on turf. The law defines turf as residential, commercial, and publicly owned land. This definition includes home, condo, apartment complex lawns, and lawns closely mowed and maintained on commercial and public properties such as parks, golf courses, cemeteries, schools, and business centers. This law does not apply to pasture, grass grown for sod (turf farms), residential vegetable or flower gardens, or any other land used for agricultural production (Washington State Department of Agriculture). The law was an attempt to reduce the amount of phosphorus entering water bodies via surface runoff and storm drains as multiple studies throughout the state have shown the negative impacts to lakes. However, this has been a challenge to enforce, at least in the local area, as the distribution and sale of fertilizers with phosphorus at local retail stores is still occurring. Smidt et. al (2022) found that fertilizer ordinances improved lake water quality and this may be a policy conversation the City and/or County may want to have. At a minimum, it is recommended that the ongoing Public Outreach efforts include this as a key topic.

7. MANAGEMENT METHODS REJECTED

The following management methods were considered but are considered inappropriate for near-term and in-lake strategies for Lacamas, Round, and Fallen Leaf Lakes.

7.1 Dredging

Dredging is an effective method of removing nutrient-laden sediments. Dredging to a depth at which phosphorus concentrations are lower than surface sediments reduces the amount of phosphorus available to contribute to internal loading. Dredging projects tend to be costly and subject to significant state and federal permitting processes. A decision must also be made regarding the placement of the dredged sediments, which carries additional costs.

7.2 Ultrasound

Ultrasound technology is a relatively recent approach for limiting algae blooms in lakes. Ultrasonic waves create a barrier preventing algae from moving up and down the water column to access nutrients and light needed for growth. One study from Australia found this approach to be ineffective (Vaughan et al., 2023) and devices installed at Lake Ketchum in Washington did not find evidence of effectiveness in reducing algae growth (Burghdoff and Williams, 2012). In addition, little is known about the potential effects of this technology on other organisms that may use similar mechanisms to rise up and down in the water column.

7.3 Full Water Column Mixing

Mixing the lake water column has been applied using solar-powered water mixers, aeration, and mechanical mixing. Visser et al. (2016) provided an extensive review of the applications of this method and results. Notably, the authors found that in some cases, mixing of nutrient-rich water near the bottom of a reservoir resulted in an increase in measured total phosphorus higher in the water column. Altering the stratification profile of the lakes could impact the water quality of the lake in other ways as well.

7.4 Physical Phosphorus Filtration at Lacamas Creek

Filtration of phosphorus at inflows has been used at some creeks. Eutrosorb F is a version of the Eutrosorb product which is a 25-pound filter which can be placed in moving water and can remove 0.25 pounds of phosphorus. However, removal of 584 kilograms of phosphorus (the estimated June inflow at Lacamas Creek) would require over 5,000 filters for this short period alone, which would create challenges for engineering, design, and construction costs, and then both space and disposal considerations and costs.

8. RECOMMENDED MANAGEMENT/LAKE RESTORATION PLAN

The data collected for this plan identified the following key insights, which form the basis for our recommendations:

- Lacamas, Round, and Fallen Leaf Lakes are generally eutrophic, with some measurements reflecting mesotrophic conditions.
- The three lakes appear to be phosphorus-limited. The majority (>75%) of the total phosphorous entering the lakes and in the lakes is orthophosphate, which is readily available for biological uptake.
- External loading via Lacamas Creek is the dominant source of phosphorus to Lacamas and Round Lakes. It is also the dominant source of water to these lakes.
- Internal loading is a meaningful component of the phosphorus budget for Lacamas and Round Lakes; however, it is a smaller component than external loading.
- The most elevated phosphorus concentrations were near the bottom of each lake, where there is relatively little Chl-a.

Specific recommendations for each lake are provided in the following sections.

8.1 Lacamas Lake

The recommended approach for reduction of HABs and overall improvement of water quality in Lacamas Lake is an annual water column stripping treatment with alum or Eutrosorb WC combined with targeted inactivation of phosphorus in the sediments. Inactivation of sediment phosphorus will focus on the deepest portions of the lake where anoxic conditions are most common, and will be achieved using alum or Eutrosorb G over a period of 5-10 years. This approach was recommended by Eutrophix (Ryan van Goethem, personal communication, 2023). This option is recommended because it will address both external and internal loading, and will allow for a smaller dosage of chemical in a given year, therefore reducing the likelihood of adverse effects to lake ecology caused by, for example, large swings in pH induced by chemical treatment, as well as spreading out costs over multiple years. Furthermore, ongoing monitoring can inform dosage for both water column stripping and sediment inactivation in future years, which will allow for more optimized treatment dosages and timing in the future.

Annual water column stripping for Lacamas Lake combined with treatments of 20% of the estimated available phosphorus in the sediments in the deepest portions of Lacamas Lake (assuming a 5-year period for sediment inactivation) would cost approximately $440,000 per year. Actual costs will depend on the results of bench scale testing to determine the necessary ratio of chemical to phosphorus concentration; these costs assume a 20:1 ratio would be sufficient. Continued monitoring is strongly recommended such that treatment effectiveness can be monitored over time, and is detailed in Section 9.

Since limited aquatic vegetation was found in Lacamas Lake, planting of native aquatic vegetation should be considered to encourage development of desired species. However, increased water clarity could lead to increased growth of aquatic plants that may be present but have not germinated due to lack of light availability. Aquatic vegetation may also provide some benefits for phosphorus reduction if dying plants are regularly removed from the lake. The effects of annual drawdowns on potential revegetation strategies should be carefully considered. Floating wetlands could be implemented as part of a revegetation plan.

8.2 Round Lake

The recommended approach is to focus initially on Lacamas Lake, and not to implement any treatment measures within Round Lake itself. This is because Round Lake is downstream of Lacamas Lake, and therefore treatment of Lacamas Lake may provide sufficient improvement of water quality in Round Lake to meaningfully reduce HABs. Costs for treatment of both Round and Lacamas Lakes together are discussed in Section 6 but are not presented again here.

As with Lacamas Lake, planting of native aquatic vegetation should be considered, especially since essentially no aquatic vegetation was observed at Round Lake. The effects of annual drawdowns on potential revegetation strategies should be carefully considered.

8.3 Fallen Leaf Lake

Fallen Leaf Lake has similar levels of phosphorus to Lacamas and Round Lakes and should continue to be monitored. However, measured cyanotoxin concentrations have never exceeded state guidelines. As such, treatment is not recommended in Fallen Leaf Lake at this time. As discussed in Section 6.3.1, prioritization of stormwater facilities in the Fallen Leaf Lake watershed for inspection, monitoring and retrofits is recommended to reduce nutrient loading to the lake.

Fallen Leaf Lake should be considered for a future water column and/or sediment inactivation treatment if elevated cyanotoxins are detected in future years; Fallen Leaf Lake should also be considered for herbicide treatment if aquatic vegetation becomes an increasing nuisance.

8.4 Watershed-wide Recommendations

In addition to in-lake treatment strategies which should provide short-term improvements in lake water quality, projects in the watershed to reduce external loading are also strongly recommended and essential for sustainably improving and preserving lake water quality.

Because of the inter-agency coordination and long-term nature of these strategies, as described in Section 6.3, specific projects are not included as part of this Lake Management Plan. However, the City should strongly consider including long-term funding for these watershed-based projects in future budgets, whether in the form of a straight funding pool, staff time ("in-kind") for identification of projects and outreach to surrounding landowners and stakeholders, establishment of a grant program for community-driven projects, or other funding mechanisms.

The Alternative Restoration Plan being developed by Ecology, anticipated to be completed by January 2025, will identify priority areas within the Lacamas watershed where resources should be targeted.

The City and Clark County have restarted discussions regarding a potential interlocal agreement. Though ongoing collaboration has been occurring for a number of years and the County has been a significant stakeholder in development of this plan, such an agreement could formalize the partnership and allow for collaboration to find additional funding through joint outreach to state and federal legislators and application of grants. Additionally, a interlocal agreement could provide joint agency support for continued efforts of existing programs in both the City and County jurisdictions monitoring of water quality like the work completed by Clark County on Fallen Leaf in 2020, and support for efforts by other partners such as the Clark Conservation District, Lacamas Watershed Council and Watershed Alliance. Additional opportunities include joint education and outreach, joint efforts to optimize stormwater programs, and additional policy considerations such as efforts to develop faster notification for HABs. Continued interagency collaboration to identify and fund watershed mitigation projects is needed for long-term lake water quality improvements.

An annual City allocation of funds to be used for public education, contributions to watershed mitigation, and outreach efforts is recommended.

9. FUTURE MONITORING AND ADAPTIVE MANAGEMENT

Continued monitoring of nutrients and related parameters in the lakes is necessary to benchmark progress towards reducing the potential for HABs to occur. This plan recommends continued monitoring, to evaluate phosphorus and Chl-a concentrations in the lakes at least once per summer, but preferably at least three times, and at least once per winter at the deepest location in the lake. Summer samples should include phosphorus concentrations both at the surface and near the bottom of the lake, while only surface samples are necessary in winter. Vertical profiles of field parameters should be taken multiple times per year. In addition, the thermistor chains should remain in the lakes with data downloads at least twice per year, and thermistor batteries replaced as necessary. This data will provide long-term insights into the duration of thermal stratification in the lakes and may be used to help determine what parameters are most influential on the timing of stratification. The creek level gage should remain in place at Lacamas Creek at Goodwin Road, with calibration verified against the staff gage at least once but preferably twice per year. Resulting flow calculations can help determine the potential phosphorus loading to the lake each year. An approximate budget for annual lake water quality monitoring to track improvements and ensure treatments are achieving desired benefits in water quality is $50,000.

We also recommend measurement of phosphorus speciation in surface sediments again after five years to determine if bioavailable phosphorus has been reduced.

Additional monitoring options for consideration include monitoring buoys equipped with multiparameter sondes capable of continuously measuring parameters such as temperature, DO, and Chl-a Fluorescence (which correlates with Chl-a concentrations). Four buoys (two in Lacamas Lake, one each in Round and Fallen Leaf Lakes) could be installed and maintained for a cost of approximately $70,000 per year (Eli Kersh, LakeTech, Inc., personal communication, 2023).

During chemical treatments ongoing monitoring will be needed to ensure an acceptable pH range, and frequent monitoring is recommended in the weeks following a treatment to document the degree to which phosphorus concentrations are reduced. Annual updates should be produced including a summary of lake treatments, monitoring data, and other relevant information, as well as recommendations for the following year.

Adaptive management is a necessary component of a successful lake management plan. It allows for adjustment of a recommended implementation plan following ongoing monitoring and evaluation of plan effectiveness. Based on results of post-treatment monitoring, the chemical dose needed for future annual treatments, the type of chemical used, the application method, and the timing of applications can be refined to produce more desirable results. If the recommended treatment strategy does not produce reductions in phosphorus concentrations and exceedances of guidelines for cyanotoxins within 3 years, other strategies could be revisited, such as inactivation of sediment phosphorus using a higher dose of chemical treatment, construction of a treatment system at the influent source, or the addition of chemical treatments in Round Lake.

10. FUNDING STRATEGY

Table 16 provides a summary of the overall costs for the recommendations outlined in Section 8.

Table 16. Summary of 10-Year Costs for Recommended Actions.

Option	Years	Annual Cost	10-Year Cost
Annual water column stripping	1-10	$180,000	$1.8 million
Sediment phosphorus inactivation	1-5	$260,000	$1.3 million
Monitoring	1-10	$50,000	$500,000
Public Outreach	1-10	$50,000	$500,000
	Total	**$540,000 (Years 1-5)** **$280,000 (Years 6-10)**	**$4.1 million**

The City of Camas received a Direct Grant Appropriation through the 2023-2025 State Capital Budget of $515,000 to support implementation of near-term management strategies identified in this LMP. This grant provides a strong foundation for funding the recommendations presented in this plan. However, additional funding will be required.

Funding mechanisms were reviewed in a 2021 memorandum (MacKay-Sposito and Geosyntec, 2021). Funds should be sought through Ecology Freshwater Algae Control Program Phase II grants, which are intended for lakes with Ecology-approved Lake Cyanobacteria Management Plans. Additional Ecology programs for consideration include the Stormwater Financial Assistance Program, and Stormwater Grants of Regional or Statewide Significance Program (GROSS). Federal sources of funding should also be evaluated including National Fish and Wildlife Foundation: Five Star Urban Water Restoration Program. By working with partners such as Clark Conservation District, funding for agricultural BMPs could be sought from the United States Department of Agriculture Natural Resources Conservation Service.

11. PARTNERSHIPS

The recommendations of this LMP will take strong partnerships and collaborations between the City and key partners. As discussed in Section 8.4, the City and Clark County are discussing a potential interlocal agreement, but additional support from other partners – including state and federal legislators – will be needed to successfully implement management strategies that will have broad and long-lasting impacts. For the near term, the City will administer the use of the $515,000 grant received through the 2023-2025 State Capital Budget and will lead in-lake treatment in coordination with Clark County and Ecology. The City will also continue to implement stormwater program improvements.

Clark County will continue to fund existing programs, in particular their Stormwater Management Plan Implementation programs, Agricultural Management programs and Septic System Management programs. Additionally, the County will continue reviewing and considering additional watershed management strategies such as Stormwater Facility Optimization, accelerating their Stormwater Capital Program, providing additional support for the Septic System Management program and expanding their efforts working with the Clark Conservation District on various programs. The County already provides broad support, technical expertise, and assistance with public outreach and education to all of the cities in implementation of their individual Stormwater NPDES programs and will look for ways to improve or expand those efforts if possible.

The Ecology Alternative Restoration Plan expected from Ecology in January 2025 will identify priority areas for improvements within the watershed and will identify specific targeted programs for additional management and project opportunities. All stakeholders and residents within the watershed will ultimately be responsible for trying to meet the Alternative Restoration Plan goals, but it is recognized the City and Clark County will likely take on the largest roles to coordinate strategies and prepare to implement Ecology's recommendations.

Ongoing public education efforts will occur, and continued collaboration between the City, County, Ecology, Clark Conservation District, and organizations such as the Lacamas Watershed Council, Watershed Alliance of Southwest Washington, City of Vancouver Water Resource Education Center, and Lower Columbia Fish Enhancement Group will be critical to successfully implementing the recommendations of this plan.

12. REFERENCES

Allan, J. D. 1995. Stream Ecology: Structure and Function of Running Waters. 388 pp.

Aquatechnex. 2022a. *Kitsap Lake Phoslock Treatment Provides Results in Year One.* https://aquatechnex.com/kitsap-lake-phoslock-treatment-provides-results-in-year-one/

Aquatechnex. 2022b. *Project Overview*. https://aquatechnex.com/lake-lorene/

Bartodziej, W., P.W. Sorensen, P.G. Bajer, K. Pilgrim, and S. Blood. 2017. "A Minnesota story: Urban shallow lake management." *NALMS Lakeline*, 23-29.

Beak Consultants, Inc. and Scientific Resources, Inc. (Beak and SRI). 1985. *Lacamas – Round Lake Diagnostic and Restoration Analysis.* Intergovernmental Resource Center

Berthiaume, C. 2023. *Kitsap Lake Algae Control and Aquatic Vegetation Management.* City of Bremerton. https://www.bremertonwa.gov/1282/Kitsap-Lake-Algae-Control-and-Aquatic-Ve

Burghdoff, M., D. Leskiw, and J. Oden. n.d. *Lake Ketchum Restoration.* Snohomish County, Washington. https://snohomishcountywa.gov/2451/Lake-Ketchum-Restoration

Burghdoff, M., and G. Williams. 2012. *Lake Ketchum Algae Control Plan – June 2012.* Snohomish County, Washington.

Brown and Caldwell. 2016. Spanaway Lake Management Plan. Prepared for Pierce County, Washington.

Carlson, R.E. 1977. "A trophic state index for lakes." *Limnol. Oceanogr*., 22, 361-368. https://doi.org/10.4319/lo.1977.22.2.0361

Chang, S.C., and M.L. Jackson. 1957. "Fractionation of Soil Phosphorus." *Soil Sci.,* 84, 133-144. https://doi.org/10.1097/00010694-195708000-00005

Churchill, J.J., M.W. Beutel, and P.S. Burgoon. 2009. "Evaluation of optimal dose and mixing regime for alum treatment of Matthiesen Creek inflow to Jameson Lake, Washington." *Lake and Reservoir Management*, 25(1), 102-110.

City of Camas. 2022. Stormwater Sewer System Operations & Maintenance Manual. Stormwater Division, Department of Public Works.

City of Camas. 2023. *Drainage Subbasins* [Map]. Camas Stormwater Management Action Planning (SMAP). https://storymaps.arcgis.com/stories/1f69b13027b64ee7a5ffea6b08d9adcd. Accessed 2023.

City of Camas. 2022. Stormwater Management Program. Stormwater Division, Department of Public Works.

Clark County Public Works. 2011. *Lacamas Creek at Goodwin Road Near Camas, Washington.* Station Analysis 2010 Water Year.

Clark County Public Works. 2021. *Fallen Leaf Lake Baseline Monitoring Report.* Clean Water Division, for the City of Camas, Washington.

Clark County. 2023. *Washington Open Data.* Accessed July 2023. https://hub-clarkcountywa.opendata.arcgis.com/datasets/zoning/explore?location=45.635352%2C-122.359777%2C11.72

Clark County. n.d. *Clark County Open Data: Digital GIS Bulk Download*. Volume 2. Accessed October 2021. https://hub-clarkcountywa.opendata.arcgis.com/

Conin, S. 1991. *Characteristics of successful riparian restoration projects in the Pacific Northwest (No. PB-92-196039/XAB; EPA-910/9-91/033)*. Environmental Protection Agency, Seattle, Washington (United States).

Deemer, B.R., Harrison, J.A. and Whitling, E.W., 2011. Microbial dinitrogen and nitrous oxide production in a small eutrophic reservoir: An in situ approach to quantifying hypolimnetic process rates. Limnology and oceanography, 56(4), pp.1189-1199.

Deemer, B.R., Henderson, S.M. and Harrison, J.A., 2015. Chemical mixing in the bottom boundary layer of a eutrophic reservoir: The effects of internal seiching on nitrogen dynamics. Limnology and oceanography, 60(5), pp.1642-1655.

Deemer, B.R. and Harrison, J.A., 2019. Summer redox dynamics in a eutrophic reservoir and sensitivity to a summer's end drawdown event. Ecosystems, 22, pp.1618-1632.

Eilers- J.M., R.B. Raymond, K.B. Vache, J.W. Sweet, C.P. Gubala, P.R. Sweets, 1996.Lacamas Lake Watershed 1995 Water Quality Monitoring Program. Report submitted to Clark County Department of Community Development, Water Quality Division, Vancouver, WA. E&S Environmental Chemistry, Inc. Corvallis, Oregon.

Georgia-Pacific Consumer Operations LLC. 2018. *Operation and Maintenance Plan for the Lacamas Lake Dams.*

Geosyntec Consultants, Inc. 2022. *Lacamas, Round, and Fallen Leaf Lakes Cyanobacterial Lake Management Plan.* Quality Assurance Project Plan. Prepared for the City of Camas.

Gleason and McCarthy. 2021. *Quality Assurance Project Plan: Lacamas Creek Bacteria, Temperature, and Nutrients Source Assessment.* Prepared for Washington Department of Ecology Water Quality Program.

Green, C. 2018. G-P gifts 190 acres to Camas. *Camas-Washougal Post-Record*. https://www.camaspostrecord.com/news/2018/sep/20/g-p-gifts-190-acres-to-camas

Grund, Y., Y. Pan, M. Rosenkranz, and E. Foster. 2022. "Long-term phosphorus reduction and phytoplankton responses in an urban lake (USA)." *Water Biology and Security*, 1, 1. https://doi.org/10.1016/j.watbs.2022.100010.

Harrison, J.A., Deemer, B.R., Birchfield, M.K. and O'Malley, M.T., 2017. Reservoir water-level drawdowns accelerate and amplify methane emission. Environmental science & technology, 51(3), pp.1267-1277.

Harwood, H. 2017. Protecting water quality and resuspension caused by wakeboard boats. North American Lake Management Society (NALMS) LakeLine, p. 12-15.

Henderson, S.M. and Deemer, B.R., 2012. Vertical propagation of lakewide internal waves. Geophysical research letters, 39(6).

Herrera Environmental Consultants. 2016. *Monitoring Report – Green Lake Alum Treatment.* Prepared for Seattle Parks and Recreation. Seattle, Washington.

Herrera Environmental Consultants. 2018. *Heart Lake Alum Treatment Plan.* Prepared for Anacortes Parks and Recreation. Anacortes, Washington.

Herrera Environmental Consultants. 2020. *Lone Lake Algae Management Plan [Draft]*. Prepared for Whidbey Island Conservation District. Coupeville, Washington.

Herrera Environmental Consultants. 2023. *Draft Vancouver Lake Management Plan. Vancouver Lake, Clark County, Washington.* Prepared for Clark County. In association with LimnoTech, Kearns & West, Aquatechnex.

Horne, A.J. and Faisst, W.K., 2022. Hypolimnetic oxygenation 6. Improvement in fisheries, hydropower, and drought management with costs of installation and operation in Camanche Reservoir, California, United States. Lake and Reservoir Management, 38(3), pp.268-285.

Interstate Technology Regulatory Council. n.d. *Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCB-1): Floating Wetlands.* https://hcb-1.itrcweb.org/floating-wetlands/

King County. 2023. *Freshwater Algae Bloom Monitoring Program*. https://www.nwtoxicalgae.org/Data.aspx?SiteID=94. Accessed 2023.

Koerselman, W. and Meuleman, A. F. M. 1996. The Vegetation N:P Ratio: a New Tool to Detect the Nature of Nutrient Limitation. The Journal of Applied Ecology, 33, 1441-1450.

Kohler, M.A., T.J. Nordenson, and W.E. Fox. 1955. *Evaporation from pans and lakes (Vol. 30).* US Government Printing Office.

Lafer, J. 1994. *Lacamas Lakes Restoration Project. Water Quality Monitoring Report 1991-1992 Progress Report.* Technical Report prepared for Clark County Water Quality Division, Vancouver, Washington.

MacKay-Sposito and Geosyntec, 2021. Funding Strategy for the Next 12-24 months . Memo to Steve Wall, City of Camas.

MacKay-Sposito and Geosyntec, 2022. Stormwater Optimization. Memo to Steve Wall, City of Camas.

Matthews, R. 2016. "Freshwater Algae in Northwest Washington – a Beginner's Guide to Algae." *Waterline Newsletter.* Washington State Lake Protection Association. https://www.walpa.org/waterline/june-2016/freshwater-algae-in-northwest-washington-a-beginners-guide-to-algae/

Moore, B., M. Mobley, J. Little, B. Kortmann, and P. Gantzer. 2015. "Aeration and Oxygenation Methods for Stratified Lakes and Reservoirs." North American Lake Management Society. *LakeLine*, Spring 2015.

Moyer, K. 2021. "Camas teens tackle toxic algae". *Camas-Washougal Post-Record*. Retrieved 2023 from https://www.camaspostrecord.com/news/2021/may/27/camas-seventh-graders-earn-spot-at-national-stem-competition-with-algaegator-invention/?fbclid=IwAR1FufCuNQ22sMfQtr61iVom5IOdecj-OvOmRwH0H5rTdnRo86c9ytqbaQM

Mueller, K.W. and Downen, M.R. 1999. 1997 Lacamas Lake Survey: The Warmwater Fish Community of a Highly Eutrophic Lowland Lake. Washington Department of Fish and Wildlife, Warmwater Enhancement Program. La Conner, Washington.

Natarajan, P., and J.S. Gulliver. 2020. *Golden Lake Phosphorus Release and Alum Dosing Feasibility Study.*

National Weather Service (NWS). 2023. *Climate of Portland.* NOAA Technical Memorandum, NWS-WR-239.

North American Lake Management Society (NALMS). 2004. *The Use of Alum for Lake Management*. North American Lake Management Society. https://www.nalms.org/wp-content/uploads/2016/05/NALMS-Alum-Position-Statement.pdf

NALMS. 2023. *Trophic State Equations*. North American Lake Management Society. https://www.nalms.org/secchidipin/monitoring-methods/trophic-state-equations/

Nolan, S., Bollens, S.M. and Rollwagen-Bollens, G., 2019. Diverse taxa of zooplankton inhabit hypoxic waters during both day and night in a temperate eutrophic lake. Journal of Plankton Research, 41(4), pp.431-447.

Nürnberg, G.K. 1988. "Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediments." *Canadian Journal of Fisheries and Aquatic Sciences,* 45(3), 453-462.

Parsons, J. 1999. Aquatic Plants Technical Assistance Program. 1998 Activity Report. Washington Department of Ecology.

Perkins, K.R., 2017. Influence of Environmental Factors on the vertical distribution of phytoplankton in Lacamas Lake, WA. Washington State University Honors Thesis.

Perkins, K.R., Rollwagen-Bollens, G., Bollens, S.M. and Harrison, J.A., 2019. Variability in the vertical distribution of chlorophyll in a spill-managed temperate reservoir. *Lake and reservoir management*, 35(2), pp.119-126.

Price, C.V., Nakagaki, N., Hitt, K.J., and Clawges, R.C. 2006. *Enhanced Historical Land-Use and Land-Cover Data Sets of the U.S. Geological Survey, U.S. Geological Survey Digital Data Series 240. [digital data set]* https://pubs.usgs.gov/ds/2006/240

Qin, B., J. Zhou, J.J. Elser, W.S. Gardner, J. Deng, and J.D. Brookes. 2020. “Water depth underpins the relative roles and fates of nitrogen and phosphorus in lakes.” *Environmental Science & Technology*, 54(6), 3191-3198.

Raymond, R.B., J.M. Eilers, K.B. Vache, J.W. Sweet, P.R. Sweets, C.P. Gubala. 1997. *Lacamas Lake Watershed 1996 Water Quality Monitoring Program.* A Report to Clark County Department of Community Development, Water Resources and Development Engineering. Vancouver, Washington. E&S Environmental Chemistry, Inc., Corvallis, Oregon.

Raymond, R.B. 1998. *Dye tracer mixing study at Lacamas Lake, 1996 and 1997.* Technical Memorandum prepared for Clark County Community Development Department, Vancouver, Washington. E&S Environmental Chemistry, Inc., Corvallis, Oregon

Raymond, R.B., J.M. Eilers, J.A. Bernert, and K.B. Vache. 1998. Lacamas Lake watershed restoration project program review. Report to Clark County Department of Public Works, E&S Environmental Chemistry, Inc., Corvallis Oregon.

Rector, J. and Hallock, D. 1993. Lake Water Quality Assessment Project, 1990. Washington State Department of Ecology.

Roberts, M. 2013. *Lake Loma Phosphorus Screening-Level Assessment.* Washington Department of Ecology.

Rose, V., Rollwagen-Bollens, G., Bollens, S.M. and Zimmerman, J., 2021. Effects of grazing and nutrients on phytoplankton blooms and microplankton assemblage structure in four temperate lakes spanning a eutrophication gradient. Water, 13(8), p.1085.

Rydin, E., Huser, B. and Welch, E.B., 2000. Amount of phosphorus inactivated by alum treatments in Washington lakes. Limnology and Oceanography, 45(1), pp.226-230.

Schnabel, J.D. 2000. *Lacamas Lake Restoration Program: WY1998 and WY1999 Water Quality Monitoring.* Clark County.

Schnabel, J.D. 2002. *Lacamas Lake Restoration Program: WY2000 and WY2001 Water Quality Monitoring.* Clark County.

Schnabel, J.D. 2004. *Lacamas Lake Nutrient Loading and In-Lake Conditions.* Clark County.

Schnabel, J.D. 2005. *Monitoring Report, Lacamas Lake Annual Data Summary for 2005.* Clark County.

Schnabel, J.D. 2006. *Monitoring Report, Lacamas Lake Annual Data Summary for 2006.* Clark County.

Schnabel, J.D. 2007. *Monitoring Report, Lacamas Lake Annual Data Summary for 2007.* Clark County.

Sharpley, A.N., et al. 2006. *Best management practices to minimize agricultural phosphorus impacts on water quality.* US Department of Agriculture Agricultural Research Service.

Smidt, S.J., Aviles, D., Belshe, E.F. and Reisinger, A.J., 2022. Impacts of residential fertilizer ordinances on Florida lacustrine water quality. Limnology and Oceanography Letters, 7(6), pp.475-482.

United States Environmental Protection Agency (USEPA). 2017. *Leaky Cyanobacteria Cells and Algaecide Treatments: A Look at the Data and Implications for Decision Making.* USEPA Cyanobacteria HABS Webinar.

USEPA. 2023. *Control Measures for Cyanobacterial HABs in Surface Water.* https://www.epa.gov/cyanohabs/control-measures-cyanobacterial-habs-surface-water.

United States Geological Survey. 2019. *StreamStats Program Online*. https://www.usgs.gov/streamstats. Accessed 2023.

Vaughan, L., D. Barnett, E. Bourke, H. Burrows, F. Robertson, B. Smith, J. Cashmore, M. Welk, M. Burch, and A. Zamyadi. 2023. "Evaluating Ultrasonicator Performance for Cyanobacteria Management at Freshwater Sources." *Toxins*, 15(3), 186. https://doi.org/10.3390/toxins15030186

Visser, P.M., B.W. Ibelings, M. Bormans, J. and Huisman. 2016. "Artificial mixing to control cyanobacterial blooms: a review." *Aquat Ecol* 50, 423–44. https://doi.org/10.1007/s10452-015-9537-0

Vollenweider R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Memorie dell'Istituto Italiano di Idrobiologia, 33, 53–83.

Washington Department of Ecology (Ecology). 2021. *Aquatic Plant and Algae Management General Permit.* Olympia, Washington.

Washington Department of Ecology (2023). Environmental Information Management System (http://www.ecology.wa.gov/eim/).

Washington Department of Fish and Wildlife. 2023. *Fishing and Shellfishing [Online].* https://wdfw.wa.gov/fishing/locations/lowland-lakes/lacamas-lake#photos

Washington Department of Health. 2008. *Washington State Recreational Guidance for Microcystins (Provisional) and Anatoxin-a (Interim/Provisional).* July.

Washington Office of Financial Management, 2023. Washington Data and Research.

Welch, E.B., H.L. Gibbons, S.K. Brattebo, and H.A. Corson-Rikert. 2017. "Distribution of aluminum and phosphorus fractions following alum treatments in a large shallow lake." *Lake and Res. Mgmt.*, 33:2, 198-204, DOI: 10.1080/10402381.2016.1276653