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Lake Whatcom Monitoring Project 2021/2022 Report

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Lake Whatcom Monitoring Project
2021/2022 Report

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Executive Summary

Background for the Lake Whatcom Annual Reports

- This report describes the results from the 2021/2022 Lake Whatcom monitoring program conducted by the Institute for Watershed Studies at Western Washington University (`www.wwu.edu/iws`).

- The major objectives in 2021/2022 were to continue long-term baseline water quality monitoring in Lake Whatcom and its major tributaries; collect storm runoff water quality data from representative streams in the watershed; and continue collection of hydrologic data from Austin and Smith Creeks.

- Each section in this report contains a brief discussion of the water quality parameters that are measured as part of the monitoring effort. For additional help with understanding the relationship between water quality data and lake, stream, or watershed ecology, we recommend the online resource "Water on the Web" (WOW, 2004; `www.waterontheweb.org`).

- The online pdf copy of this report contains red hyperlinks that will open online citations, and blue hyperlinks that will jump to referenced tables and figures or to the section that contains additional information about a specific topic. These hyperlinks are active if the report is opened using Adobe Reader, which can be downloaded free from `www.adobe.com/products/reader.html`.

- This report is part of an on-going series of annual reports and special project reports that provide a complete documentation of the monitoring program over time. A summary of the Institute for Watershed Studies Lake Whatcom reports, including special project reports, is included in Section 5.2, beginning on page 91, and many of the reports are available online through Western CEDAR, the WWU repository for open access scholarship, under the Institute for Watershed Studies Lake Whatcom collection (`http://cedar.wwu.edu/iws_lakewhatcom`).

Summary of 2021/2022 Monitoring Project

- During the summer the lake's water column was thermally stratified into a warm surface layer (the epilimnion) and a cool bottom layer (the hypolimnion). Most of the 2021/2022 temperature profiles fell within historical ranges, with stable stratification present at Sites 1–4 by mid-late May (Section 2.3.1, page 4).[1]

- The hypolimnetic oxygen concentrations have declined over time at Site 1 (Section 2.3.2, page 5), causing the lake to be listed by the Department of Ecology on the 1998 303d list of impaired waterbodies in the state of Washington. The hypolimnetic oxygen loss was apparent at Site 1 after the lake became fully stratified in June, and by August the oxygen concentrations were <2 mg/L from 12 meters to the bottom.

- Nitrate depletion was evident at all sites in the photosynthetic zone during the summer due to algal uptake of this essential nutrient (Section 2.3.5, page 10). Unlike the other indicators of phytoplankton productivity, the dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonium) trend has not stabilized in recent years. A month-by-month analysis of near-surface DIN showed that water column concentrations have declined in general, not just in the summer. Nitrate depletion also occurred in the hypolimnion at Sites 1 and 2 due to nitrate reduction by bacteria. Anaerobic conditions in the hypolimnion at Sites 1 and 2 resulted in elevated concentrations of ammonium by the end of the summer.

- The summer near-surface total phosphorus concentrations continued to follow erratic patterns, with no significant correlations with year (Section 2.3.5, page 12), reflecting the complicated nature of phosphorus movement in the water column. Hypolimnetic phosphorus remains elevated in the summer at Sites 1 and 2 when dissolved oxygen is low.

- The summer near-surface chlorophyll concentrations have increased significantly over time at all sites (Section 2.3.6, page 13). Despite being quite variable, the concentrations appear to have stabilized since 2004, ranging from 3.7–6.7 μg/L at Site 1 and 2.6–4.6 μg/L at Sites 2–4.

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[1] These links direct the reader to sections with additional information on the summary topic.

- All of the mid-basin coliform counts were less than 10 cfu/100 mL (Section 2.3.7, page 15). The coliform counts at the Bloedel-Donovan recreational area (collected offshore from the swimming area) were slightly higher than mid-basin counts, but passed the freshwater *Primary Contact Recreational* bacteria standard for Washington in place prior to 2021 (see Section 2.3.7, page 15 for discussion of changes in standards).

- The concentrations of trihalomethanes and haloacetic acids (THMs and HAAs) in Bellingham's treated drinking water have increased over time, but have been declining in recent years. The concentrations of both types of disinfection by-products remained below the maximum contaminant levels of 0.080 mg/L and 0.060 mg/L, respectively (Section 2.3.8, page 16).

- Monthly tributary samples were collected at 12 locations in the Lake Whatcom watershed (Section 3, page 57). Most of the tributaries had low concentrations of total suspended solids, low alkalinities and conductivities, and low levels of nutrients (phosphorus and nitrogen). The residential streams had higher concentrations of total suspended solids, higher alkalinities and conductivities, higher coliform counts, and higher nutrient concentrations.

- Hydrograph data were collected at Austin and Smith Creeks using rating curves to calculate discharge (Section 4.1, page 78).

- Storm runoff samples were collected in Carpenter Creek (five storm events), Olsen Creek (two storm events), and Smith Creek (two storm events) using time-paced automated samplers (Section 4, page 78). The water quality data are sent to the City of Bellingham for use in watershed modeling.

1 Background

This report is part of an on-going series of annual reports and special project reports that document the Lake Whatcom monitoring program over time. Many of the reports are available online through Western CEDAR, the WWU repository for open access scholarship, under the Institute for Watershed Studies Lake Whatcom collection (`http://cedar.wwu.edu/iws_lakewhatcom`). Reports that are not available on CEDAR may be available in the Institute for Watershed Studies (IWS) library or through the City of Bellingham Public Works Department. A summary of the Lake Whatcom annual and special project reports is included in Section 5.2, beginning on page 91.

Each section in this report contains a brief discussion of the water quality parameters that are measured as part of the monitoring effort. For additional help with understanding the relationship between water quality data and lake, stream, or watershed ecology, we recommend the online resource "Water on the Web" (`www.waterontheweb.org`; WOW, 2004).

Lake Whatcom is the primary drinking water source for the City of Bellingham and parts of Whatcom County, including Sudden Valley. It also serves as a primary or supplemental water source to various water systems adjacent to the City of Bellingham.

The lake and its watershed provide recreational opportunities, as well as important habitats for fish and wildlife. The lake is used as a storage reservoir to buffer peak storm water flows in Whatcom Creek. Because of its aesthetic appeal, the watershed is highly valued for residential development. Historically, most of the nonresidential portion of the watershed was zoned for forestry and was managed by state or private timber companies.

Through a land acquisition program initiated in 2001, the city has purchased over 2,400 acres to set aside for preservation.[2] Additionally, approximately 7,800 acres of forest lands formerly managed by the Department of Natural Resources was reconveyed to Whatcom County in January 2014 to be managed as low impact park lands. The Lake Whatcom reconveyance planning process is summarized online.[3]

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[2] `https://cob.org/services/environment/lake-whatcom/lw-property-acquisition-program`

[3] `www.whatcomcounty.us/625/Lake-Whatcom-Reconveyance`

1.1 Objectives

The City of Bellingham and Western Washington University have collaborated on water quality studies in Lake Whatcom since the early 1960s. Beginning in 1988, a monitoring program was initiated by the City and WWU that was designed to provide long-term lake data for temperature, pH, dissolved oxygen, conductivity, turbidity, nutrients (nitrogen and phosphorus), and other representative water quality measurements. The major goal of the long-term monitoring effort is to provide a record of Lake Whatcom's water quality over time.

The major objectives of the 2021/2022 Lake Whatcom monitoring program were to continue long-term baseline water quality monitoring in Lake Whatcom and its major tributaries; collect storm runoff water quality data from representative streams in the watershed; and continue collection of hydrologic data from Austin and Smith Creeks.

Detailed site descriptions can be found in Appendix A. The historical lake data are plotted in Appendix B. The current quality control results are in Appendix C. The monitoring data are available online at `www.wwu.edu/iws` as described in Appendix D (page 345). Table 2.1 (page 18) lists abbreviations and units used to describe water quality analyses; Tables 2.2 & 3.1 (pages 19 & 62) list the locations, depths, and frequency for lake and tributary sampling.

2 Lake Whatcom Monitoring

2.1 Site Descriptions

Water quality samples were collected at five long-term monitoring sites in Lake Whatcom (Figure A1, page 100 in Appendix A.1). Sites 1–2 are located at the deepest points in their respective basins. The Intake site is located adjacent to the underwater intake point where the City of Bellingham withdraws lake water from basin 2. Site 3 is located at the deepest point in the northern sub-basin of basin 3 and Site 4 is located at the deepest point in the southern sub-basin of basin 3. Water samples were also collected at the City of Bellingham Lake Whatcom Gatehouse, which is located onshore and west of the Intake site.

2.2 Field Sampling and Analytical Methods

The lake was sampled on October 7, 12 & 19, November 2 & 11 and December 2 & 7, 2021; and February 14 & 16, April 7, 11 & 14, May 3, 5 & 10, June 7 & 9, July 5 & 7, August 2 & 4 and September 6 & 8, 2022. Each sampling event is a multi-day task; all samples were collected during daylight hours, typically between 10:00 am and 3:00 pm. The analytical and sampling procedures are summarized in Tables 2.1 & 2.2 (pages 18 & 19). Table 2.3 (page 20) summarizes missing data from the 2021/2022 sampling season.

A YSI EXO1 multiparameter field meter was used to measure temperature, pH, dissolved oxygen, and conductivity in the field. Raw water and bacteriological samples were collected using a VanDorn sampler; plankton samples were collected using a 30-L Schindler trap equipped with a 20 μm mesh plankton net. The water and bacteriological samples were stored on ice and in the dark until they reached the laboratory. Plankton samples were placed in a cooler and returned to the laboratory unpreserved. The plankton sample volumes were measured in the laboratory and the samples were preserved with Lugol's solution. Total organic carbon analyses were done by AmTest[4] and by IWS. The bacteria samples were analyzed by the City of Bellingham.

2.3 Results and Discussion

The lake monitoring data include monthly field measurements (conductivity, dissolved oxygen, pH, Secchi depth, and water temperature); laboratory analyses for ambient water quality parameters (ammonium,[5] nitrate/nitrite,[6] total nitrogen, soluble phosphate, total phosphorus, alkalinity, turbidity, chlorophyll); plankton and bacteria counts; and total organic carbon measurements.

The 2021/2022 temperature, dissolved oxygen, pH, and conductivity profiles are shown in Figures B1–B50 (Appendix B, pages 104–153). Tables 2.4–2.8 (pages 21–25) summarize the current field measurements, ambient water quality, and

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[4] AmTest, 13600 Northeast 126th Place, Suite C, Kirkland, WA, 98034–8720.

[5] Nearly all ammonia (NH_4^+) is ionized to ammonium (NH_3) in surface water. Earlier IWS reports used "ammonia" and "ammonium" interchangeably; we now use "ammonium" to indicate that the data represent the concentration of ionized ammonia.

[6] Nitrate and nitrite were analyzed together because nitrite concentrations are very low in surface water. For simplicity, nitrate/nitrite will be referred to as "nitrate" in this document.

coliform data, and all of the current data are plotted in comparison with historic data in Figures B66–B146 (Appendix B, pages 170–251). These figures are scaled to plot the full range of Lake Whatcom water quality data including minimum, maximum, and outlier values, and do not provide the best illustration of trends that occur in the lake. Separate tables and figures are provided to show trends and illustrate specific patterns in the data. The raw data are available online at `www.wwu.edu/iws` as described in Appendix D (page 345).

2.3.1 Water temperature

The 2021/2022 monthly temperature profiles for Sites 1–4 were plotted as overlay points on shaded polygons that summarize the 1988–2022 historic temperature ranges (Figures 2.1–2.13, pages 28–40). The monthly YSI profiles for temperature, dissolved oxygen, pH, and conductivity at Sites 1–4 and the Intake were included in Appendix B (Figures B1–B50, pages 104–153).

The summer temperature profiles (e.g., Figure 2.7, page 34) show how the lake stratifies into a warm surface layer (*epilimnion*), and cool bottom layer (*hypolimnion*). The transition zone between the epilimnion and hypolimnion (*metalimnion*) is a region of rapidly changing water temperature. When stratified, the temperature profiles show distinct differences between the surface and bottom of the water column. Stratification develops gradually, and once stable, persists until fall or winter, depending on location in the lake. Seasonal weather differences alter the timing of lake stratification; if the spring is cool, cloudy, and windy, the lake may stratify later than when it has been hot and sunny.

In Lake Whatcom, all sites except the Intake[7] are usually stratified by late spring or early summer. Stratification may begin as early as April, but is often not stable until May or June. The stability of stratification is determined in part by the temperature differences in the water column, but also by water circulation and local weather patterns. Once the water column temperature differs by at least 5°C (ΔT $\geq$5°C), it is unlikely that the lake will destratify.[8]

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[7] The Intake is too shallow to develop stable stratification (see Appendix B, Figures B1–B46).

[8] The ΔT is the difference between the epilimnion and hypolimnion temperatures.

As the weather becomes colder and days shorten, the lake cools and the surface and bottom water temperatures become more similar. Eventually the water column will start to mix from the surface to the bottom and the lake will destratify. Basins 1 and 2 (Sites 1–2) usually destratify by the end of October or early November, but basin 3 (Sites 3–4) is usually still stratified in November (Figure 2.2, page 29). Complete destratification of basin 3 occurs in December or early January, so by February the temperatures are uniform throughout the water column at all sites (Figure 2.4, page 31).

Although destratification is relatively abrupt, the process of mixing the entire water column is not instantaneous. When the lake begins to destratify, water temperatures may be uniform from the surface to the bottom, but the rate of water circulation may not be sufficient to replenish hypolimnetic oxygen concentrations. This phenomenon, where temperature is uniform, but dissolved compounds (e.g., dissolved oxygen) remain partially stratified, is common in the early stages of destratification, when the basin is starting to mix (see November 2013 temperature and oxygen profiles from Site 2; Figure B.7 in Matthews, et al., 2015).

The lake was still stratified at all sites in October 2021 (Figure 2.1, page 28). Sites 1–2 were completely destratified by November (Figure 2.2, page 29). Sites 3–4 were close to destratification in December 2021 ($\Delta T \leq 3°$ C); the entire lake was destratified in February 2022 (Figures 2.3–2.4, pages 30–31).

The water column was starting to stratify in early May 2022 ($\Delta T = 2.3$–$3.9°$ C). Sites 1–4 had developed stable stratification ($\Delta T > 5°$ C) at the June sampling event (Figure 2.7, pages 34). All sites remained stratified through September, with temperatures falling within typical historical ranges (Figures 2.7–2.10, pages 34–37).

2.3.2 Dissolved oxygen

The 2021/2022 monthly oxygen profiles for Sites 1–4 were plotted as overlay points on shaded polygons that summarize the 1988–2022 historic temperature ranges (Figures 2.1–2.13, pages 28–40).[9] The monthly YSI profiles for temperature, dissolved oxygen, pH, and conductivity at Sites 1–4 and the Intake were included in Appendix B (Figures B1–B50, pages 104–153).

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[9] October–December 2022 are not part of the 2021/2022 sampling period, but the temperature/oxygen profiles were included to provide information on the timing of destratification.

As in past years, Sites 1–2 developed severe hypolimnetic oxygen deficits during the summer (Figures 2.8–2.10, pages 35–37). Hypolimnetic oxygen depletion only becomes apparent after stratification, when the lower waters of the basin are isolated from the lake's surface and biological respiration consumes the oxygen dissolved in the water. Biological respiration usually increases when there is an abundant supply of organic matter (e.g., decomposing algae). In basin 3, which has a very large, well-oxygenated hypolimnion, respiration has relatively little influence on hypolimnetic oxygen concentrations. In contrast, there is rapid depletion of the hypolimnetic oxygen concentrations at Sites 1–2. These two sites are in shallow basins that have small hypolimnions compared to their photic zones[10] so decomposition of algae and other organic matter causes a significant drop in hypolimnetic oxygen over the summer. This oxygen depletion may be apparent in May if the lake stratifies early in the spring, but is more commonly observed beginning in June (Figure 2.7, page 34).

Low oxygen conditions are associated with a number of unappealing water quality problems in lakes, including loss of aquatic habitat; release of phosphorus from the sediments; increased rates of algal production due to release of phosphorus; unpleasant odors during lake destratification; fish kills, particularly during lake destratification; release of metals and organics from the sediments; increased mercury methylation; increased drinking water treatment costs; increased taste and odor problems in drinking water; and increased risks associated with disinfection by-products created during the drinking water treatment process.

The levels of hypolimnetic oxygen have declined over time at Site 1, causing the lake to be listed by the Department of Ecology as an "impaired" waterbody (Pelletier, 1998).[11] The increasing rate of oxygen loss is most apparent during July and August, after the lake develops stable stratification but before oxygen levels drop near zero. To illustrate this trend we fitted the July and August data using an exponential function (see discussion by Matthews, et al., 2004). As indicated in Figures 2.14–2.17 (pages 41–44), there were significant negative correlations[12]

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[10] The photic zone is the region with enough light to support algal photosynthesis, which extends to about 10 m below the surface in Lake Whatcom. Assuming a photic zone of 0–10 m, the photic zones for basins 1, 2, and 3 would be 75%, 70%, and 17% of the basin's volume, respectively (Mitchell, et al., 2010).

[11] `www.ecy.wa.gov/programs/wq/303d`.

[12] Correlation analyses examine the relationships between two variables. The test statistic ranges from –1 to +1; the closer to ±1, the stronger the correlation. The significance is measured using the p-value; significant correlations have p-values <0.05.

between dissolved oxygen and time for all hypolimnetic samples collected during July and August. Although Site 1 didn't develop stable stratification until late May, the July hypolimnetic oxygen concentrations were already <5 mg/L and by August the oxygen concentrations were <2 mg/L (Figures 2.14–2.17).

A region of supersaturated oxygen was evident in the metalimnion at all sites in August (Figures 2.9, page 36; Figures B41–B45, pages 144–148). This was caused by the accumulation of phytoplankton along the density gradient between the epilimnion and hypolimnion where light and nutrients are sufficient to support very high levels of photosynthesis. Chlorophyll concentrations within the metalimnetic oxygen peak may be 4–5 times higher than those measured near the surface of the lake (Matthews and DeLuna, 2008). Metalimnetic oxygen peaks are common at Site 1 during the summer, and may occur at Sites 2–4, but will usually be at different depths because the metalimnions are at different depths. When present, the metalimnions form at approximately 5–10 m at Site 1, 10–15 m at Site 2, and 15–20 m at Sites 3–4.

Hypolimnetic oxygen loss is much less obvious in basin 3, in part due to the much larger hypolimnetic volume. Sites 3 and 4 often develop small oxygen sags near the thermocline during late summer. These are caused by respiration of heterotrophic bacteria that accumulate along the density gradient between the epilimnion and hypolimnion (e.g., Figure 2.1, page 28; Figure B4, page 107; Matthews and DeLuna, 2008). From October through December, which is usually the last month of stratification in basin 3, the hypolimnetic oxygen concentrations at Sites 3–4 are often lower than in the epilimnion, which likely reflects continued biological respiration in the isolated hypolimnion (e.g., Figures 2.3 & B14, pages 30 & 117). But the hypolimnion in basin 3 rarely drops below 5–6 mg/L of dissolved oxygen.[13]

Hypolimnetic hydrogen sulfide: Bacteria require an energy source (e.g., organic carbon) and an electron acceptor (e.g., oxygen) for basic growth and metabolism. Under anaerobic conditions, when oxygen is not available, there is a predictable sequence whereby different types of anaerobic bacteria use alter-

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[13] From 1998–2019, the deep sample from Site 3 was taken at 80 m; however, this depth is very close to the lake bottom and was frequently contaminated by the bottom sediments. Starting in the 2019–2020 report, we no longer sample at 80 m and instead use 75 m as the deepest measurement.

nate electron acceptors.[14] First, bacteria will use nitrate as an alternate to oxygen, converting nitrate to nitrite and nitrogen gas. Next, bacteria use manganese and ferrous ions. When these compounds are exhausted, bacteria use sulfate, converting it to hydrogen sulfide, a colorless gas with a strong, rotten-egg smell. If the electron acceptors listed above are unavailable, bacteria can use carbon dioxide, converting it to methane.

Hydrogen sulfide is commonly present in anaerobic lake sediments, but if the overlying water contains oxygen the sulfide will be converted into sulfates or other compounds. If the overlying water is anaerobic, hydrogen sulfide can build up to detectable levels during stratification. Hydrogen sulfide is an indicator of the degree of anoxia in the hypolimnion because it will not persist in oxygenated waters and is formed after the nitrate, manganese, and ferrous ions are exhausted.

The hypolimnion at Sites 1–2 usually contain detectable concentrations of hydrogen sulfide by October (Table 2.9, page 26). Hydrogen sulfide concentrations are measured in October because that is the latest month that is consistently stratified at Sites 1–2, so the hydrogen sulfide concentrations should be near their highest levels. The values of hydrogen sulfide obtained from Site 1 and 2 were relatively low, with Site 2 below detection limits.

2.3.3 Conductivity and pH

The pH and conductivity data followed trends that were fairly typical for Lake Whatcom (Figures B1–B50 and B76–B85, pages 104–153 and 180–189). Epilimnetic pH values increased during the summer due to photosynthetic activity and hypolimnetic pH values decreased due to decomposition and the release of dissolved compounds from the sediments (Figures B31–B45, pages 134–B45).

The conductivity concentrations were elevated in hypolimnetic samples at Sites 1–2, coinciding with periods of low oxygen near the bottom (e.g., Figures B46 & B2, pages 149 & 105). The historical data show what appears to be a decreasing trend in the conductivity values from 1988–2002, but this was caused by using increasingly sensitive equipment during the past three decades and does not indicate any actual change in the conductivity in the lake (Matthews, et al., 2004). Occasional spikes in conductivity at Site 3 are associated with low oxygen in samples collected very close to the bottom sediments.

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[14] For a more complete discussion of anaerobic decomposition in lakes, see Wetzel, 2001.

2.3.4 Alkalinity and turbidity

Lake Whatcom is a soft water lake so most alkalinity values were low (≤25 mg/L; Figures B86–B90, pages 191–195). During the summer the alkalinity values at the bottom of Sites 1–2 increased due to decomposition and the release of dissolved compounds from the sediments into the lower portion of the water column.

Turbidity values in the lake were usually low (1–3 NTU) except during late summer in samples from near the bottom of the lake. The high turbidity levels during this time are an indication of increasing turbulence in the lower hypolimnion as the lake begins to destratify. The highest turbidity peaks were measured at Sites 1–2, followed by Sites 3 and 4 (Figures B91–B95, pages 196–200).

Suspended sediments from storm events can also cause elevated turbidity levels in the lake. Major storm events usually occur during winter or early spring when the lake is destratified, so the turbidity levels will be high throughout the water column. Storm-related turbidity peaks are easier to see in samples from the Intake and Site 4 where there are fewer distracting late summer hypolimnetic turbidity peaks. Of note was the large storm system that affected Whatcom County in November 2021. Turbidity peaks from this storm can be seen on the right side of the plots from the Intake, Site 3, and Site 4 (Figures B93–B95; pages 198–200). These peaks are among the highest that the Institute for Watershed Studies has measured in the lake.

2.3.5 Nitrogen and phosphorus

The nitrogen and phosphorus data are illustrated in Figures B96–B120 (pages 201–225). Nitrogen and phosphorus are important nutrients that influence the amount and type of microbiota (e.g., algae) that grow in the lake. We measured inorganic forms of nitrogen and phosphorus (nitrite, nitrate, ammonium, and soluble phosphate) as well as total nitrogen and total phosphorus, which includes inorganic and organic compounds.[15]

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[15] Organic nitrogen and phosphorus comes from living or decomposing plants and animals, and may include bacteria, algae, leaf fragments, and other organic particles.

Nitrogen: Most algae use dissolved inorganic nitrogen (DIN)[16] for growth. Nitrate depletion was evident at all sites in the photosynthetic zone during the summer (Figures B101–B105, pages 206–210), particularly at Site 1, where the epilimnetic nitrate concentrations usually drop below 20 μg-N/L by the end of the summer. Because nitrogen is required for algal growth, depletion of epilimnetic DIN concentrations is an indirect way to measure phytoplankton productivity. And, because algal densities have been increasing throughout the lake, it was not surprising to find that the DIN concentrations were declining over time (Figure 2.18, page 45). But, unlike the other indicators of phytoplankton productivity (see **Indications of eutrophication**, beginning on page 14), the DIN trend has not stabilized in recent years.

A month-by-month analysis of near-surface DIN showed that water column concentrations have declined in general, not just in the summer (Figure 2.19, page 46). Summer DIN concentrations are most likely declining because of higher lake productivity, with phytoplankton depleting DIN through uptake into their cells. When the summer DIN concentrations were adjusted by subtracting them from the median spring DIN values ($\Delta\text{DIN} = \text{DIN}_{\text{spring}} - \text{DIN}_{\text{summer}}$), the trend with year was only marginally significant or not statistically significant, depending on site (Figure 2.20, page 47). Because phytoplankton uptake of DIN would be lower in the spring, this weak trend observed when comparing spring and summer DIN suggests that the overall decline in DIN is not wholly the result of phytoplankton uptake.

The reason for the lake-wide drop in DIN is not known, but similar trends have been reported for lakes in the midwestern and northeastern region of the USA (Oliver, et al., 2017), lakes in the Sierra Nevadas (Sickman, et al., 2003), lakes in the Adirondacks (Waller, et al., 2012), as well as lakes and rivers in northern Italy (Rogora, et al., 2012). Most of these studies attribute the declining DIN concentrations to decreasing amounts of nitrogen entering lakes from atmospheric deposition, but without a detailed nitrogen budget analysis for Lake Whatcom, it would be premature to attribute the declining DIN to a specific cause. The implication, however, is that Lake Whatcom water quality conditions may become increasingly favorable for the growth of nitrogen-fixing Cyanobacteria, many of which

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[16] Dissolved inorganic nitrogen includes ammonium, nitrate, and nitrite. Usually, epilimnetic concentrations of ammonium and nitrite are low, so DIN is nearly equivalent to nitrate. When DIN is not available, some algae can use organic nitrogen and some Cyanobacteria, and a few uncommon species of diatoms, can convert dissolved nitrogen gas to ammonia (not ammonium) via nitrogen fixation.

are capable of releasing toxins. Recent summer algal counts from Lake Whatcom revealed that the lake contained many species of Cyanobacteria (Matthews, et al., 2012), but the nitrogen-fixing species were not abundant. It will be important to continue tracking the densities of Cyanobacteria in the lake and to watch for increases in the densities of nitrogen-fixing species.

Hypolimnetic nitrate concentrations dropped below 20 μg-N/L at Sites 1–2 in late summer (Figures B101–B102, pages 206–207). In anaerobic environments, bacteria reduce nitrate (NO_3^-) to nitrite (NO_2^-) and nitrogen gas (N_2). The historical data indicate that nitrate reduction has been common in the hypolimnion at Site 1, but was not common at Site 2 until the summer of 1999 (Figure B102, page 207). Since then, the only year that Site 2 hypolimnetic nitrate concentrations did not drop below 20 μg-N/L was 2007. Matthews, et al. (2008) hypothesized that the 2007 results were caused by a combination of late spring stratification and early fall destratification, which shortened the period of anoxia in the hypolimnion.

Ammonium, along with hydrogen sulfide, is often an indicator of hypolimnetic anoxia.[17] Ammonium is readily taken up by plants as a growth nutrient. In oxygenated environments, ammonium is rarely present in high concentrations because it is rapidly converted to nitrate through biological and chemical processes. In low oxygen environments, like the hypolimnion at Sites 1–2, ammonium concentrations increase during late summer, reaching maximum concentrations just prior to destratification (Figures B96 & B97, pages 201 & 202).

Elevated hypolimnetic ammonium concentrations have been common at both sites throughout the monitoring period, but beginning in 1999 the concentrations increased noticeably at Site 2 (Figure B97, page 202). The hypolimnion in Site 2 tends to be smaller than Site 1, potentially concentrating ammonium in a smaller volume of water.

The October 2021 ammonium concentrations near the bottom of Site 1 (425 μg-N/L at 20 meters) were consistent with previous years, but were much higher at the bottom of Site 2 (577 μg-N/L at 20 meters). This is consistent with the relatively higher hydrogen sulfide concentrations at the bottom of Site 2 in 2021. Site 1 had elevated ammonium concentrations at 20 meters in October 2022 (310 μg-N/L), but ammonium values were lower at the bottom of Site 2 (167 μg-N/L

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[17] Ammonium is produced during decomposition of organic matter; hydrogen sulfide is produced by bacteria that use sulfate (SO_4^{2-}) instead of oxygen, creating sulfide (S^{2-}) that reacts with hydrogen ions to form hydrogen sulfide (H_2S). See hydrogen sulfide discussion on page 7.

at 20 meters). Both sites are usually destratified by November, which causes the ammonium concentrations to drop through winter and spring (see annual patterns in Figures B96 & B97, pages 201 & 202).

Sites 3–4 often have slightly elevated ammonium concentrations in the metalimnion at 20 m, or near the bottom at 80–90 m (Figures B99–B100, pages 204–205). This is caused by bacterial decomposition of organic matter, but the concentrations never approach the levels found in the hypolimnion at Sites 1–2.

Phosphorus: Although the Lake Whatcom microbiota require nitrogen, phosphorus is usually what limits microbial growth (Bittner, 1993; Liang, 1994; Matthews, et al., 2002a; McDonald, 1994). The total phosphorus concentration in the water column is a complex mixture of soluble and insoluble phosphorus compounds, only some of which can be used by algae to sustain growth. Soluble forms of phosphorus (e.g., orthophosphate) are easily taken up by algae and other microbiota, and, as a result, are rarely found in high concentrations in the water column. Insoluble phosphorus can be present in the water column bound to the surface of tiny particles or as suspended organic matter (e.g., live or dead algae). Some microbiota produce enzymes that release phosphorus from the surface of suspended soil particles. Liang (1994) and Groce (2011) demonstrated that $\geq$50% of the total phosphorus associated with soils in the Lake Whatcom watershed was potentially "bioavailable" through enzyme action. Algal growth tests revealed that 37–92% (median=78%) of the total phosphorus in storm runoff from Anderson, Austin, and Smith Creeks was bioavailable (Deacon, 2015).

Prior to 2000, the median epilimnetic phosphorus concentrations in Lake Whatcom were <5 μg-P/L at Sites 2–4 and approximately 5–8 μg-P/L at Site 1 (Figure 2.21, page 48). Since 2000, the median epilimnetic phosphorus concentrations have often been in the detectable range ($\geq$5 μg-P/L), but the pattern is quite erratic, reflecting the complicated nature of phosphorus movement in the water column (Figure 2.21, page 48).

Total phosphorus and soluble phosphate concentrations were usually low except in the hypolimnion at Sites 1–2 just prior to destratification (Figures B111–B115, pages 216–220 and B116–B120, pages 221–225). When hypolimnetic oxygen concentrations are low, sediment-bound phosphorus becomes soluble and leaches into the overlying water. Although median summer phosphorus at the bottom of the hypolimnion has been relatively stable at all sites (with the exception of increases over time in Site 2: Figure 2.22, page 49), it is worth noting that phosphorus concentrations at the bottom of the hypolimnion are substantially higher than in the epilimnion (note difference in scale between Figure 2.21 & 2.22).

Prior to destratification, hypolimnetic phosphorus may be taken up by microbiota in the hypolimnion or metalimnion (see Section 2.3.2 and Matthews and DeLuna, 2008). When the lake mixes in the fall, the hypolimnetic phosphorus will be distributed throughout the water column. As oxygen concentrations increase during mixing, any soluble phosphorus that has not been taken up by biota will usually be converted back into insoluble phosphorus. Because phosphorus moves back and forth between soluble and insoluble forms and between organic and inorganic compounds, it can be difficult to interpret total phosphorus trends. For example, when algal densities increase, their growth usually results in the reduction of soluble and bioavailable fractions of phosphorus in the epilimnion. This uptake moves the phosphorus into the "live-algae" fraction of organic phosphorus, which should show up in total phosphorus measurements. But algae are not distributed homogeneously in the water column (Matthews and Deluna, 2008), making it difficult to estimate the amount of phosphorus that is incorporated into algal biomass.

2.3.6 Chlorophyll, plankton, and Secchi depth

Site 1 continued to have the highest chlorophyll concentrations of all the sites (Figures B121–B125, pages 226–230). Peak chlorophyll concentrations were usually collected at 0–15 m, while samples from 20 m had relatively low chlorophyll concentrations because light levels are not optimal for algal growth at this depth.

The plankton counts (Figures B137–B146, pages 242–251) were usually dominated by golden algae (Chrysophyta)[18]. Substantial numbers of green algae (Chlorophyta) and bluegreen bacteria (Cyanobacteria) were also measured at all sites during summer and late fall. Previous analyses of algal biomass in Lake Whatcom indicated that although Chrysophyta dominate the numerical plankton counts, Chlorophyta and Cyanobacteria may dominate the plankton biomass, particularly in late summer and early fall (Ashurst, 2003; Matthews, et al., 2002b).

Secchi depths (Figures B126–B130, pages 231–235) showed no clear seasonal pattern because transparency in Lake Whatcom is affected by particulates from

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[18] Several algal taxonomic groups are combined to ease interpretation; details on algal taxonomy can be found in Matthews (2021).

storm events as well as algal blooms.

Indications of eutrophication: Eutrophication is the term used to describe a lake that is becoming more biologically productive. It can apply to an unproductive lake that is becoming slightly more eutrophic, or a productive lake that is becoming extremely eutrophic (see Wetzel, 2001, for more about eutrophication and Matthews, et al., 2005, for a description of the chemical and biological indicators of eutrophication in Lake Whatcom).

Chlorophyll is a direct measure of algal biomass and generally provides a better indication of changes in the lake's biological productivity than phosphorus. Similarly, although algal counts are useful for looking at trends within the same type of algae (e.g., are the numbers of Cyanobacteria increasing?), cell counts are not as good as chlorophyll for estimating algal biomass. The actual relationship between chlorophyll and algae cell counts is complex. The amount of chlorophyll in a cell is influenced by the physiological age and condition of the cell, light intensity, nutrient availability, and many other factors. In addition, while most types of algae are counted by individual cells, a few types must be counted by colonies because the cells are too difficult to see.

The median near-surface summer chlorophyll concentrations have increased significantly at all sites since 1994 (Figure 2.23, page 50). Site 1 has shown the most year-to-year variability, which is reflected by a slightly lower correlation statistic compared to Sites 2–4 (Site 1 Kendall's τ = 0.395; Sites 2–4 Kendalls τ = 0.462, 0.527, 0.477, respectively).[19] Although the annual chlorophyll concentrations are quite variable, the median near-surface summer concentrations seem to have stabilized since 2004, ranging from 3.7–6.7 μg/L at Site 1 and 2.6–4.6 μg/L at Sites 2–4 (Figures B121–B125, pages 226–230).

Under certain conditions and in certain lakes, a thin layer of algae can form deep in the water column (i.e., not at the surface) – this is known as a deep chlorophyll maximum. Deep chlorophyll maxima are thought to be a product of lake depth, stratification, and light, with deeper, relatively clear stratified lakes frequently observing this pattern (Fee, 1976). These deep chlorophyll maxima occur frequently in Lake Whatcom, with the highest values of chlorophyll often observed at 10 or 15 m (Figures B121–B125, pages 226–230). For example, the very high chlorophyll value at Site 1 in July 2010 was at 10 m. These layers can be thin (from a

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[19] See discussion of correlation in footnote on page 6

few centimeters to a few meters) and may not be observed with discrete sampling. Another way to detect them is to examine dissolved oxygen profiles, which will spike near the deep chlorophyll layer because of increased algal photosynthesis (Figures 2.7–2.10, pages 34–37). For further discussion, see page 7.

Except for the dinoflagellates,[20] the algae counts have increased significantly since 1994 (Figure 2.24, page 51). Cyanobacteria, which are often used as bioindicators of eutrophication, have increased at all sites (Figure 2.25, page 52). The Cyanobacteria counts are dominated by *Aphanothece*, *Aphanocapsa*, *Cyanodictyon*, and *Snowella*, genera that are not usually associated with toxic blooms, but some of which have led to filter clogging incidences at the water treatment plant.[21] As with chlorophyll, the algae counts appear to have stabilized since 2004.

2.3.7 Coliform bacteria

This sampling period (2021–2022) follows a change in the surface water standards based on freshwater "designated use" categories, which for Lake Whatcom is "Primary Contact Recreation," described in Chapter 173–201A–200 of the Washington Administrative Code, Water Quality Standards for Surface Waters of the state of Washington. The standard for bacteria prior to (and including) December 31, 2020 was:

> *Fecal coliform organism levels within an averaging period must not exceed a geometric mean value of 100 CFU or MPN per 100 mL, with not more than 10 percent of all samples (or any single sample when less than ten sample points exist) obtained within an averaging period exceeding 200 CFU or MPN per 100 mL.*

The standard for bacteria after December 31, 2020 is:

> E. coli *organism levels within an averaging period must not exceed a geometric mean value of 100 CFU or MPN per 100 mL, with not more than 10 percent of all samples (or any single sample when less*

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[20] Dinoflagellates are small single-cell algae that are common in Lake Whatcom, but rarely have high densities in the plankton counts.

[21] P. Wendling, pers. comm., City of Bellingham Public Works Dept.

> *than ten sample points exist) obtained within the averaging period exceeding 320 CFU or MPN per 100 mL.*

The city, in collaboration with the Washington Department of Ecology, examined whether fecal coliform data can transfer to the new *E. coli* standard.[22] The Dept. of Ecology utilized a linear regression approach with paired sampling data on fecal coliform and *E. coli* in Whatcom Creek and found sufficient agreement between the two measures to apply a translator to *E. coli* data to allow for trend analysis. A similar approach will be utilized for Lake Whatcom, with a transition to *E. coli* as the sole indicator species in January 2023. During this transition phase (i. e. , the reporting year October 2021-September 2022), fecal coliform data will continue to be included in this annual report and the standard in place prior to 2021 will be used.

All of the mid-basin (Sites 1–4) and Intake values for fecal coliforms[23] were less than 10 cfu[24]/100 mL (Tables 2.4– 2.8, pages 21–25, Figures B131–B135, pages 236–240) and passed the freshwater *Primary Contact Recreation* bacteria standard in place prior to 2021.

Coliform samples collected offshore from the Bloedel-Donovan swimming area had slightly higher counts than at Site 1 (mid-basin) (Figure B136, page 241). None of the Bloedel-Donovan counts exceeded 100 cfu/100 mL and the geometric mean was 2.8 cfu/100 mL, so this site passed both parts of the freshwater *Primary Contact Recreation* bacteria standard in place prior to 2022.

2.3.8 Total organic carbon and disinfection by-products

Total organic carbon concentrations, along with plankton and chlorophyll data, are used to help assess the likelihood of developing potentially harmful disinfection by-products through the reaction of chlorine with organic compounds during the drinking water treatment process. Algae excrete dissolved organic carbon into water, which can react with chlorine to form disinfection by-products, predominately chloroform and other trihalomethanes (THMs). When algal densities (or total organic carbon concentrations) increase, we expect to see an increase in THMs. To minimize risk, limits are set on the levels of disinfection by-products

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[22] P. Wendling, pers. comm., City of Bellingham Public Works Dept.

[23] Fecal coliforms are currently called “thermotolerant” coliforms (APHA, 2017).

[24] Colony forming unit/100 mL; cfu/100 mL is sometimes labeled “colonies/100 mL.”

allowed in treated drinking water through the Safe Drinking Water Act's Disinfection Byproduct Rule. This Rule was adopted in 1979 and has undergone two major revisions (Phase I in 1998; Phase II in 2005). The sampling requirement doubled under Phase II; currently the City samples eight locations in the water distribution system.[25]

The 2021/2022 total organic carbon concentrations ranged from 1.8–2.5 mg/L (AmTest) and 1.8–2.4 mg/L (IWS; Table 2.10, page 27). The samples were split and analyzed by AmTest and the IWS laboratory to compare results. The median difference between AmTest and IWS concentrations was ±0.19 mg/L. Larger differences could have been caused by small particulates that were unevenly distributed in the split samples or differences in the analytical methodologies.

The 2021/2022 THMs and HAAs remained below the maximum contaminant levels of 0.080 mg/L and 0.060 mg/L, respectively, described in Chapter 246–290–310 of Washington Administrative Code, Water Quality Standards for Public Water Supplies. The THMs concentrations (1991–2022) have showed a significant increase over time, particularly during the spring and summer (Quarters 2–3; Figures 2.26–2.27, pages 53–54), when algal densities are higher. However, in recent years THMs concentrations appear to be declining, likely due to operational changes by the City of Bellingham.[26]

Haloacetic acids (HAAs), another type of disinfection by-product, also increased until 2014, but have declined during the past 5–7 years, resulting in an overall non-significant trend over time (Figure 2.28, page 55). Spring, summer, and fall HAA data followed this trend and were not significantly correlated with year; however, winter HAA concentrations (Quarter 1) are still exhibiting positive increases over time (Figure 2.29, page 56). According to Sung, et al. (2000), HAAs are not as closely linked to algal concentrations and chlorine dose as THMs. In addition, HAAs can be degraded by the microbial biofilm that grows on the surface of water treatment filtration media (Baribeau, et al., 2005). Although microbial biofilm on filtration media can be a major site of HAA degradation (Grigorescu and Hozalski, 2010), bioremediation is thought to be occurring in the City of Bellingham's distribution system by pipe and reservoir biofilm.[27]

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[25] P. Wendling, pers. comm., City of Bellingham Public Works Dept.
[26] P. Wendling, pers. comm., City of Bellingham Public Works Dept.
[27] P. Wendling, pers. comm., City of Bellingham Public Works Dept.

Abbrev.	Parameter	Method	Historic DL[†]	2021/2022 MDL[†]	Sensitivity or Confidence limit
IWS field measurements:					
cond	Conductivity	YSI (2017)	–	–	± 2 μS/cm
do	Dissolved oxygen	YSI (2017)	–	–	± 0.1 mg/L
ph	pH	YSI (2017)	–	–	± 0.1 pH unit
temp	Temperature	YSI (2017)	–	–	± 0.1° C
disch	Discharge	Rantz et al. (1982); SOP-IWS-6	–	–	–
secchi	Secchi depth	Lind (1985)	–	–	± 0.1 m
IWS laboratory analyses:					
alk	Alkalinity	APHA (2017) #2320; SOP-IWS-8	–	–	± 0.4 mg/L
cond	Conductivity	APHA (2017) #2510; SOP-IWS-8	–	–	± 2.1 μS/cm
do	Dissolved oxygen	APHA (2017) #4500-O.C.; SOP-IWS-8	–	–	± 0.1 mg/L
ph	pH-lab	APHA (2017) #4500-H^+; SOP-IWS-8	–	–	± 0.1 pH unit
tss	T. suspended solids	APHA (2017) #2540 D; SOP-IWS-13	2 mg/L	2.9 mg/L	± 2.0 mg/L
turb	Turbidity	APHA (2017) #2130; SOP-IWS-8	–	–	± 0.2 NTU
nh4	Ammonium (auto)	APHA (2017) #4500-NH_3 H; SOP-IWS-19	10 μg-N/L	9.2 μg-N/L	± 10.5 μg-N/L
no3	Nitrite/nitrate (auto)	APHA (2017) #4500-NO_3 I; SOP-IWS-22	20 μg-N/L	27.5 μg-N/L	± 25.7 μg-N/L
tn	T. nitrogen (auto)	APHA (2017) #4500-N C; SOP-IWS-22	100 μg-N/L	83.6 μg-N/L	± 56.9 μg-N/L
srp	Sol. phosphate (auto)	APHA (2017) #4500-P G; SOP-IWS-22	5 μg-P/L	2.2 μg-P/L	± 3.8 μg-P/L
tp	T. phosphorus (auto)	APHA (2017) #4500-P J; SOP-IWS-22	5 μg-P/L	0.8 μg-P/L	± 1.9 μg-P/L
toc[‡]	T. organic carbon	APHA (2017) #5310 B	1.0 mg/L	0.09 mg/L	± 0.11 mg/L
IWS plankton analyses:					
chl	Chlorophyll	APHA (2017) #10200 H; SOP-LW-16	–	–	± 0.1 μg/L
chlo	Chlorophyta	Lind (1985), Schindler trap	–	–	–
cyan	Cyanobacteria	Lind (1985), Schindler trap	–	–	–
chry	Chrysophyta	Lind (1985), Schindler trap	–	–	–
pyrr	Pyrrophyta	Lind (1985), Schindler trap	–	–	–
City coliform analyses:					
fc	Fecal coliform[§]	APHA (2017) #9222 D	1 cfu/100 mL	1 cfu/100 mL	–
Edge Analytical analyses:					
H_2S	Hydrogen sulfide	APHA (2017) #4500-S2 F	–	0.044 mg/L	–
AmTest analyses:					
toc[‡]	T. organic carbon	APHA (2017) #5310 B	1.0 mg/L	0.5 mg/L	–

[†] Historic detection limits (DL) are usually higher than current method detection limits (MDL).

[‡] Total organic carbon analyses are run in duplicate by IWS and AmTest to evaluate analytical equivalence.

[§] Fecal coliforms are now called thermotolerant coliforms (APHA 2017).

Table 2.1: Summary of IWS, AmTest, Edge Analytical, and City of Bellingham analytical methods and parameter abbreviations.

Parameter	Feb	Apr	May	Jun	Jul	Aug	Sep	Oct[†]	Nov[†]	Dec[†]	Locations[‡]
DO - field	●	●	●	●	●	●	●	●	●	●	Sites 1, 2, Intake - every 1 m; Sites 3, 4 - every 1 m to 10 m then every 5 m; Gatehouse
pH - field	●	●	●	●	●	●	●	●	●	●	
Temp - field	●	●	●	●	●	●	●	●	●	●	
Cond - field	●	●	●	●	●	●	●	●	●	●	
Secchi depth	●	●	●	●	●	●	●	●	●	●	Sites 1, 2, 3, 4, Intake
Alkalinity	●	●	●	●	●	●	●	●	●	●	Sites 1, 2 - 0.3, 5, 10, 15, 20 m; Intake - 0.3, 5, 10 m; Site 3 - 0.3, 5, 10, 20, 40, 60, 75 m; Site 4 - 0.3, 5, 10, 20, 40 60, 80, 90 m; Gatehouse
Ammonium	●	●	●	●	●	●	●	●	●	●	
Nitrate/nitrite	●	●	●	●	●	●	●	●	●	●	
T. nitrogen	●	●	●	●	●	●	●	●	●	●	
Sol. phosphate	●	●	●	●	●	●	●	●	●	●	
T. phosphorus	●	●	●	●	●	●	●	●	●	●	
Turbidity	●	●	●	●	●	●	●	●	●	●	
T. organic carbon	●				●						Sites 1, 2, 3, 4, Intake - 0.3 m and bottom only
Chlorophyll	●	●	●	●	●	●	●	●	●	●	Sites 1, 2, 3, 4 - 0.3, 5, 10, 15, 20 m; Intake - 0.3, 5, 10 m
Plankton	●	●	●	●	●	●	●	●	●	●	Sites 1, 2, 3, 4, Intake; 5 m
Bacteria (City)	●	●	●	●	●	●	●	●	●	●	Sites 1, 2, 3, 4, Intake, Bloedel-Donovan; 0.3 m
H_2S - opt								●			Sites 1, 2 - 10, 15, 20 m

[†] Samples will be collected Feb-Dec in 2022 and 2023; field work will end in September 2024 to allow time to complete all analyses unless the monitoring contract is extended past December 2024.

[‡] Samples within each parameter subgroup are collected at all locations listed in this column.

Table 2.2: Lake Whatcom lake monitoring schedule. All field and laboratory methods are summarized in Table 2.1; missing data resulting from the sampling and laboratory issues are summarized in Table 2.3.

Month	Missing Sample Summary	Comments
October 2021	No missing data	
November 2021	Sites 1, 2, Intake: pH missing from 1-4, 6-9, 11-14, and 16-19m	Field pH meter failed; lab pH values read from collected water samples, which are taken at 5-m intervals
December 2021	All nitrate data missing	Unacceptable laboratory variability
February 2022	No missing data	
April 2022	Sites 1, 2, Intake: Chlorophyll missing at all depths	Unacceptable laboratory variability
May 2022	No missing data	
June 2022	Site 4: Alkalinity at surface missing	Sample not collected
July 2022	No missing data	
August 2022	No missing data	
September 2022	Site 3: Nitrate missing from 20, 40, 60, and 75m	Unacceptable laboratory variability

Table 2.3: Summary of missing lake data due to sampling or laboratory issues.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	18.7	20.4	21.0	27.5
Conductivity (μS/cm)	56.3	58.3	59.3	77.4
Dissolved oxygen (mg/L)	0.0	10.2	8.5	12
pH	6.4	7.3	7.3	9.1
Temperature (°C)	6.0	11.1	11.8	23.2
Turbidity (NTU)	0.5	0.8	1.2	6.7
Nitrogen, ammonium (μg-N/L)	<10	<10	24.8	424.8
Nitrogen, nitrate/nitrite (μg-N/L)	<20	182	150.8	300.2
Nitrogen, total (μg-N/L)	188.8	311.5	321.6	698.8
Phosphorus, soluble (μg-P/L)	<5	<5	<5	36.1
Phosphorus, total (μg-P/L)	<5	5.8	8.0	65.9
Chlorophyll (μg/L)	0.0	2.5	3.1	13.9
Secchi depth (m)	3.1	4.5	4.6	5.5
Coliforms, fecal (cfu/100 mL)[‡]	<1	1	1.5	6.0

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 2.4: Summary of Site 1 water quality data, Oct. 2021 – Sept. 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	17.8	19.1	19.6	21.9
Conductivity (μS/cm)	55.5	56.3	56.8	58.2
Dissolved oxygen (mg/L)	8.9	10.3	10.3	11.9
pH	7.3	7.7	7.8	8.4
Temperature (°C)	6.7	11.4	13.9	23.2
Turbidity (NTU)	0.0	0.5	0.7	2.7
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	30.4
Nitrogen, nitrate/nitrite (μg-N/L)	43.3	196.0	170.2	317.3
Nitrogen, total (μg-N/L)	204.1	328.2	307.4	386.9
Phosphorus, soluble (μg-P/L)	<5	<5	<5	<5
Phosphorus, total (μg-P/L)	<5	<5	<5	8.0
Chlorophyll (μg/L)	1.2	2.5	2.8	5.6
Secchi depth (m)	2.0	5.0	5.0	7.5
Coliforms, fecal (cfu/100 mL)[‡]	<1	1.0	1.3	4.0

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 2.5: Summary of Intake water quality data, Oct. 2021– Sept. 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	18.0	19.0	19.7	28.3
Conductivity (μS/cm)	55.4	56.4	57.2	76.7
Dissolved oxygen (mg/L)	0.0	10.2	9.6	11.9
pH	6	7.3	7.4	8.5
Temperature (°C)	6.6	11.0	12.1	23.1
Turbidity (NTU)	0.4	0.6	1.0	5.3
Nitrogen, ammonium (μg-N/L)	<10	<10	20.9	577.4
Nitrogen, nitrate/nitrite (μg-N/L)	26.2	237.6	199.0	329.1
Nitrogen, total (μg-N/L)	<100	356	348.7	938.2
Phosphorus, soluble (μg-P/L)	<5	<5	<5	32.6
Phosphorus, total (μg-P/L)	<5	<5	5.6	71.7
Chlorophyll (μg/L)	0.7	2.6	2.6	5.9
Secchi depth (m)	2.0	5.2	5.1	7.0
Coliforms, fecal (cfu/100 mL)[‡]	<1	1.0	1.1	2.0

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 2.6: Summary of Site 2 water quality data, Oct. 2021– Sept. 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	17.3	18.9	19.1	20.7
Conductivity (μS/cm)	55.7	56.4	56.7	58.5
Dissolved oxygen (mg/L)	6.3	10.0	9.9	11.9
pH	6.6	7.2	7.4	8.4
Temperature (°C)	6.5	7.7	10.3	23
Turbidity (NTU)	0.2	0.4	0.8	5.0
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	35.5
Nitrogen, nitrate/nitrite (μg-N/L)	41.6	314.2	262.2	403.5
Nitrogen, total (μg-N/L)	144.6	379.6	376.5	575.5
Phosphorus, soluble (μg-P/L)	<5	<5	<5	<5
Phosphorus, total (μg-P/L)	<5	<5	<5	10.9
Chlorophyll (μg/L)	0.6	2.6	2.7	6.1
Secchi depth (m)	1.3	6.0	5.3	8.0
Coliforms, fecal (cfu/100 mL)[‡]	<1	1.0	1.1	2.0

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 2.7: Summary of Site 3 water quality data, Oct. 2021– Sept. 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	16.3	18.8	19.0	20.9
Conductivity (μS/cm)	55.7	56.3	56.6	58
Dissolved oxygen (mg/L)	7.8	9.9	9.9	11.9
pH	6.5	7.1	7.2	8.2
Temperature (°C)	6.5	7.2	9.8	22.2
Turbidity (NTU)	0.2	0.4	0.7	5.3
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	29.8
Nitrogen, nitrate/nitrite (μg-N/L)	45.2	328.6	285.9	403.3
Nitrogen, total (μg-N/L)	210.9	406.9	410.9	633.8
Phosphorus, soluble (μg-P/L)	<5	<5	<5	<5
Phosphorus, total (μg-P/L)	<5	<5	<5	35.1
Chlorophyll (μg/L)	0.1	2.1	2.4	6.0
Secchi depth (m)	1.3	5.5	5.3	8.8
Coliforms, fecal (cfu/100 mL)[‡]	<1	1.0	1.0	1.0

[†] Uncensored arithmetic means except coliforms (geometric mean);

[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 2.8: Summary of Site 4 water quality data, Oct. 2021– Sept. 2022.

	H_2S (mg/L)			H_2S (mg/L)	
Year	Site 1	Site 2	Year	Site 1	Site 2
1999[†]	0.03–0.04	0.40	2011	0.12	0.16
2000[†]	0.27	0.53	2012	na	na
2001[†]	0.42	0.76	2013	0.20[§]	0.16
2002[†]	0.09	0.32	2014	0.28	0.66
2003[†]	0.05	0.05	2015	0.51	0.41
2004[†]	0.25	0.25	2016	0.64	0.51
2005[‡]	0.13, 0.12	0.25, 0.42	2017	0.68*	<0.05
2006	0.20	0.42	2018	0.32	0.39
2007	0.40	0.20	2019	0.10	0.22
2008	0.28	0.38	2020	0.29	0.51
2009	0.15	0.47	2021	0.25	0.51
2010	0.38	0.40	2022	0.09	<0.05

[†] H_2S samples analyzed by HACH test kit.
[‡] HACH (first value) vs. Edge Analytical (second value)
[§] Corrected value (1.20 in Matthews, et al., 2015)
*Sample collected at 15 meters; sample from 20 m contained sediment.

Table 2.9: October hypolimnetic hydrogen sulfide concentrations at Sites 1 and 2 (20 m). The H_2S samples have been analyzed by Edge Analytical since 2005; earlier samples were analyzed using a HACH field test kit.

Site	Depth (m)	Date	AmTest TOC (mg/L)	IWS TOC (mg/L)	Date	AmTest TOC (mg/L)	IWS TOC (mg/L)
Site 1	0	Feb 16, 2022	2.2	2.0	Aug 4, 2022	2.4	2.4
	20	Feb 16, 2022	2.2	2.0	Aug 4, 2022	na[†]	2.1
Intake	0	Feb 16, 2022	2.1	1.9	Aug 4, 2022	2.2	2.4
	10	Feb 16, 2022	2.0	1.8	Aug 4, 2022	2.4	2.3
Site 2	0	Feb 16, 2022	2.3	1.9	Aug 4, 2022	2.2	2.4
	20	Feb 16, 2022	2.5	1.9	Aug 4, 2022	2.0	2.1
Site 3	0	Feb 14, 2022	2.2	1.8	Aug 2, 2022	2.3	2.4
	75	Feb 14, 2022	2.0	1.9	Aug 2, 2022	1.8	2.0
Site 4	0	Feb 14, 2022	2.3	1.8	Aug 2, 2022	2.1	2.3
	90	Feb 14, 2022	2.2	1.8	Aug 2, 2022	1.9	2.0

[†] Sample vial broke in transit

Table 2.10: Lake Whatcom 2021/2022 total organic carbon data. February and Aug samples were split and analyzed by AmTest (TOC-AM) and IWS (TOC-IWS). Differences can be expected when concentrations are low and if there are particles present in one sample but not the other.

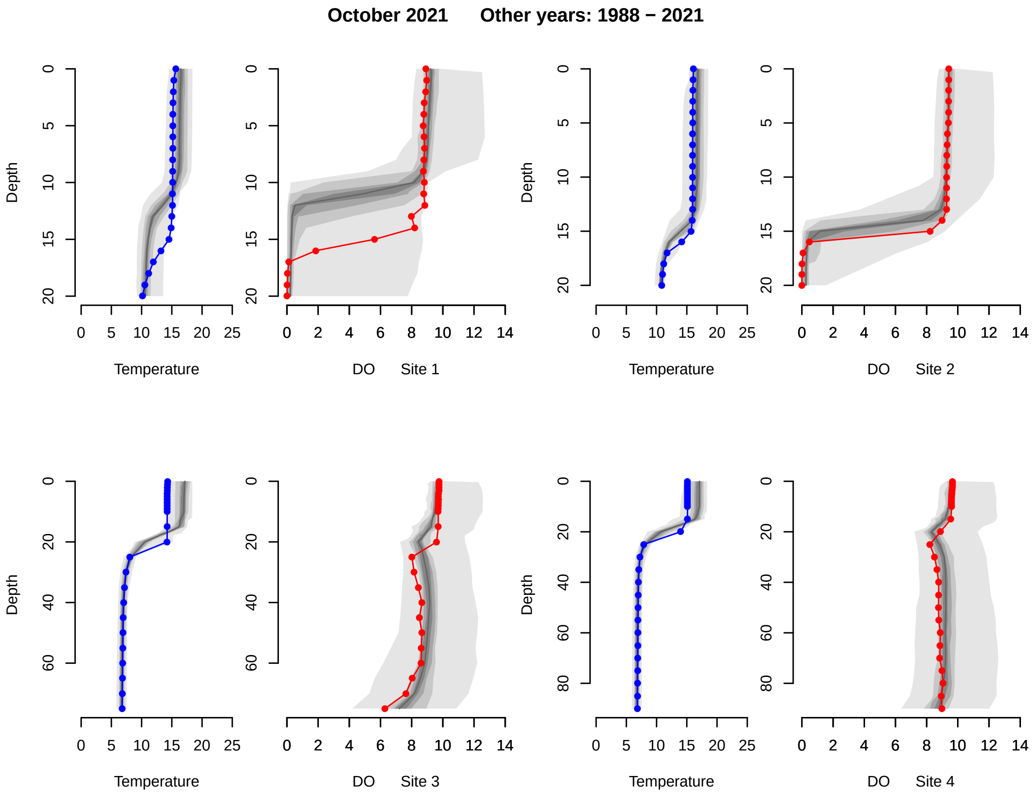


Figure 2.1: October 2021 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2021 data.

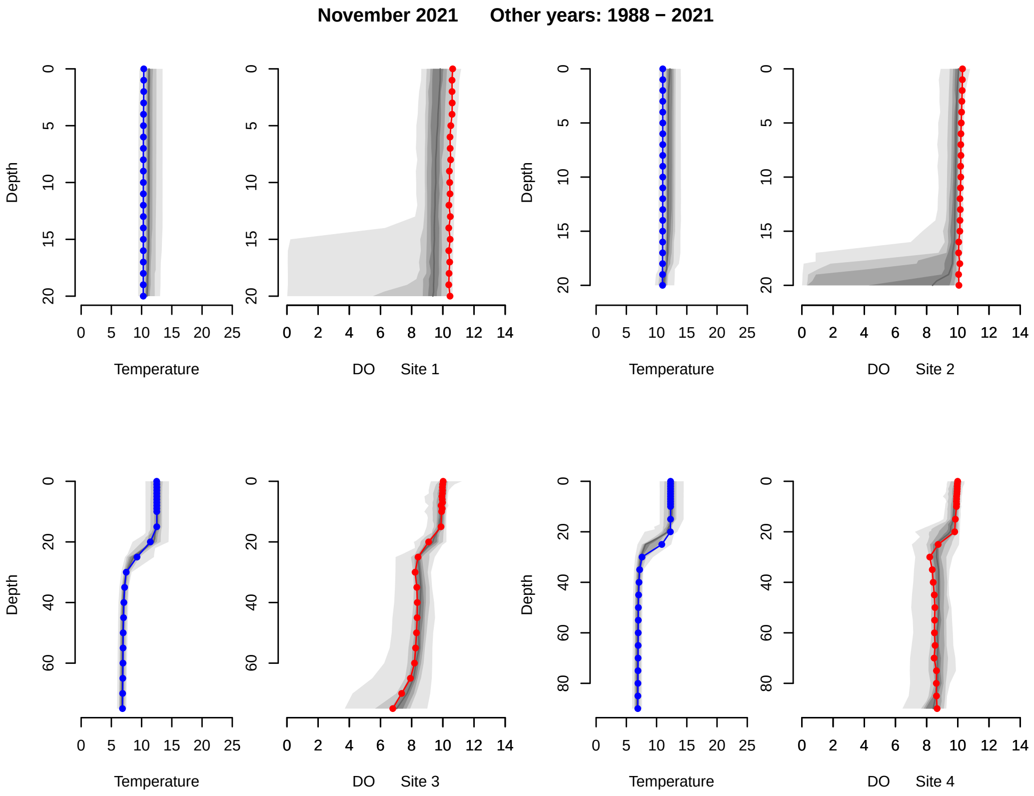


Figure 2.2: November 2021 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2021 data.

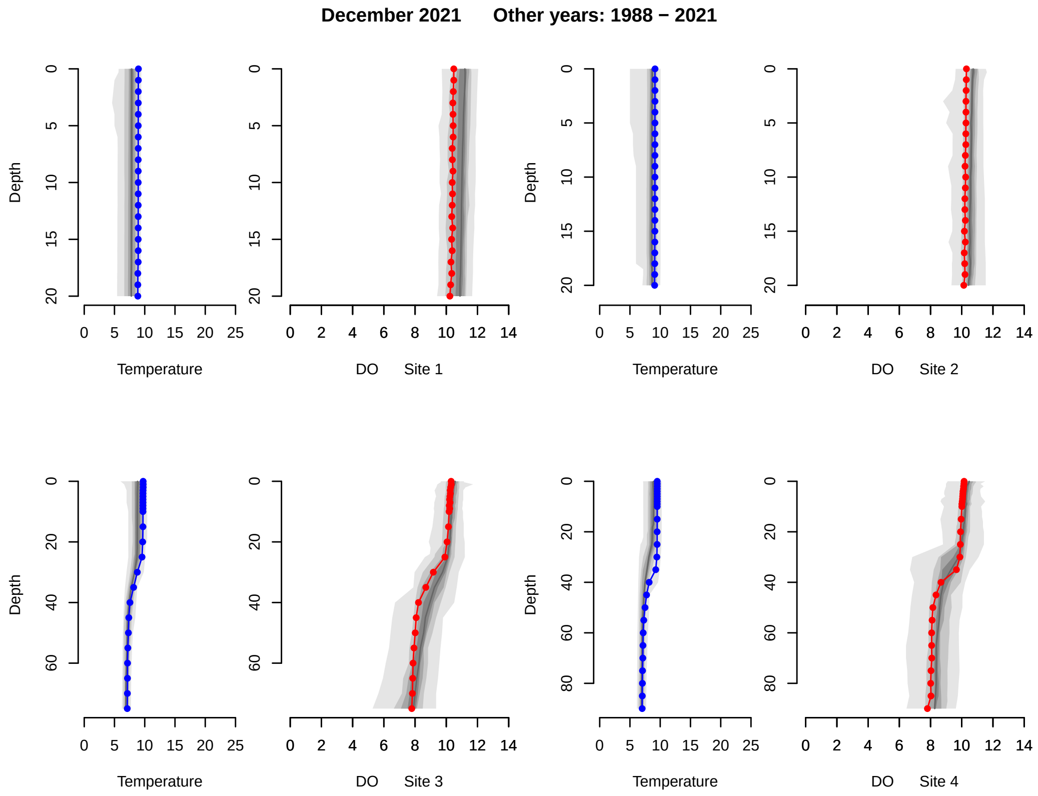


Figure 2.3: December 2021 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2021 data.

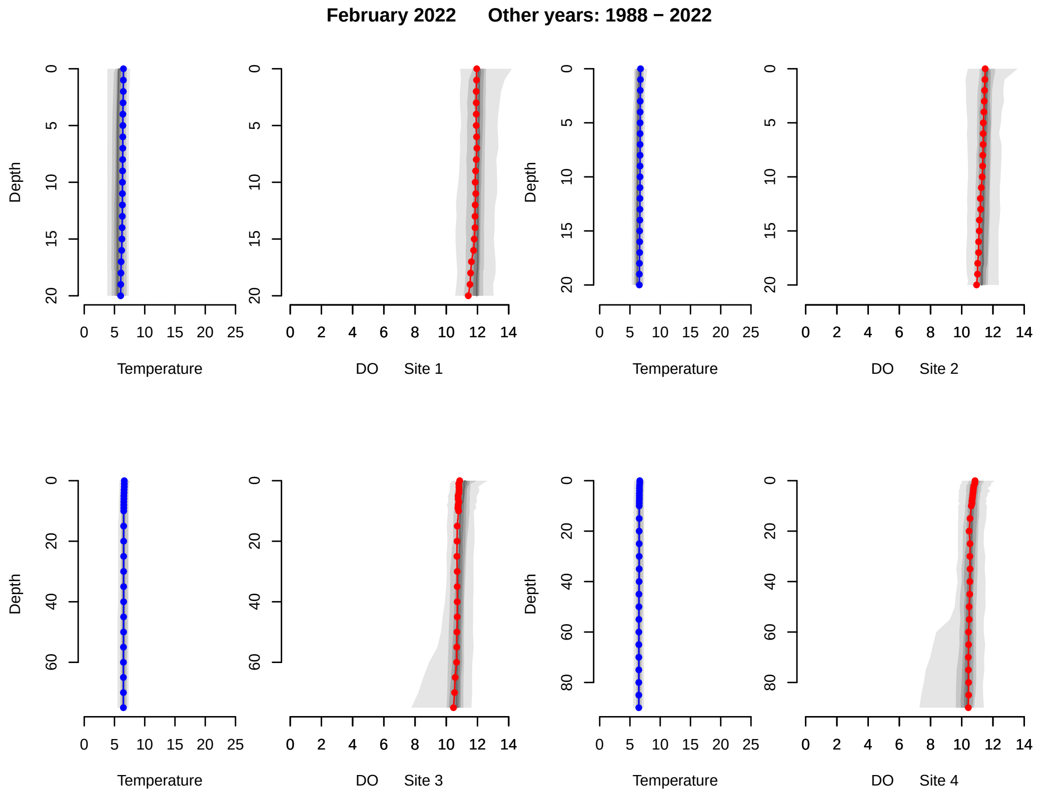


Figure 2.4: February 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

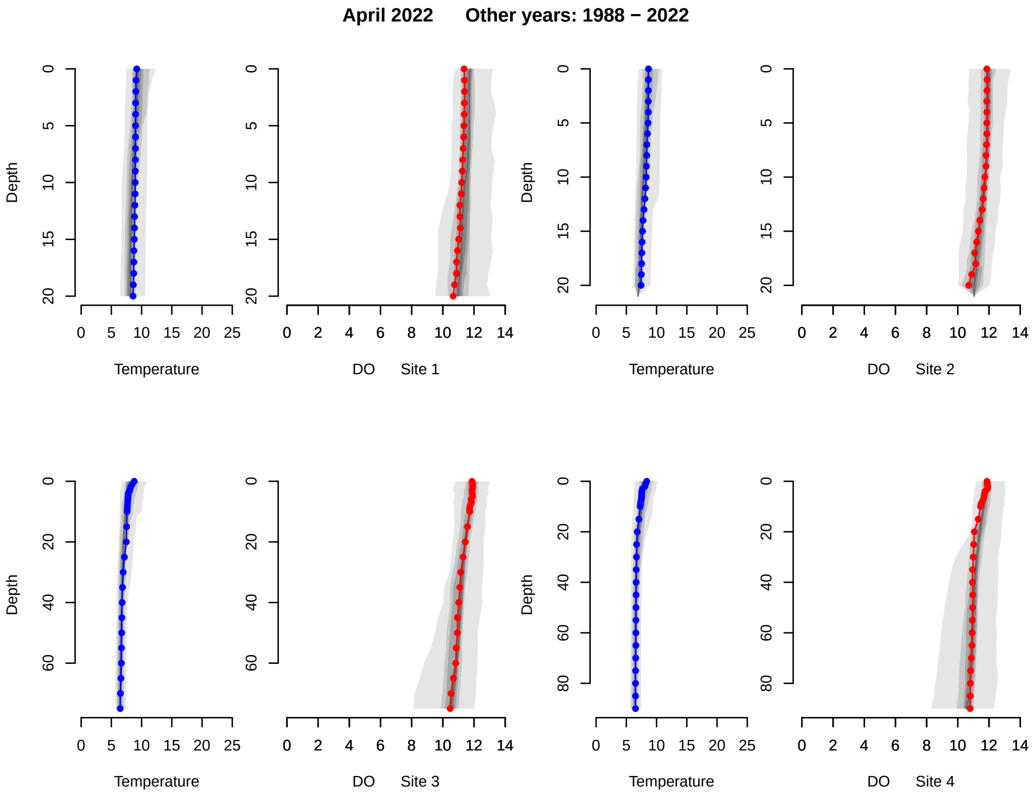


Figure 2.5: April 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

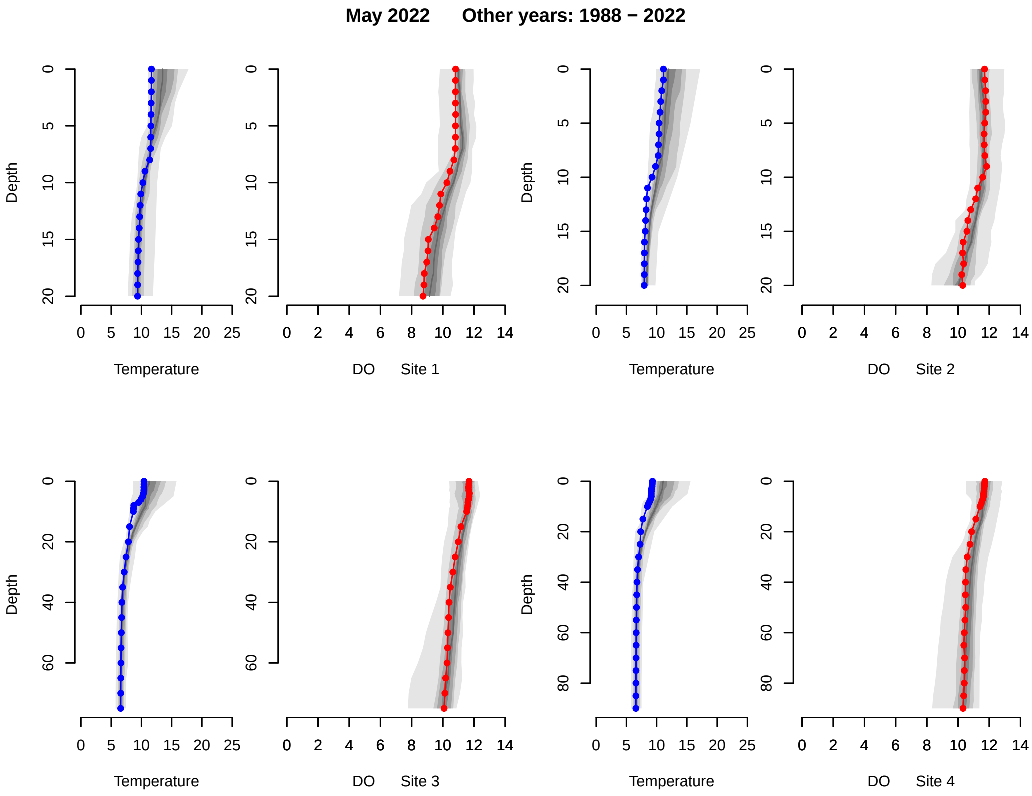


Figure 2.6: May 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

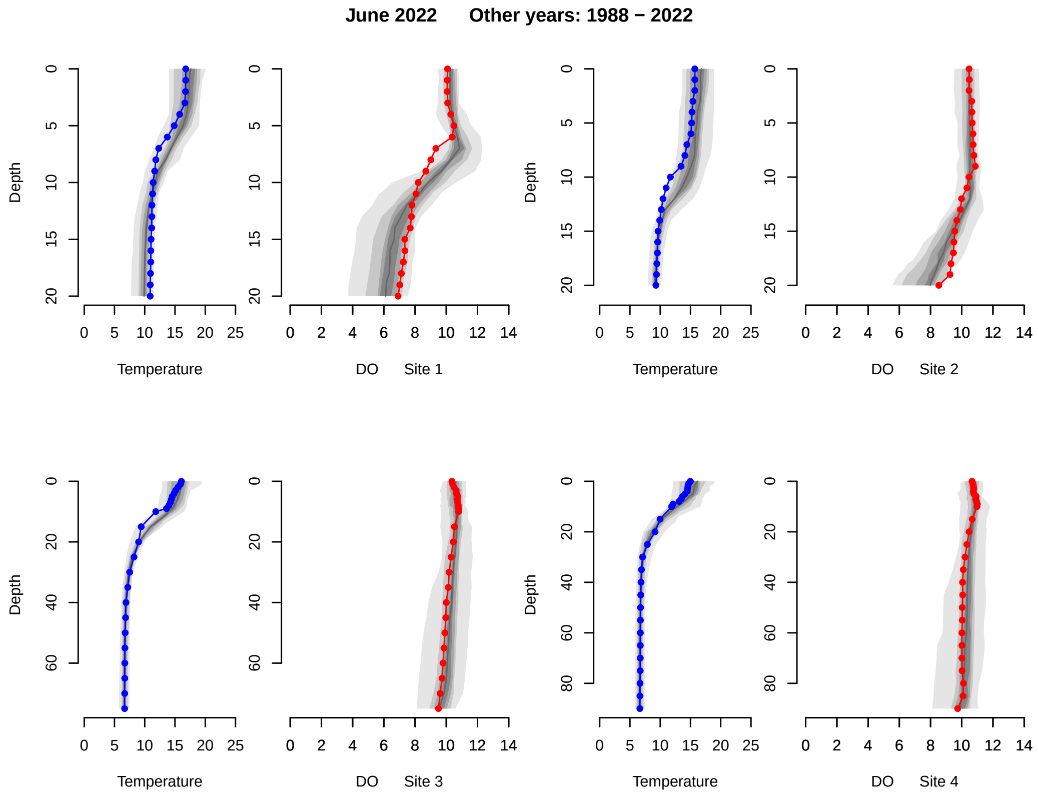


Figure 2.7: June 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

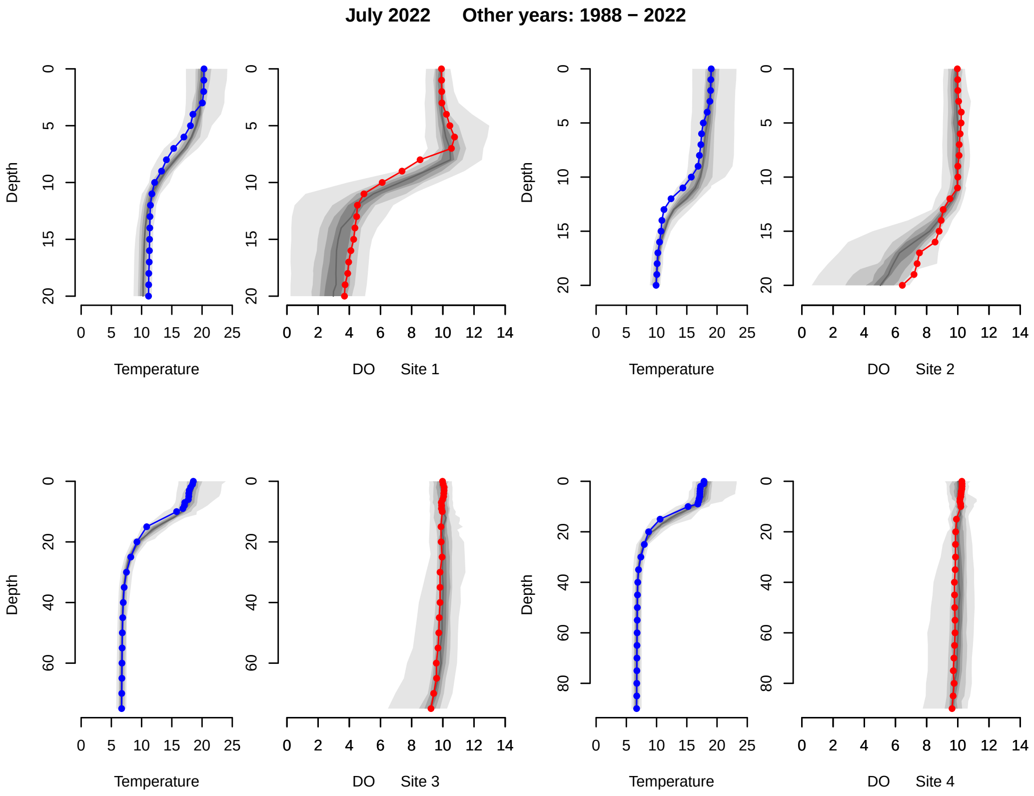


Figure 2.8: July 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

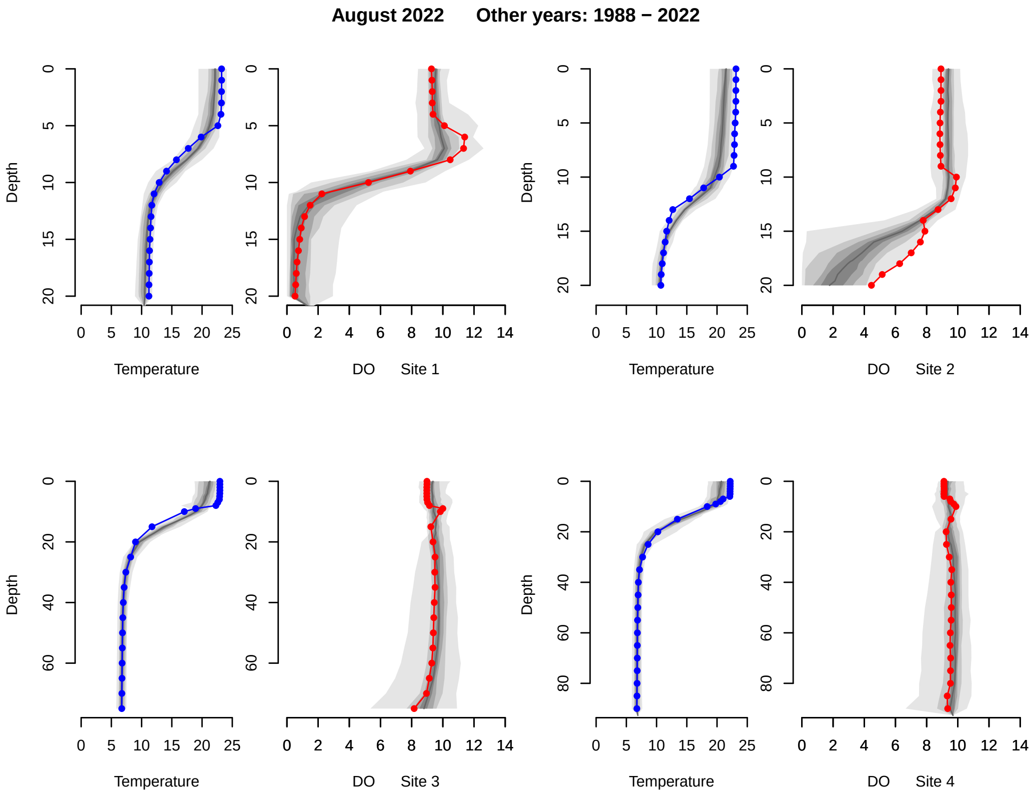


Figure 2.9: August 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

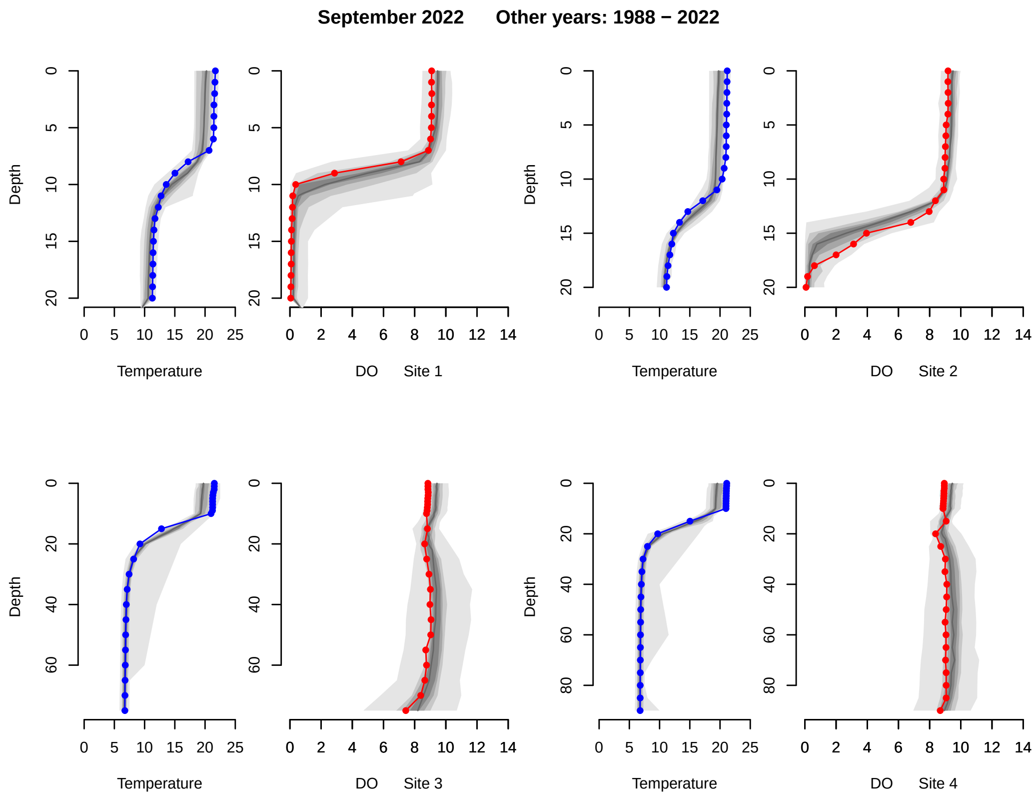


Figure 2.10: September 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data.

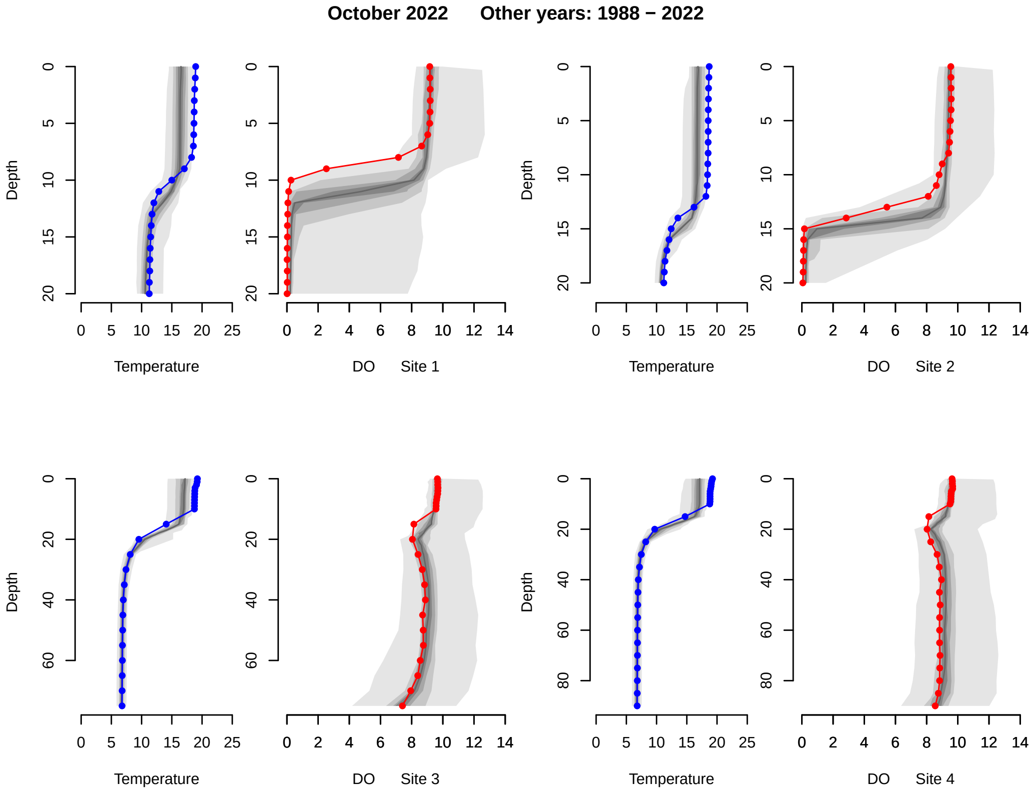


Figure 2.11: October 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data. October 2022 is not part of the 2021/2022 sampling period, but were included to to provide information on the timing of destratification.

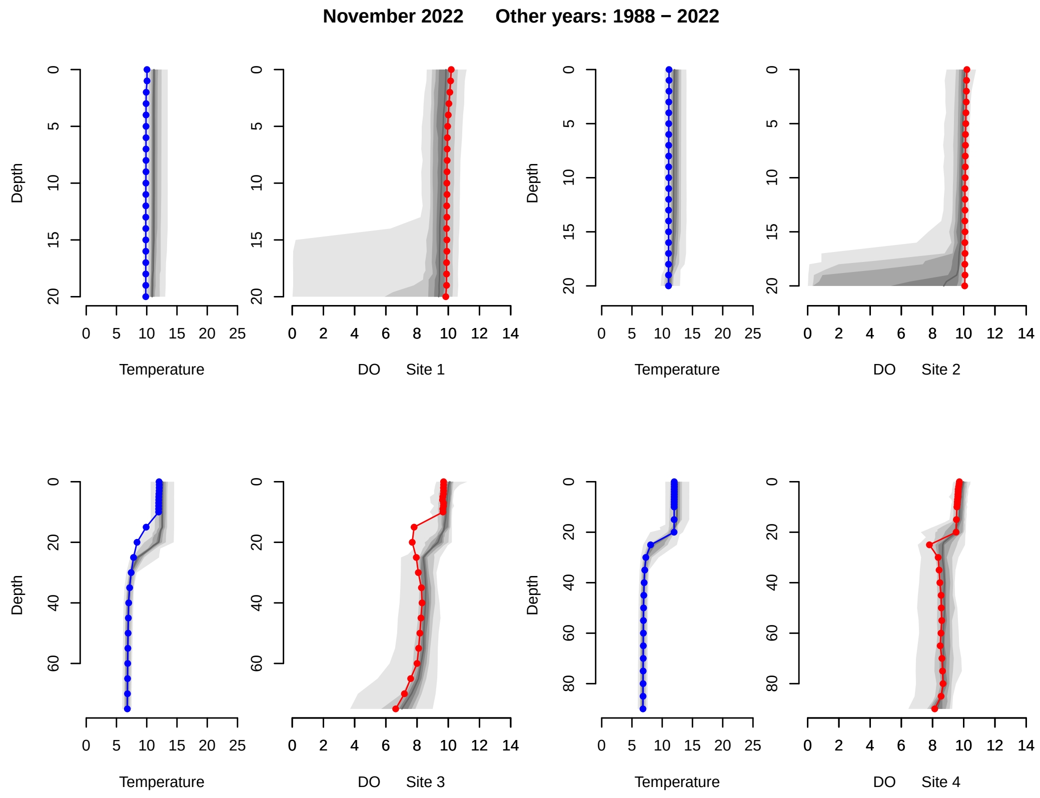


Figure 2.12: November 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data. November 2022 is not part of the 2021/2022 sampling period, but were included to to provide information on the timing of destratification.

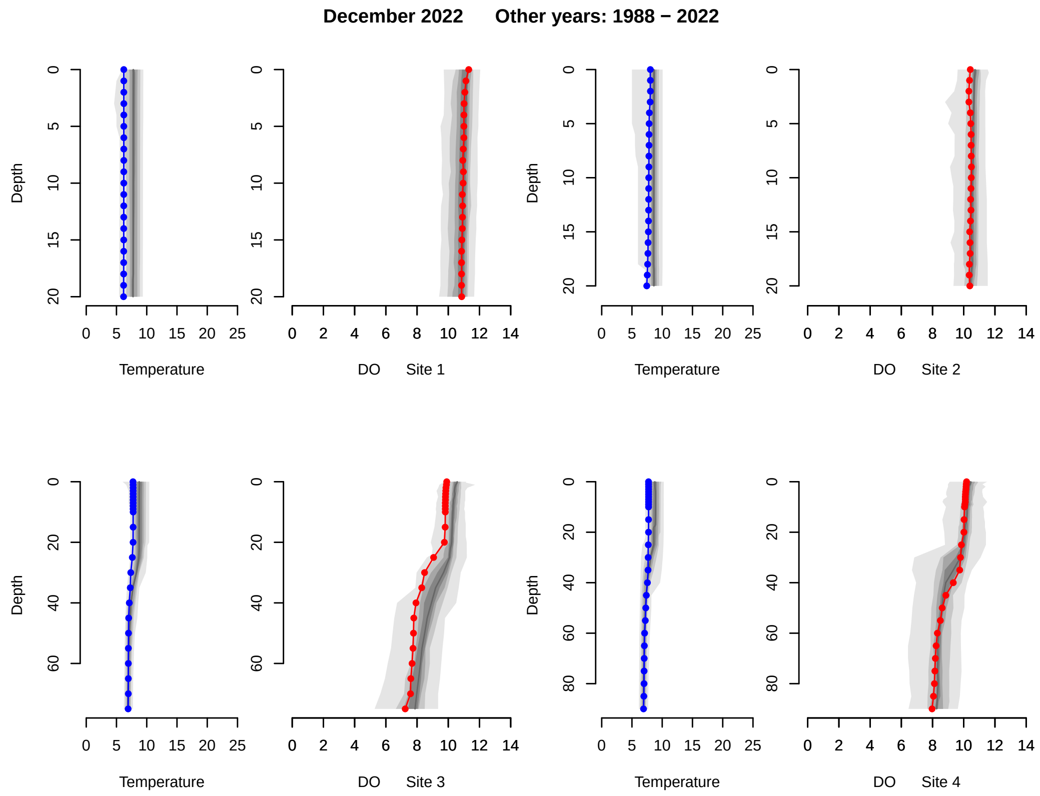


Figure 2.13: December 2022 temperature (-●-) and dissolved oxygen (-●-) profiles compared to historic ranges. The gradation in shading shows the approximate frequency of the 1988–2022 data. December 2022 is not part of the 2021/2022 sampling period, but were included to to provide information on the timing of destratification.

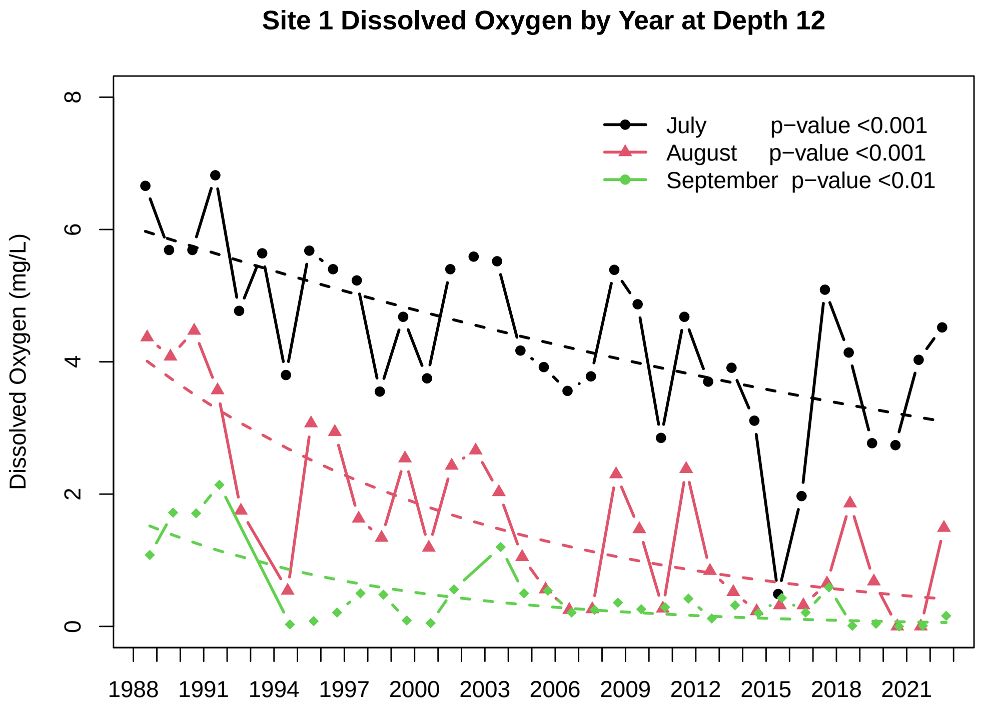


Figure 2.14: Relationship between dissolved oxygen and time at Site 1, 12 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

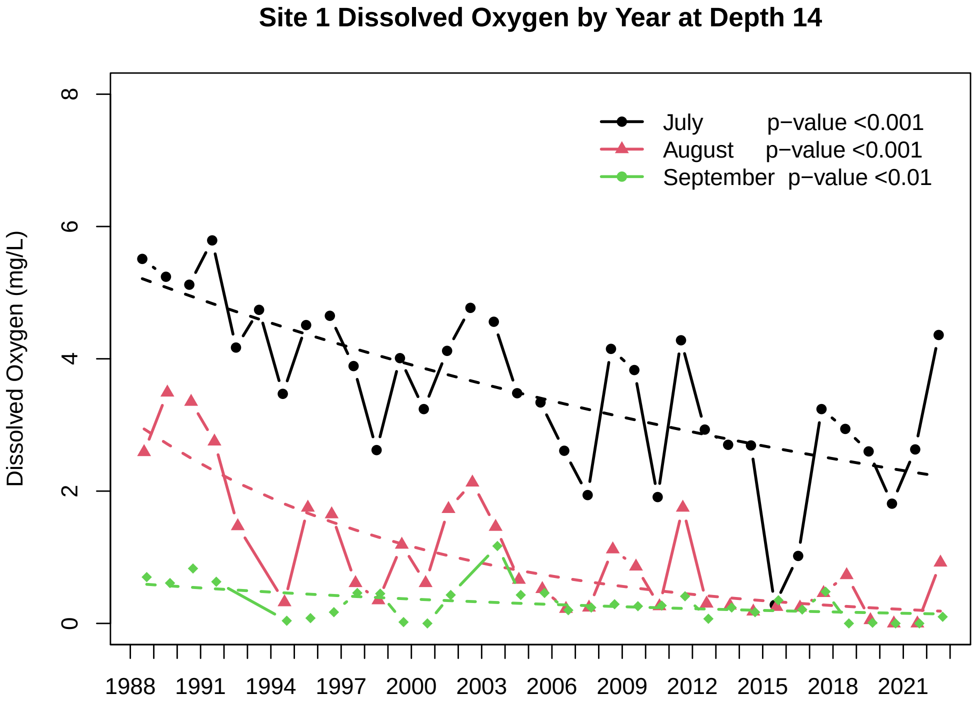


Figure 2.15: Relationship between dissolved oxygen and time at Site 1, 14 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

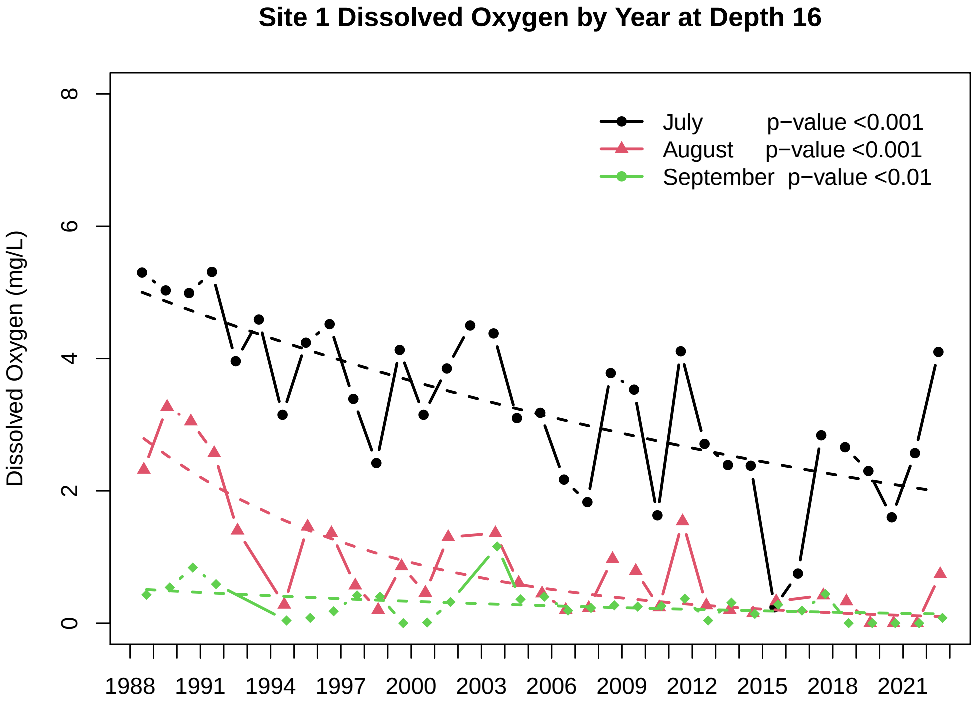


Figure 2.16: Relationship between dissolved oxygen and time at Site 1, 16 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

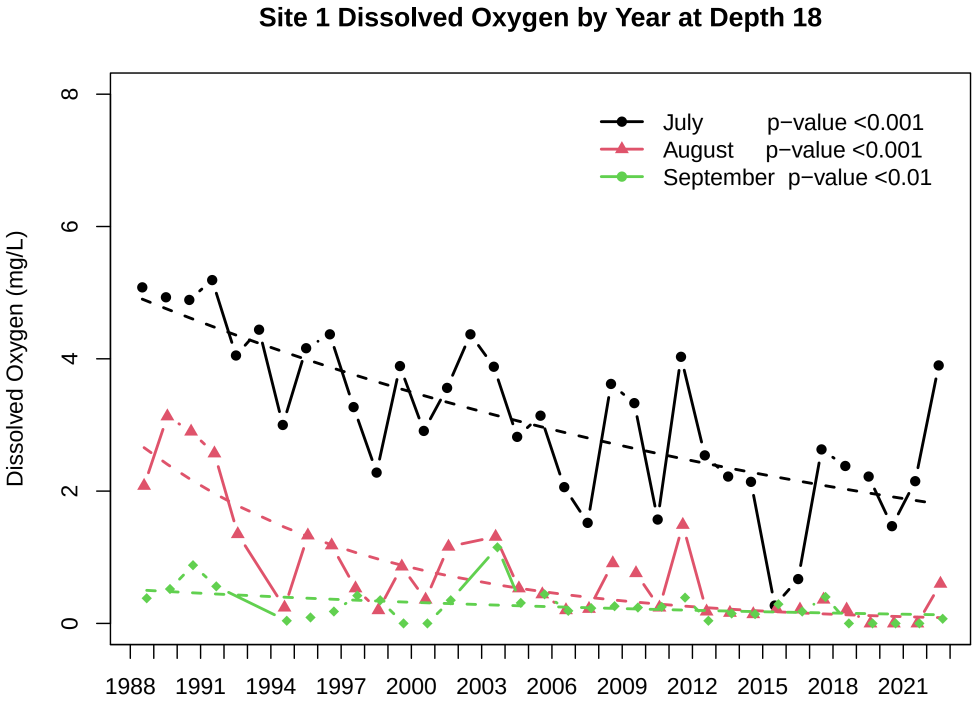


Figure 2.17: Relationship between dissolved oxygen and time at Site 1, 18 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

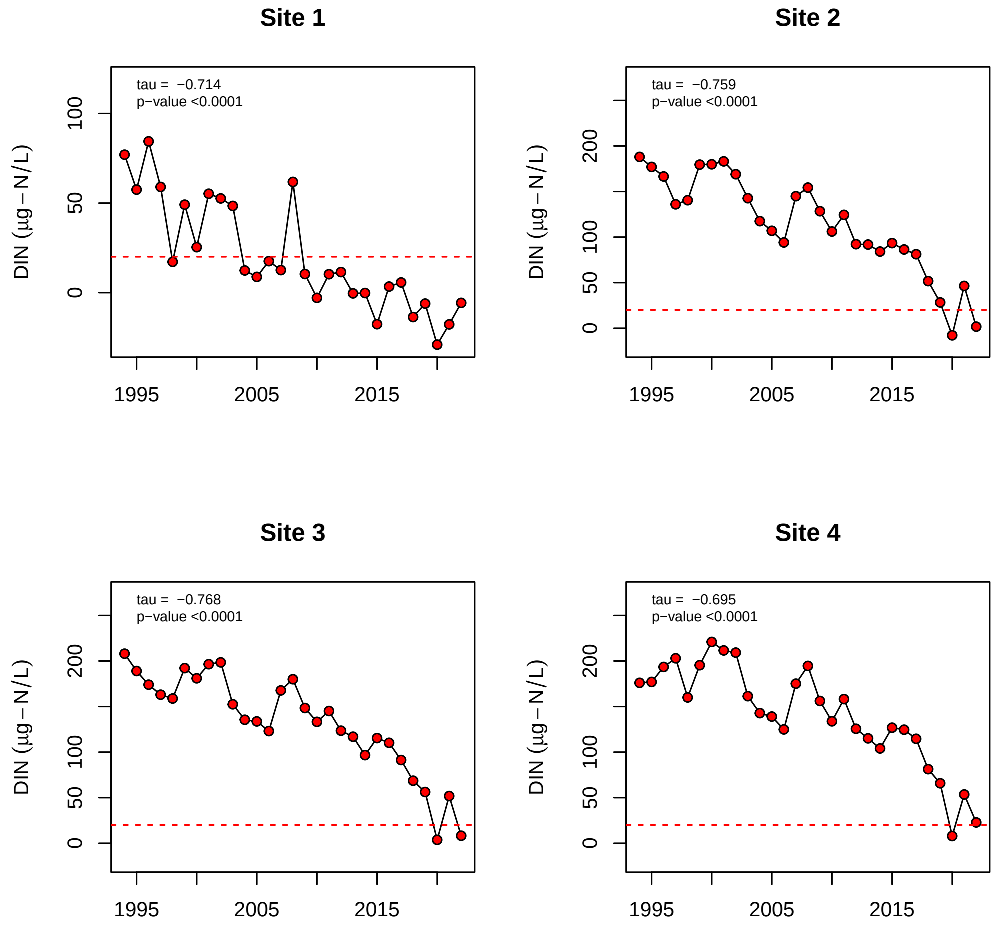


Figure 2.18: Minimum summer, near-surface dissolved inorganic nitrogen (DIN) concentrations (1994–2022 June-Oct, depths $\leq$5 m). Uncensored (raw) data were used to illustrate that minimum values are dropping below analytical detection limits (dashed red line); negative values represent regression results for concentrations below the detection limit. Note differences in y-axis scale between Site 1 and Sites 2–4. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

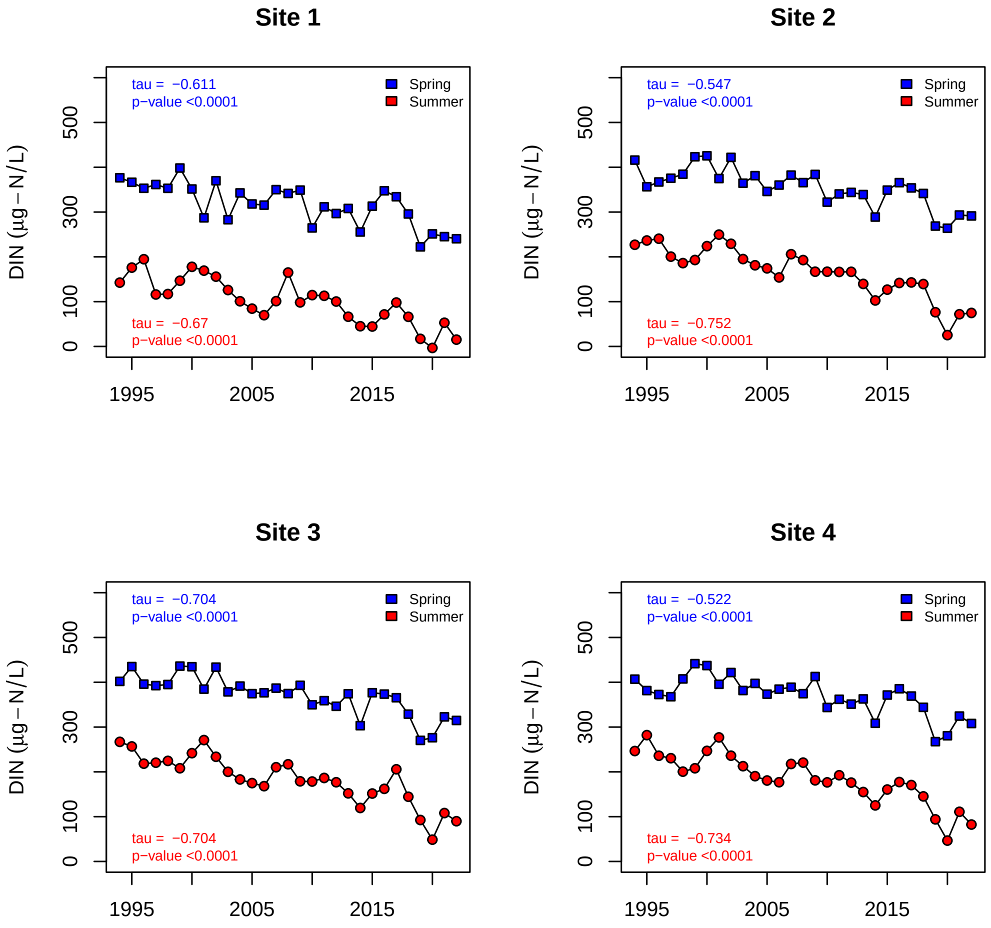


Figure 2.19: Comparison of median spring (Feb-May) vs. summer (June-Oct) near-surface dissolved inorganic nitrogen (DIN) concentrations (1994–2022, depths $\leq$5 m). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

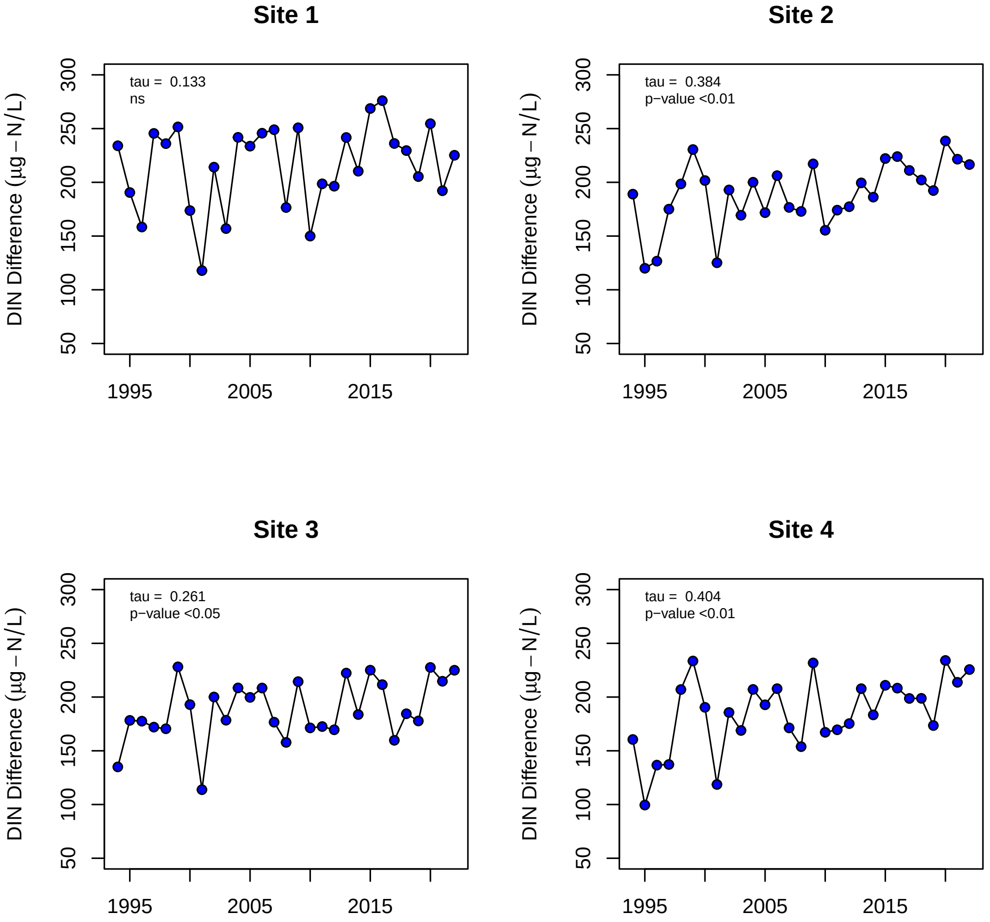
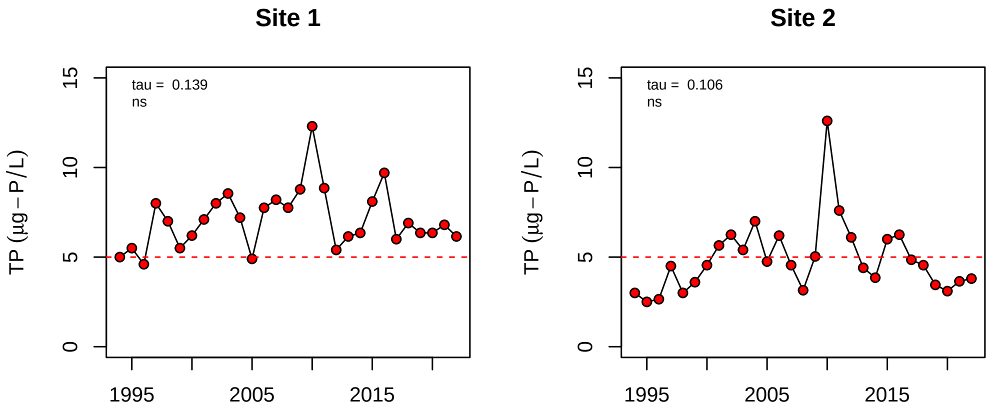


Figure 2.20: Differences between median spring (Feb-May) and summer (June-Oct) near-surface dissolved inorganic nitrogen (DIN) concentrations (1994–2022, depths $\leq$5 m; DIN difference = $\text{DIN}_{\text{spring}}$-$\text{DIN}_{\text{summer}}$). Kendall's τ correlations were used because the data were not monotonic-linear; correlations were marginally significant (p-value <0.05) or not significant (p-value >0.05).



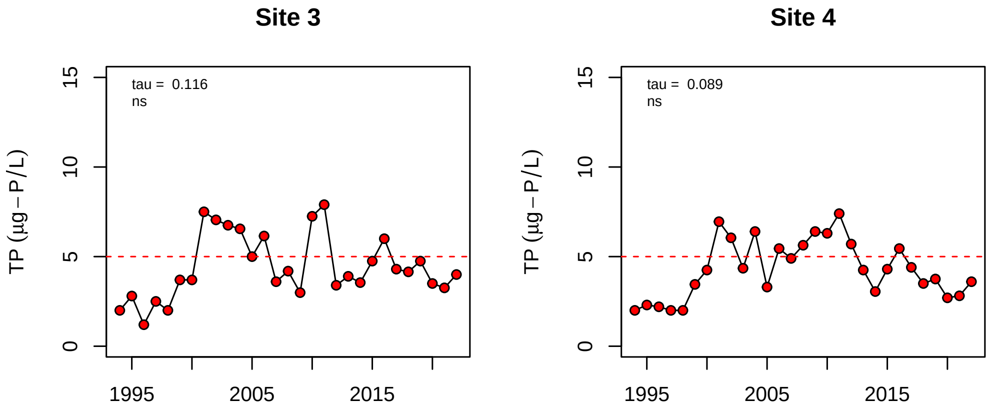


Figure 2.21: Median summer, near-surface total phosphorus concentrations (1994–2022, June-Oct, depths $\leq$5 m). Uncensored (raw) data were used to illustrate when median values are below analytical detection limits (dashed red line). Kendall's τ correlations were used because the data were not monotonic-linear; none of the correlations were significant.

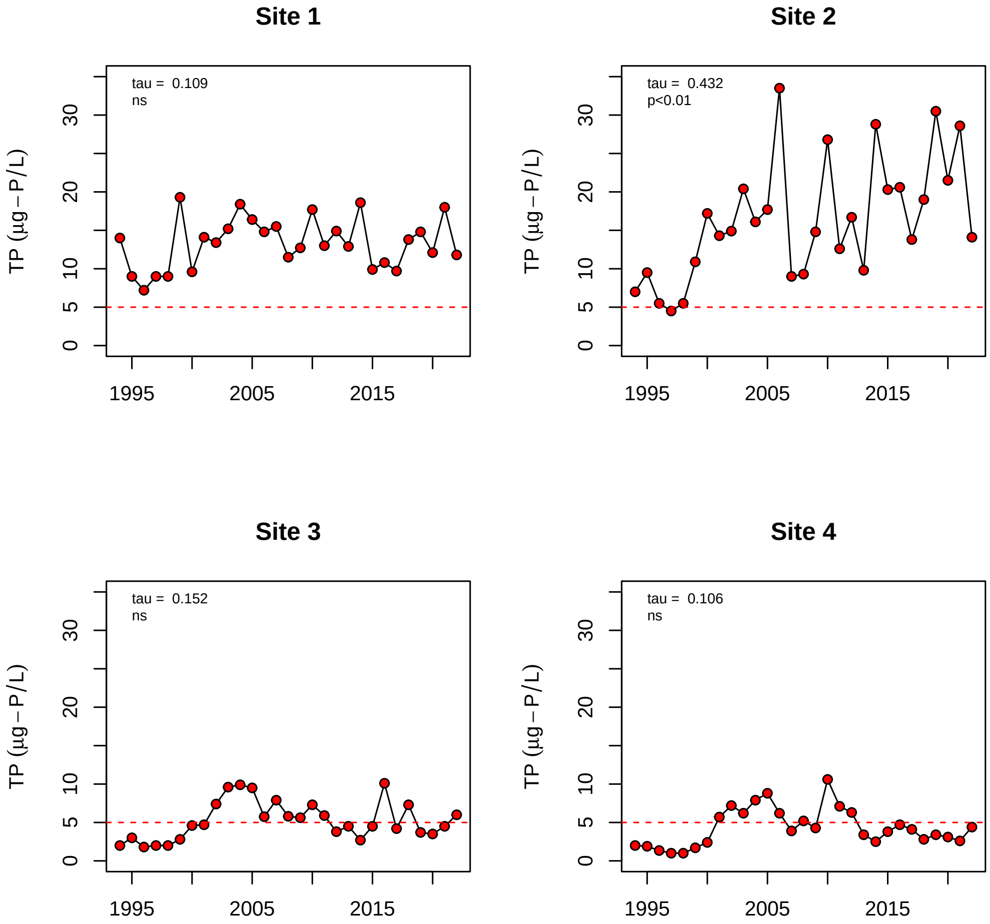


Figure 2.22: Median summer, near-bottom total phosphorus concentrations (1994–2022, June-Oct). Depths are specific to site, where Site 1 and 2 depth ≥20 m, Site 3 depth ≥75 m, and Site 4 depth ≥90 m. Between 1994–1998, 1-3 samples were missing during this June-Oct sampling period at these specific depths. Uncensored (raw) data were used to illustrate when median values are below analytical detection limits (dashed red line). Kendall's τ correlations were used because the data were not monotonic-linear.

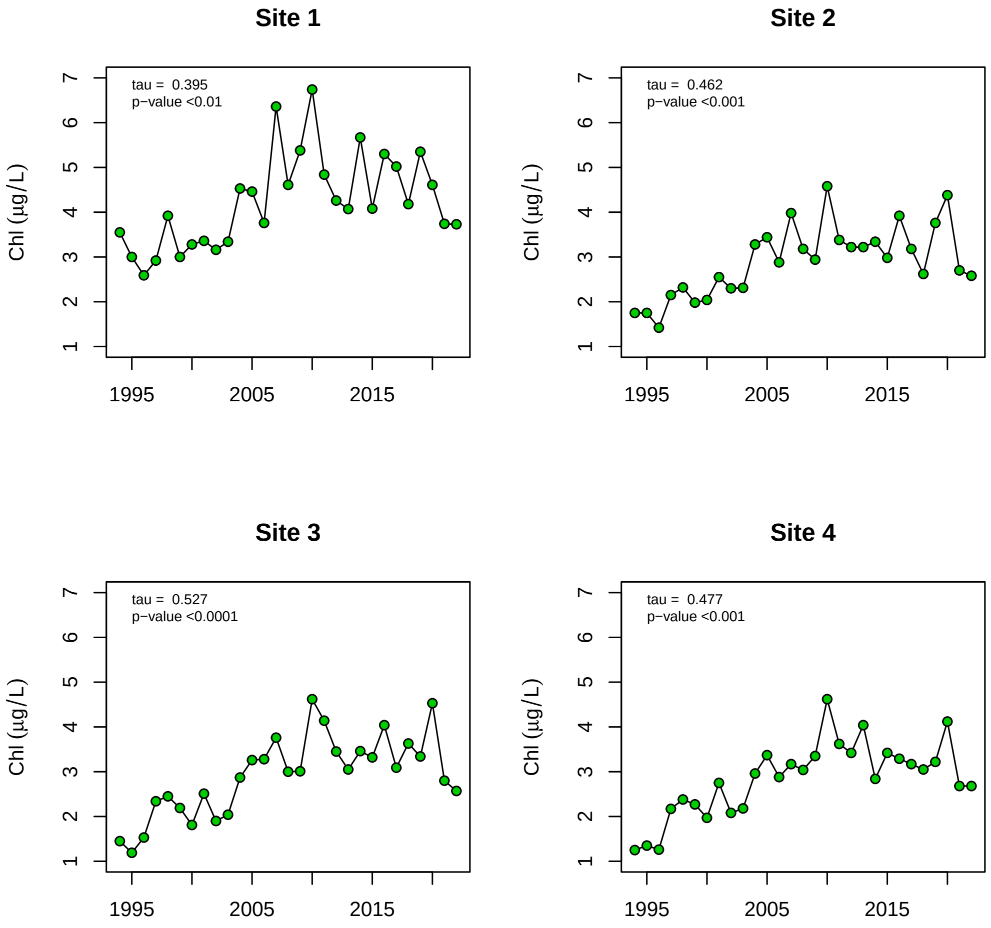


Figure 2.23: Median summer near-surface chlorophyll concentrations (1994–2022, June-October, depths ≤5 m). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

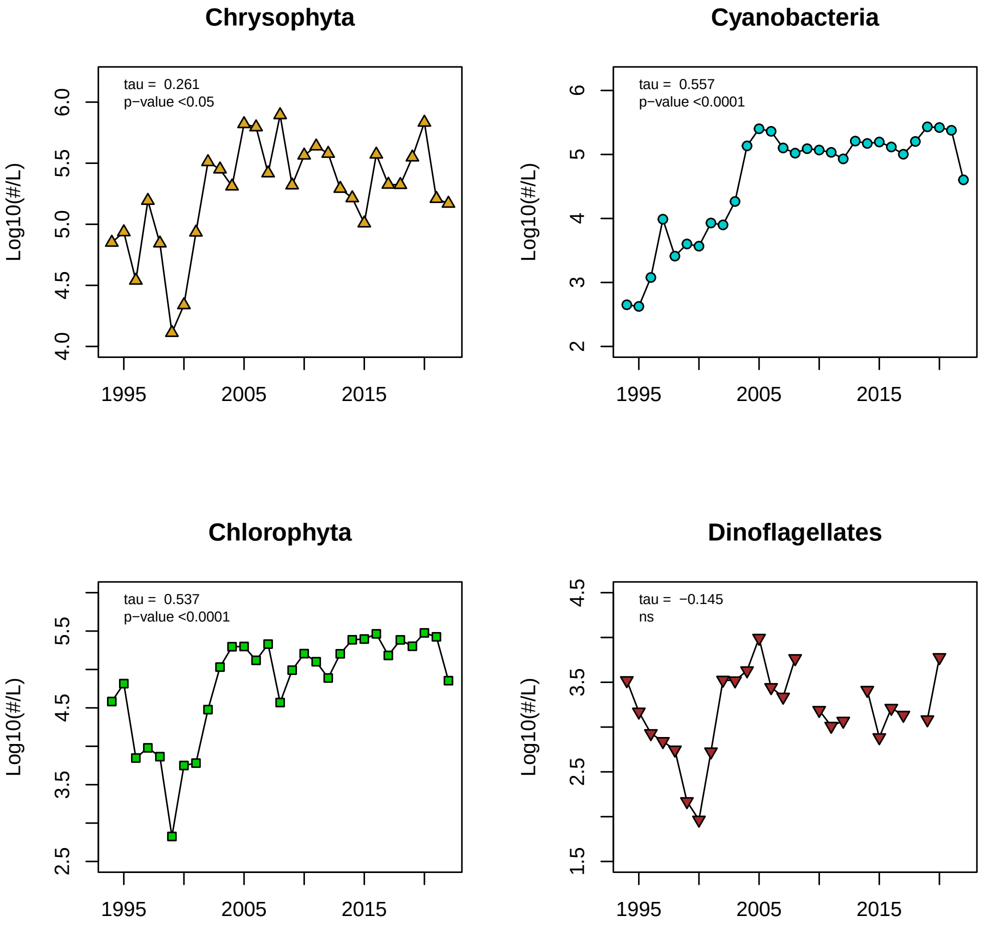


Figure 2.24: Log_{10} plots of median summer, near-surface algae counts (1994-2022, June-October, all sites and depths). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations except Dinoflagellates were significant. Note difference in vertical axis scales.

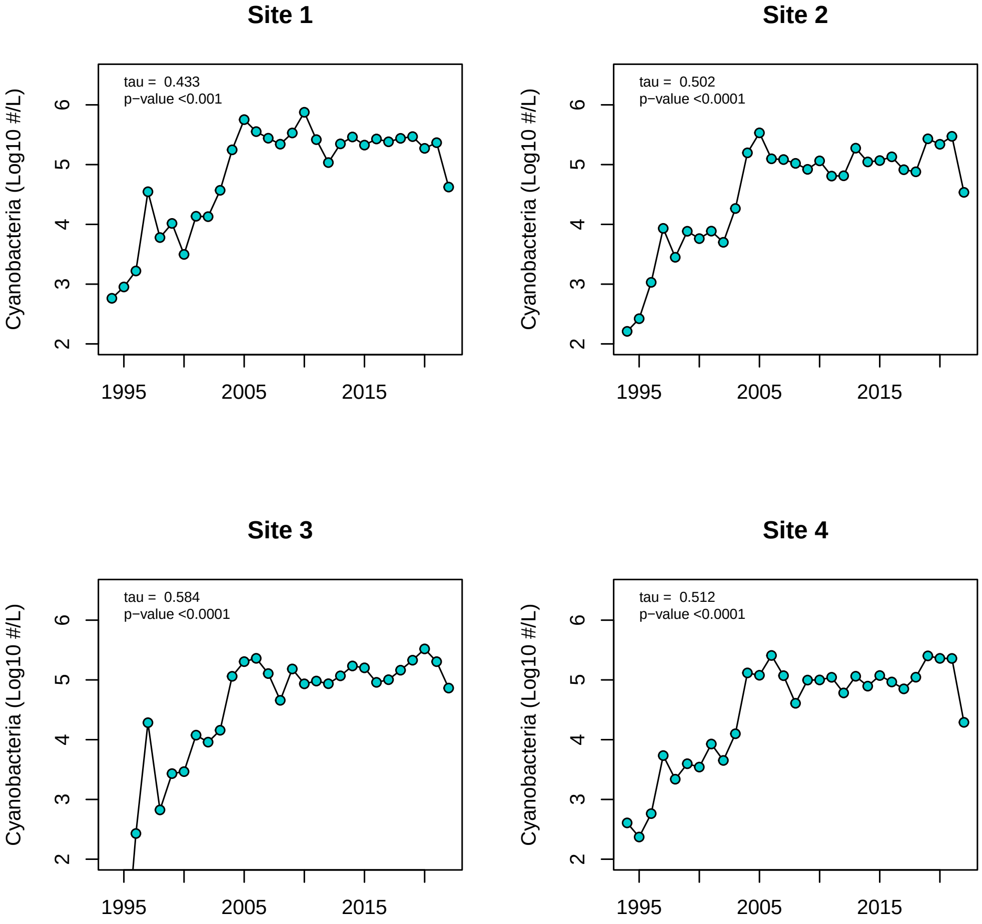


Figure 2.25: Log_{10} plots of median summer, near-surface Cyanobacteria counts (1994–2022, June-October, depths ≤ 5 m). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

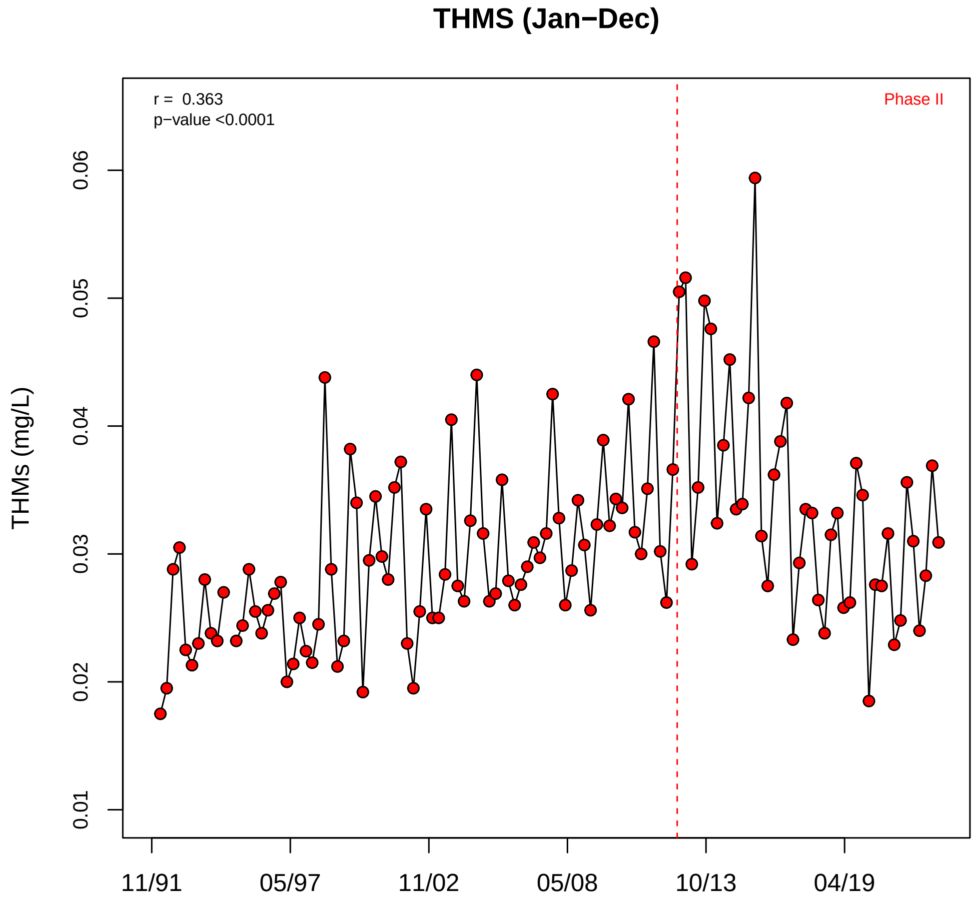


Figure 2.26: Total trihalomethanes (THMs) quarterly average concentrations in the Bellingham water distribution system (data provided by the City of Bellingham Public Works Department). The recommended maximum contaminant level for total THMs is 0.080 mg/l; all samples were below the level. The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlation was used because the data were not monotonic-linear; the correlation was significant.

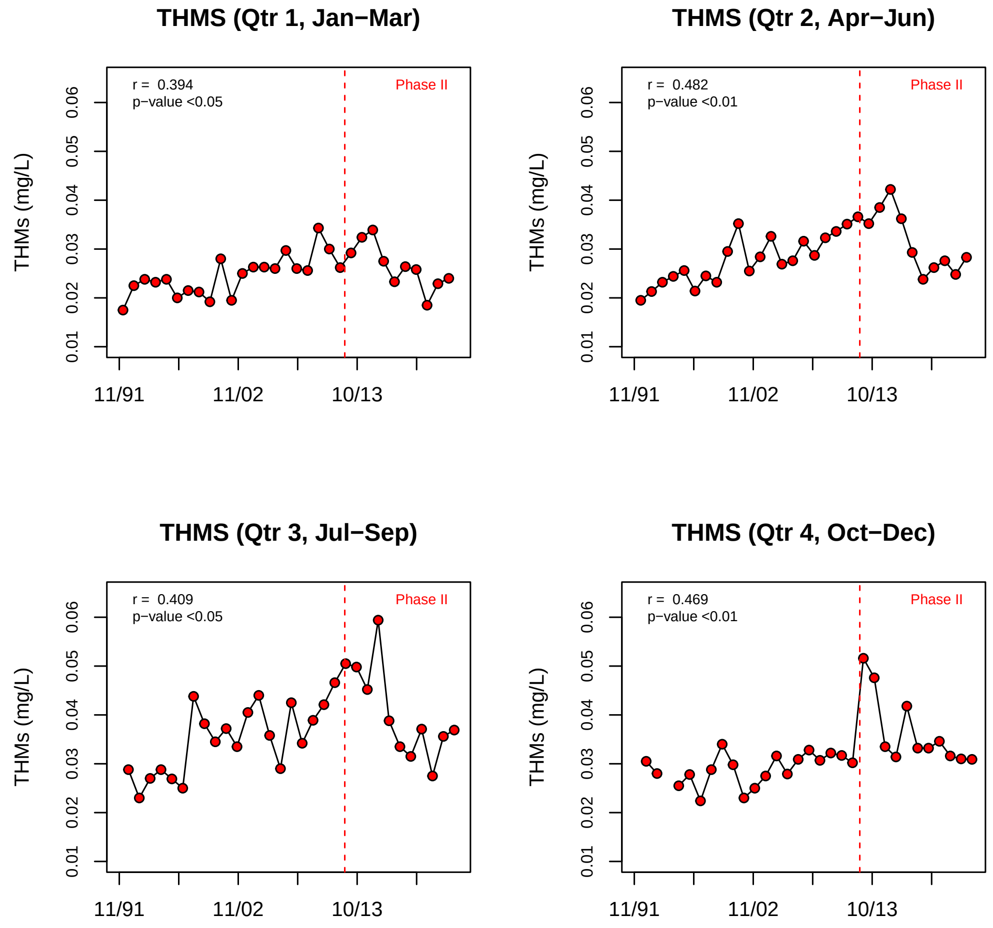


Figure 2.27: Total trihalomethanes (THMs) quarterly average concentrations in the Bellingham water distribution system plotted by quarter (data provided by the City of Bellingham Public Works Department). The recommended maximum contaminant level for total THMs is 0.080 mg/l; all samples were below the level. The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations of total THMs with time were significant.

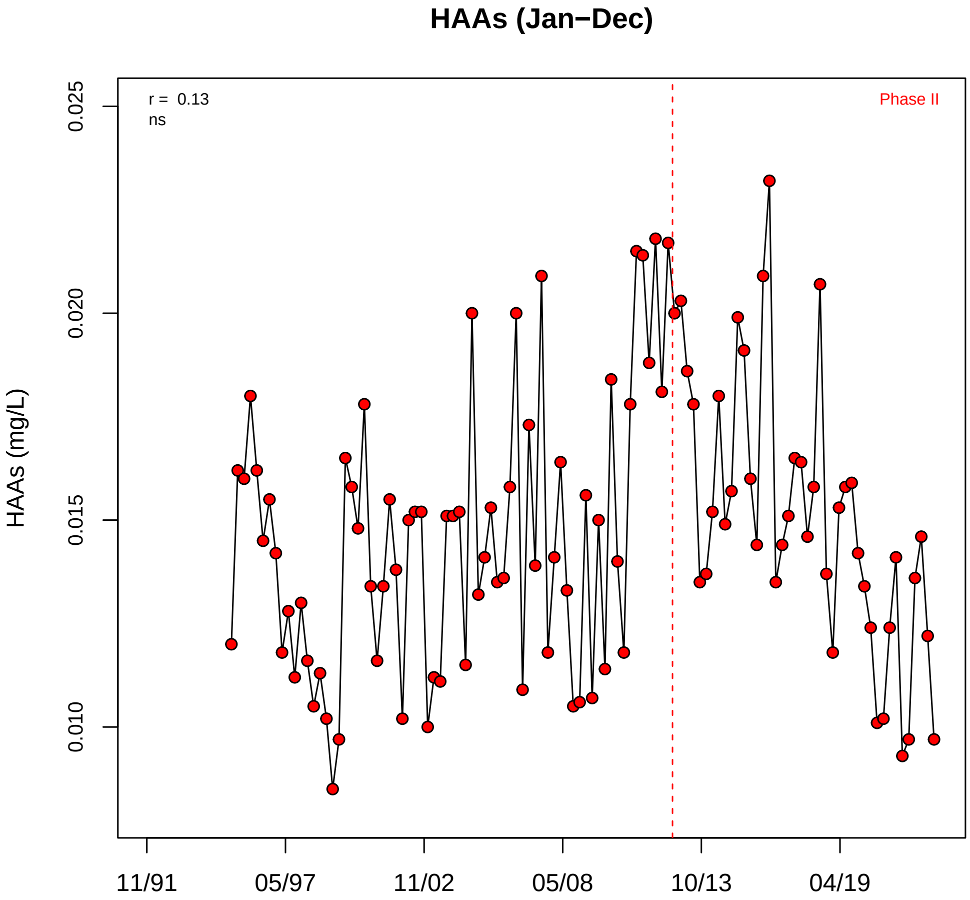


Figure 2.28: Haloacetic acids (HAAs) quarterly average concentrations in the Bellingham water distribution system (data provided by the City of Bellingham Public Works Department). The recommended maximum contaminant level for HAAs is 0.060 mg/l; all samples were below the level. The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlation was used because the data were not monotonic-linear; the correlation was significant.

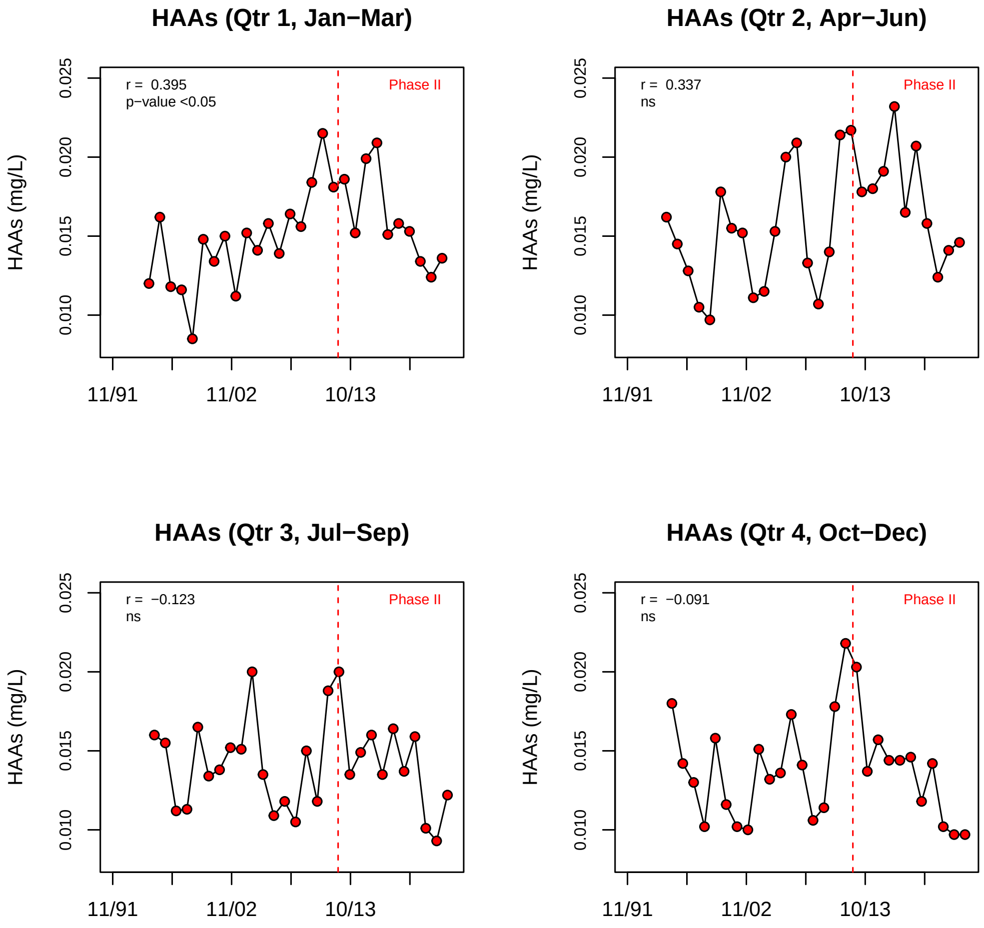


Figure 2.29: Haloacetic acids (HAAs) quarterly average concentrations in the Bellingham water distribution system plotted by quarter (data provided by the City of Bellingham Public Works Department). The recommended maximum contaminant level for HAAs is 0.060 mg/l; all samples were below the level. The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlations were used because the data were not monotonic-linear; the Quarter 1 and Quarter 2 correlations of HAAs with time were significant.

3 Tributary Monitoring

The major objective for the tributary monitoring was to provide baseline water quality data for the tributaries that flow into Lake Whatcom. Whatcom Creek was also sampled to provide baseline data for the lake's outlet. Monthly samples were collected in 2004–2006, 2010–2012, and 2014. The level of effort was reduced in 2007–2009, with samples collected twice each year. Monthly sampling was re-initiated in January 2016 and has continued through 2022.

3.1 Site Descriptions

Samples were collected from Anderson, Austin, Blue Canyon, Brannian, Carpenter, Euclid, Millwheel, Olsen, Silver Beach, Smith, and Whatcom Creeks and the Park Place drain. The sampling locations for these sites are described in Appendix A.2 and shown on Figure A2, page 101.

3.2 Field Sampling and Analytical Methods

The tributaries were sampled on October 11, November 8, and December 13, 2021; and January 12, February 9, March 9, April 19, May 10, June 14, July 12, August 9, and September 13, 2022. All samples were collected during daylight hours, typically between 10:00 am and 3:00 pm. The analytical and sampling procedures are summarized in Tables 2.1 & 3.1 (pages 18 & 62). Table 3.2 (page 63) summarizes missing data from the 2021/2022 sampling season.

A YSI ProODO LDO field meter was used to measure temperature and dissolved oxygen in the field. Raw water and bacteriological samples were stored on ice and in the dark until they reached the laboratory. The bacteria samples were analyzed by the City of Bellingham and total organic carbon analyses were analyzed by AmTest[28] and by IWS.

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[28] AmTest, 13600 Northeast 126th Place, Suite C, Kirkland, WA, 98034–8720.

3.3 Results and Discussion

The tributary data include field measurements (dissolved oxygen and temperature); laboratory analyses for ambient water quality parameters (ammonium,[29] nitrate/nitrite,[30] total nitrogen, soluble phosphate, total phosphorus, alkalinity, conductivity, pH, total suspended solids, and turbidity); bacteria counts; and total organic carbon measurements.

The 2021/2022 tributary data are summarized in Table 3.3 (page 64), with descriptive statistics for each site listed in Tables 3.4–3.15 (pages 65–76). The total organic carbon data are listed in Table 3.16 (page 77). Because of missing samples during the 2021/2022 field season due to insufficient flow in creeks to sample (see Table 3.2, page 63), the summary statistics for these sites are biased toward water quality conditions present during spring, fall, and winter, with less representation of summer conditions.

Historical tributary data from 2004 to the present are plotted in Appendix B.4 (Figures B147–B185, pages 254–292). These figures include a dashed (blue) horizontal line that shows the median value for Smith Creek and a solid (red) horizontal line that shows the median value for each site. Smith Creek was chosen as a reference because it is a major tributary to the lake and has a history of being relatively unpolluted.

In Table 3.3, the "typical ranges" for alkalinity, conductivity, total suspended solids, ammonium, and soluble phosphate were derived from historic water quality data for Lake Whatcom tributaries that flow through predominantly forested portions of the watershed (Anderson, Brannian, Olsen, and Smith Creeks). The temperature, dissolved oxygen, and pH ranges were based on WAC 173-201A, Tables 200 (1)(c), 200(1)(d), and 200 (1)(g) for salmonid spawning, rearing, and migration, with the qualification that the single monthly grab samples from the Lake Whatcom tributaries may not show the lowest 1-day minimum dissolved oxygen or the maximum 7-day temperature. The turbidity range was based on historical watershed data and WAC 173-201A Table 200 (1)(e), which limits anthropogenic contributions to no more than 5 NTU over background. The coliform

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[29] Nearly all ammonia (NH_4^+) is ionized to ammonium (NH_3) in surface water. Earlier IWS reports used "ammonia" and "ammonium" interchangeably; we now use "ammonium" to indicate that the data represent the concentration of ionized ammonia.

[30] Nitrate and nitrite were analyzed together because nitrite concentrations are very low in surface water. For simplicity, nitrate/nitrite will be referred to as "nitrate" in this document.

range was based on the WAC 173-201A Table 200 (2)(b) standard for *Primary Contact Recreation* in place prior to 2021.[31] The total phosphorus range was based on the lake nutrient criteria action value for the Coast Range, Puget Lowlands, and Northern Rockies Ecoregions listed from WAC 173-201A-230, Table 230(1). The lake nutrient criteria require collecting multiple samples from the epilimnion during summer, so the total phosphorus range in Table 3.3 can only be used as a general reference.

Water temperatures and dissolved oxygen concentrations followed typical seasonal cycles, with most sites having colder temperatures and higher oxygen concentrations during the winter, and warmer temperatures and lower oxygen concentrations during the summer (Figures B147–B152). Whatcom Creek had higher temperatures and slightly lower oxygen concentrations than most other sites, reflecting the influence of Lake Whatcom (Figures B147 and B150).

The residential tributaries (Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain) often have slightly elevated temperatures and lower dissolved oxygen concentrations (Figures B149 and B152). But the dry conditions meant that some of the residential sites could not be sampled during late summer when high temperatures and low oxygen concentrations are most common (Table 3.2).

Most of the tributaries in the Lake Whatcom watershed had relatively low concentrations of dissolved solids, indicated by conductivities $\leq$100 μS/cm and alkalinities $\leq$30 mg/L (Table 3.3; Figures B153–B161). Sites that did not match this description included some residential tributaries (Silver Beach Creek and the Park Place drain) and Blue Canyon Creek, which drains an area rich in soluble minerals. Most sites also had low total suspended solids concentrations ($\leq$5 mg/L) and low turbidities ($\leq$5 NTU) except during periods of high precipitation and runoff (Figures B162–B167). The only site that had consistently high solids and turbidity values was Millwheel Creek, which is often turbid due to disturbed sediments in an upstream pond.

The median ammonium concentrations were generally low ($\leq$10 μg-N/L) except in Park Place (Table 3.3; Figures B168–B170). Ammonium does not persist long in oxygenated surface waters. When present in streams, it usually indicates a near-by source such as an upstream wetland with anaerobic soils or a pollution source.

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[31] See Section 2.3.7, page 15 for discussion.

Most of the tributaries had lower total nitrogen and nitrate concentrations than Smith Creek (Figures B171– B176). The relatively high nitrate and total nitrogen concentrations in Smith Creek are probably due to the presence of nitrogen-fixing alders (*Alnus rubra*) in the riparian zone upstream from the sampling site. High nitrate and total nitrogen concentrations are not necessarily an indication of water pollution, and low nitrate concentrations actually favor the growth of nuisance Cyanobacteria. The exceptionally low nitrate concentrations in Whatcom Creek (Figure B171) reflect algal uptake of nitrogen in the lake.

Soluble inorganic phosphate is quickly removed from surface water by biota, so high concentrations of soluble phosphate usually indicate a nearby source such as an anaerobic wetland or a pollution source. The median 2021/2022 soluble phosphate concentrations were ≤ 10 μg-P/L at all sites except Millwheel Creek, Silver Beach Creek, and the Park Place drain (Table 3.3). The historical data indicate that although soluble phosphate concentrations were generally low, nearly all sites have had a few high peaks, and high concentrations were common in residential streams.

Total phosphorus concentrations were higher than soluble phosphate concentrations (Figures B177–B182). The median 2021/2022 concentrations were ≤ 20 μg-P/L at all sites except Millwheel Creek, Silver Beach Creek, and the Park Place drain (Table 3.3). As with soluble phosphate, nearly all sites have had occasional high total phosphorus peaks.

There was a particularly large storm and flooding event that occurred within the Lake Whatcom watershed in November 2021. Tributary samples collected in December 2021 and January 2022 exhibited elevated total suspended solids (Figures B162–B164), turbidity (Figures B165–B167), total phosphorus (Figures B180–B182), and total nitrogen (Figures B174–B176), especially in Smith, Austin, Brannian, Carpenter, Olsen, and Silver Beach Creeks. See also Table B1 for outlier data points.

High coliform counts are an indicator of residential pollution (Table 3.3; Figures B183–B185). Although most of the sites had relatively low coliform counts during 2021/2022, Millwheel Creek exceeded a geometric mean of 100 cfu/100 mL. Four sites (Olsen, Millwheel, and Silver Beach Creeks, and the Park Place drain) had more than 10% of the samples that exceeded 200 cfu/100 mL. Several of the small residential tributaries could not be sampled during the late summer (see Table 3.2), when coliform counts are often higher, so these sites may have exceeded the coliform criteria by a greater margin than what is indicated in the summary tables.

The total organic carbon concentrations from February and August 2022 are included in Table 3.16 (page 77). Several of the residential sites (Millwheel and Silver Beach Creeks and the Park Place drain) had slightly elevated ($\geq$3 mg/L) total organic carbon concentrations. Blue Canyon, Brannian, Euclid, and Millwheel Creeks could not be sampled in summer because of insufficient flow (Table 3.2). The paired samples analyzed by IWS and AmTest were very similar, with a median difference of 0.3 mg/L. Larger differences could have been caused by small particulates that were unevenly distributed in the split samples or differences in analytical methodologies.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DO -field	●	●	●	●	●	●	●	●	●	●	●	●
pH - lab	●	●	●	●	●	●	●	●	●	●	●	●
Temp - field	●	●	●	●	●	●	●	●	●	●	●	●
Cond - lab	●	●	●	●	●	●	●	●	●	●	●	●
Alkalinity	●	●	●	●	●	●	●	●	●	●	●	●
Ammonium	●	●	●	●	●	●	●	●	●	●	●	●
Nitrate/nitrite	●	●	●	●	●	●	●	●	●	●	●	●
T. nitrogen	●	●	●	●	●	●	●	●	●	●	●	●
Sol. phosphate	●	●	●	●	●	●	●	●	●	●	●	●
T. phosphorus	●	●	●	●	●	●	●	●	●	●	●	●
T. susp. solids	●	●	●	●	●	●	●	●	●	●	●	●
Turbidity	●	●	●	●	●	●	●	●	●	●	●	●
T. organic carbon	●	●	●	●	●	●	●	●	●	●	●	●
Bacteria (City)	●	●	●	●	●	●	●	●	●	●	●	●

Table 3.1: Lake Whatcom tributary monitoring schedule. All field and laboratory methods are summarized in Table 2.1.

Month	Sample Summary	Comments
October 2021	No data for Park Place No TOC data	Construction TOC not collected
November 2021	No data for Park Place No TOC data	Construction TOC not collected
December 2021	No data for Park Place No TOC data All nitrate data missing	Construction TOC not collected Unacceptable laboratory variability
January 2022	No data for Park Place	Construction
February 2022	No data for Park Place	Construction
March 2022	No missing data	
April 2022	Ammonium data missing for Park Place	Equipment malfunction
May 2022	No missing data	
June 2022	No missing data	
July 2022	No missing data	
August 2022	All field and laboratory data missing for Blue Canyon, Brannian, Euclid, and Millwheel Creeks	Insufficient flow
September 2022	All field and laboratory data missing for Blue Canyon, Brannian, Carpenter, Euclid, Millwheel, and Silver Beach Creeks	Insufficient flow

Table 3.2: Summary of missing tributary data due to sampling or laboratory issues.

	Typical range	Anderson	Austin	Brannian	Olsen	Smith	Whatcom
Alkalinity	med. $\leq$30 mg/L	yes	yes	yes	yes	yes	yes
Conductivity	med. $\leq$100 μS	yes	yes	yes	yes	yes	yes
D. oxygen†	min. $\geq$8.0 mg/L	yes	yes	yes	yes	no	yes
pH	6.5–8.5	yes	yes	yes	yes	yes	no
Temperature†	max. $\leq$17.5 C	yes	yes	yes	yes	yes	no
T. susp. solids	med. $\leq$5 mg/L	yes	yes	yes	yes	yes	yes
Turbidity	med. $\leq$5 NTU	yes	yes	yes	yes	yes	yes
Ammonium	med. $\leq$10 μg-N/L	yes	yes	yes	yes	yes	yes
Sol. phosphate	med. $\leq$10 μg-P/L	yes	yes	yes	yes	yes	yes
T. phosphorus	med. $\leq$20 μg-P/L	yes	yes	yes	yes	yes	yes
F. coliforms	gmean $\leq$100 cfu	yes	yes	yes	yes	yes	yes
	max. 10% >200 cfu	yes	yes	yes	no	yes	yes

	Typical range	Blue Canyon	Carpenter	Euclid	Mill-wheel	Park Place	Silver Beach
Alkalinity	med. $\leq$30 mg/L	no	yes	yes	yes	no	no
Conductivity	med. $\leq$100 μS	no	yes	yes	yes	no	no
D. oxygen†	min. $\geq$8.0 mg/L	yes	yes	no	no	no	yes
pH	6.5–8.5	yes	yes	yes	yes	yes	yes
Temperature†	max. $\leq$17.5 C	yes	yes	yes	no	no	yes
T. susp. solids	med. $\leq$5 mg/L	yes	yes	yes	no	yes	yes
Turbidity	med. $\leq$5 NTU	yes	yes	yes	no	yes	yes
Ammonium	med. $\leq$10 μg-N/L	yes	yes	yes	yes	no	yes
Sol. phosphate	med. $\leq$10 μg-P/L	yes	yes	yes	no	no	no
T. phosphorus	med. $\leq$20 μg-P/L	yes	yes	yes	no	no	no
F. coliforms	gmean $\leq$100 cfu	yes	yes	yes	no	yes	yes
	Max. 10% >200 cfu	yes	yes	yes	no	no	no

†Many of the residential creeks were not sampled during part of the summer due to low flow, which is when water temperatures are usually high and dissolved oxygen concentrations low.

Table 3.3: Comparison of October 2021-September 2022 water quality in Lake Whatcom tributaries ("no" indicates that the site does not fall within the water quality ranges or meet the criteria described on page 58).

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	10.3	18.1	18.7	27.2
Conductivity (μS/cm)	35.6	52.8	54.9	68.4
Dissolved oxygen (mg/L)	8.2	10.8	10.5	12.3
pH	6.6	6.9	6.9	7.0
Temperature (°C)	5.1	8.8	9.4	15
Total suspended solids (mg/L)	<2	<2	3.0	15.5
Turbidity (NTU)	0.3	1.3	2.3	13.2
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	25.8
Nitrogen, nitrate/nitrite (μg-N/L)	165.1	330.3	315.8	663.9
Nitrogen, total (μg-N/L)	292.3	453.2	470.9	771.7
Phosphorus, soluble (μg-P/L)	<5	7.7	7.7	14.8
Phosphorus, total (μg-P/L)	9.6	14.4	16.8	30.2
Total organic carbon (mg/L)	0.7	2.6	2.6	3.8
Coliforms, fecal (cfu/100 mL)[‡]	2.0	26.5	29.6	350.0
(Percent of samples >200 cfu/100 mL = 8)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.4: Summary of Anderson Creek water quality data, October 2021-September 2022. See Table 3.2 for missing data.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	7.4	16.9	20	41.5
Conductivity (μS/cm)	32	55.6	72	159.9
Dissolved oxygen (mg/L)	9.9	12	11.7	13.4
pH	7.0	7.5	7.4	7.9
Temperature (°C)	4	8	9.4	16.3
Total suspended solids (mg/L)	<2	<2	9.6	85.0
Turbidity (NTU)	0.4	1.2	3.8	28.5
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	17.1
Nitrogen, nitrate/nitrite (μg-N/L)	85.7	245.2	386.4	1081.5
Nitrogen, total (μg-N/L)	180.7	351.4	496	1395.7
Phosphorus, soluble (μg-P/L)	<5	5.5	5.5	10.9
Phosphorus, total (μg-P/L)	<5	9.2	12.3	47.3
Total organic carbon (mg/L)	1.8	2.1	2.2	2.7
Coliforms, fecal (cfu/100 mL)[‡]	1.0	15.5	18.0	210.0
(Percent of samples >200 cfu/100 mL = 8)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 3.5: Summary of Austin Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	48.9	137.7	128.3	179.2
Conductivity (μS/cm)	121.0	294.9	267.6	351
Dissolved oxygen (mg/L)	10.2	11.8	11.8	13
pH	8.0	8.3	8.3	8.5
Temperature (°C)	4.8	8.5	8.5	14.7
Total suspended solids (mg/L)	<2	<2	3.4	17
Turbidity (NTU)	0.4	0.9	1.8	8.0
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	<10
Nitrogen, nitrate/nitrite (μg-N/L)	240.5	398.8	673.9	2660.5
Nitrogen, total (μg-N/L)	226.1	465	536.7	1474.1
Phosphorus, soluble (μg-P/L)	<5	6.3	5.7	8.8
Phosphorus, total (μg-P/L)	<5	6.4	6.6	17.4
Total organic carbon (mg/L)	2.0	2.4	2.6	4.0
Coliforms, fecal (cfu/100 mL)[‡]	<1	1.0	1.4	7.0
(Percent of samples >200 cfu/100 mL = 0)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.6: Summary of Blue Canyon Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	6	9.3	10.6	20.4
Conductivity (μS/cm)	25.2	34.6	38.2	63.3
Dissolved oxygen (mg/L)	8.4	11.8	11.3	12.8
pH	6.7	6.9	6.9	7.2
Temperature (°C)	4.7	7.4	8.3	14.7
Total suspended solids (mg/L)	<2	<2	9.2	83
Turbidity (NTU)	0.6	1.1	10.2	92.3
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	17.1
Nitrogen, nitrate/nitrite (μg-N/L)	185.8	454.9	495.8	1555.3
Nitrogen, total (μg-N/L)	287.9	527.1	642.7	1682.3
Phosphorus, soluble (μg-P/L)	<5	<5	<5	8.6
Phosphorus, total (μg-P/L)	<5	6.8	31.3	259.4
Total organic carbon (mg/L)	1.7	2.1	2.2	2.7
Coliforms, fecal (cfu/100 mL)[‡]	<1	7.0	4.3	32.0
(Percent of samples >200 cfu/100 mL = 0)				

[†] Uncensored arithmetic means except coliforms (geometric mean);

[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 3.7: Summary of Brannian Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	12.1	23.2	27.2	49
Conductivity (μS/cm)	44.3	60.7	72.8	114.7
Dissolved oxygen (mg/L)	9.7	12	11.7	13.5
pH	6.9	7.6	7.5	7.9
Temperature (°C)	3.6	7.7	8.9	16.8
Total suspended solids (mg/L)	<2	<2	11.2	62.5
Turbidity (NTU)	0.7	2.2	4.7	31.6
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	28.5
Nitrogen, nitrate/nitrite (μg-N/L)	42.1	310.7	412.9	1049.5
Nitrogen, total (μg-N/L)	316	461.8	606.9	1326.7
Phosphorus, soluble (μg-P/L)	<5	7.6	6.7	11.3
Phosphorus, total (μg-P/L)	<5	13.9	16	58.9
Total organic carbon (mg/L)	3.1	3.8	4	5.4
Coliforms, fecal (cfu/100 mL)[‡]	1.0	45	34.3	220.0
(Percent of samples >200 cfu/100 mL = 9)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 3.8: Summary of Carpenter Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	14.1	26.6	26.9	46.1
Conductivity (μS/cm)	60.1	84.9	87.9	136.8
Dissolved oxygen (mg/L)	7.5	11.1	10.6	12.2
pH	6.8	7.2	7.2	7.4
Temperature (°C)	5.5	9.0	9.5	17.3
Total suspended solids (mg/L)	<2	2.5	4.0	17.1
Turbidity (NTU)	0.5	1.5	1.8	4.4
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	23.6
Nitrogen, nitrate/nitrite (μg-N/L)	54.3	161.9	218.5	589.8
Nitrogen, total (μg-N/L)	190.5	311.5	366.6	796.9
Phosphorus, soluble (μg-P/L)	<5	6.8	6.3	9.6
Phosphorus, total (μg-P/L)	<5	11.6	11.1	18.9
Total organic carbon (mg/L)	2.7	2.8	3.1	3.9
Coliforms, fecal (cfu/100 mL)[‡]	3.0	14.5	15.4	230.0
(Percent of samples >200 cfu/100 mL = 10)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 3.9: Summary of Euclid Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean†	Max.
Alkalinity (mg/L $CaCO_3$)	15.2	28.4	32.6	65.8
Conductivity (μS/cm)	56.4	78.4	84.6	149.4
Dissolved oxygen (mg/L)	2.9	11.7	10.7	13.9
pH	6.9	7.3	7.4	8.1
Temperature (°C)	5.6	9.3	10.9	25
Total suspended solids (mg/L)	<2	6.8	8.0	25.5
Turbidity (NTU)	4.9	7.7	10.4	26.1
Nitrogen, ammonium (μg-N/L)	<0	<10	49.5	411.4
Nitrogen, nitrate/nitrite (μg-N/L)	<20	192.1	193.4	545.5
Nitrogen, total (μg-N/L)	240.4	475	581.5	1191.2
Phosphorus, soluble (μg-P/L)	7.2	11.4	22.7	116.3
Phosphorus, total (μg-P/L)	19.9	33.5	64.0	300.3
Total organic carbon (mg/L)	3.5	3.7	4.3	6.9
Coliforms, fecal (cfu/100 mL)‡	10.0	145.0	105.7	350.0
(Percent of samples >200 cfu/100 mL = 30)				

†Uncensored arithmetic means except coliforms (geometric mean);
‡Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.10: Summary of Millwheel Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	9.2	17.6	24.7	51.7
Conductivity (μS/cm)	33.8	50.3	65.3	131.7
Dissolved oxygen (mg/L)	9.6	12.2	11.8	13.9
pH	7.0	7.5	7.5	7.9
Temperature (°C)	2.7	7.0	8.8	16.5
Total suspended solids (mg/L)	<2	3.1	34.8	332.0
Turbidity (NTU)	0.3	2.2	11.8	106
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	90.5
Nitrogen, nitrate/nitrite (μg-N/L)	46.2	321.7	393.3	929.3
Nitrogen, total (μg-N/L)	137.6	440.1	554.2	1065.5
Phosphorus, soluble (μg-P/L)	<5	5.8	7.8	28
Phosphorus, total (μg-P/L)	<5	11.6	33.5	257.8
Total organic carbon (mg/L)	2.1	2.5	2.7	4.0
Coliforms, fecal (cfu/100 mL)[‡]	1.0	10.0	13.5	290.0
(Percent of samples >200 cfu/100 mL = 17)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.11: Summary of Olsen Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	65.6	91.8	99.1	135.7
Conductivity (μS/cm)	179.5	236.3	260.1	345
Dissolved oxygen (mg/L)	0.4	9.7	8.0	12.0
pH	7.3	7.6	7.5	7.7
Temperature (°C)	7.0	13.6	13.6	19.9
Total suspended solids (mg/L)	<2	2.8	4.6	13.5
Turbidity (NTU)	1.1	3.7	5.4	15.5
Nitrogen, ammonium (μg-N/L)	20.8	29.6	67.1	266.5
Nitrogen, nitrate/nitrite (μg-N/L)	359.8	483.7	474.8	622.2
Nitrogen, total (μg-N/L)	547.1	677.9	680.4	845.6
Phosphorus, soluble (μg-P/L)	5.9	10.6	10.5	16.0
Phosphorus, total (μg-P/L)	13.5	21.2	30.2	70.2
Total organic carbon (mg/L)	2.9	3.6	3.6	4.1
Coliforms, fecal (cfu/100 mL)[‡]	1.0	35.0	30.9	220.0
(Percent of samples >200 cfu/100 mL = 14)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., <1 ⇒ 1).

Table 3.12: Summary of Park Place outlet water quality data, October 2021-September 2022. Note that samples were not taken on several dates due to construction activities (Table 3.2).

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	26.4	61.6	68.2	128.5
Conductivity (μS/cm)	92.4	149.5	172.6	314
Dissolved oxygen (mg/L)	9.2	11.4	11.5	13.5
pH	7.6	8.0	7.9	8.2
Temperature (°C)	4.3	8.8	9.6	17.1
Total suspended solids (mg/L)	<2	2.5	8.8	74.5
Turbidity (NTU)	1.0	2.4	4.9	26.8
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	17.2
Nitrogen, nitrate/nitrite (μg-N/L)	214.2	450.3	494.7	1107
Nitrogen, total (μg-N/L)	367.4	695.8	779.7	1409.6
Phosphorus, soluble (μg-P/L)	<5	11.0	12.3	26.6
Phosphorus, total (μg-P/L)	11.9	20.2	27.6	95.4
Total organic carbon (mg/L)	4.3	4.8	4.8	5.5
Coliforms, fecal (cfu/100 mL)[‡]	4.0	100.0	66.5	250.0
(Percent of samples >200 cfu/100 mL = 18)				

[†] Uncensored arithmetic means except coliforms (geometric mean);
[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.13: Summary of Silver Beach Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean[†]	Max.
Alkalinity (mg/L $CaCO_3$)	10.3	16.4	19.8	40
Conductivity (μS/cm)	30.3	46.9	57.3	110.9
Dissolved oxygen (mg/L)	4.5	12.3	11.3	13.8
pH	7.1	7.5	7.4	7.6
Temperature (°C)	3.0	7.2	9.0	16.6
Total suspended solids (mg/L)	<2	<2	6.2	58
Turbidity (NTU)	0.2	0.9	3.8	35.3
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	16.9
Nitrogen, nitrate/nitrite (μg-N/L)	113	490.6	602.1	1293.5
Nitrogen, total (μg-N/L)	208.7	639	733.9	1512.5
Phosphorus, soluble (μg-P/L)	<5	5	<5	7.7
Phosphorus, total (μg-P/L)	<5	6.5	11.9	58.5
Total organic carbon (mg/L)	2.0	2.3	2.5	3.4
Coliforms, fecal (cfu/100 mL)[‡]	<1	11.0	9.4	76.0
(Percent of samples >200 cfu/100 mL = 0)				

[†] Uncensored arithmetic means except coliforms (geometric mean);

[‡] Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.14: Summary of Smith Creek water quality data, October 2021-September 2022.

Variable	Min.	Med.	Mean†	Max.
Alkalinity (mg/L $CaCO_3$)	18.1	21	21.6	26.3
Conductivity (μS/cm)	57.5	61	62.3	77
Dissolved oxygen (mg/L)	8.6	11.2	10.9	12.5
pH	7.4	7.5	7.7	8.8
Temperature (°C)	5.8	11.6	13.3	24.2
Total suspended solids (mg/L)	<2	2.1	2.0	4.5
Turbidity (NTU)	0.6	0.9	1.3	2.4
Nitrogen, ammonium (μg-N/L)	<10	<10	11.4	46.0
Nitrogen, nitrate/nitrite (μg-N/L)	<20	162.9	137.7	285.6
Nitrogen, total (μg-N/L)	209.4	321.8	340.5	529
Phosphorus, soluble (μg-P/L)	<5	<5	<5	5.2
Phosphorus, total (μg-P/L)	<5	9.9	9.8	17.8
Total organic carbon (mg/L)	2.0	2.2	2.5	3.4
Coliforms, fecal (cfu/100 mL)‡	1.0	6.0	6.5	35.0
(Percent of samples >200 cfu/100 mL = 0)				

†Uncensored arithmetic means except coliforms (geometric mean);
‡Censored values replaced with closest integer (i.e., $<1 \Rightarrow 1$).

Table 3.15: Summary of Whatcom Creek water quality data, October 2021-September 2022.

Site	Date	TOC-AM (mg/L)	TOC-IWS (mg/L)	Date	TOC-AM (mg/L)	TOC-IWS (mg/L)
Anderson	Feb 9, 2022	2.9	2.6	Aug 9, 2022	1.9	2.0
Austin (lower)	Feb 9, 2022	2.2	2.0	Aug 9, 2022	1.5[†]	1.9
Blue Canyon	Feb 9, 2022	2.5	2.4	Aug 9, 2022	insufficient flow	
Brannian	Feb 9, 2022	2.1	1.9	Aug 9, 2022	insufficient flow	
Carpenter	Feb 9, 2022	3.8	3.7	Aug 9, 2022	3.2	3.1
Euclid	Feb 9, 2022	2.9	2.7	Aug 9, 2022	insufficient flow	
Millwheel	Feb 9, 2022	3.8	3.5	Aug 9, 2022	insufficient flow	
Olsen	Feb 9, 2022	2.6	2.5	Aug 9, 2022	2.1	2.4
Park Place	Feb 9, 2022	construction		Aug 9, 2022	3.9	3.9
Silver Beach	Feb 9, 2022	4.9	4.4	Aug 9, 2022	5.4	5.3
Smith	Feb 9, 2022	2.4	2.5	Aug 9, 2022	2.2	2.3
Whatcom	Feb 9, 2022	2.1	2.0	Aug 9, 2022	2.8	3.4

[†] Sample vial broke in transit; replacement sample taken 3 days after other tributaries

Table 3.16: Lake Whatcom 2022 tributary total organic carbon data. February and August samples were split and analyzed by AmTest (TOC-AM) and IWS (TOC-IWS).

4 Storm Water Monitoring

4.1 Hydrograph Monitoring

Recording hydrographs are installed in Austin Creek and Smith Creek; the data are plotted in Figures 4.1–4.2 (pages 83–84). The location of each hydrograph is described in Appendix A.2 (page 96). All hydrograph data, including data from previous years, are online at `www.wwu.edu/iws`. All results are reported as Pacific Standard Time, without Daylight Saving Time adjustment. Field notes, comments on missing data, and rating curves for each water year are available upon request to the City of Bellingham or the Institute for Watershed Studies.

Rating curves for Smith and Austin Creeks were generated in MS Excel®[32] using a standard power curve given by the following equation (Kennedy, 1984; Rantz et al., 1982; WMO, 2010):

(1) $Q_e = a(s - b)^c$

where Q_e is the estimated stream discharge at a respective stage height; s is the creek stage height and coefficients a, b, and c are empirical fitting parameters. The power equation is suitable when the system is relatively stable, which is assumed for Smith and Austin Creeks. The empirical constants a, b, and c are determined by iterative approximations to obtain the best fit between measured discharges and estimated (Q_e) at the respective stages.

About 109 stage-discharge values in Austin Creek and 98 in Smith Creek collected between the 2017 and 2022 water years were used to develop the rating curves. Some isolated high-flow measurements collected from Smith Creek ranging back to 2013 were also used. The measured stage-discharge values for each creek were broken up in three segments based on changes in flow magnitude. The Q_e values were estimated for each segment using a generalized reduced gradient (GRD) nonlinear solver in Excel®. The GRD solver iteratively adjusts the a, b, and c values to optimize the Q_e discharge estimate by minimizing the sum of the square of the error between the measured and estimated (Q_e) at a respective stage. The Excel® technique was validated by producing statistically similar discharge values produced by Aquarius in both Smith and Austin Creek for the 2021 water year ($R^2 \approx 1$). The 2022 water year results show a good good fit to Austin and

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[32] Prior to this year (2021/22), the software Aquarius was used.

Smith measured values (Figures 4.3–4.4, pages 85–86).

The 15-minute stage data (s) recorded at the Smith and Austin creek-gauging stations were used along with the values in Table 4.1 and Equation (1) to estimate the discharge time series for the 2022 water year. The resulting 15-minute discharge values were aggregated into 1-hour averages (Figures 4.1–4.2, pages 83–84). The rainfall runoff from the intense atmospheric river that occurred in mid-November 2021 elevated creek stages about 2.0 ft beyond the upper bounds of each rating curve resulting in extrapolated discharges greater than 600 cfs. These high discharges should be considered somewhat suspect.

The storm also damaged the Smith Creek gauge resulting in a stage data gap between November 14, 2021, and March 7, 2022. Discharge values for the gap period were estimated using rainfall and weather variables from City of Bellingham gauges in the Lake Whatcom watershed and the Distributed-Hydrology-Soils-Vegetation Model (DHSVM) that is calibrated to the Smith Creek basin (Wigmosta, et al., 1994; Kelleher, 2006). Note that the DHSVM produced discharges about 600 cfs in Smith Creek on November 14 and 15, possibly adding validity to the rating curve estimates (Figure 4.2, page 84).

4.2 Site Descriptions

The 2021/2022 storm water sampling focused on Carpenter, Olsen, and Smith Creeks (Figure A2, page 101). Earlier storm water sampling in the Lake Whatcom watershed summarized in previous annual reports (see Section 5.2, page 91).

4.3 Field Sampling and Analytical Methods

Five storm events were sampled in Carpenter Creek, two in Olsen Creek, and two in Smith Creek (Table 4.2, page 82). The samples were collected using time-paced ISCO samplers provided by the City of Bellingham and analyzed for total suspended solids, total phosphorus, soluble reactive phosphorus, total nitrogen, and nitrate/nitrite[33] as described in Table 2.1 (page 18).

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[33] Nitrate and nitrite were analyzed together because nitrite concentrations are very low in surface water and require low level analytical techniques to measure accurately. For simplicity, nitrate/nitrite will be referred to as "nitrate" in this document.

Dry summers have a direct impact on stream flow (base flow), which is supported by soil water and groundwater. As illustrated in the hydrographs for the Lake Whatcom watershed (Figures 4.1–4.2, pages 83–84), stream discharge decreased over the course of the summer as soils dried out and groundwater levels declined due to low rainfall and high levels of evapotranspiration from vegetation. Moreover, most late summer rainfall goes into replenishing soil water (storage) rather than direct runoff into streams. Lower summer stream flows and groundwater levels will also reduce runoff into the lake. When coupled with higher summer lake withdrawals and lake evaporation, the lake level will usually drop over the course of the summer, reaching a minimum in late fall.

As indicated in Table 3.2 (page 63), many of the smaller tributaries to Lake Whatcom were dry, or nearly dry during late summer. Storm water data are used by the City as part of their watershed modeling program and will be reported directly to the City to be incorporated into the model. Storm water data are available upon request to the City of Bellingham or the Institute for Watershed Studies.

Creek	Segment	a	b	c
Austin	$0 < s < 1.0$	12.4078	0.0000	2.7433
Austin	$1.0 \leq s < 1.8$	13.2517	0.0000	2.5732
Austin	$s \geq 1.8$	102.4866	1.2120	1.1879
Smith	$0 < s < 2.0$	0.0235	0.2920	8.6748
Smith	$2.0 \leq s < 2.8$	0.0214	0.0000	7.0750
Smith	$s \geq 2.8$	1.0465	0.0000	3.5361

Table 4.1: Rating curve values used in Equation (1) for Austin and Smith Creeks WY2022, where s is the measured stage height and a, b, and c are empirical constants.

Carpenter Creek			
Start Date	Start Time	End Date	End Time
Oct 28, 2021	02:00	Oct 29, 2021	10:00
Nov 11, 2021	15:30	Nov 13, 2021	02:00
Nov 13, 2021	19:00	Nov 16, 2021	11:00
Jan 11, 2022	12:00	Jan 13, 2022	09:00
Feb 28, 2022	13:15	Mar 2, 2022	09:15

Olsen Creek			
Start Date	Start Time	End Date	End Time
Jan 11, 2022	12:00	Jan 13, 2022	09:00
Feb 28, 2022	13:00	Mar 2, 2022	09:00

Smith Creek			
Start Date	Start Time	End Date	End Time
Nov 4, 2021	09:00	Nov 6, 2021	01:00
Nov 11, 2021	15:30	Nov 13, 2021	02:00

Table 4.2: Summary of 2021-2022 storm event sampling dates for Carpenter, Olsen, and Smith Creeks. Time is Pacific Standard.

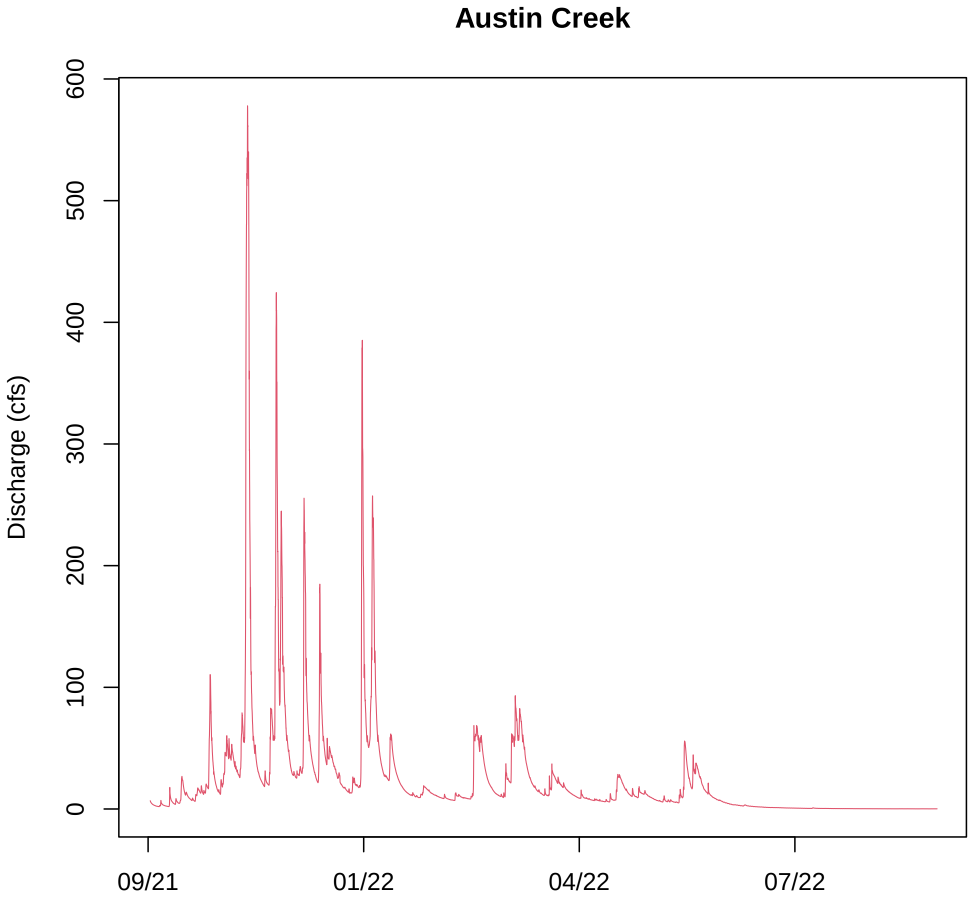

Figure 4.1: Austin Creek hydrograph for WY2022 (October 1, 2021–September 30, 2022). Data were recorded at 15 minute intervals, but plotted at 1 hour intervals for consistency with Smith Creek.

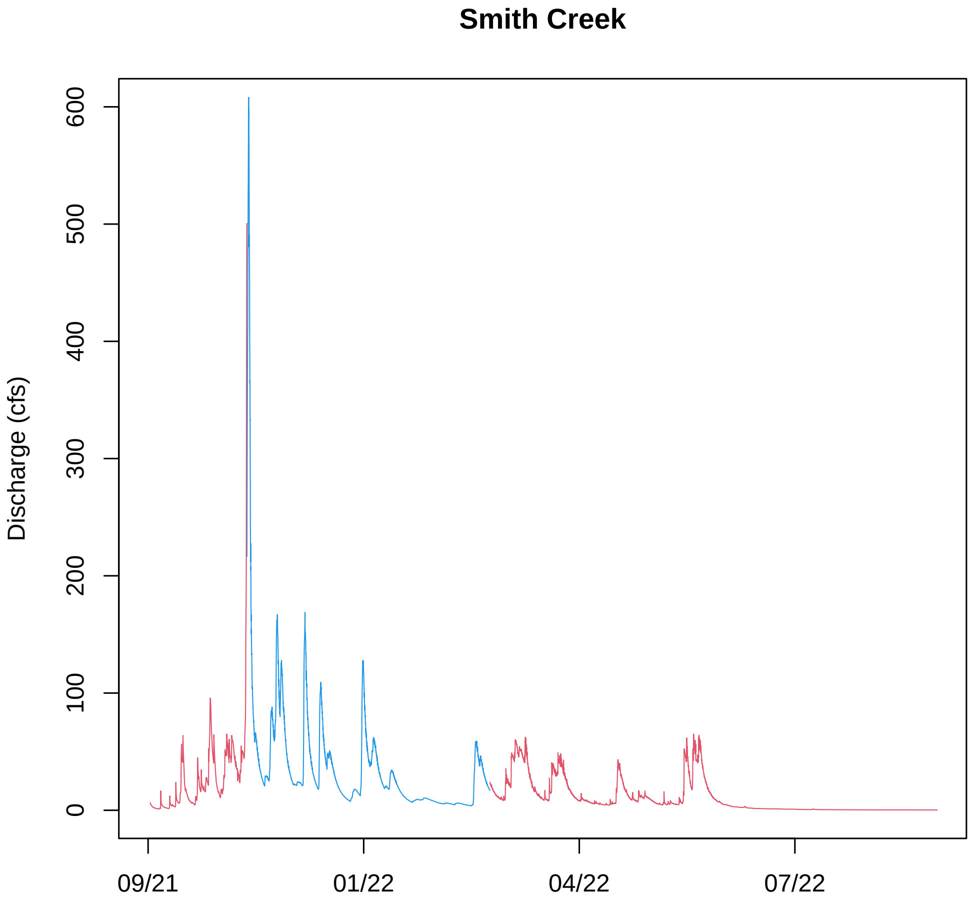

Figure 4.2: Smith Creek hydrograph for WY2022 (October 1, 2021–September 30, 2022). The red line represents field-collected data, whereas the blue line represents model-simulated data during the period when the gauge was out of commission because of flooding in November 2021 (see Section 4 for details). Gauge data were recorded at 15 minute intervals, but were plotted at 1 hour intervals to match the model-simulated data.

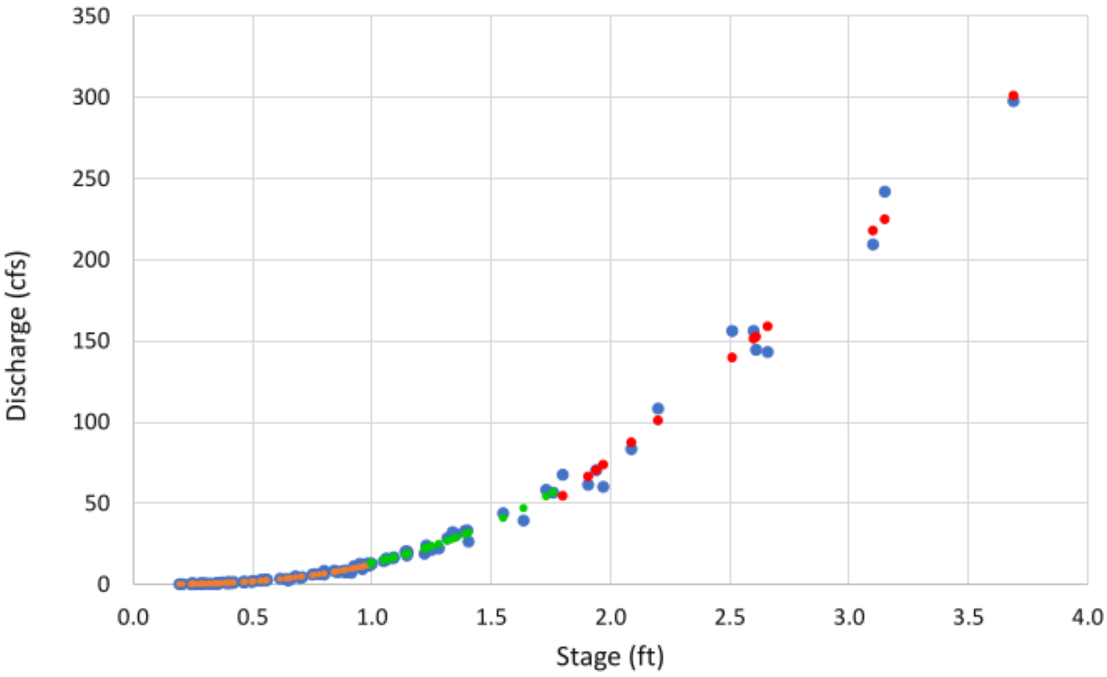

Figure 4.3: Austin Creek measured stage-discharge values (blue symbols) and rating curve values estimated using Equation (1). The orange is for segment $0 < s < 1.0$, green is for $1.0 \leq s < 1.8$, and red is for $s \geq 1.8$ (see Table 4.1).

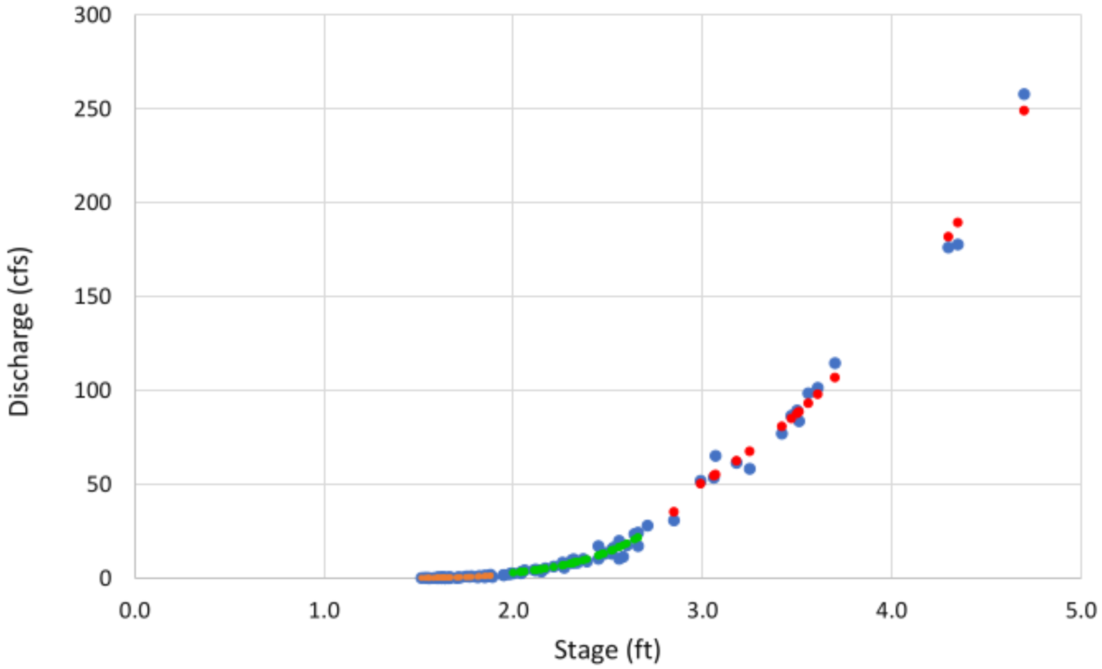

Figure 4.4: Smith Creek measured stage-discharge values (blue symbols) and rating curve values estimated using Equation (1). The orange is for segment $0 < s < 2.0$, green is for $2.0 \leq s < 2.8$, and red is for $s \geq 2.8$ (see Table 4.1).

5 References and Related Reports

5.1 Cited References

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5.2 Related Reports

The following is a list of annual reports and special project reports produced by the Institute for Watershed Studies since 1987 as part of the Lake Whatcom monitoring program sponsored by the City of Bellingham and Western Washington University. Many of the reports are available online at `www.wwu.edu/iws` (follow links to the Lake Whatcom project under Lake Studies); older reports are available in the IWS library and through the city of Bellingham Public Works Department. This list does not include research reports, student projects, or publications that were not prepared specifically for the City of Bellingham. Contact IWS for information about additional Lake Whatcom publications.

Annual monitoring reports (listed reverse chronological):

Strecker, A., R. A. Matthews, M. Hilles, J. Pickens, R. Mitchell, and G. B. Matthews. 2022. Lake Whatcom Monitoring Project, 2020/2021 Final Report, February 28, 2022. Report to the City of Bellingham, WA.

Strecker, A., R. A. Matthews, M. Hilles, J. Pickens, R. Mitchell, and G. B. Matthews. 2021. Lake Whatcom Monitoring Project, 2019/2020 Final Report, February 24, 2021. Report to the City of Bellingham, WA.

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Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. Lake Whatcom Monitoring Project, 2005/2006 Final Report, April 11, 2007. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. Lake Whatcom Monitoring Project, 2004/2005 Final Report, March 30, 2006. Report to the City of Bellingham, WA.

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Rector, J. M. and R. A. Matthews. Lake Whatcom Monitoring Program, August 1987 Final Report. Institute for Watershed Studies Report, Western Washington University, Bellingham, WA.

Other Lake Whatcom reports (listed reverse chronological):

Matthews, R. A., M. Hilles and J. Vandersypen. Austin Creek and Beaver Creek Sampling Project, October 11, 2005. Report to the City of Bellingham, WA.

Matthews, R. A. Relationship between Drinking Water Treatment Chemical Usage and Lake Whatcom water Quality and Algal Data, October 4, 2004. Report to the City of Bellingham, WA.

Matthews, R. A. Strawberry Sill Water Quality Analysis, March 19, 2004. Report to the City of Bellingham, WA.

Matthews, R. A., M. Saunders, M A. Hilles, and J. Vandersypen. Park Place Wet Pond Monitoring Project, 1994–2000 Summary Report, February 2, 2001. Report to the City of Bellingham, WA.

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Walker, S., R. Matthews, and G. Matthews. Lake Whatcom Storm Runoff Project, Final Report, January 13, 1992. Report to the City of Bellingham, WA.

Creahan, K., T. Loranger, B. Gall, D. Brakke, and R. Matthews. Lake Whatcom Watershed Management Plan, December, 1986, revised July, 1987. Institute for Watershed Studies Report, Western Washington University, Bellingham, WA.

A Site Descriptions

Figures A1–A2 (pages 100–101) show the locations of the current monitoring sites and Table A1 (page 99) lists the approximate GPS coordinates for the lake and creek sites. All site descriptions, including text descriptions and GPS coordinates, are approximate. For detailed information about sampling locations, contact IWS.

A.1 Lake Whatcom Monitoring Sites

Site 1 is located in the north central portion of basin 1 along a straight line from the Bloedel Donovan boat launch to the house located at 171 E. North Shore Rd. The depth at Site 1 should be at least 25 meters; samples are collected from the surface to 20 m.

Site 2 is located in the south central portion of basin 2 just west of the intersection of a line joining the boat house at 73 Strawberry Point and the point of Geneva sill. Samples are collected from the surface to 20 m.

The **Intake Site** location is omitted from this report at the City's request.

Site 3 is located in the northern portion of basin 3, mid-basin just north of a line between the old railroad bridge and Lakewood. The depth at Site 3 should be at least 80 m; samples are collected from the surface to 75 m.

Site 4 is located in the southern portion of basin 3, mid-basin, and just north of South Bay. The depth at Site 4 should be at least 90 m; samples are collected from the surface to 90 m.

A.2 Tributary Monitoring Sites

Anderson Creek samples are collected using a sampling pole from the downstream side of the South Bay Rd. bridge. The Anderson Creek hydrograph[34] is mounted in the stilling well on the east side of Anderson Creek, directly adjacent

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[34] This hydrograph is no longer maintained by IWS; data are available on the USGS web site at `http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=12201950`.

to the bridge over Anderson Creek (South Bay Rd.), approximately 0.5 km from the mouth of the creek.

The **Austin Creek** hydrograph gauge and sampling site is located approximately 15 m downstream from Lake Whatcom Blvd. From October 2004 through September 2006, three additional sampling sites were sampled in the Austin Creek watershed, so for clarification, the gauged site has been renamed **Lower Austin Creek**.

Blue Canyon Creek samples are collected downstream from the culvert under Blue Canyon Rd. in the second of three small streams that cross the road. During conditions of low flow or high lake levels, samples are collected, if possible, approximately 7 m upstream from the road crossing.

Brannian Creek samples are collected using a sampling pole from the downstream side of South Bay Rd., approximately 40 m upstream from the USGS hydrograph gauge. This site was added in October 2004 as part of the monthly 2004–2006 creek monitoring project.

Carpenter Creek samples are collected approximately 7 m upstream from North Shore Dr. near the USGS hydrograph gauge. This site was added in October 2004 as part of the monthly 2004–2006 creek monitoring project.

Euclid Ave. samples are collected from a small tributary off Euclid Avenue near the USGS hydrograph gauge. The site was added in October 2004 as part of the monthly 2004–2006 creek monitoring project.

Millwheel Creek samples are collected approximately 8 m upstream from Flynn St. near the USGS hydrograph gauge. The creek is unnamed on most topographic maps, but has been called “Millwheel Creek” by residents of the watershed due to its proximity to the old mill pond. This site was added in October 2004 as part of the monthly 2004–2006 creek monitoring project.

Olsen Creek samples are collected upstream from North Shore Dr., approximately 3 meters upstream from the bridge. This site was added in October 2004 as part of the 2004–2006 monthly creek monitoring project.

Park Place samples are collected from the storm drain that empties into Lake Whatcom at Park Place Ln. Samples from this site include outlet flow from the Park Place storm water treatment facility.

Silver Beach Creek samples are collected approximately 75 m upstream from the culvert under North Shore Rd., just upstream from the USGS hydrograph gauge.

The **Smith Creek** hydrograph is mounted on the south wall of a sandstone bluff directly underneath the bridge over Smith Creek (North Shore Rd.) approximately 1 km upstream from the mouth of the creek. Water samples are collected near the old bridge site, at the end of North Shore Rd. approximately 500 m downstream from the IWS hydrograph gauge. During periods of low flow, Smith Creek is sampled approximately 15 m downstream from the IWS hydrograph gauge.

Whatcom Creek samples are collected approximately 2 m downstream from the foot bridge below the Lake Whatcom outlet spillway. This site was added in October 2004 as part of the monthly 2004–2006 creek monitoring project.

A.3 Storm Water Monitoring Sites

The 2021/2022 storm water monitoring program focused on collecting storm runoff data from Carpenter, Olsen, and Smith Creeks. Carpenter Creek samples are collected approximately 7 m upstream from North Shore Dr. near the USGS hydrograph gauge. Olsen Creek samples are collected upstream from North Shore Dr., approximately 3 meters upstream from the bridge. Smith Creek samples are collected near the old bridge site, at the end of North Shore Rd. approximately 500 m downstream from the IWS hydrograph gauge.

For information about other storm water sites that have been monitored by IWS, refer to the annual reports listed in Section 5.2 (page 91).

Lake Sites	Latitude (°N)	Longitude (°W)
Site 1	48.760	-122.411
Intake	(GPS omitted)	
Site 2	48.743	-122.382
Site 3	48.738	-122.336
Site 4	48.695	-122.304

Tributary/Stormwater Sites	Latitude (°N)	Longitude (°W)
Anderson	48.673	-122.268
Austin (lower)	48.713	-122.331
Blue Canyon	48.685	-122.283
Brannian	48.669	-122.279
Carpenter	48.754	-122.354
Euclid	48.748	-122.410
Millwheel	48.755	-122.416
Olsen	48.751	-122.354
Park Place	48.769	-122.409
Silver Beach	48.769	-122.407
Smith	48.732	-122.309
Whatcom	48.757	-122.422

Table A1: Approximate GPS coordinates for Lake Whatcom sampling sites.

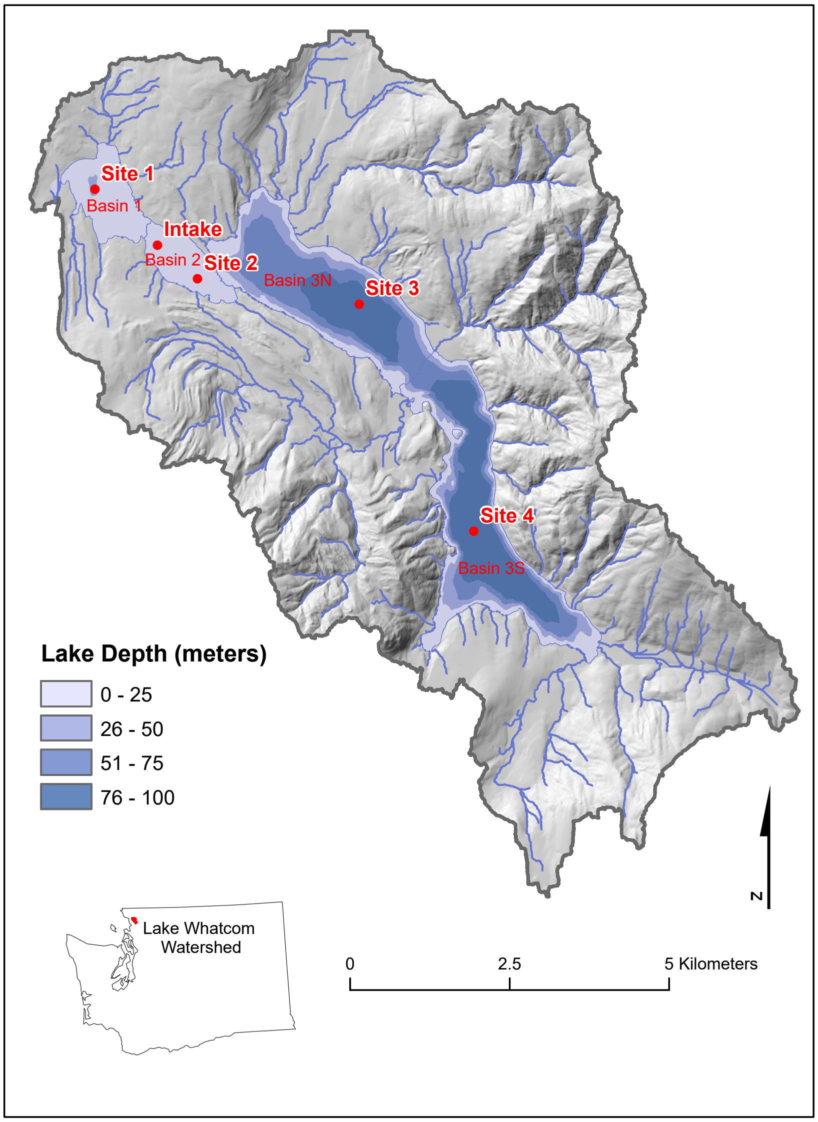

Figure A1: Lake Whatcom lake sampling sites. Basemap created using data from Western Washington University, Skagit County, the Nooksack Tribe, and the City of Bellingham.

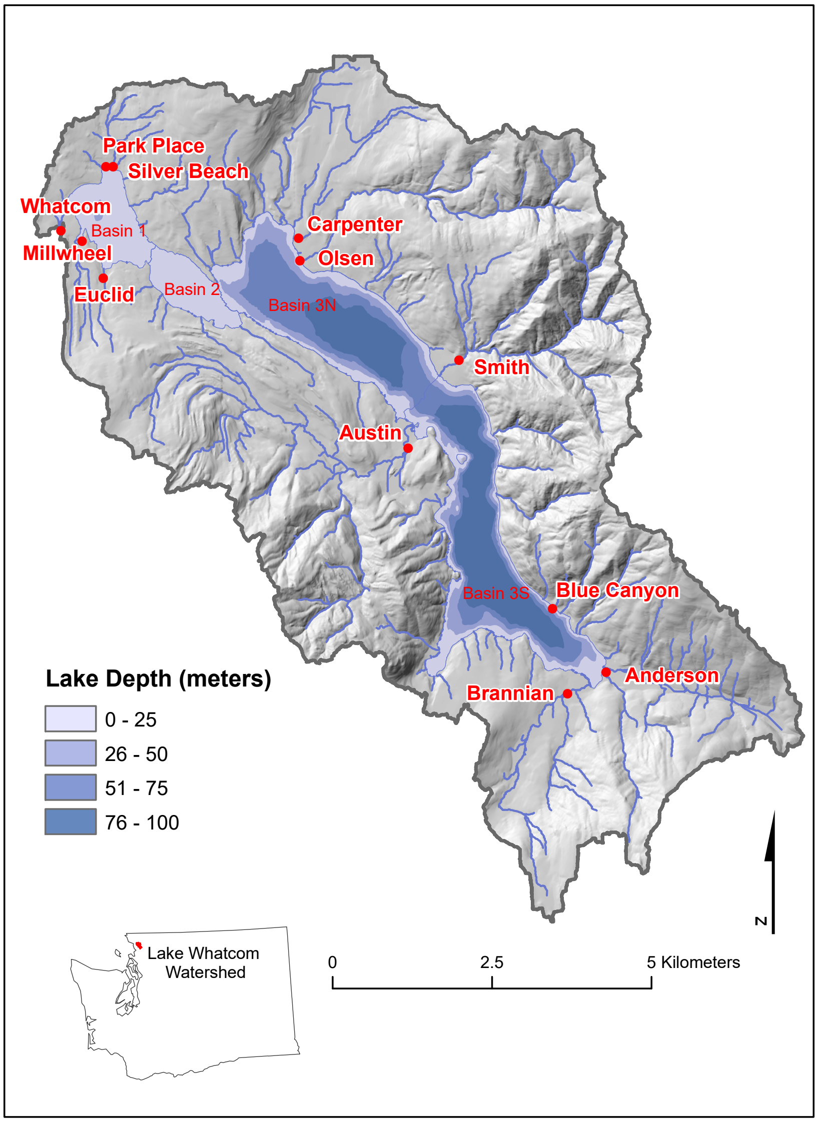

Figure A2: Lake Whatcom tributary and storm water sampling sites. Basemap created using data from Western Washington University, Skagit County, the Nooksack Tribe, and the City of Bellingham.

B Long-Term Water Quality Figures

The current and historic Lake Whatcom water quality data are plotted on the following pages. Detection limits and abbreviations for each parameter are listed in Table 2.1 (page 18).

The historic detection limits for each parameter were estimated based on an analysis of historic detection ranges, instrument limitations, and analyst judgment on the lowest repeatable concentration for each test. Over time, some analytical techniques have improved so that current detection limits are lower than the historic limits listed in Table 2.1, page 18). Because the Lake Whatcom data set includes long-term monitoring data that have been collected using a variety of analytical techniques, this report sets conservative historic detection limits to allow comparisons between all years.

In the Lake Whatcom report, unless indicated, no data substitutions are used for below detection values (“bdl” data). Instead, we identify summary statistics that include bdl values, and, if appropriate, discuss the implications of including these values in the analysis.

Because of the length of the data record, many of the figures reflect trends related to improvements in analytical techniques over time and the introduction of increasingly sensitive field equipment (see, for example, Figures B81–B85, pages 185–189, which show the effect of using increasingly sensitive conductivity probes). These changes generally result in a reduction in analytical variability, and sometimes result in lower detection limits.

B.1 Monthly YSI Profiles

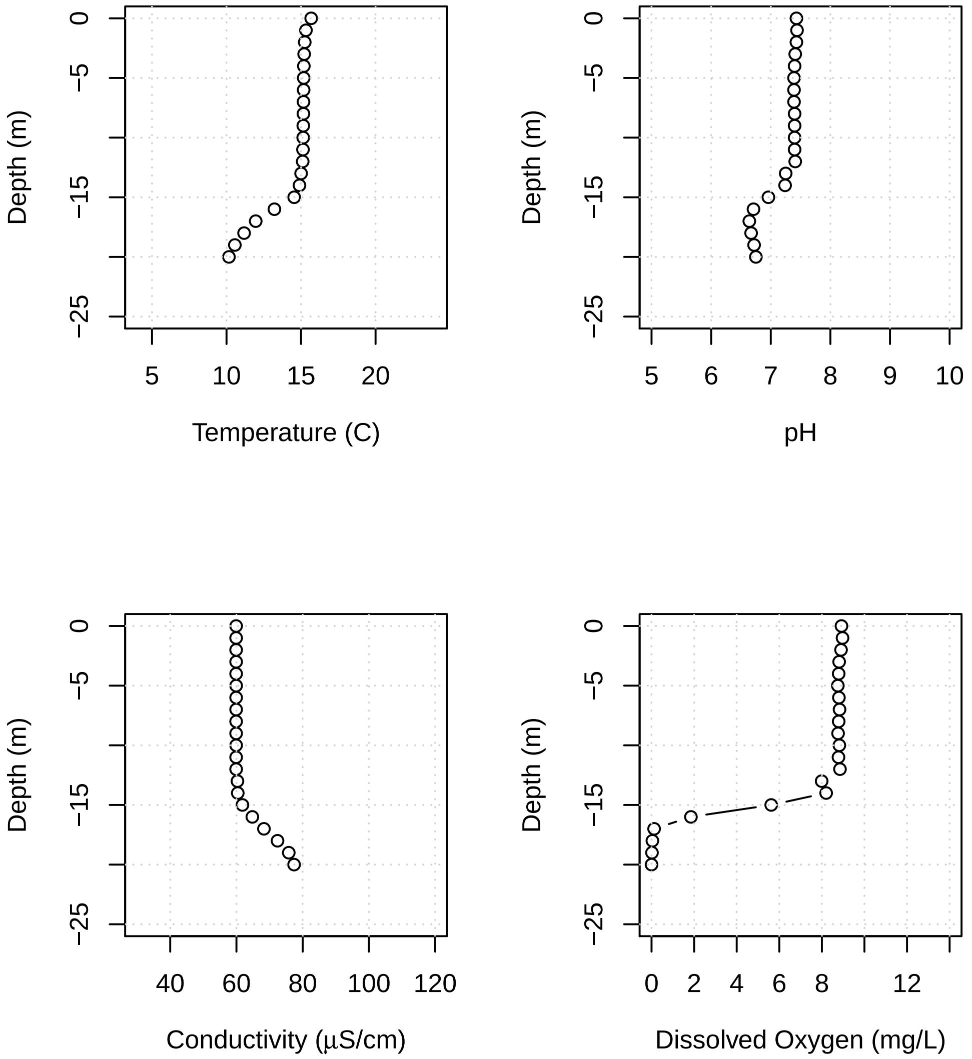

Figure B1: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, October 7, 2021.

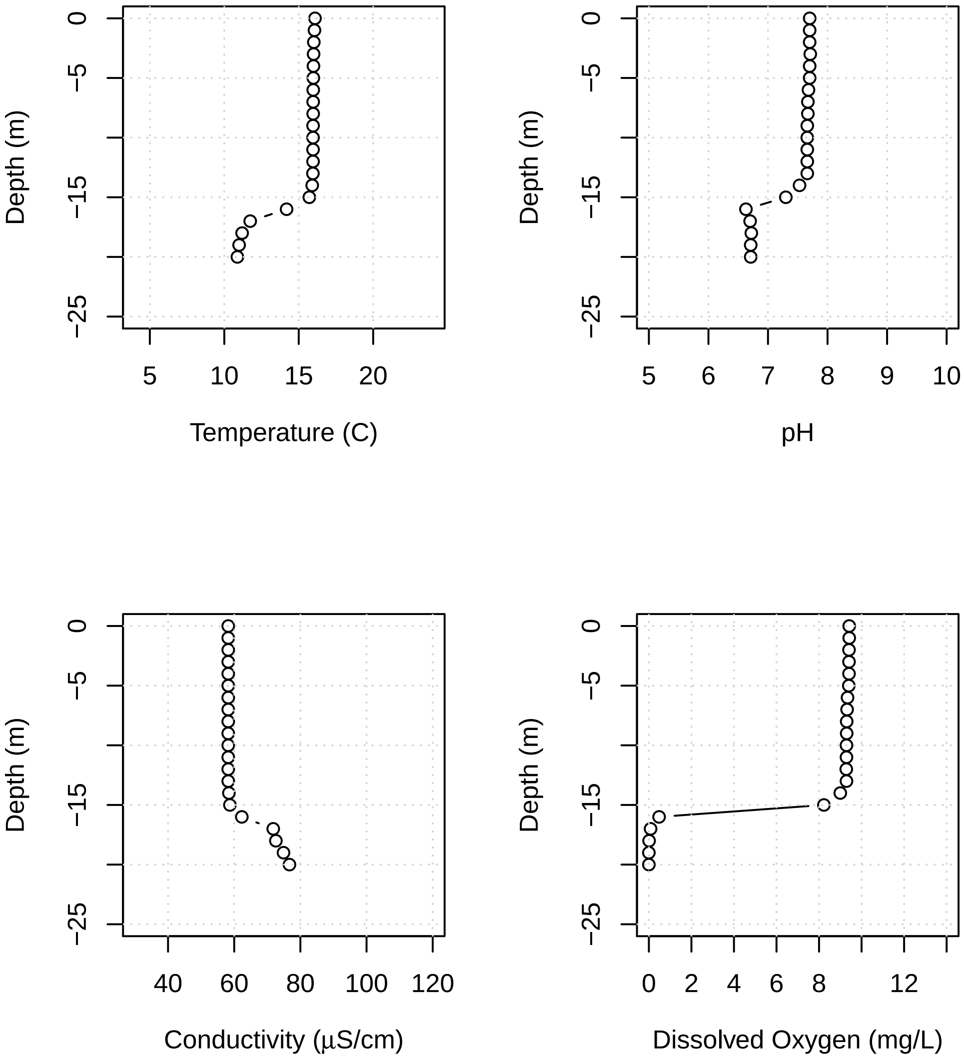

Figure B2: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, October 7, 2021.

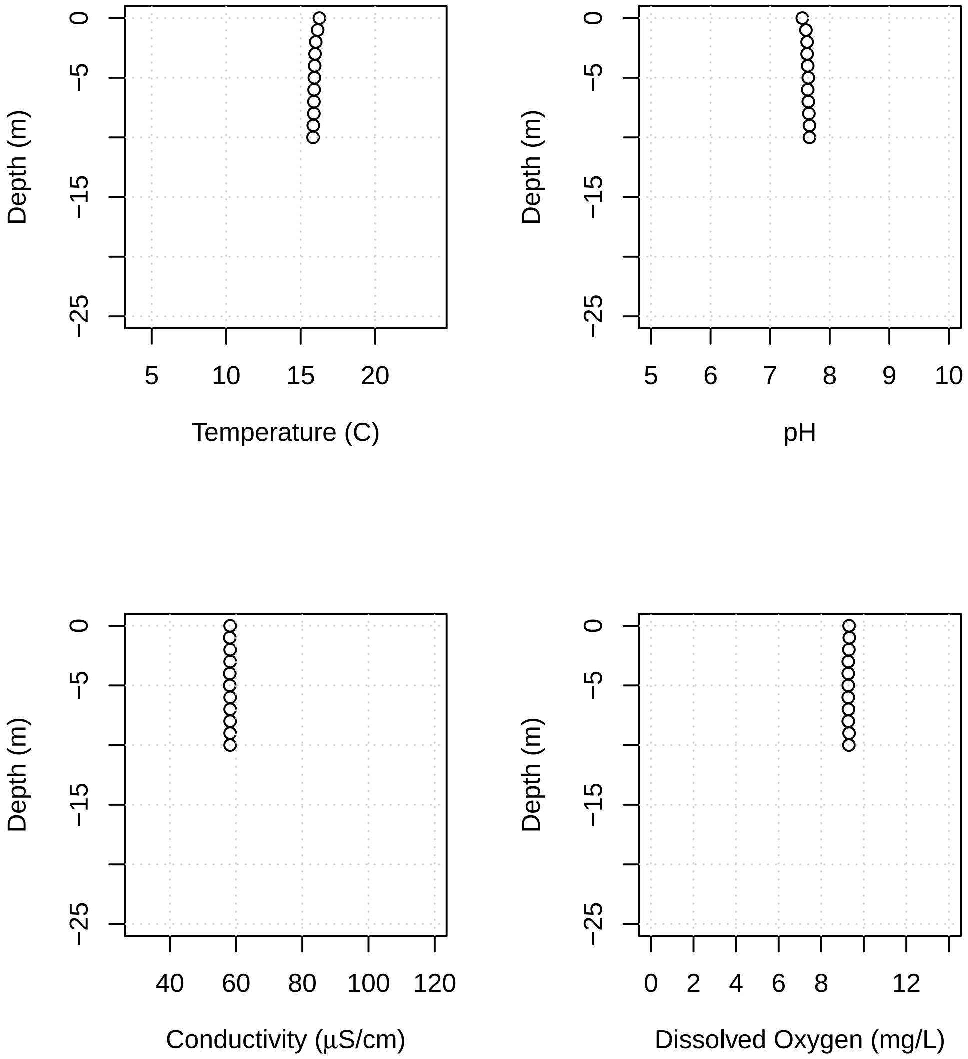

Figure B3: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, October 7, 2021.

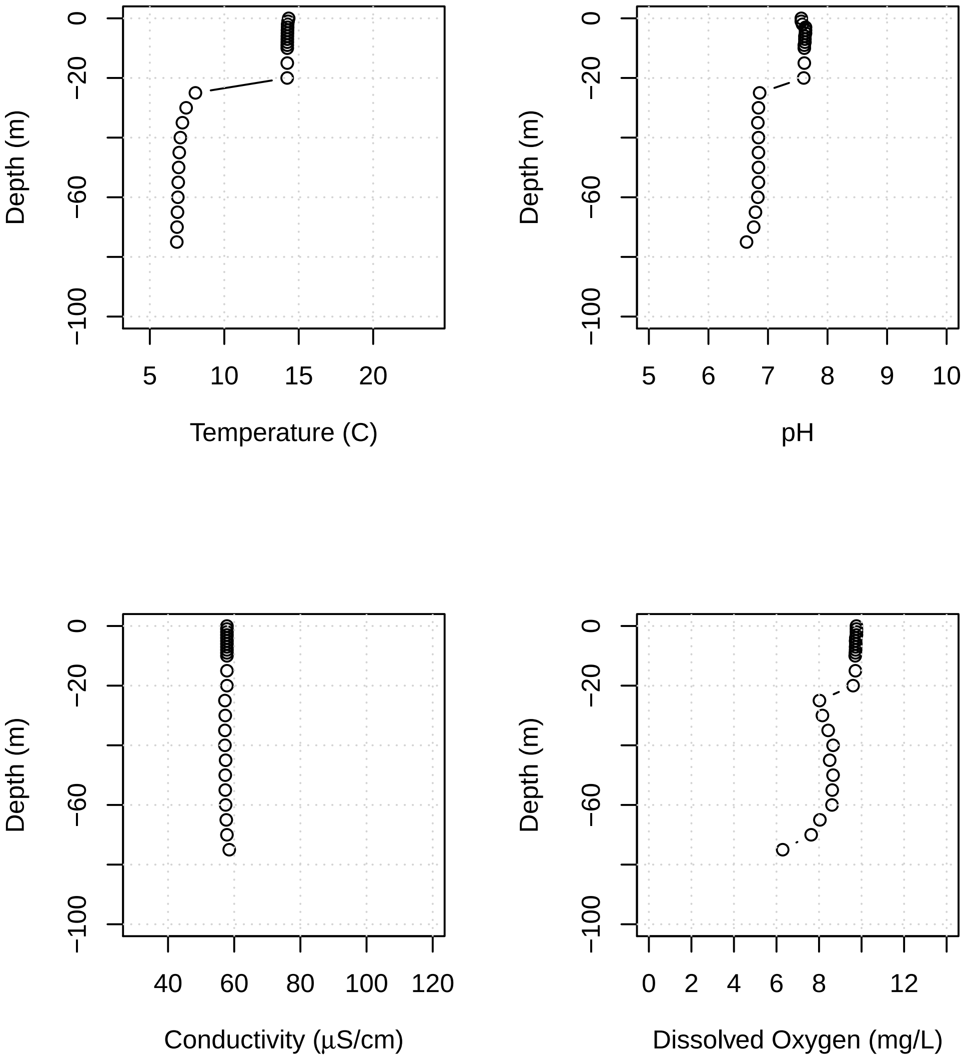

Figure B4: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, October 19, 2021.

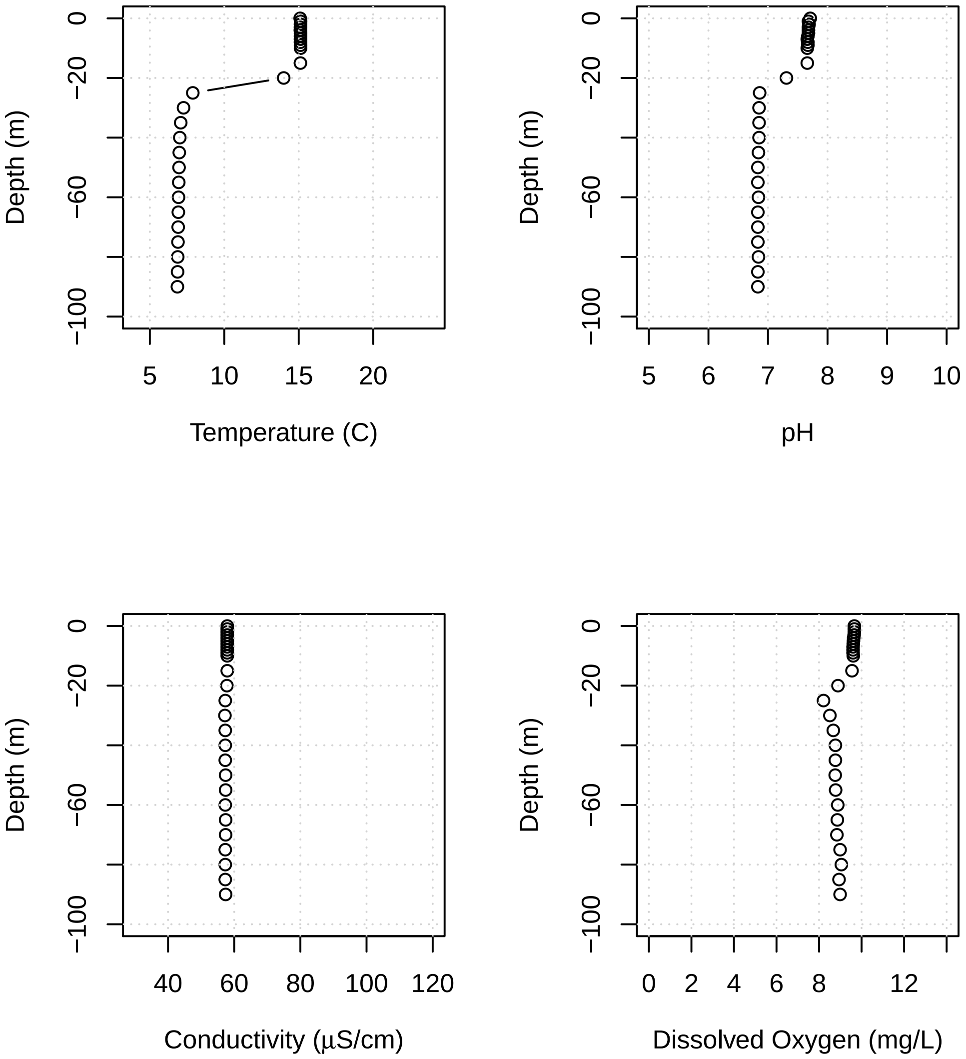

Figure B5: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, October 12, 2021.

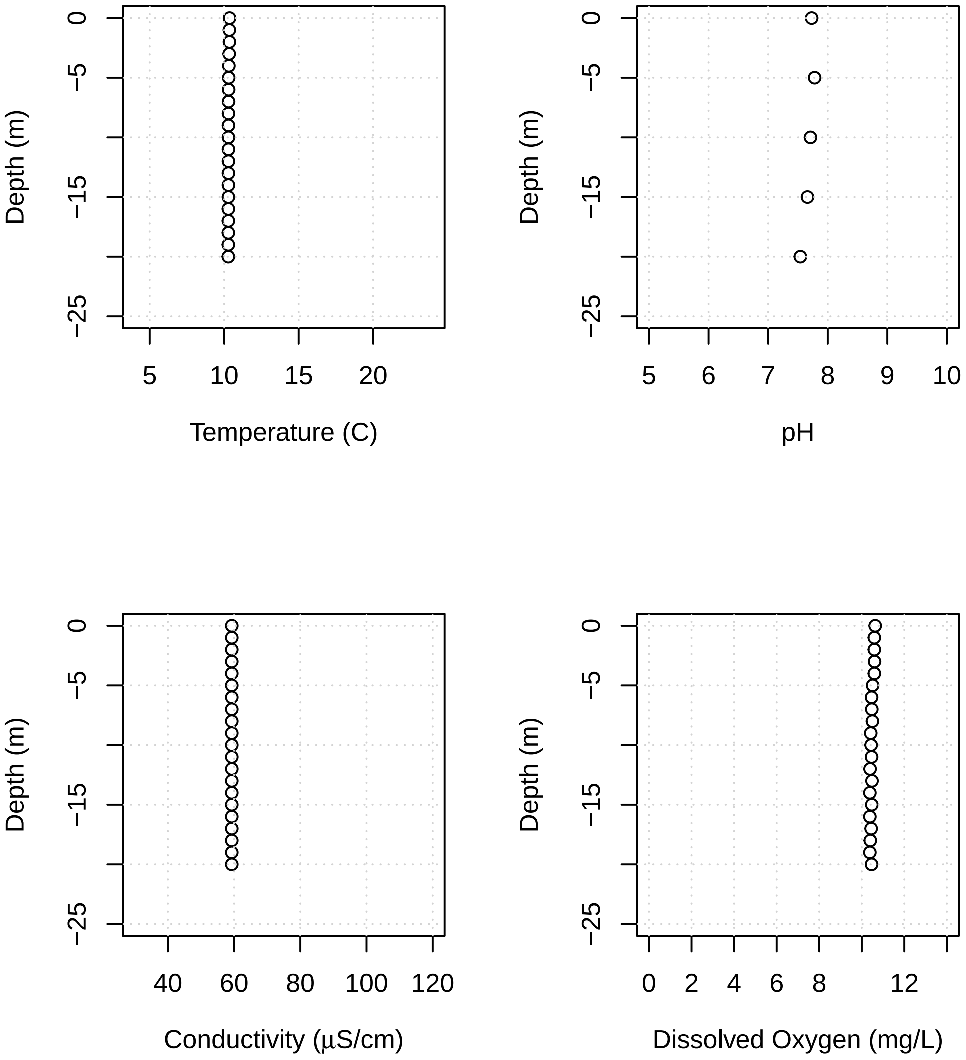

Figure B6: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, November 11, 2021.

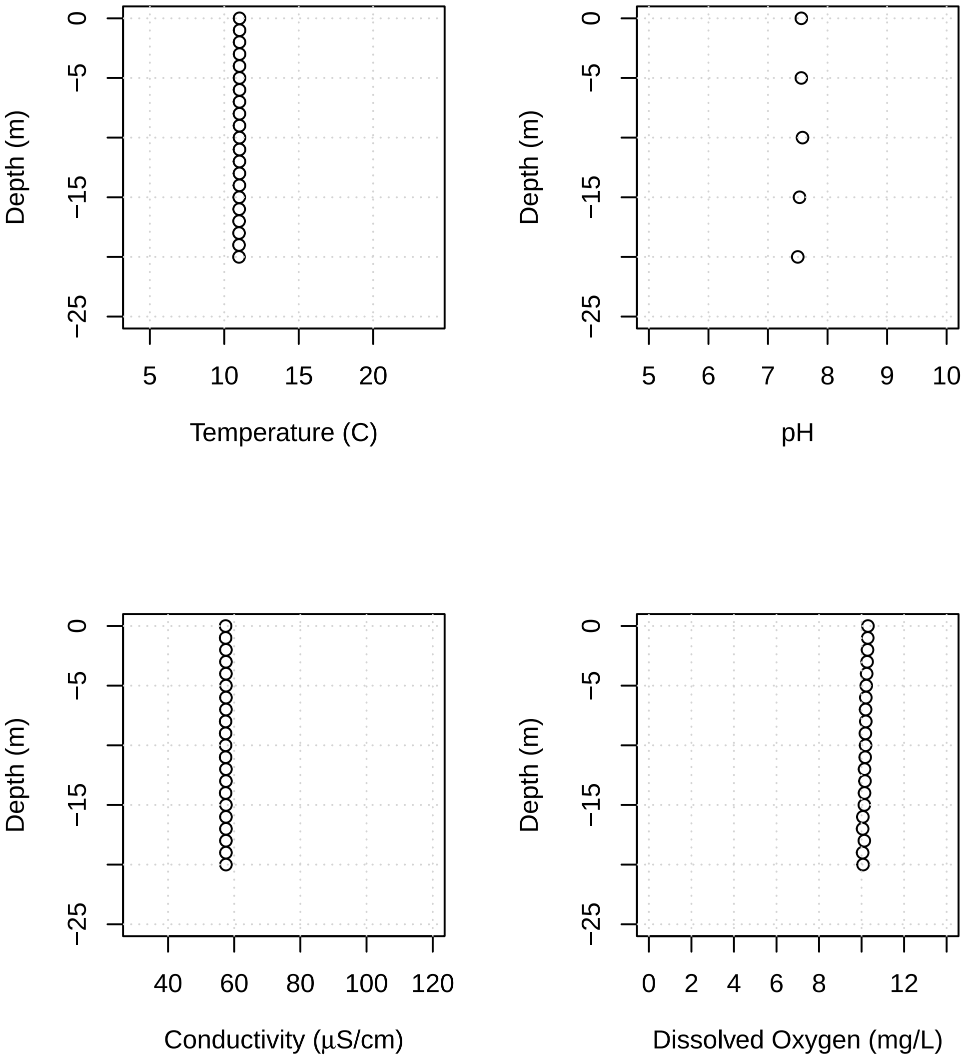

Figure B7: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, November 11, 2021.

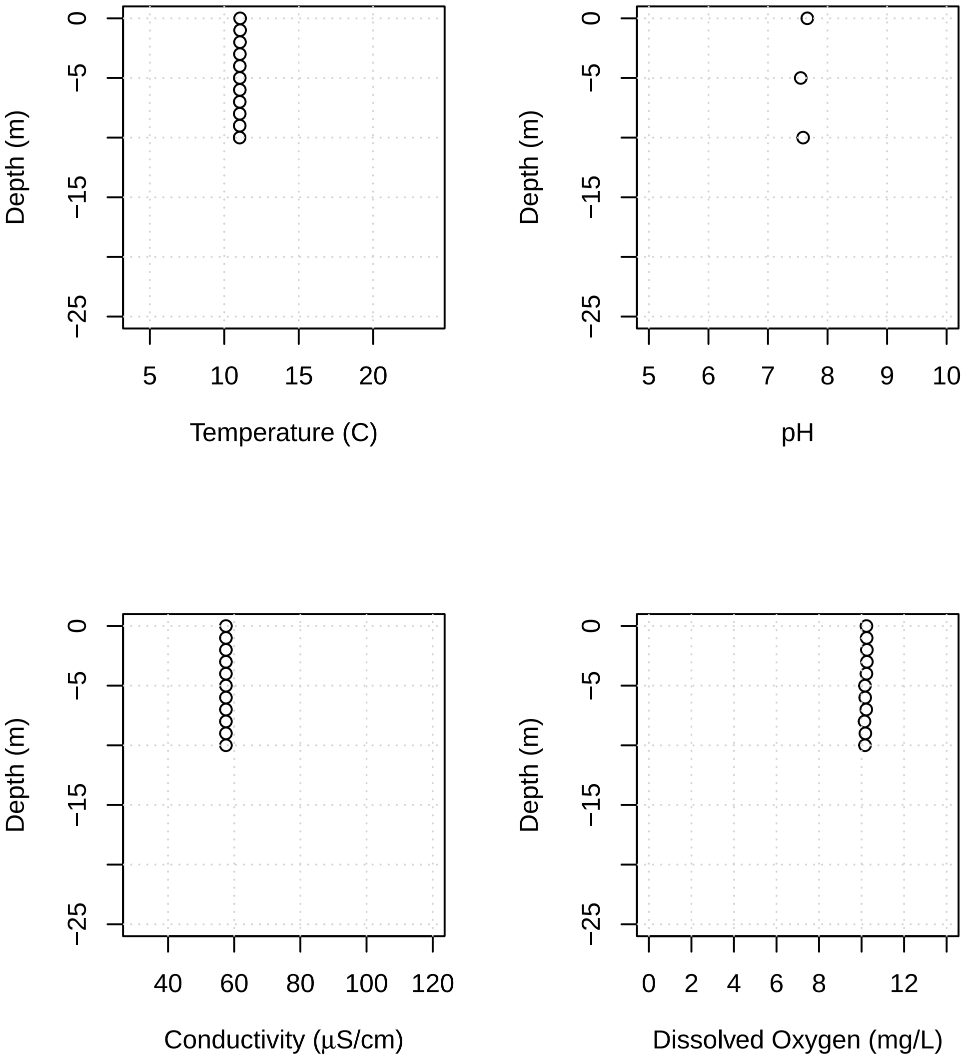

Figure B8: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, November 11, 2021.

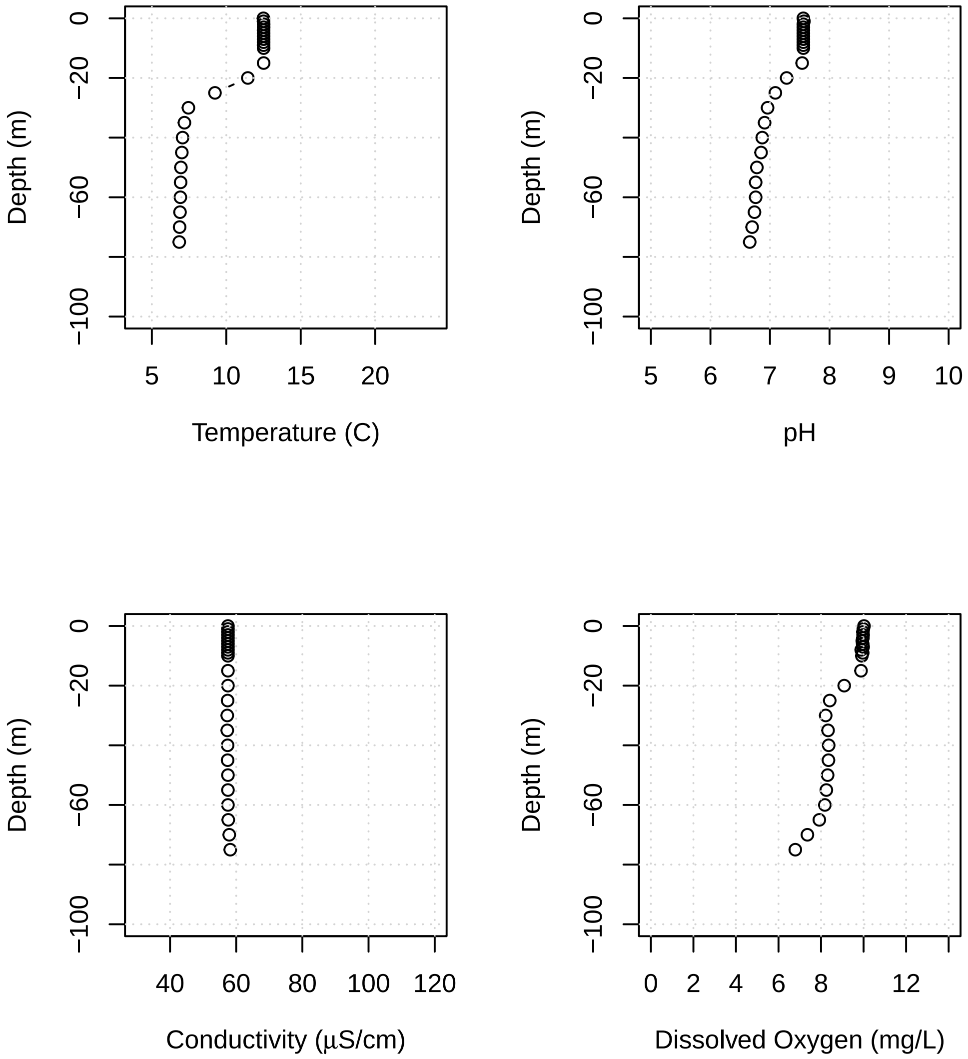

Figure B9: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, November 2, 2021.

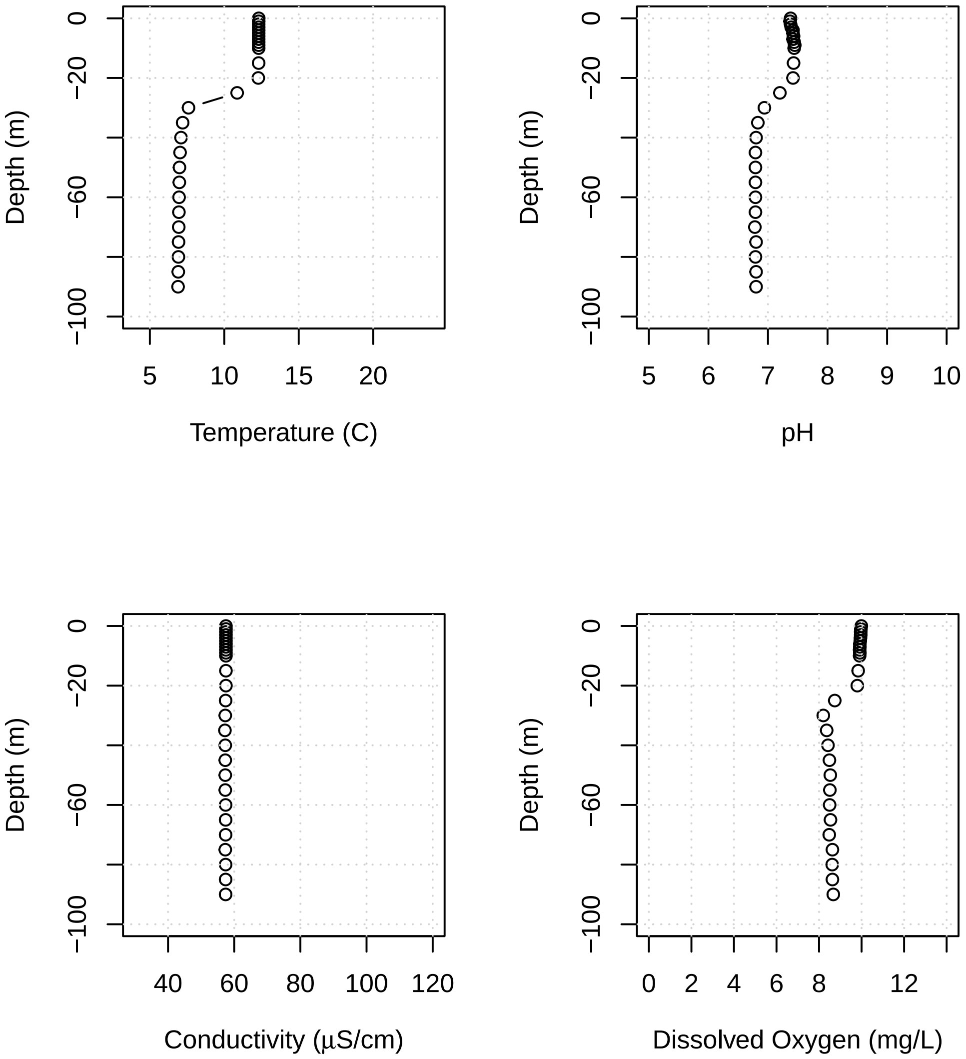

Figure B10: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, November 2, 2021.

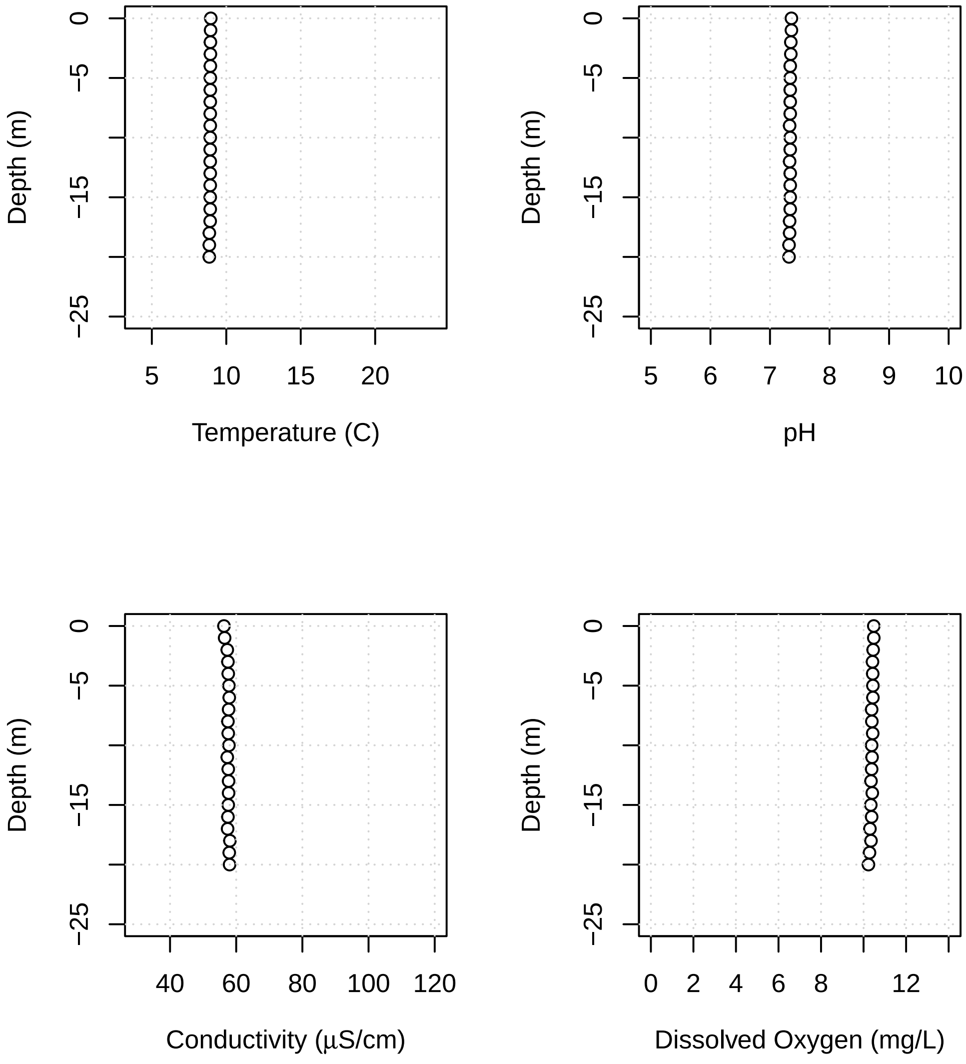

Figure B11: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, December 9, 2021.

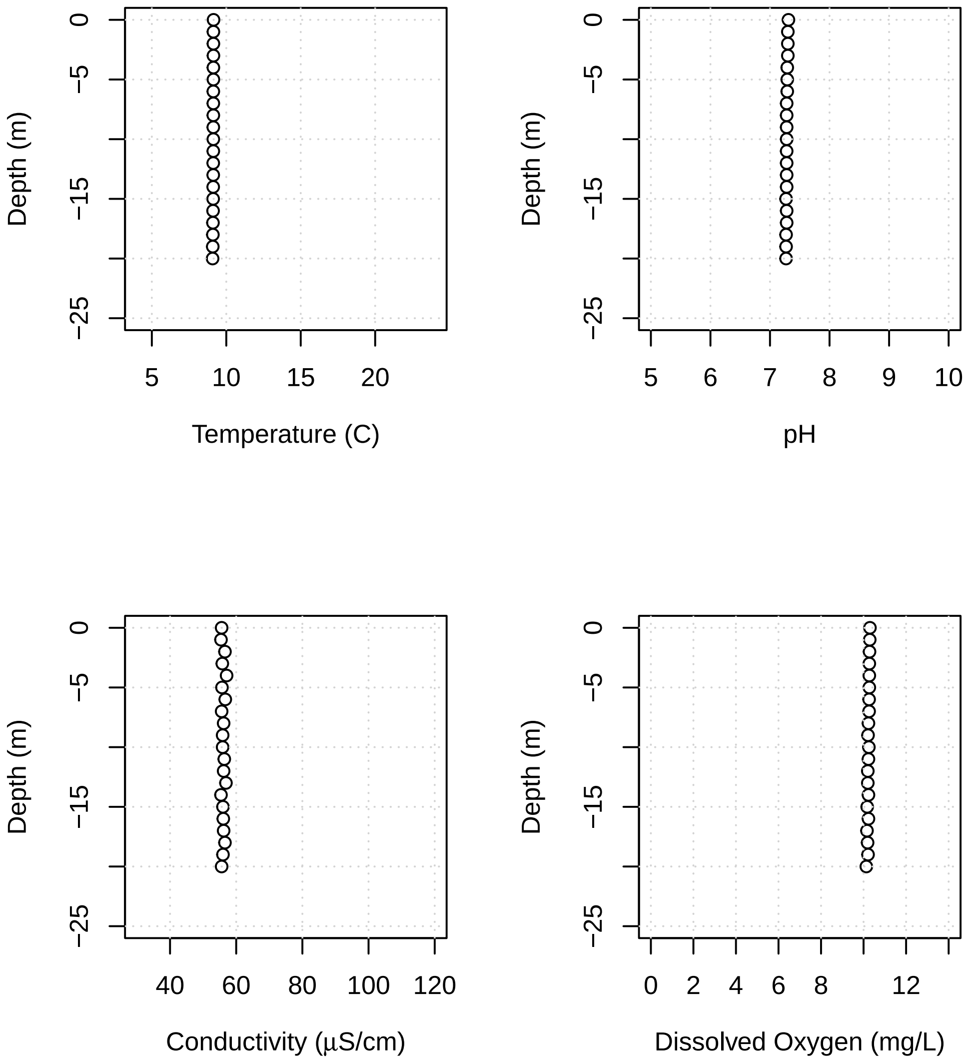

Figure B12: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, December 9, 2021.

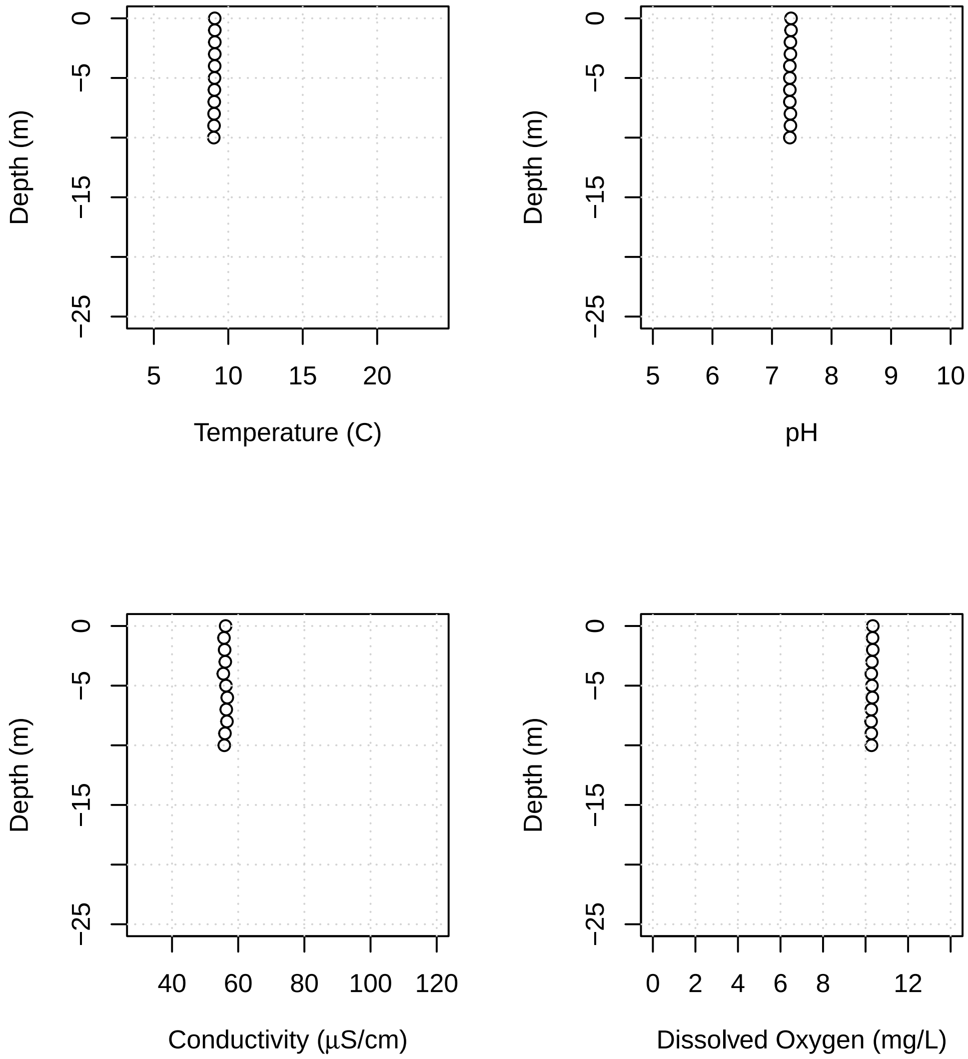

Figure B13: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, December 9, 2021.

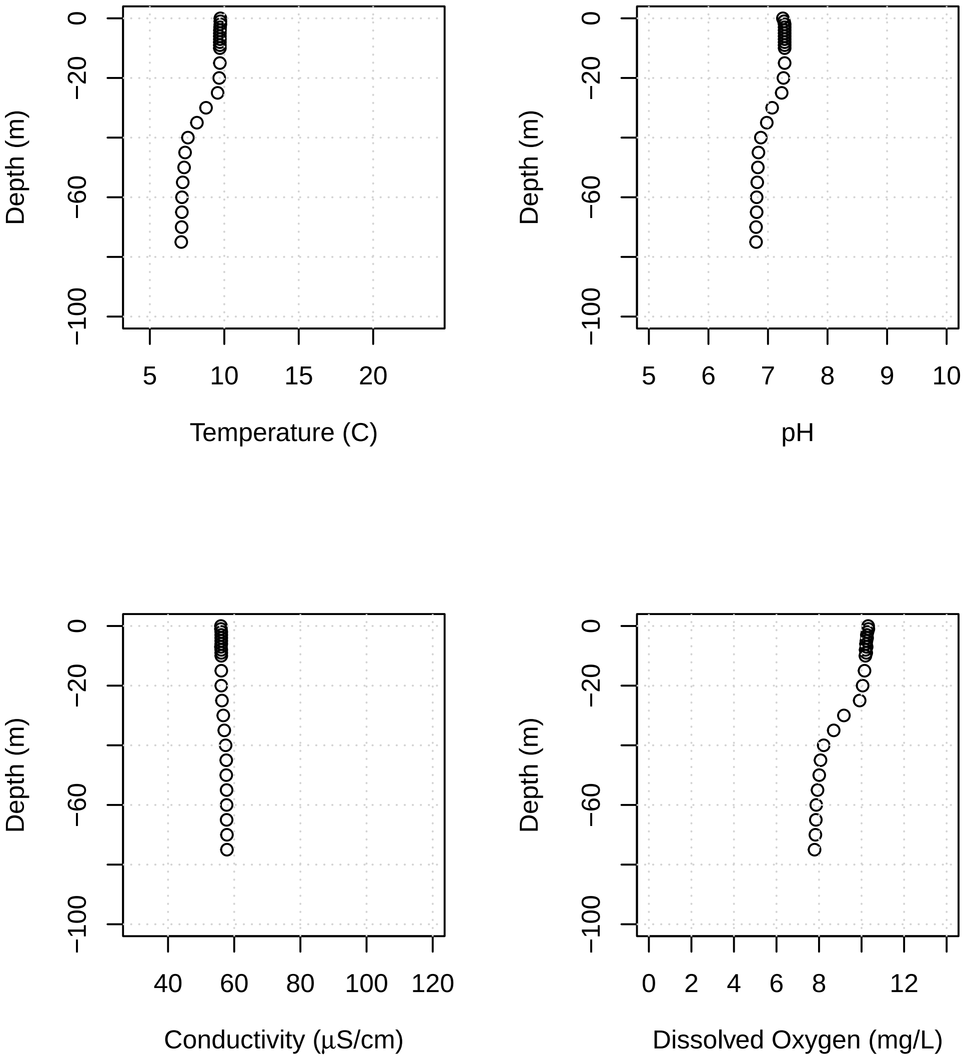

Figure B14: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, December 2, 2021.

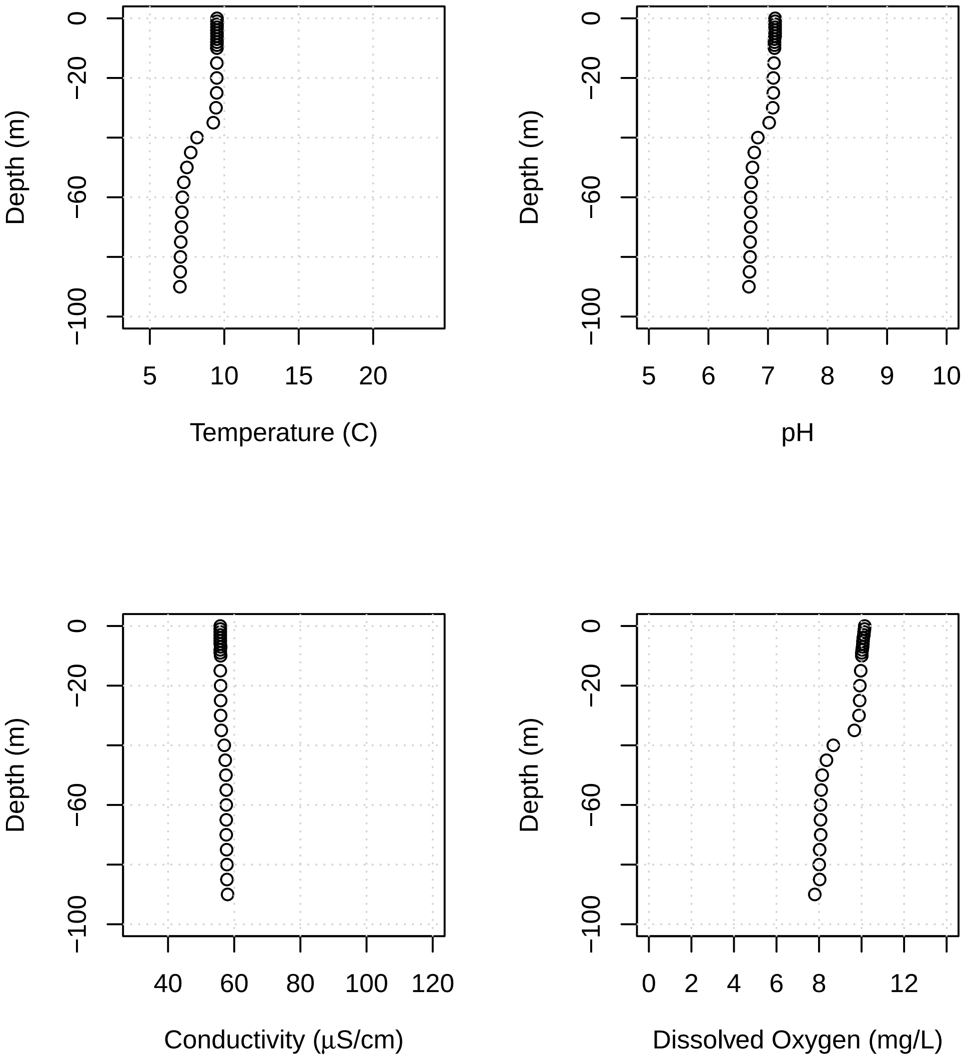

Figure B15: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, December 2, 2021.

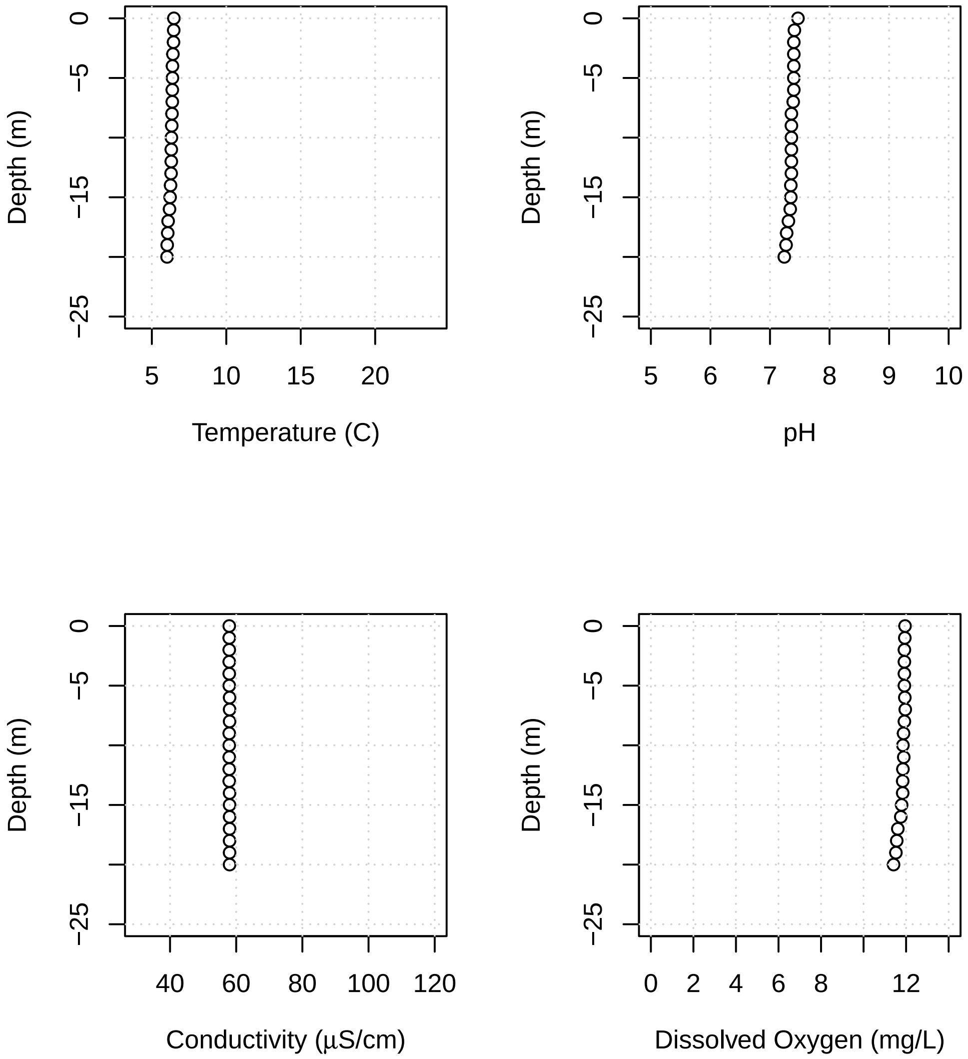

Figure B16: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, February 16, 2022.

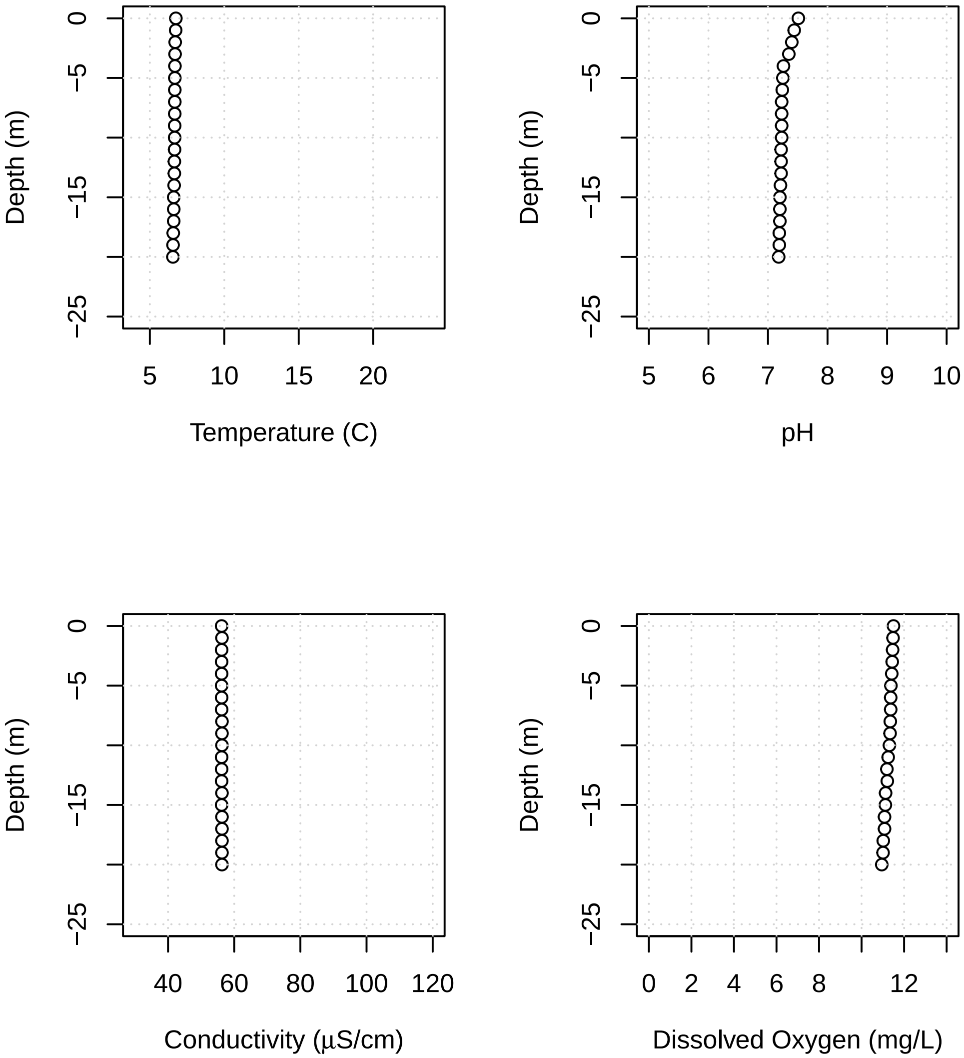

Figure B17: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, February 16, 2022.

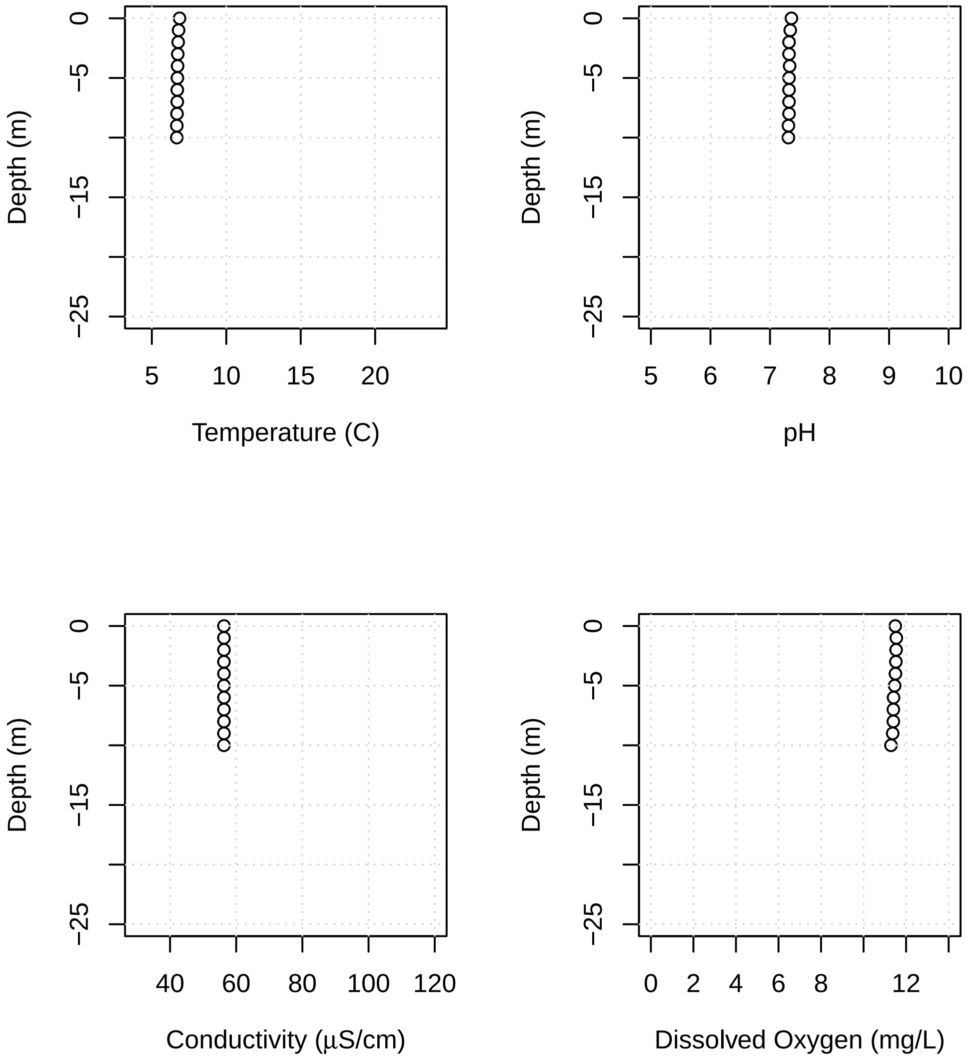

Figure B18: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, February 16, 2022.

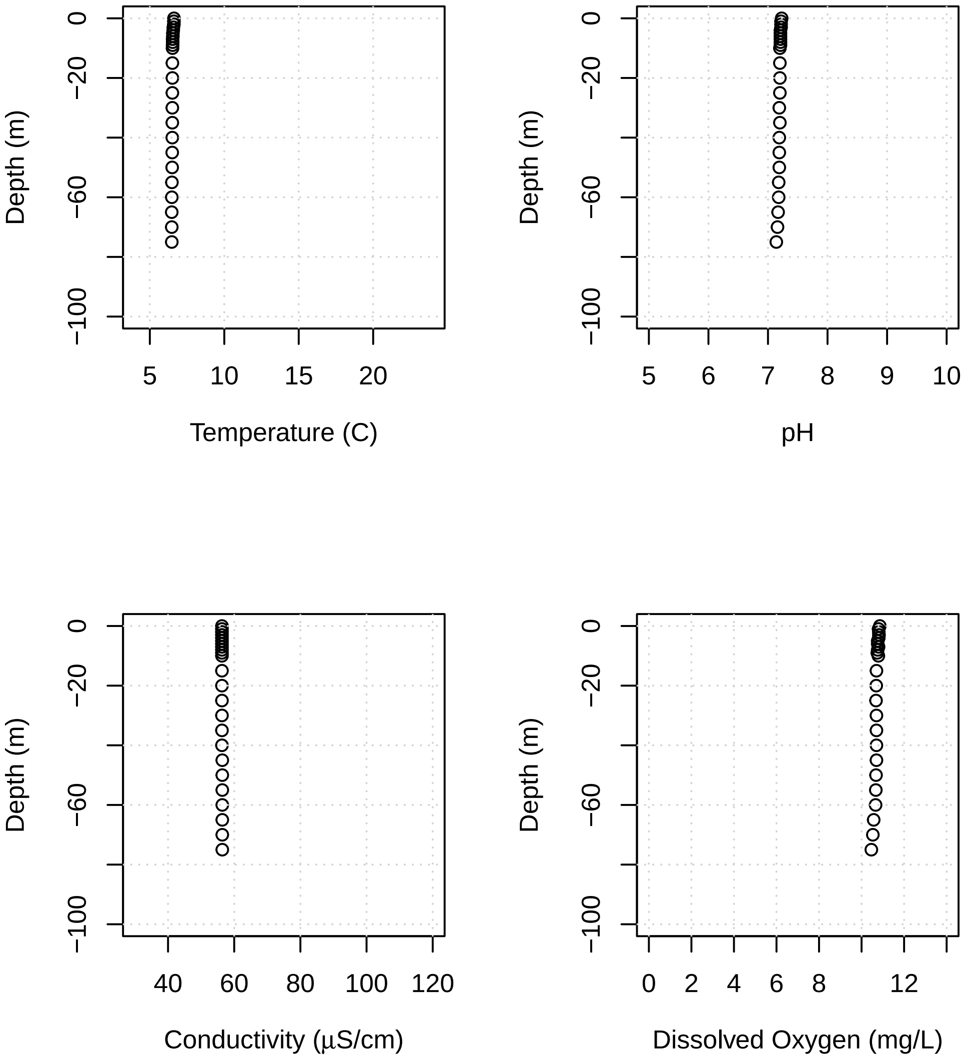

Figure B19: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, February 14, 2022.

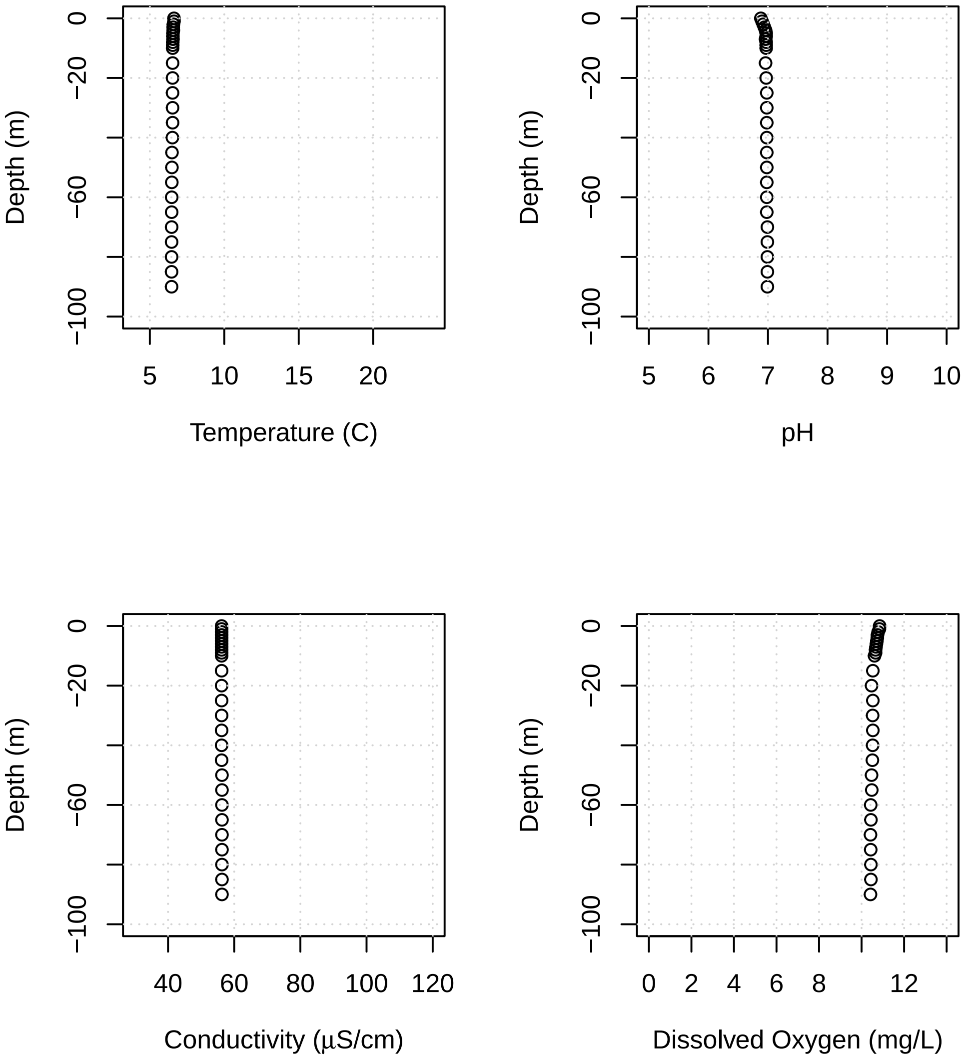

Figure B20: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, February 14, 2022.

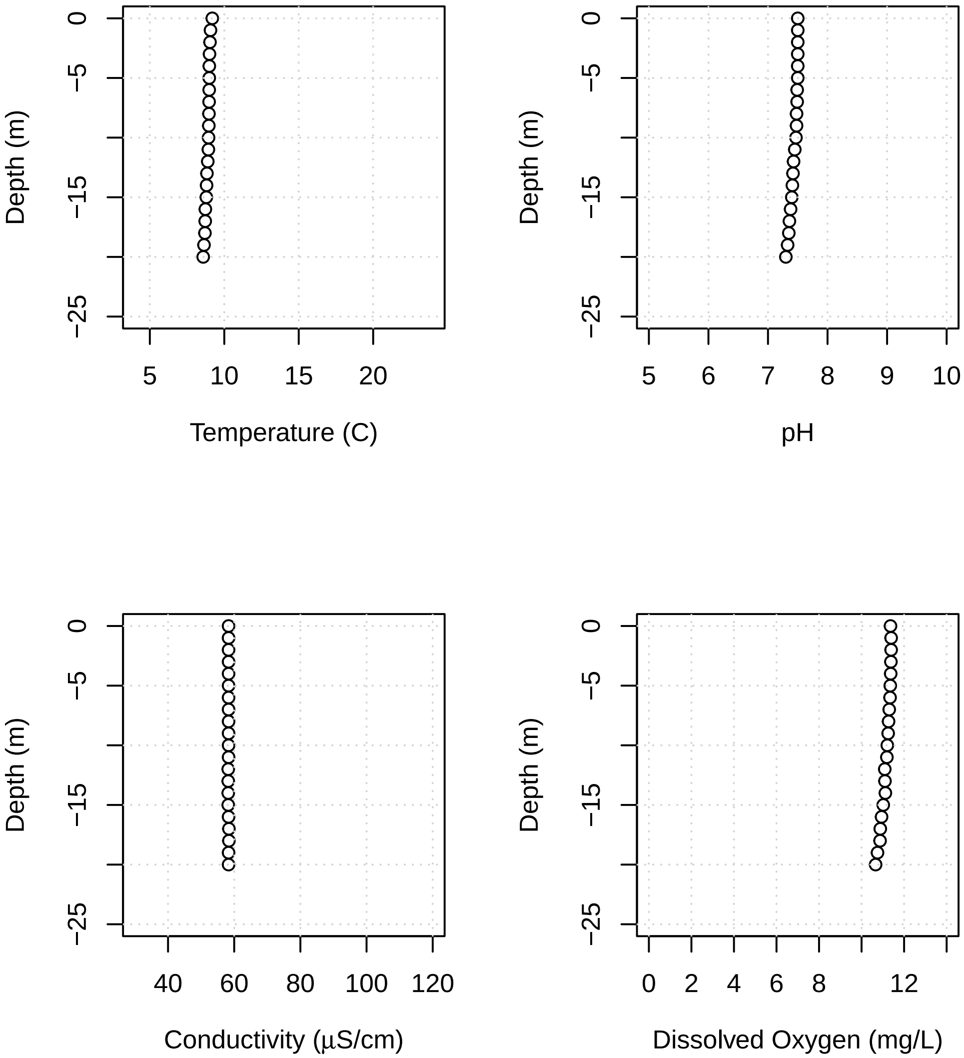

Figure B21: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, April 14, 2022.

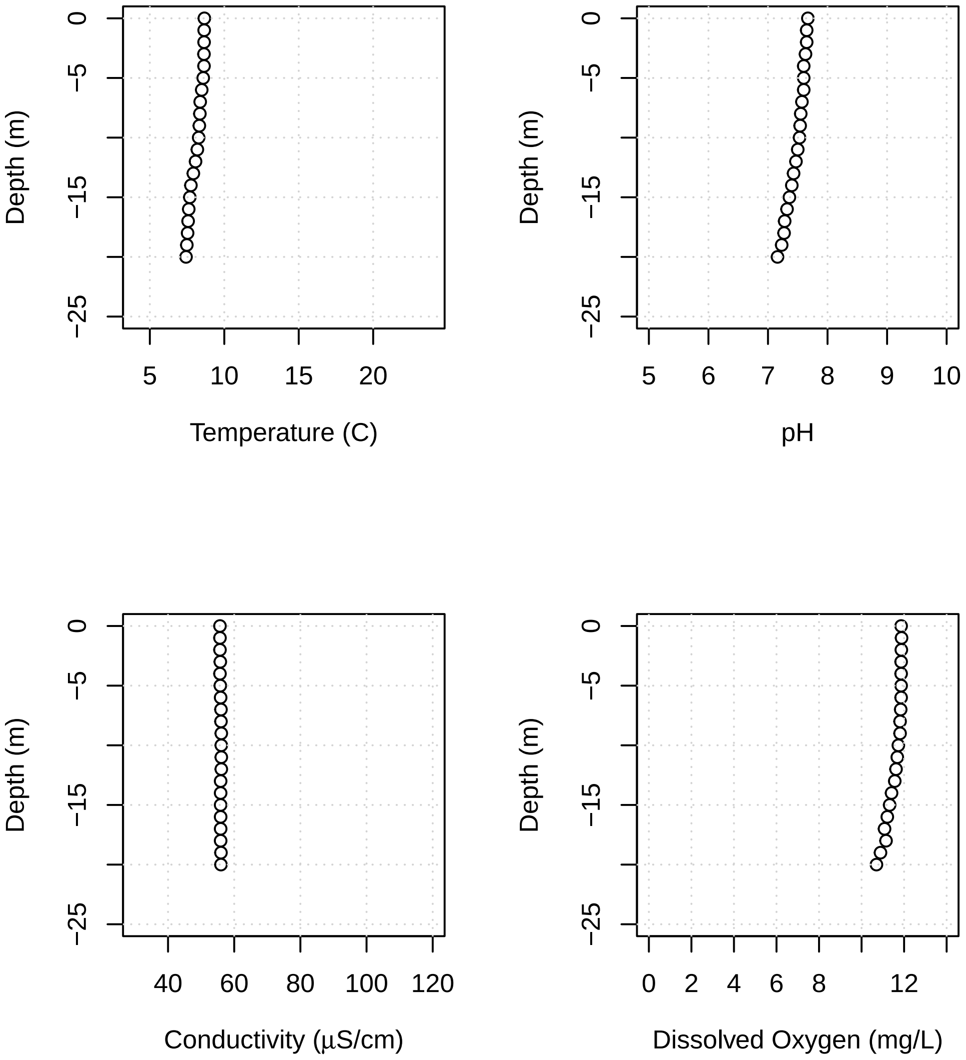

Figure B22: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, April 11, 2022.

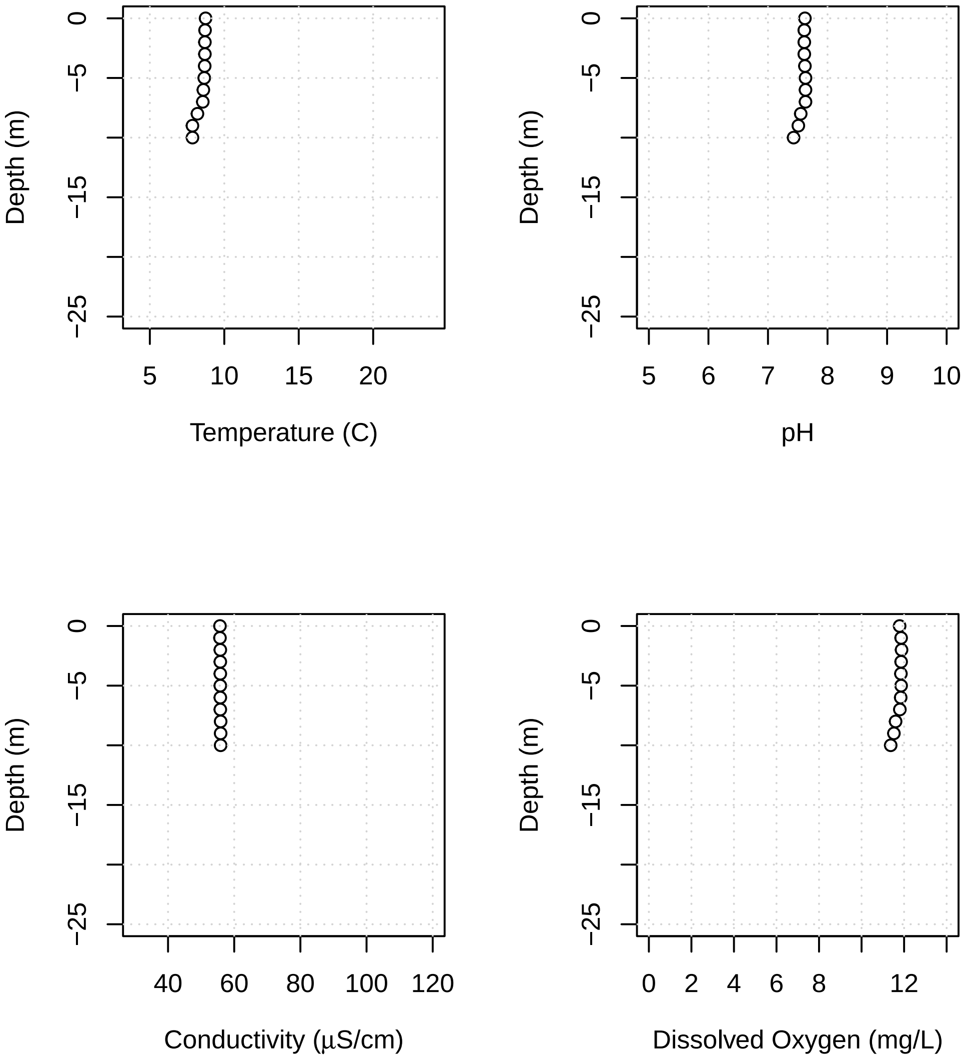

Figure B23: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, April 11, 2022.

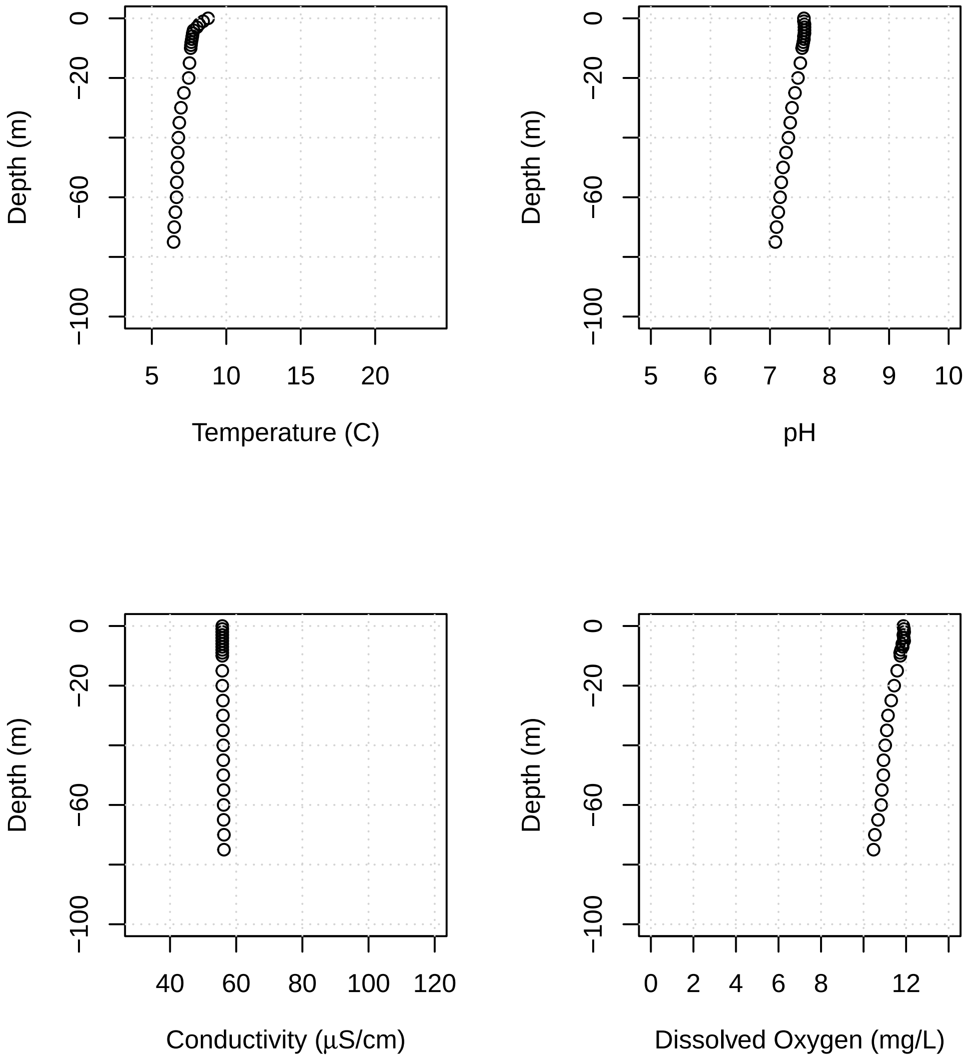

Figure B24: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, April 7, 2022.

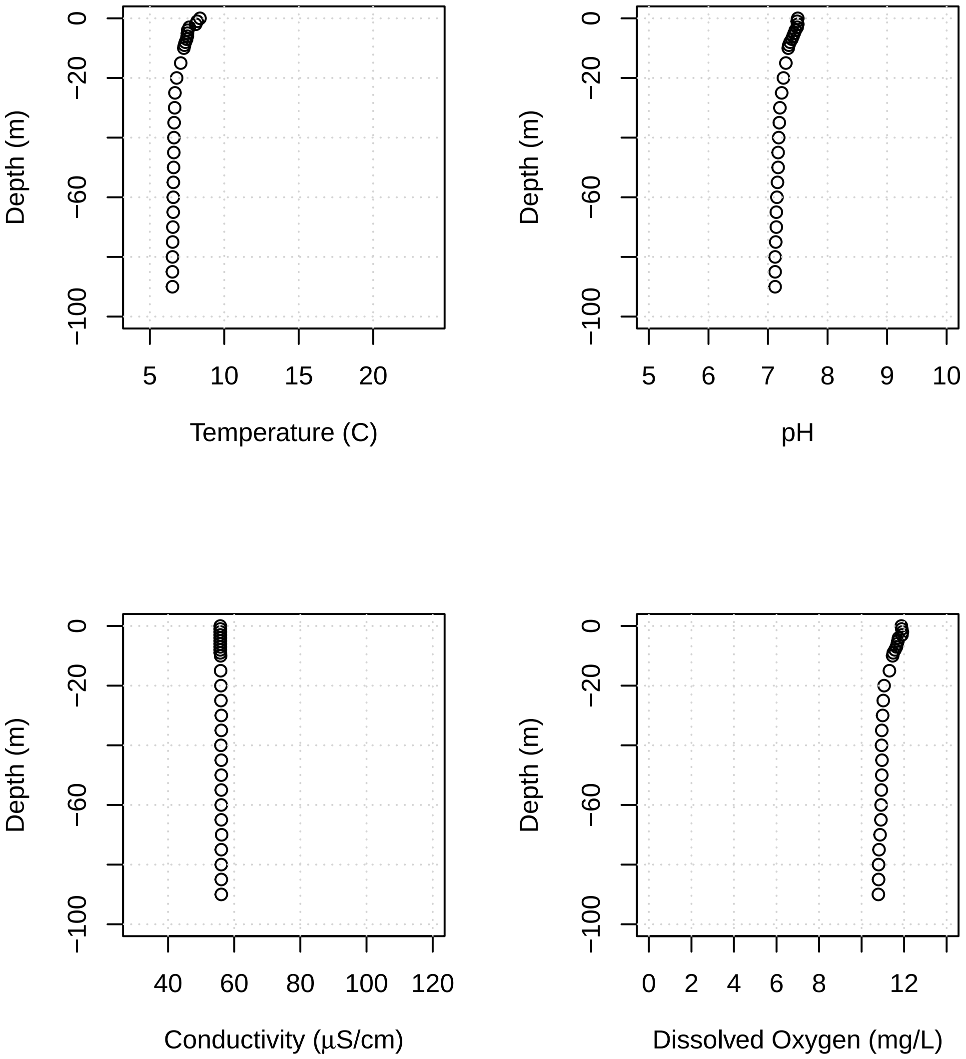

Figure B25: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, April 7, 2022.

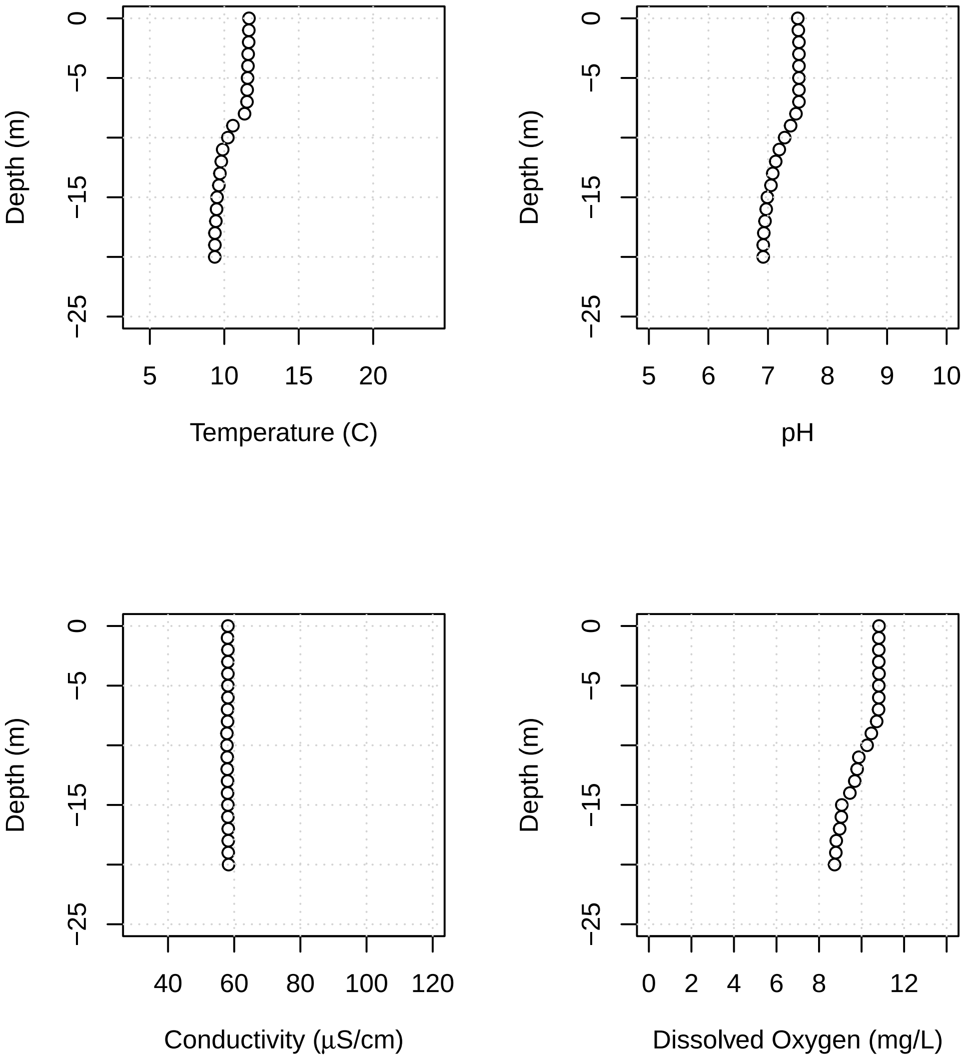

Figure B26: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, May 10, 2022.

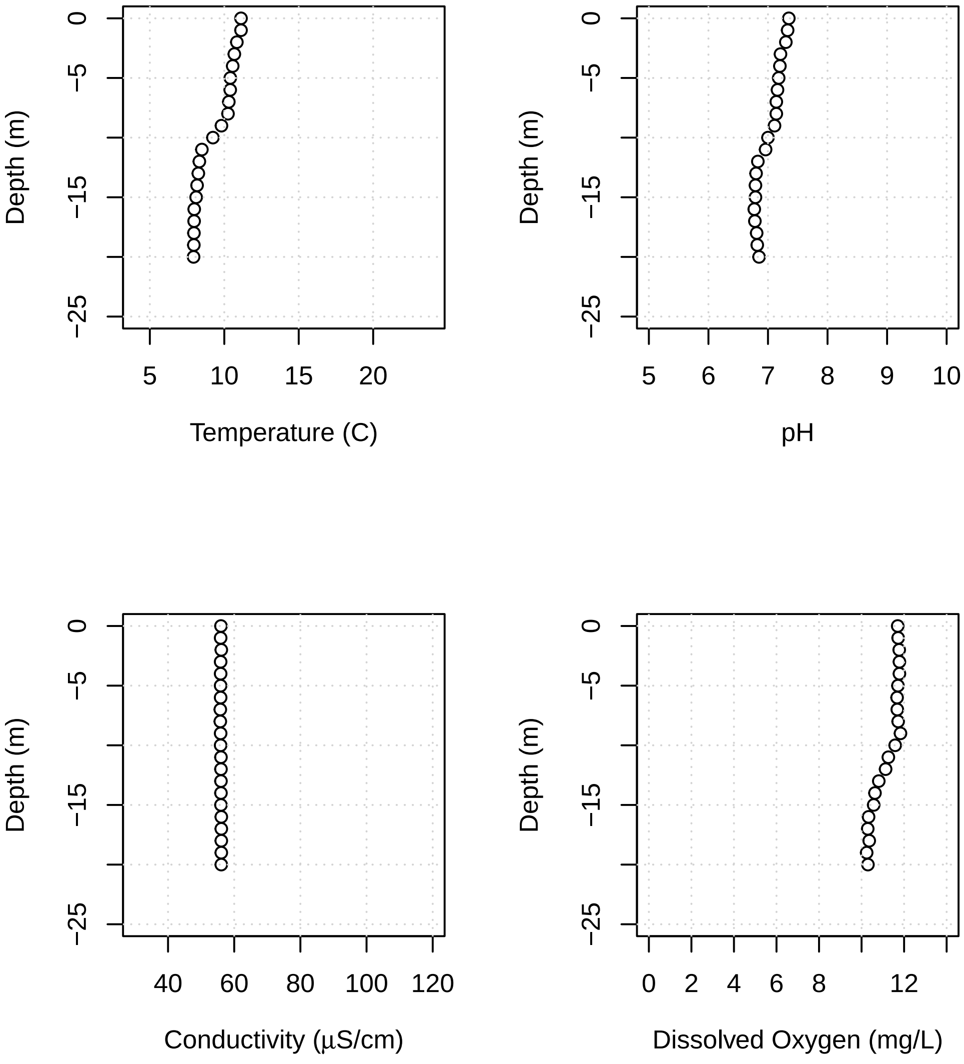

Figure B27: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, May 5, 2022.

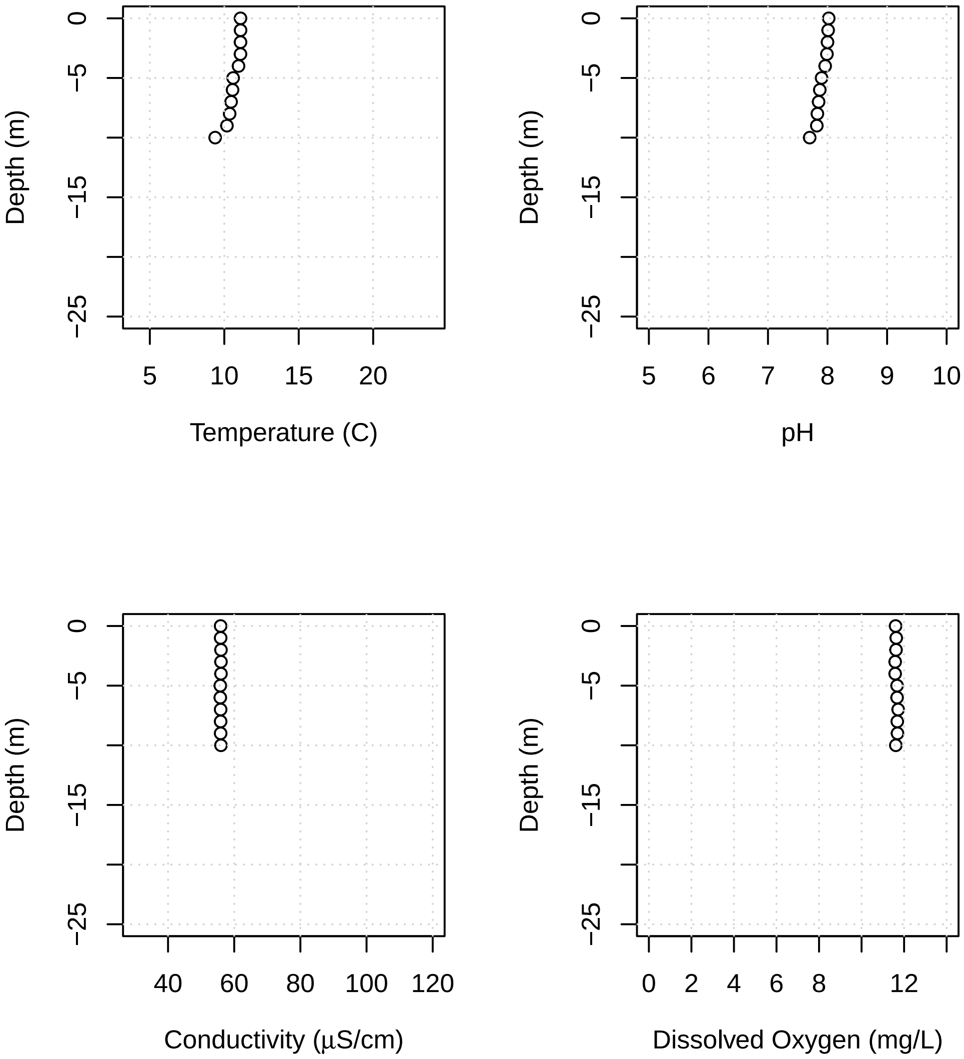

Figure B28: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, May 5, 2022.

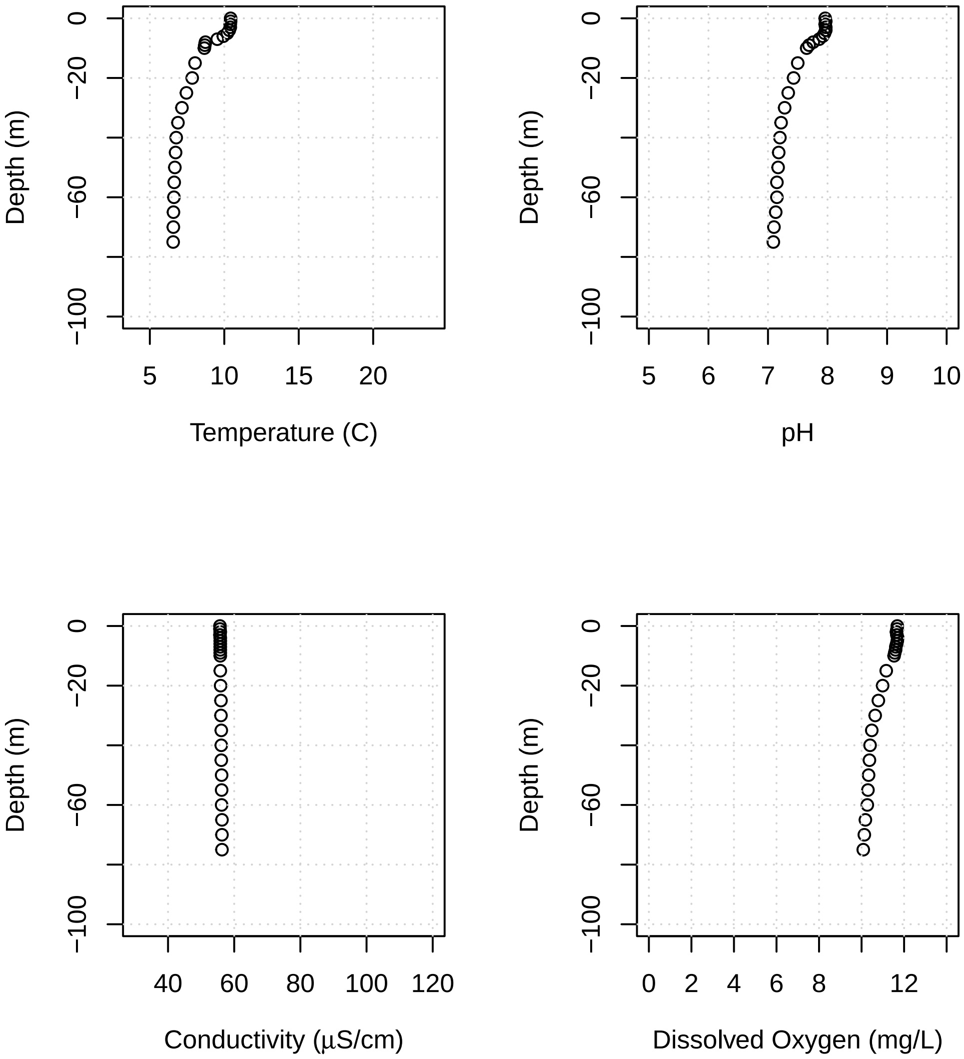

Figure B29: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, May 3, 2022.

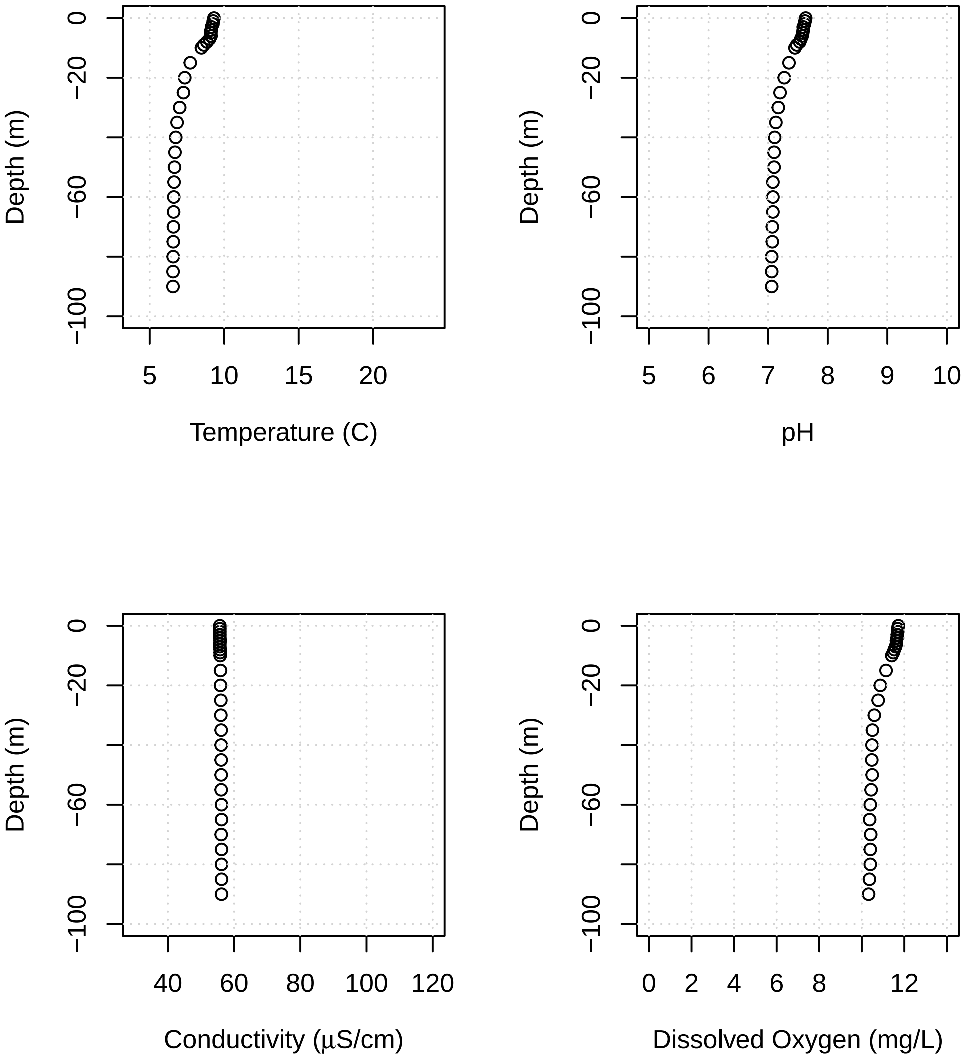

Figure B30: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, May 3, 2022.

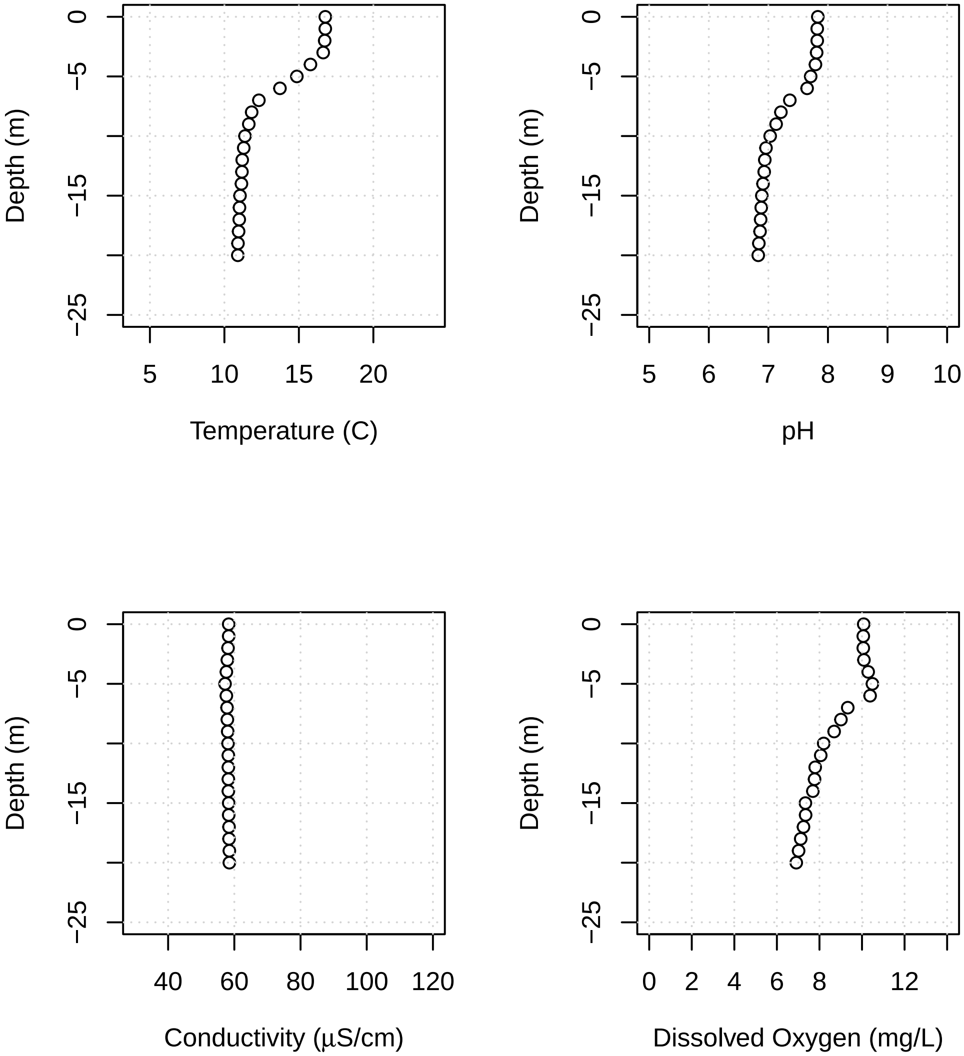

Figure B31: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, June 9, 2022.

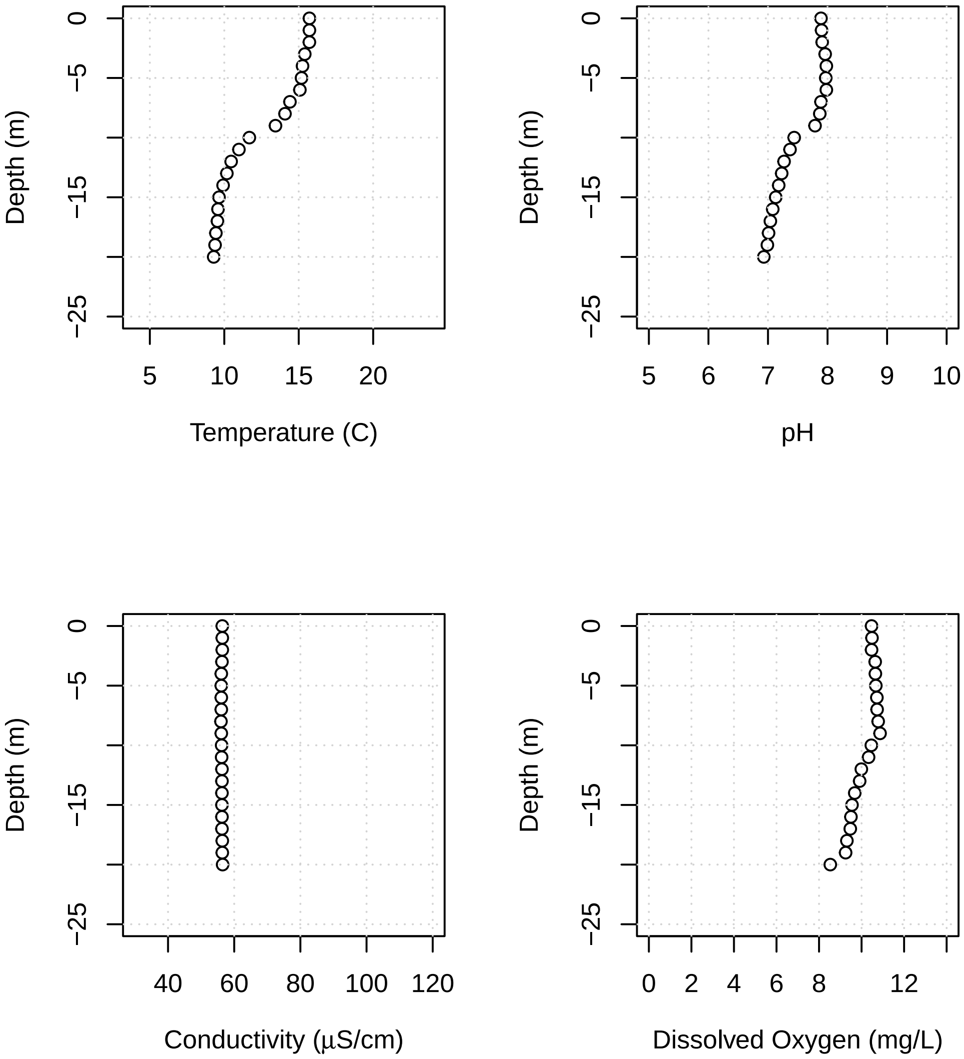

Figure B32: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, June 9, 2022.

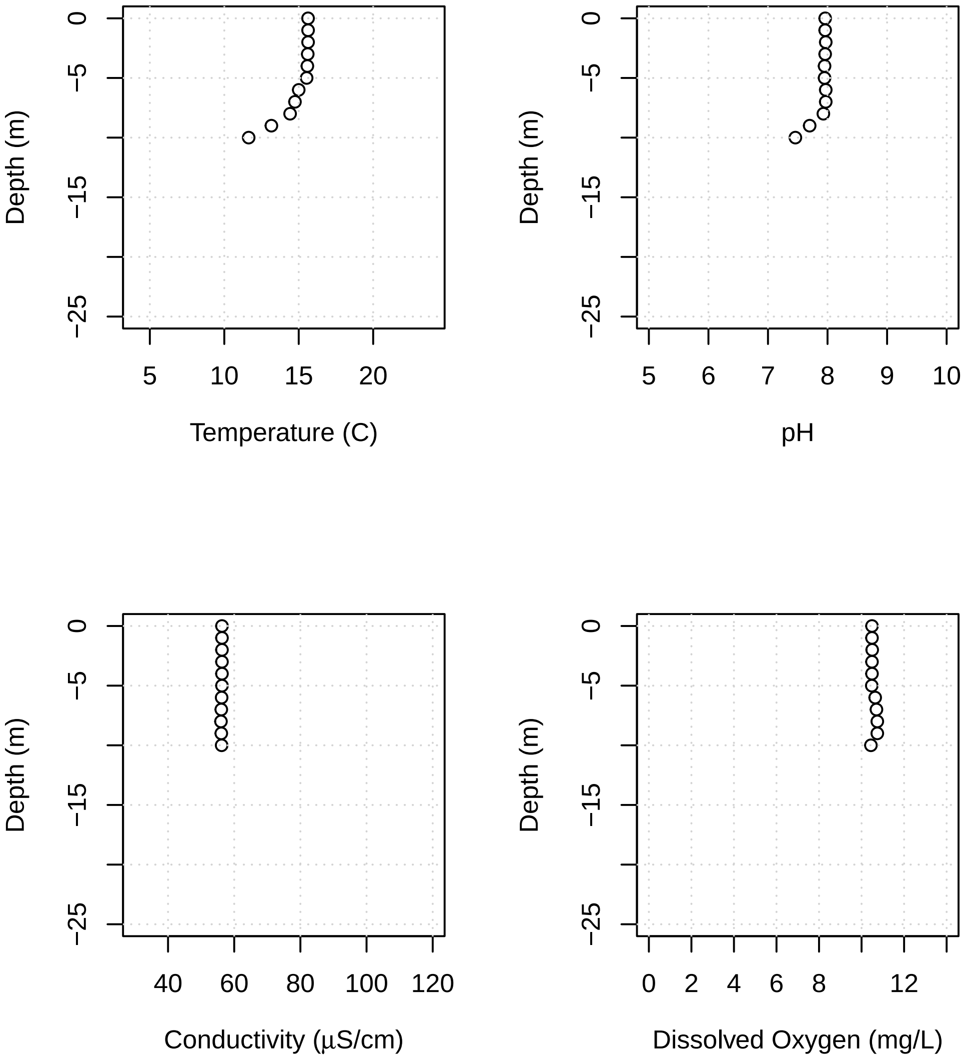

Figure B33: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, June 9, 2022.

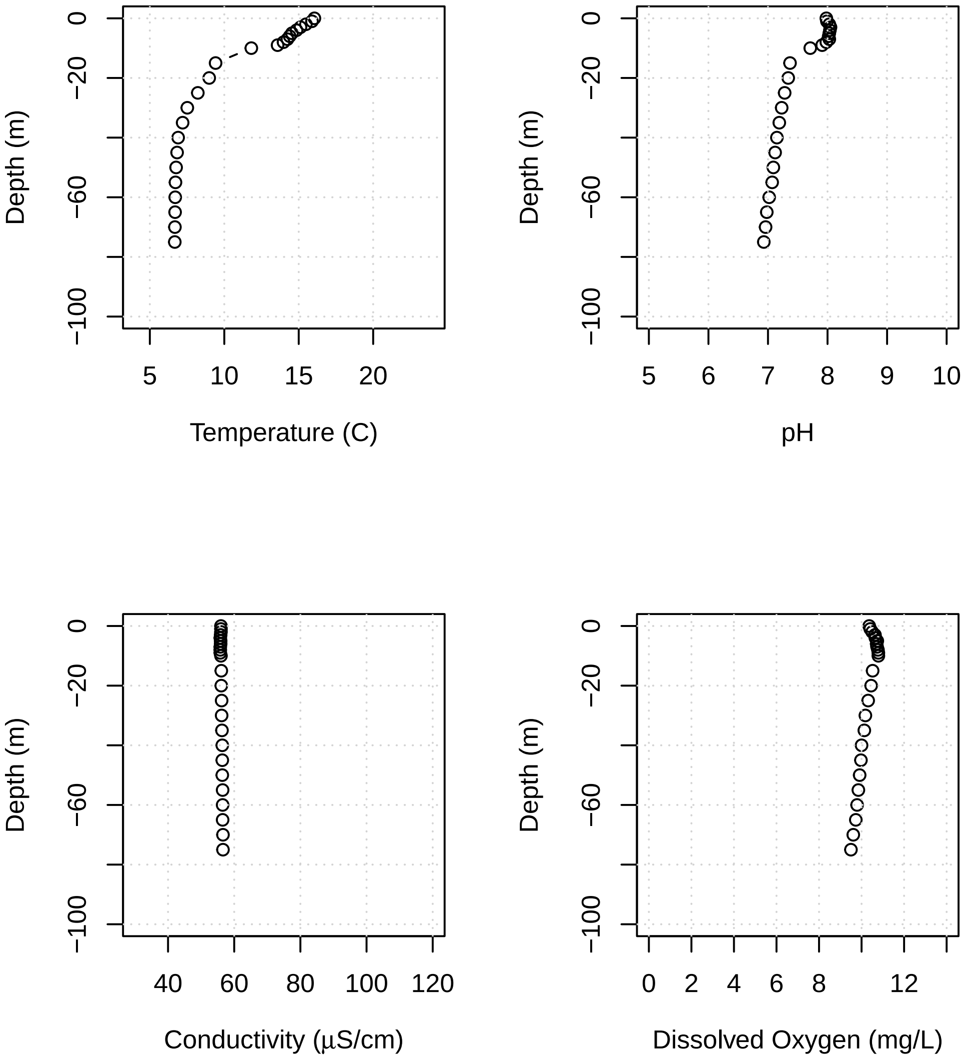

Figure B34: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, June 7, 2022.

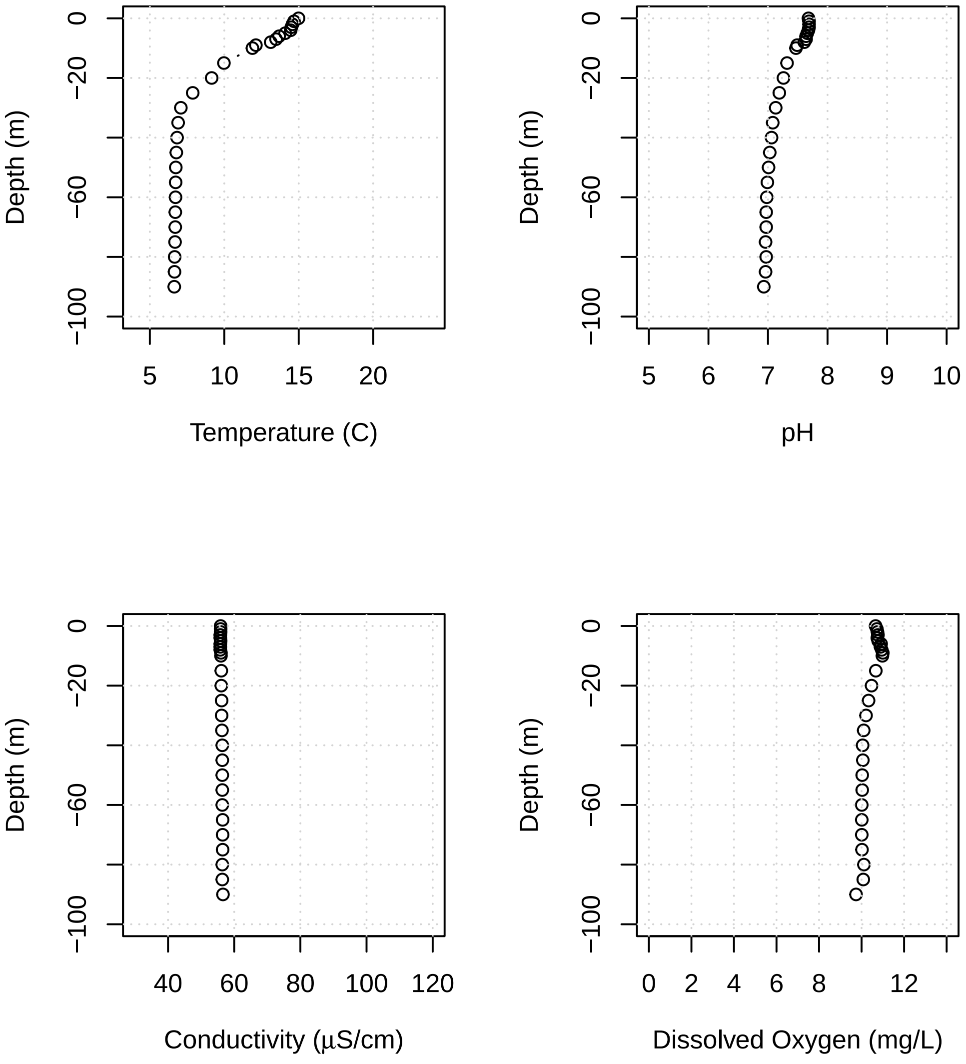

Figure B35: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, June 7, 2022.

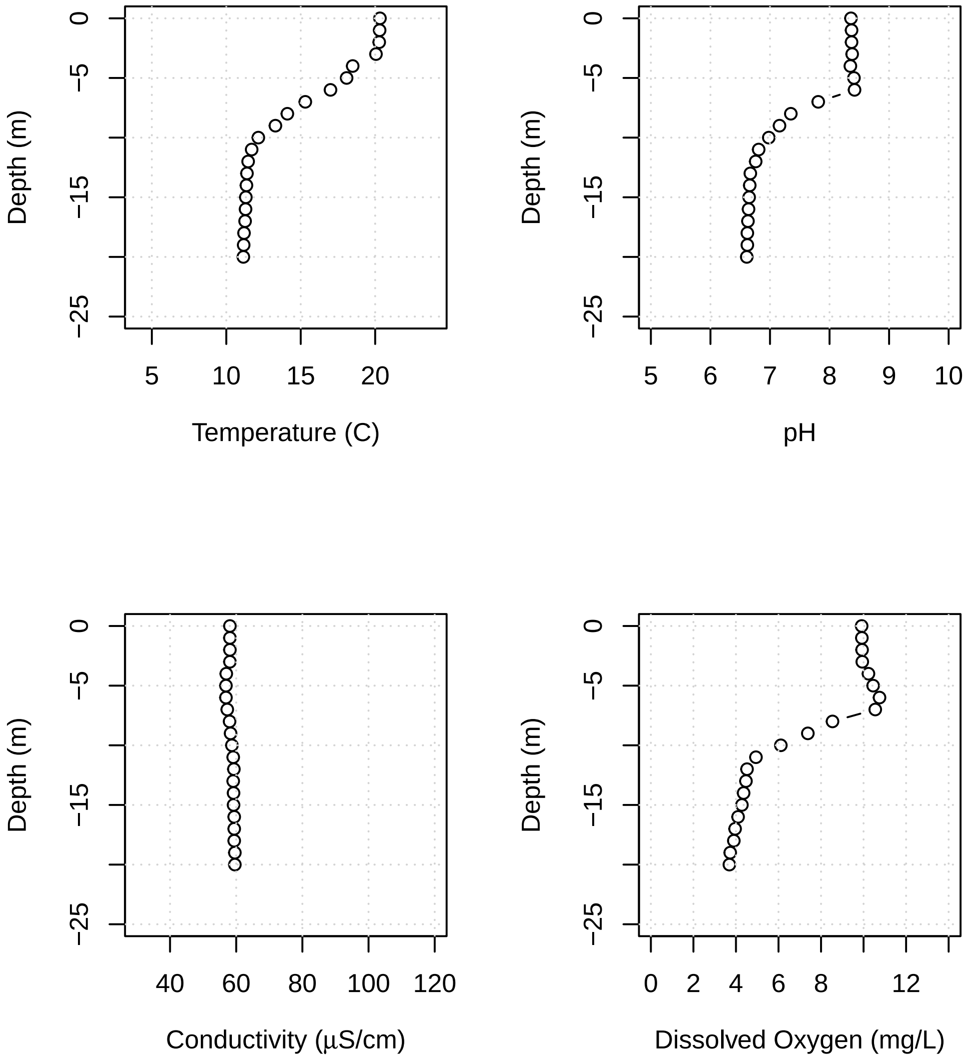

Figure B36: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, July 6, 2022.

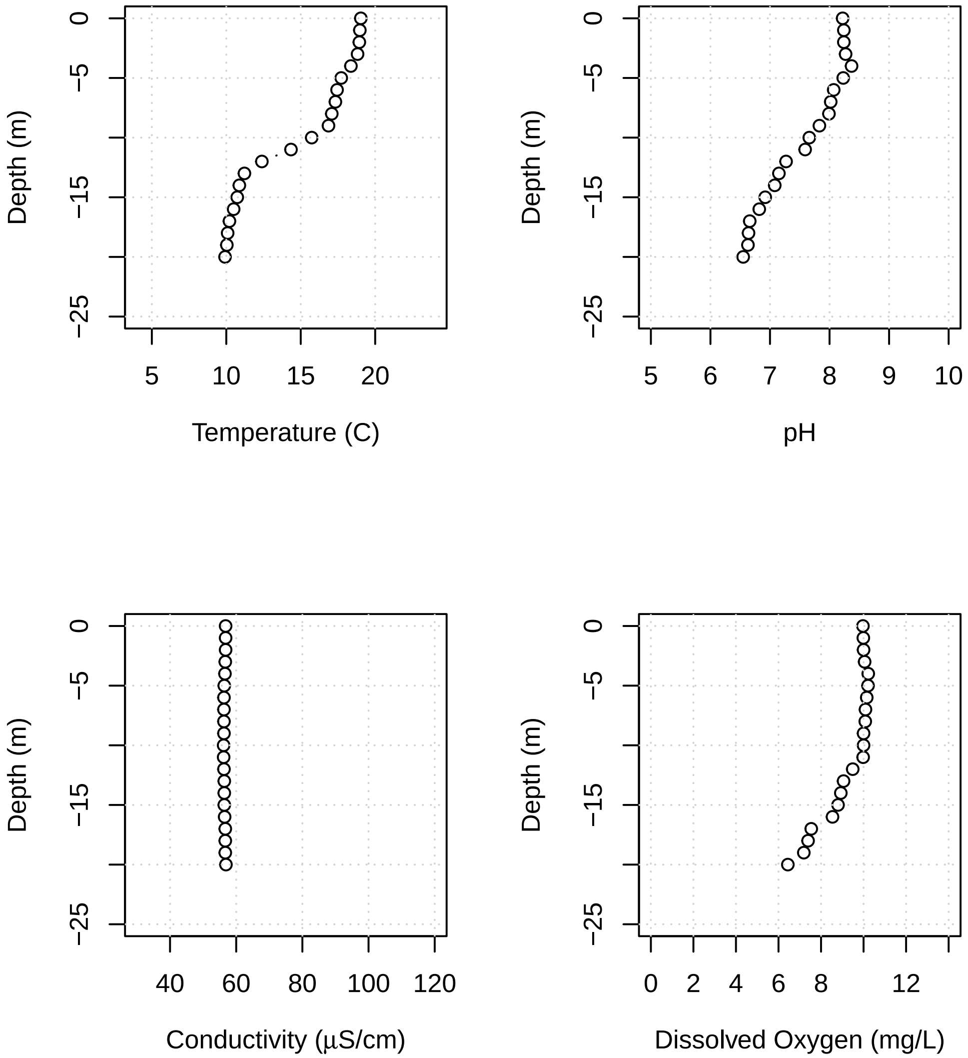

Figure B37: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, July 7, 2022.

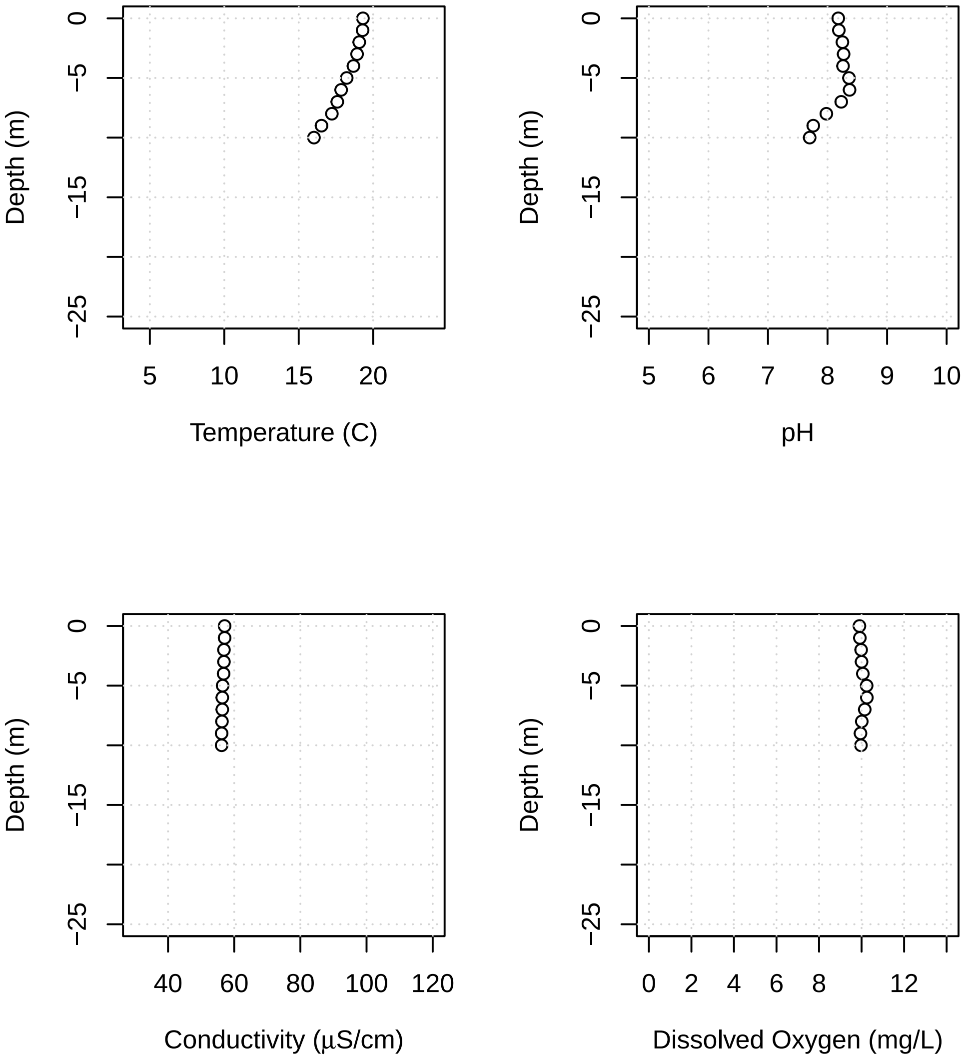

Figure B38: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, July 7, 2022.

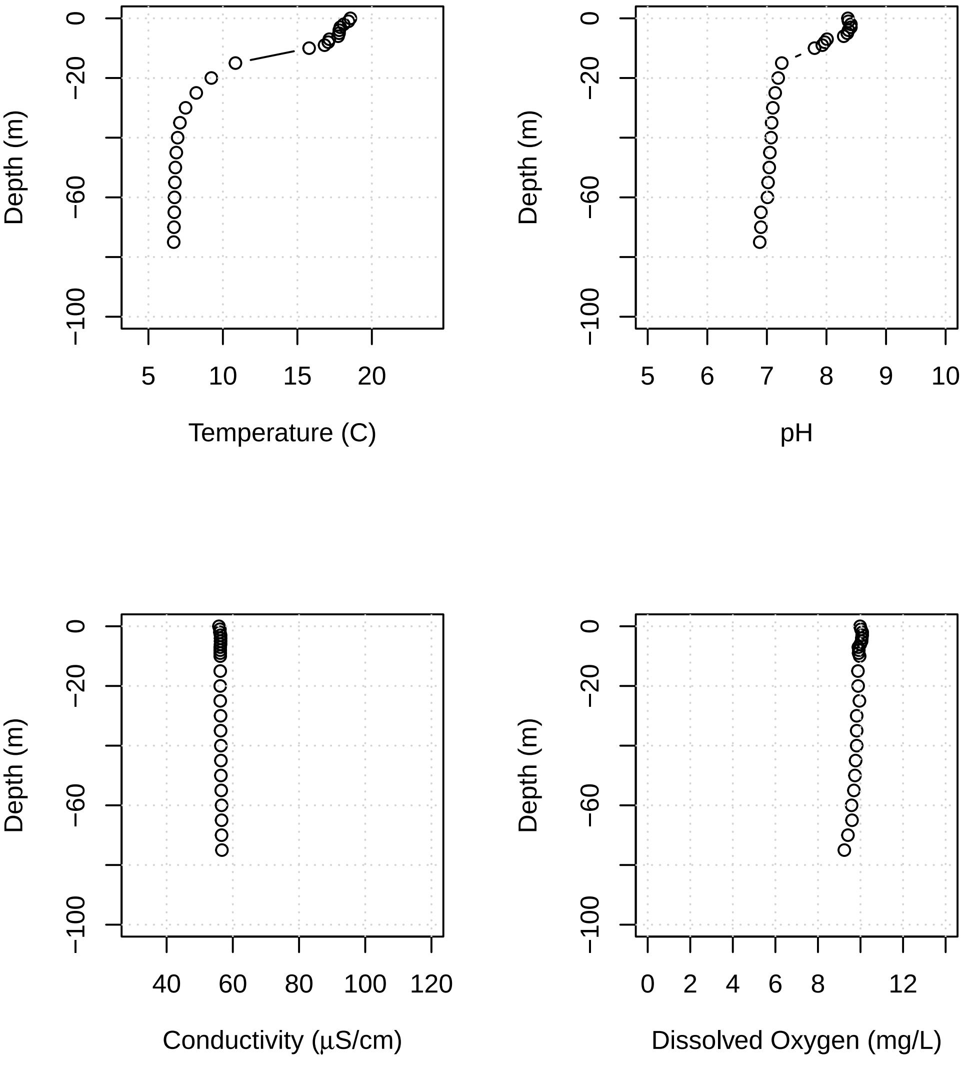

Figure B39: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, July 5, 2022.

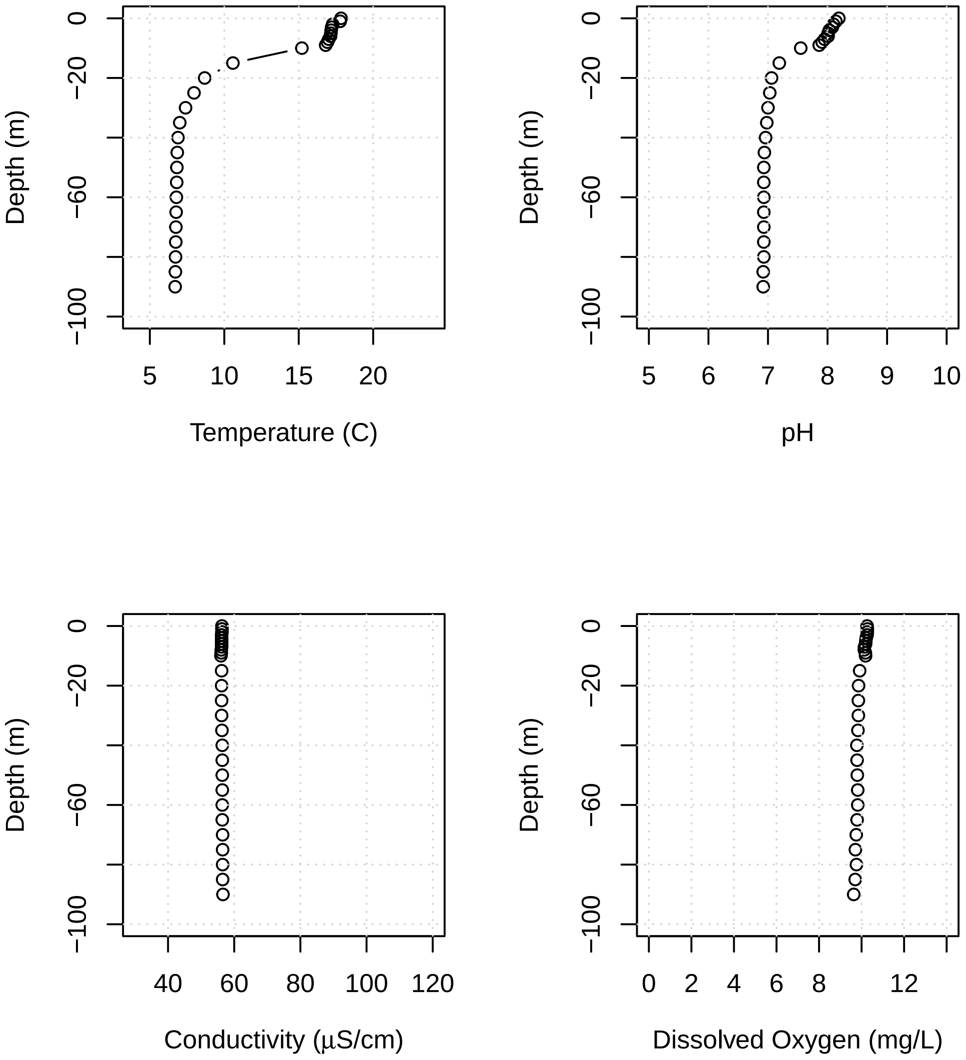

Figure B40: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, July 5, 2022.

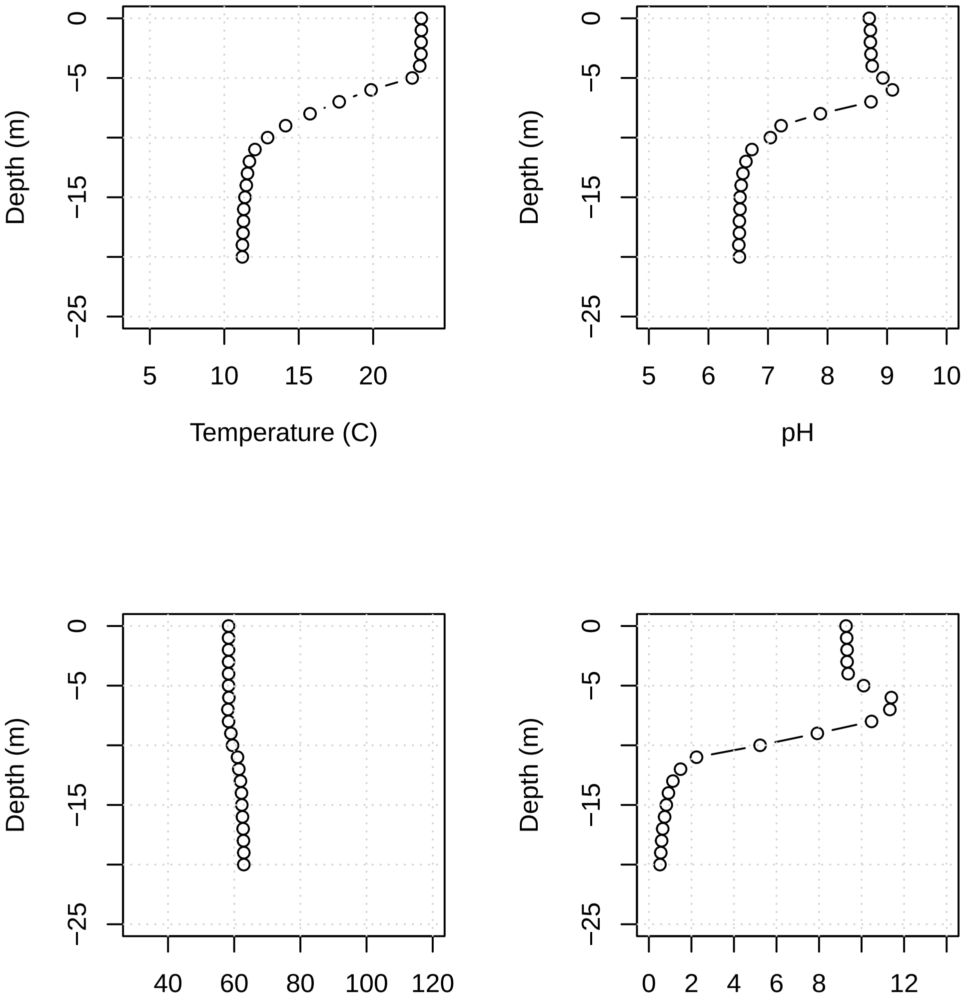

Figure B41: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, August 4, 2022.

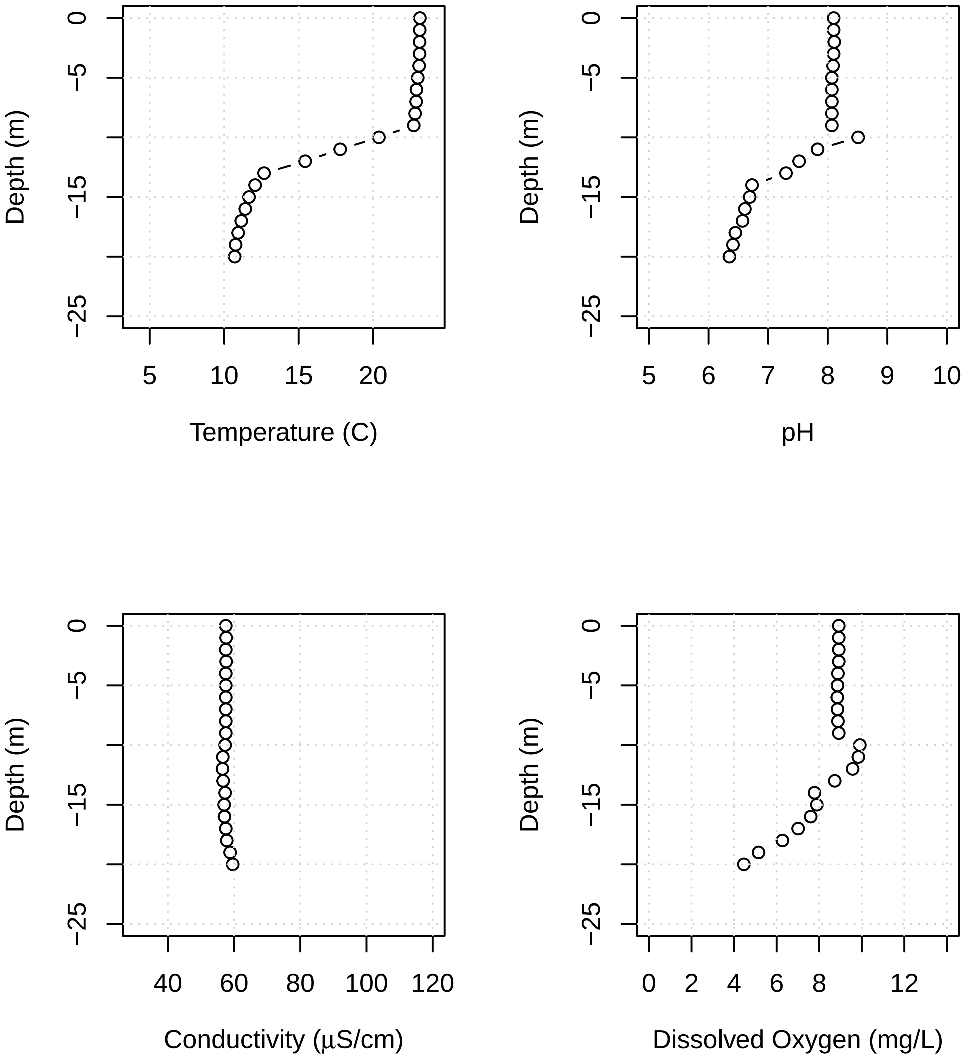

Figure B42: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, August 4, 2022.

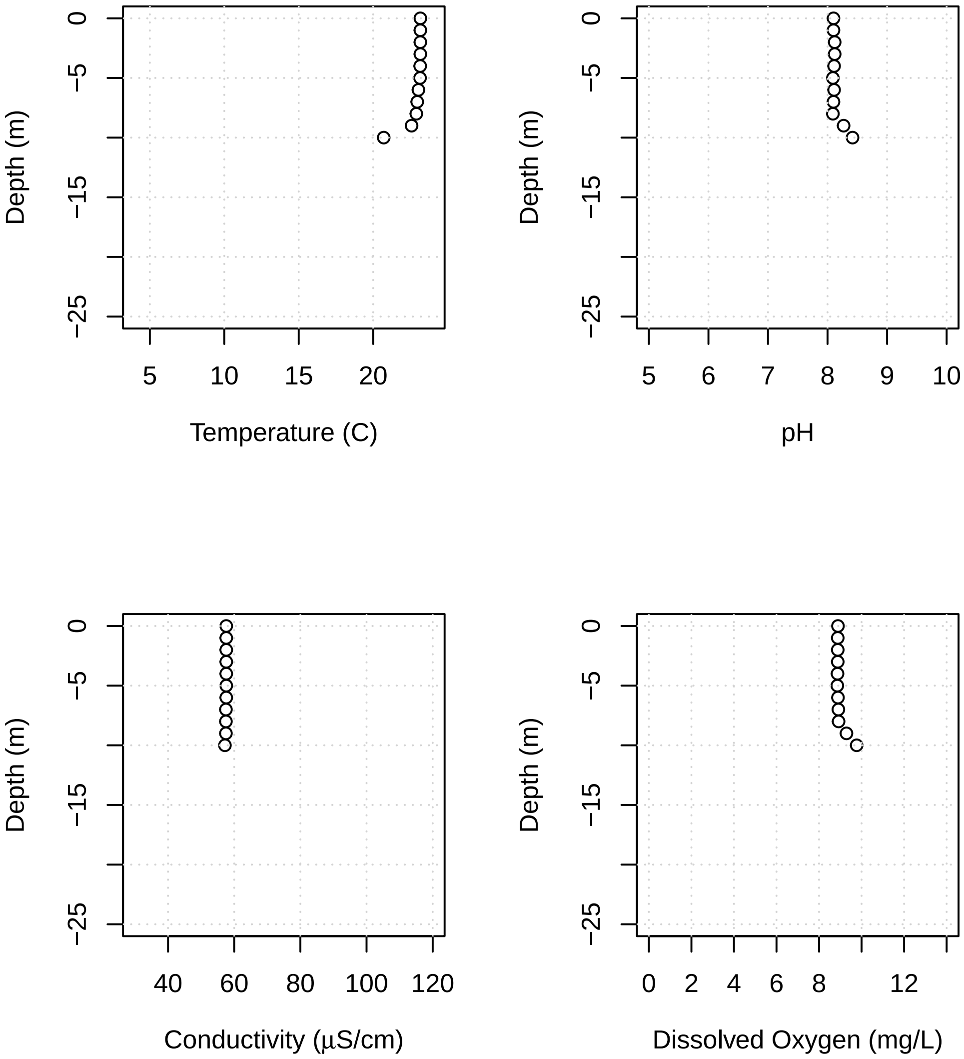

Figure B43: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, August 4, 2022.

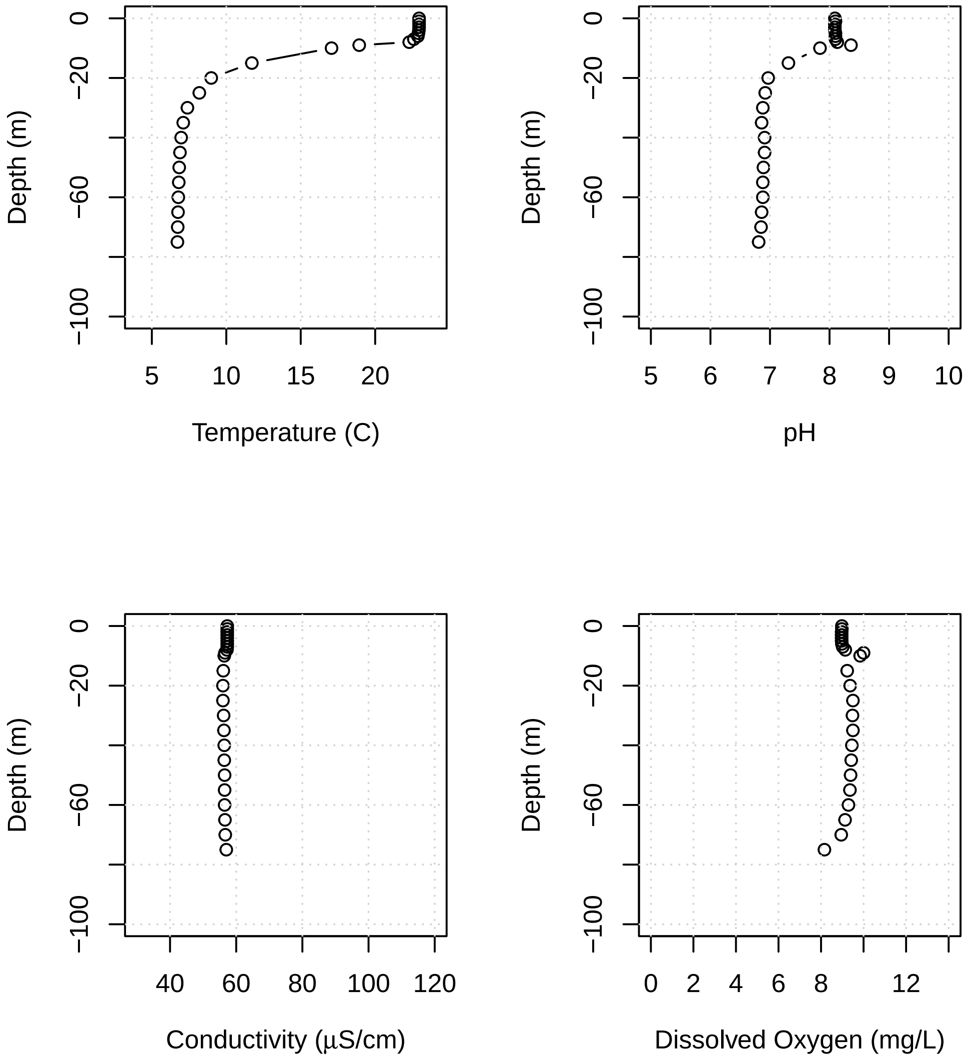

Figure B44: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, August 2, 2022.

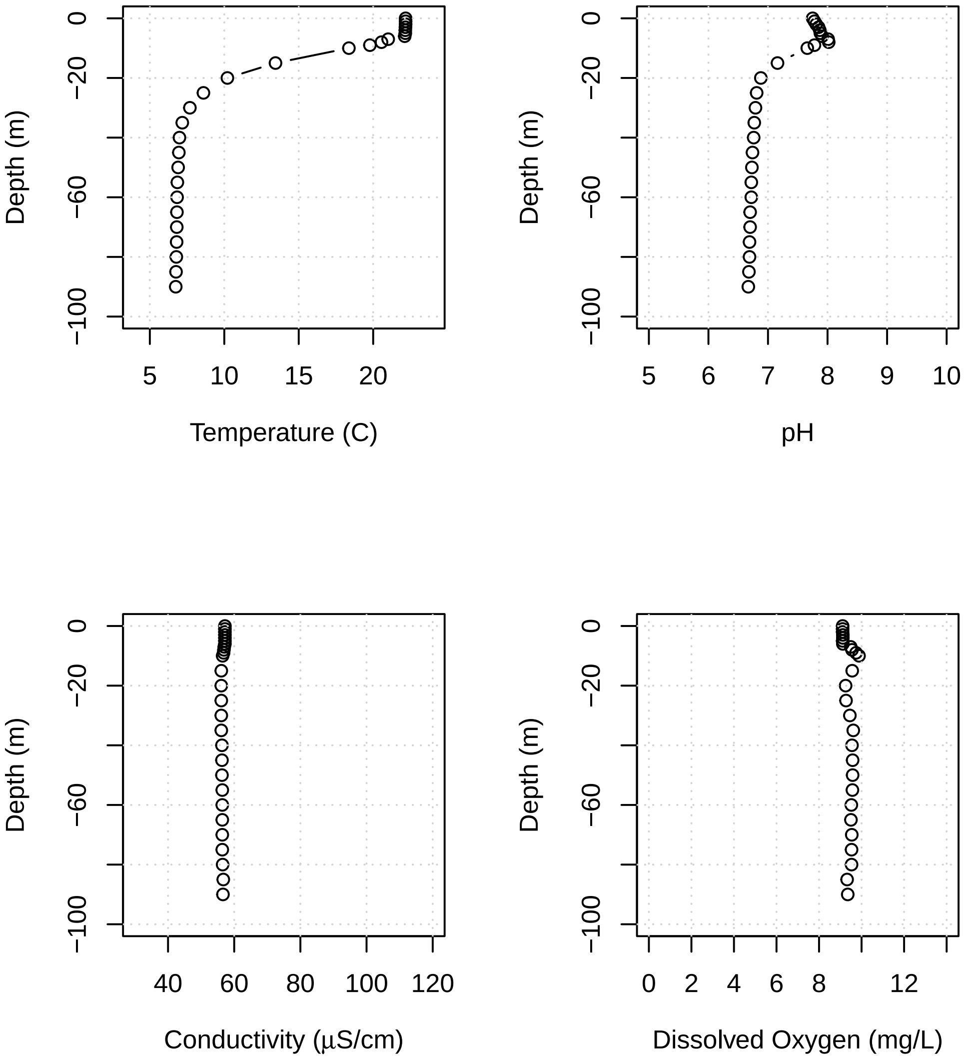

Figure B45: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, August 2, 2022.

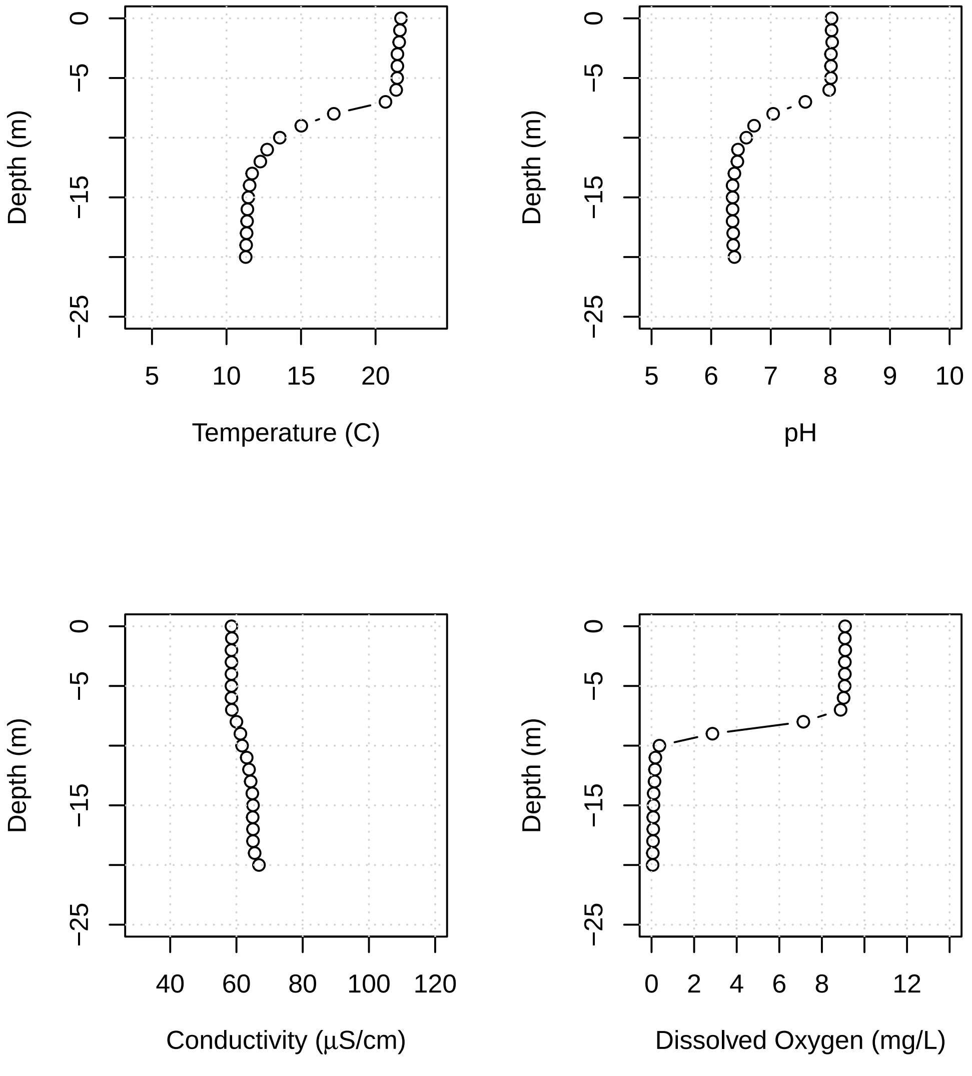

Figure B46: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, September 8, 2022.

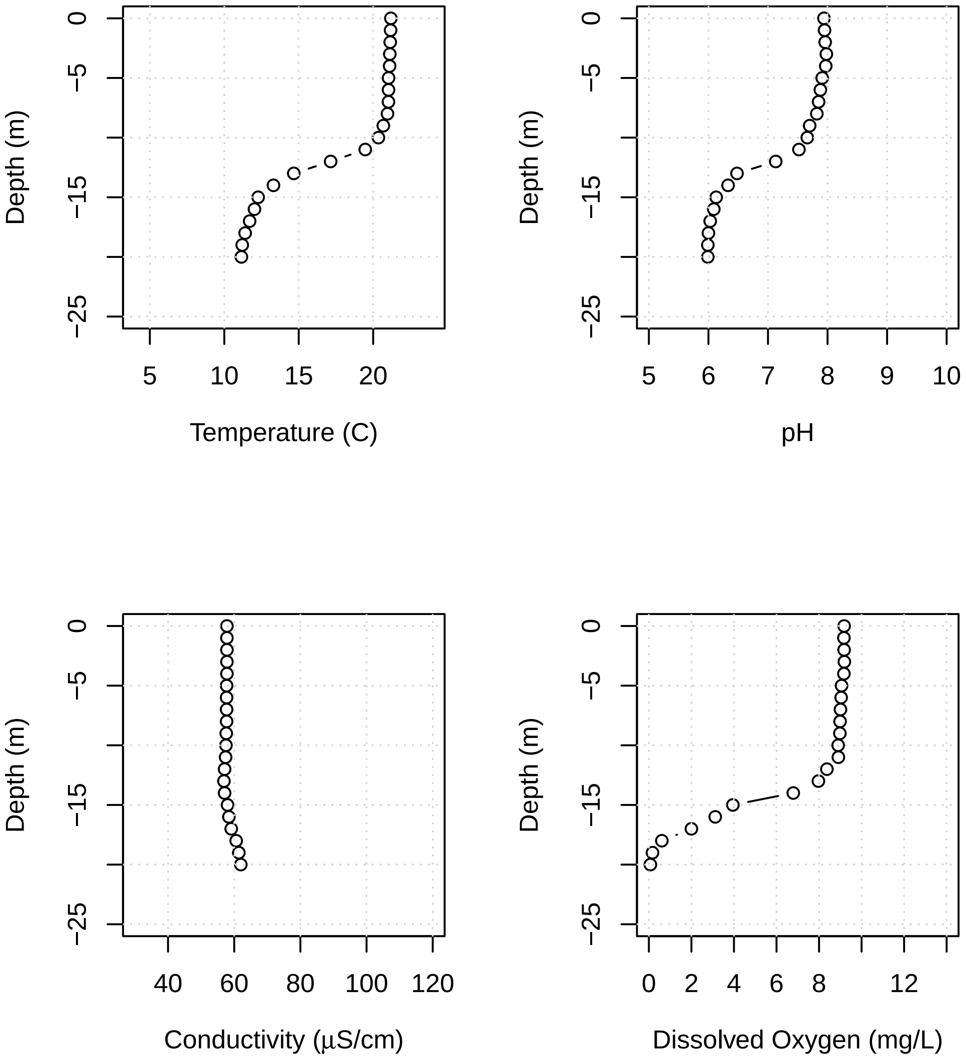

Figure B47: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, September 8, 2022.

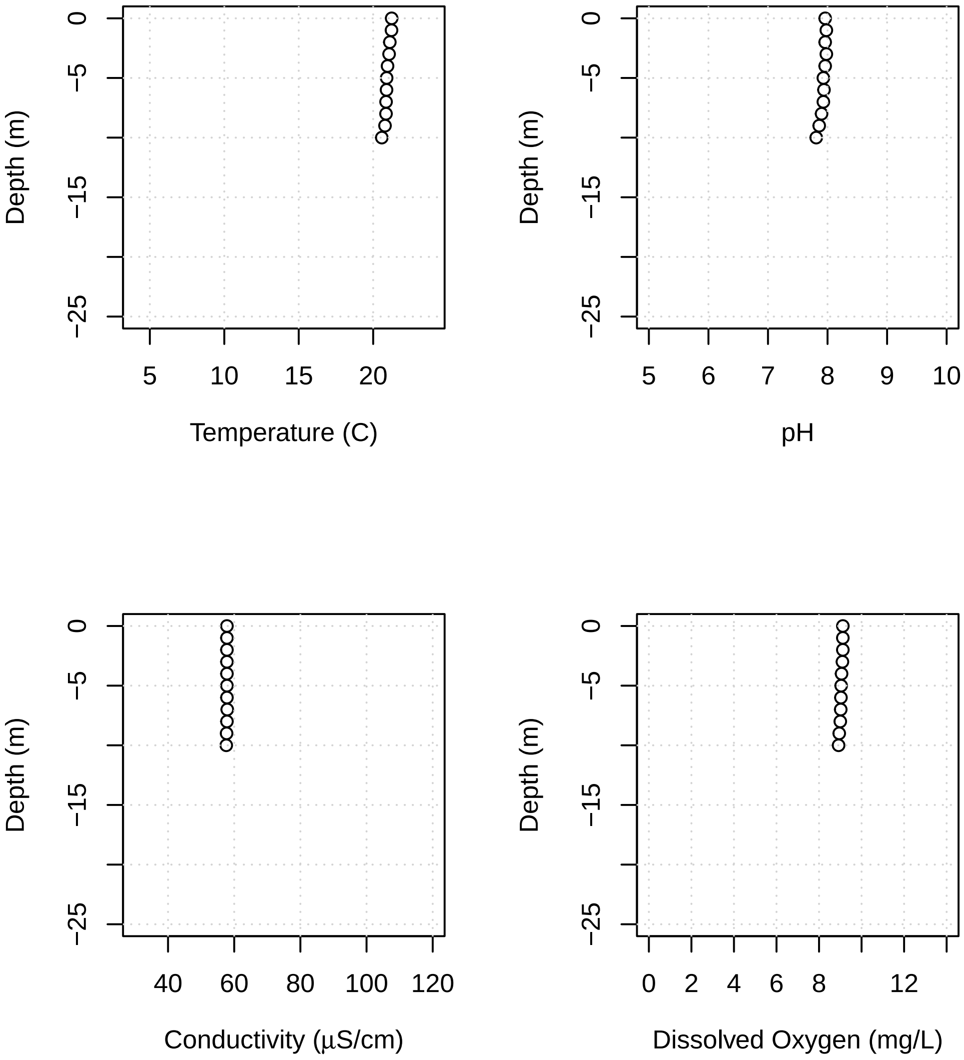

Figure B48: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, September 8, 2022.

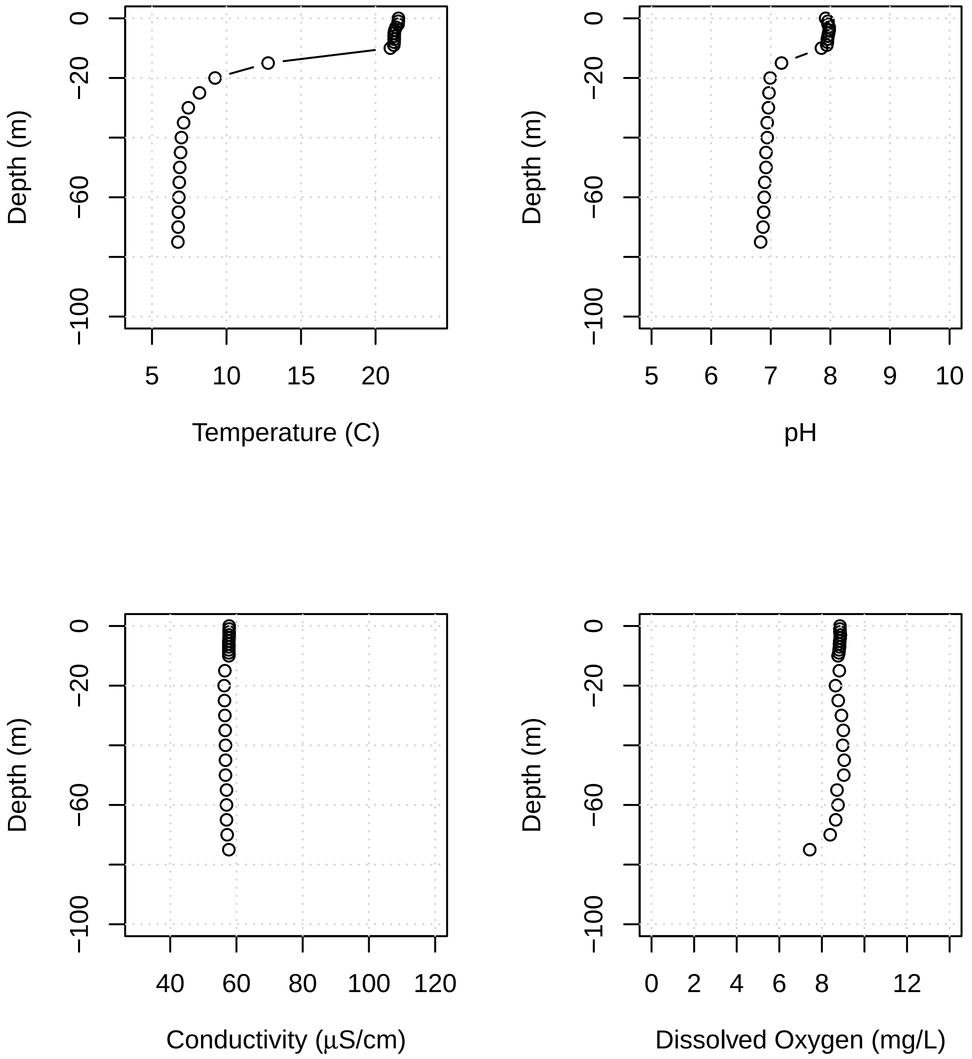

Figure B49: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, September 6, 2022.

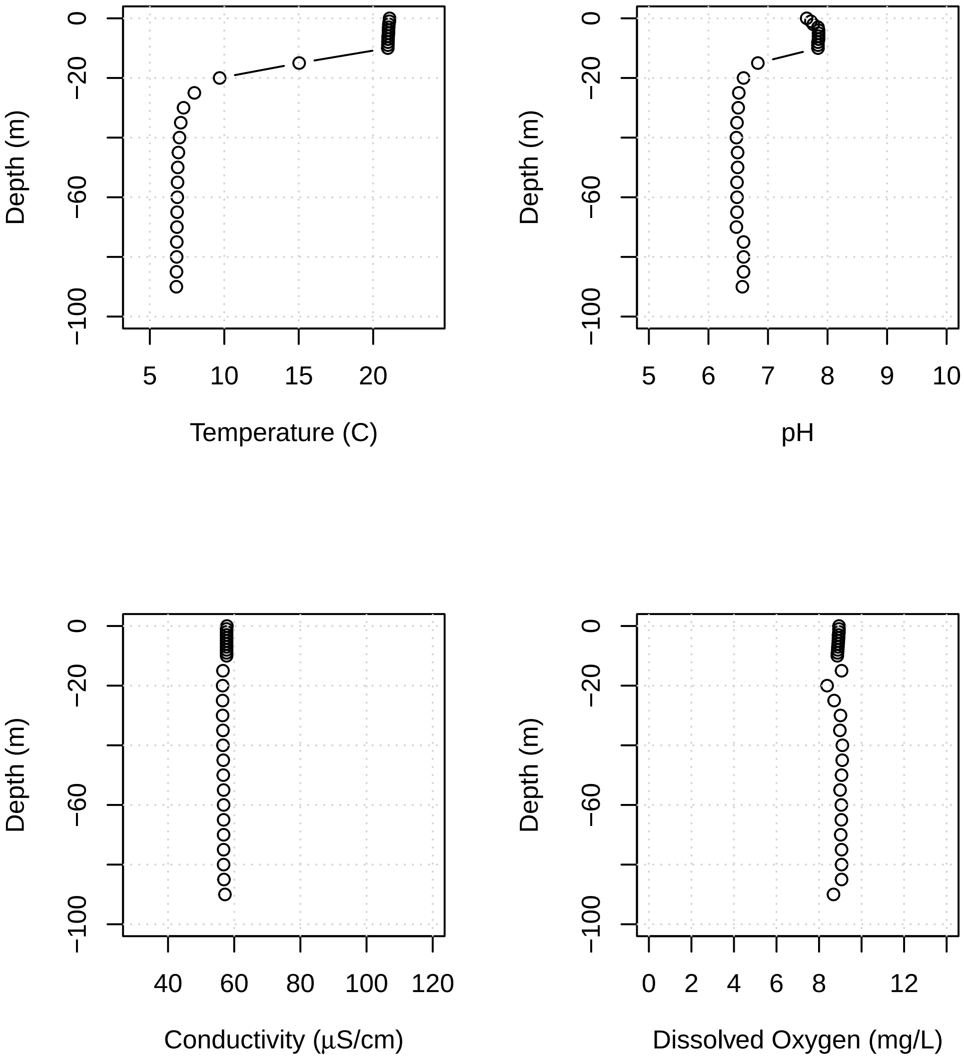

Figure B50: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, September 6, 2022.

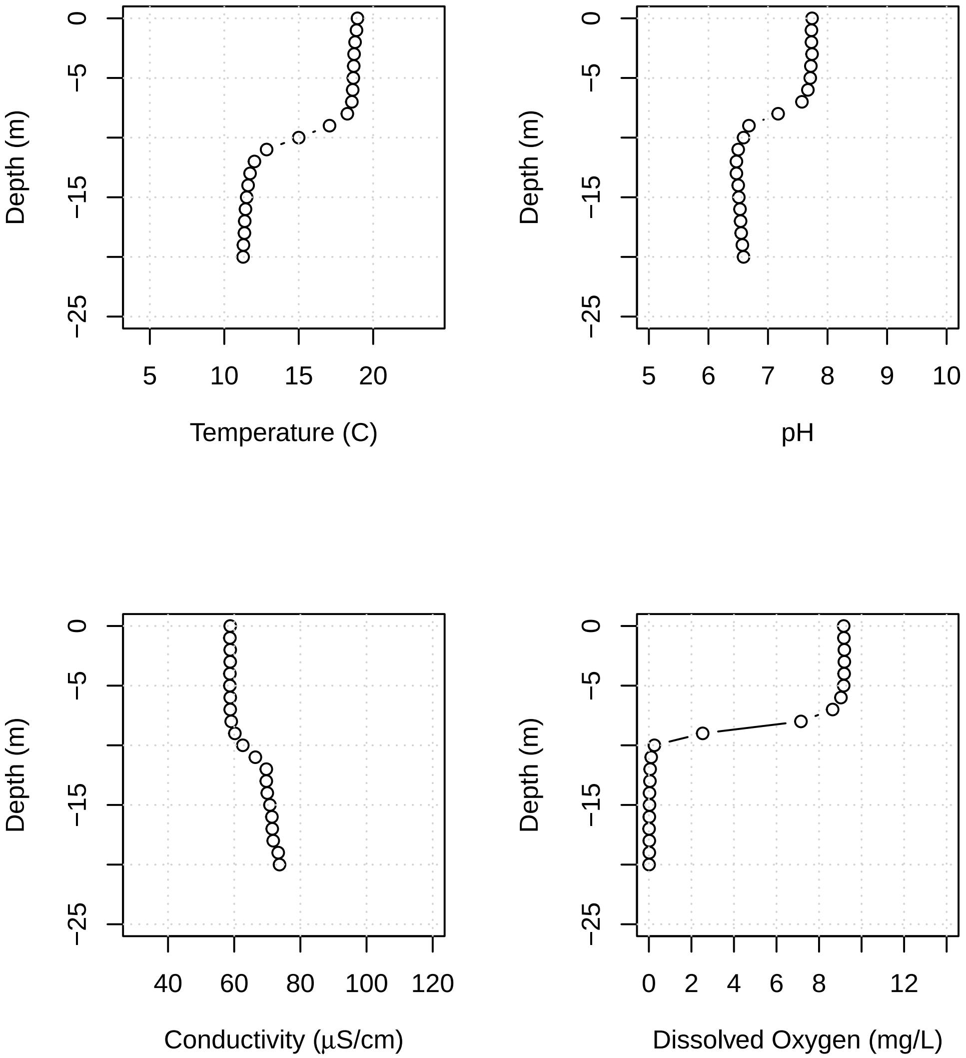

Figure B51: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, October 5, 2022.

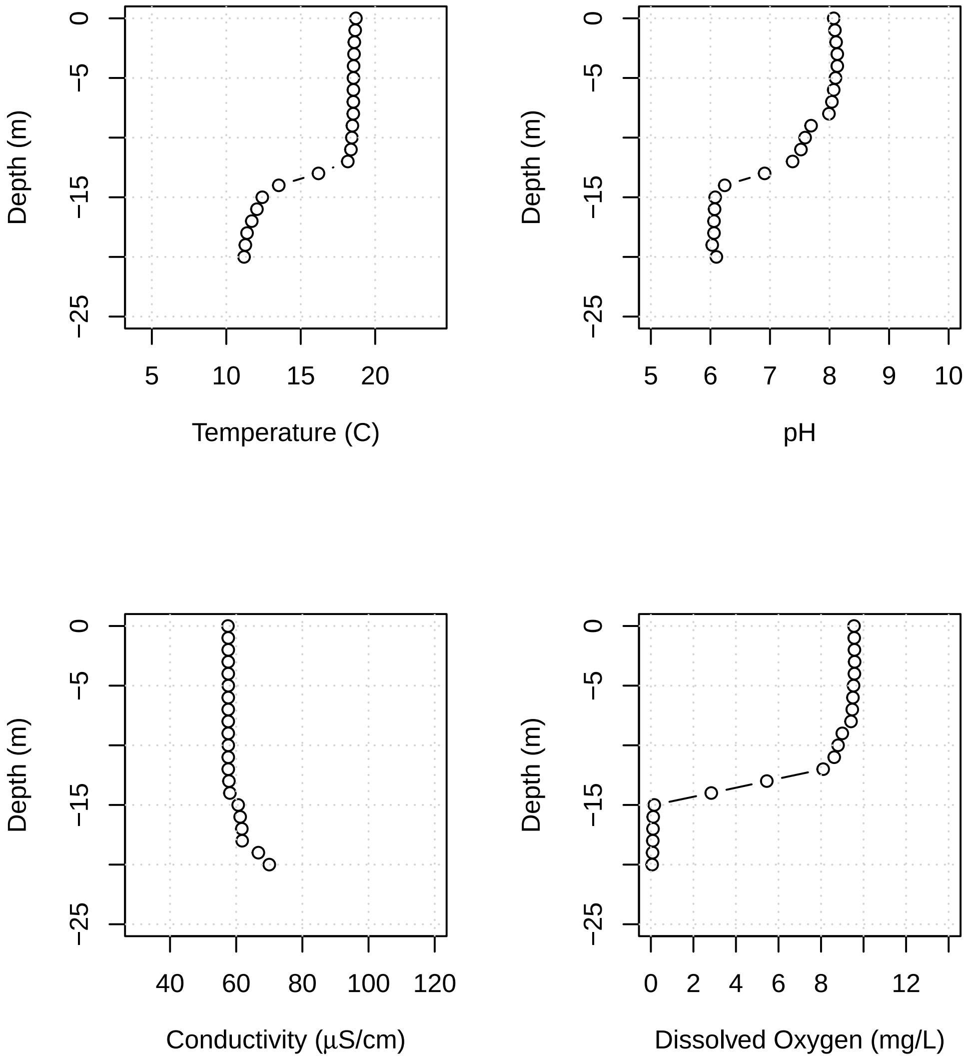

Figure B52: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, October 5, 2022.

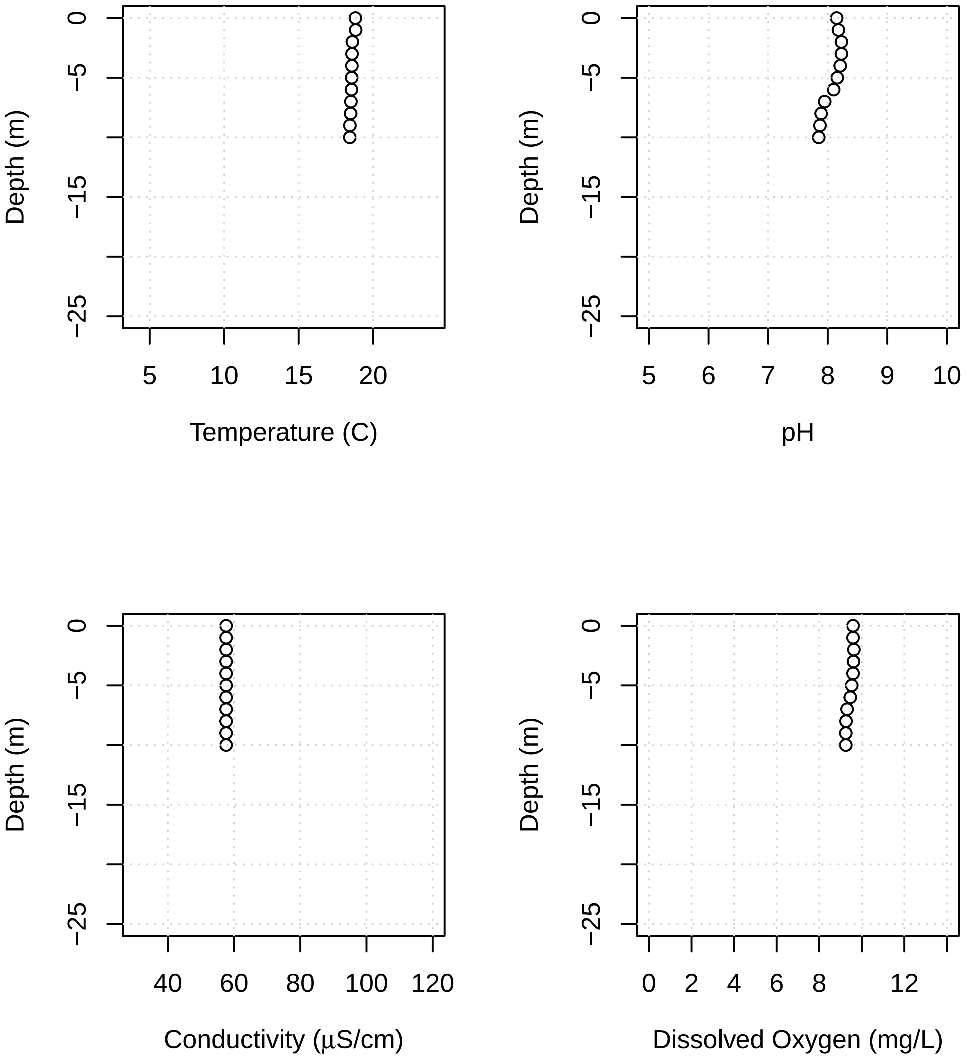

Figure B53: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, October 5, 2022.

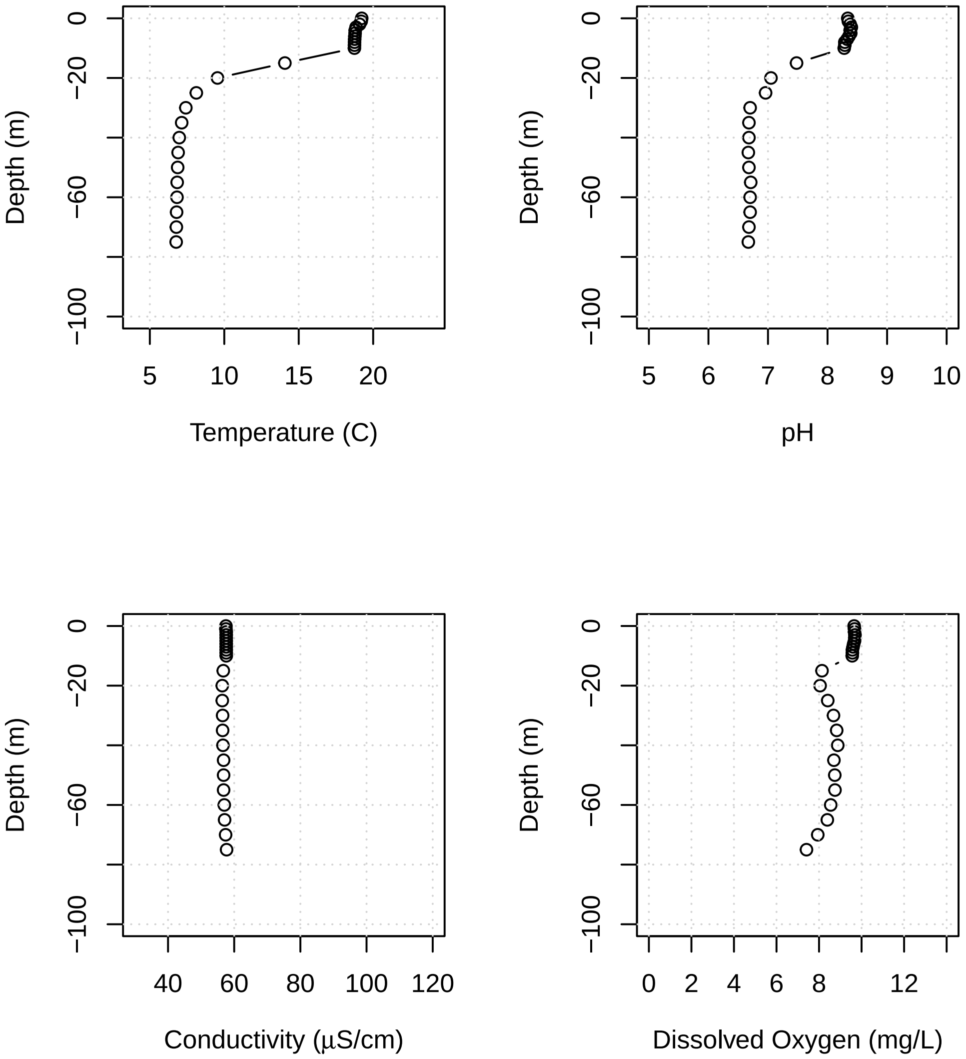

Figure B54: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, October 3, 2022.

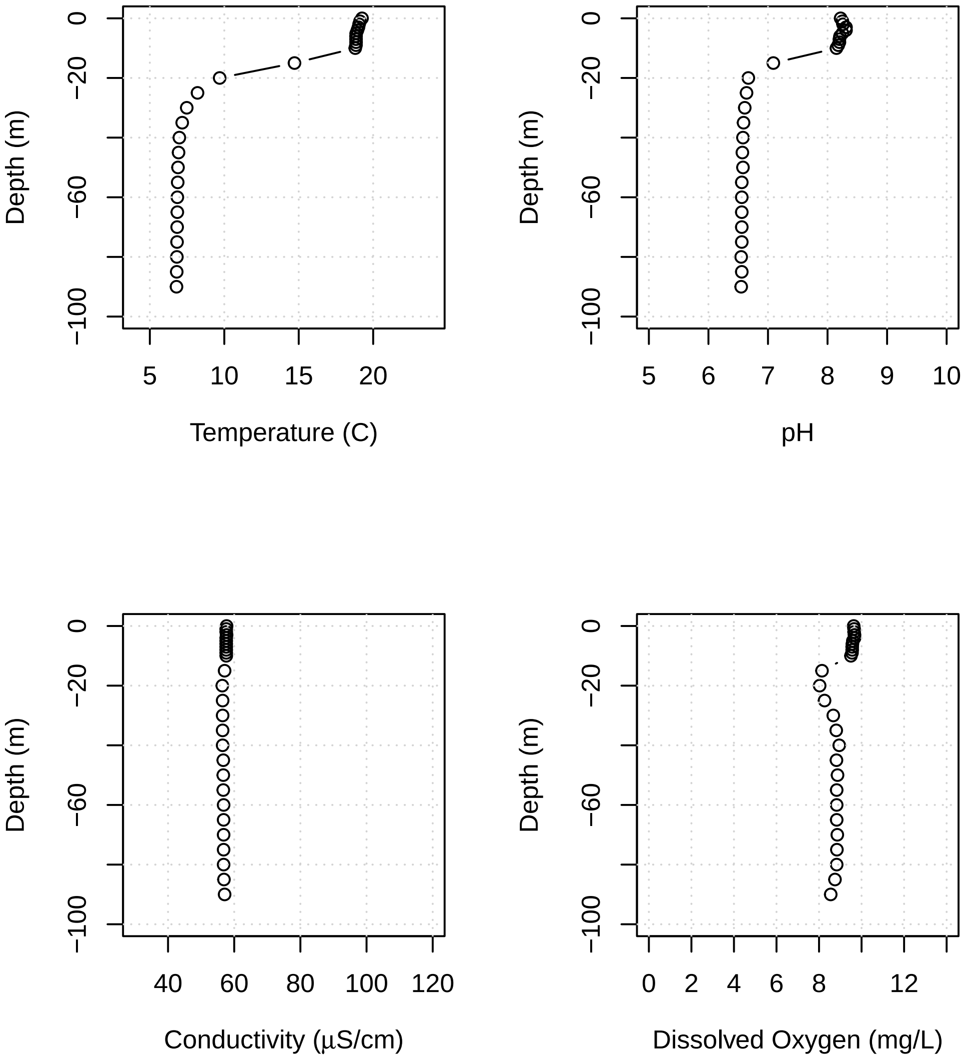

Figure B55: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, October 3, 2022.

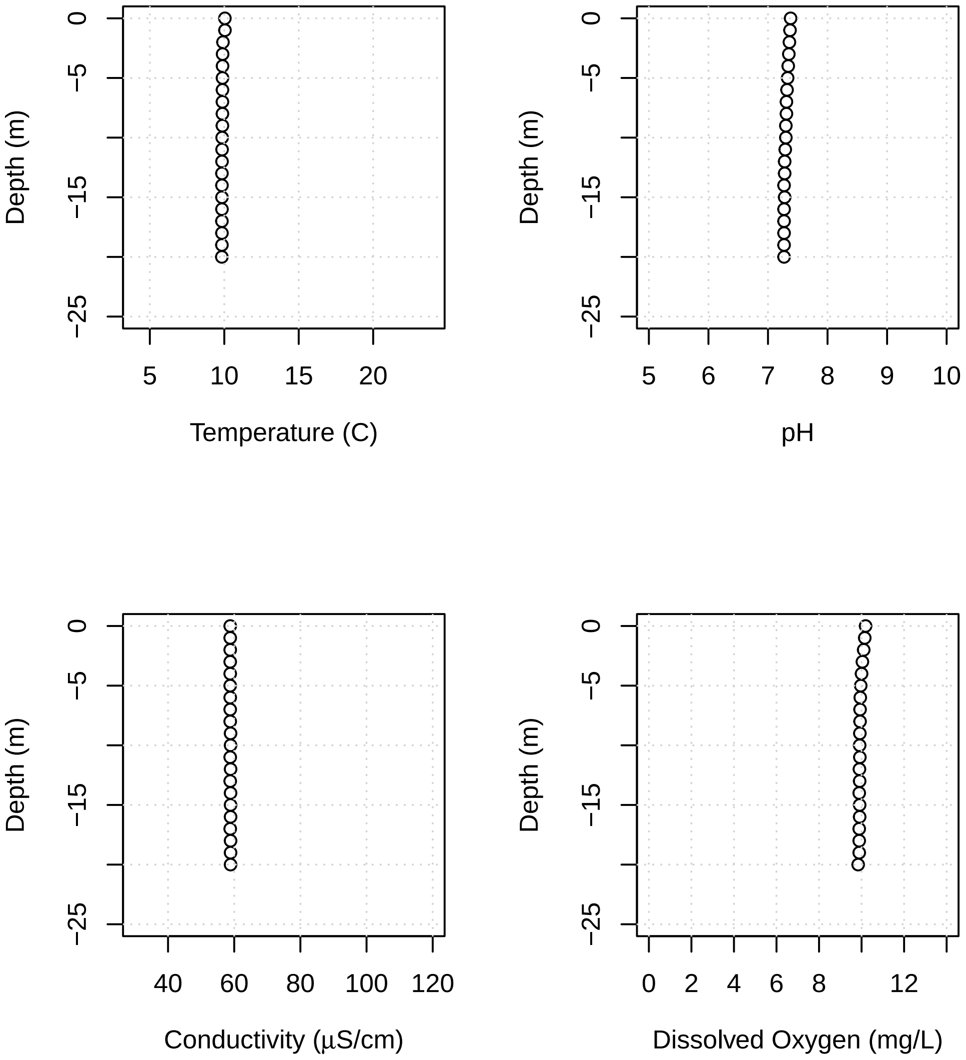

Figure B56: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, November 14, 2022.

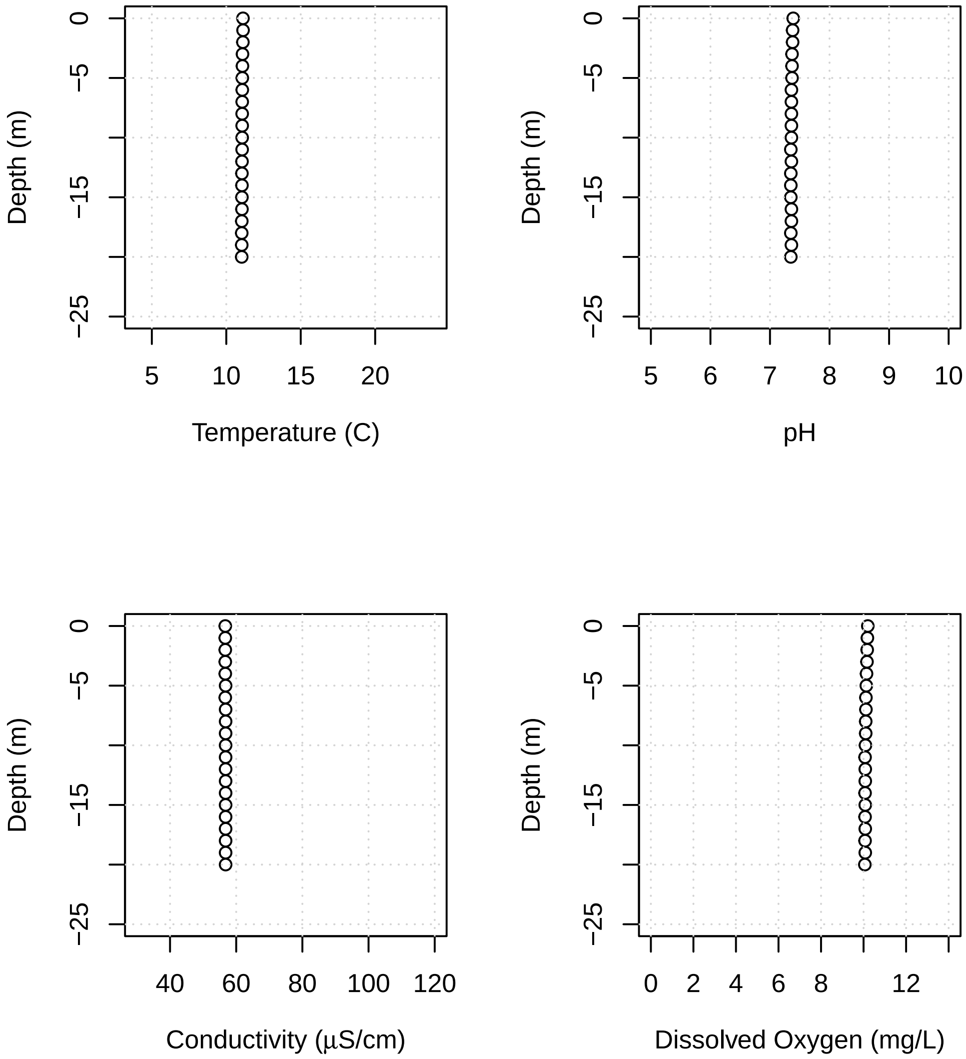

Figure B57: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, November 14, 2022.

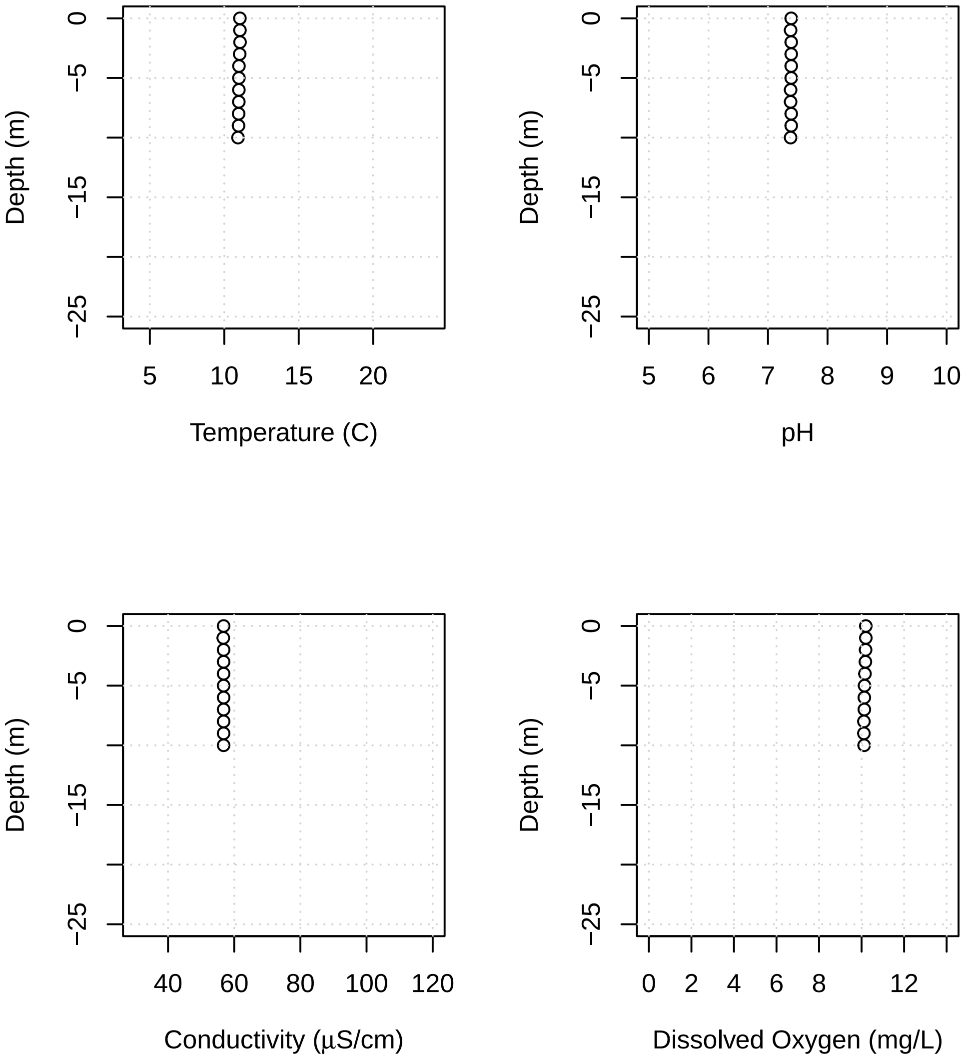

Figure B58: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, November 14, 2022.

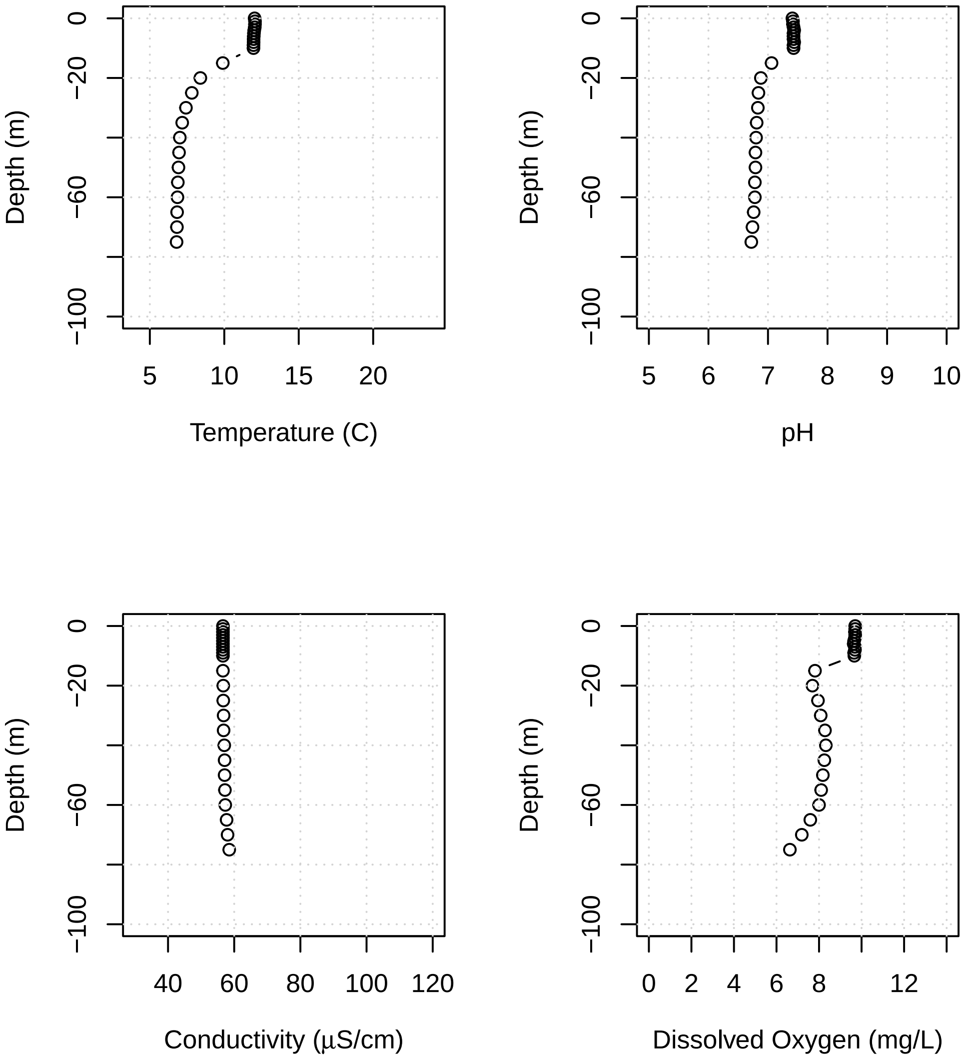

Figure B59: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, November 9, 2022.

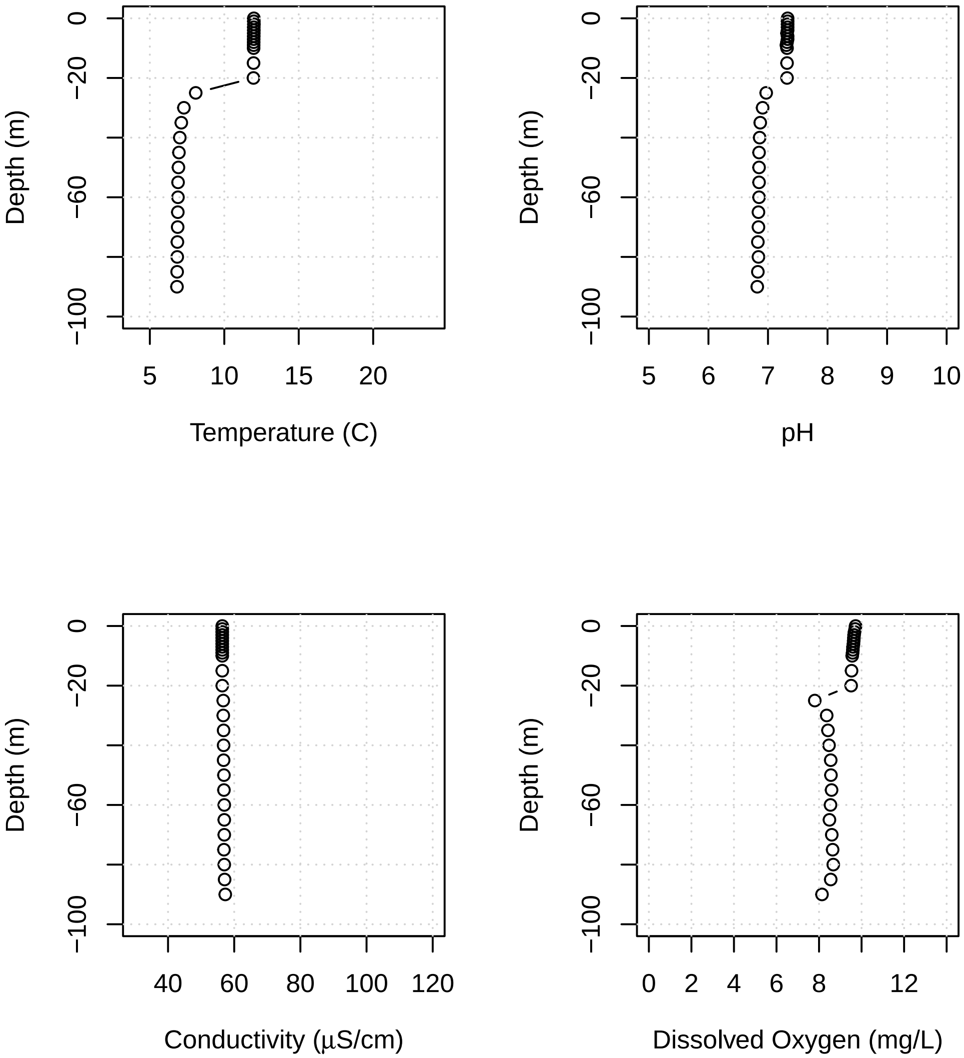

Figure B60: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, November 9, 2022.

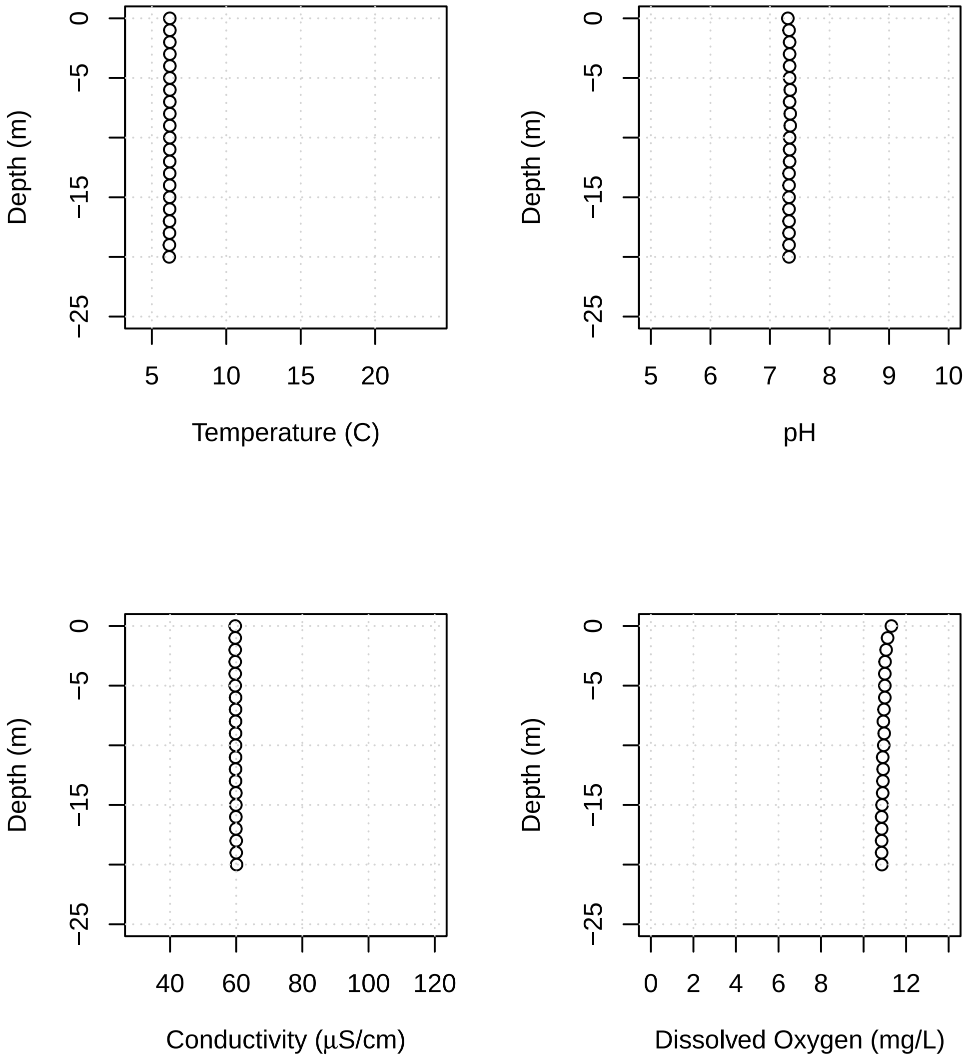

Figure B61: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, December 6, 2022.

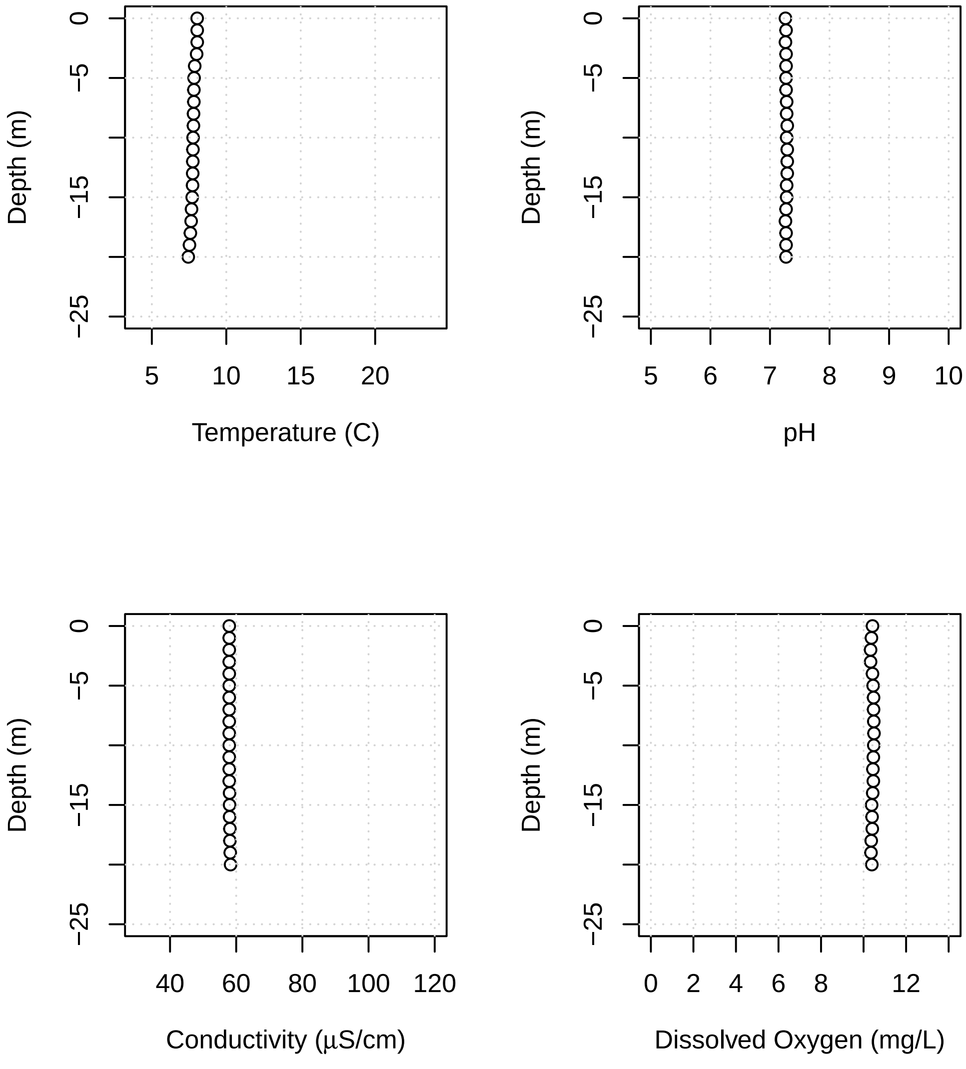

Figure B62: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, December 6, 2022.

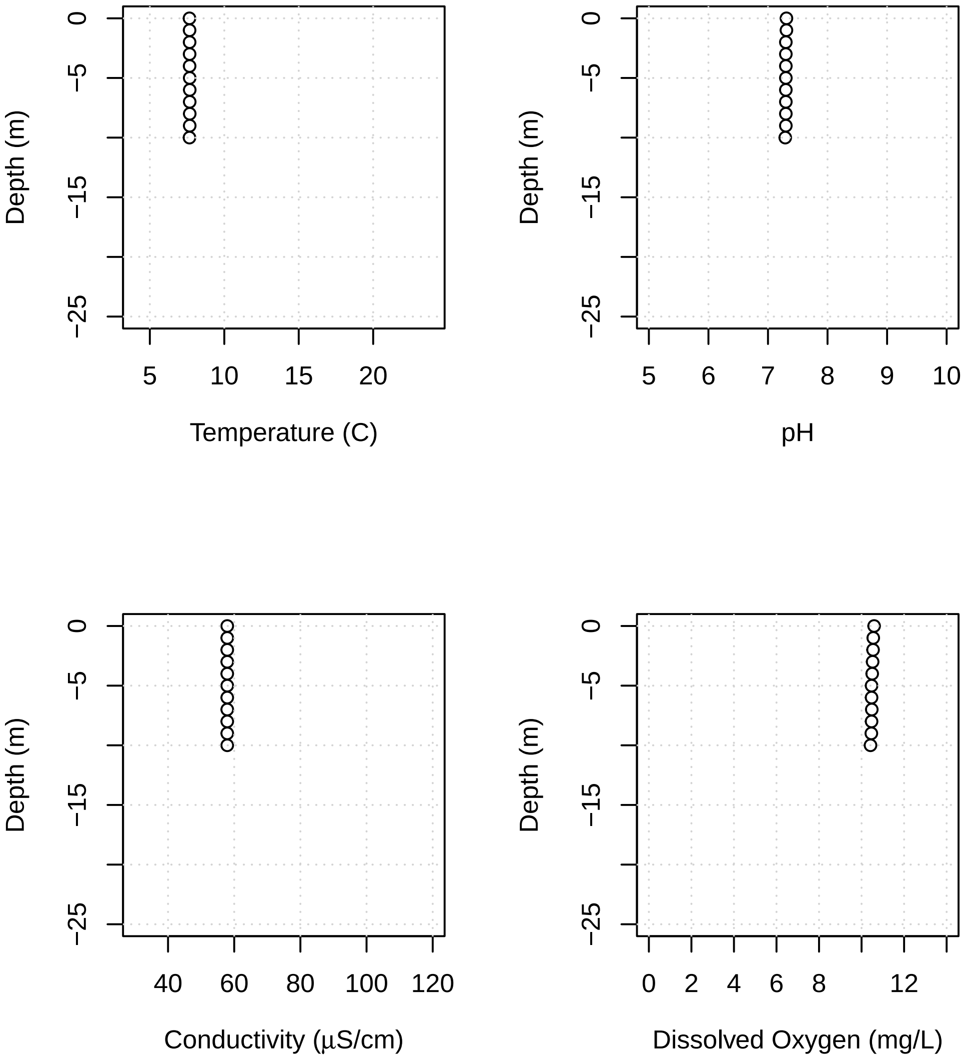

Figure B63: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, December 6, 2022.

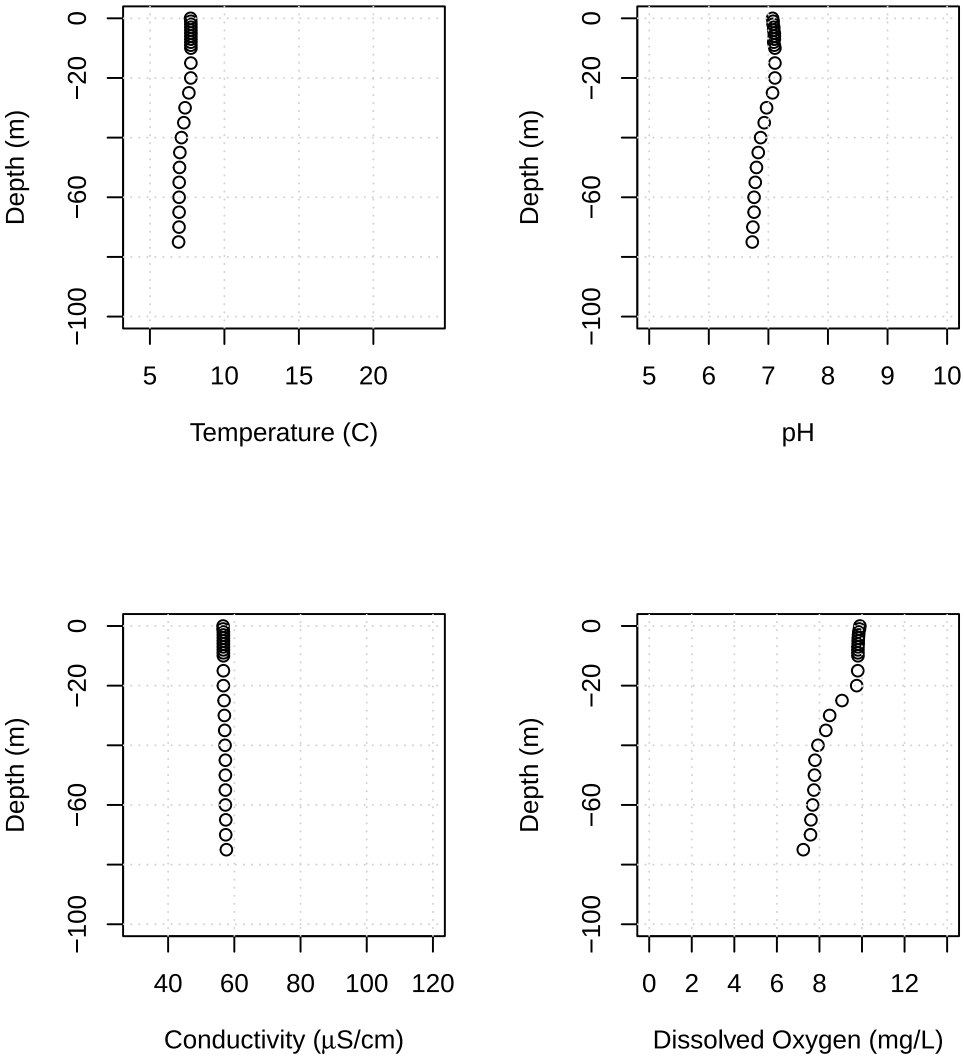

Figure B64: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, December 13, 2022.

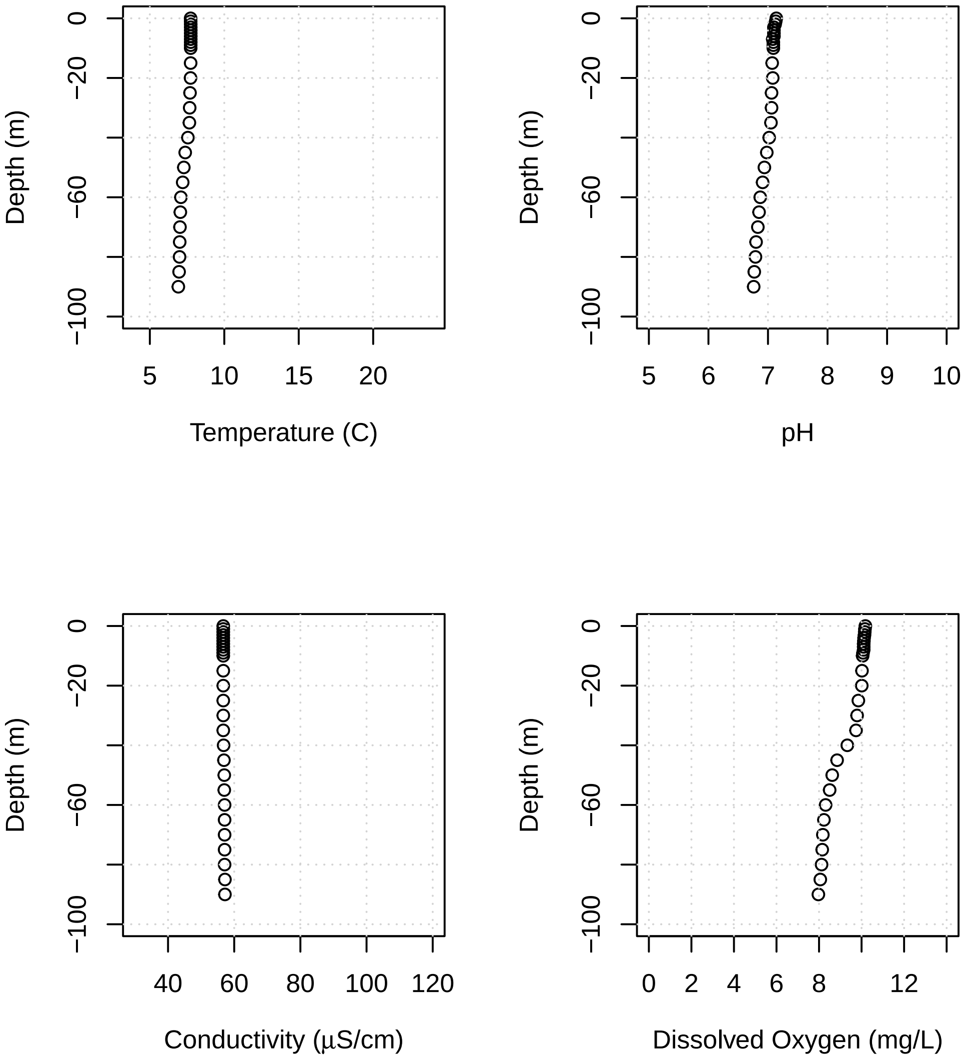

Figure B65: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, December 13, 2022.

B.2 Long-term YSI/Hydrolab Data (1988-present)

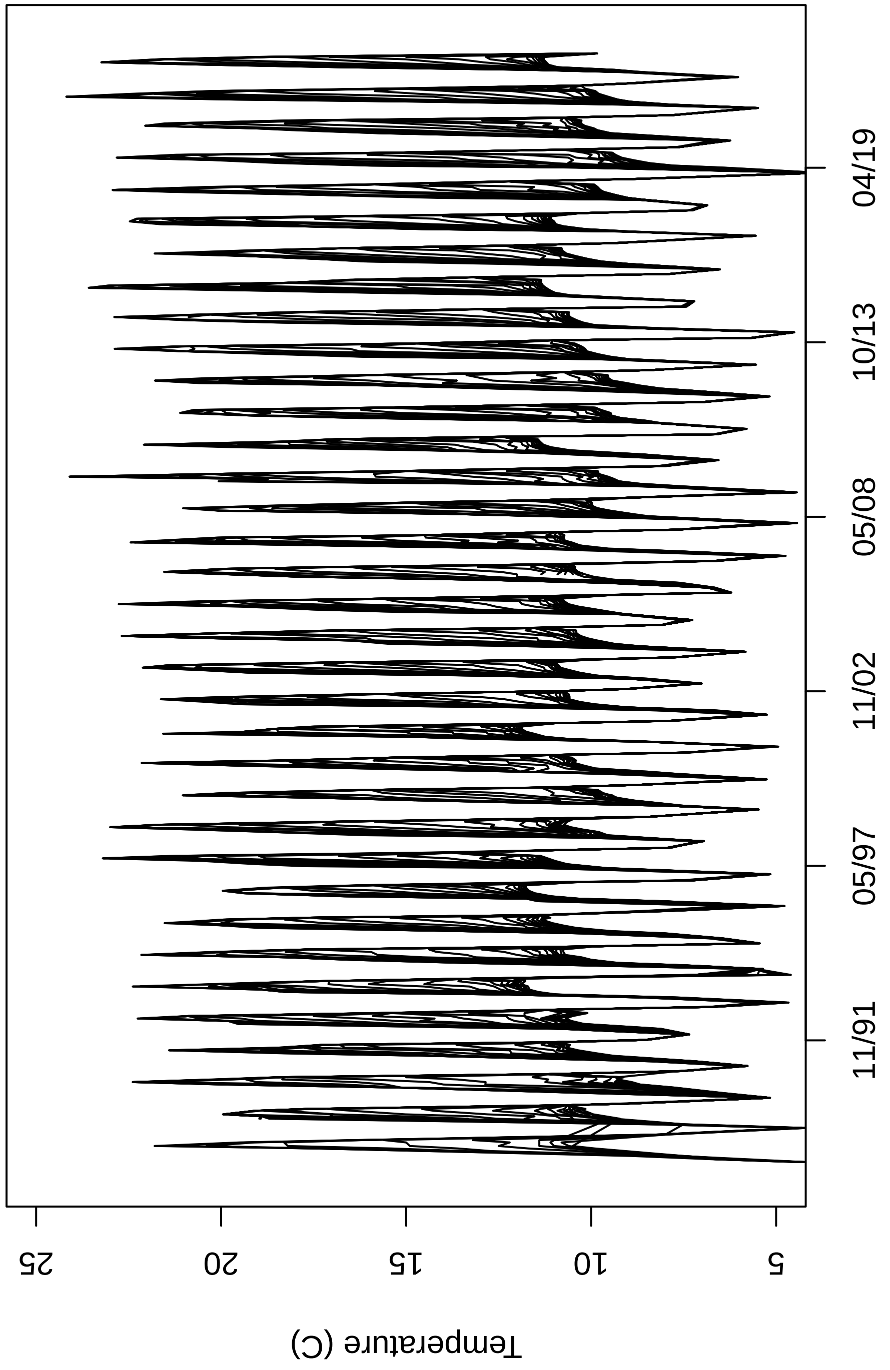

Figure B66: Lake Whatcom historic temperature data for Site 1.

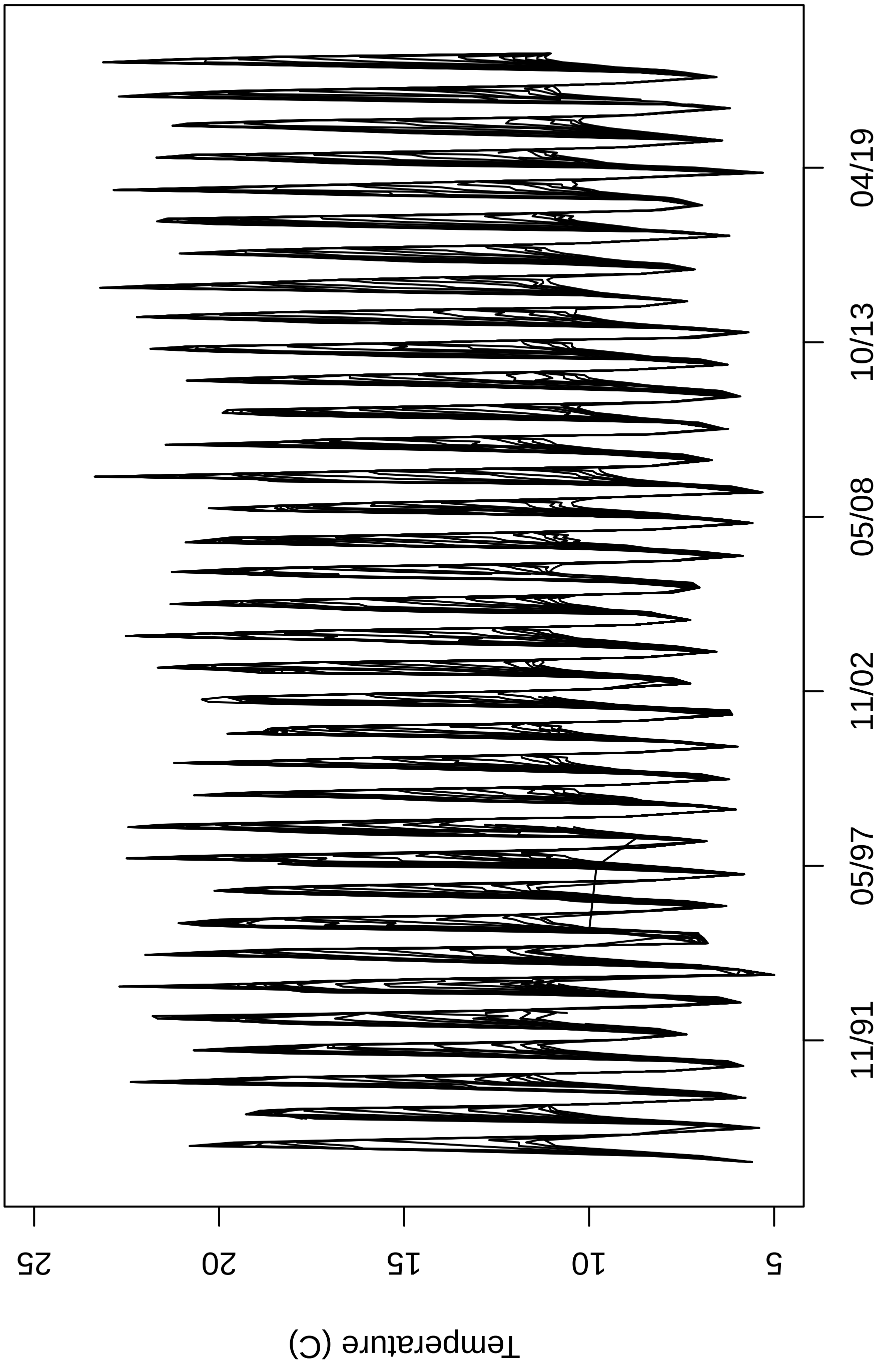

Figure B67: Lake Whatcom historic temperature data for Site 2.

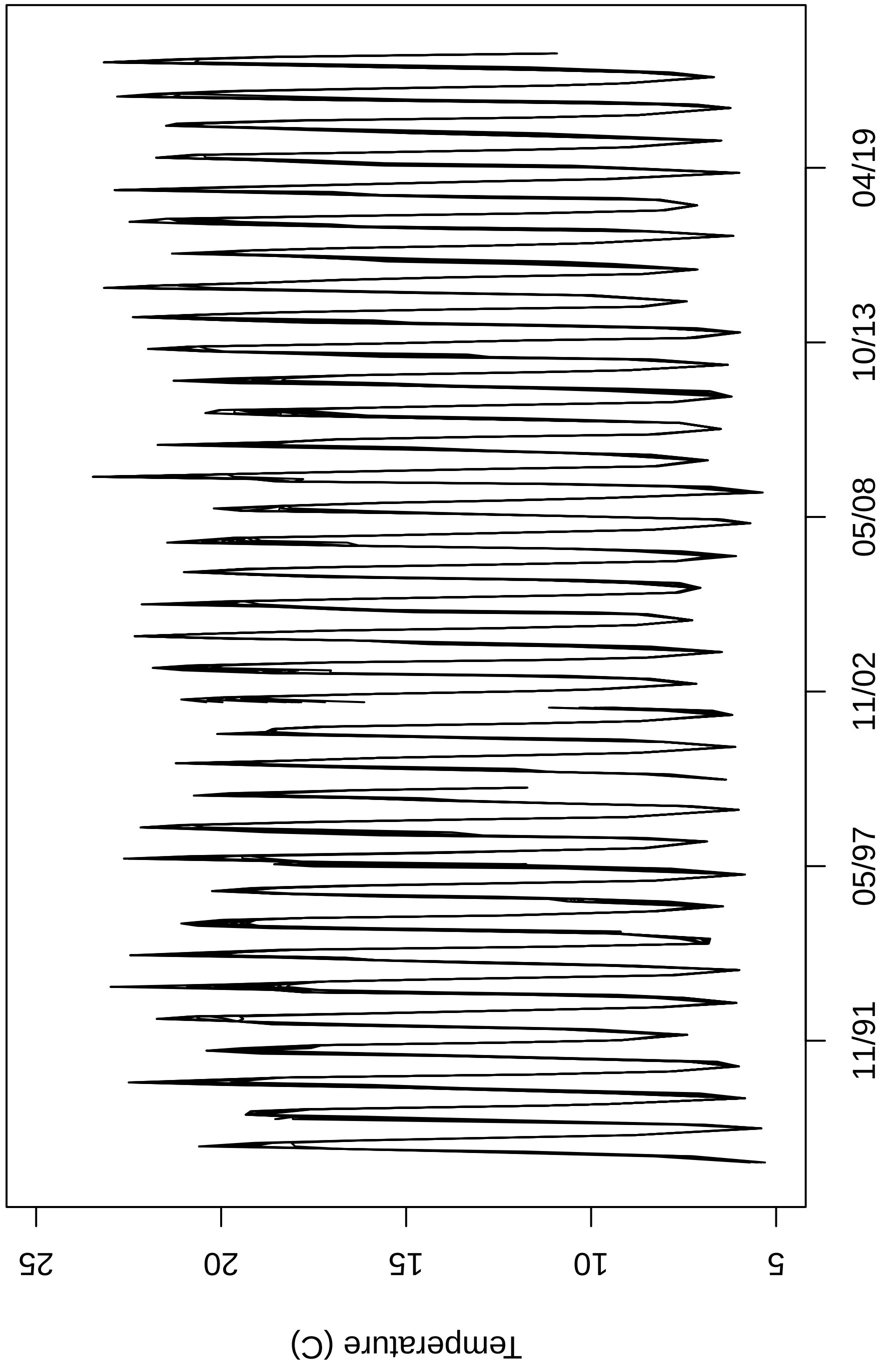

Figure B68: Lake Whatcom historic temperature data for the Intake.

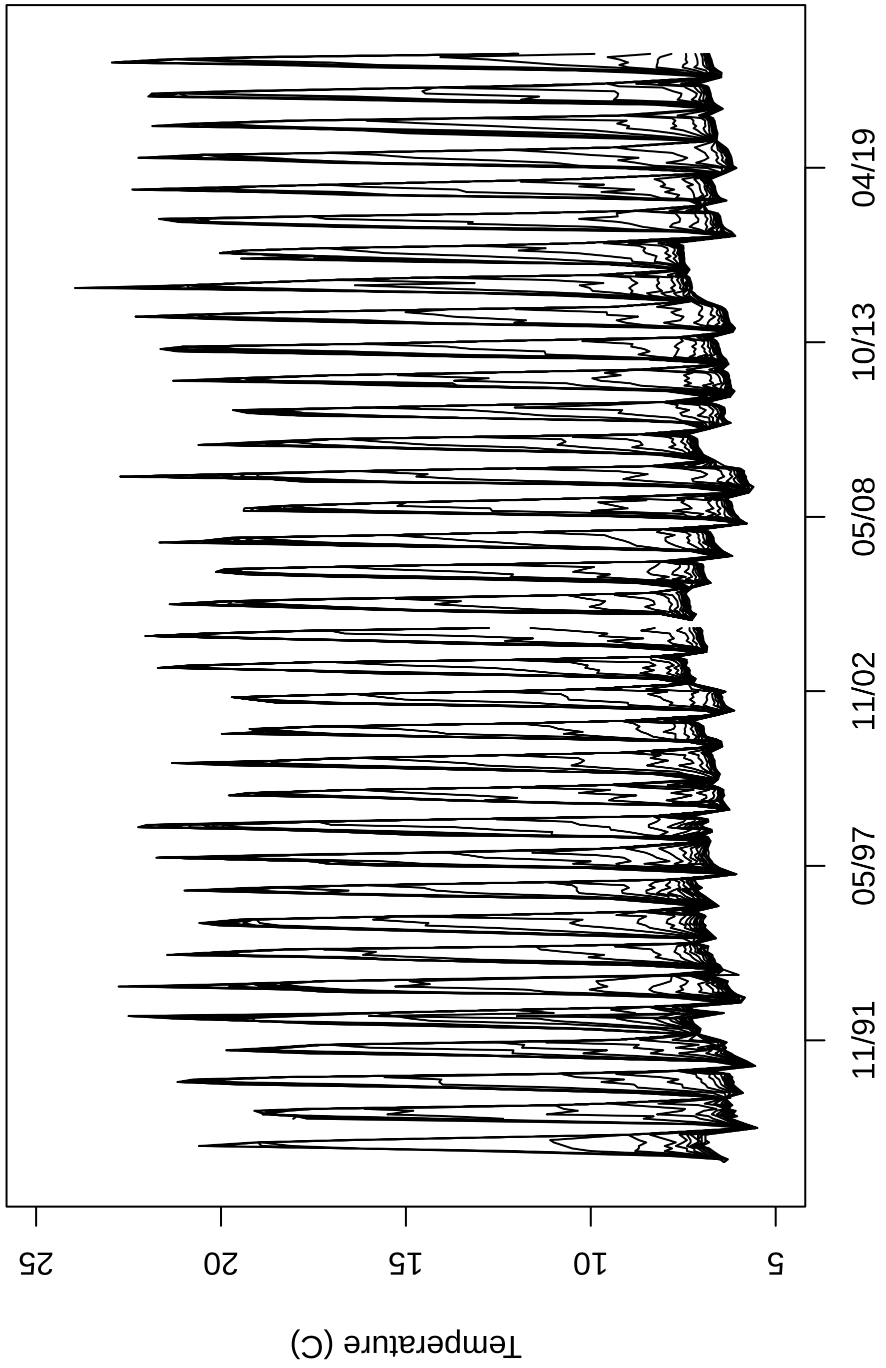

Figure B69: Lake Whatcom historic temperature data for Site 3.

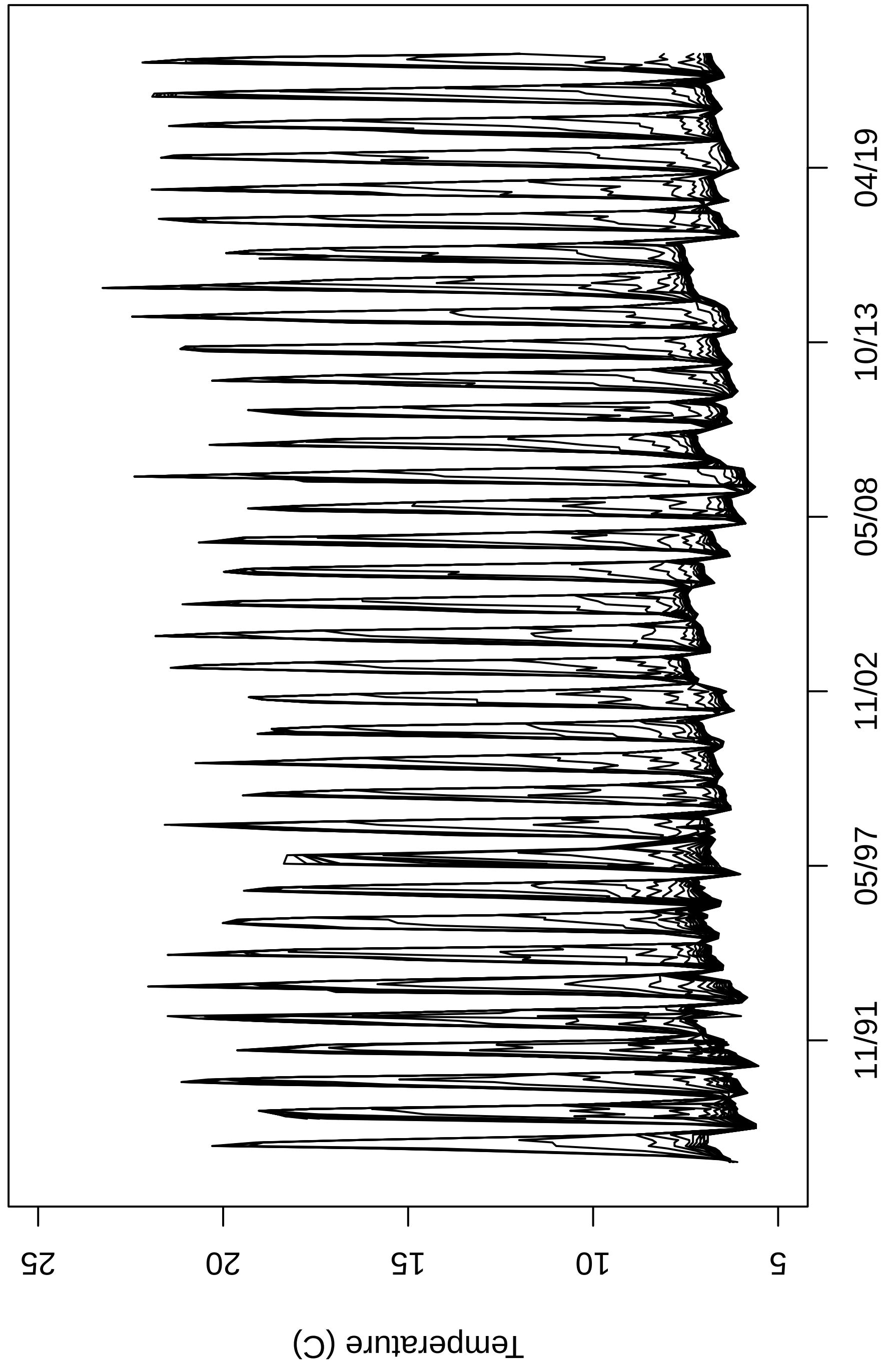

Figure B70: Lake Whatcom historic temperature data for Site 4.

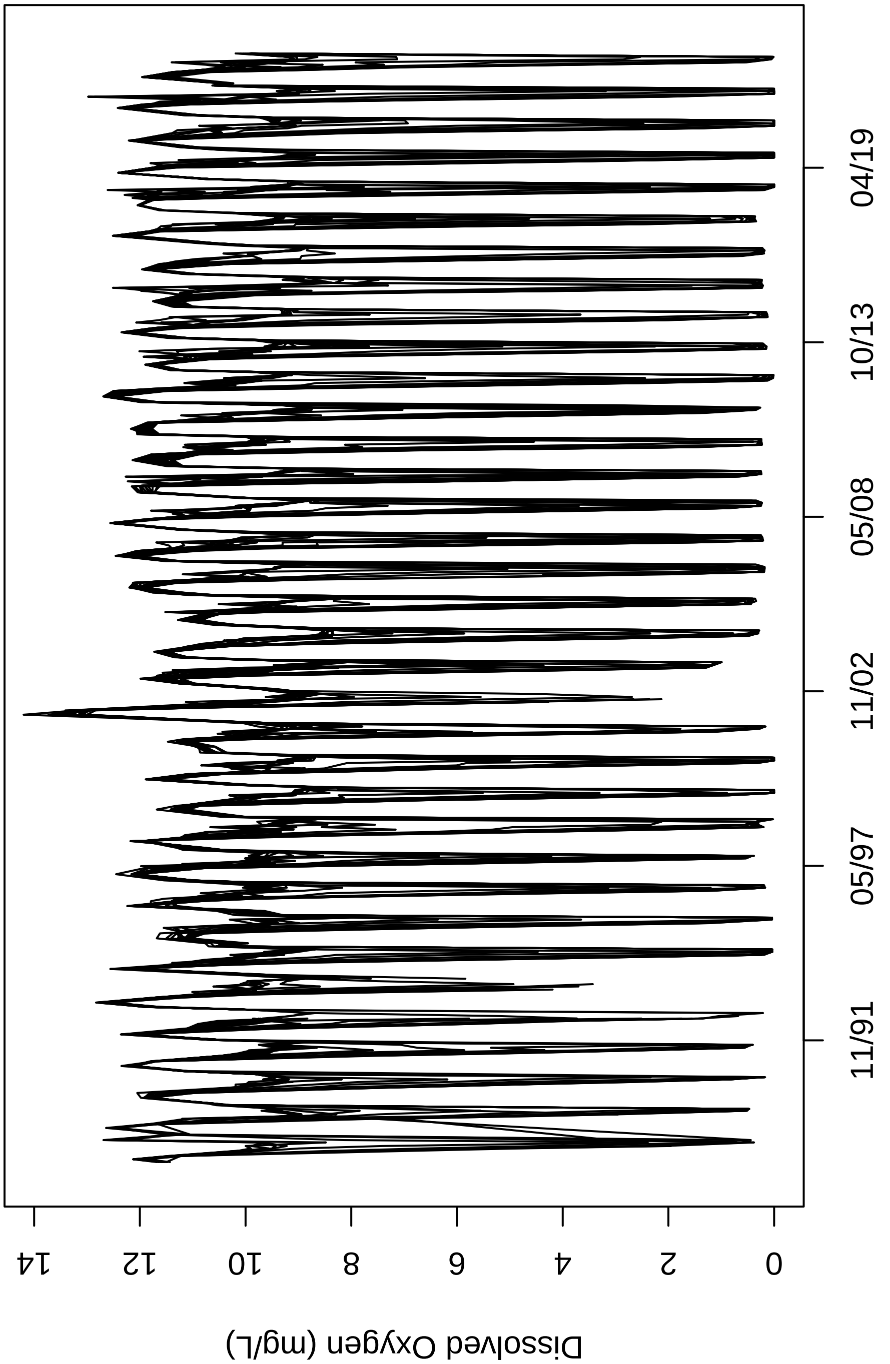

Figure B71: Lake Whatcom historic dissolved oxygen data for Site 1.

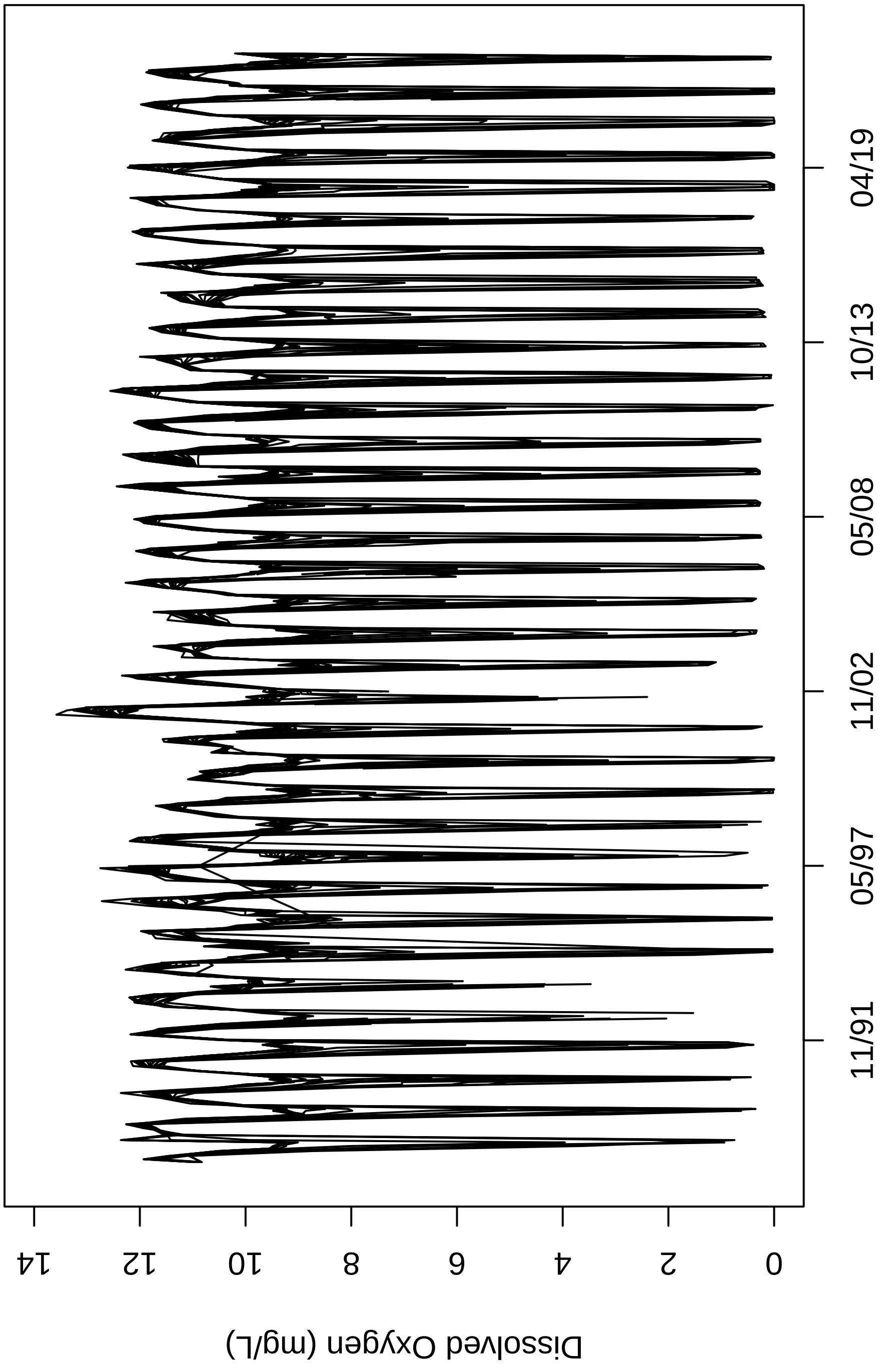

Figure B72: Lake Whatcom historic dissolved oxygen data for Site 2.

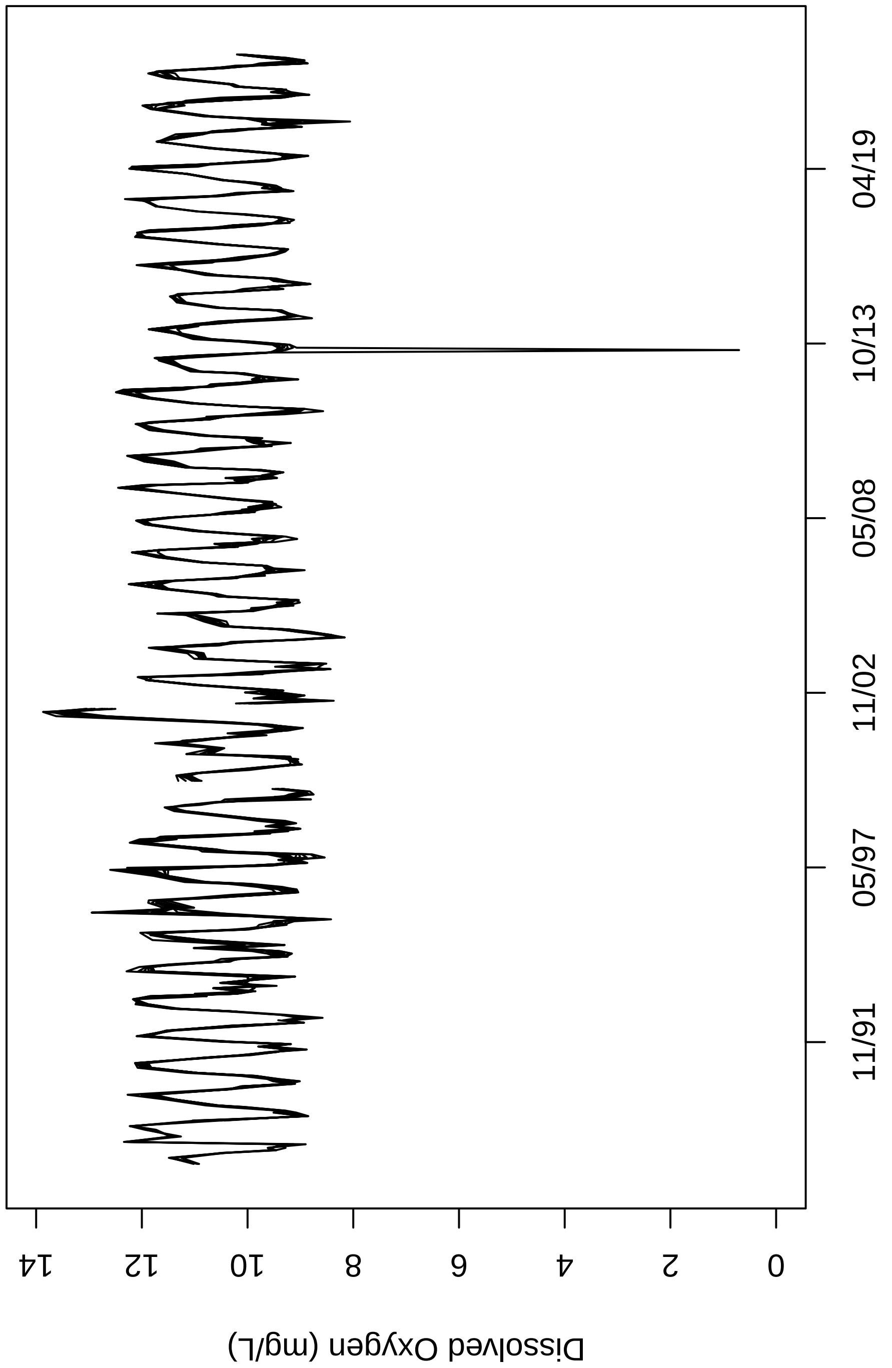

Figure B73: Lake Whatcom historic dissolved oxygen data for the Intake. See discussion of the low dissolved oxygen value in Matthews et al. (2014).

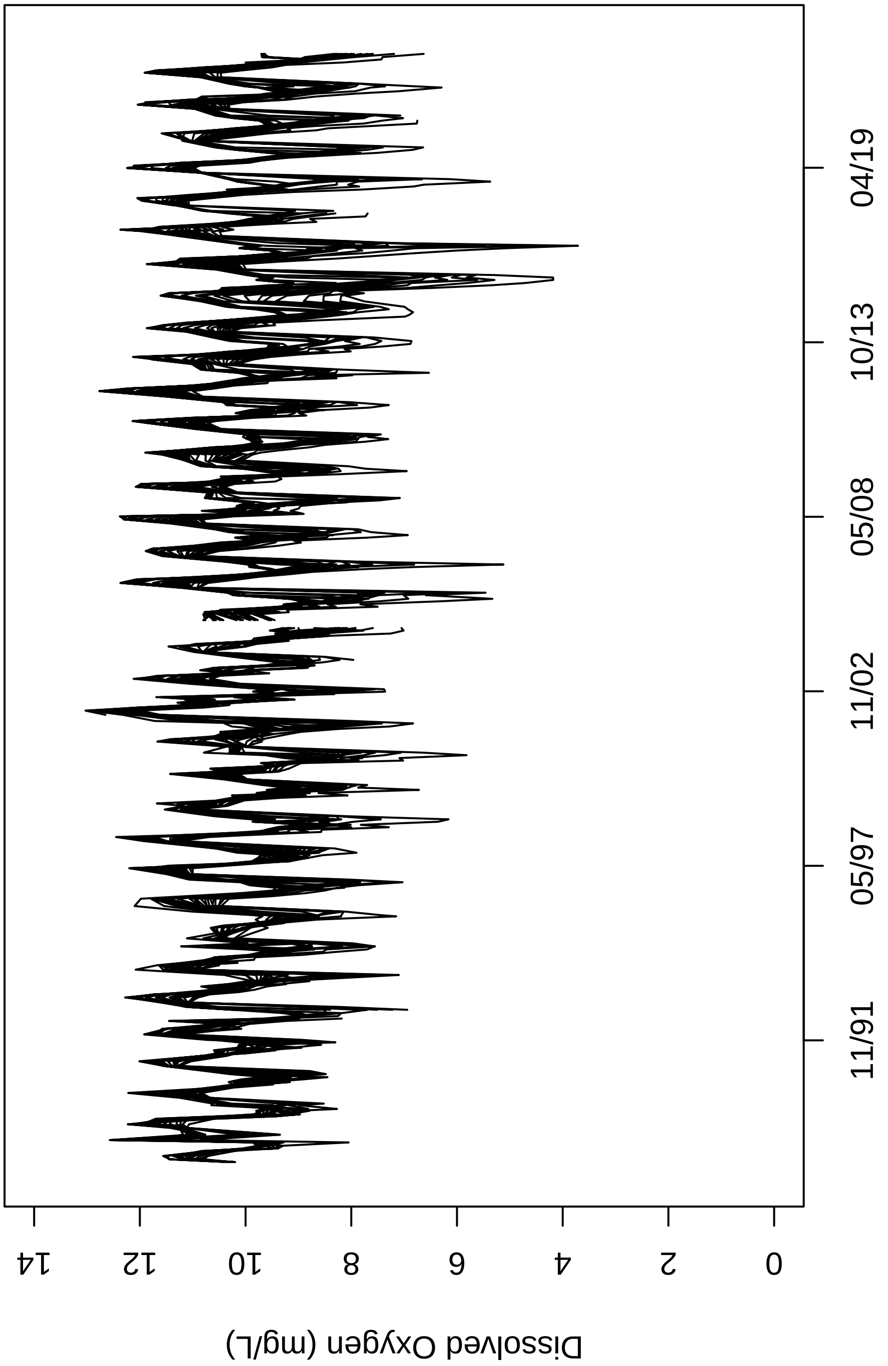

Figure B74: Lake Whatcom historic dissolved oxygen data for Site 3.

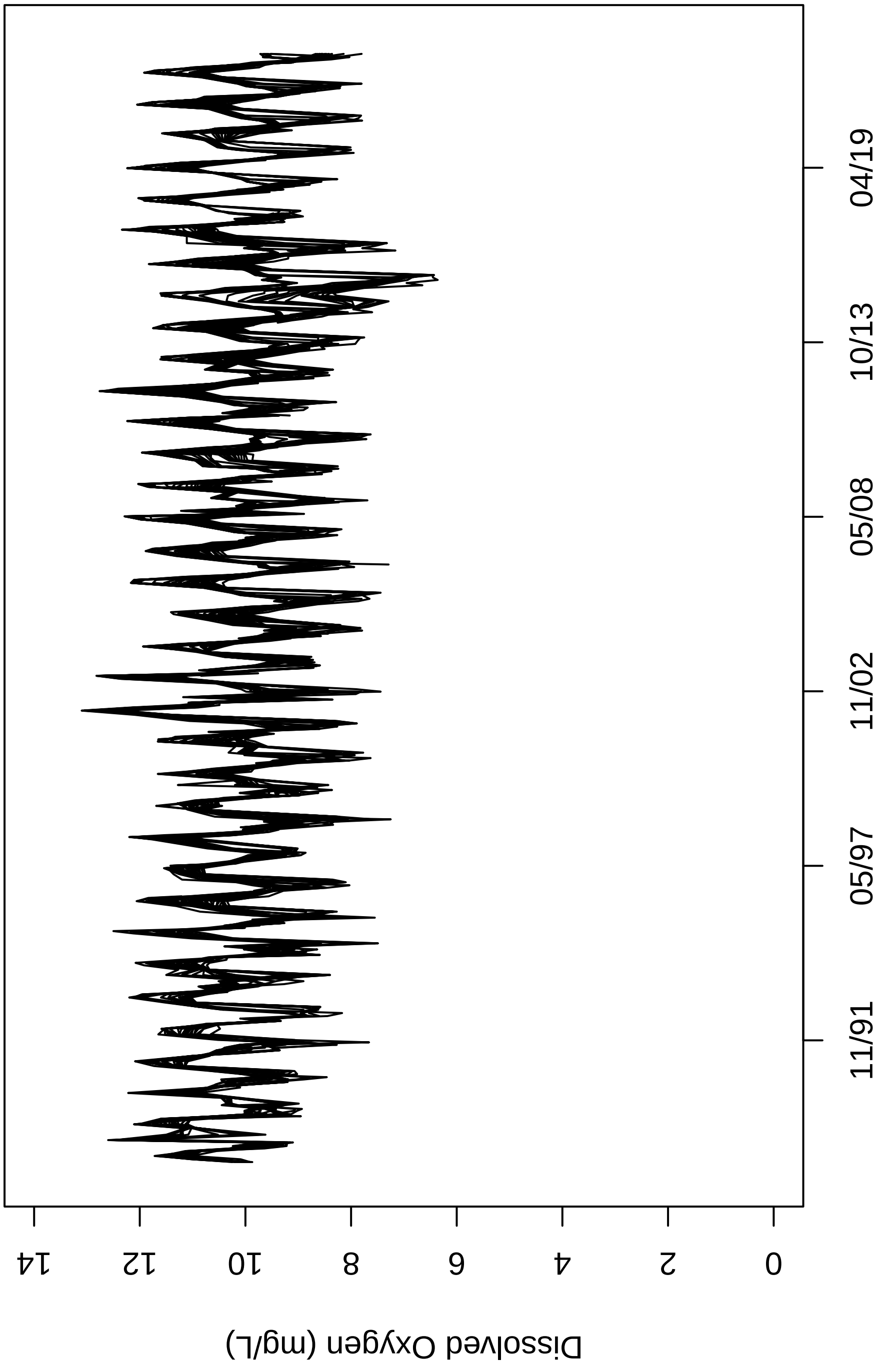

Figure B75: Lake Whatcom historic dissolved oxygen data for Site 4.

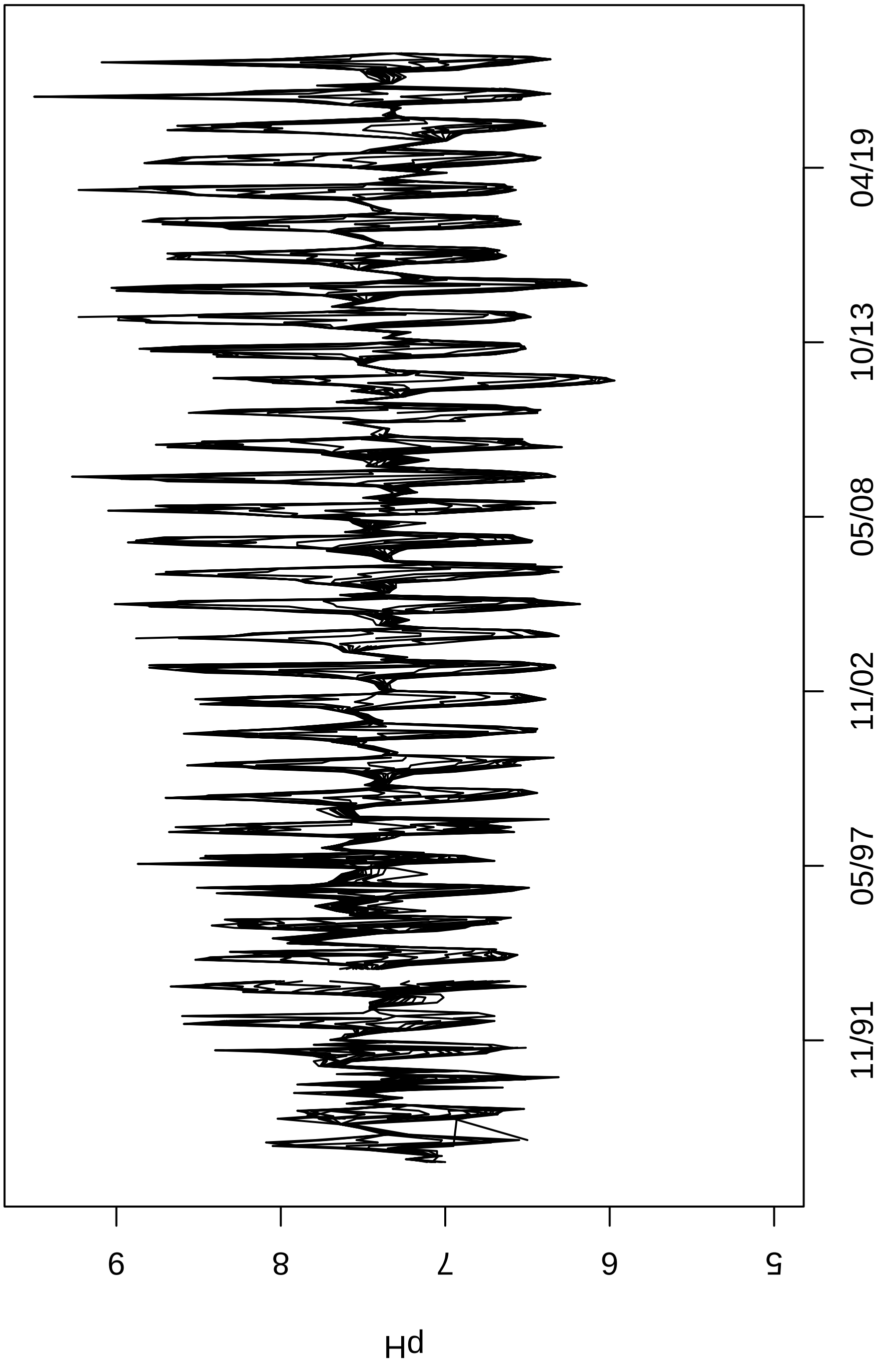

Figure B76: Lake Whatcom historic pH data for Site 1.

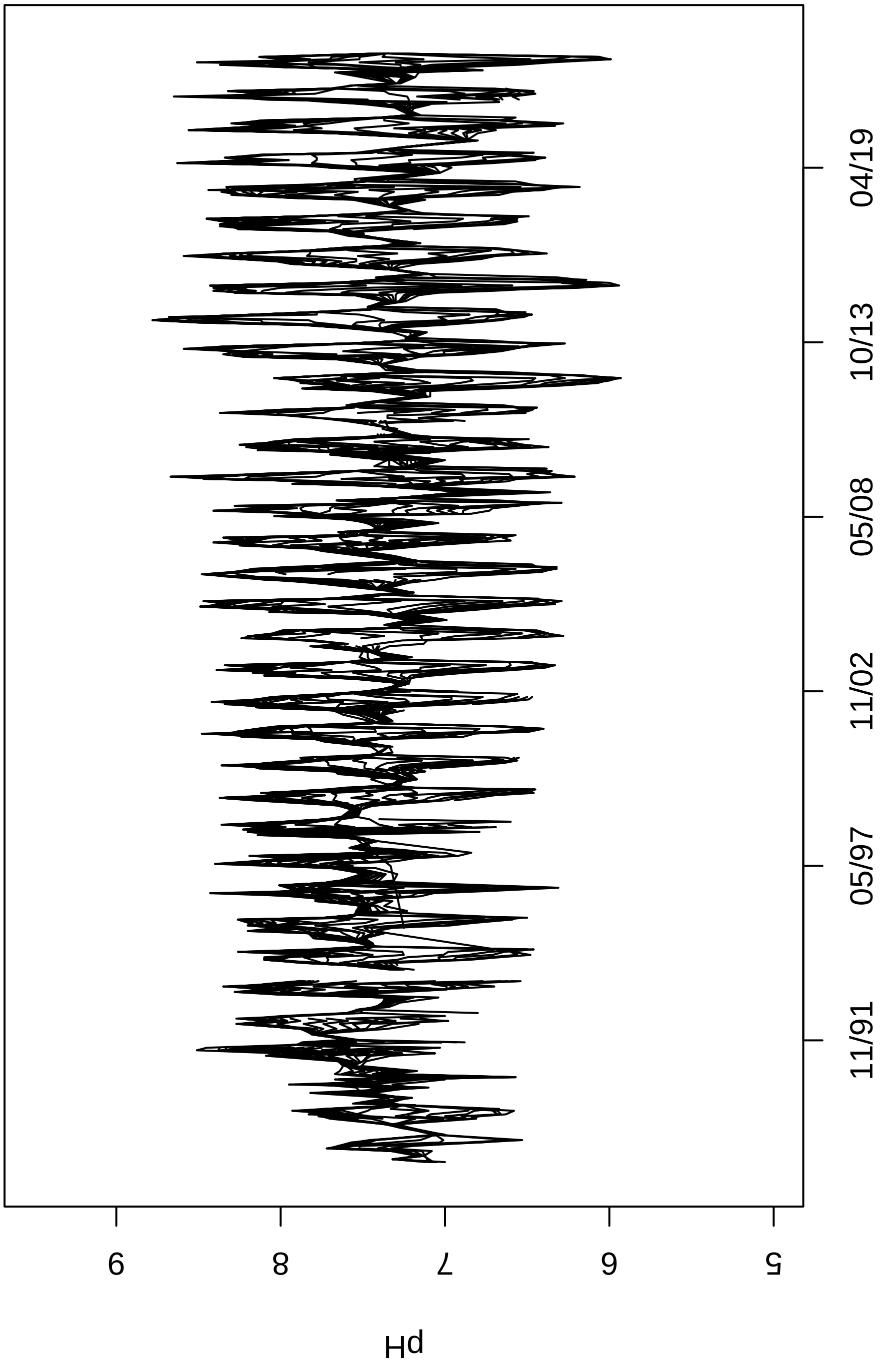

Figure B77: Lake Whatcom historic pH data for Site 2.

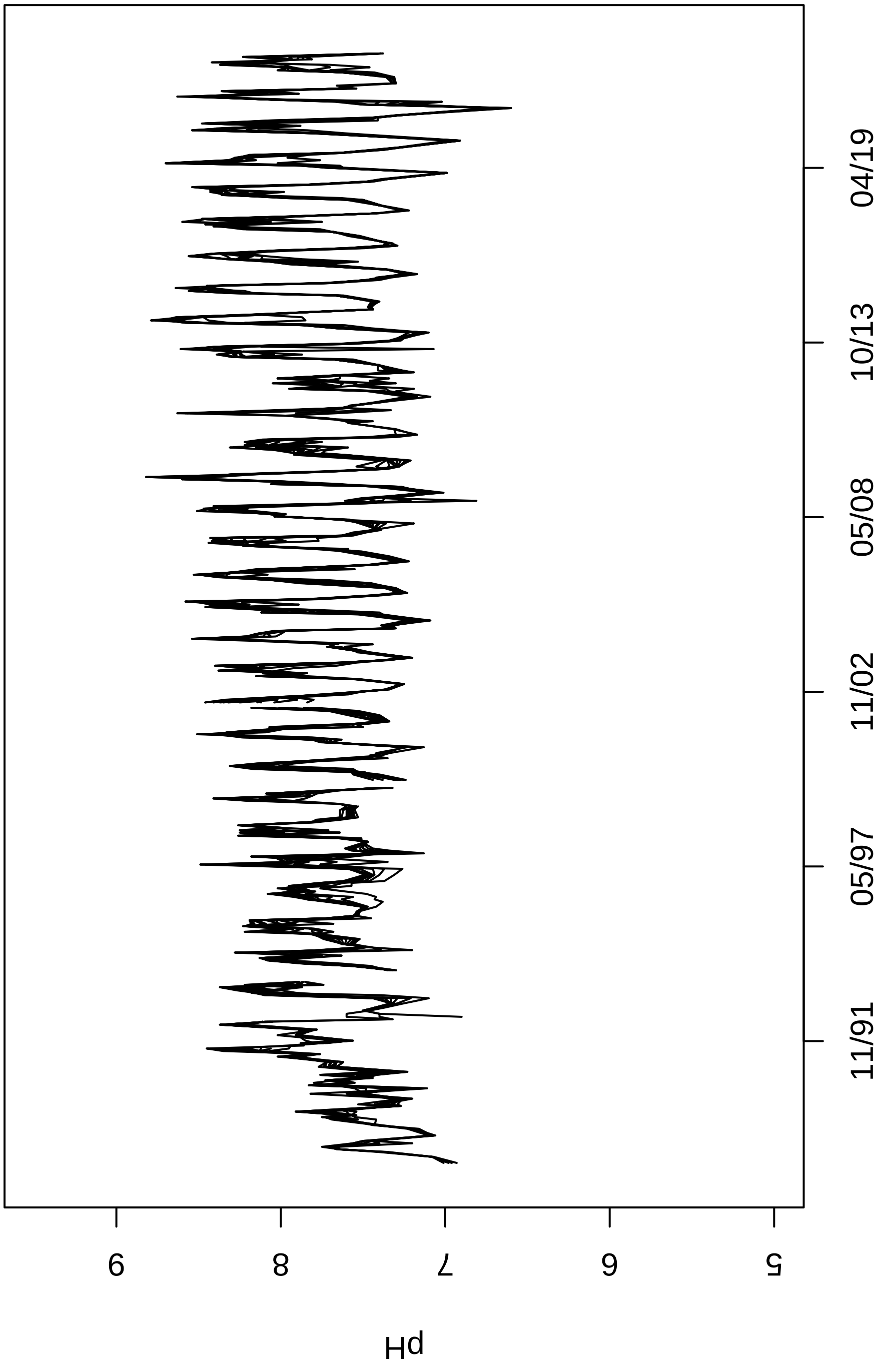

Figure B78: Lake Whatcom historic pH data for the Intake.

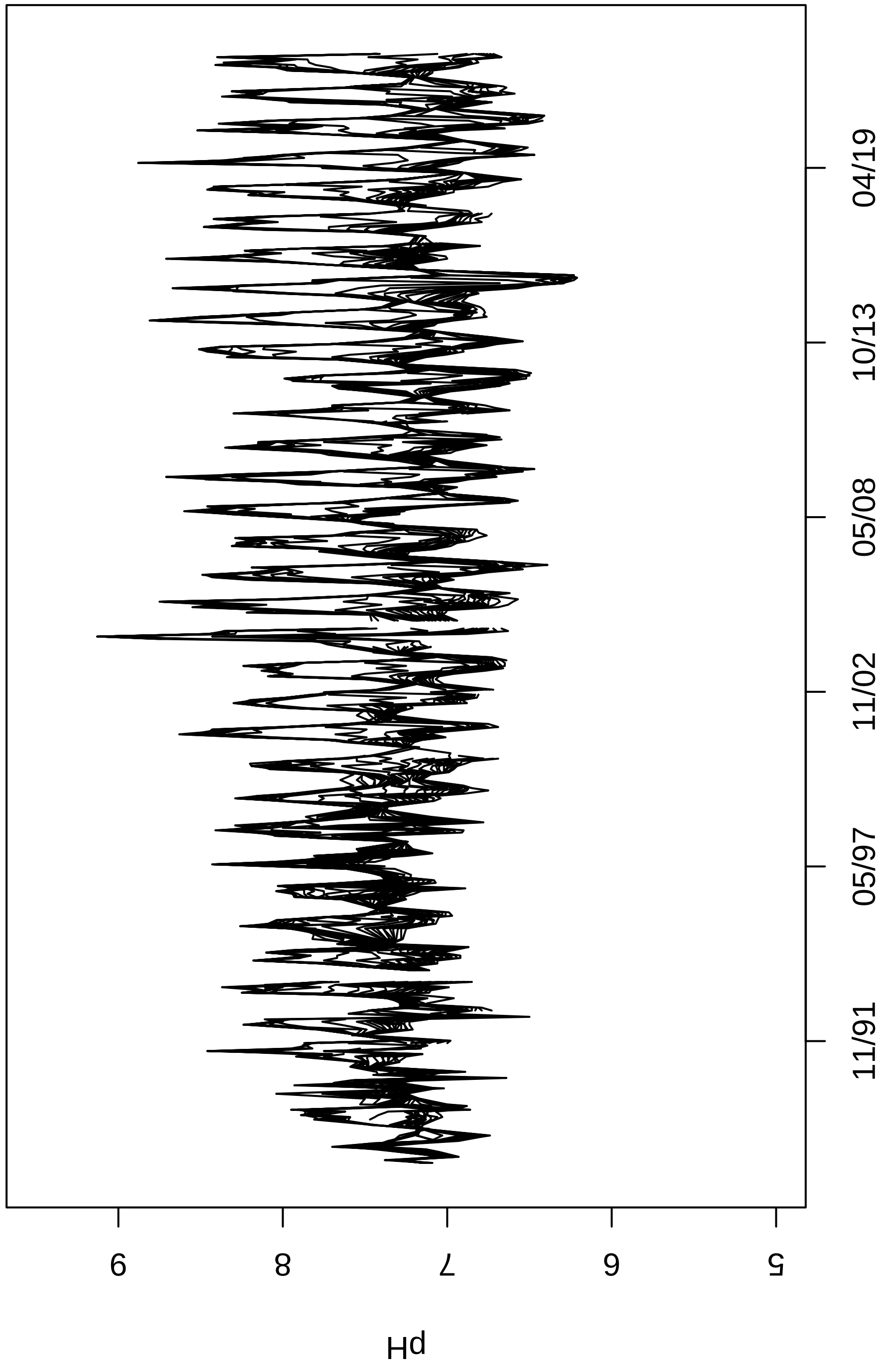

Figure B79: Lake Whatcom historic pH data for Site 3.

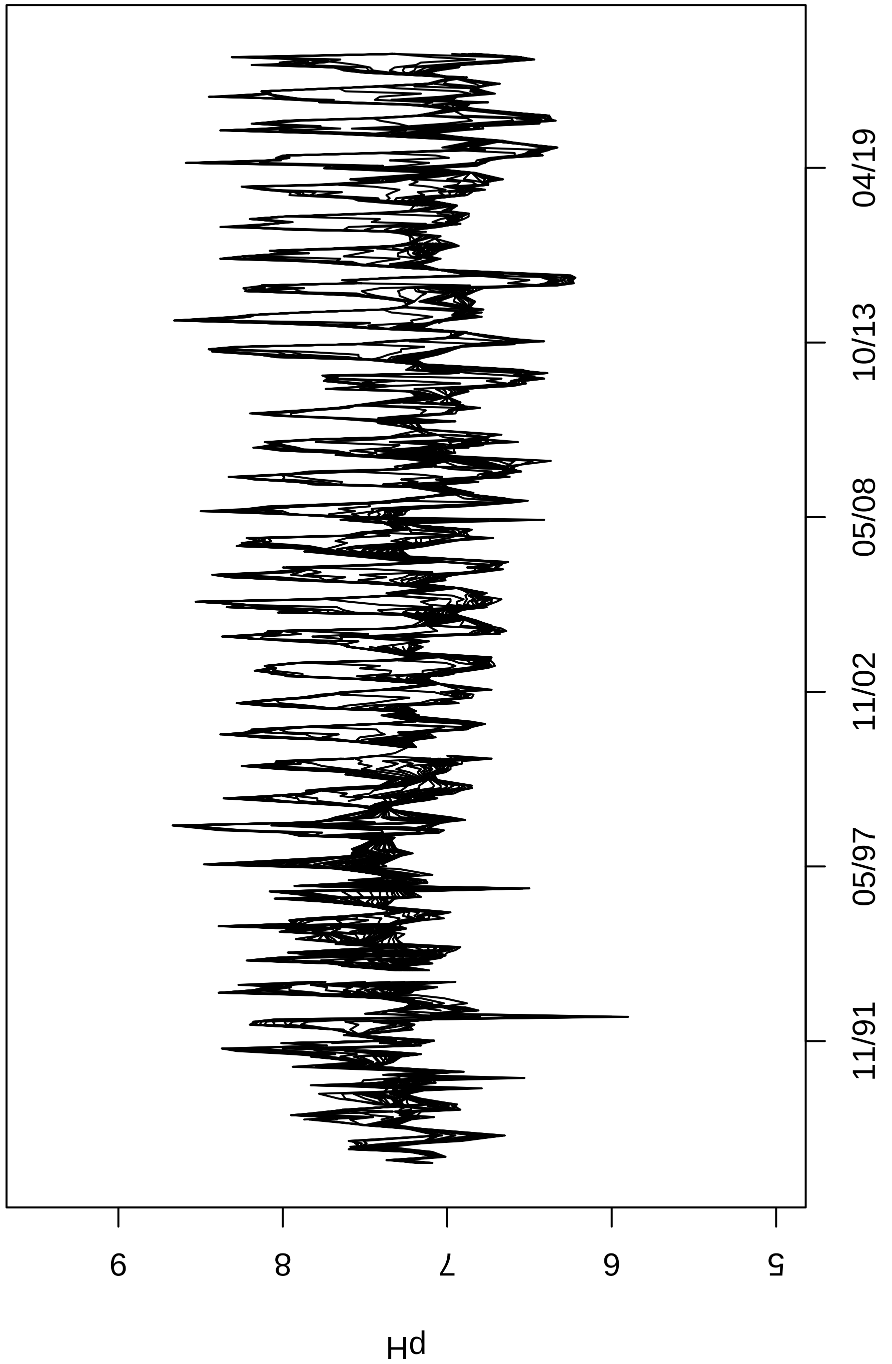

Figure B80: Lake Whatcom historic pH data for Site 4.

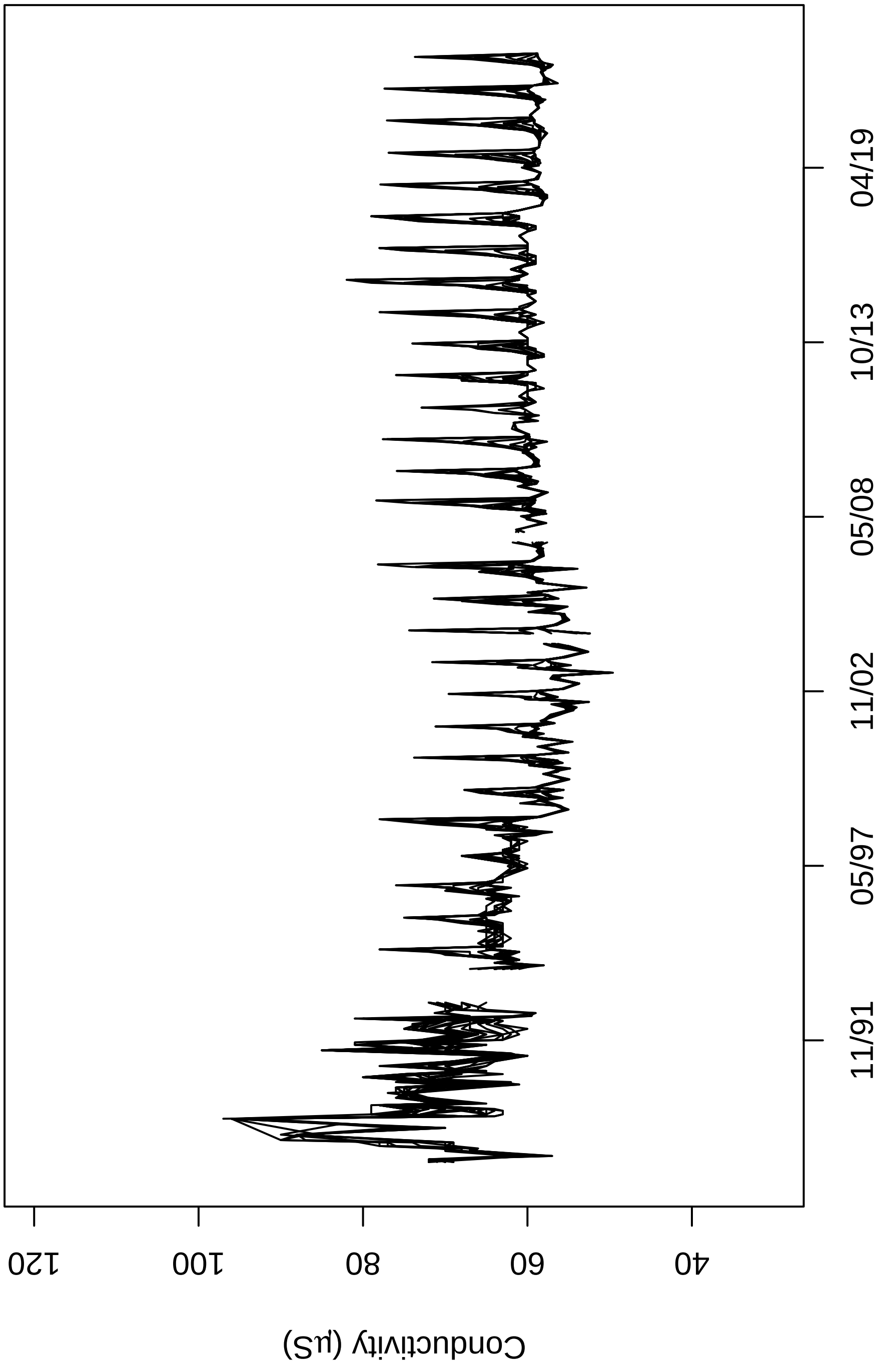

Figure B81: Lake Whatcom historic conductivity data for Site 1. The decreasing conductivity trend is the result of changing to more sensitive equipment.

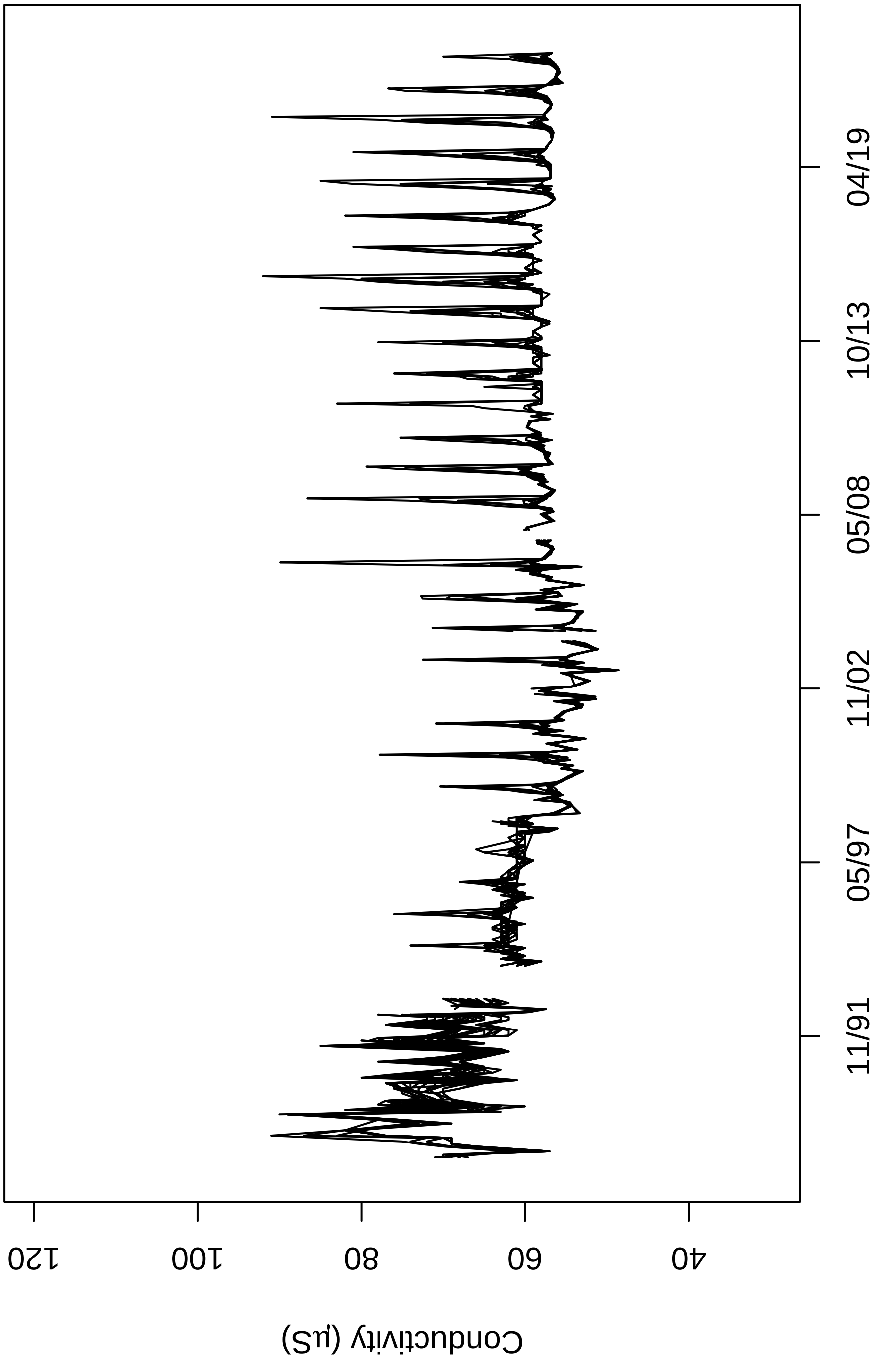

Figure B82: Lake Whatcom historic conductivity data for Site 2. The decreasing conductivity trend is the result of changing to more sensitive equipment.

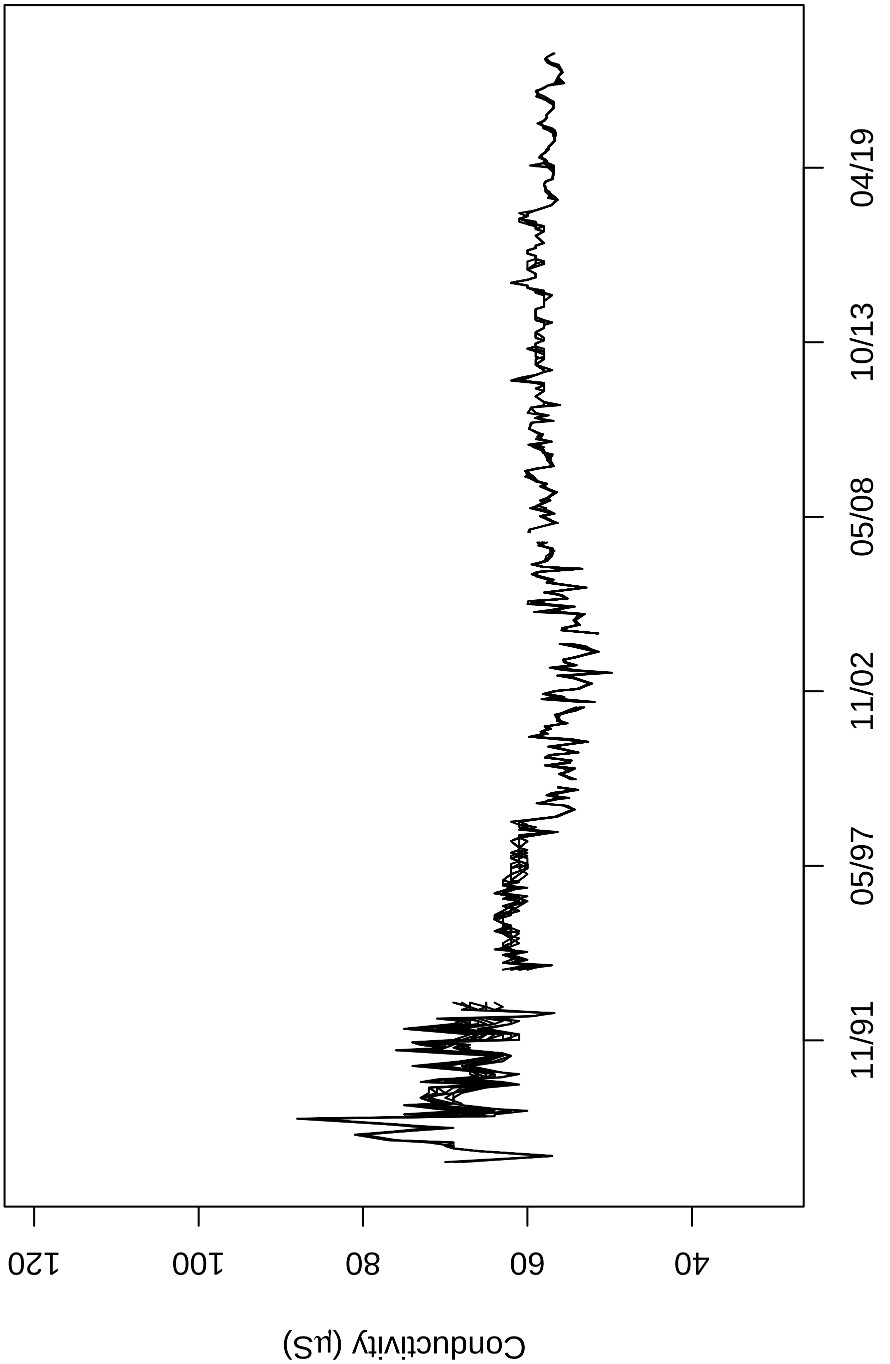

Figure B83: Lake Whatcom historic conductivity data for the Intake. The decreasing conductivity trend is the result of changing to more sensitive equipment.

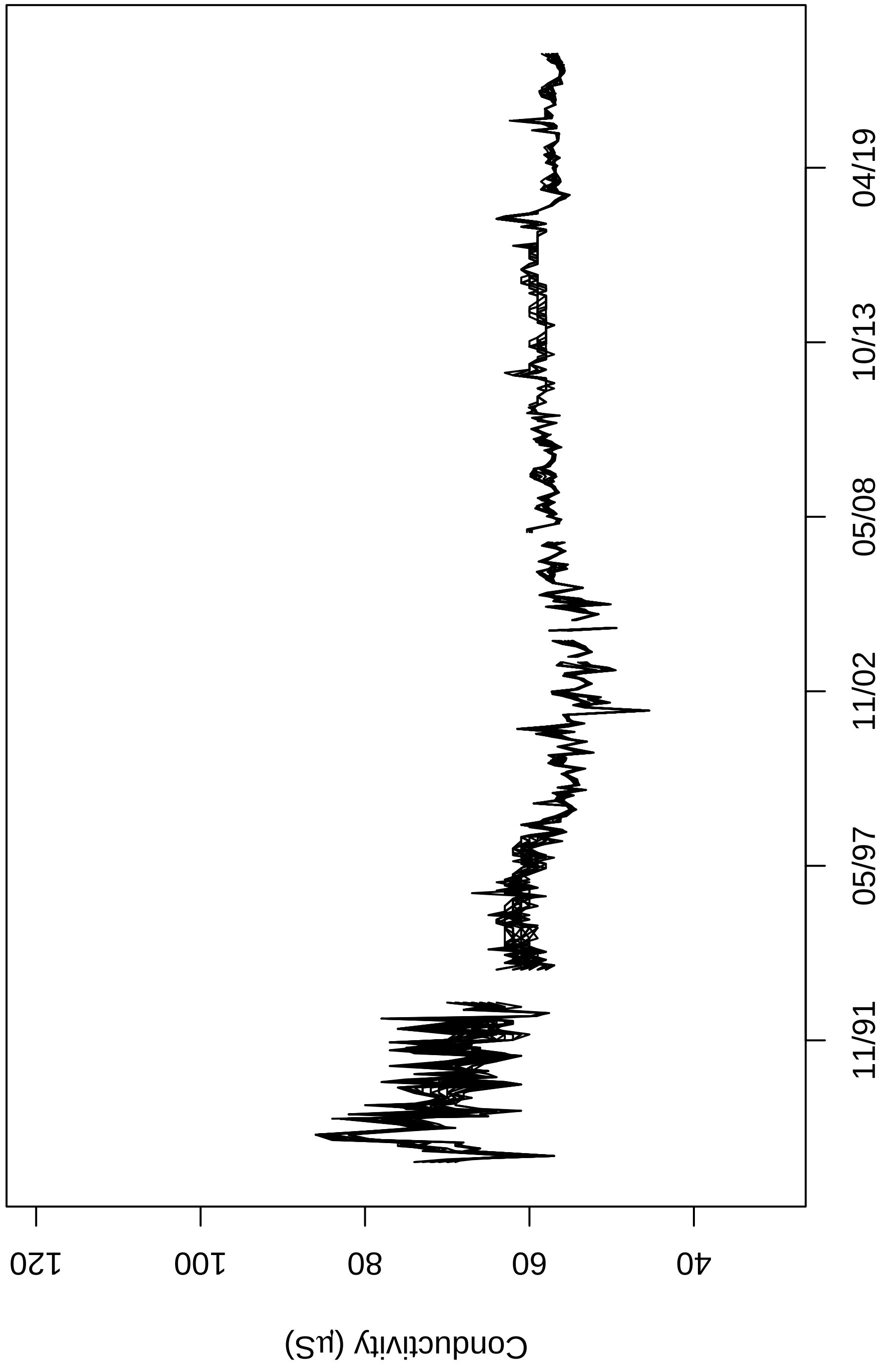

Figure B84: Lake Whatcom historic conductivity data for Site 3. The decreasing conductivity trend is the result of changing to more sensitive equipment.

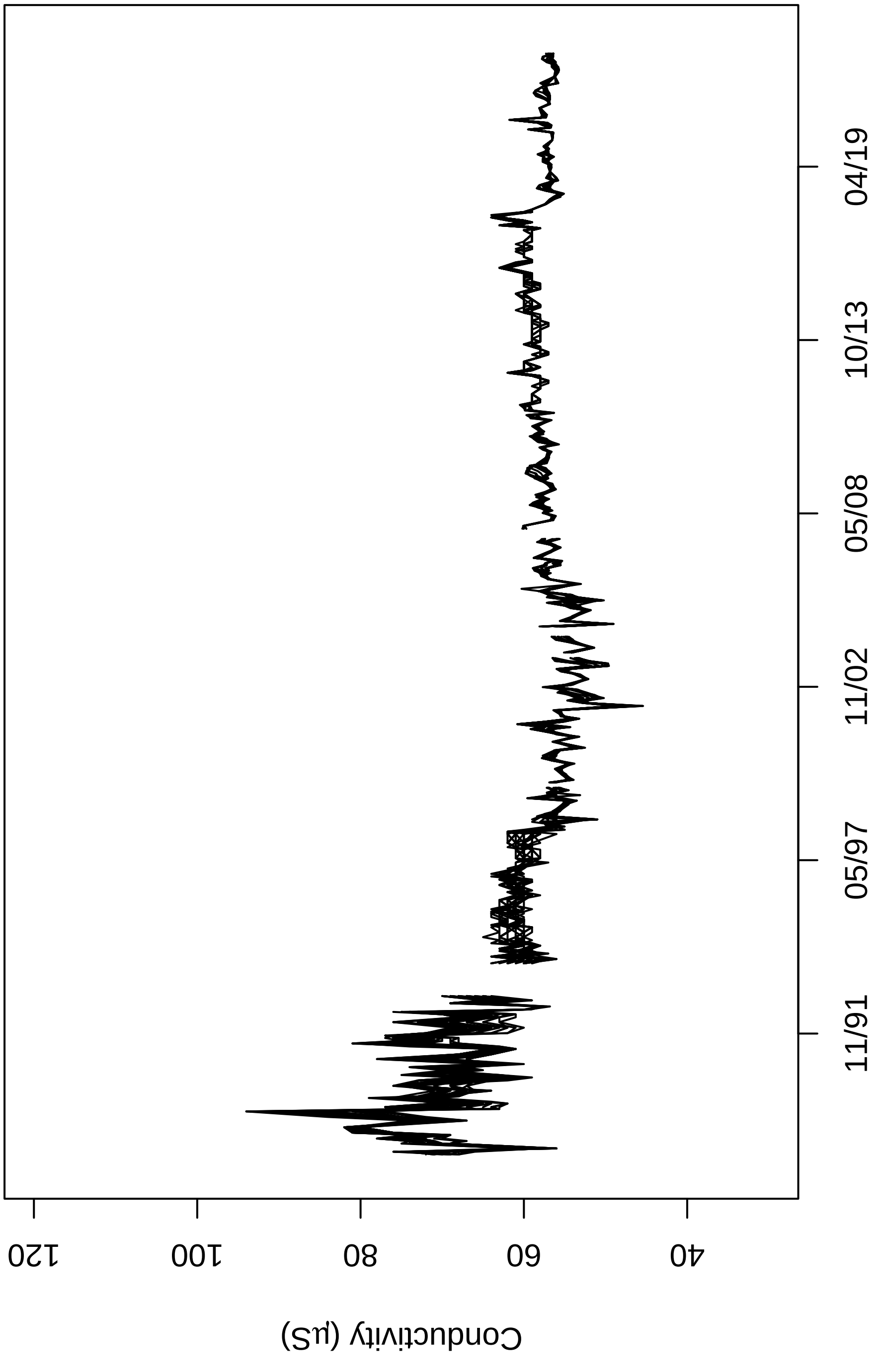

Figure B85: Lake Whatcom historic conductivity data for Site 4. The decreasing conductivity trend is the result of changing to more sensitive equipment.

B.3 Long-term Water Quality Data (1988-present)

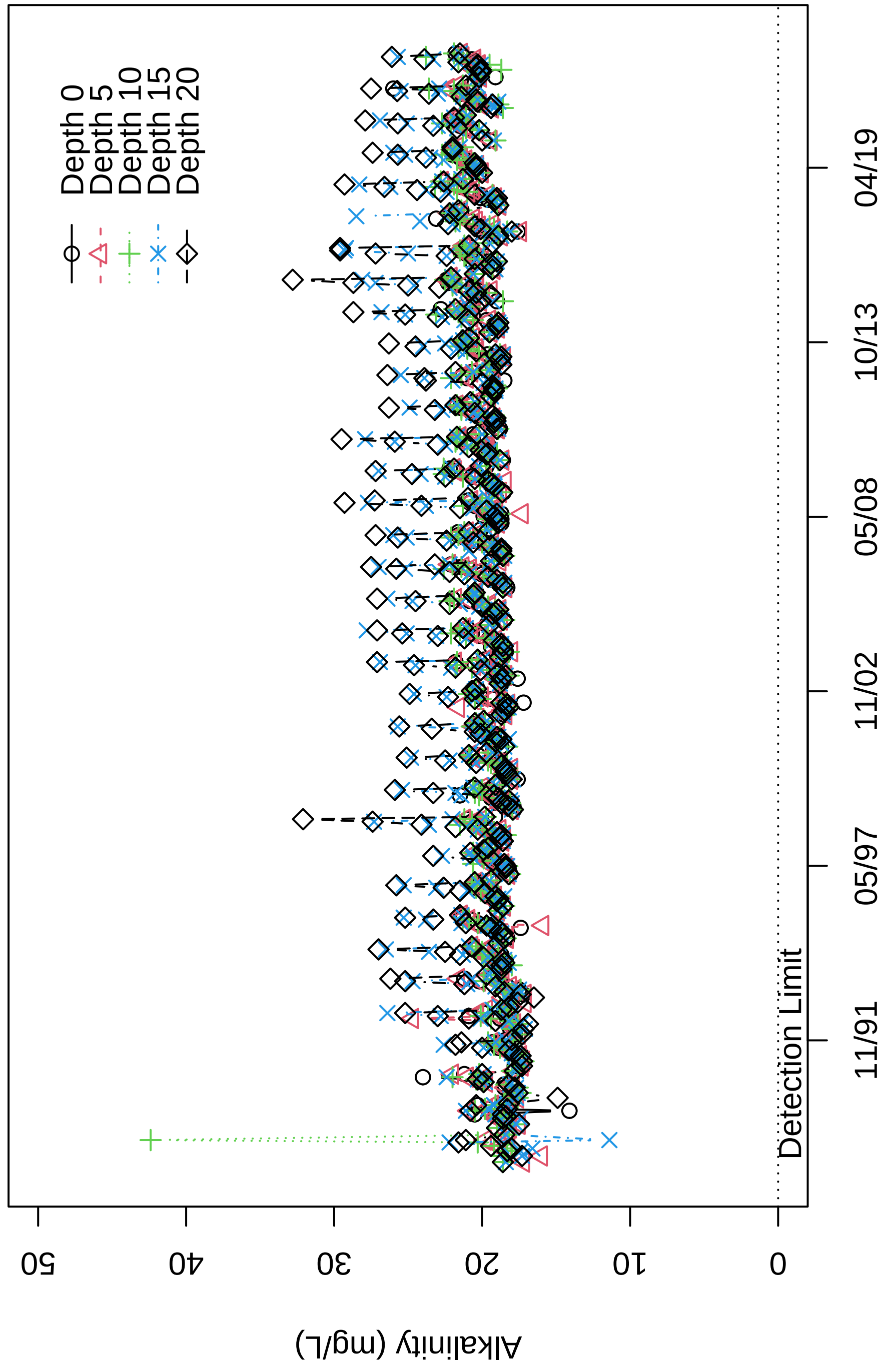

Figure B86: Lake Whatcom alkalinity data for Site 1.

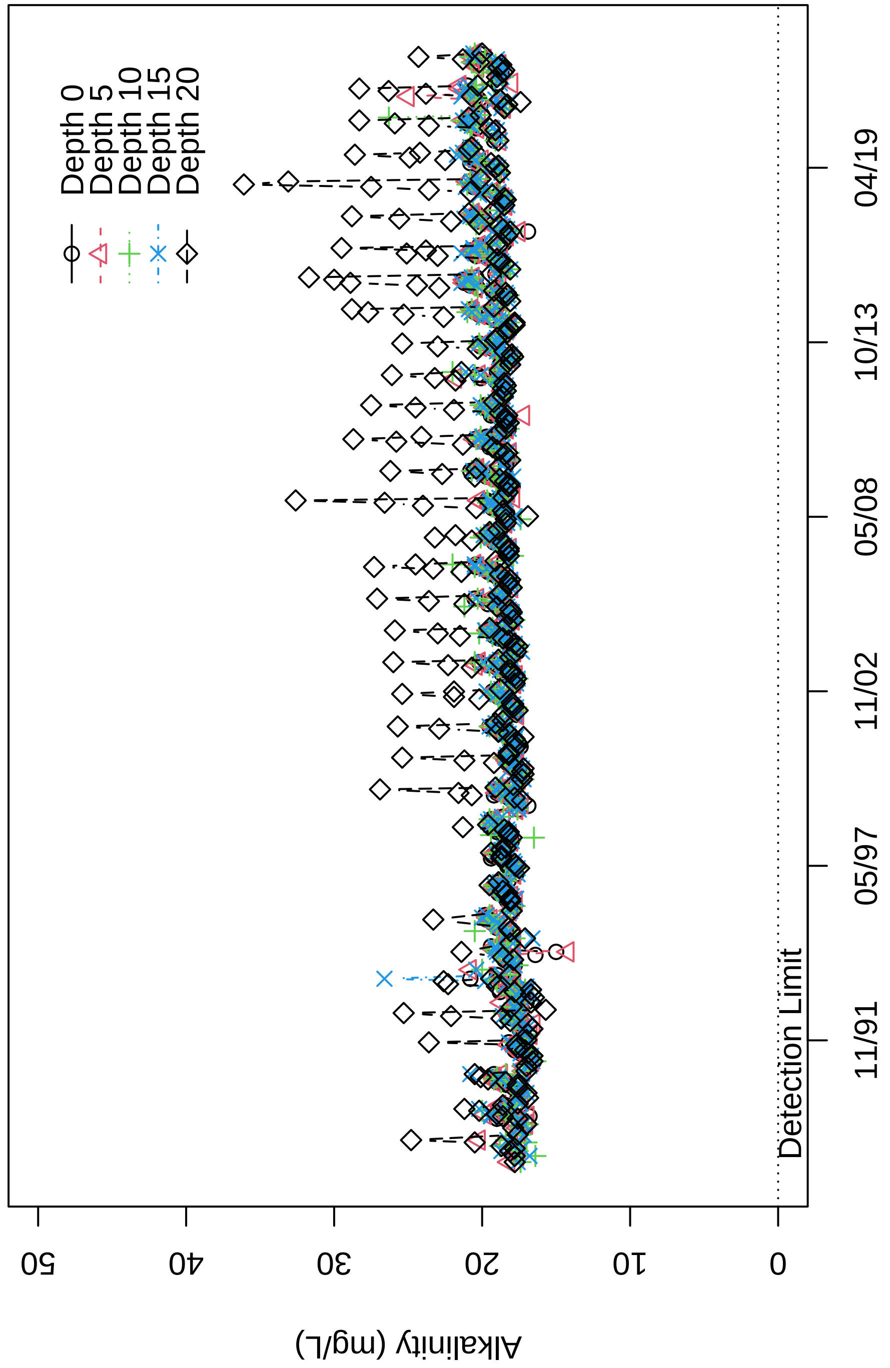

Figure B87: Lake Whatcom alkalinity data for Site 2.

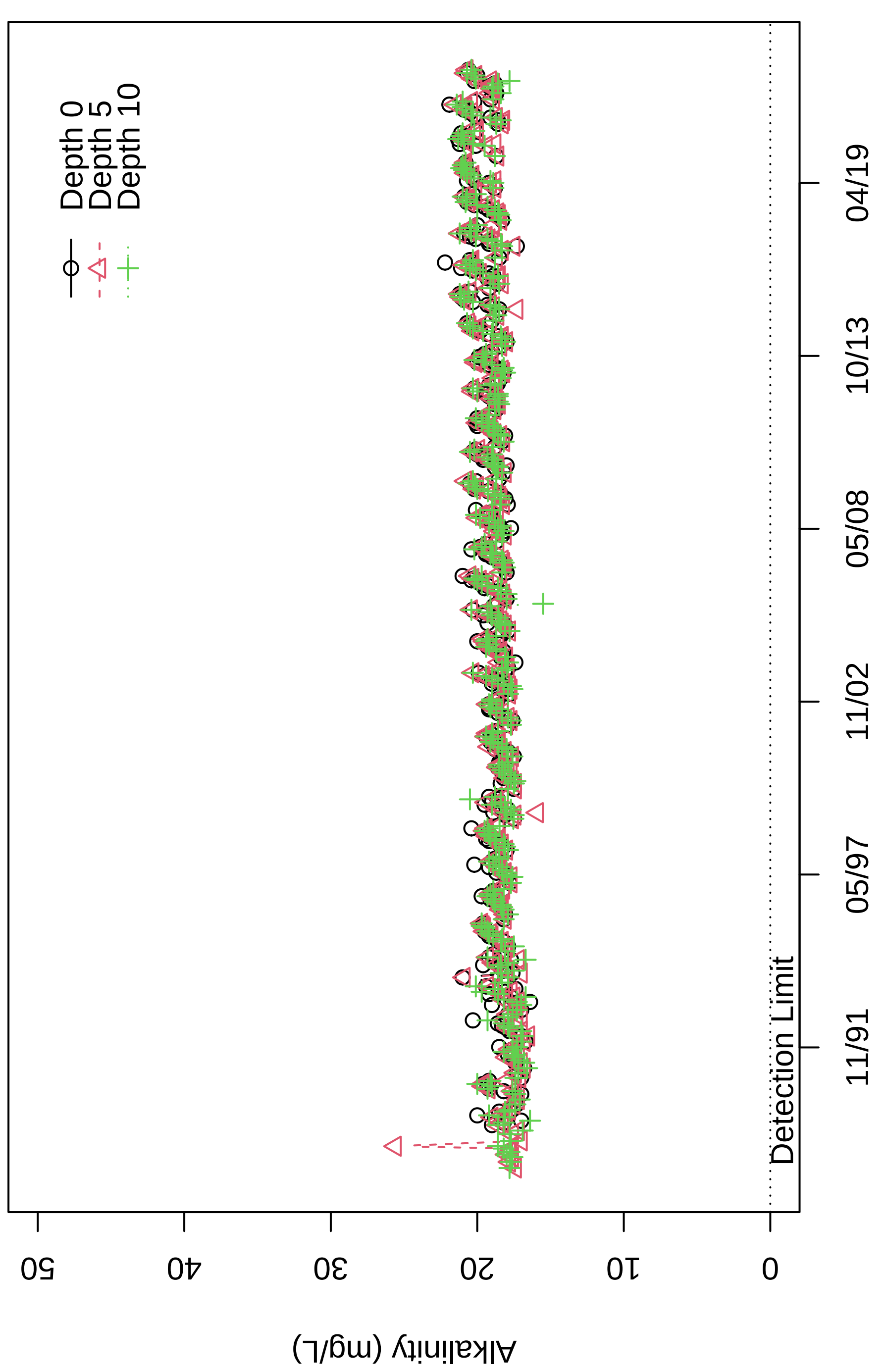

Figure B88: Lake Whatcom alkalinity data for the Intake site.

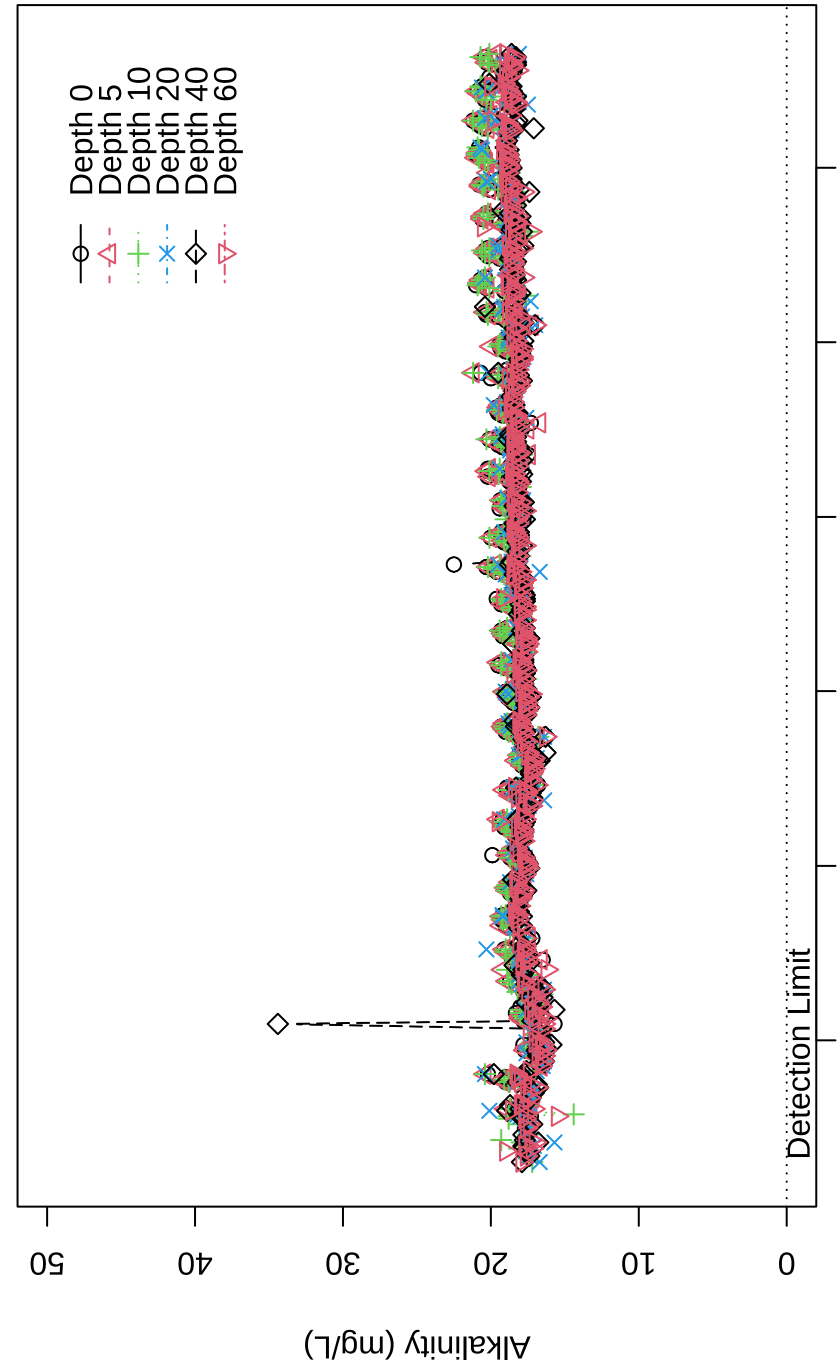

Figure B89: Lake Whatcom alkalinity data for Site 3.

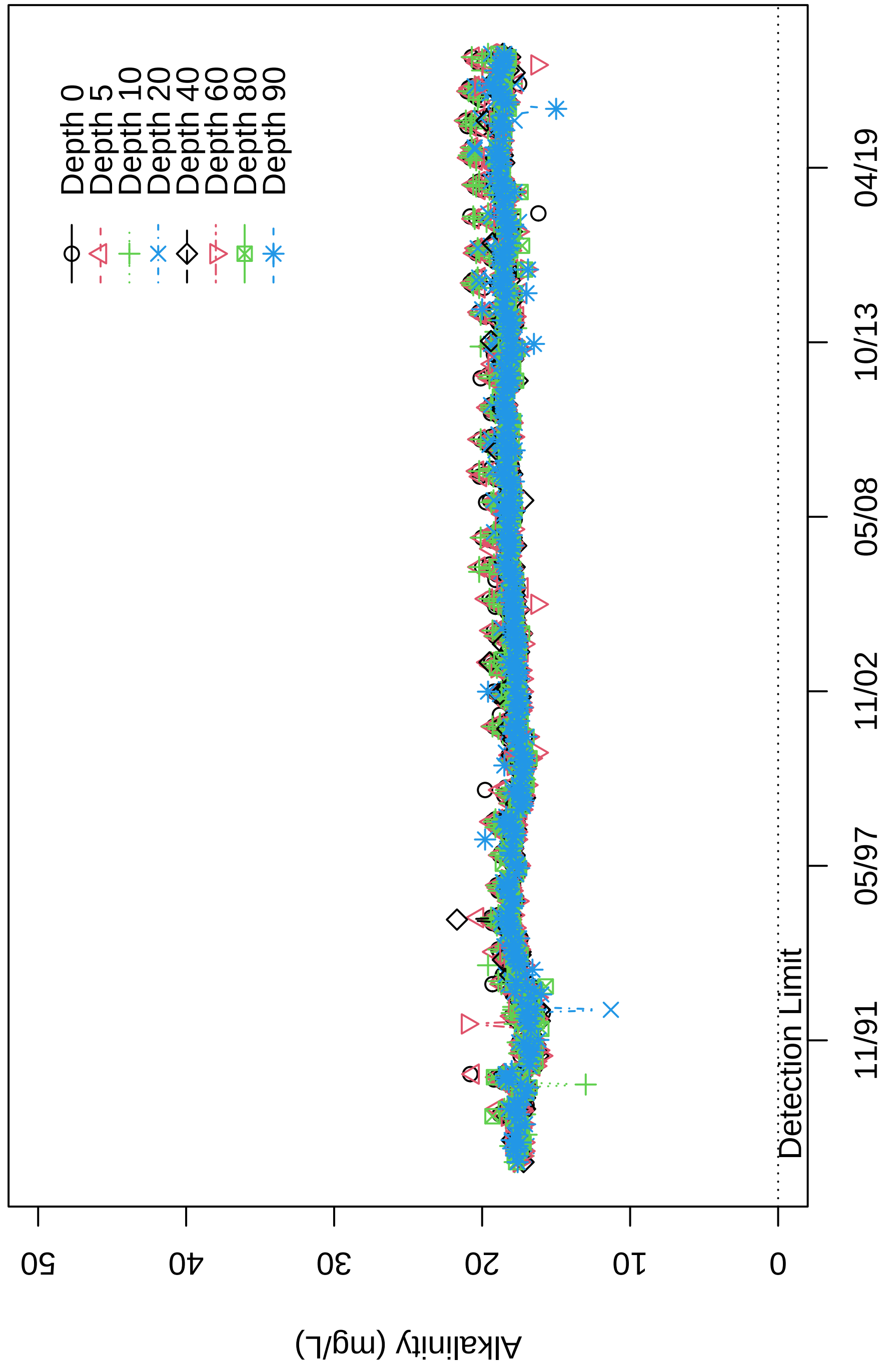

Figure B90: Lake Whatcom alkalinity data for Site 4.

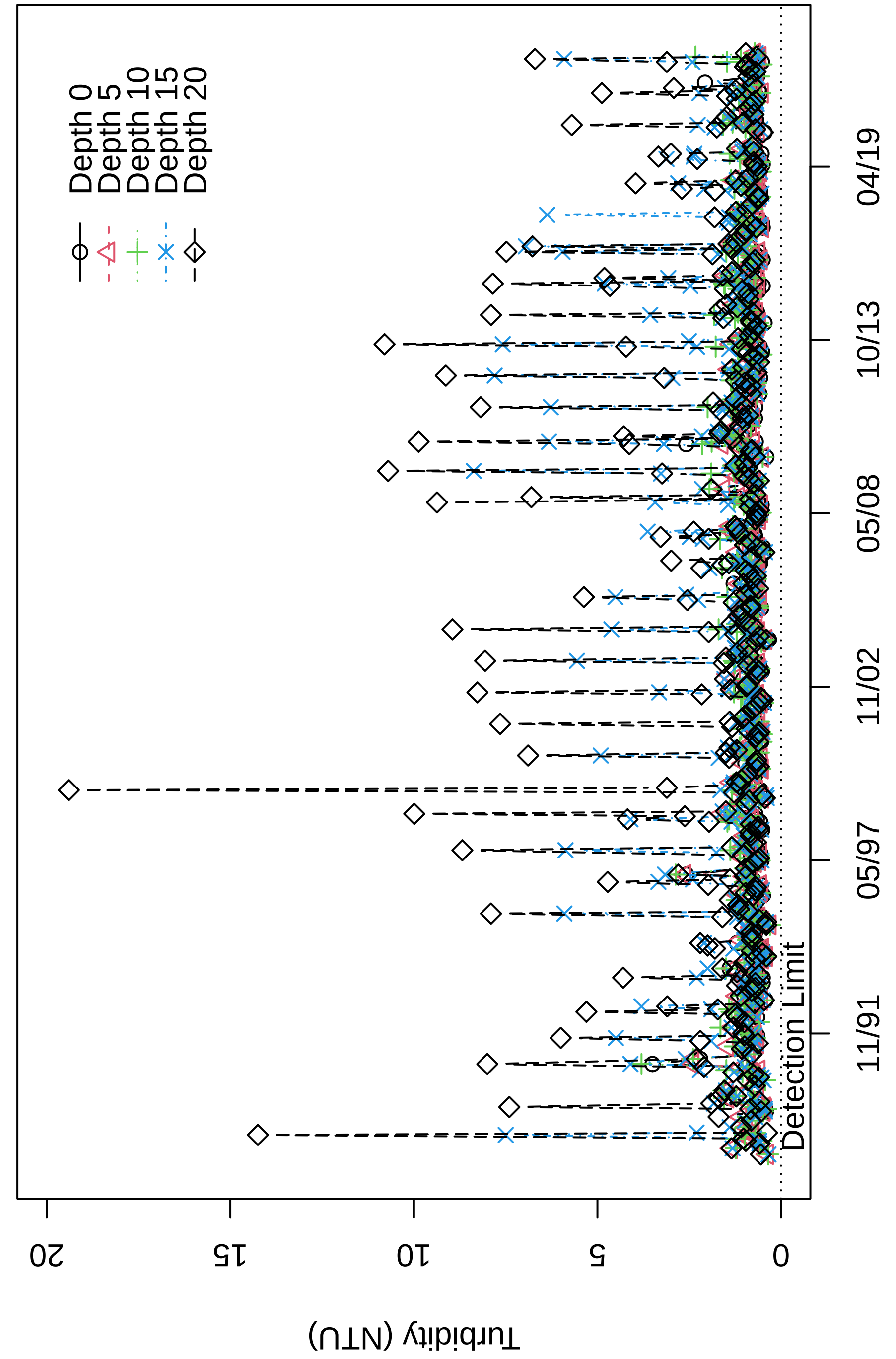

Figure B91: Lake Whatcom turbidity data for Site 1.

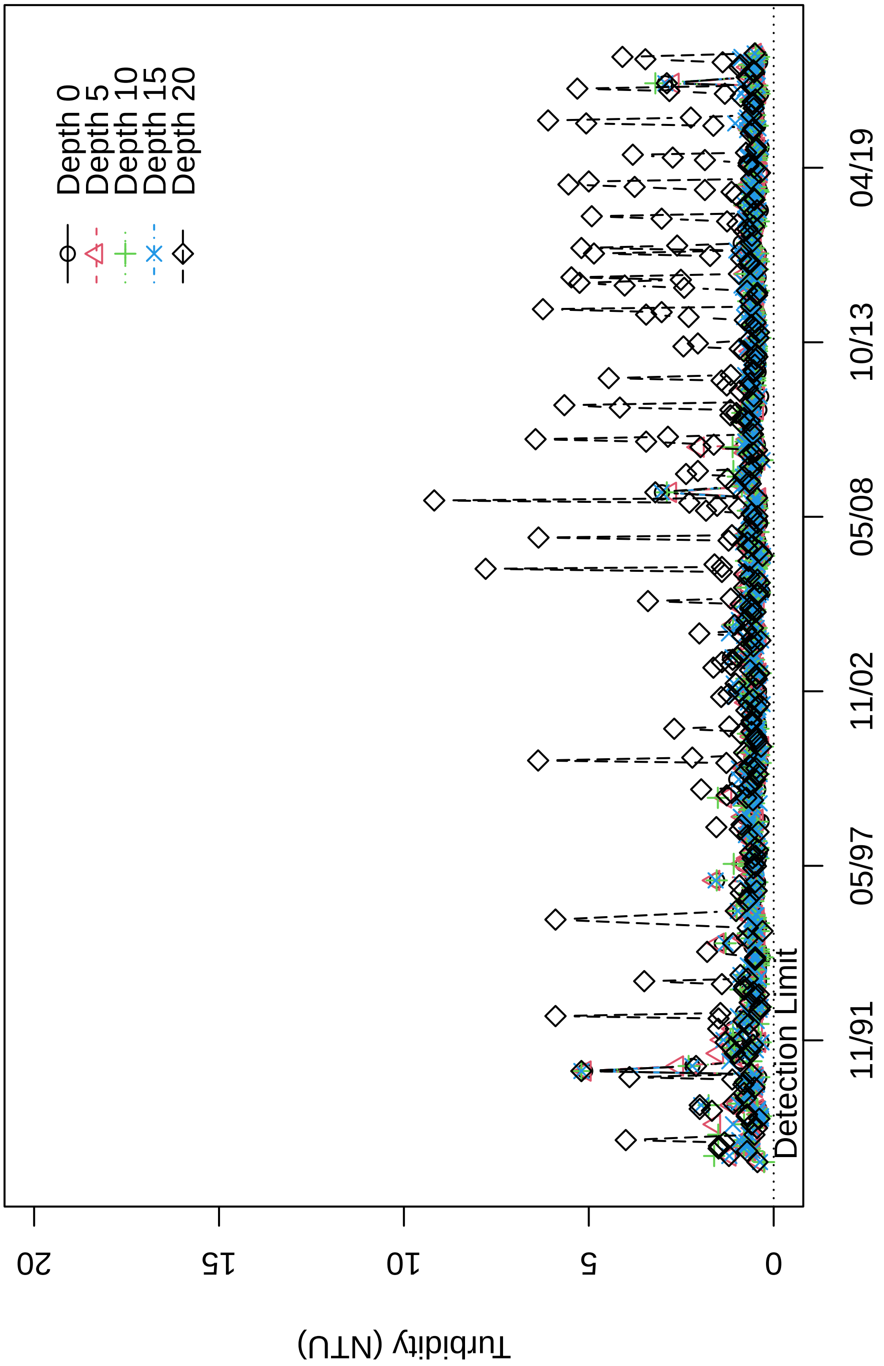

Figure B92: Lake Whatcom turbidity data for Site 2.

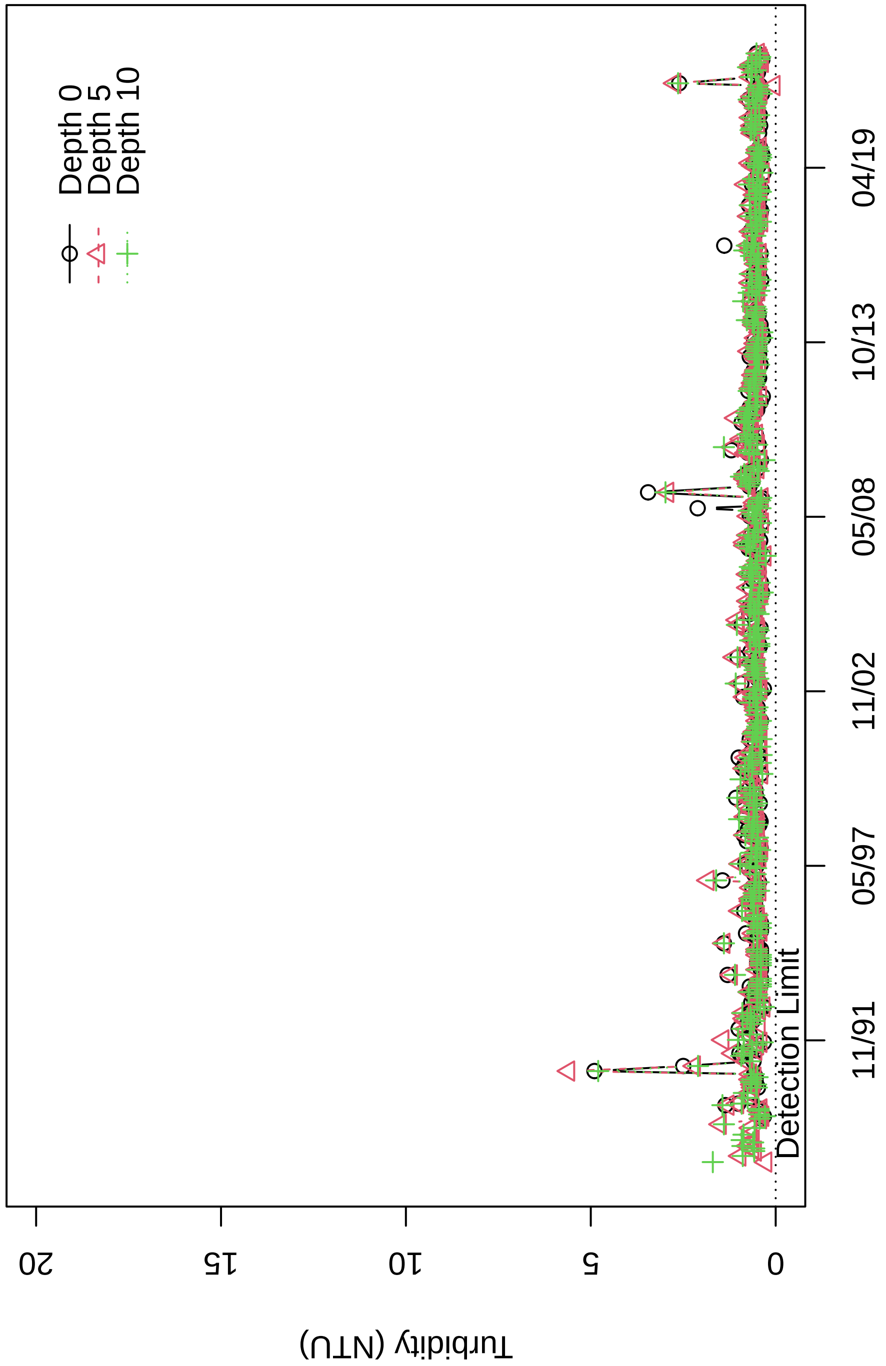

Figure B93: Lake Whatcom turbidity data for the Intake site.

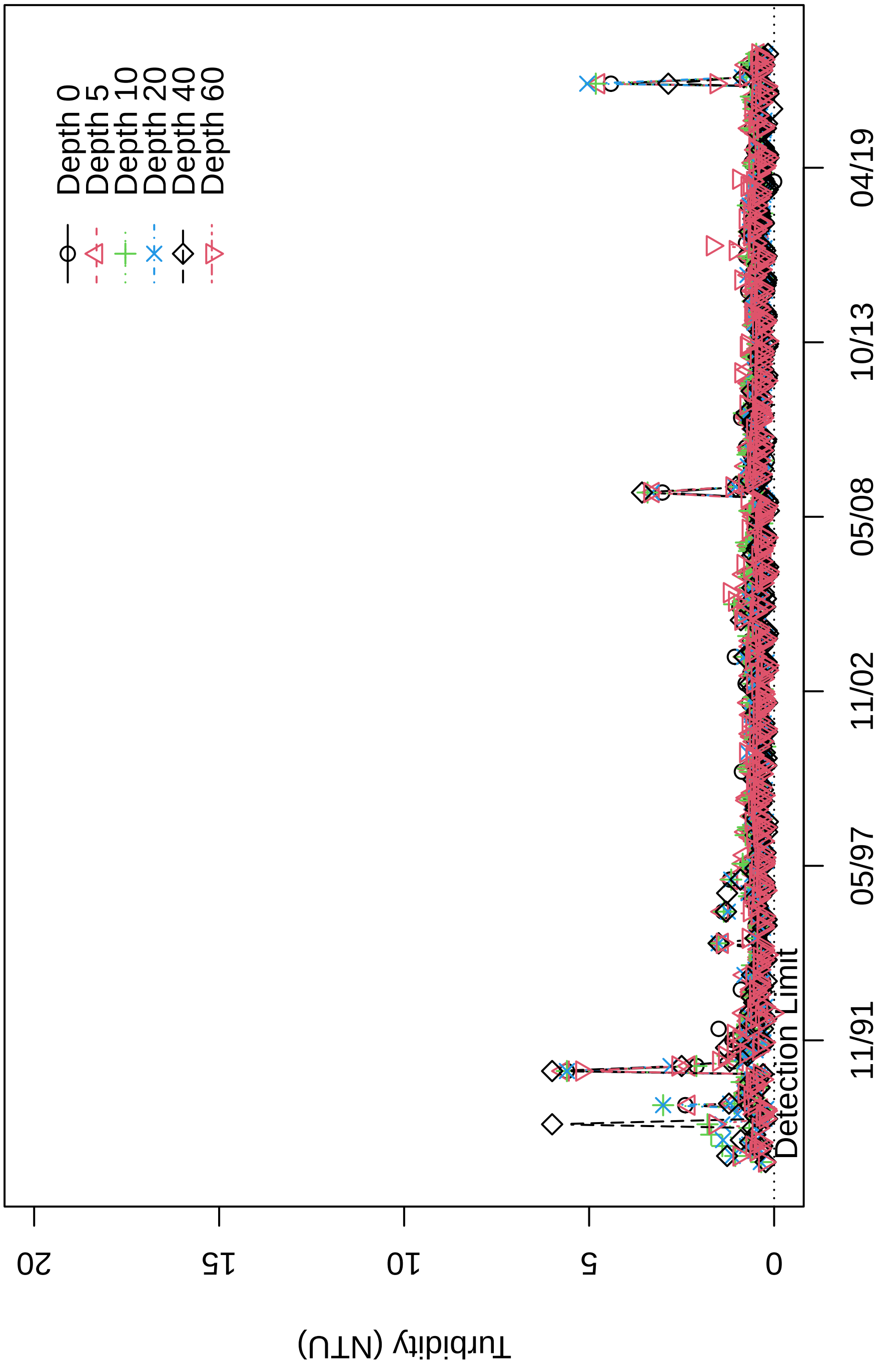

Figure B94: Lake Whatcom turbidity data for Site 3.

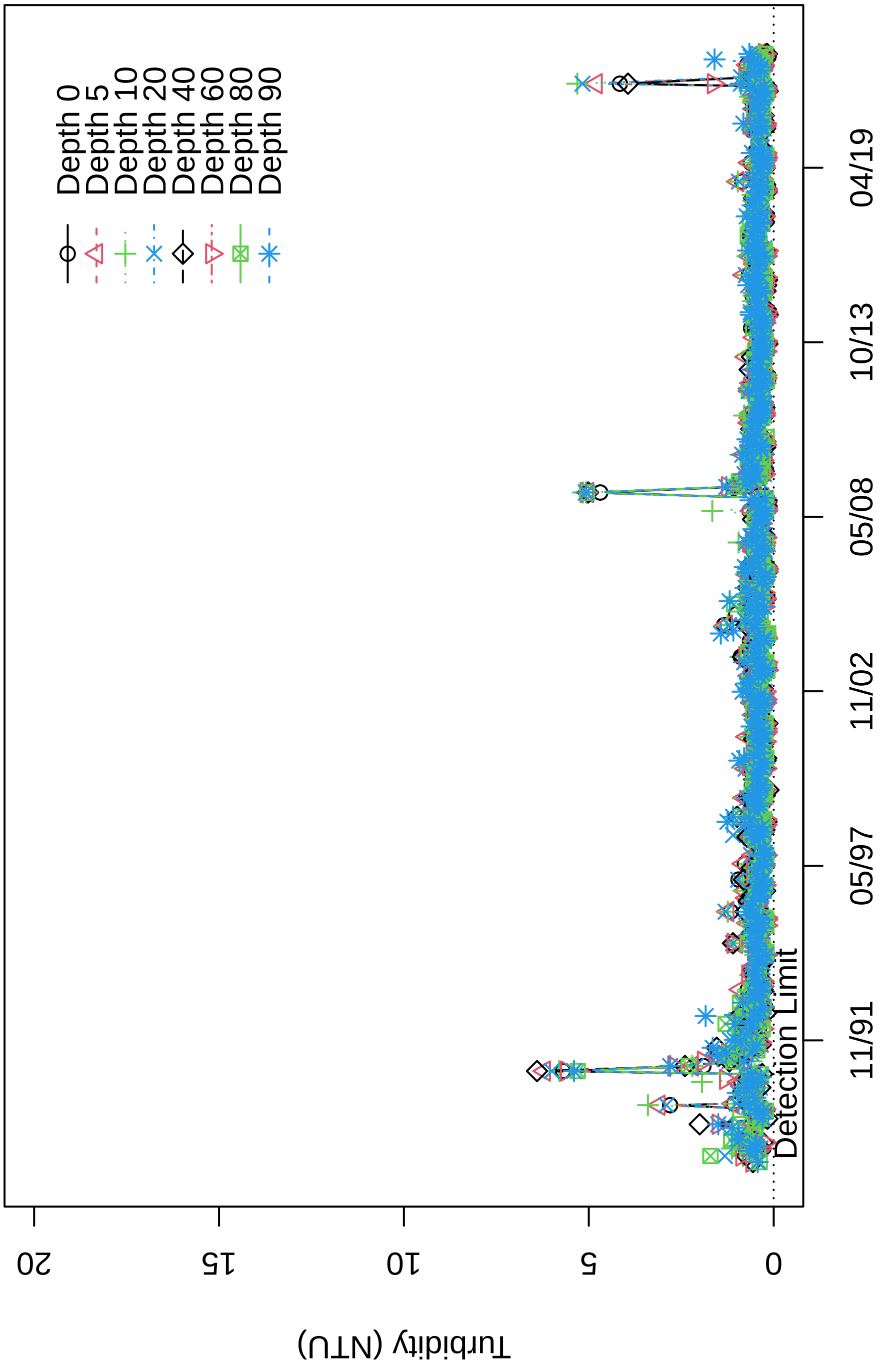

Figure B95: Lake Whatcom turbidity data for Site 4.

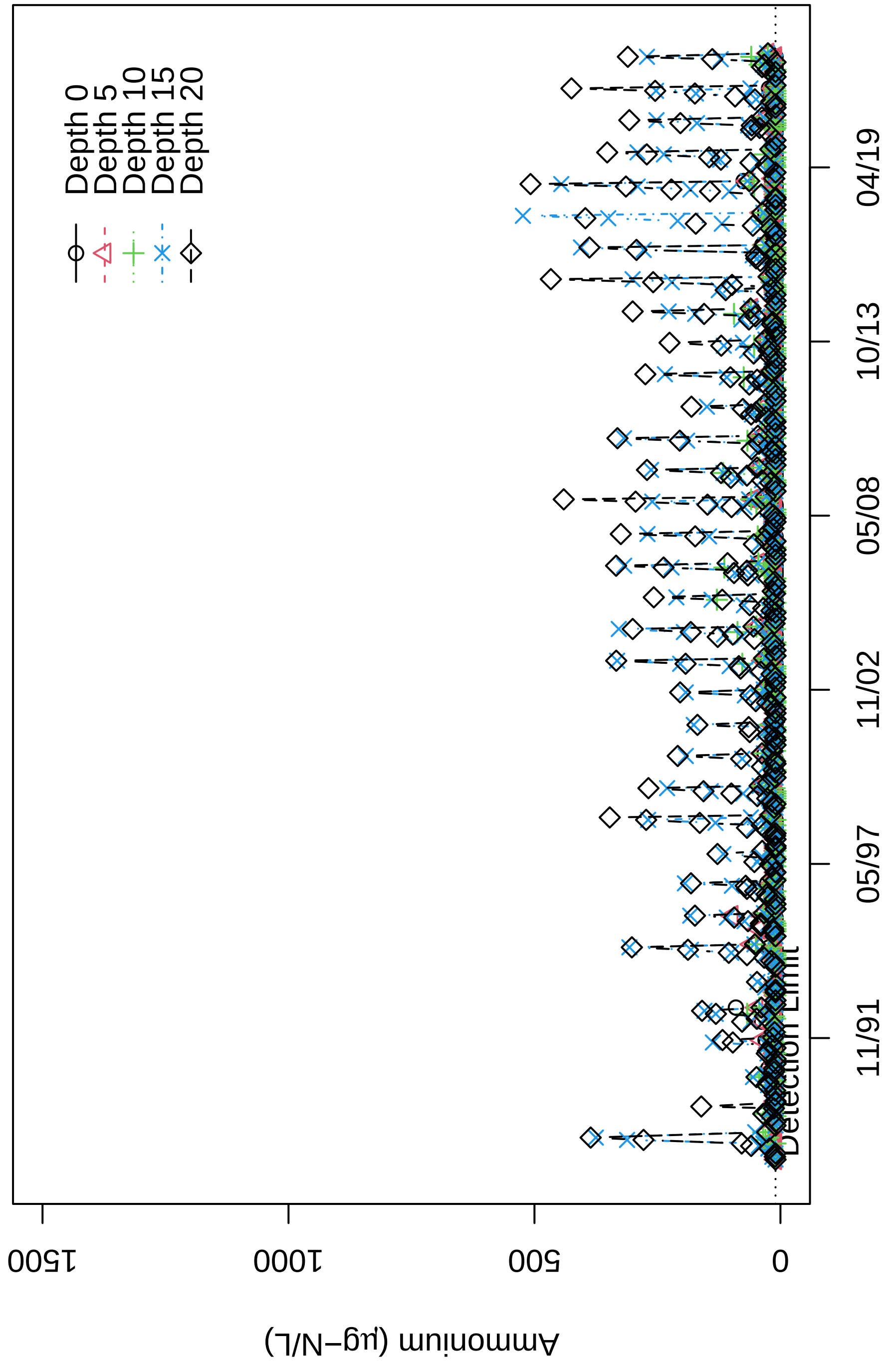

Figure B96: Lake Whatcom ammonium data for Site 1.

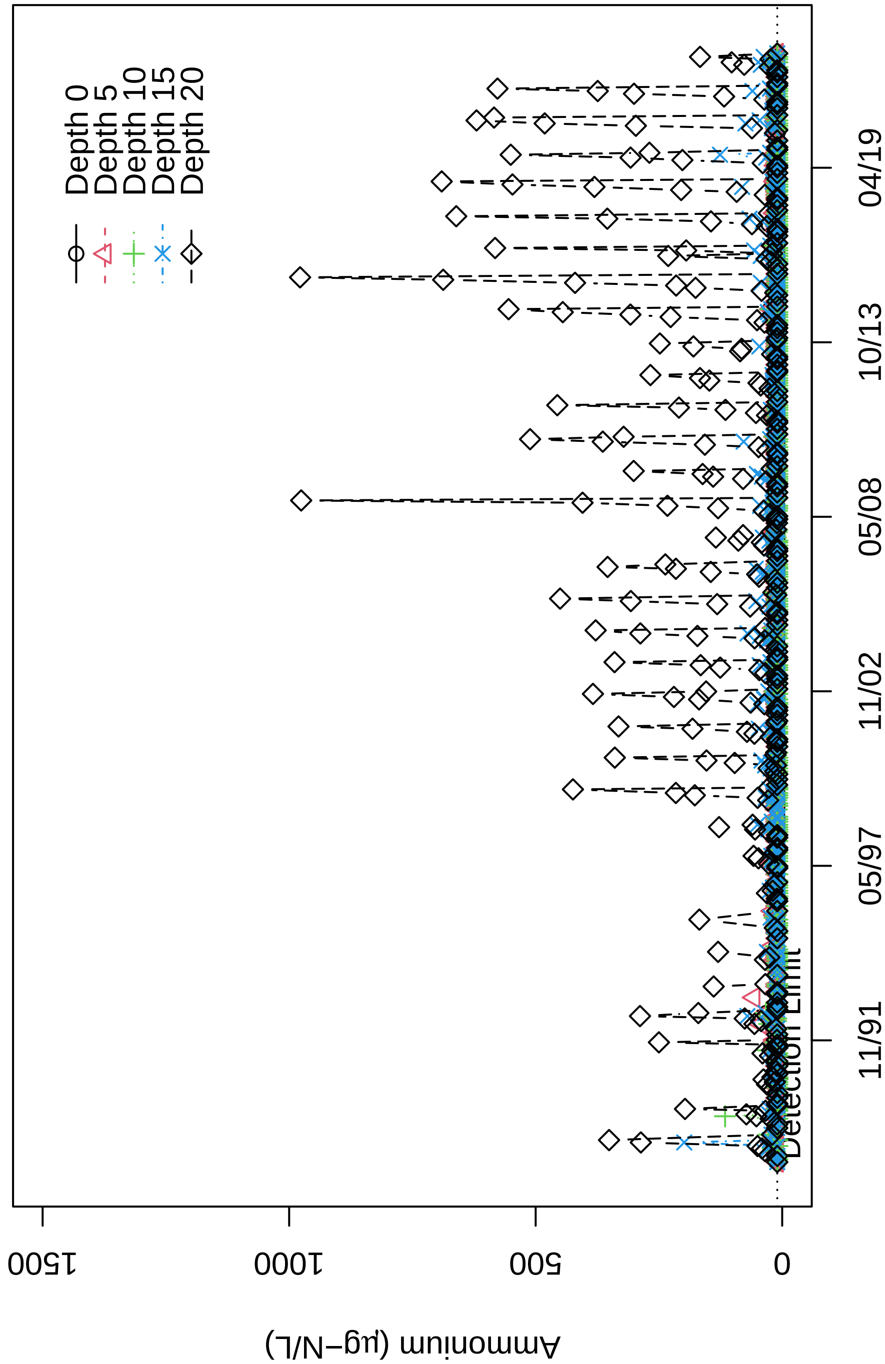

Figure B97: Lake Whatcom ammonium data for Site 2.

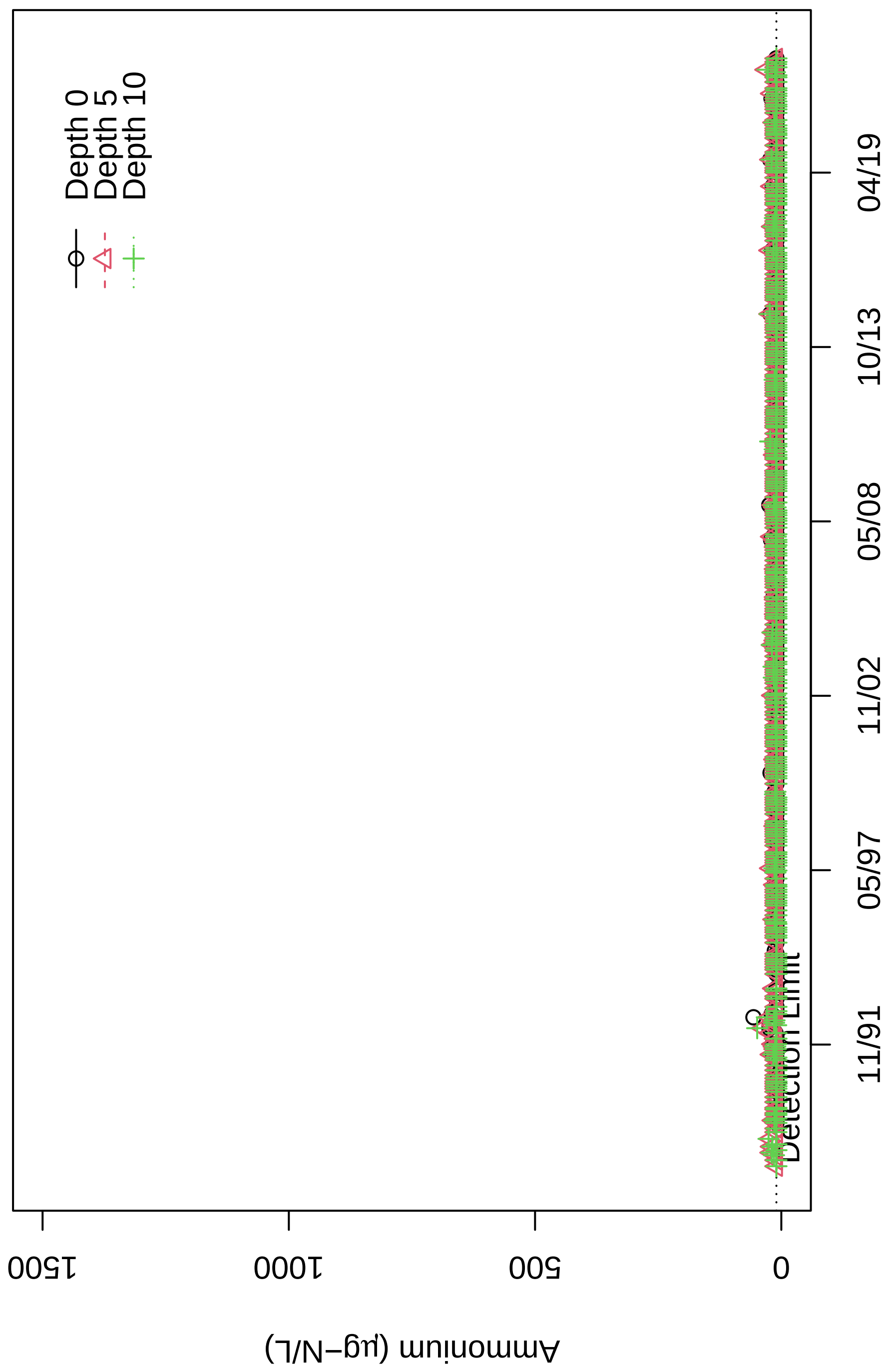

Figure B98: Lake Whatcom ammonium data for the Intake site.

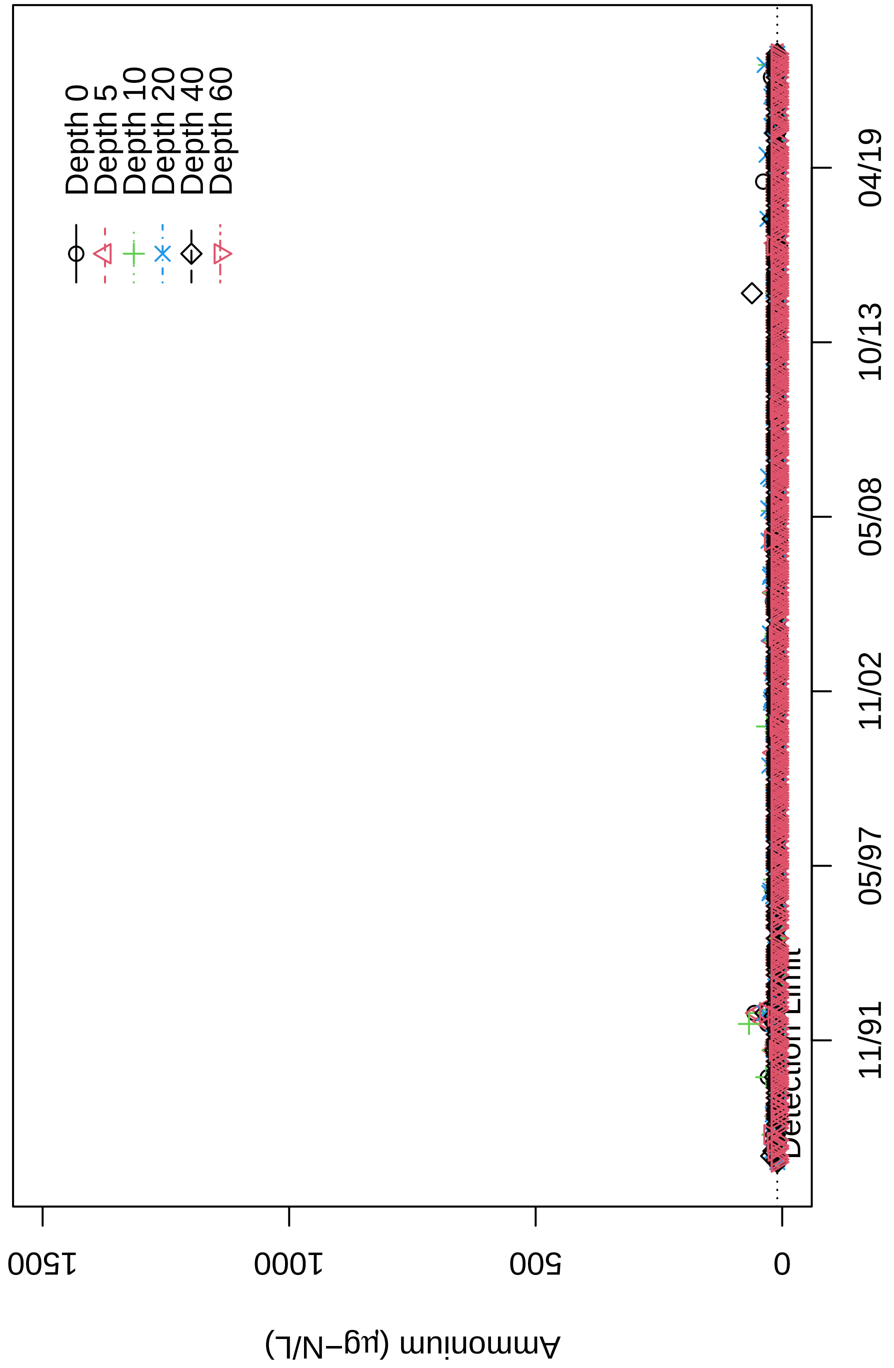

Figure B99: Lake Whatcom ammonium data for Site 3.

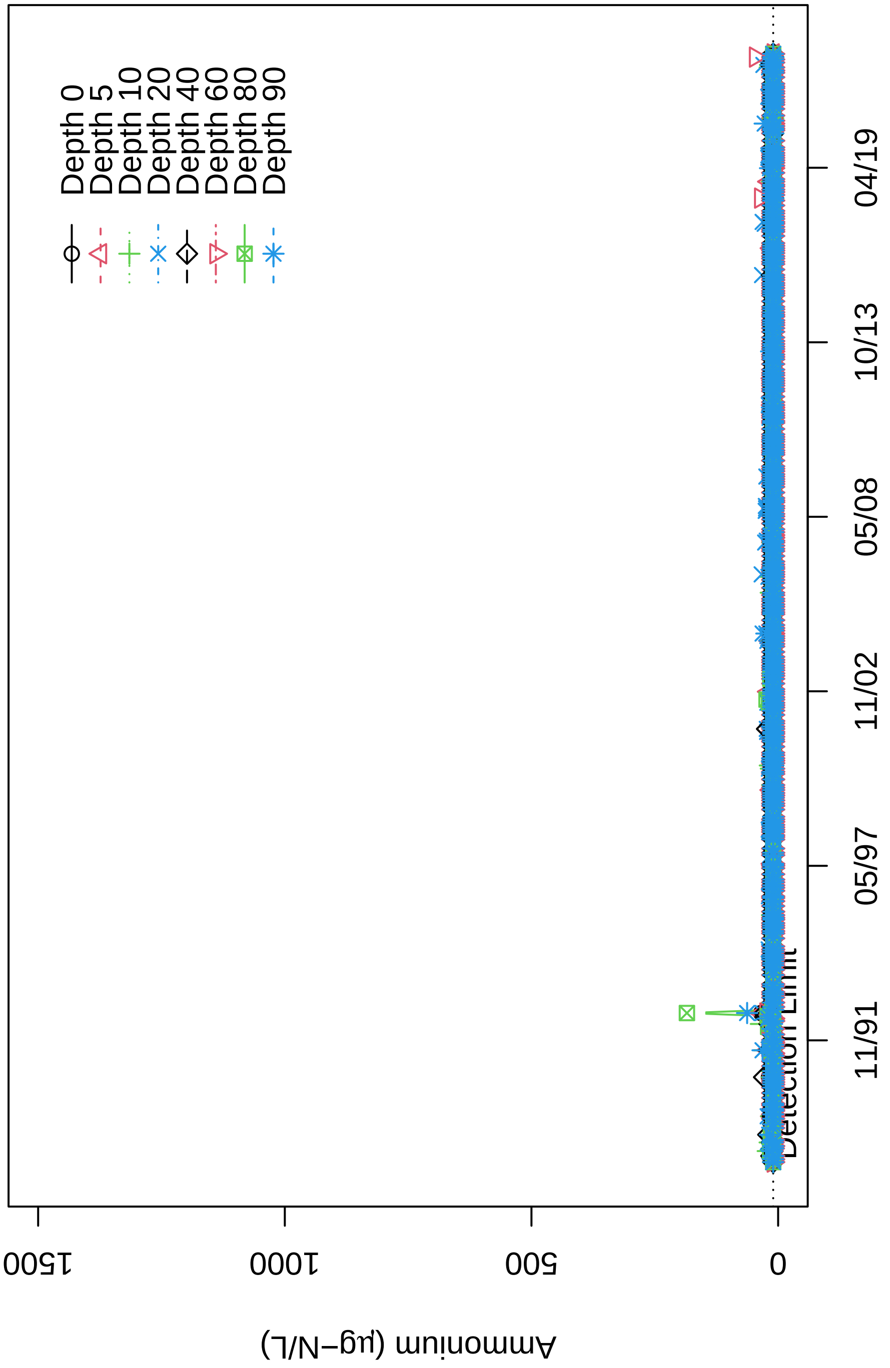

Figure B100: Lake Whatcom ammonium data for Site 4.

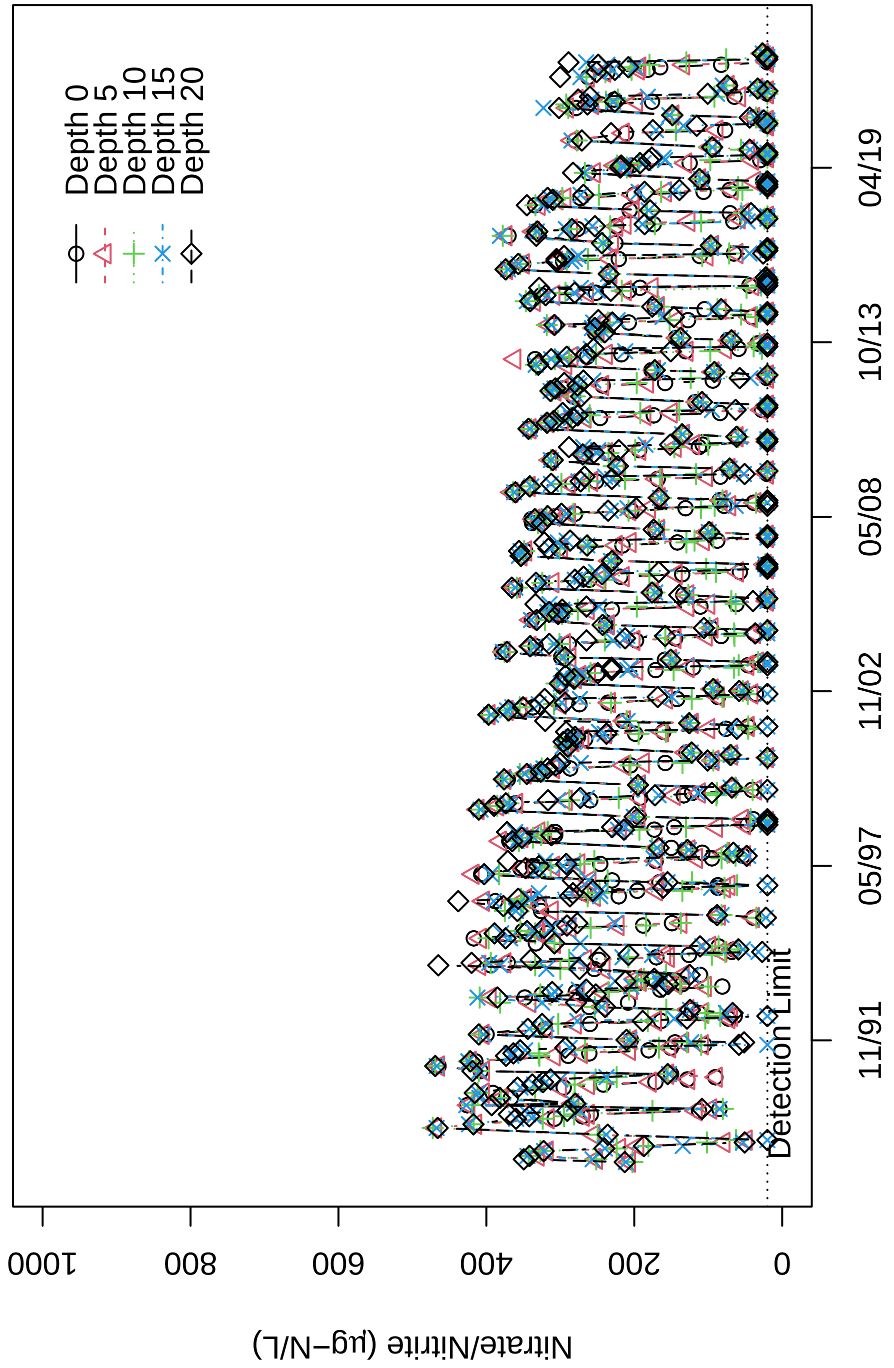

Figure B101: Lake Whatcom nitrate/nitrite data for Site 1.

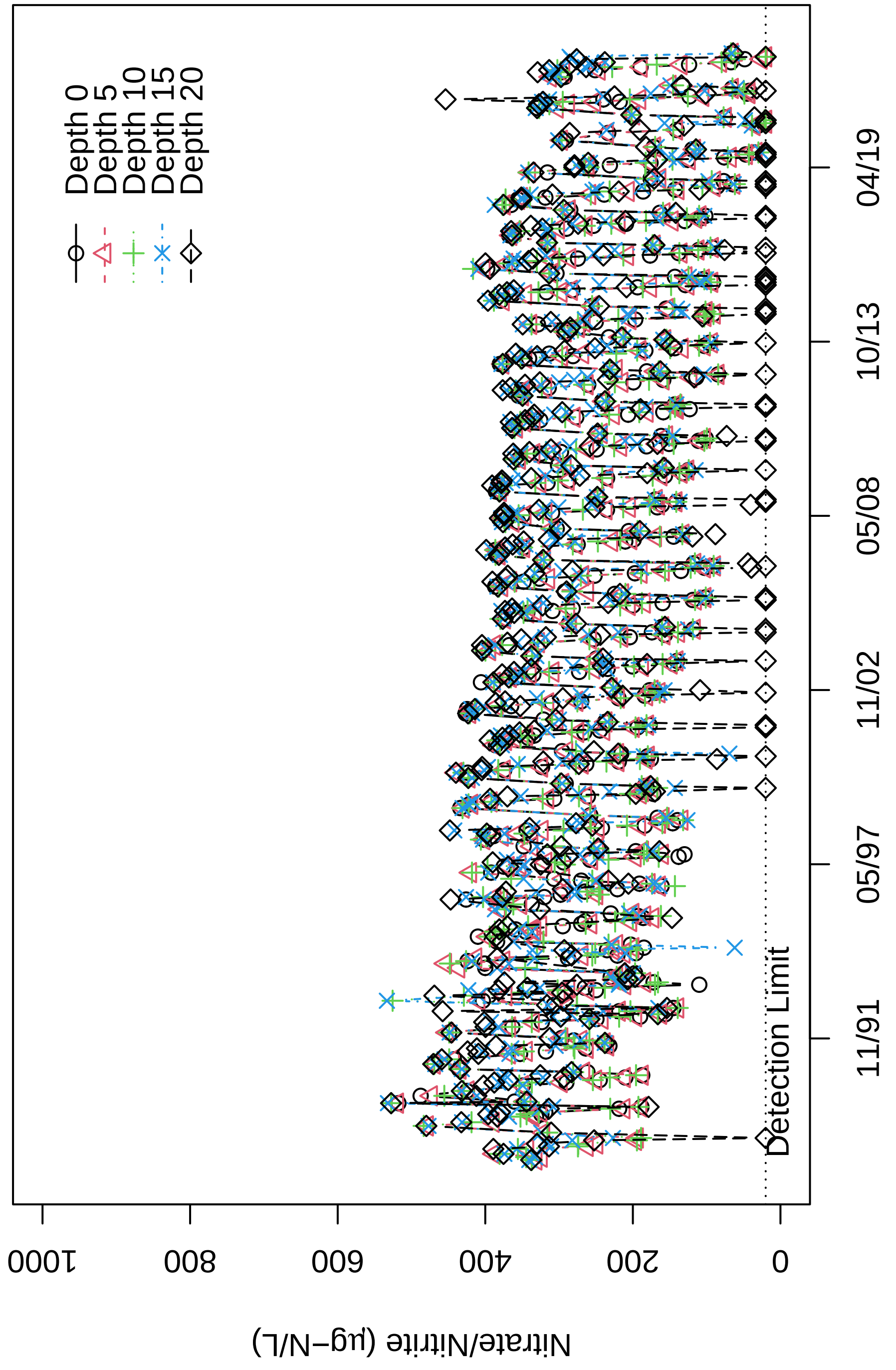

Figure B102: Lake Whatcom nitrate/nitrite data for Site 2.

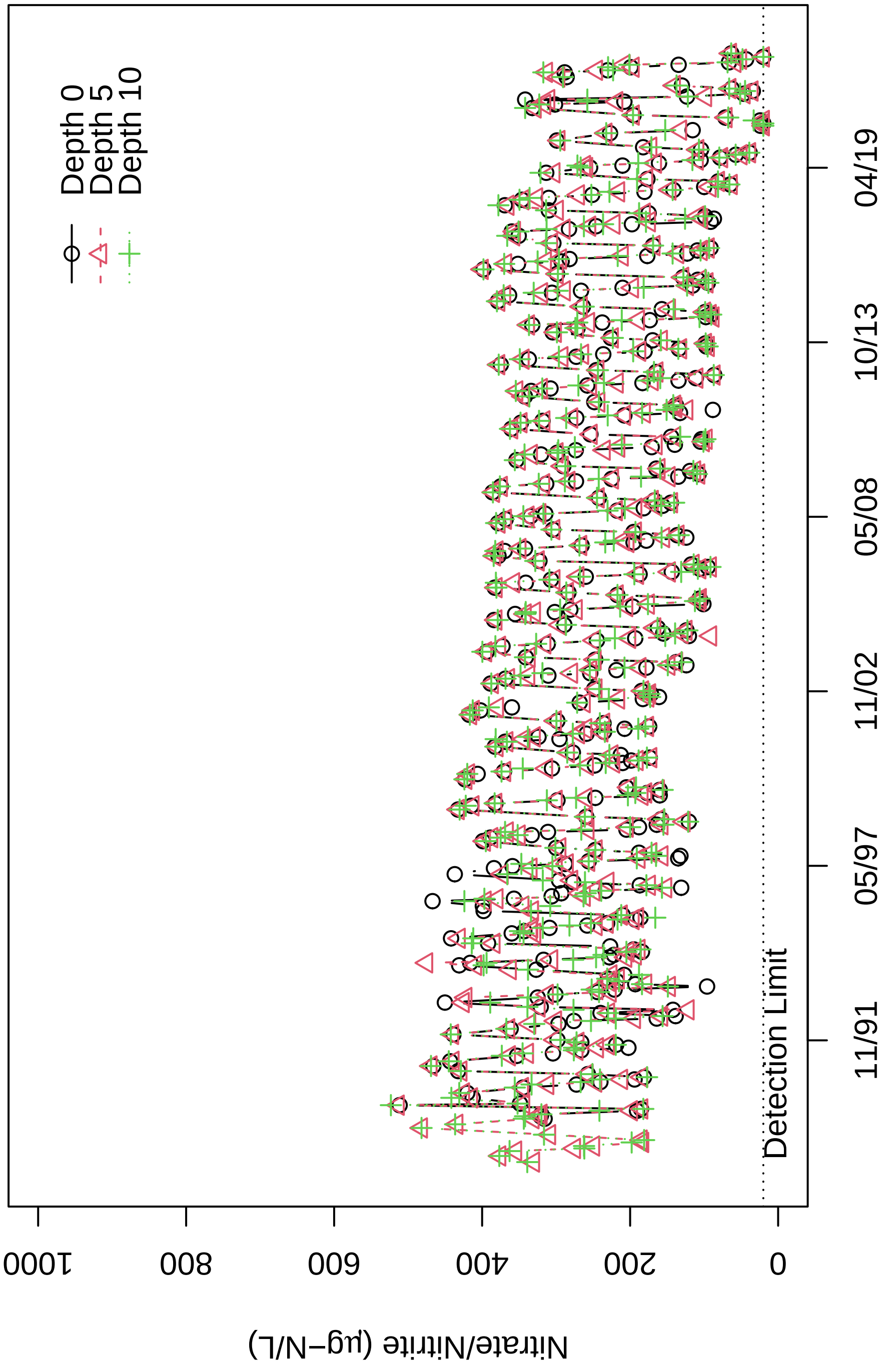

Figure B103: Lake Whatcom nitrate/nitrite data for the Intake site.

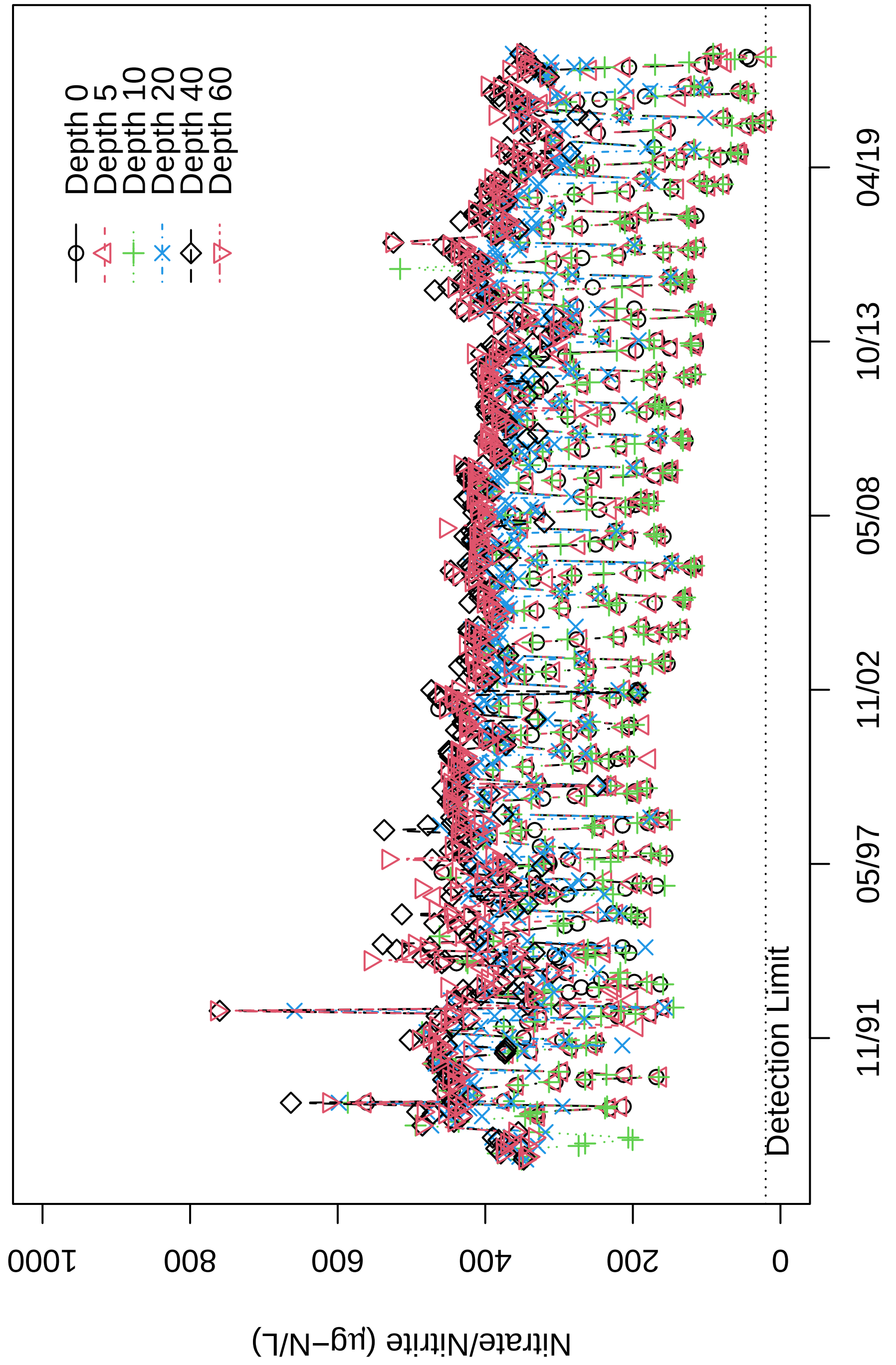

Figure B104: Lake Whatcom nitrate/nitrite data for Site 3.

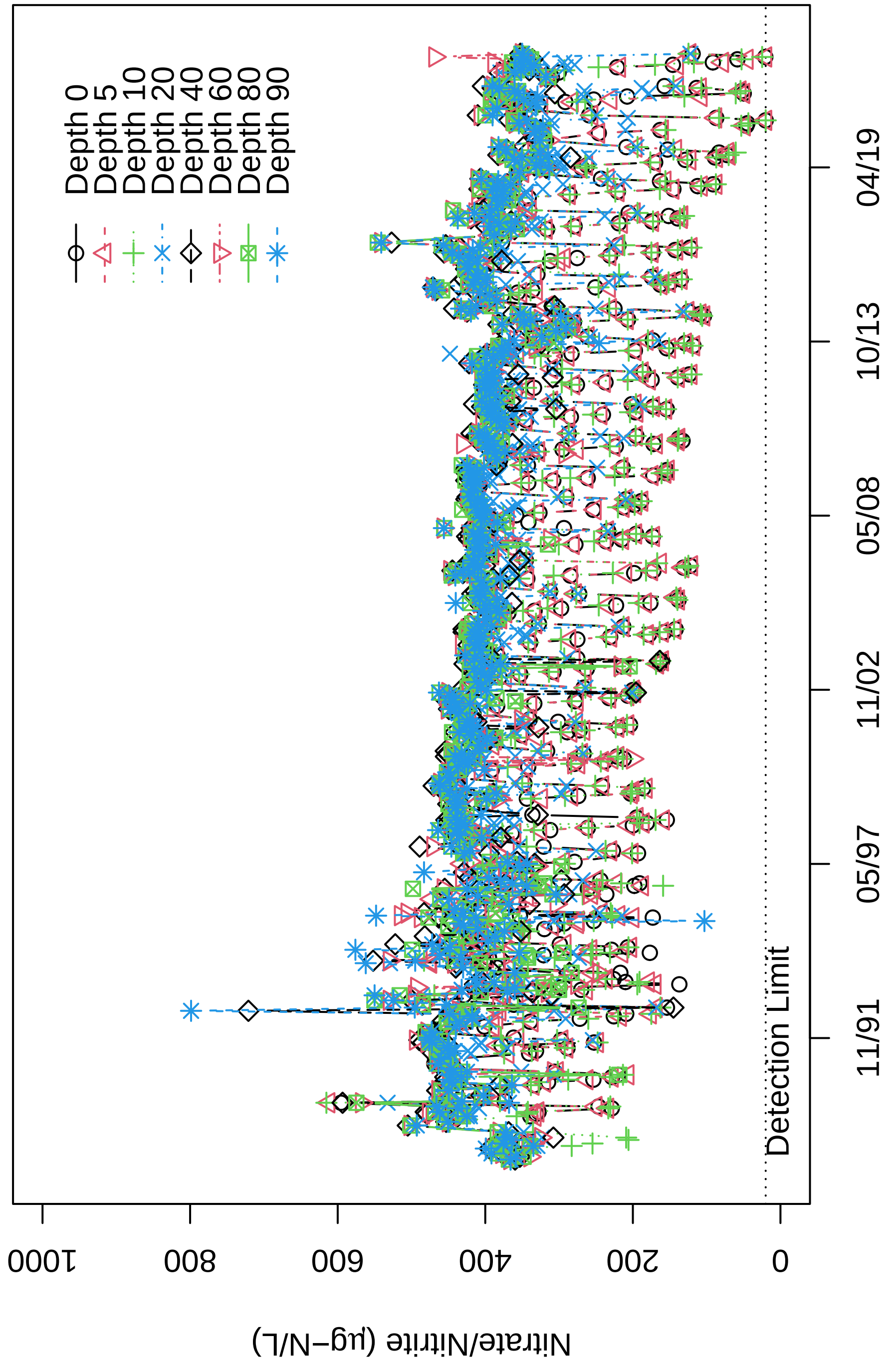

Figure B105: Lake Whatcom nitrate/nitrite data for Site 4.

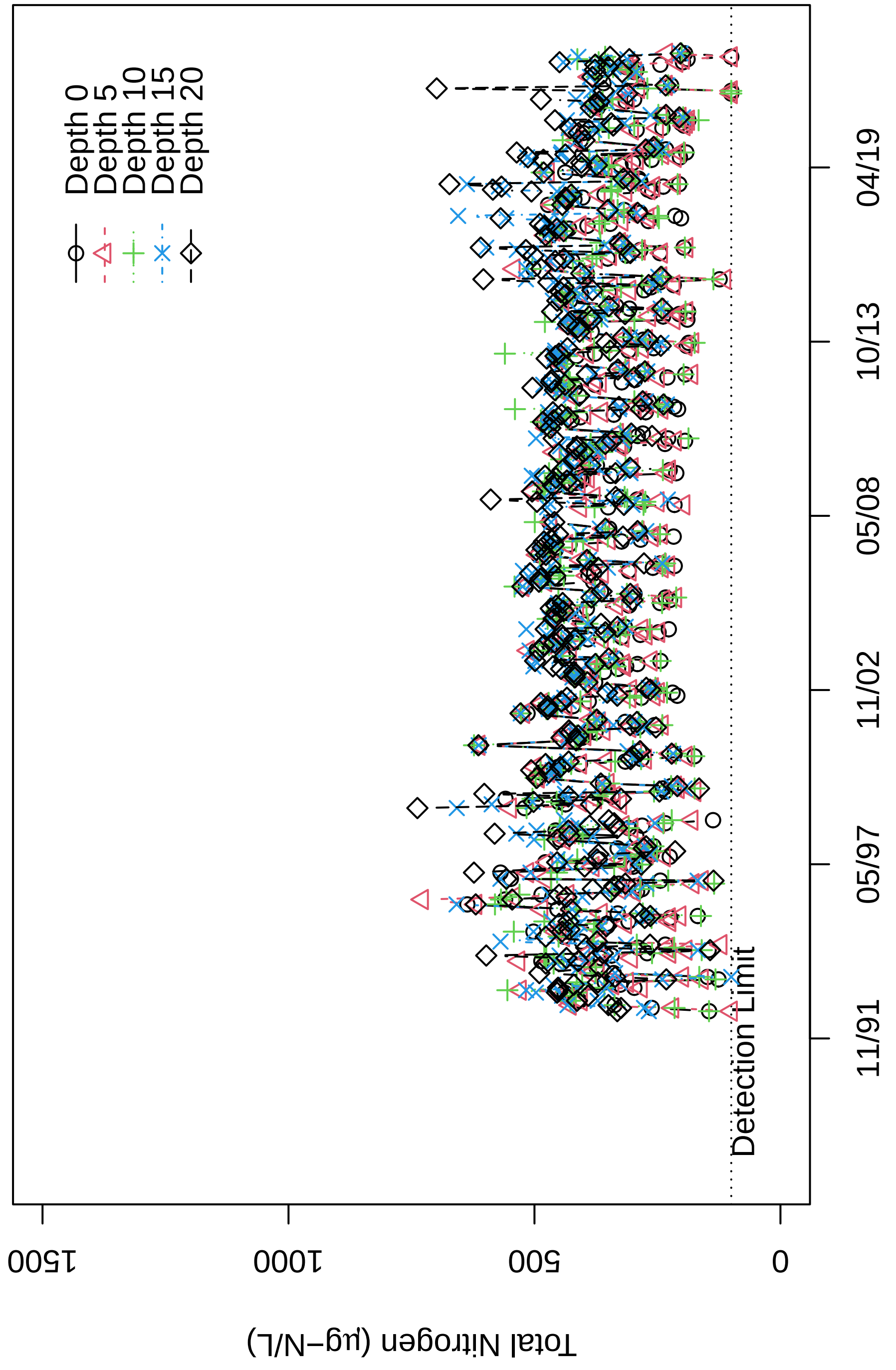

Figure B106: Lake Whatcom total nitrogen data for Site 1.

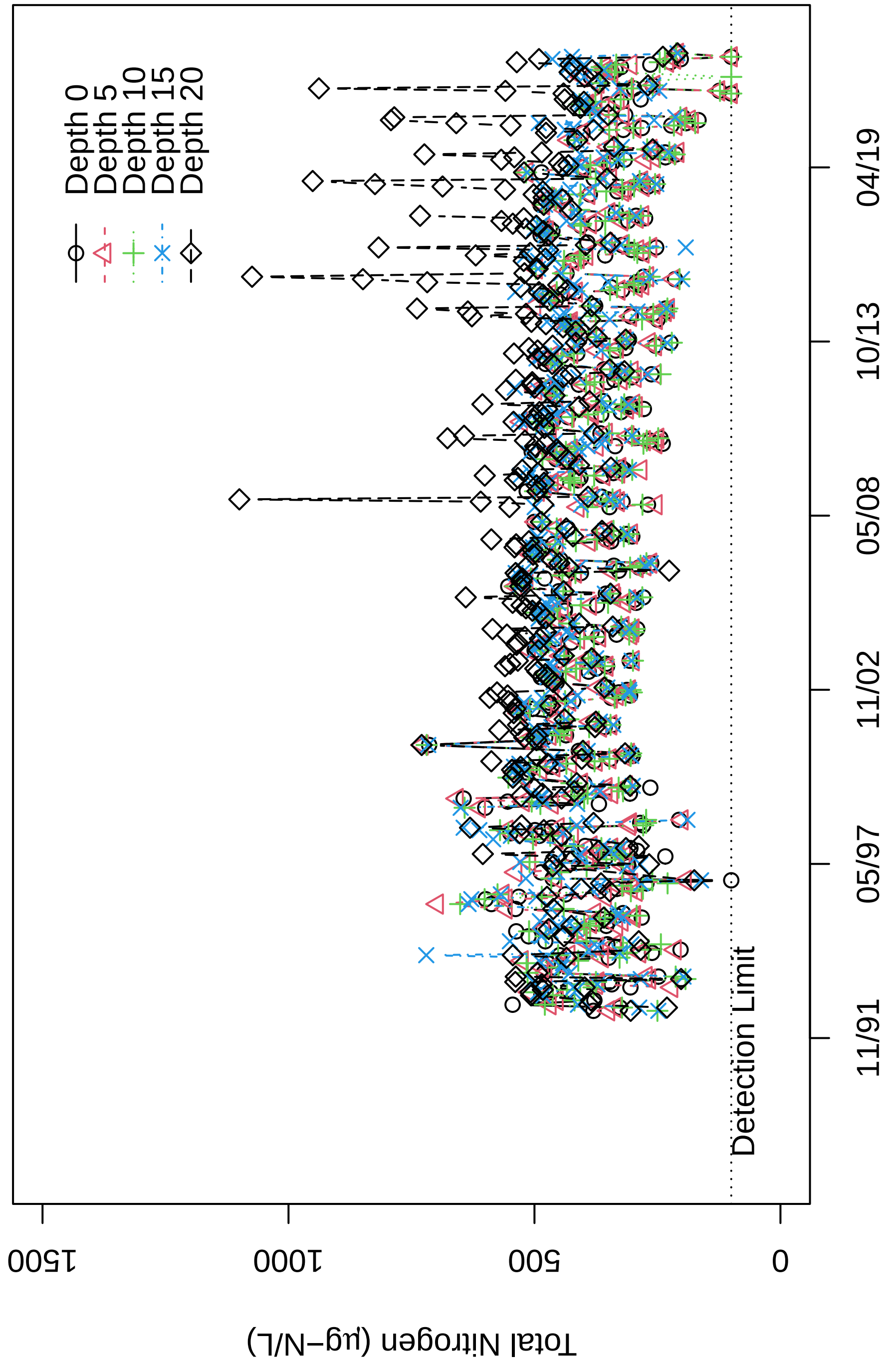

Figure B107: Lake Whatcom total nitrogen data for Site 2.

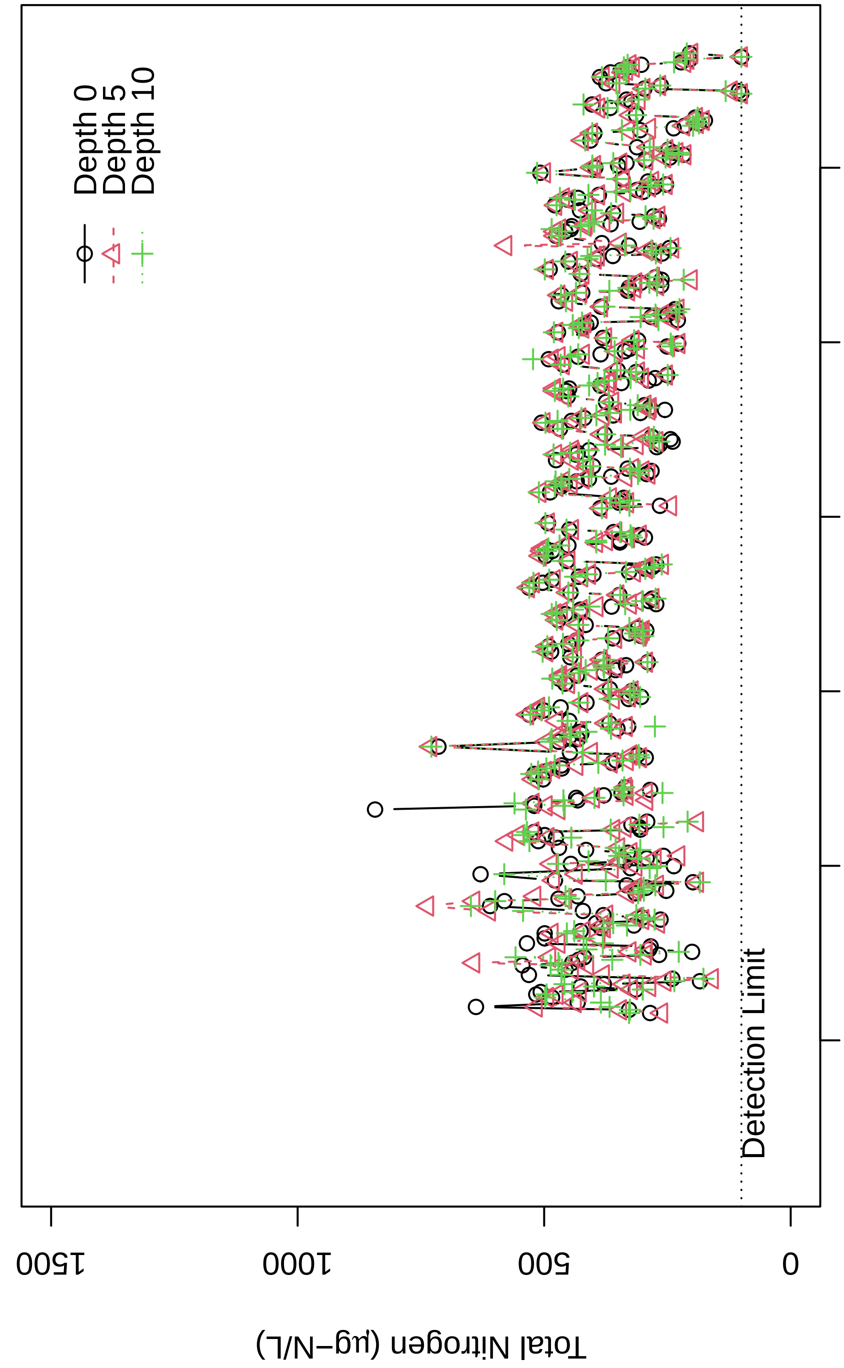

Figure B108: Lake Whatcom total nitrogen data for the Intake site.

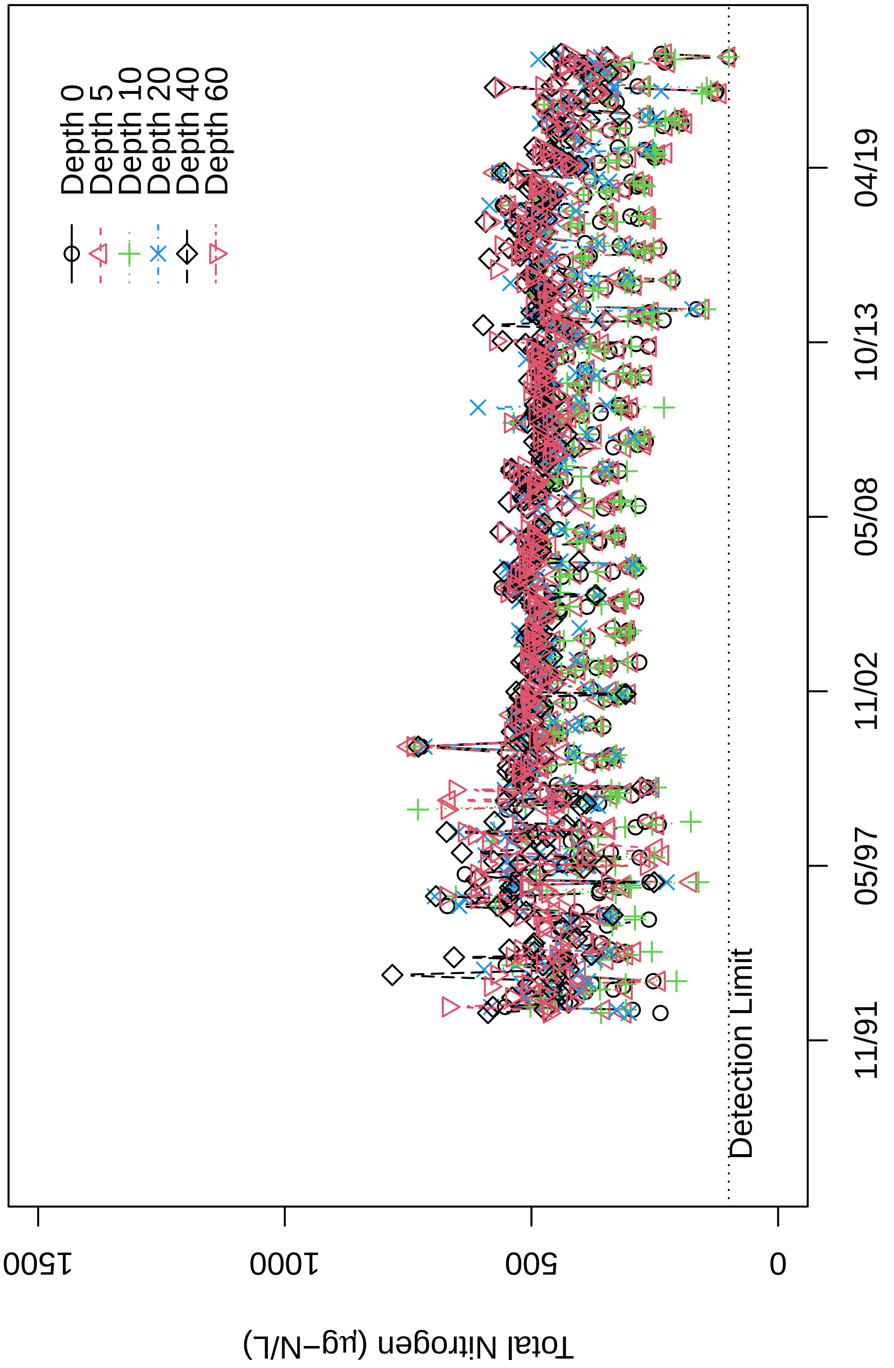

Figure B109: Lake Whatcom total nitrogen data for Site 3.

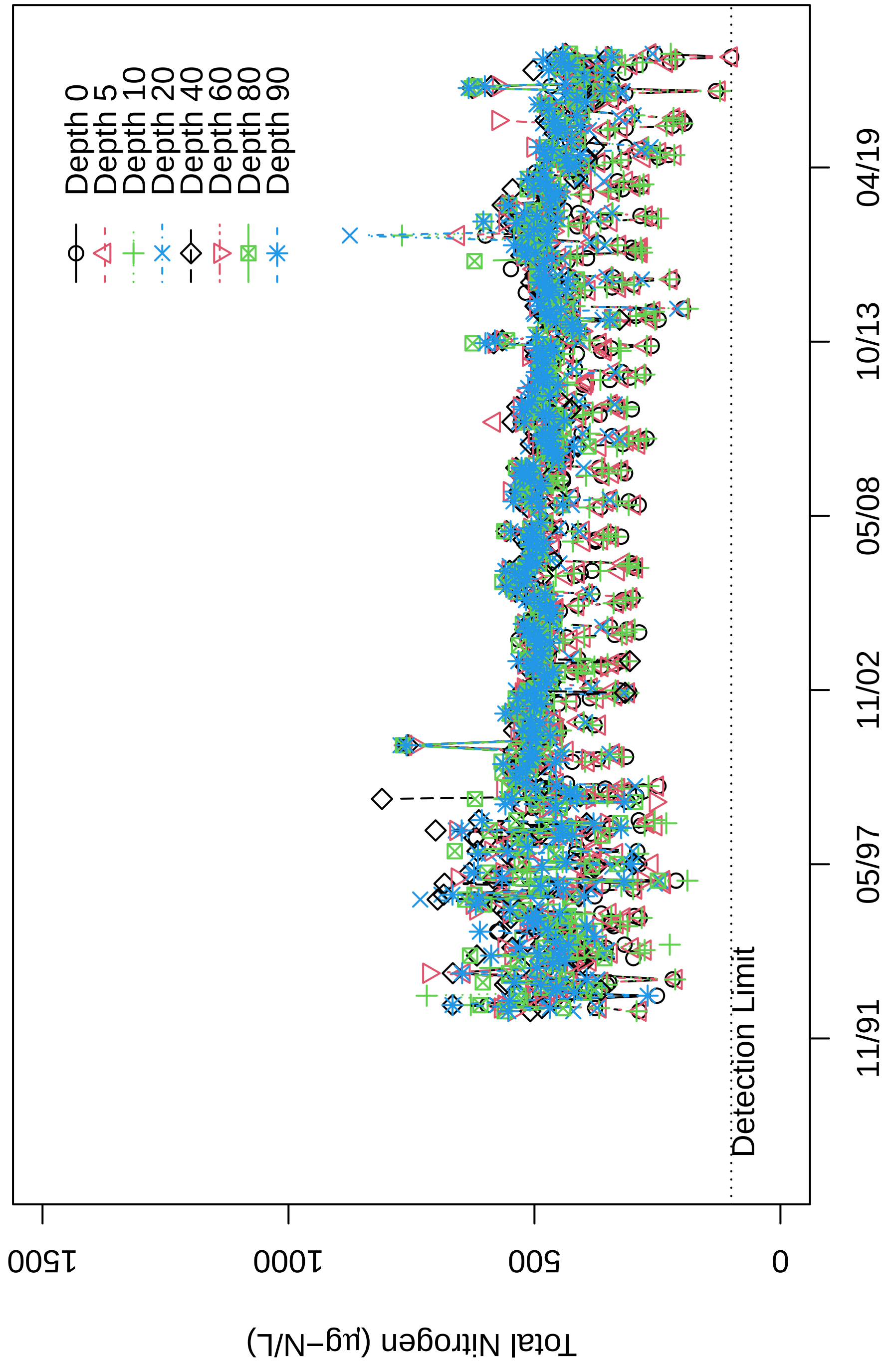

Figure B110: Lake Whatcom total nitrogen data for Site 4.

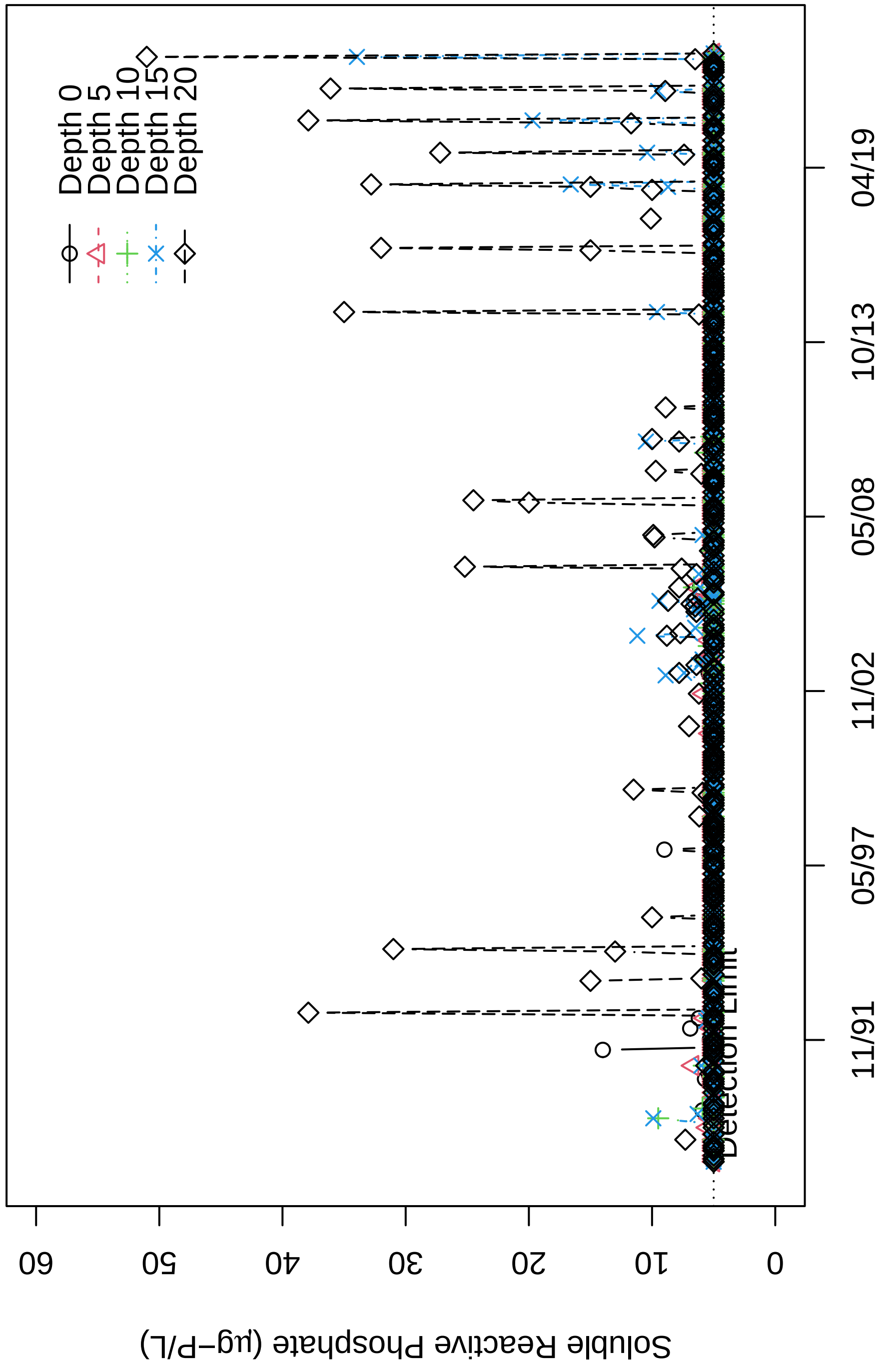

Figure B111: Lake Whatcom soluble phosphate data for Site 1.

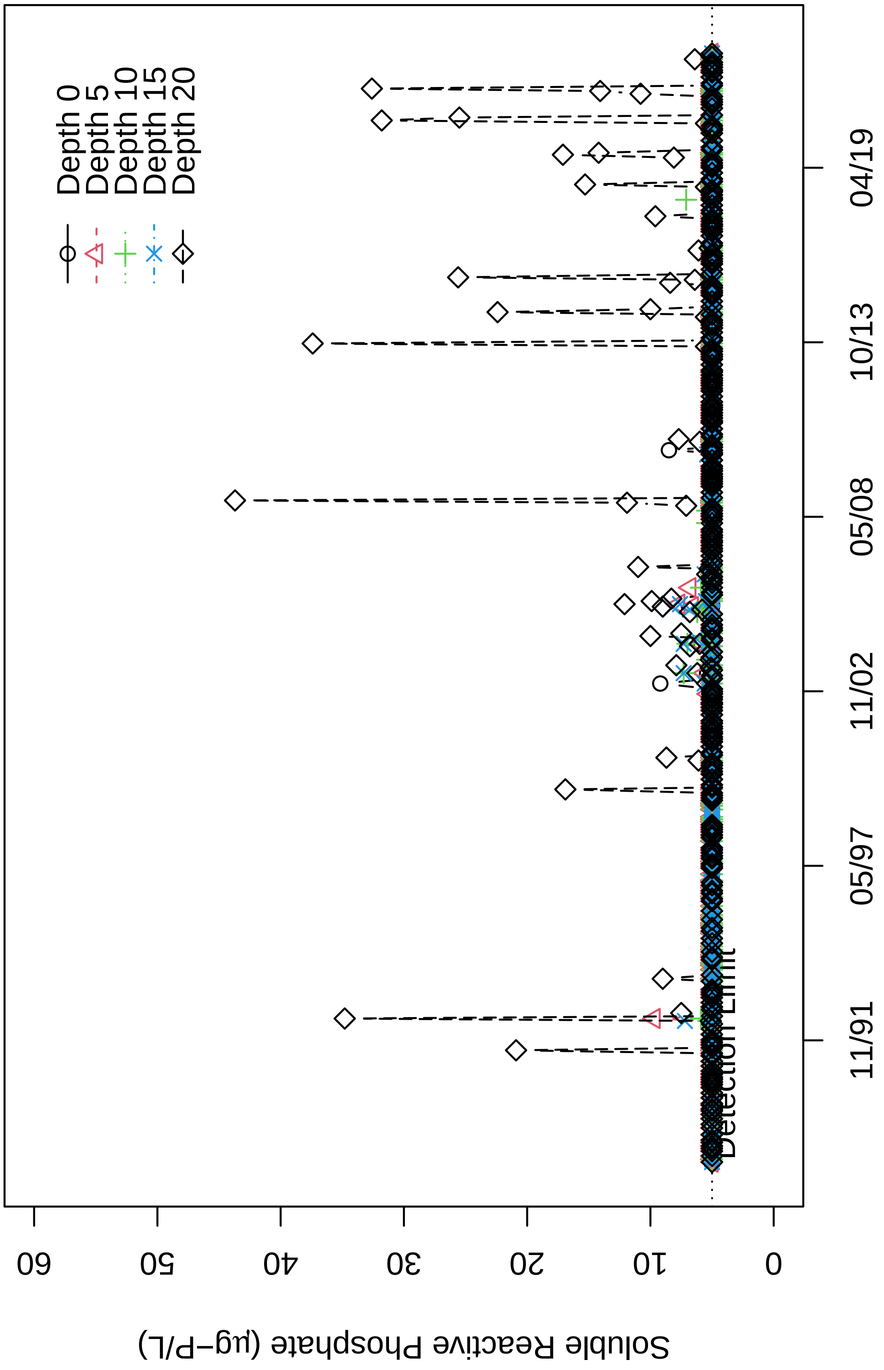

Figure B112: Lake Whatcom soluble phosphate data for Site 2.

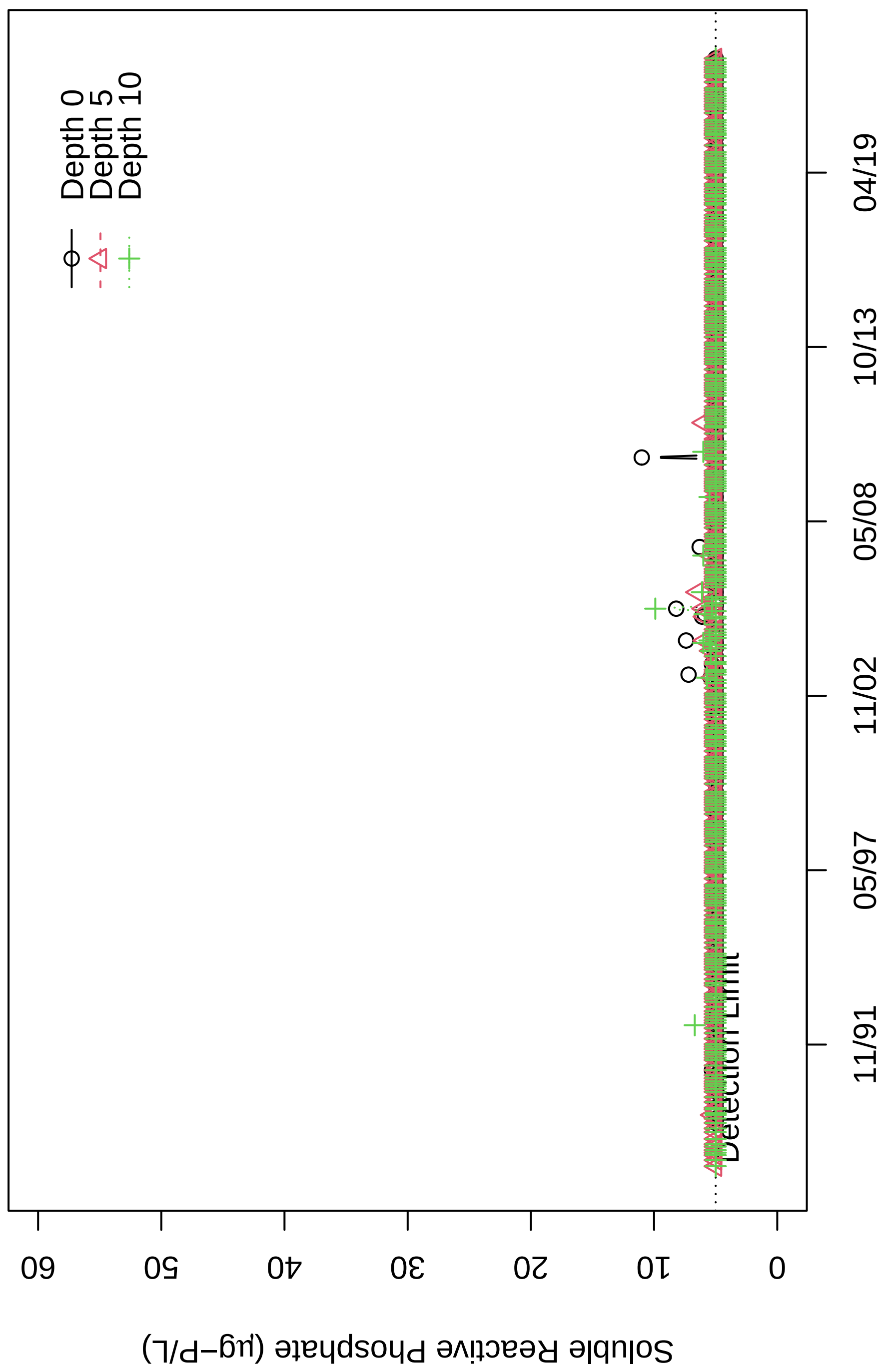

Figure B113: Lake Whatcom soluble phosphate data for the Intake site.

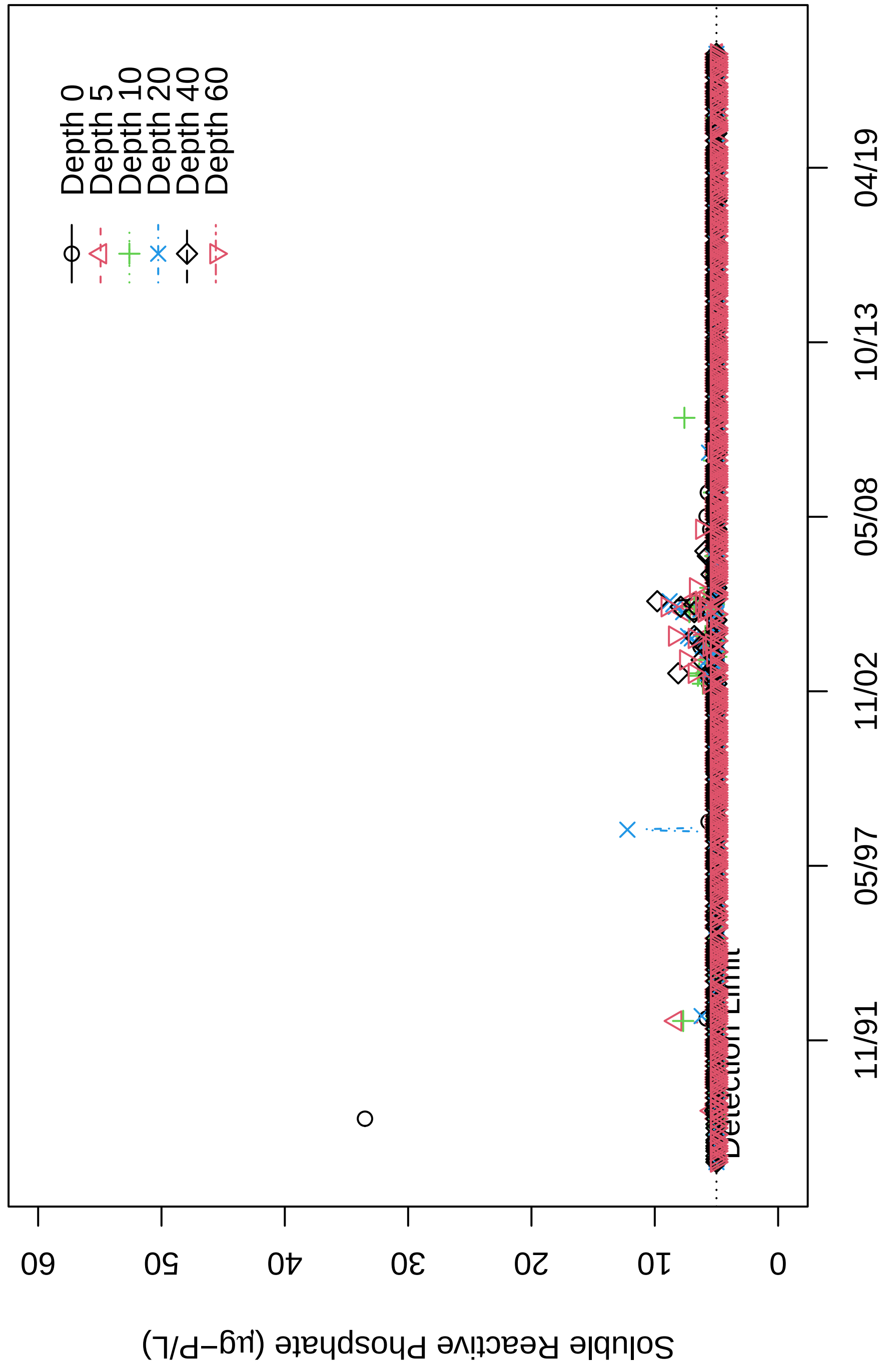

Figure B114: Lake Whatcom soluble phosphate data for Site 3.

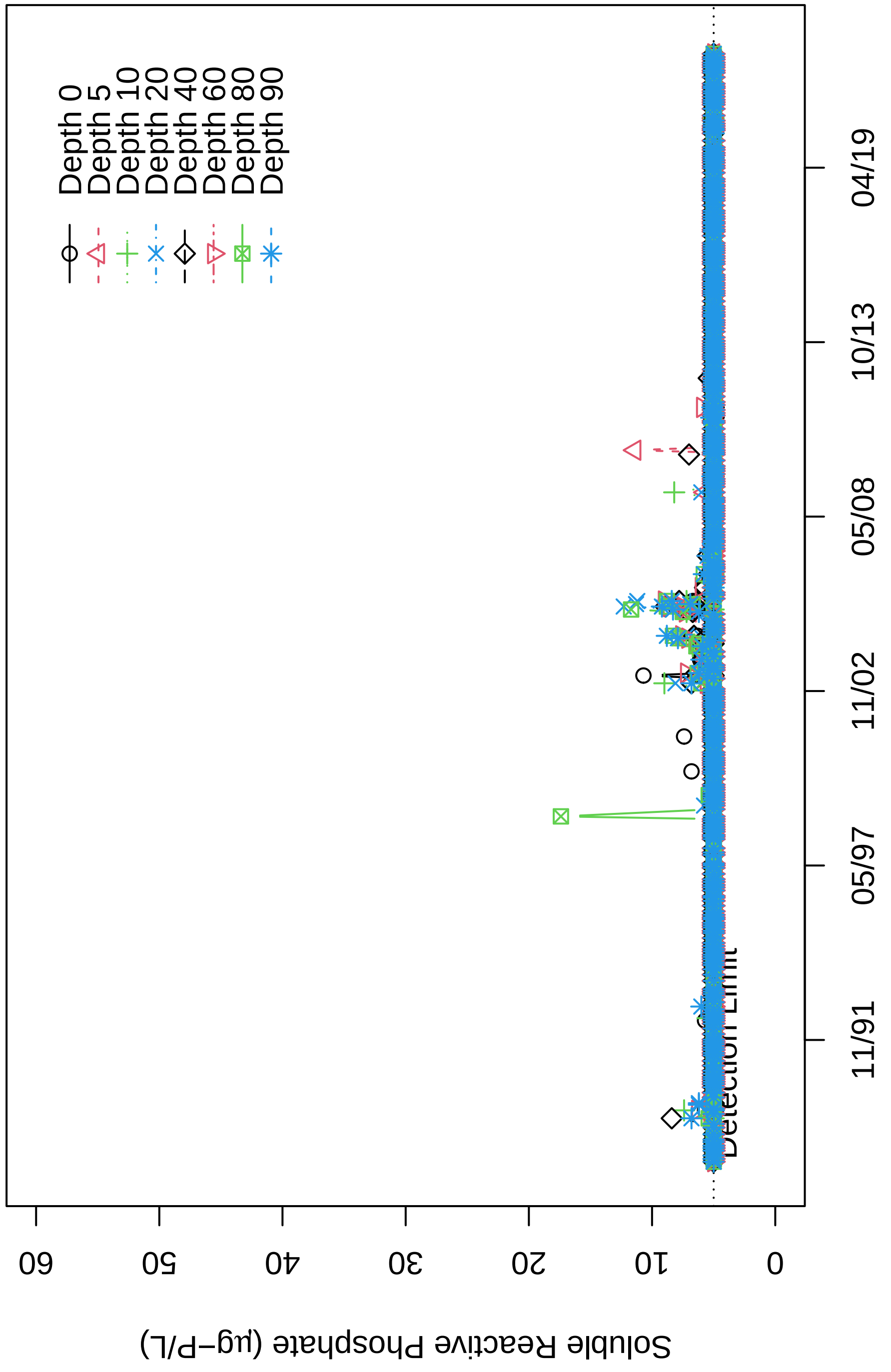

Figure B115: Lake Whatcom soluble phosphate data for Site 4.

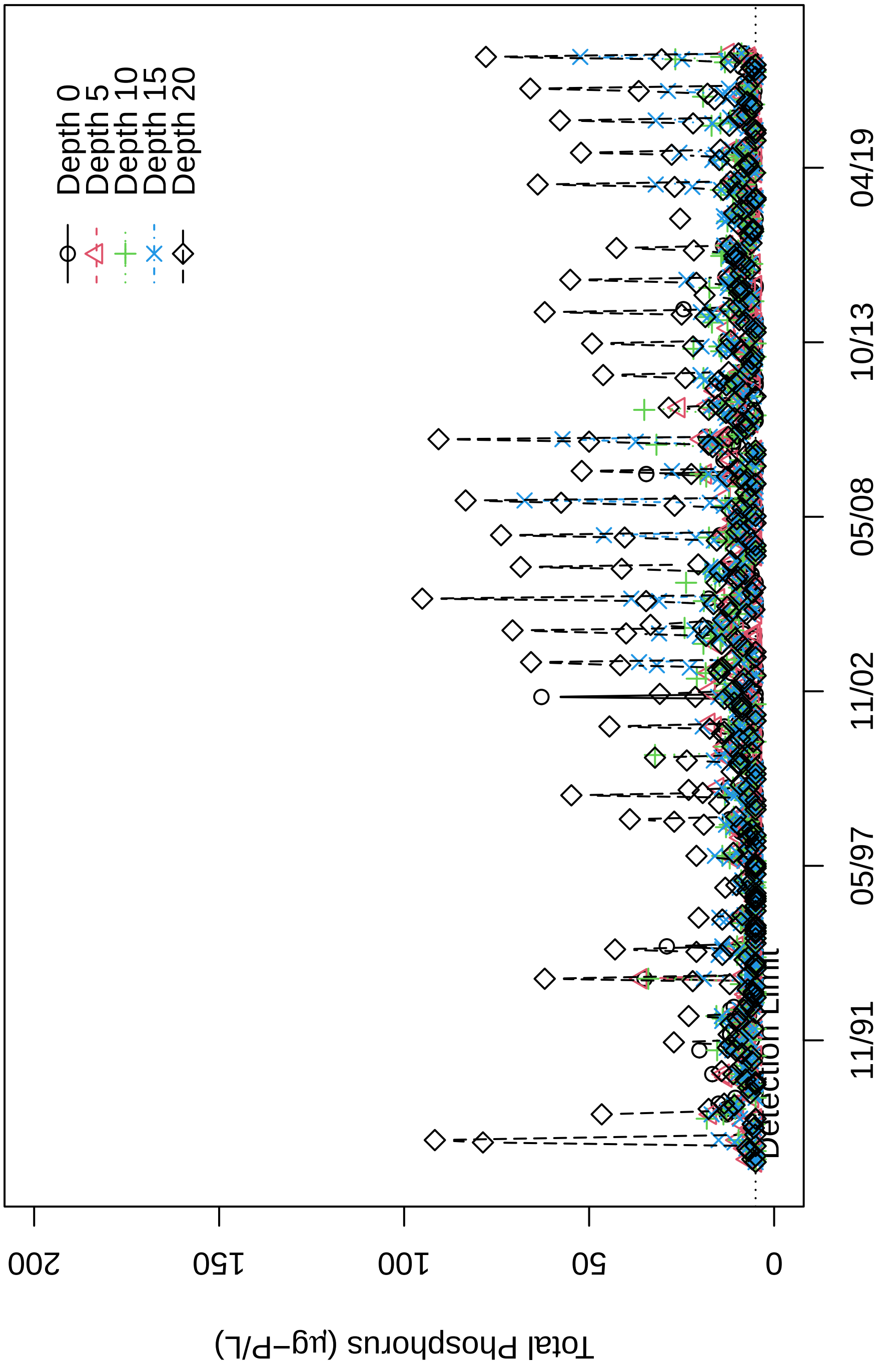

Figure B116: Lake Whatcom total phosphorus data for Site 1.

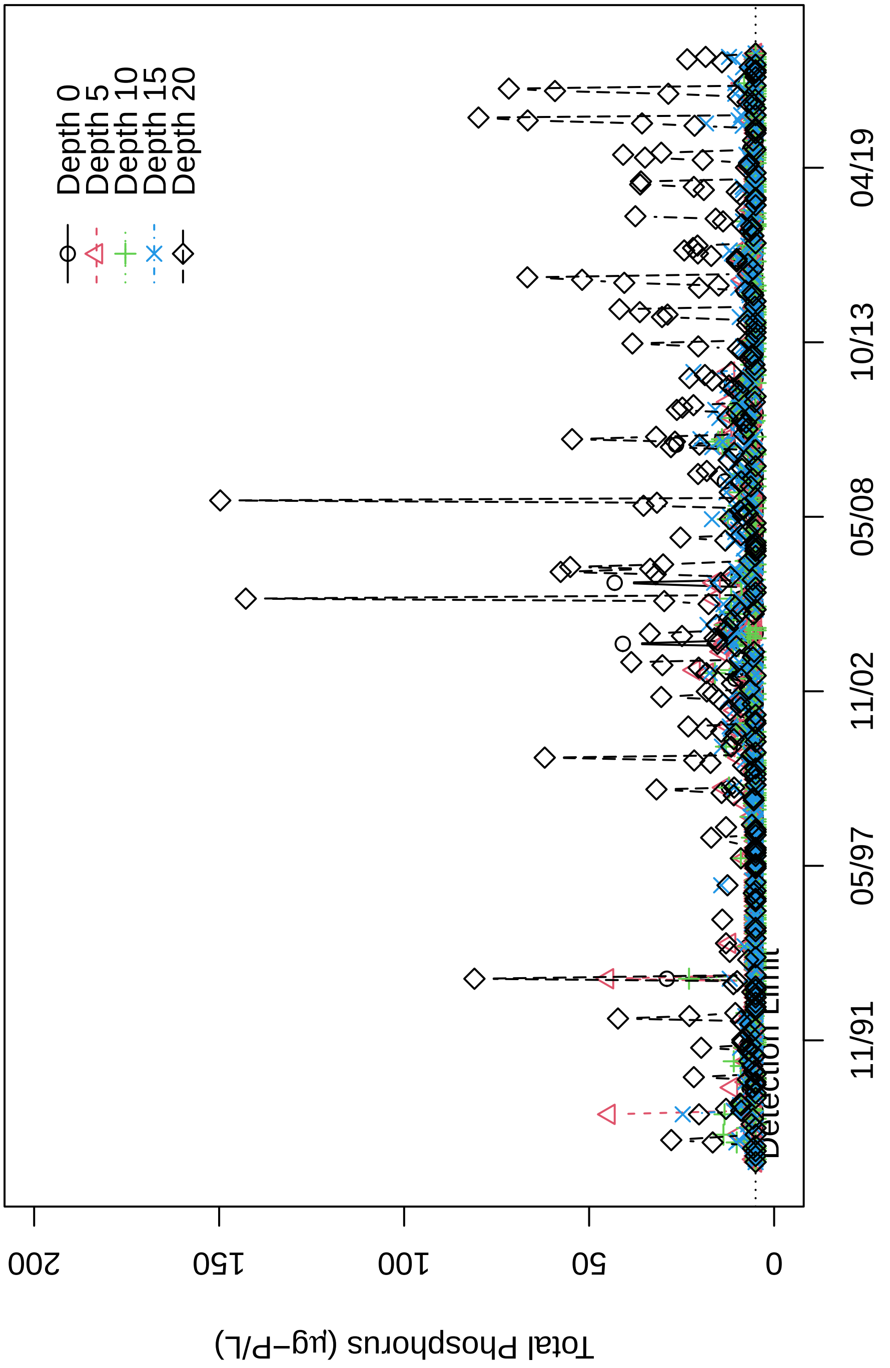

Figure B117: Lake Whatcom total phosphorus data for Site 2.

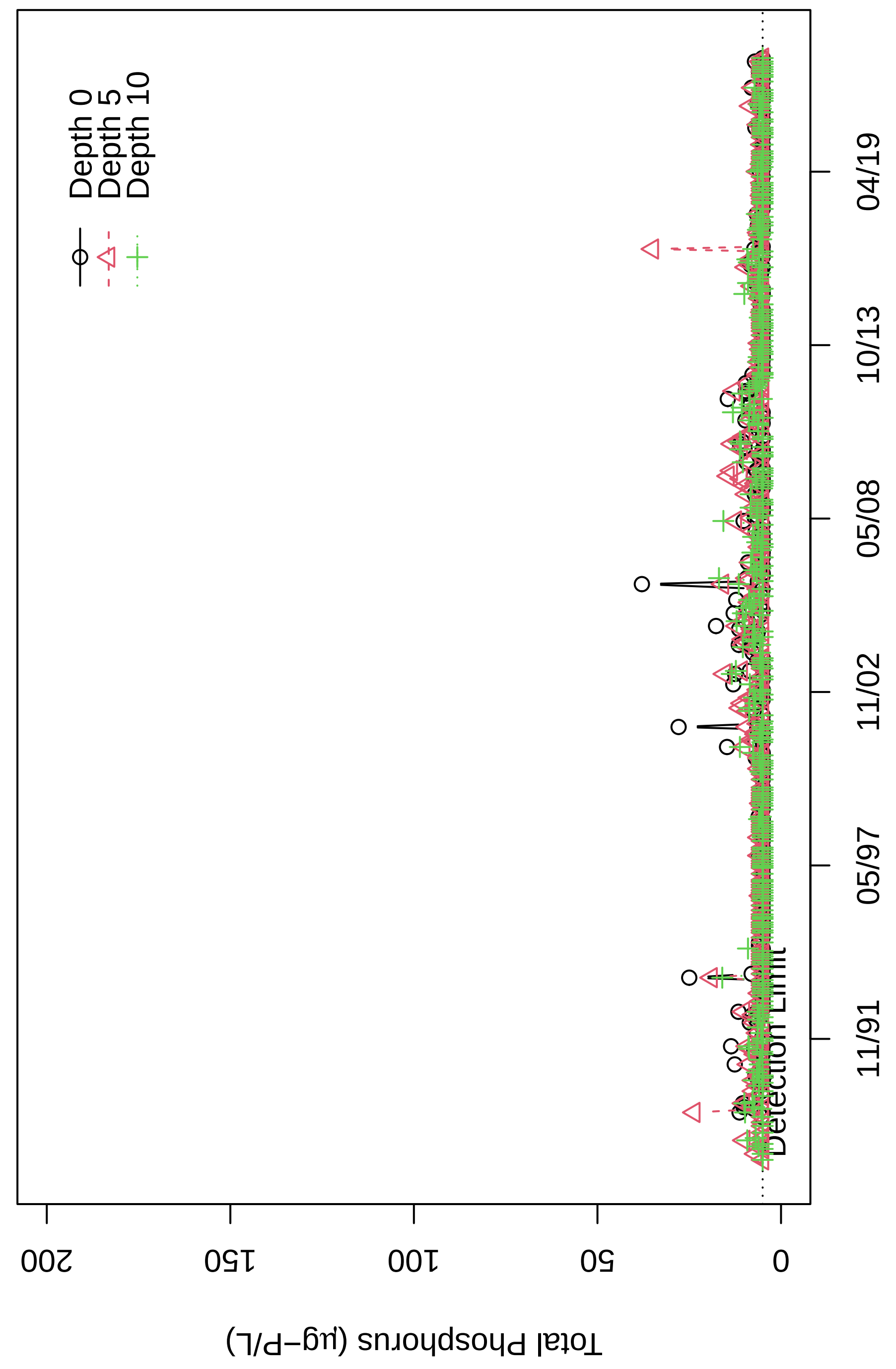

Figure B118: Lake Whatcom total phosphorus data for the Intake site.

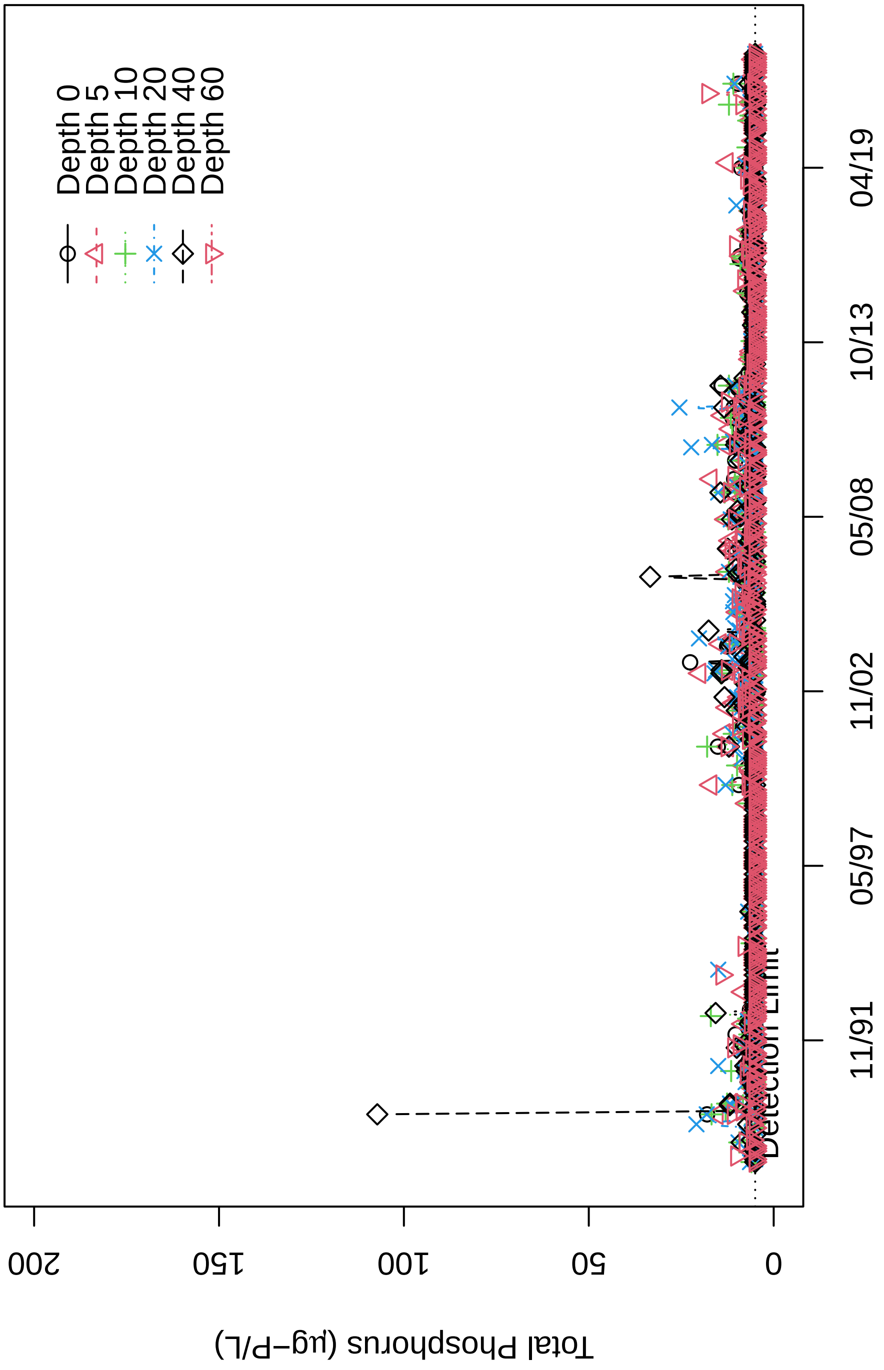

Figure B119: Lake Whatcom total phosphorus data for Site 3.

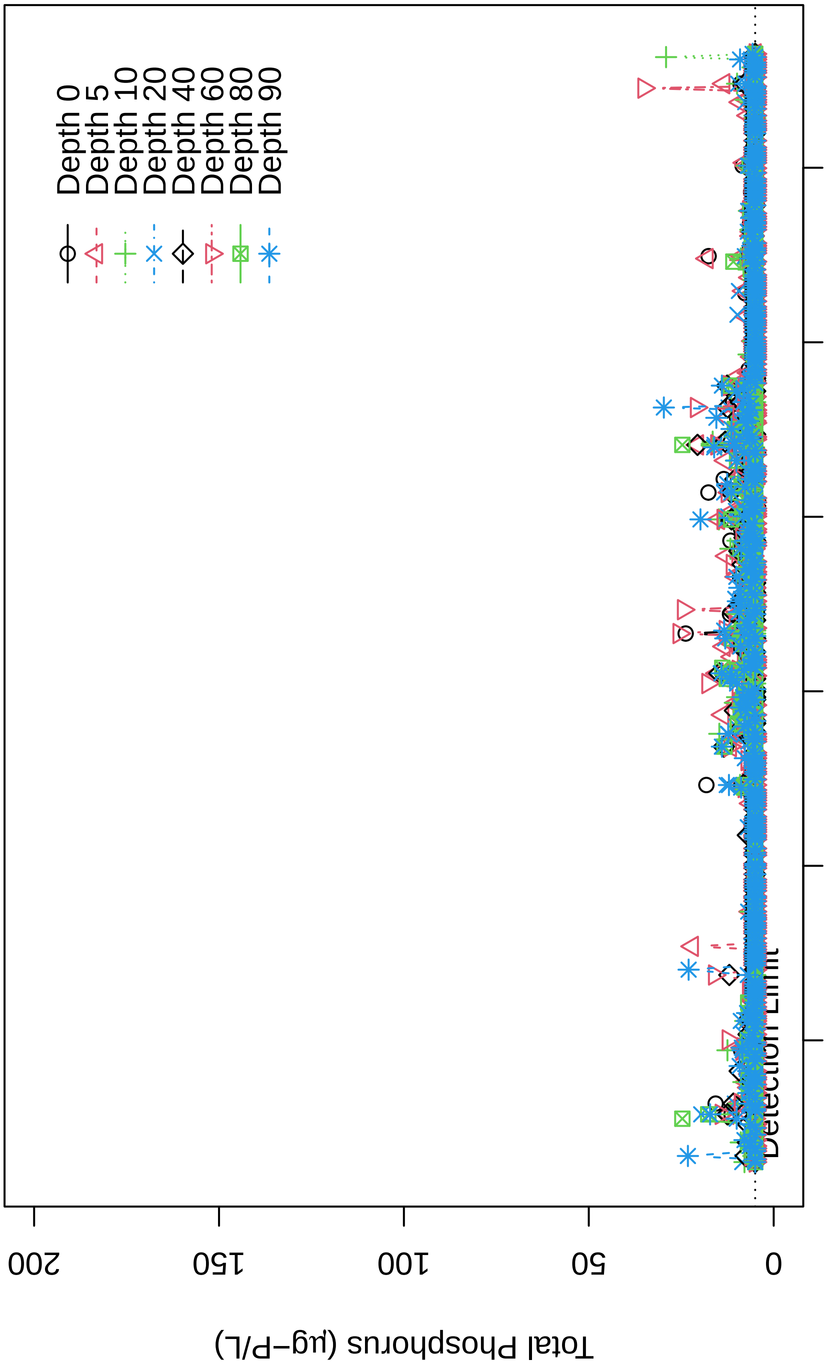

Figure B120: Lake Whatcom total phosphorus data for Site 4.

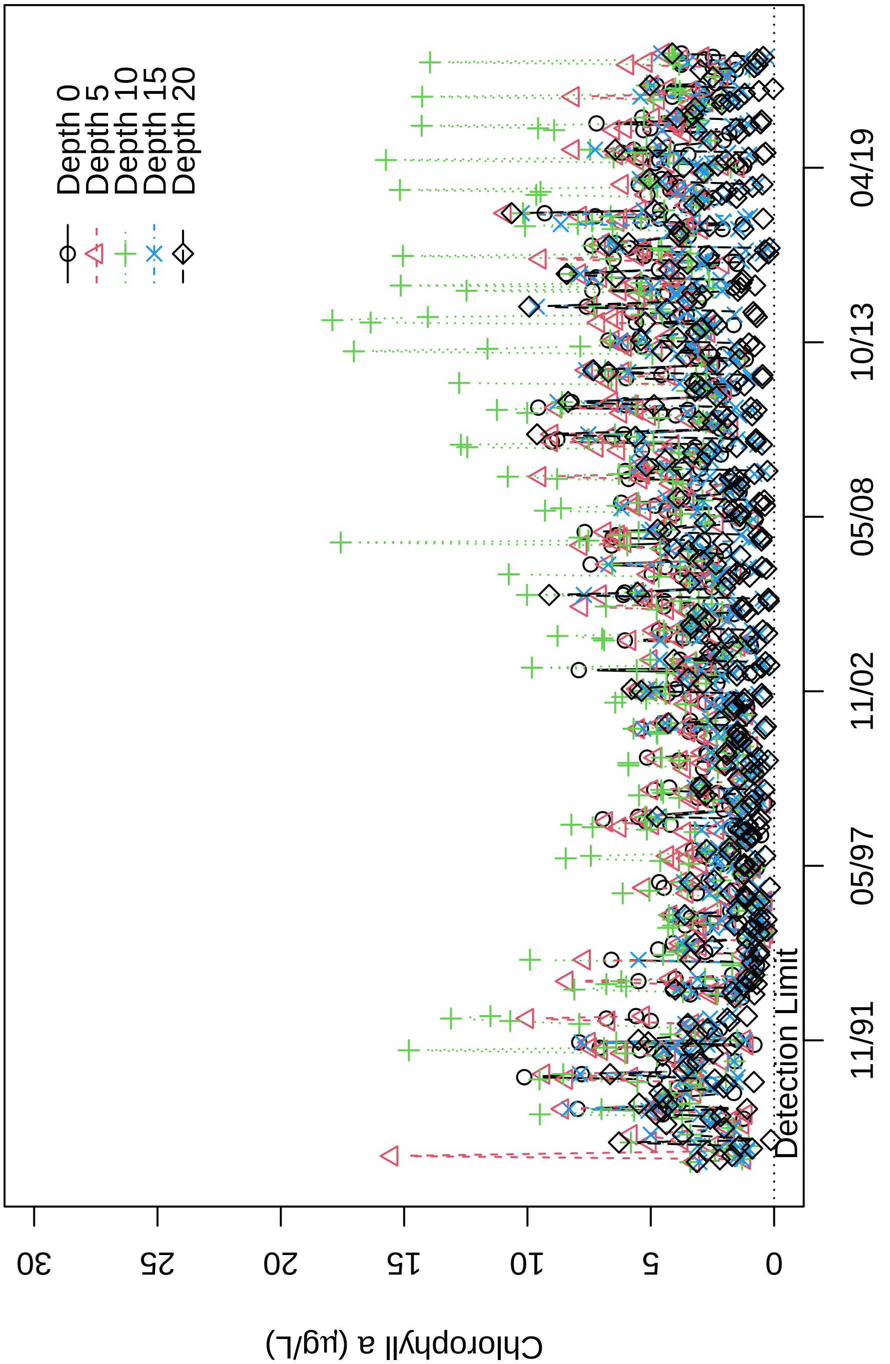

Figure B121: Lake Whatcom chlorophyll data for Site 1.

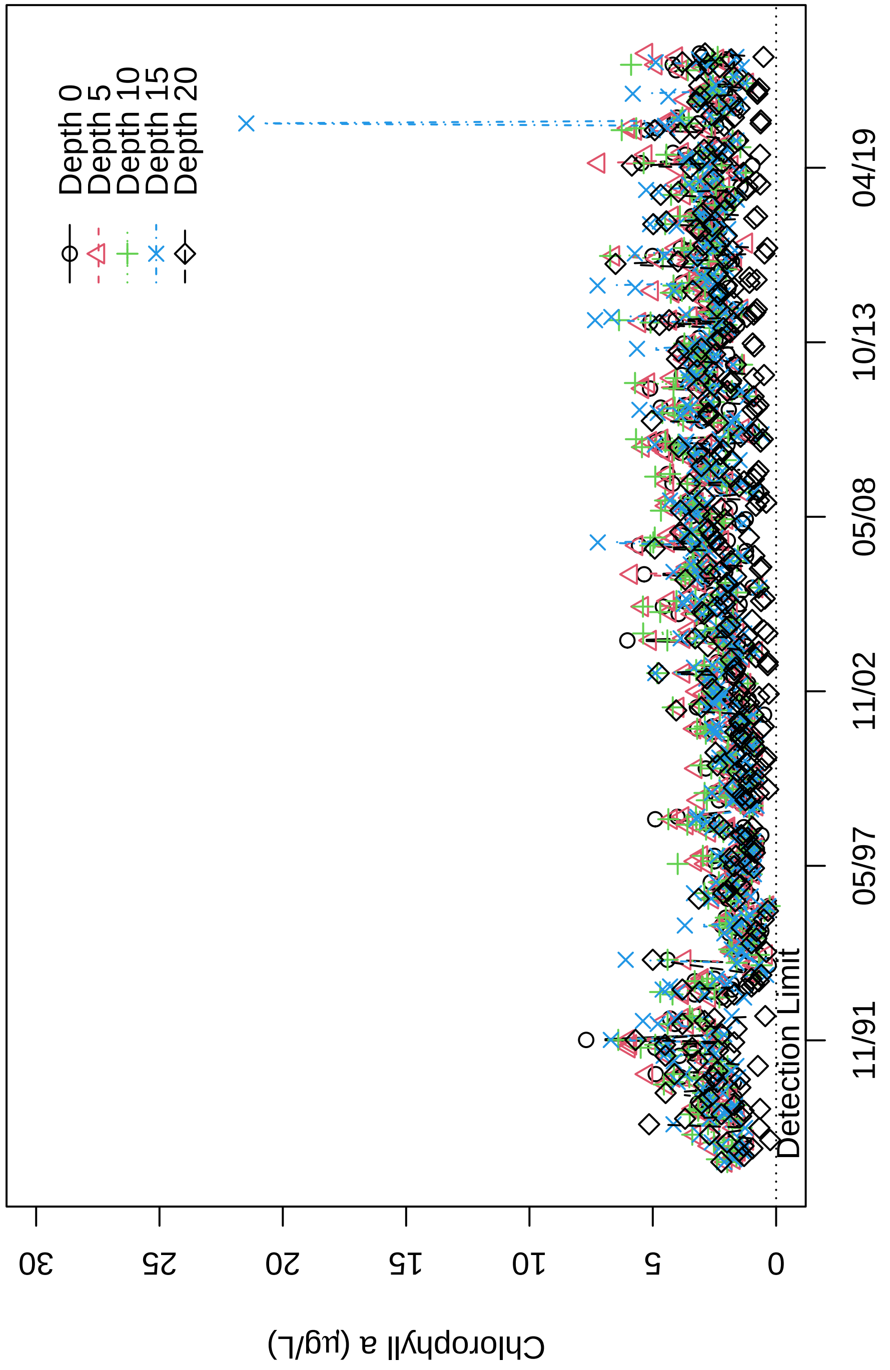

Figure B122: Lake Whatcom chlorophyll data for Site 2.

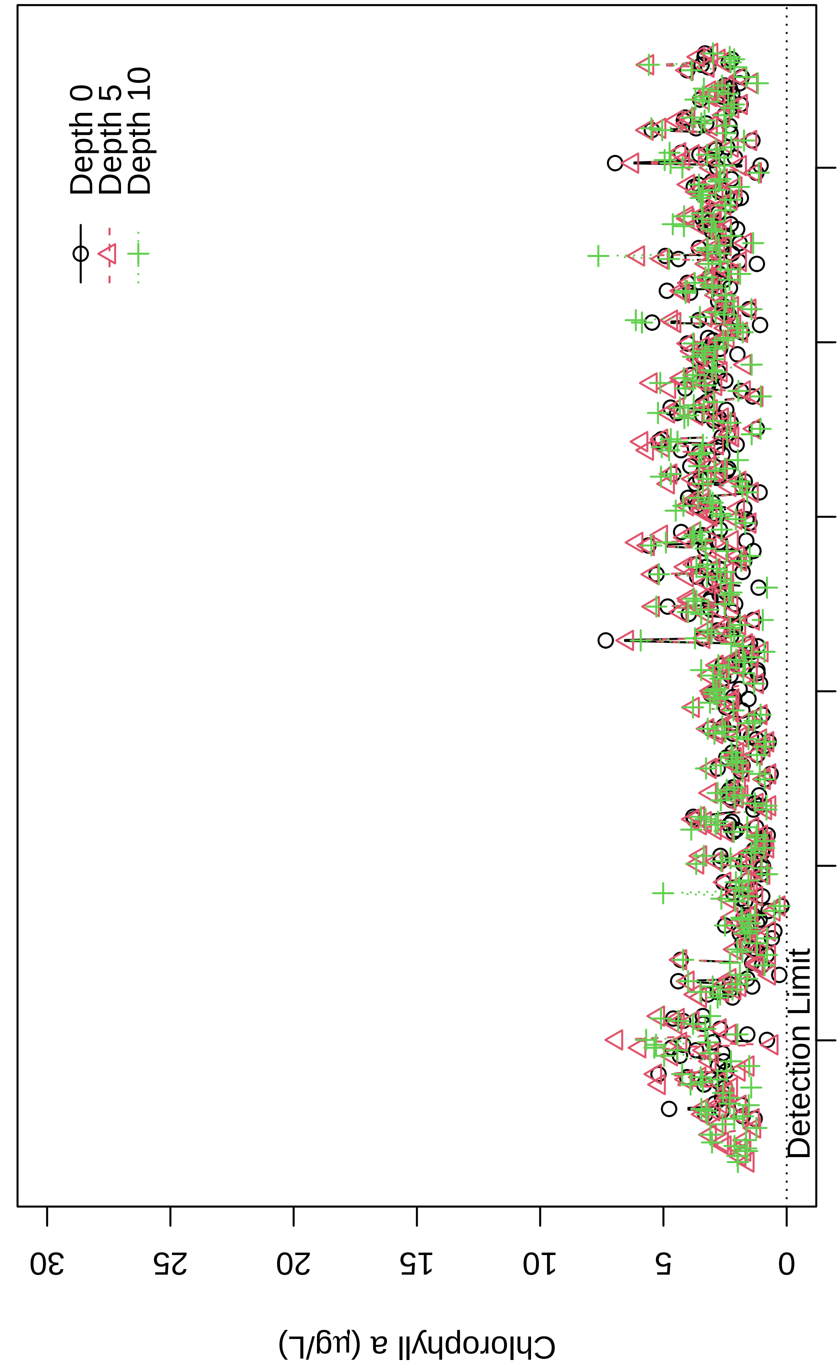

Figure B123: Lake Whatcom chlorophyll data for the Intake site.

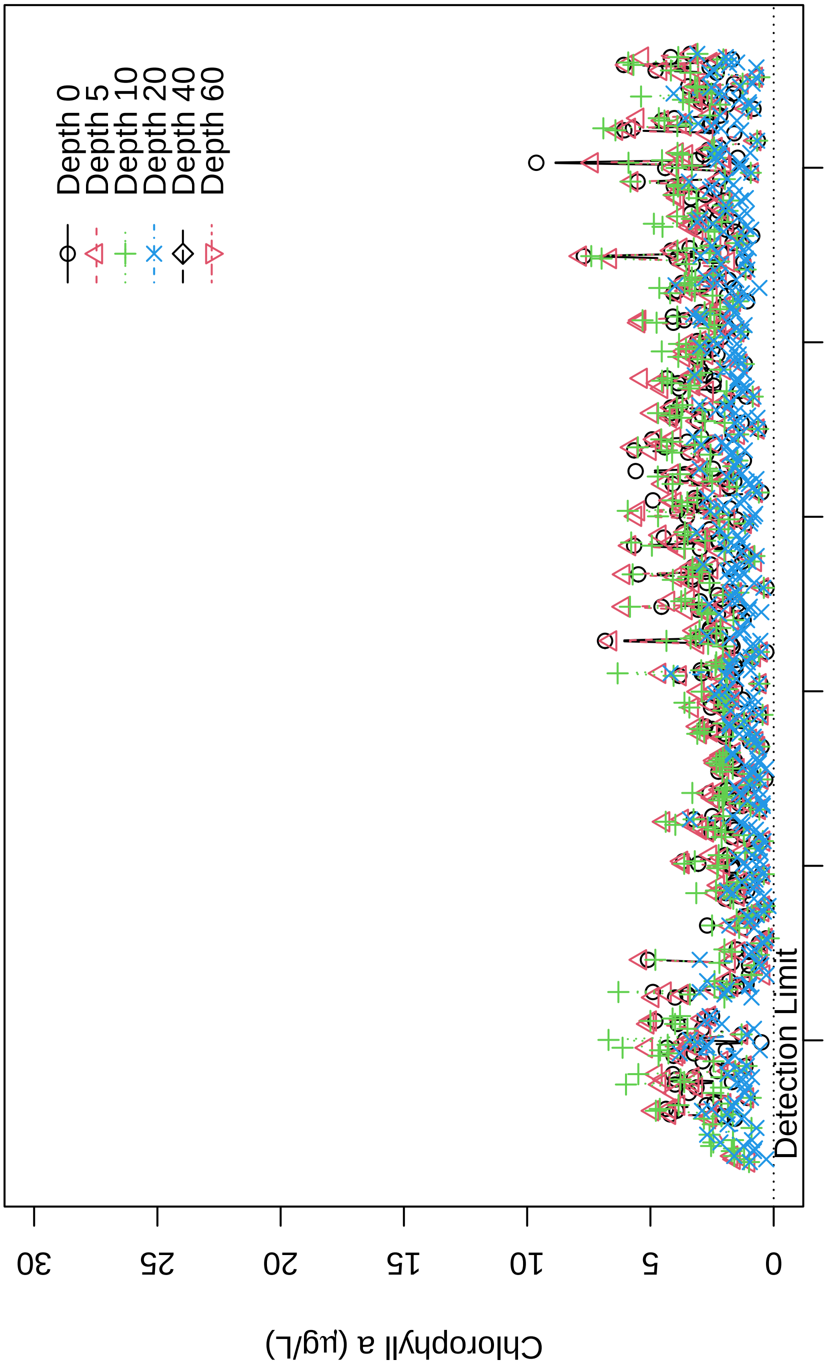

Figure B124: Lake Whatcom chlorophyll data for Site 3.

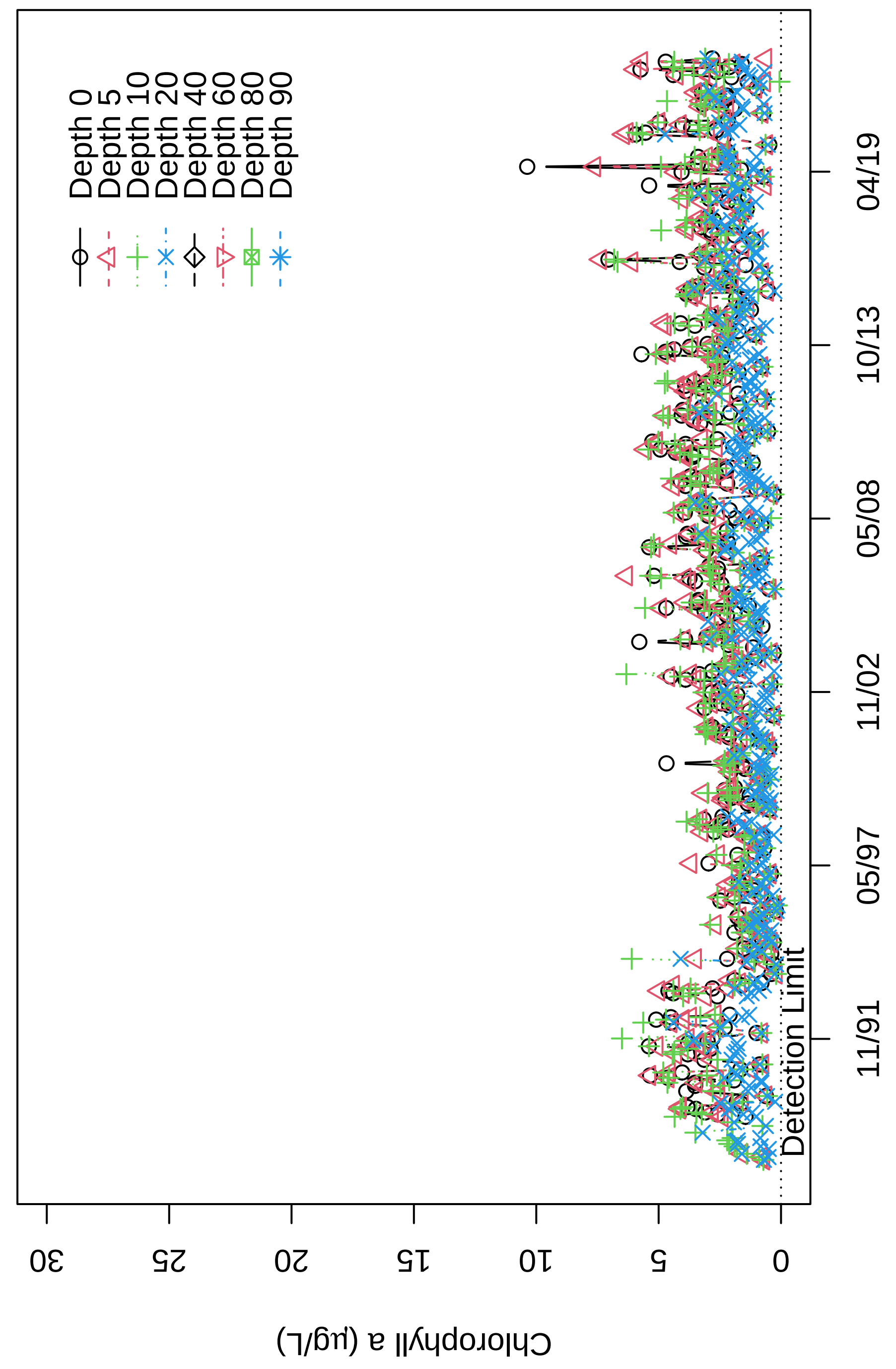

Figure B125: Lake Whatcom chlorophyll data for Site 4.

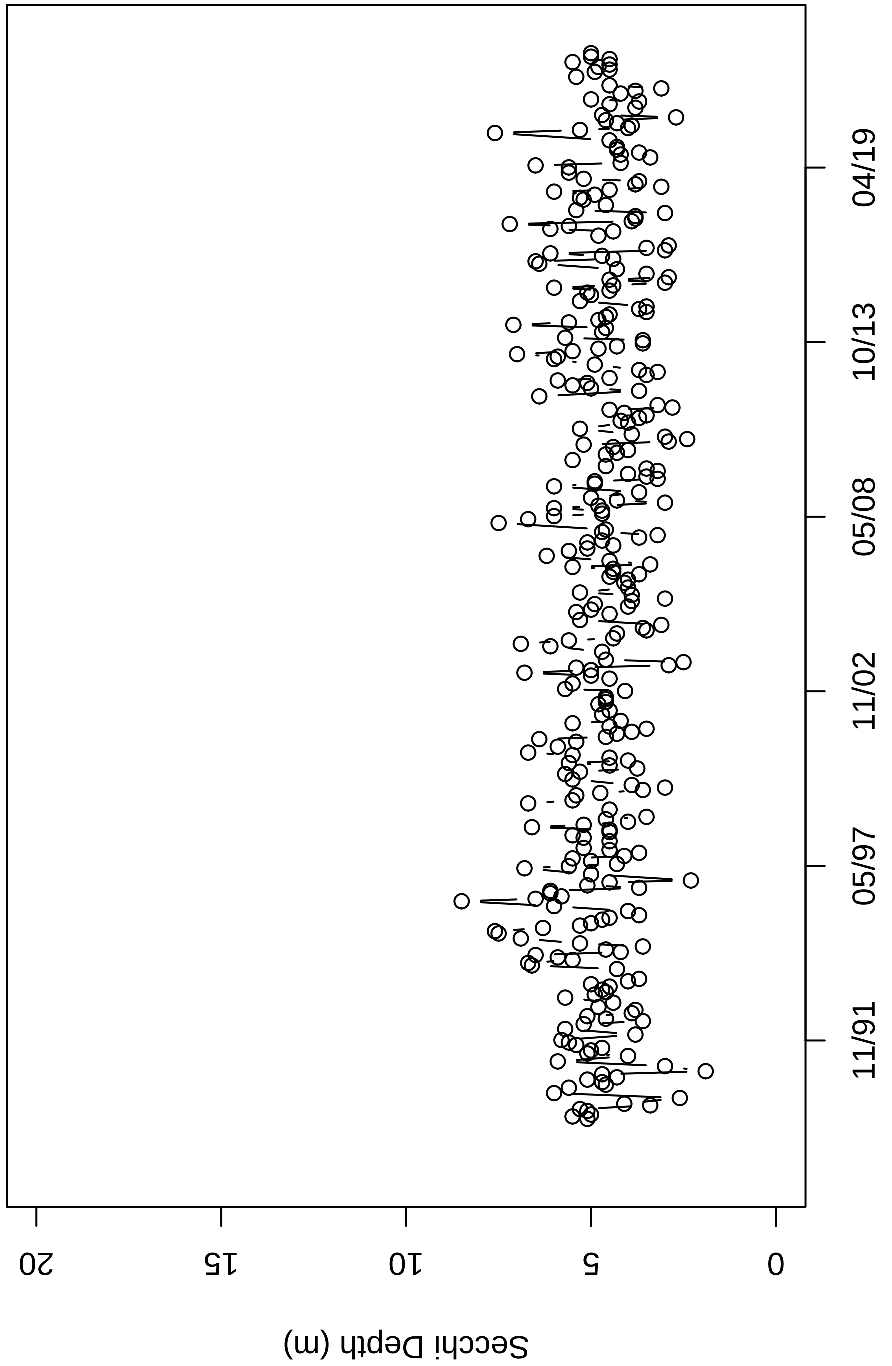

Figure B126: Lake Whatcom Secchi depths for Site 1.

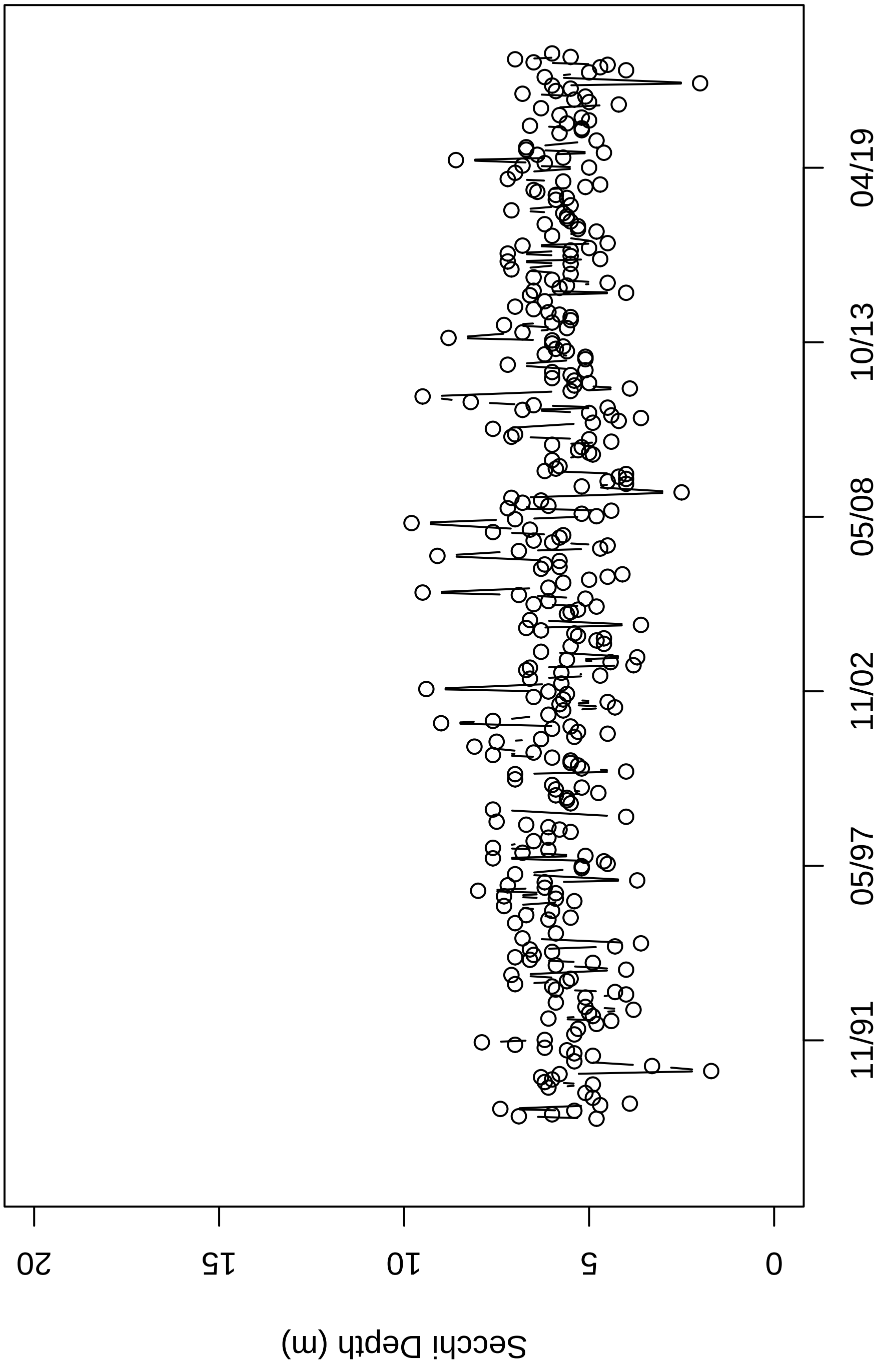

Figure B127: Lake Whatcom Secchi depths for Site 2.

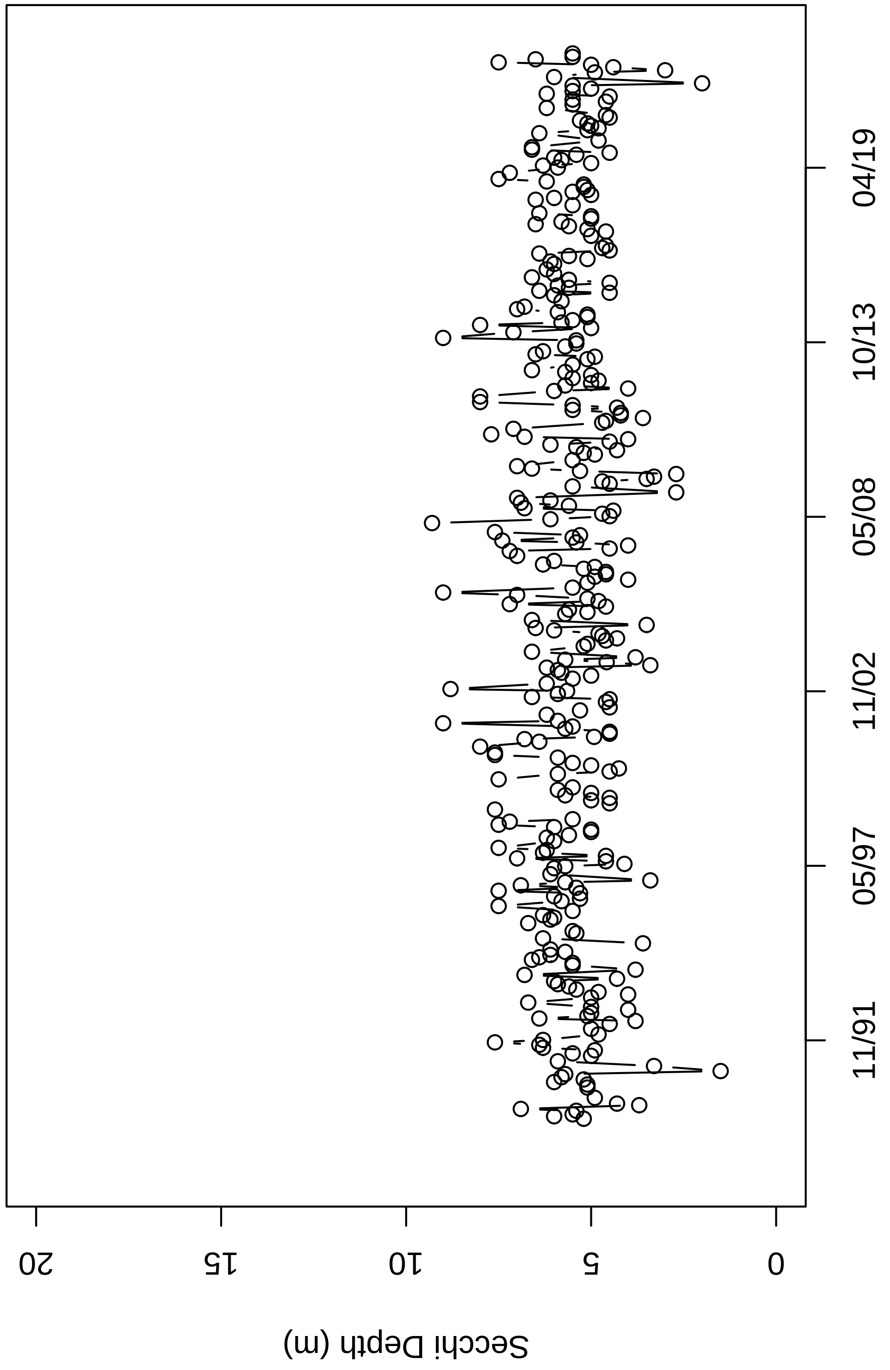

Figure B128: Lake Whatcom Secchi depths for the Intake site.

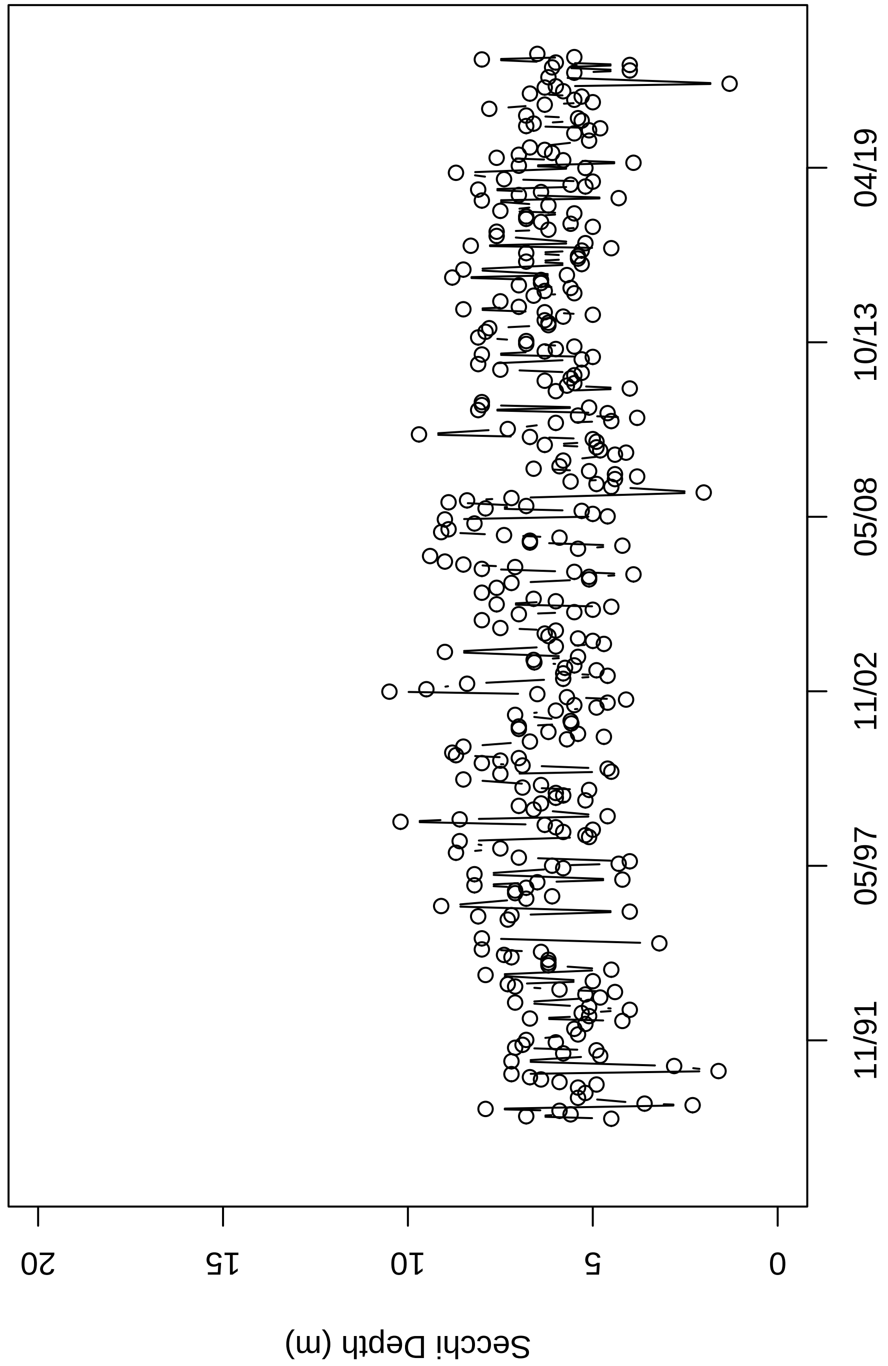

Figure B129: Lake Whatcom Secchi depths for Site 3.

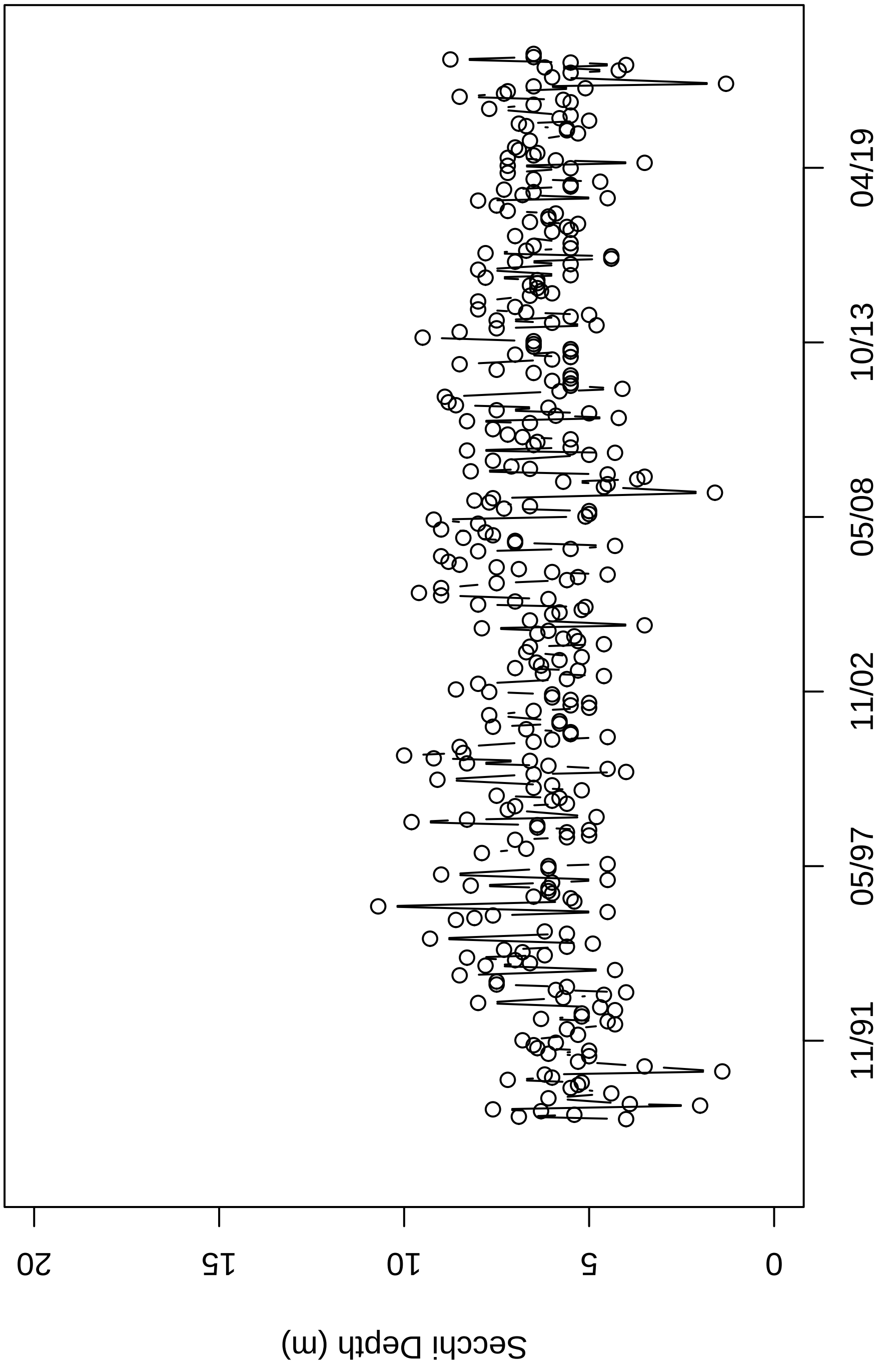

Figure B130: Lake Whatcom Secchi depths for Site 4.

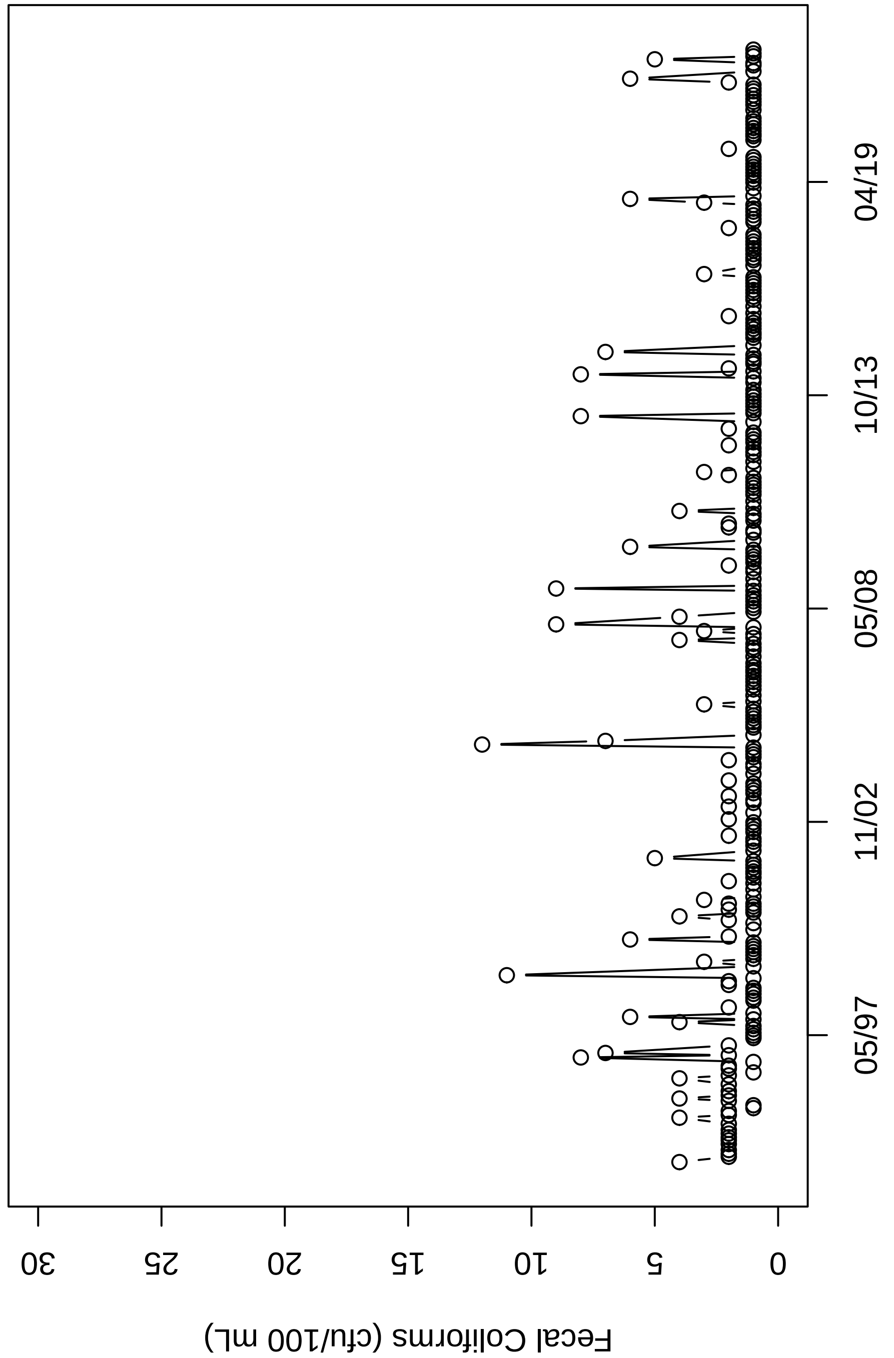

Figure B131: Lake Whatcom fecal coliform data for Site 1.

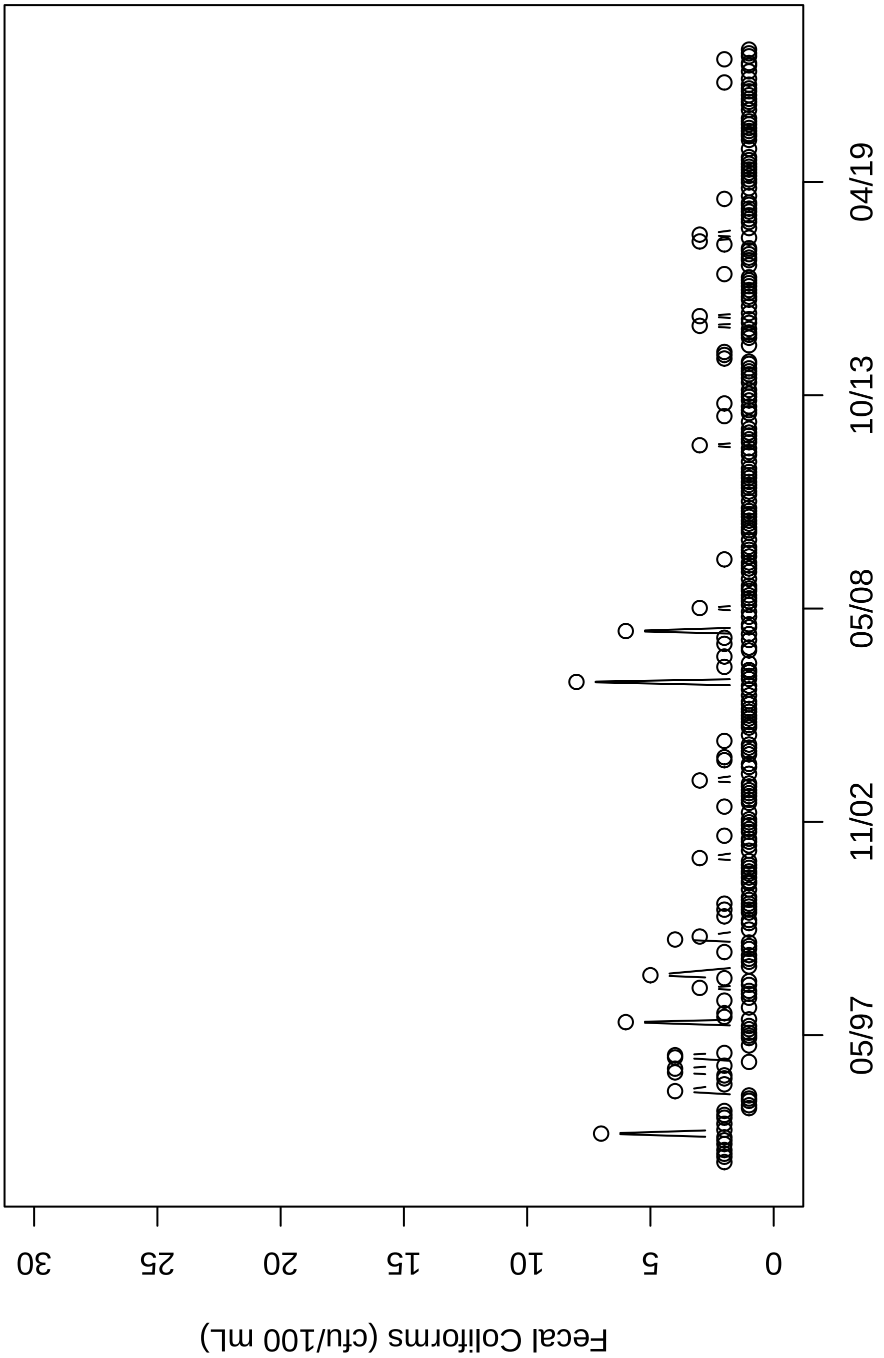

Figure B132: Lake Whatcom fecal coliform data for Site 2.

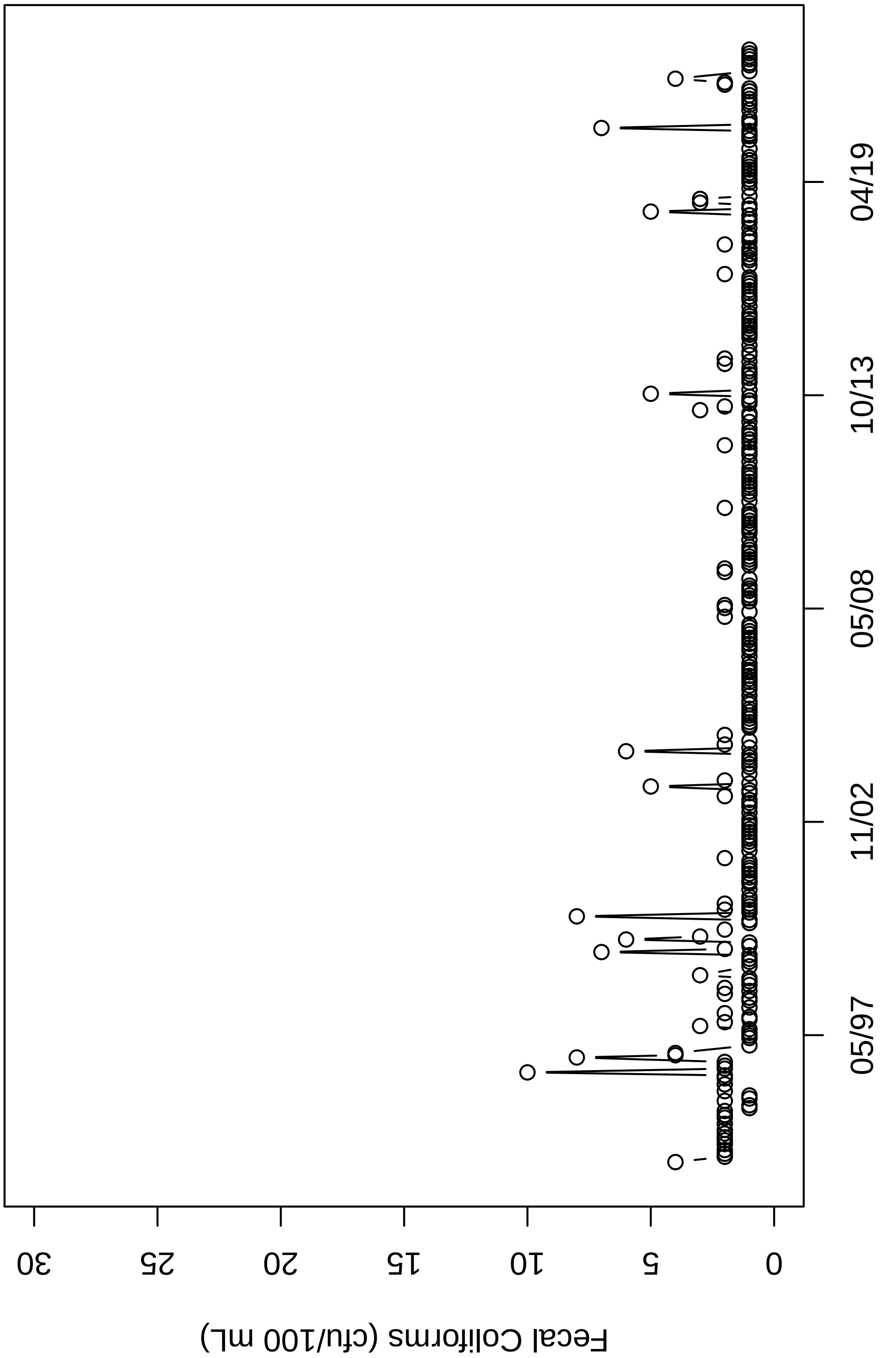

Figure B133: Lake Whatcom fecal coliform data for the Intake site.

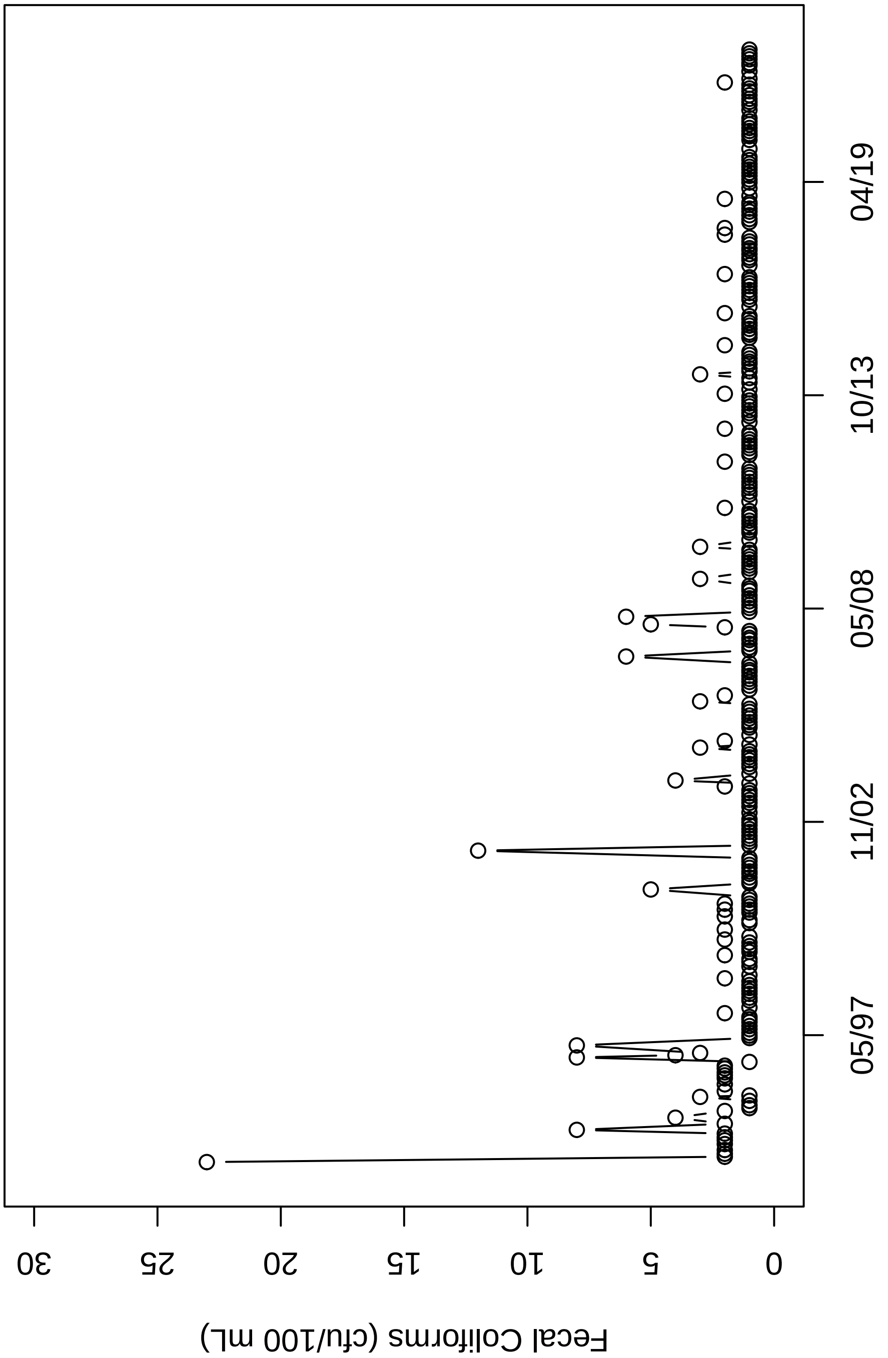

Figure B134: Lake Whatcom fecal coliform data for Site 3.

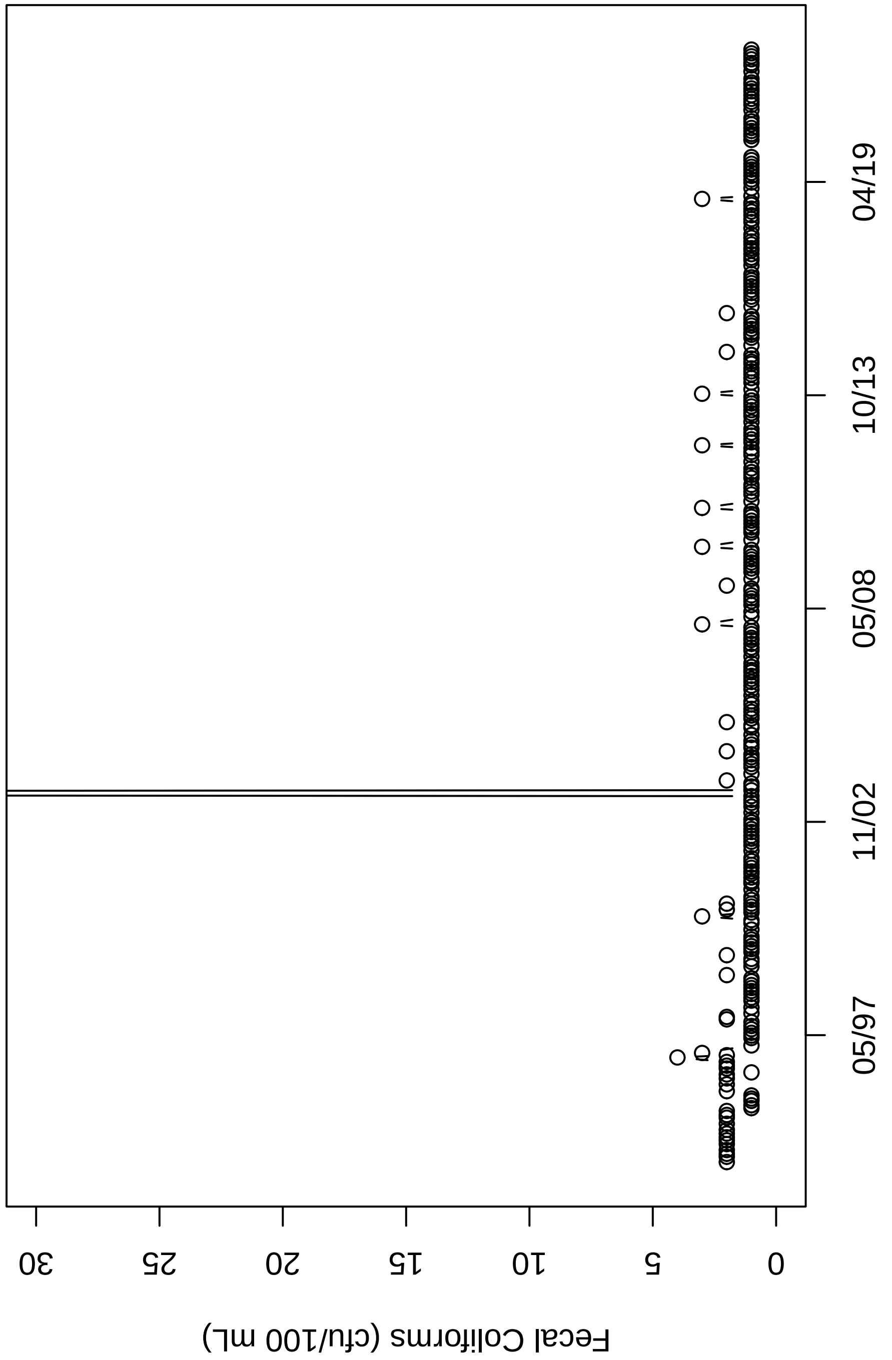

Figure B135: Lake Whatcom fecal coliform data for Site 4.

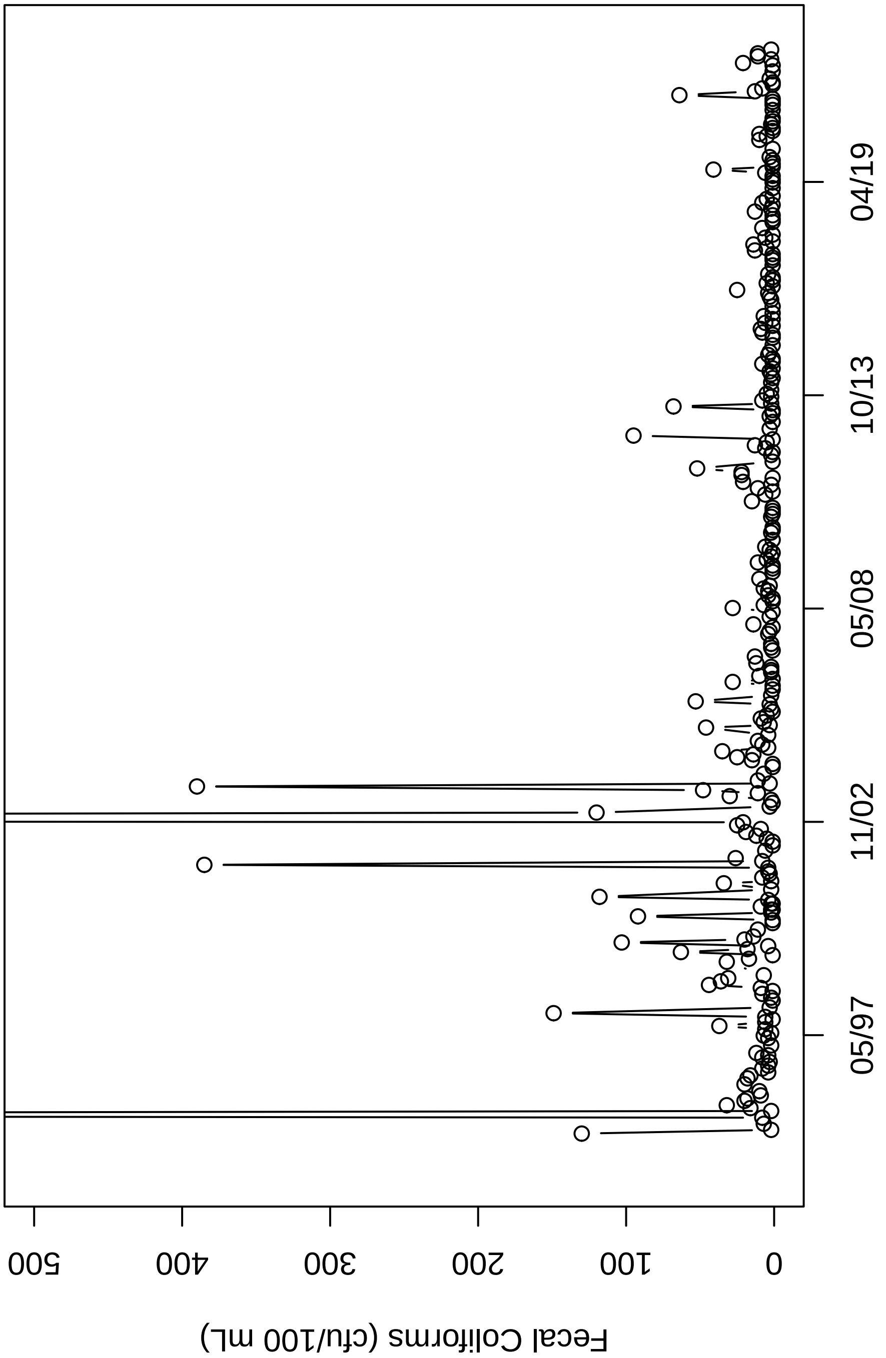

Figure B136: Lake Whatcom fecal coliform data for Bloedel Donovan. Note difference in y-axis scaling compared to Sites 1-4. Two data points are outside of the plot range: May 1995, 1600 cfu/100 mL; December 2002, 2700 cfu/100 mL

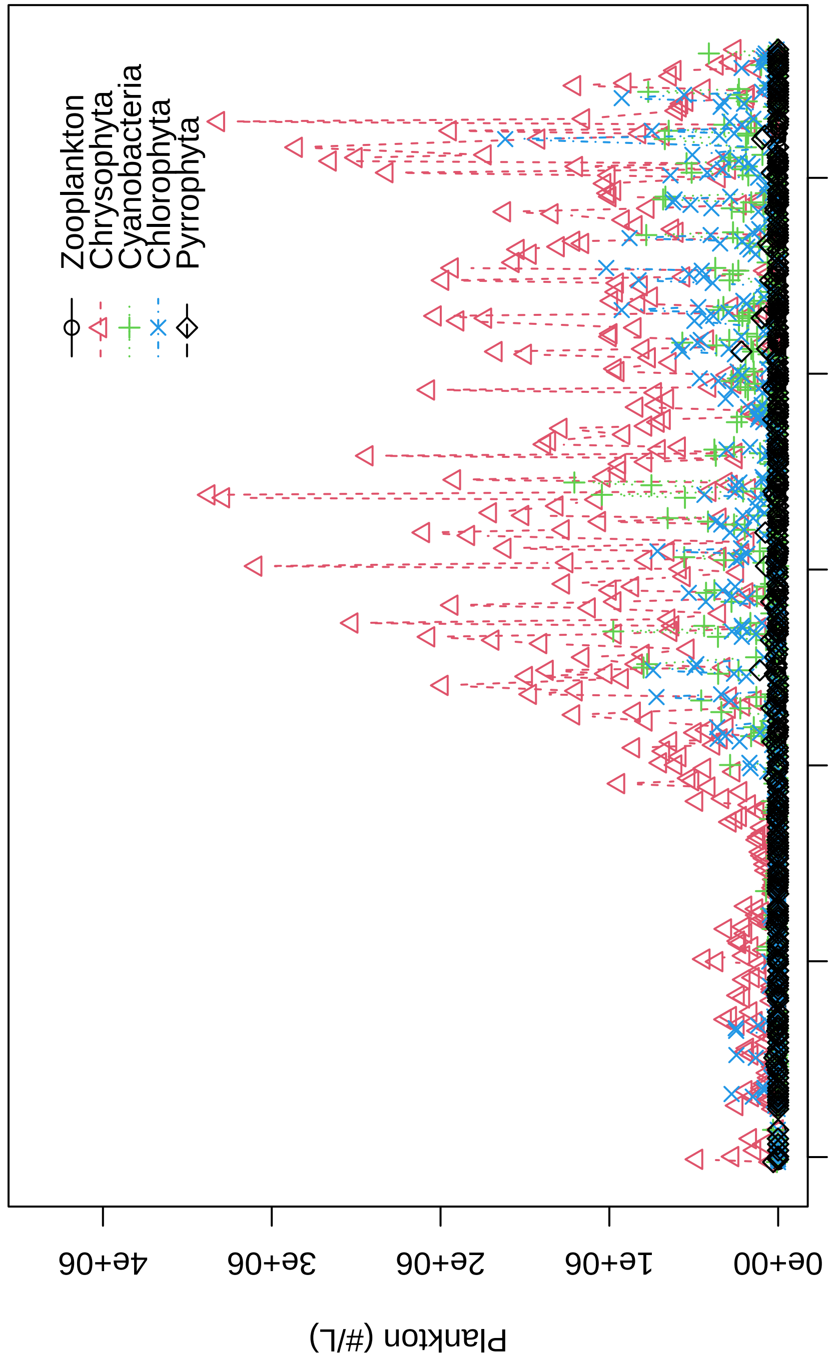

Figure B137: Lake Whatcom plankton data for Site 1.

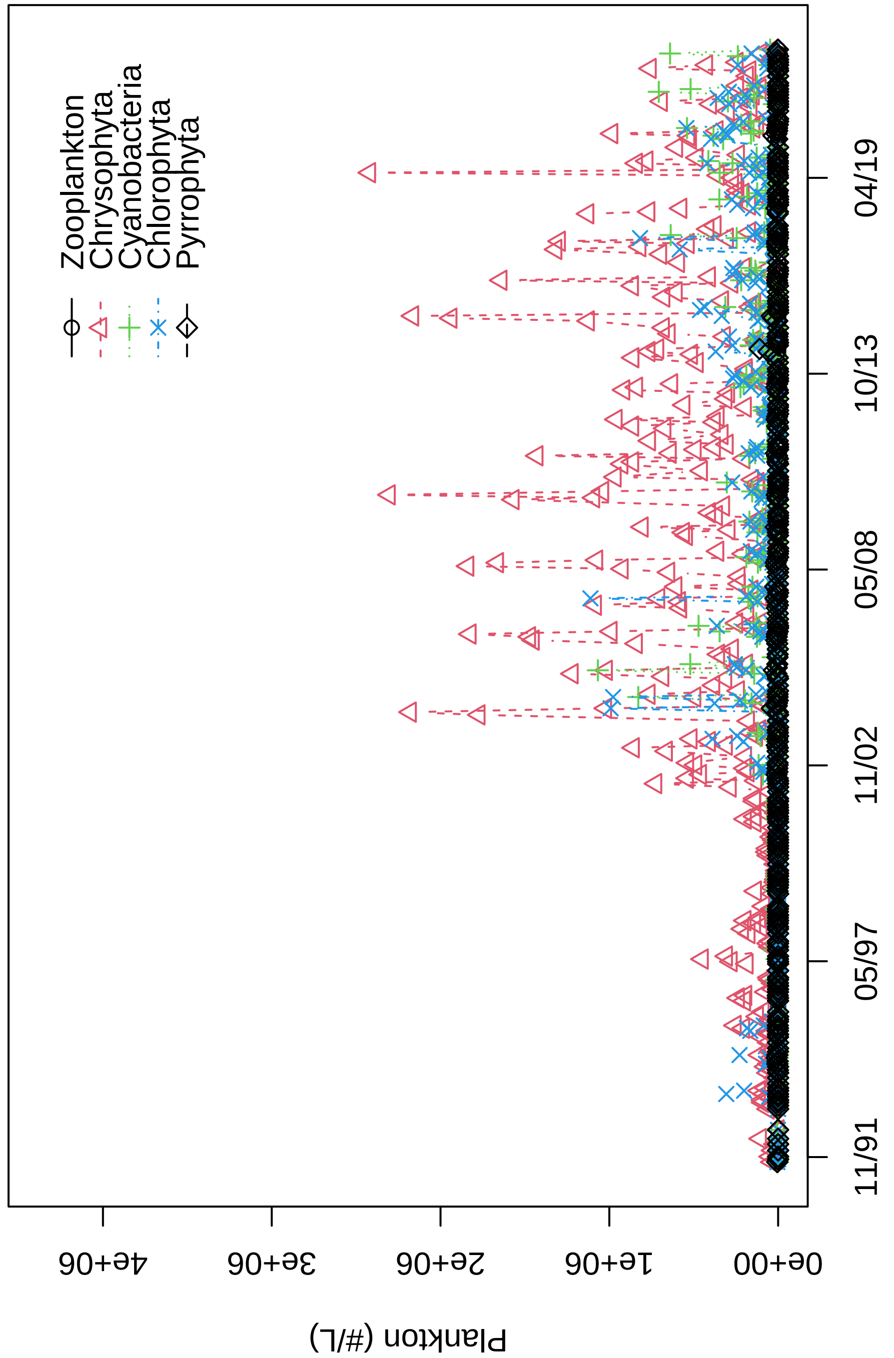

Figure B138: Lake Whatcom plankton data for Site 2.

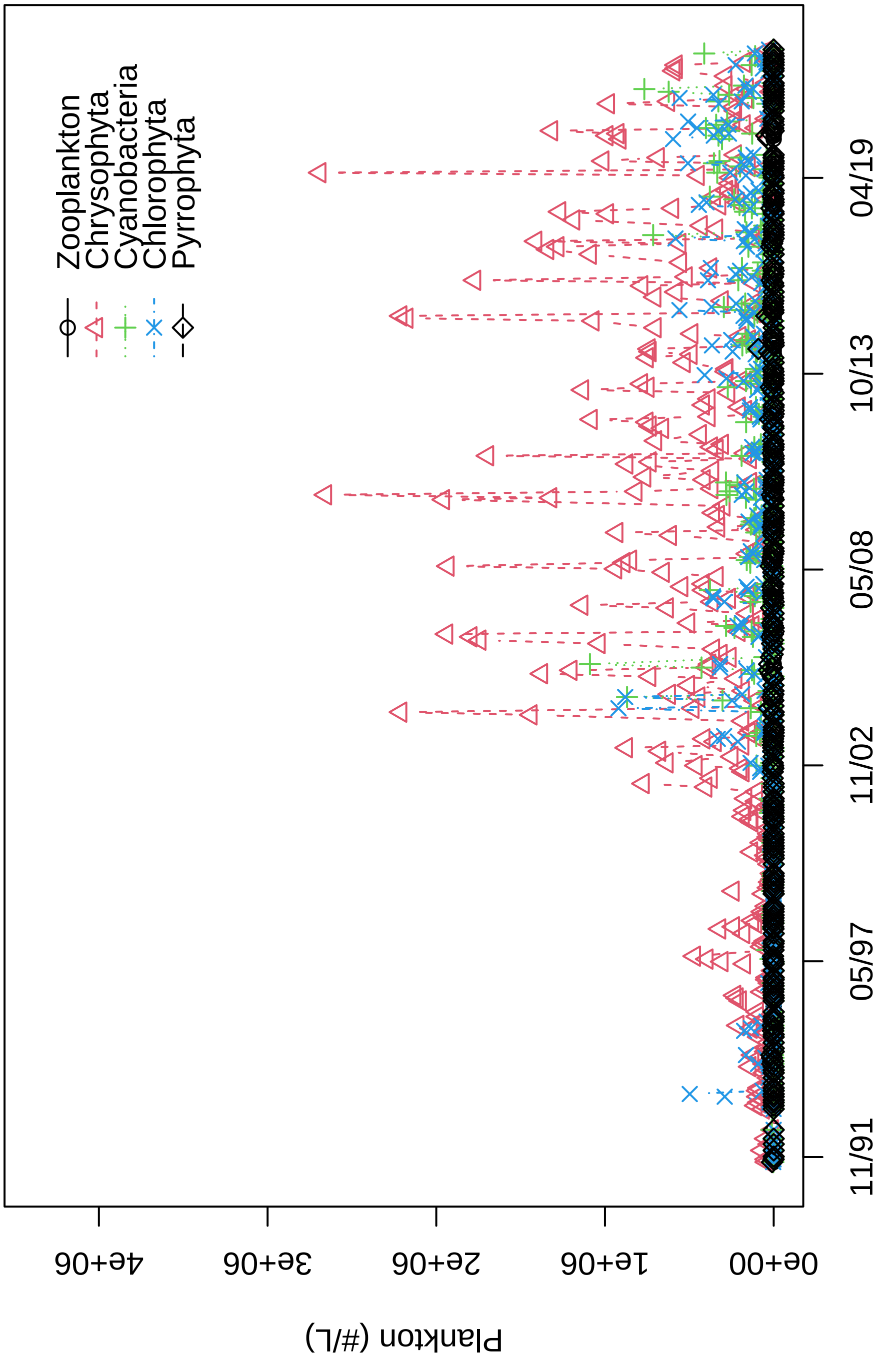

Figure B139: Lake Whatcom plankton data for the Intake Site.

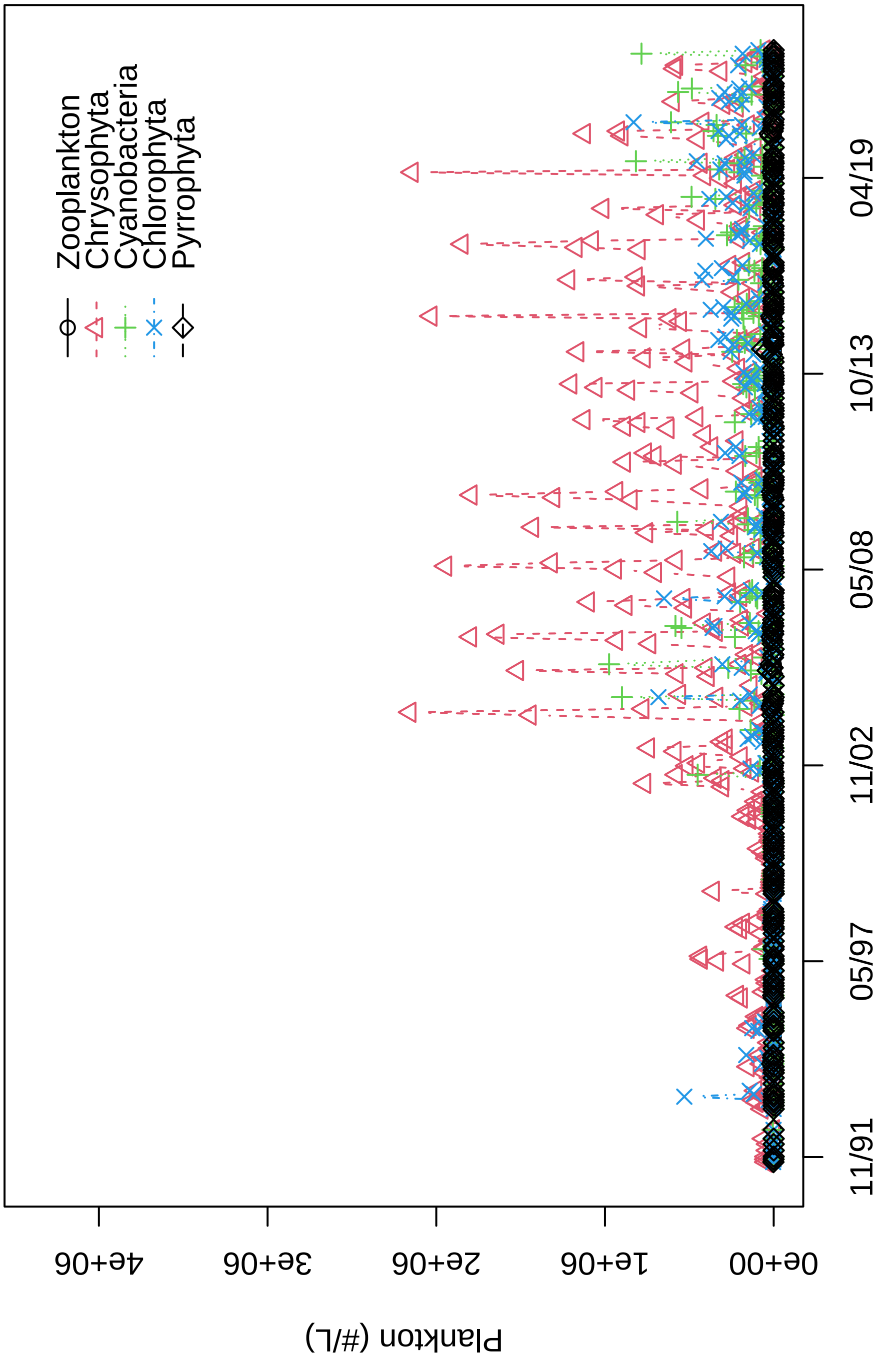

Figure B140: Lake Whatcom plankton data for Site 3.

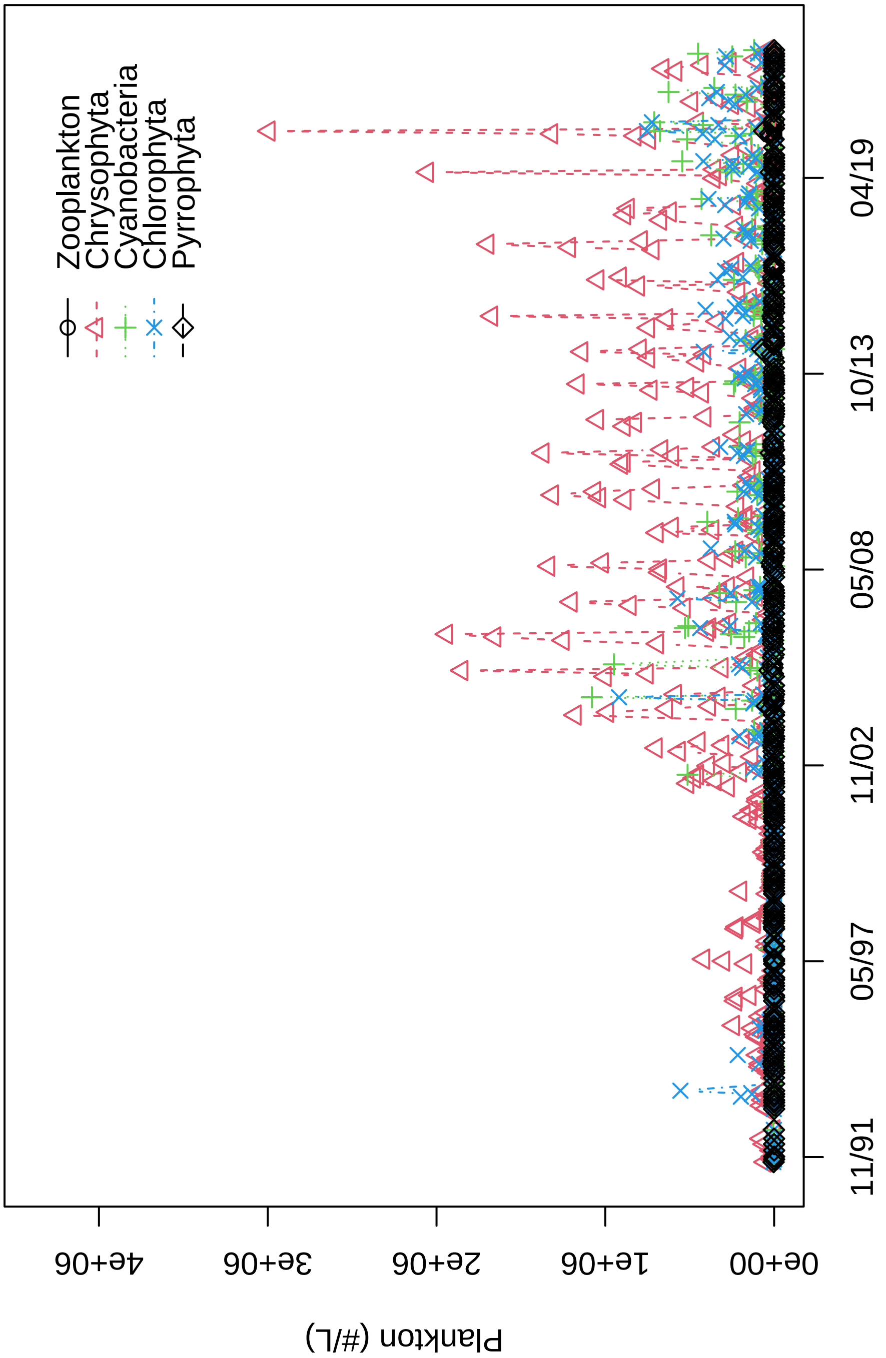

Figure B141: Lake Whatcom plankton data for Site 4.

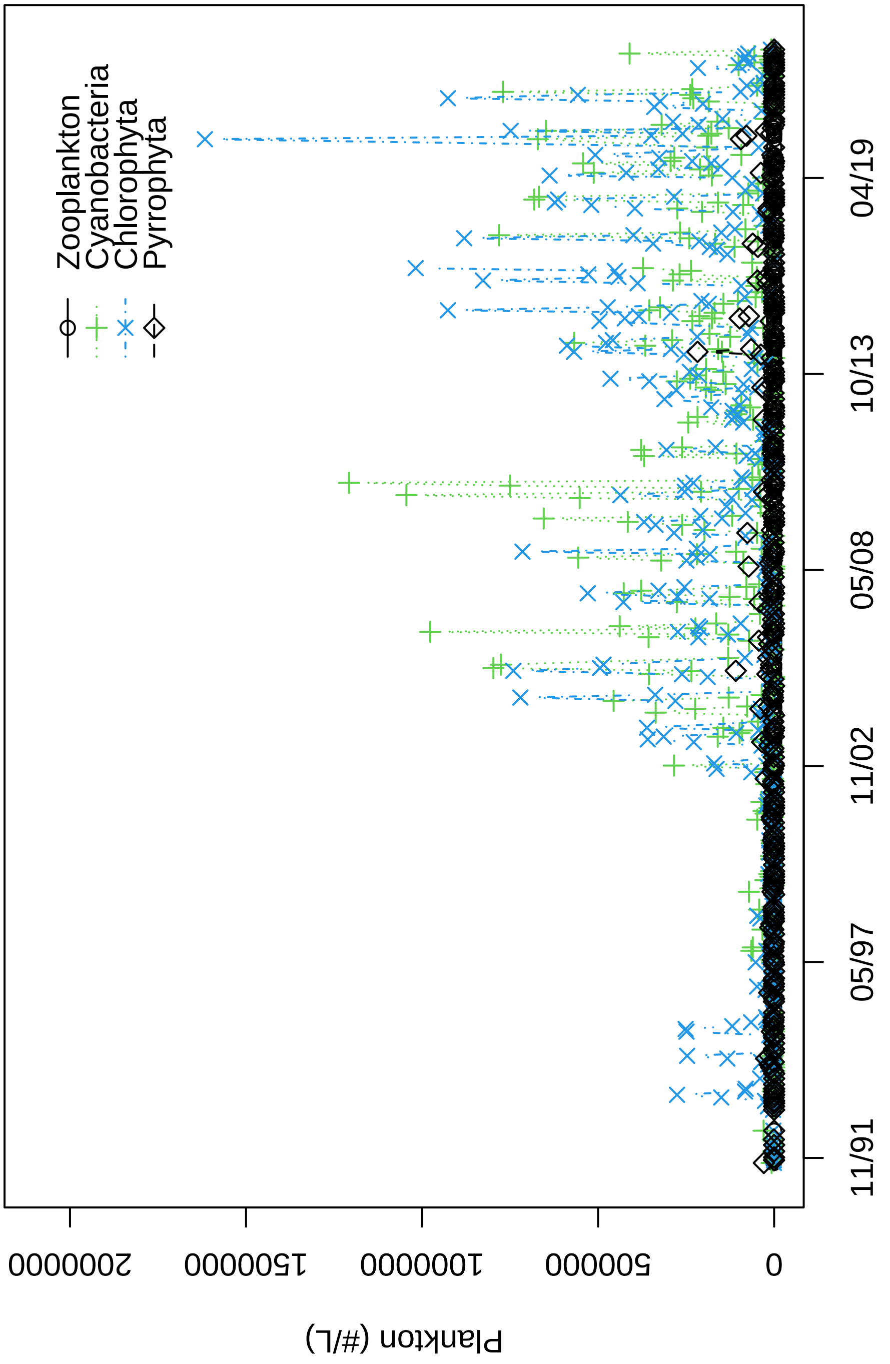

Figure B142: Lake Whatcom plankton data for Site 1, with Chrysophyta omitted to show remaining plankton groups.

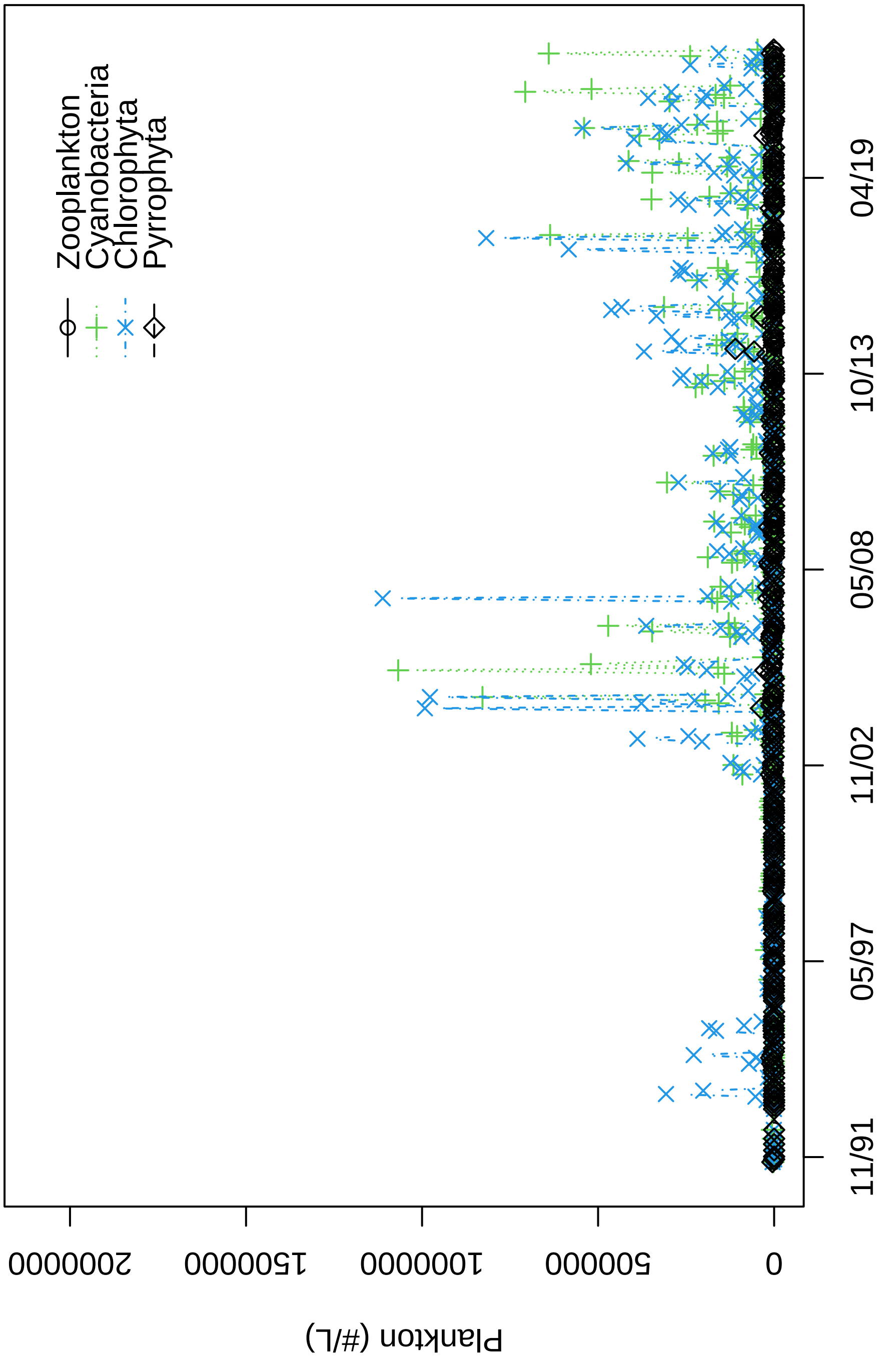

Figure B143: Lake Whatcom plankton data for Site 2, with Chrysophyta omitted to show remaining plankton groups.

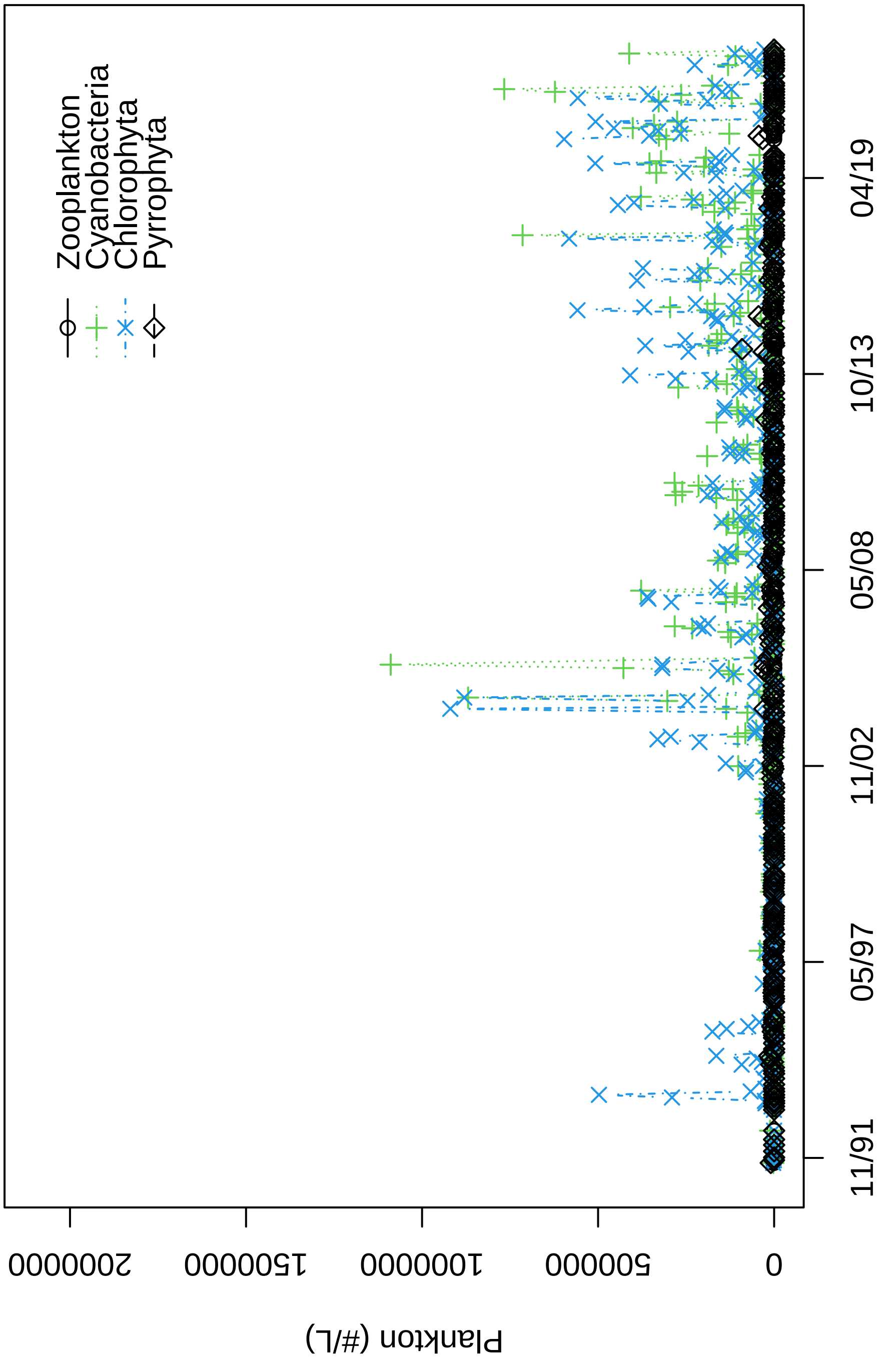

Figure B144: Lake Whatcom plankton data for the Intake Site, with Chrysophyta omitted to show remaining plankton groups.

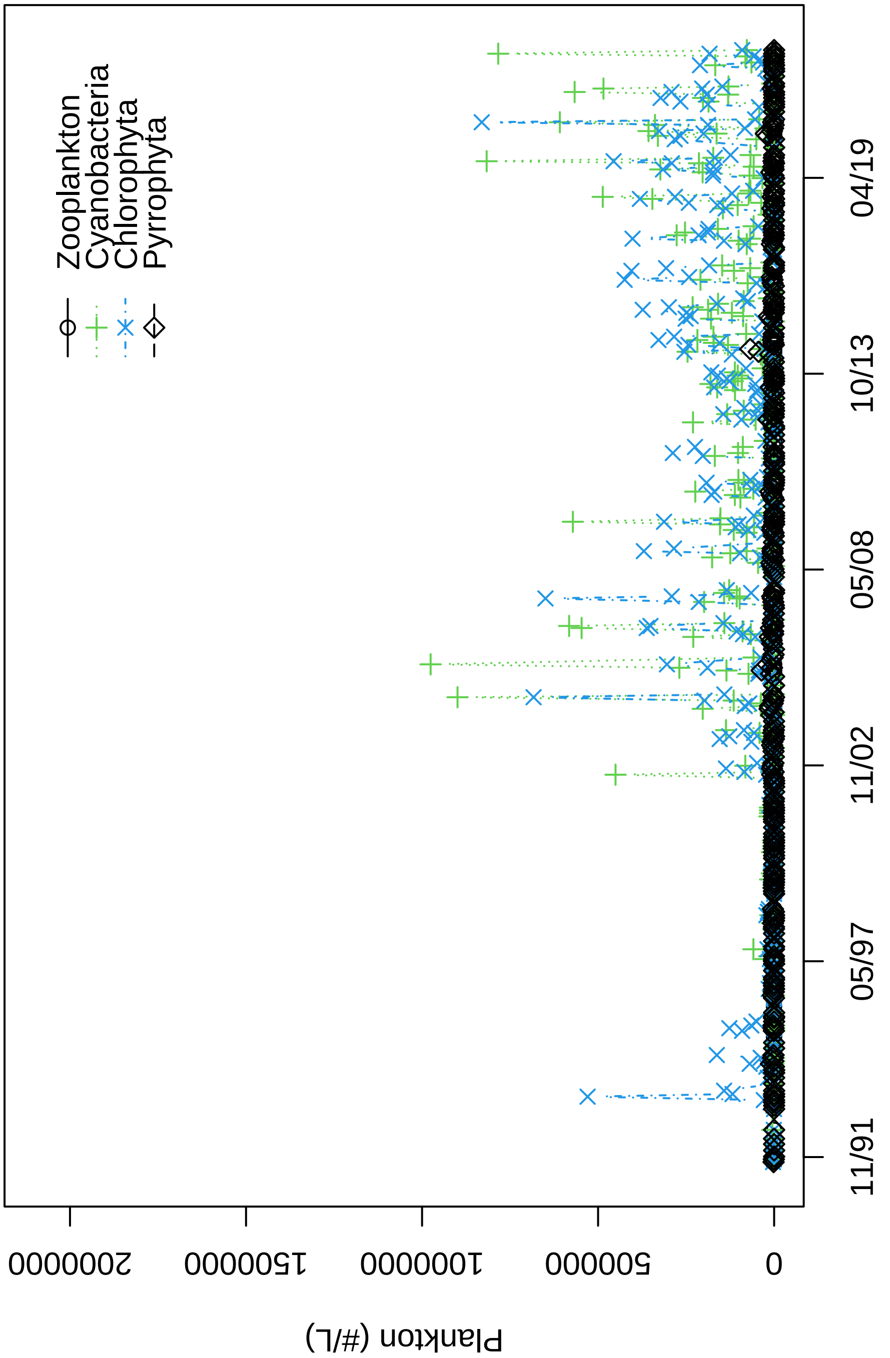

Figure B145: Lake Whatcom plankton data for Site 3, with Chrysophyta omitted to show remaining plankton groups.

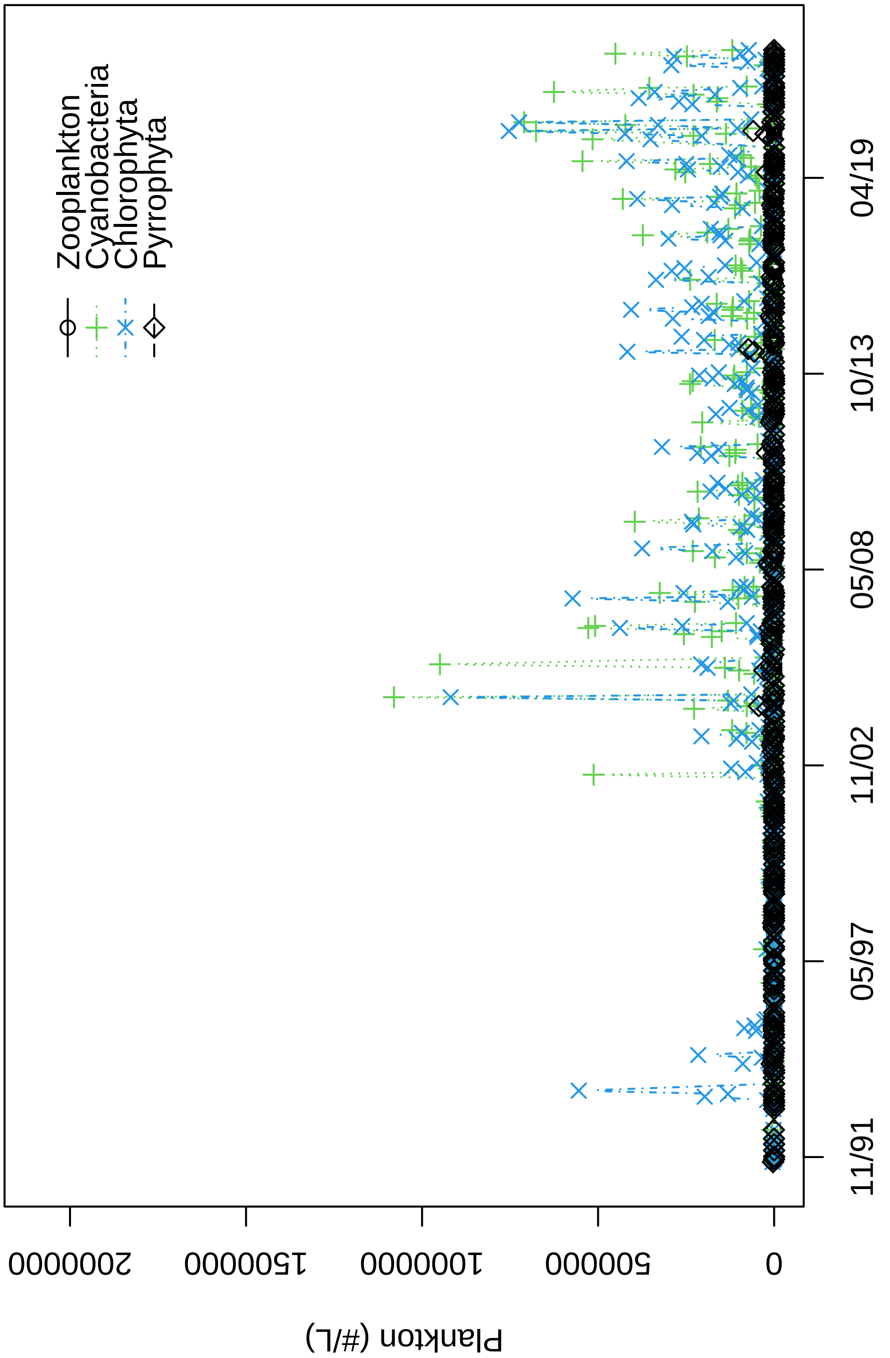

Figure B146: Lake Whatcom plankton data for Site 4, with Chrysophyta omitted to show remaining plankton groups.

B.4 Lake Whatcom Tributary Data (2004-present)

The figures in this appendix include the monthly or biannual baseline data collected from 2004 through the current monitoring period. Each figure includes a dashed (blue) horizontal line that shows the median value for Smith Creek and a solid (red) horizontal line that shows the median value for each creek. Smith Creek was chosen as a reference because it is a major tributary to the lake and has a history of being relatively unpolluted. The figures were scaled to include all but extreme outliers; off-scale outliers are listed in Table B1 (page 253).

Site	Date	Parameter	Concentration
Anderson	January 10, 2006	Total susp. solids	168.8 mg/L
Austin	January 10, 2006	Total susp. solids	166.5 mg/L
Brannian	March 3, 2014	Total phosphorus	349.8 μg-P/L
	March 3, 2014	Total susp. solids	328.5 mg/L
	January 12, 2022	Total phosphorus	259.4μg-P/L
Millwheel	February 8, 2005	Ammonium	569.4 μg-N/L
	February 8, 2005	Soluble phosphate	116.5 μg-P/L
	July 11, 2011	Ammonium	291.7 μg-N/L
	October 12, 2011	Total phosphorus	521.8 μg-P/L
	September 12, 2012	Ammonium	837.7 μg-N/L
	September 12, 2012	Total phosphorus	452.2 μg-P/L
	July 8, 2014	Total phosphorus	788.2 μg-P/L
	July 8, 2014	Soluble phosphate	165.1 μg-P/L
	July 8, 2014	Ammonium	1956.4 μg-N/L
	September 9, 2014	Total phosphorus	263.5 μg-P/L
	October 9, 2018	Total phosphorus	1,342 μg-P/L
	July 12, 2019	Total phosphorus	292.0 μg-P/L
	July 12, 2019	Ammonium	291.0 μg-N/L
	July 12, 2022	Total phosphorus	300.3 μg-P/L
	July 12, 2022	Soluble phosphate	116.3 μg-P/L
	July 12, 2022	Ammonium	411.4 μg-N/L
Olsen	January 10, 2006	Total susp. solids	166.9 mg/L
	January 12, 2022	Total phosphorus	257.8 μg-P/L
	January 12, 2022	Total susp. solids	332 mg/L
Park Place	August 1, 2006	F. coliforms	18,000 cfu/100 mL
	July 18, 2017	F. coliforms	19,000 cfu/100 mL
	May 14, 2019	Ammonium	693.3 μg-N/L
	May 14, 2019	Soluble phosphate	111.8 μg-P/L
	September 13, 2022	Ammonium	266.5 μg-N/L
Silver Beach	August 1, 2006	F. coliforms	12,000 cfu/100 mL

Table B1: List of outliers omitted from Figures B147–B185 to preserve scale.

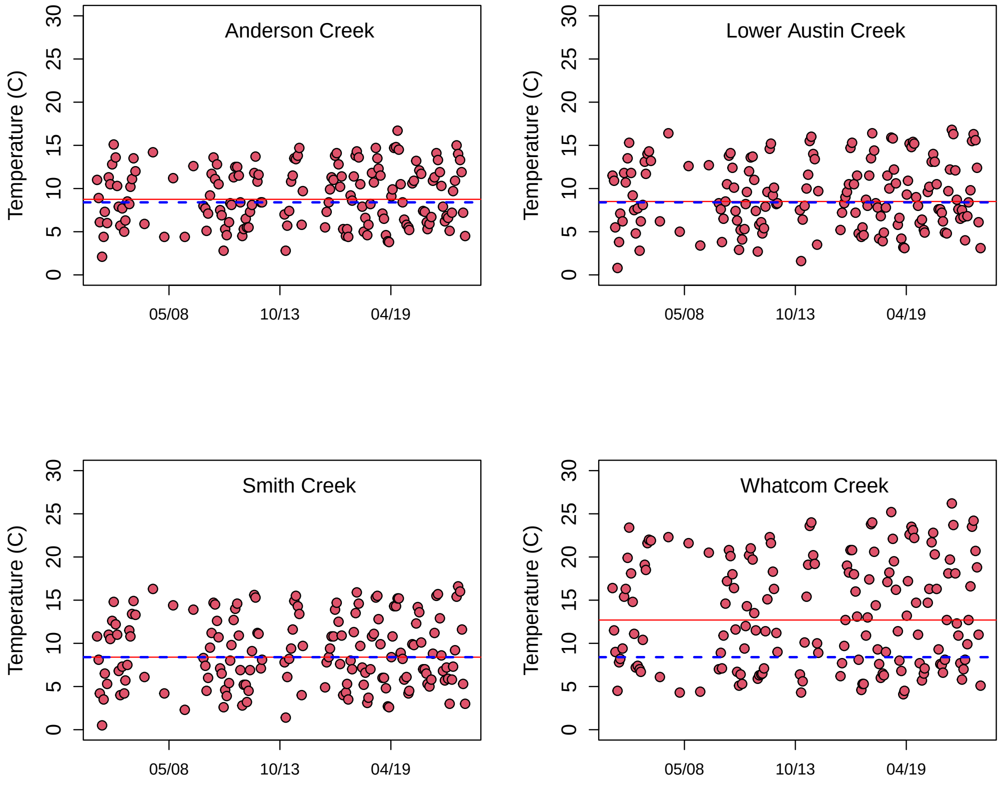

Figure B147: Temperature data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

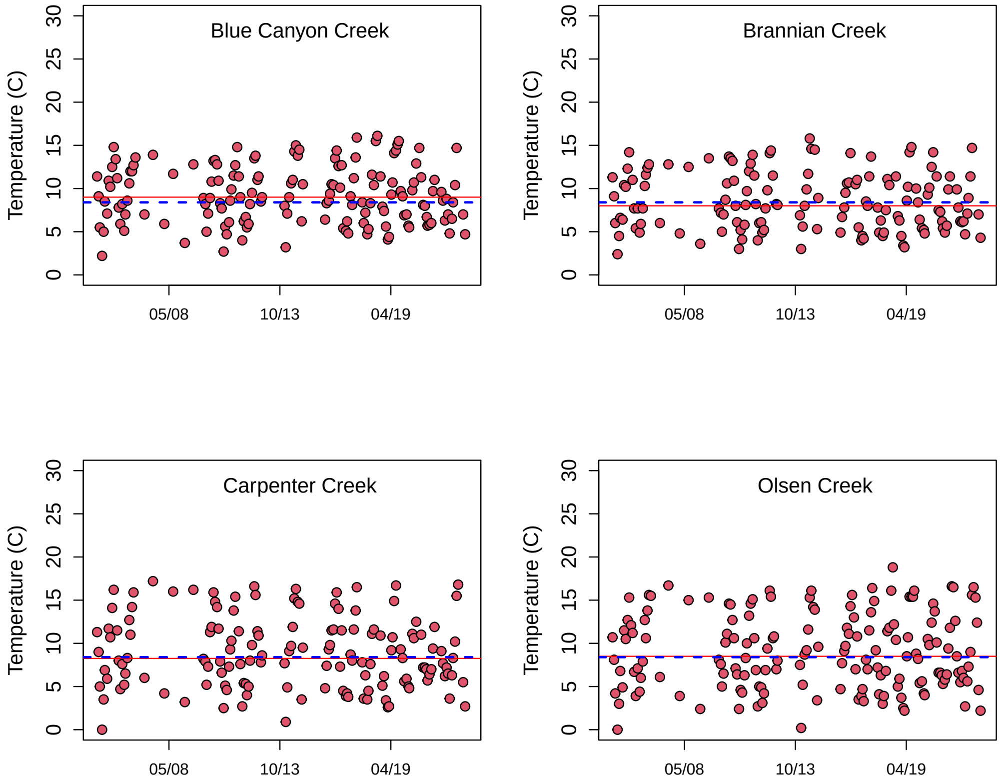

Figure B148: Temperature data Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

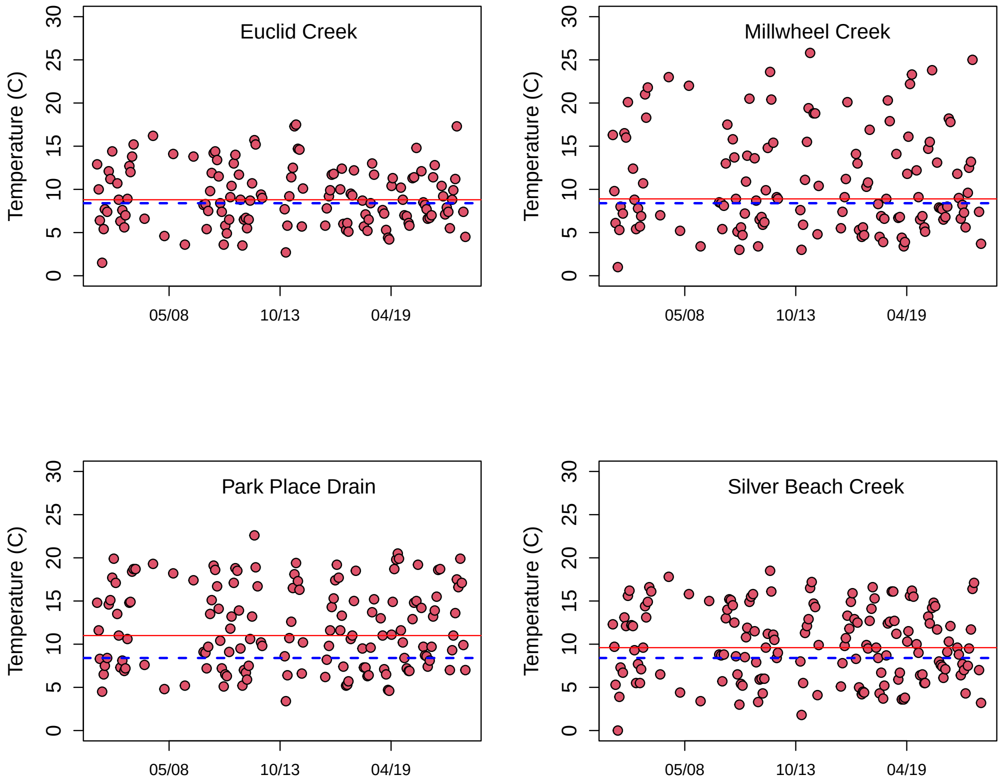

Figure B149: Temperature data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

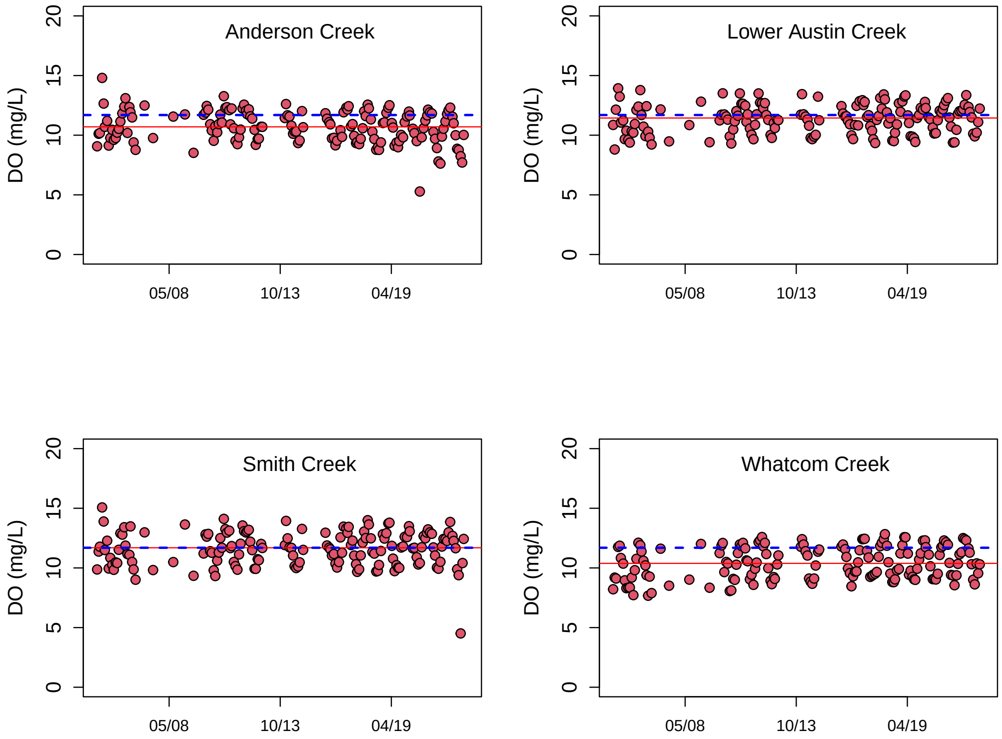

Figure B150: Dissolved oxygen data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

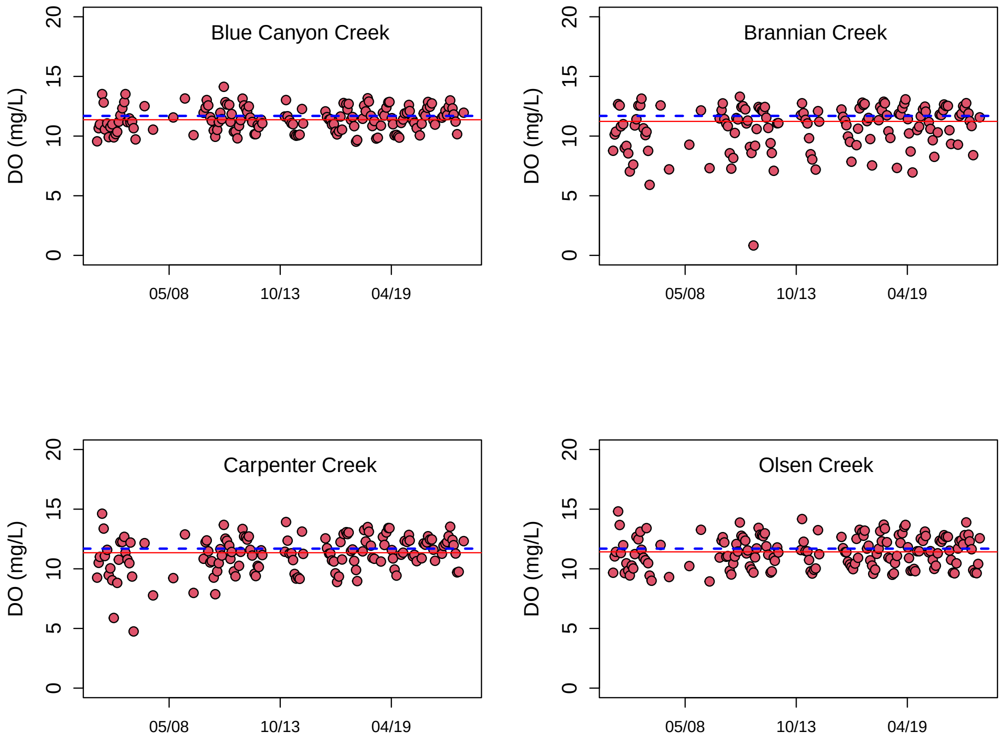

Figure B151: Dissolved oxygen data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

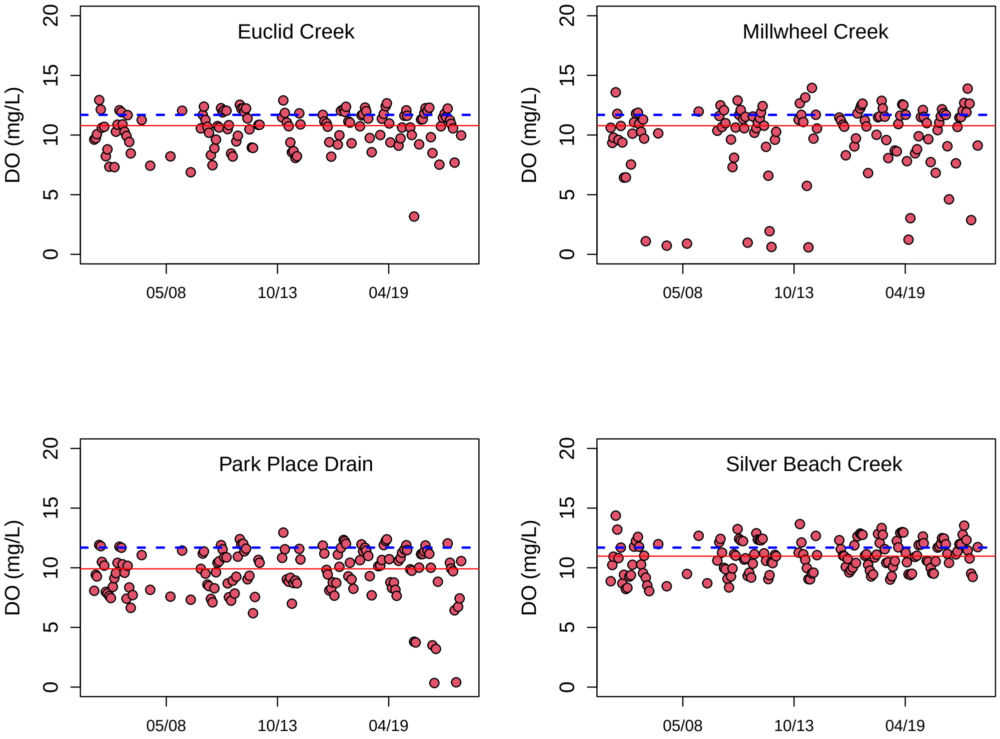

Figure B152: Dissolved oxygen data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

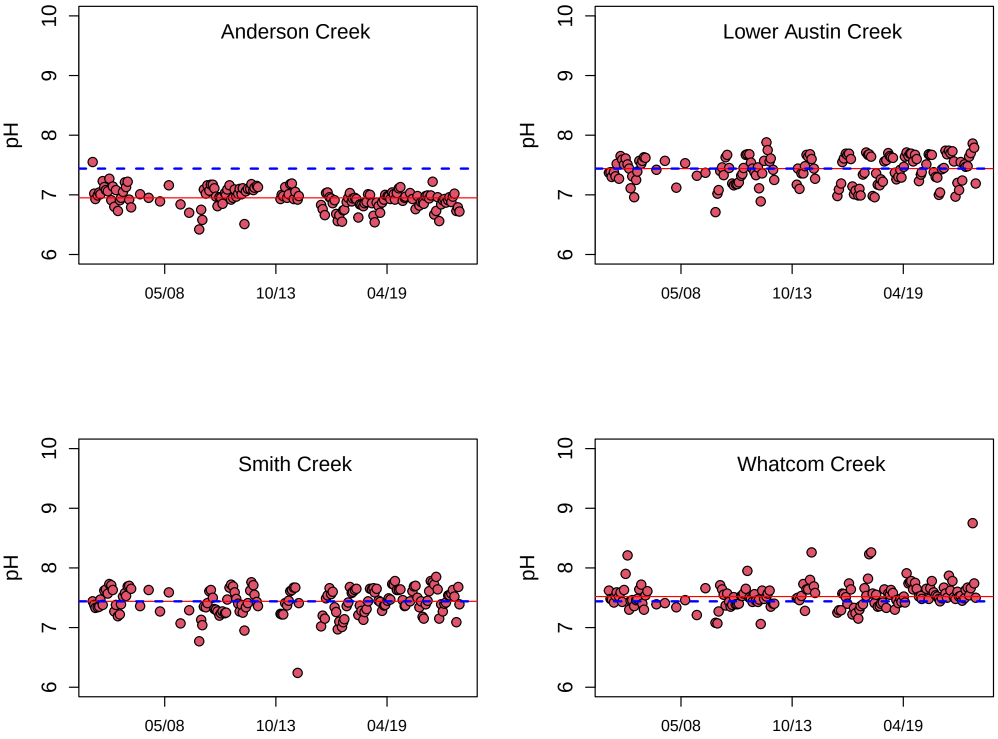

Figure B153: Tributary pH data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

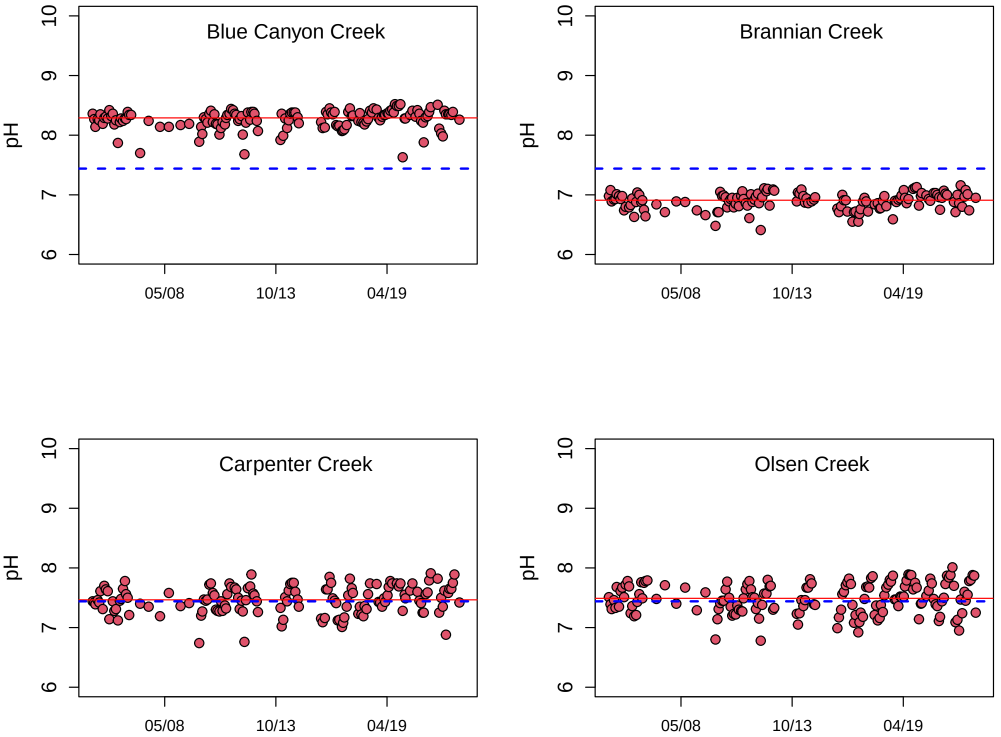

Figure B154: Tributary pH data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

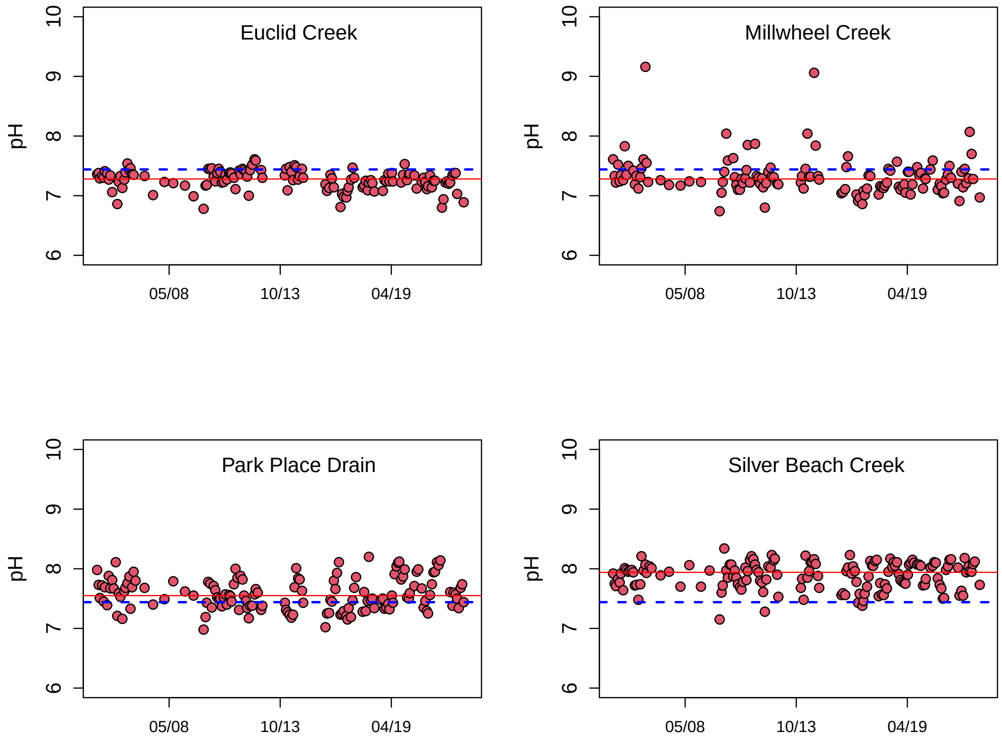

Figure B155: Tributary pH data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

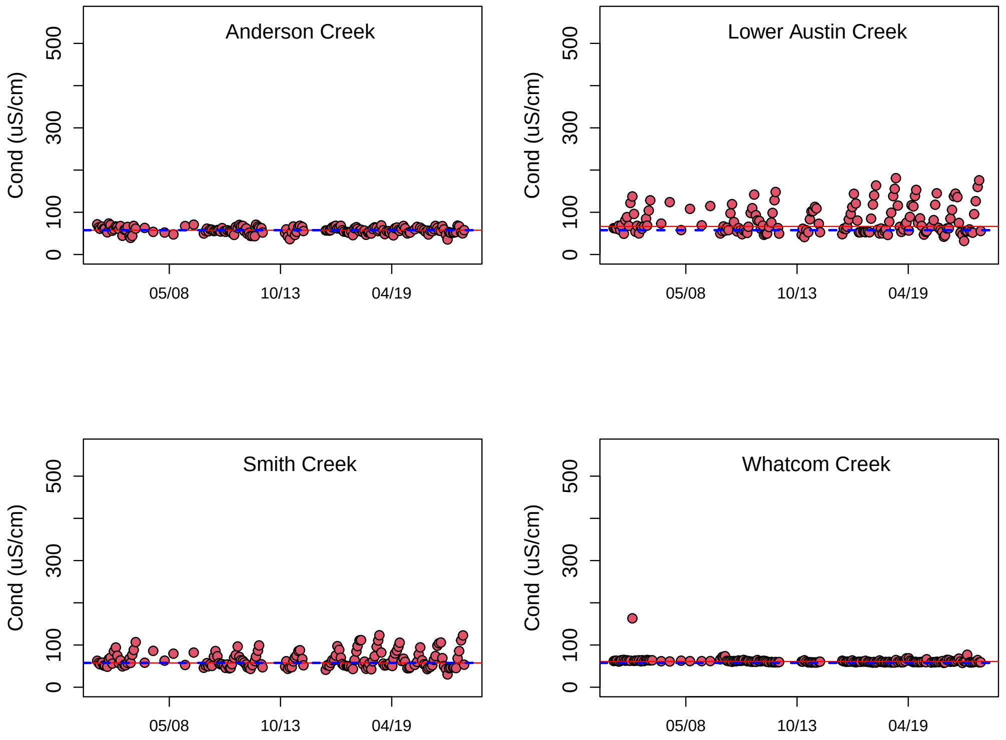

Figure B156: Conductivity data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

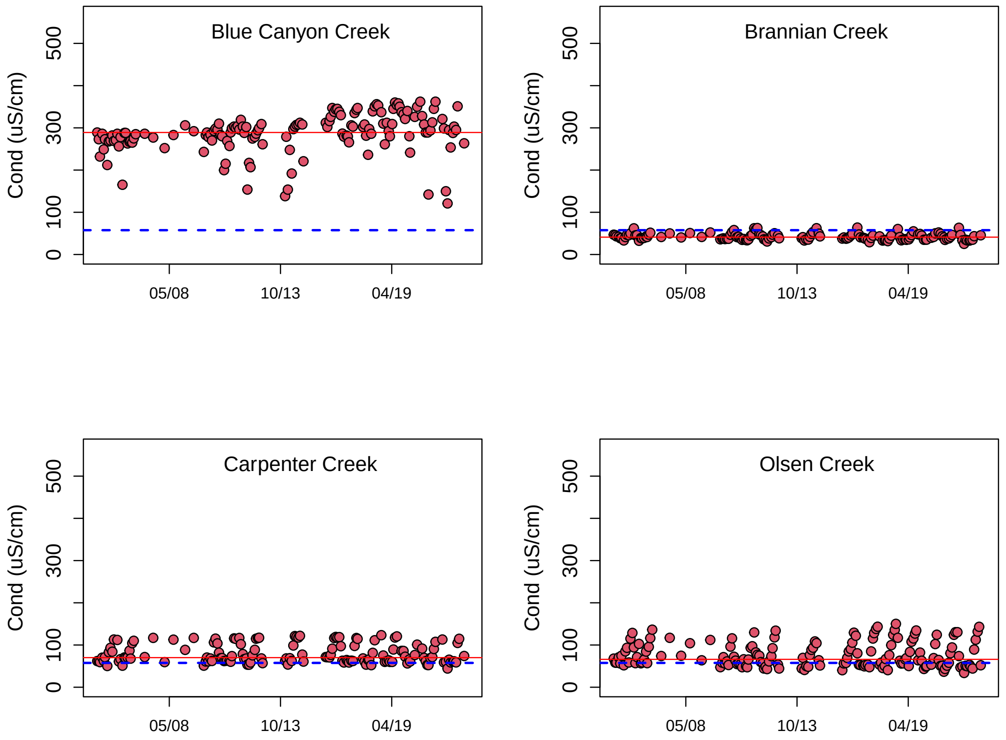

Figure B157: Conductivity data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

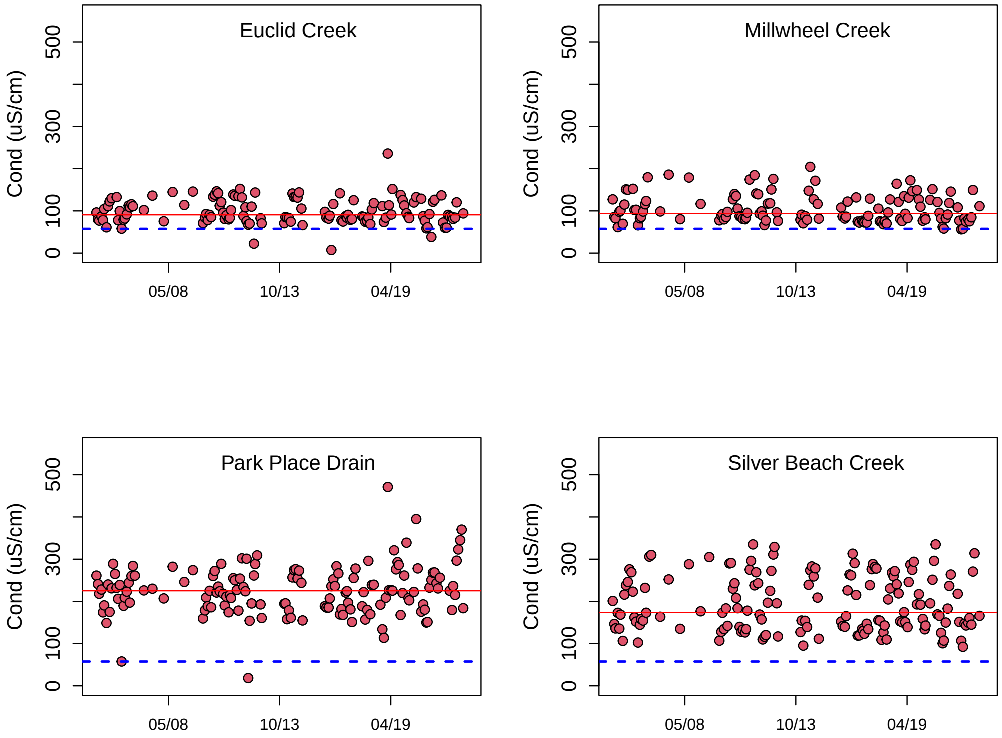

Figure B158: Conductivity data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

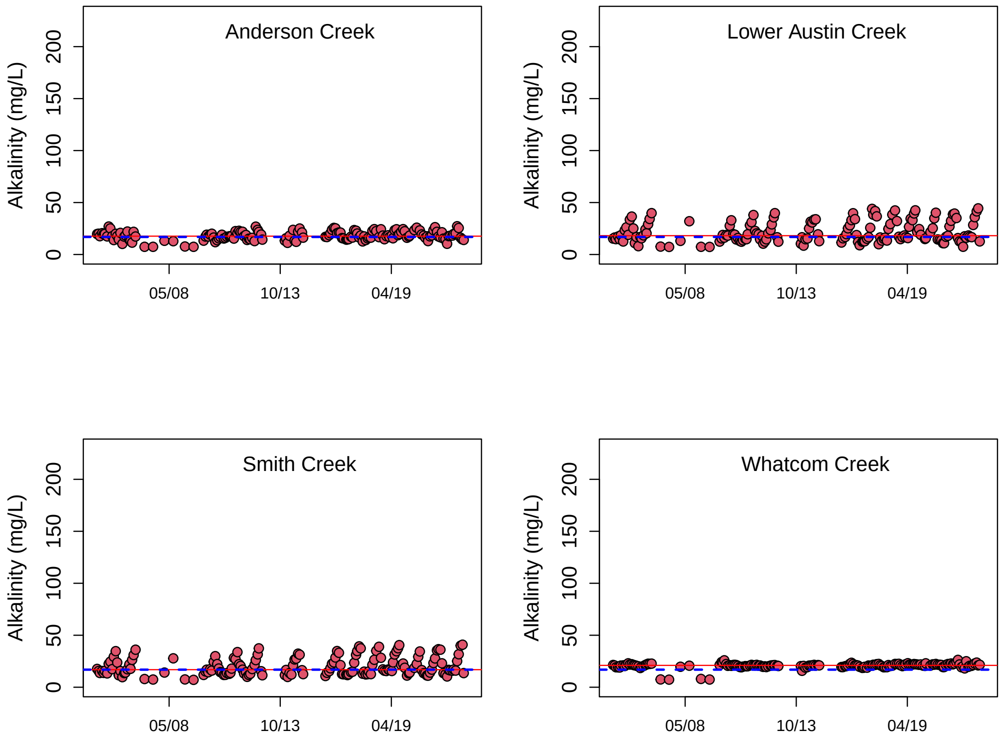

Figure B159: Alkalinity data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

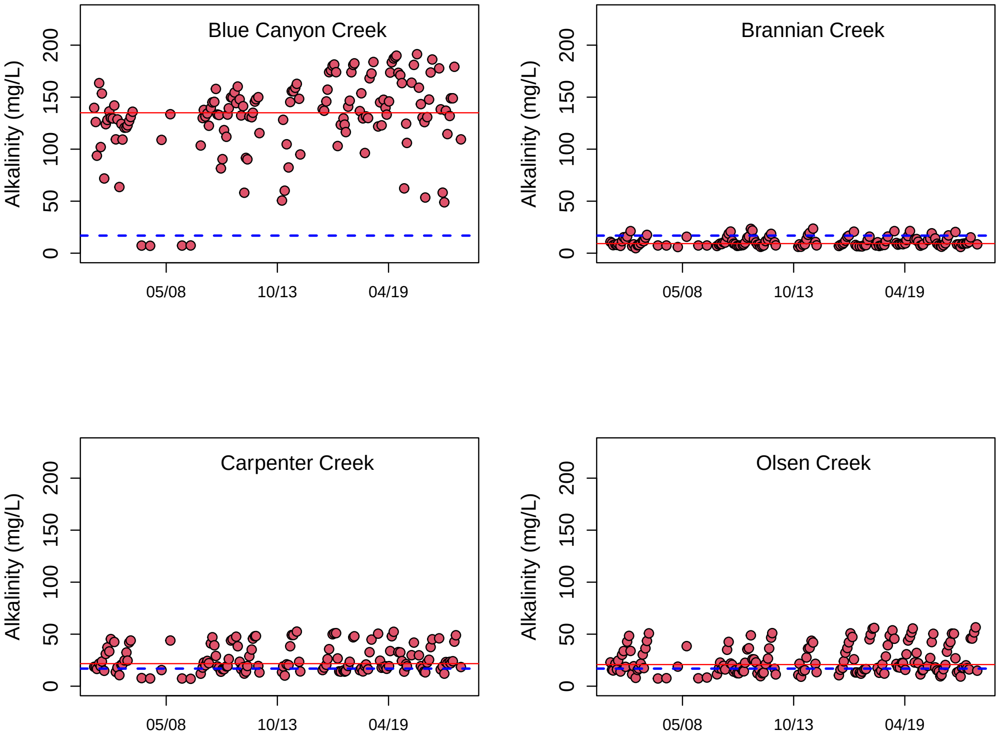

Figure B160: Alkalinity data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

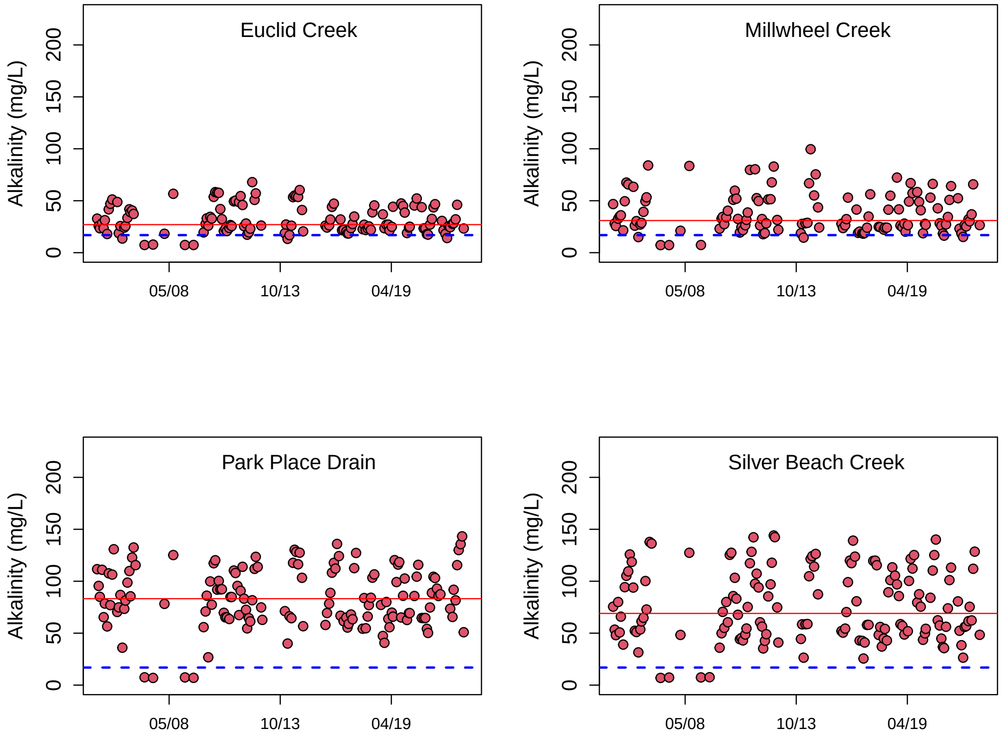

Figure B161: Alkalinity data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

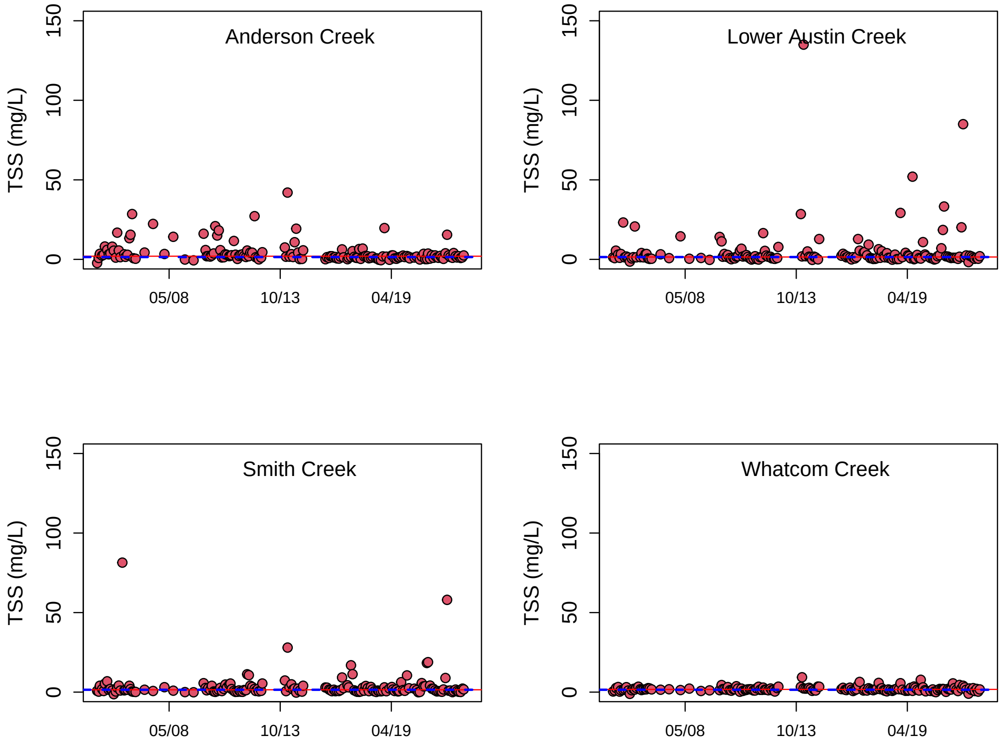

Figure B162: Total suspended solids data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

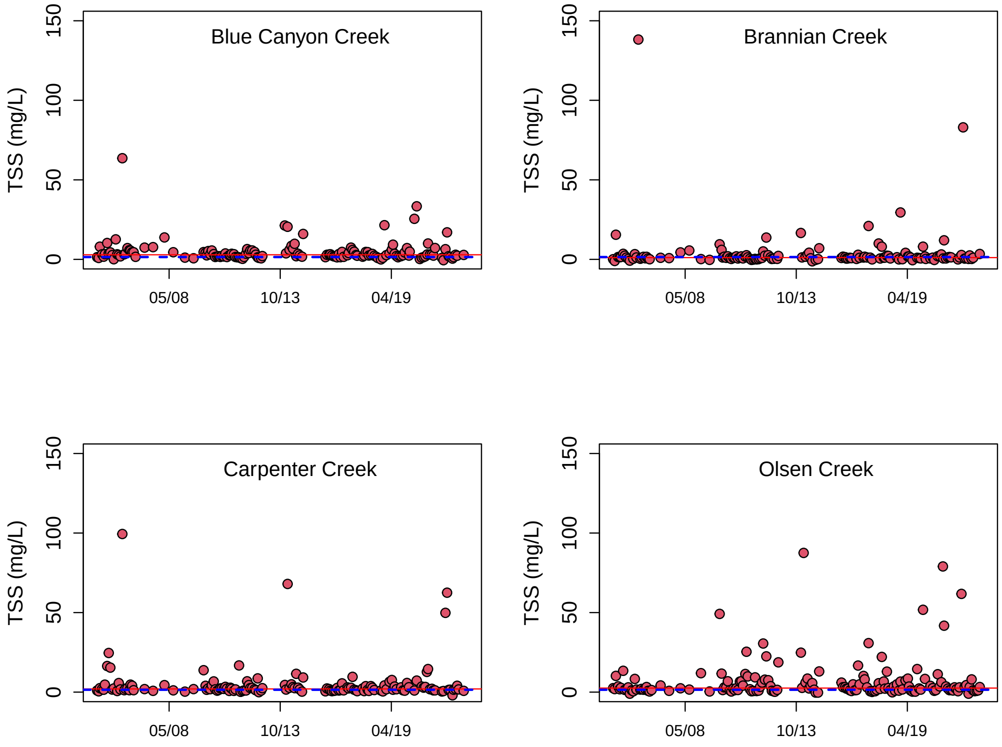

Figure B163: Total suspended solids data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

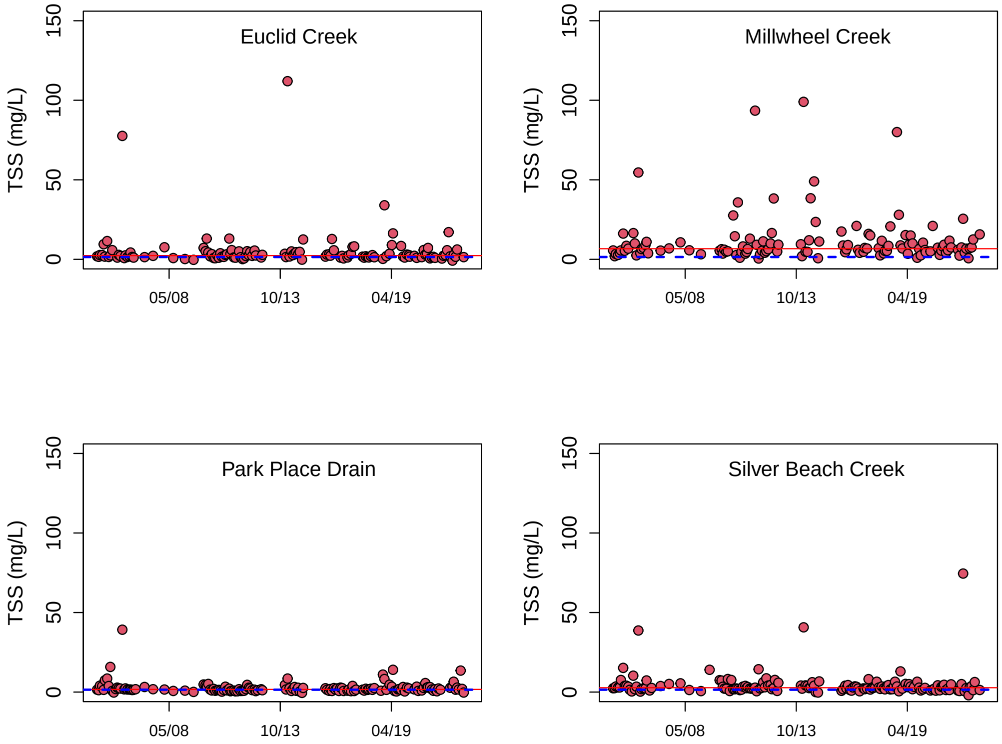
Euclid Creek
Millwheel Creek
Park Place Drain
Silver Beach Creek

Figure B164: Total suspended solids data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

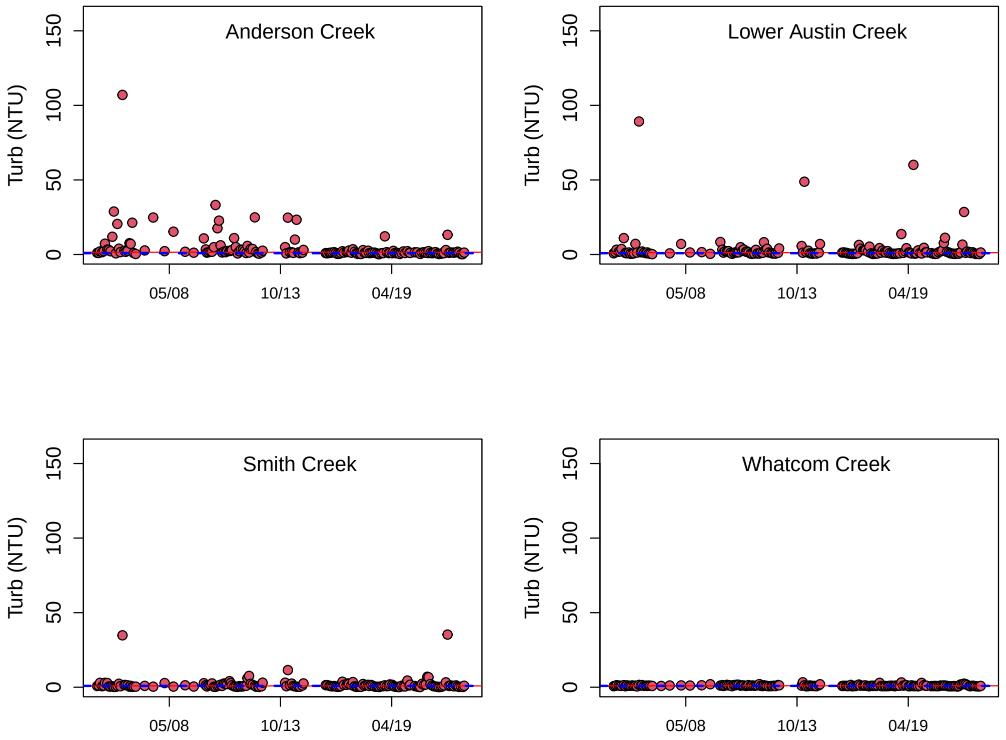

Figure B165: Turbidity data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

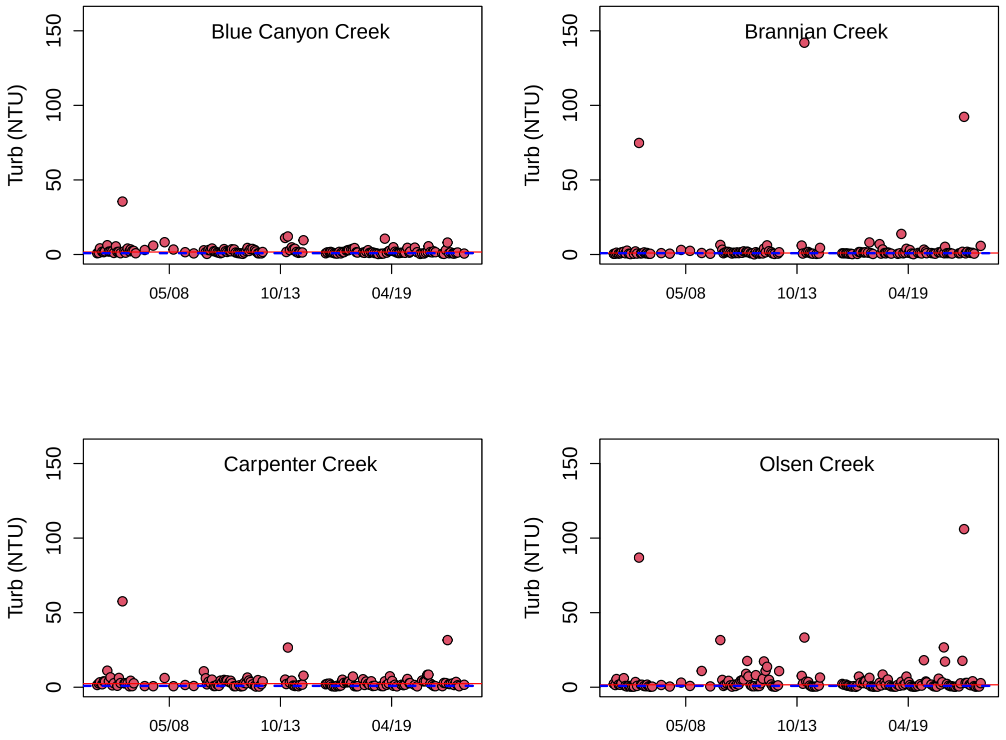

Figure B166: Turbidity data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

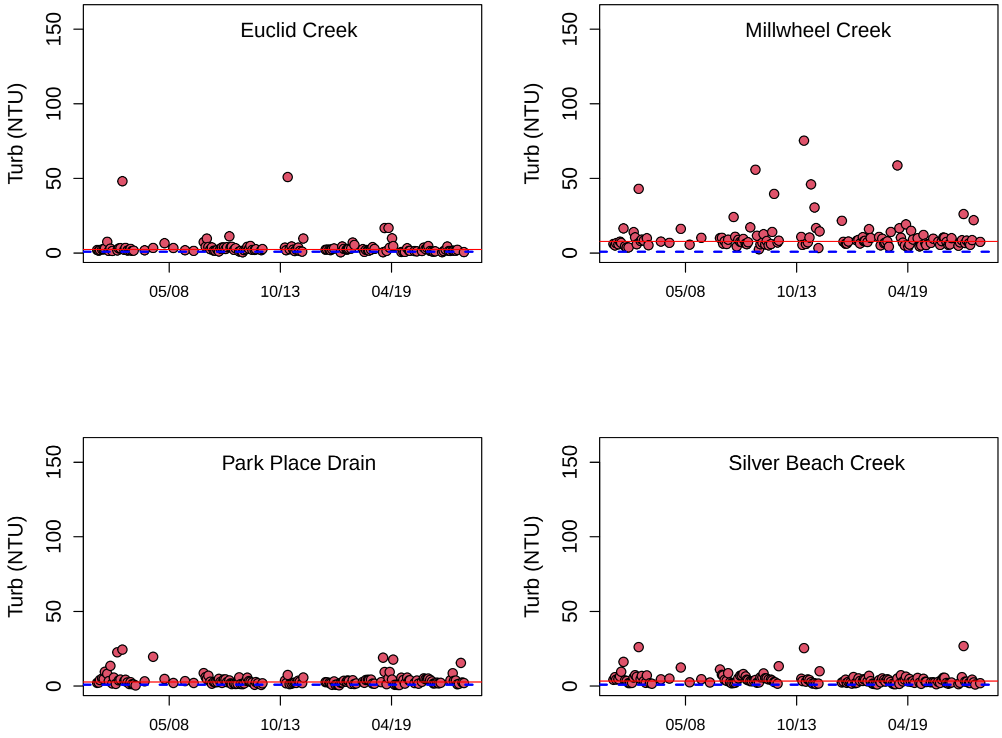

Figure B167: Turbidity data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

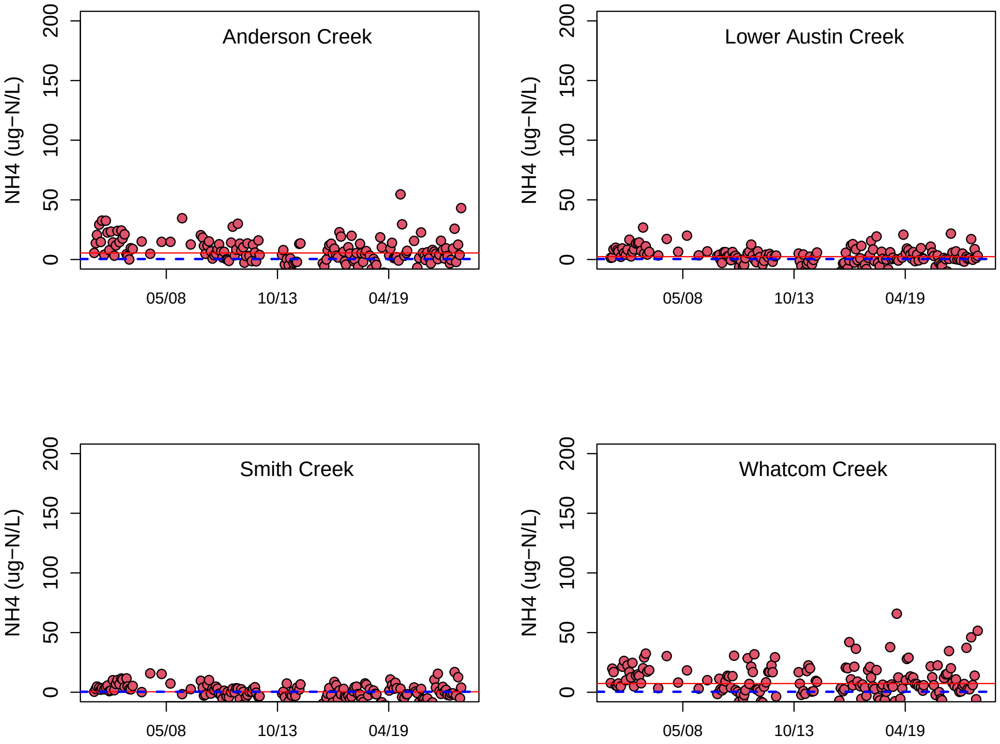

Figure B168: Ammonium data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

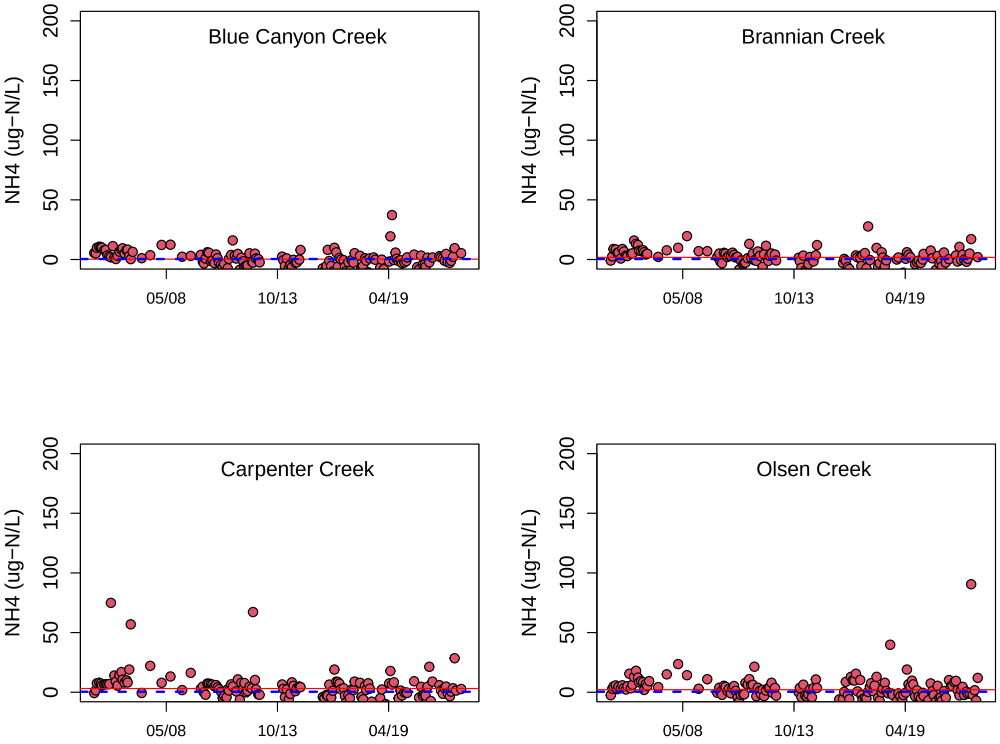

Figure B169: Ammonium data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

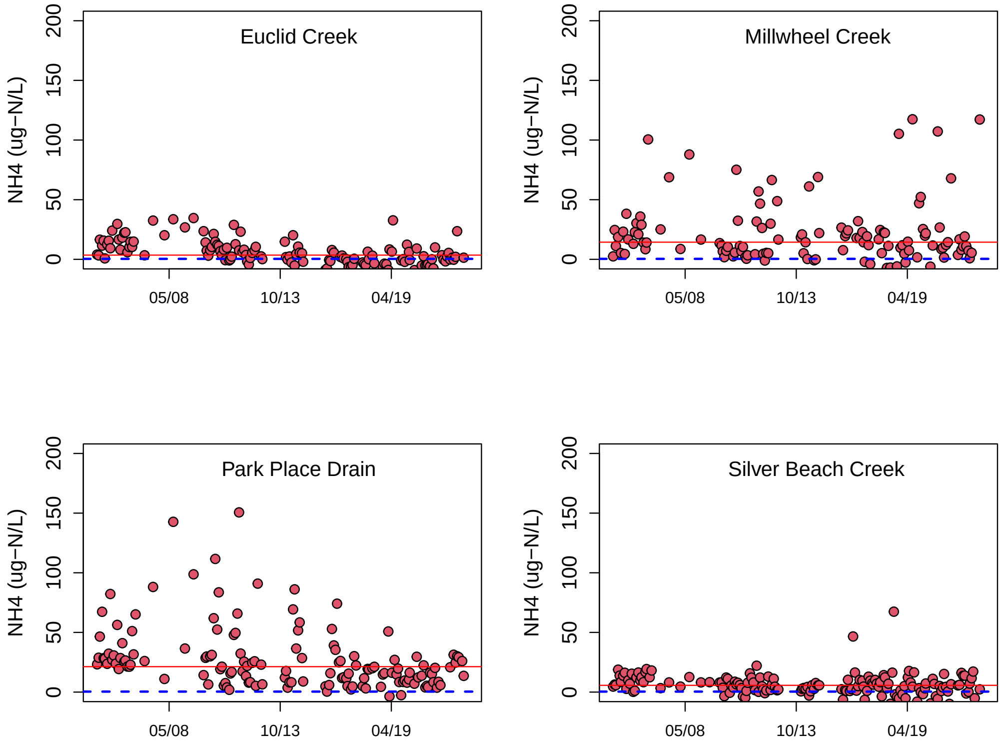

Figure B170: Ammonium data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

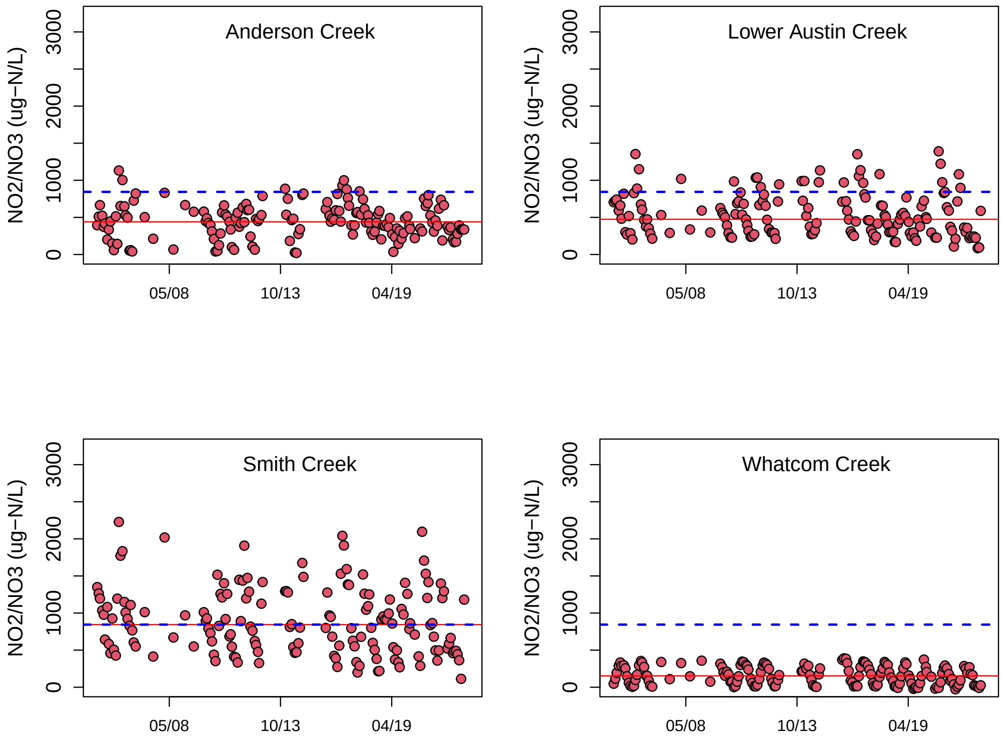

Figure B171: Nitrate/nitrite data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

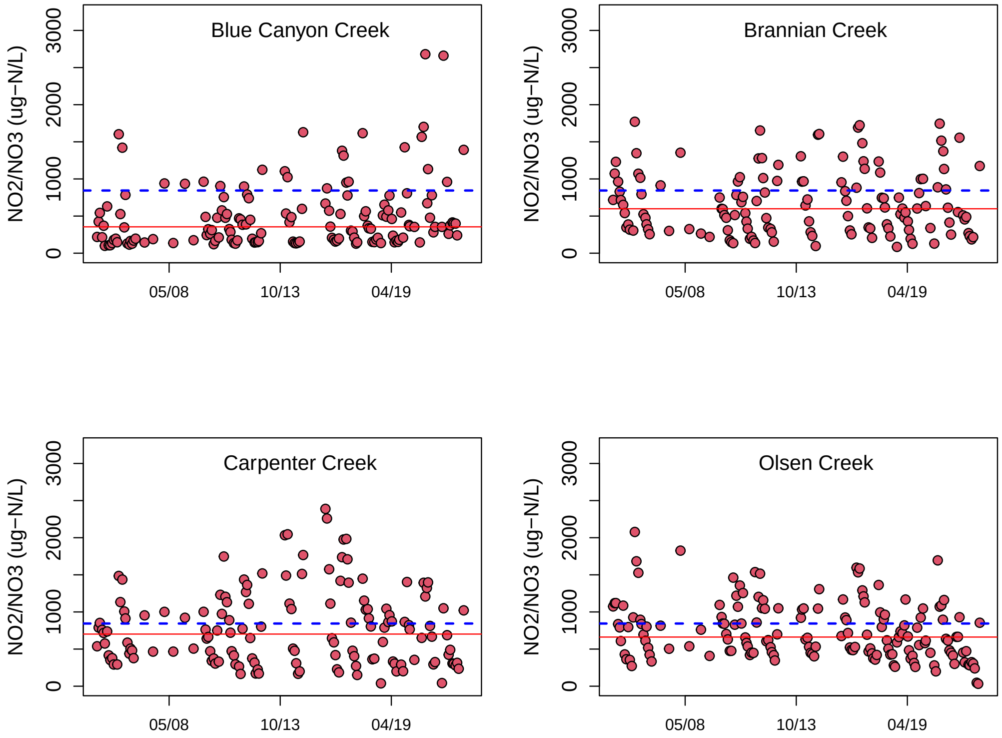

Figure B172: Nitrate/nitrite data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

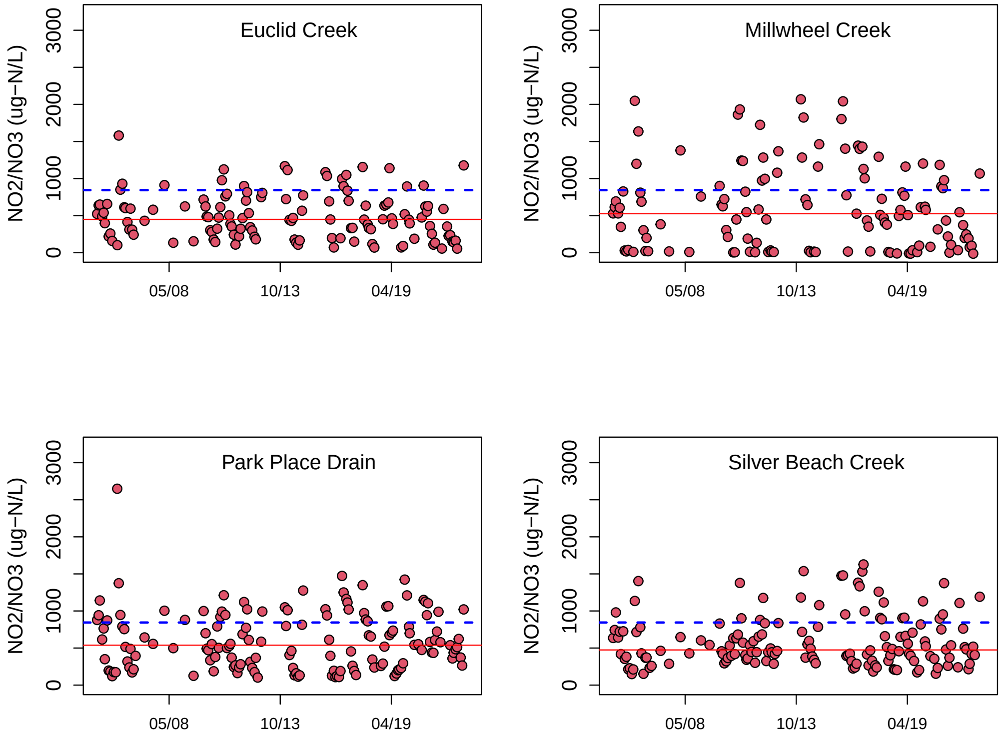

Figure B173: Nitrate/nitrite data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

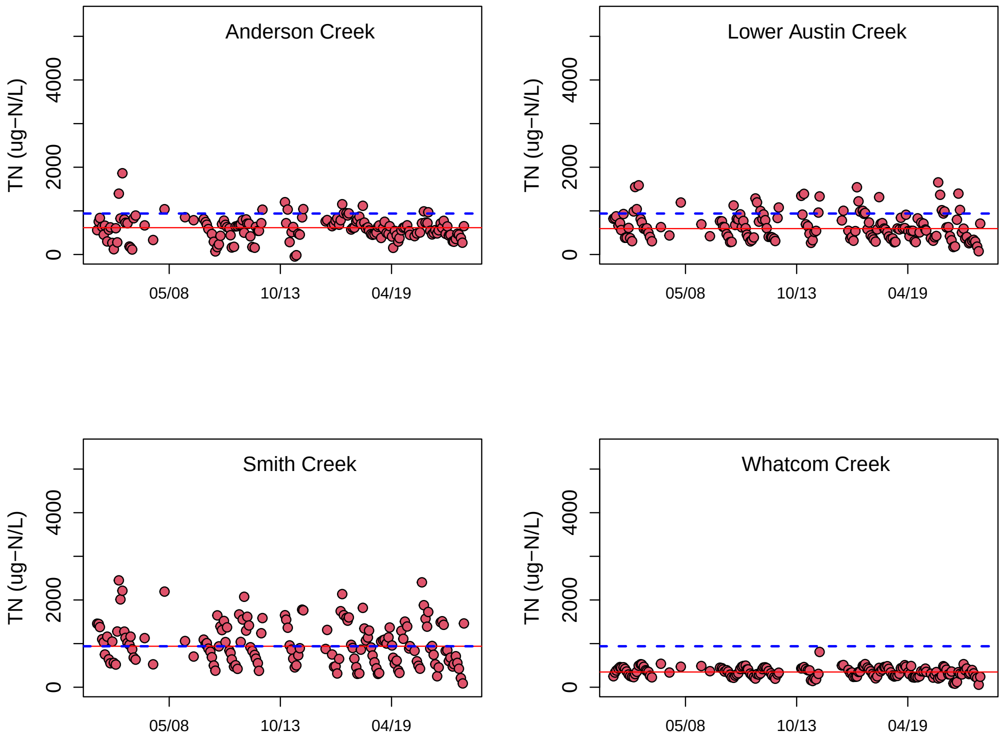

Figure B174: Total nitrogen data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

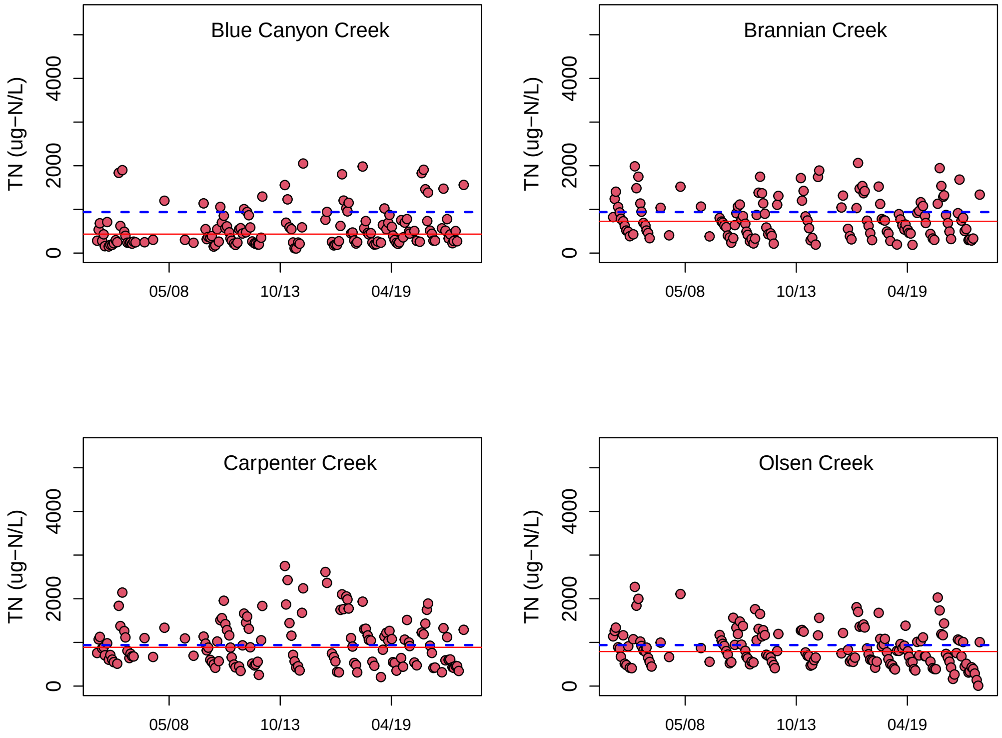

Figure B175: Total nitrogen data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

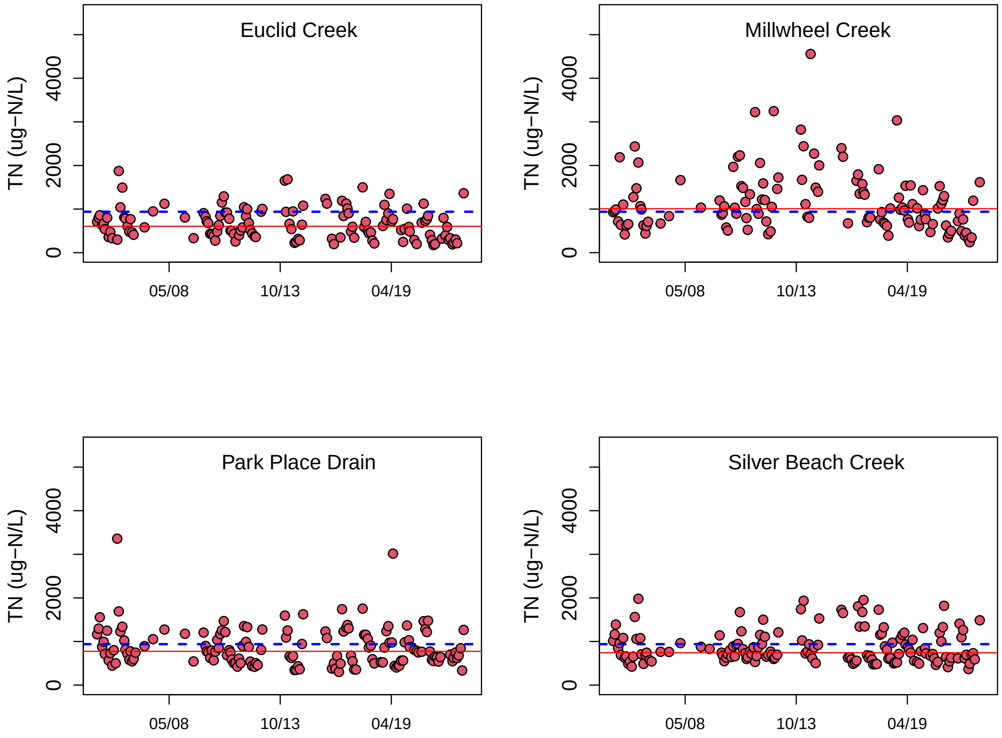

Figure B176: Total nitrogen data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

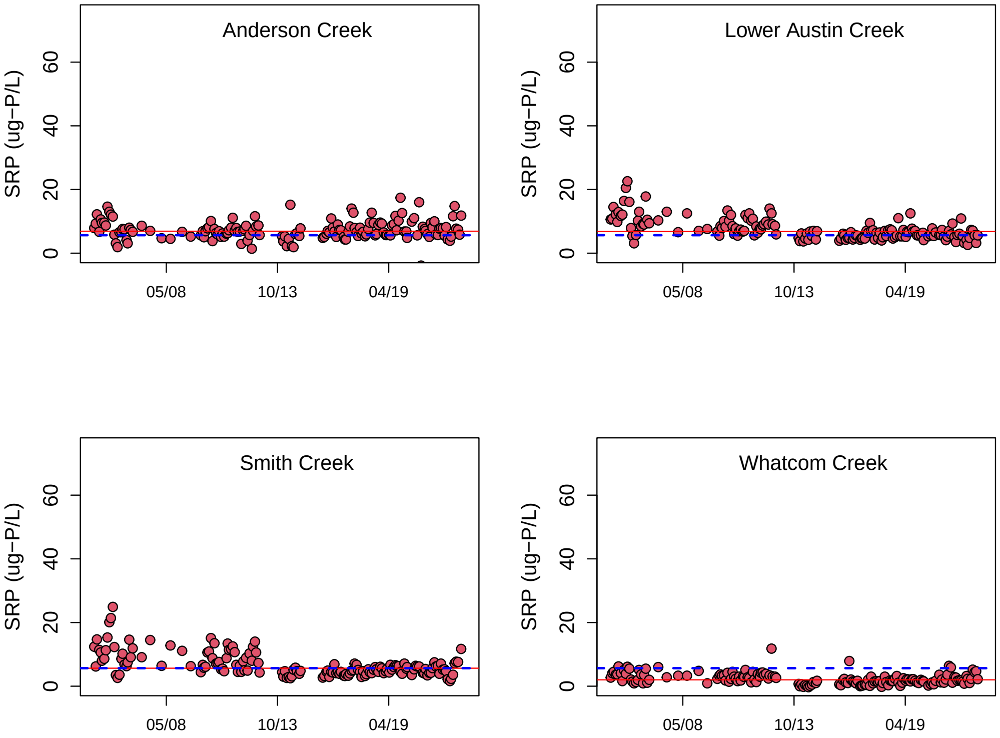

Figure B177: Soluble phosphate data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

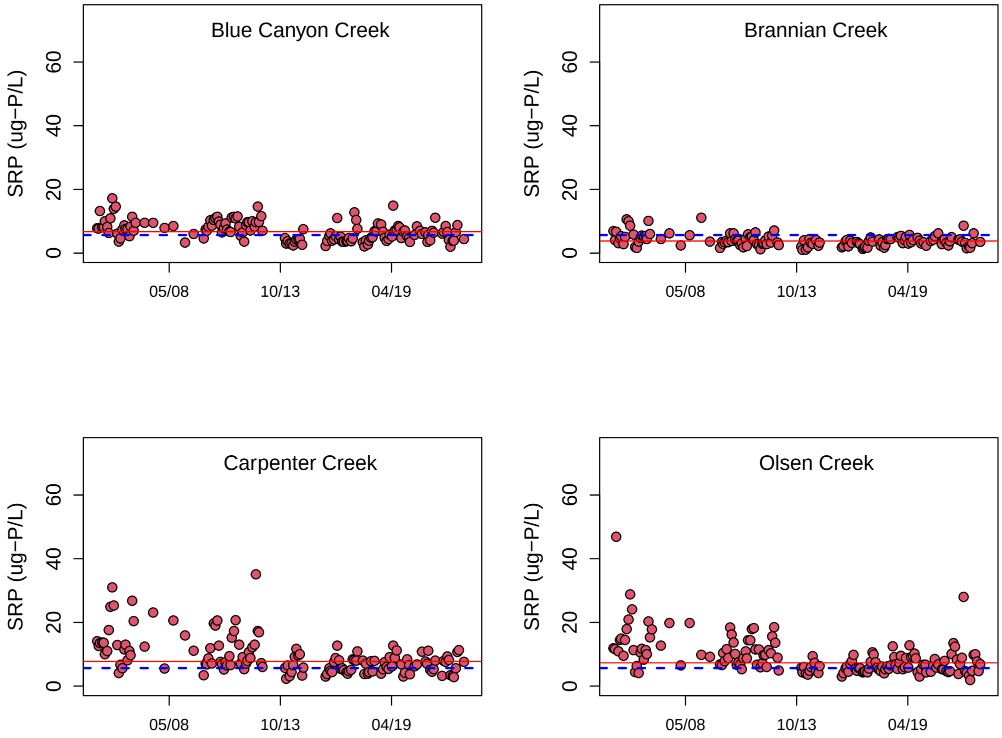

Figure B178: Soluble phosphate data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

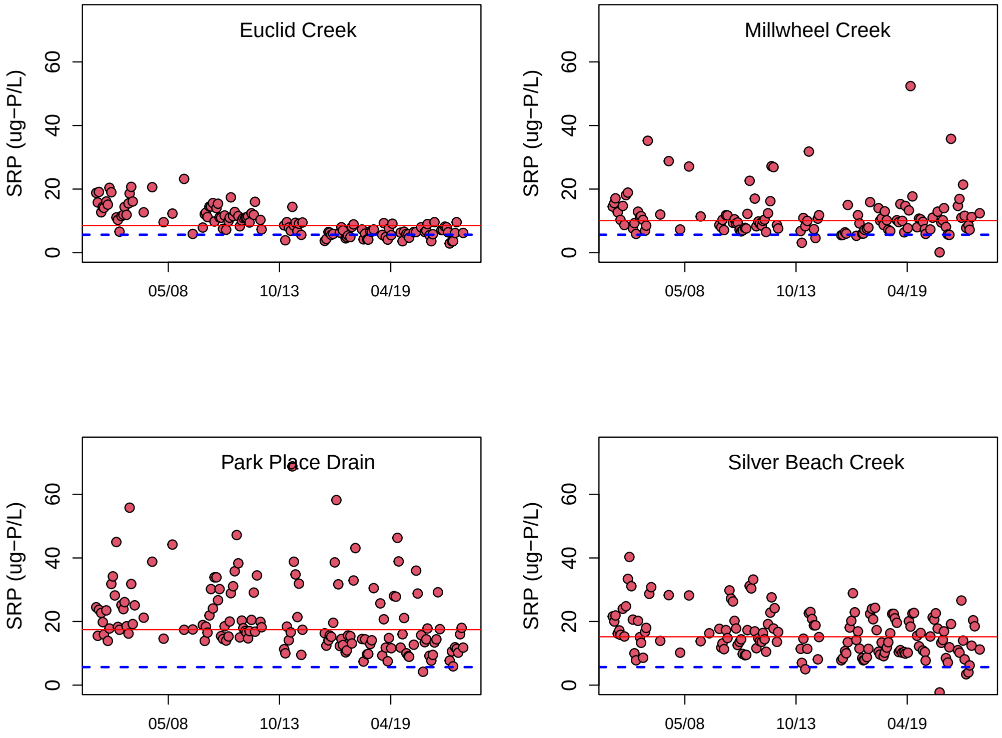

Figure B179: Soluble phosphate data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

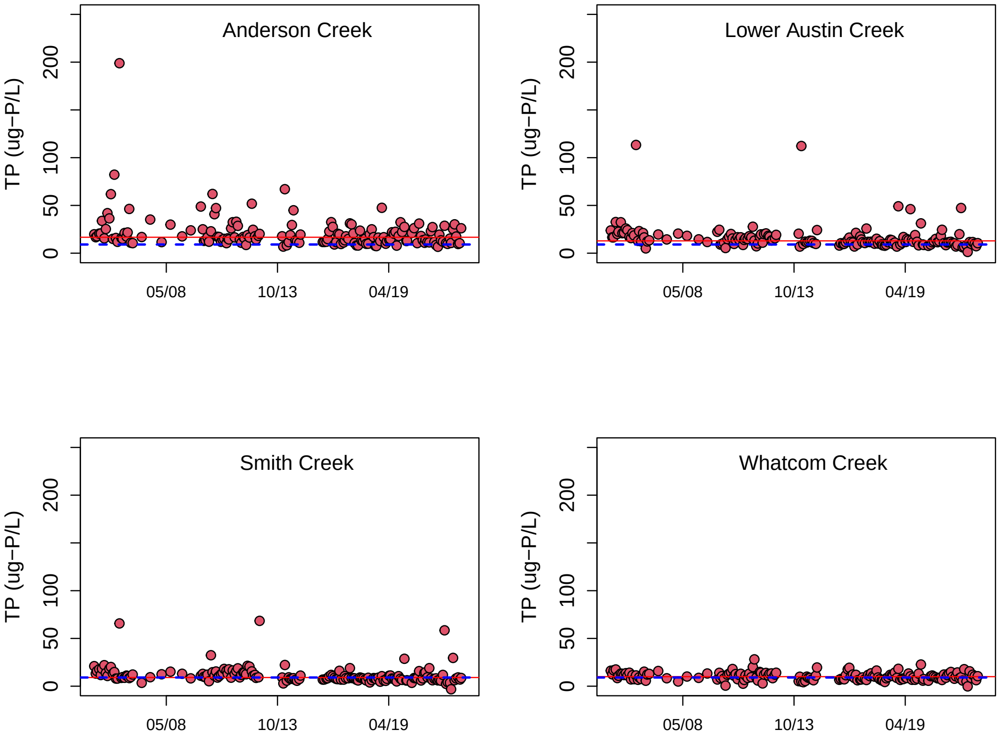

Figure B180: Total phosphorus data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

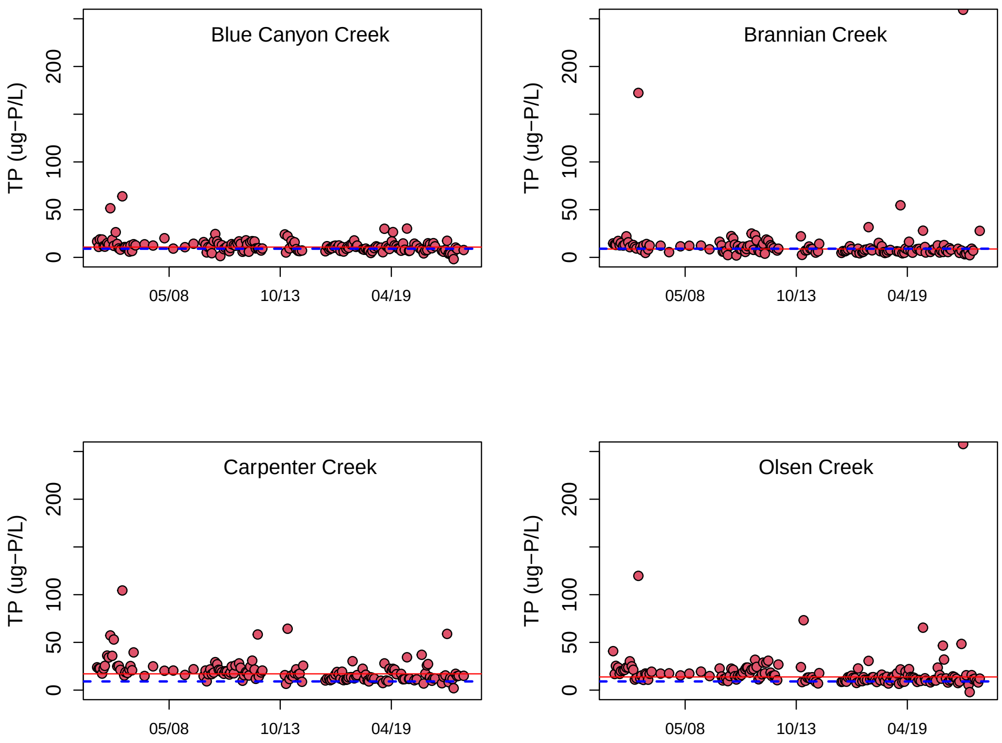

Figure B181: Total phosphorus data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

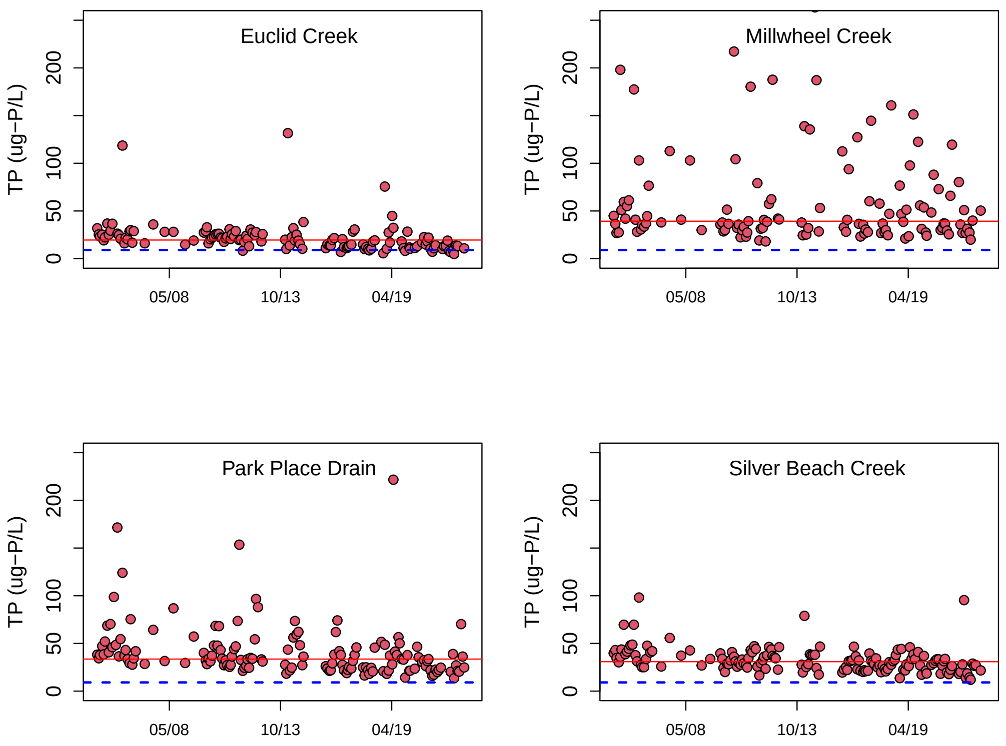

Figure B182: Total phosphorus data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

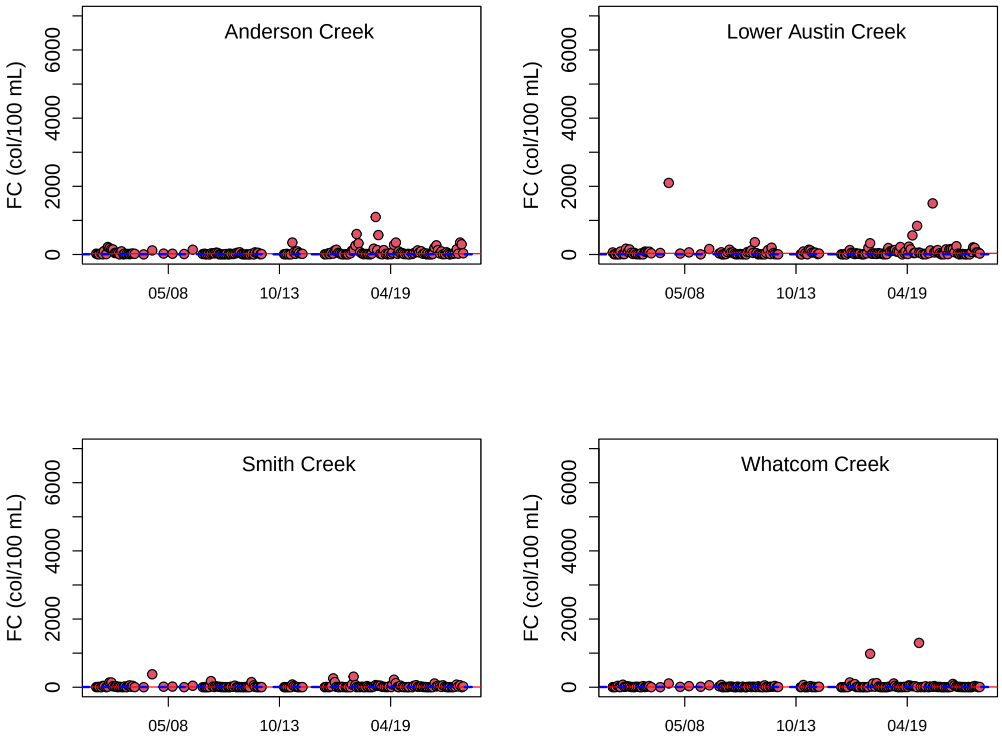

Figure B183: Fecal coliform data for Anderson, Austin, Smith, and Whatcom Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

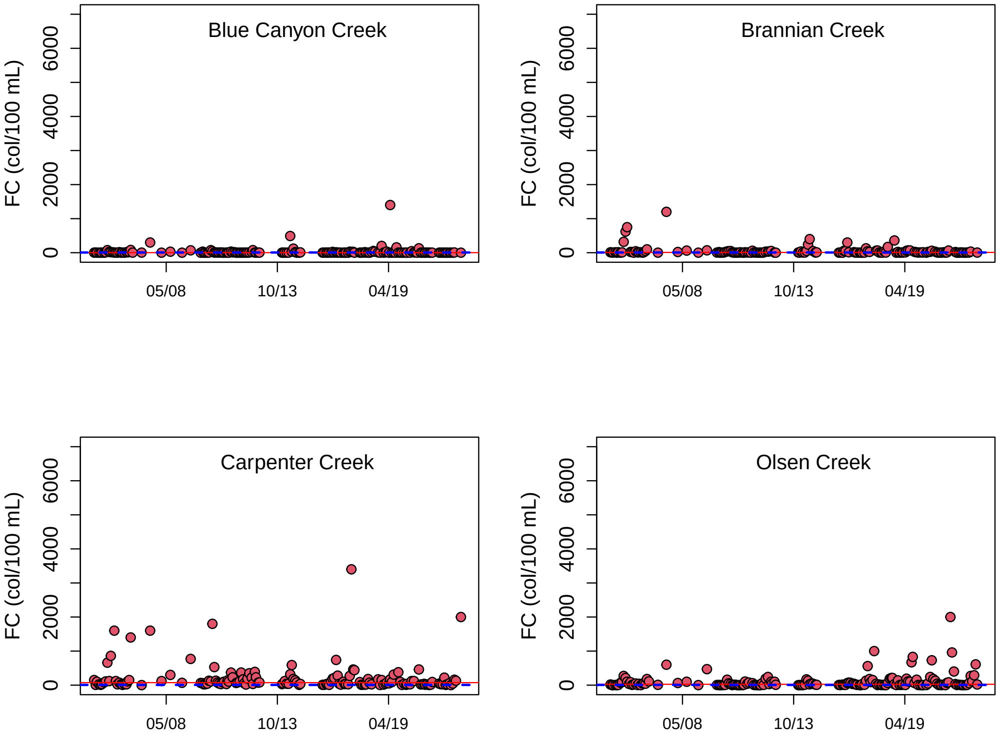

Figure B184: Fecal coliform data for Blue Canyon, Brannian, Carpenter, and Olsen Creeks. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

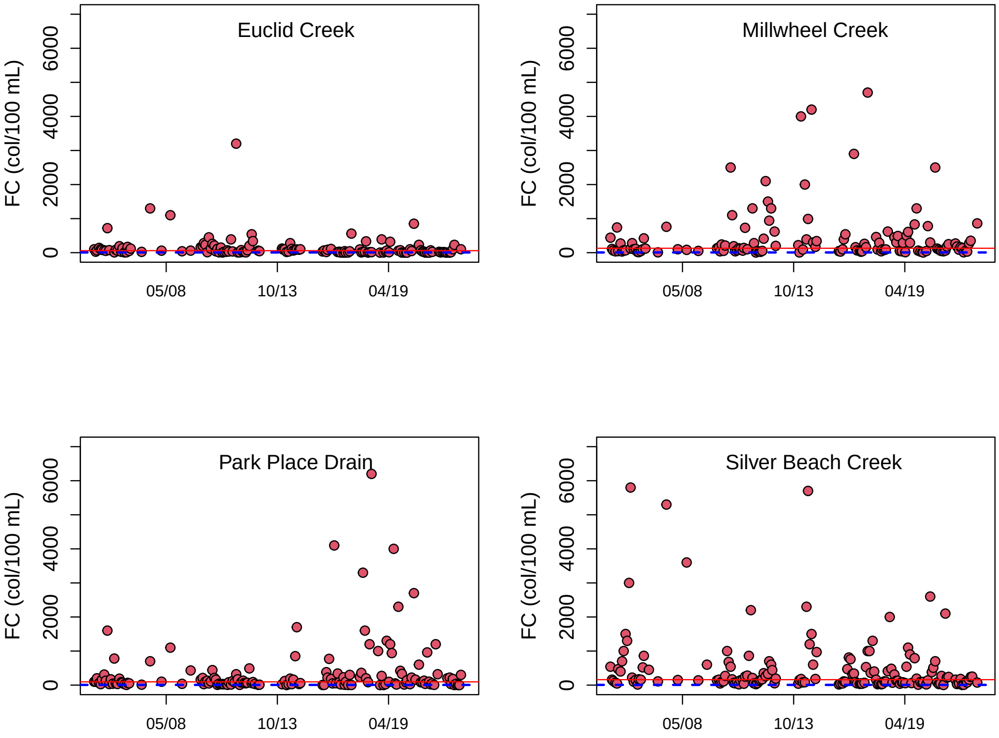

Figure B185: Fecal coliform data for Euclid, Millwheel, and Silver Beach Creeks and the Park Place drain. Dashed (blue) horizontal reference line shows the median value for Smith Creek; solid (red) horizontal reference line shows the median value for each creek.

C Quality Control

C.1 Performance Evaluation Reports

In order to maintain a high degree of accuracy and confidence in the water quality data all personnel associated with this project were trained according to standard operating procedures for the methods listed in Table 2.1 (page 18). Single-blind quality control tests were conducted as part of the IWS laboratory certification process (Table C1).

C.2 Laboratory Duplicates, Spikes, and Check Standards

Ten percent of all samples analyzed in the laboratory were duplicated to measure analytical precision. Sample matrix spikes were analyzed during each analytical run to evaluate analyte recovery for the nutrient analyses (ammonium, nitrate/nitrite, total nitrogen, soluble reactive phosphate, and total phosphorus). Check standards were analyzed during each analytical run to evaluate measurement precision and accuracy.[35] The quality control results for laboratory duplicates, matrix spikes, and check standards are plotted in control charts (Figures C1–C30, pages 296–325). Data that exceed the plotting range of the control charts are in Table C2, page 295.

C.3 Field Duplicates

Ten percent of all samples collected in the field were duplicated to measure sample replication (Figures C31–C48, pages 326–343). Samples collected using field meters (conductivity, dissolved oxygen, and pH) were evaluated using water samples collected from the same depth as the field meter measurement. The absolute mean difference for the field duplicates was calculated as follows:

$$\text{Absolute mean difference} = \frac{\sum |\text{Original Sample} - \text{Duplicate Sample}|}{\text{number of duplicate pairs}}$$

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[35] External check standards are not available for all analytes.

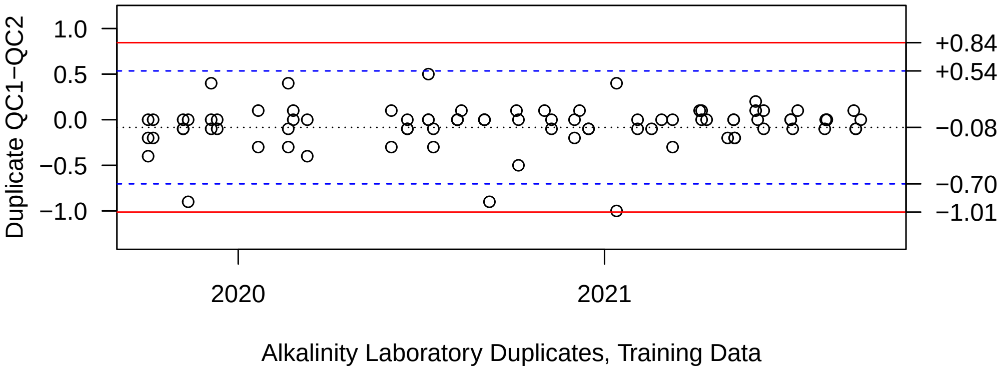
	Reported Value	Assigned Value	Acceptance Limits	Test Result
Specific conductivity (μS/cm at 25°C)	381	379	341–417	accept
Total alkalinity (mg/L as $CaCO_3$)	87.9	88.9	75.6–102	accept
Ammonium nitrogen, auto (mg-N/L) †	17.6	19.1	15.4–22.6	accept
Nitrate/nitrite nitrogen, auto (mg-N/L)	21.2	21.3	17.8–24.6	accept
Nitrite nitrogen, auto (mg-N/L)	2.12	2.04	1.73–2.35	accept
Organic carbon, dissolved (mg/L)	2.90	2.96	2.60–3.36	accept
	5.09	5.26	4.66–5.79	accept
Organic carbon, total (mg/L)	21.3	21.4	17.3–25.5	accept
Orthophosphate, manual (mg-P/L)	3.98	4.02	3.42–4.62	accept
Orthophosphate, auto (mg-P/L)	4.13	4.02	3.42–4.62	accept
Total phosphorus, manual (mg-P/L)	0.730	0.731	0.547–0.922	accept
Total phosphorus, auto (mg-P/L)	0.697	0.731	0.547–0.922	accept
pH	7.25	7.23	7.03–7.43	accept
Solids, non-filterable (mg/L)	89.5	87.7	72.1–97.3	accept
Turbidity (NTU)	12.9	13.7	11.3–16.1	accept

†The manual method is no longer used and has been removed from quality control testing

Table C1: Single-blind quality control results, WP–282 (5/27/2022); all results were within acceptance limits. IWS is applying for certification for total and dissolved organic carbon analyses; results for total organic carbon are from 2022, whereas the 2018 performance evaluation results for dissolved organic carbon (WP–114, 05/31/2018; WP–116, 11/29/2018) are reported here.

Year	Month	Analyte	Type	Testing or Training	Value
2019	October	orthophosphate	spike	training	55
	October	turbidity	lab duplicate	training	0.77
	November	orthophosphate	spike	training	136
	December	orthophosphate	lab duplicate	training	5.05
2020	January	nitrate/nitrite	lab duplicate	training	-135.36
	January	nitrate/nitrite	lab duplicate	training	124.92
	February	total phosphorus	lab duplicate	training	46.22
	July	dissolved oxygen	lab duplicate	training	0.38
	September	ammonium	lab duplicate	training	90.43
	November	orthophosphate	lab duplicate	training	6.37
	December	nitrate/nitrite	check	training	34
2021	January	alkalinity	lab duplicate	training	-1
	January	total nitrogen	lab duplicate	training	-129.43
	January	total phosphorus	spike	training	146
	February	alkalinity	lab duplicate	training	-2
	February	total suspended solids	lab duplicate	training	-8.25
	April	alkalinity	check	training	0.09
	April	conductivity	lab duplicate	training	-2.8
	May	dissolved oxygen	lab duplicate	training	0.34
	July	nitrate/nitrite	spike	training	67
	July	nitrate/nitrite	spike	training	63
	September	total nitrogen	lab duplicate	training	-152.35
	November	alkalinity	lab duplicate	testing	-2.1
	November	orthophosphate	lab duplicate	testing	5.91
	December	pH	lab duplicate	testing	-0.8
2022	January	turbidity	lab duplicate	testing	1.2
	February	total phosphorus	check	testing	-4.34
	February	total phosphorus	check	testing	-5.3
	February	turbidity	lab duplicate	testing	-0.46
	March	turbidity	lab duplicate	testing	0.51
	March	alkalinity	lab duplicate	testing	1.3
	March	pH	lab duplicate	testing	-0.55
	March	total nitrogen	lab duplicate	testing	235.95
	April	total nitrogen	check	testing	77.92
	May	total phosphorus	check	testing	5.6
	May	alkalinity	lab duplicate	testing	7.5
	May	conductivity	lab duplicate	testing	-15.3
	June	pH	lab duplicate	testing	0.3
	July	nitrate/nitrite	lab duplicate	testing	-158.19

Table C2: Data in this table denote quality control values that exceeded ±4 std. dev. from the training mean. Unplotted points were included in QC calculations, but were not plotted to preserve plotting scale (Figures C1–C30).



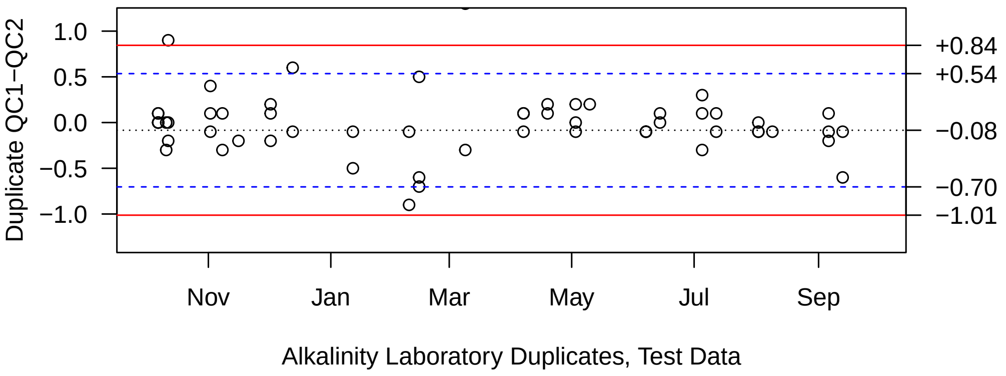
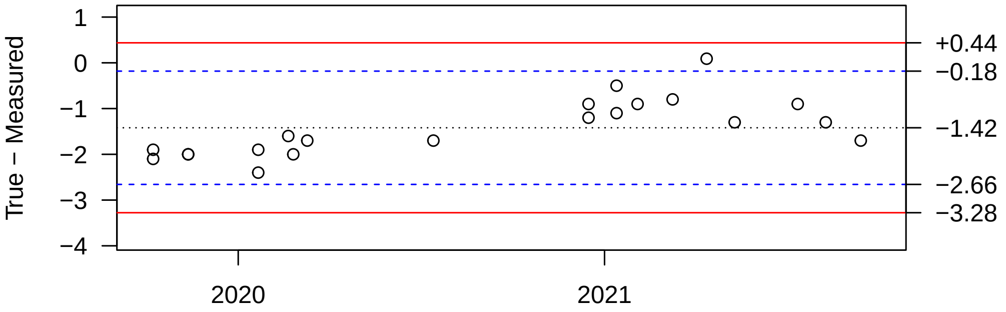
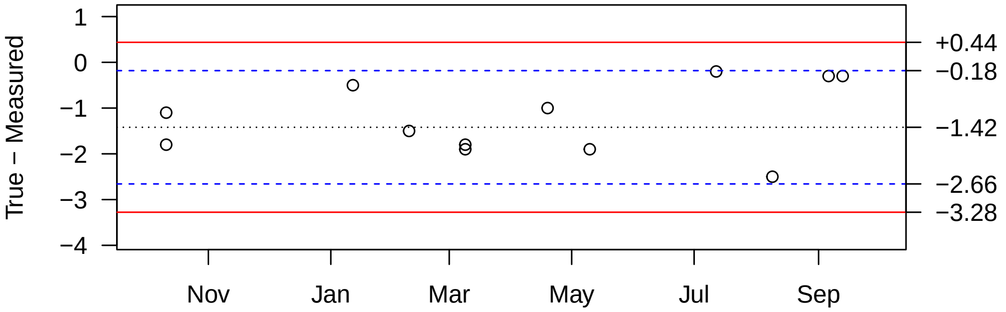


Figure C1: Alkalinity laboratory duplicates (mg/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

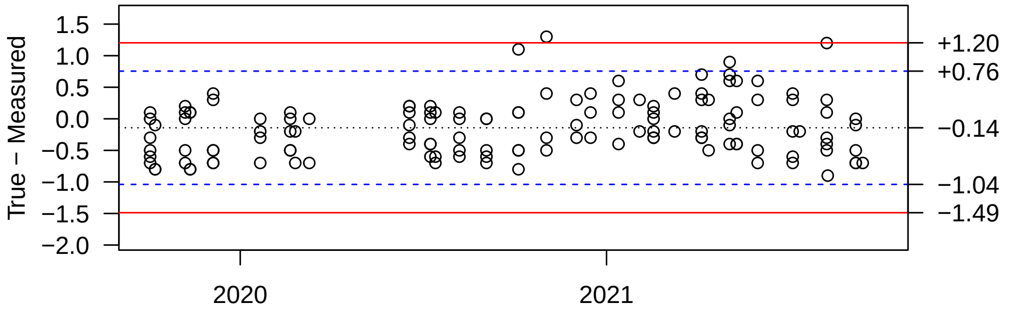


Alkalinity Check Standards, Training Data

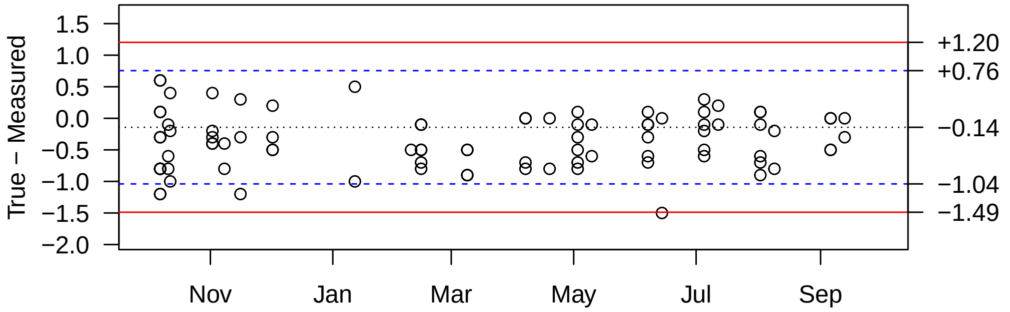


Alkalinity Check Standards, Test Data

Figure C2: Alkalinity high-range check standards (mg/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

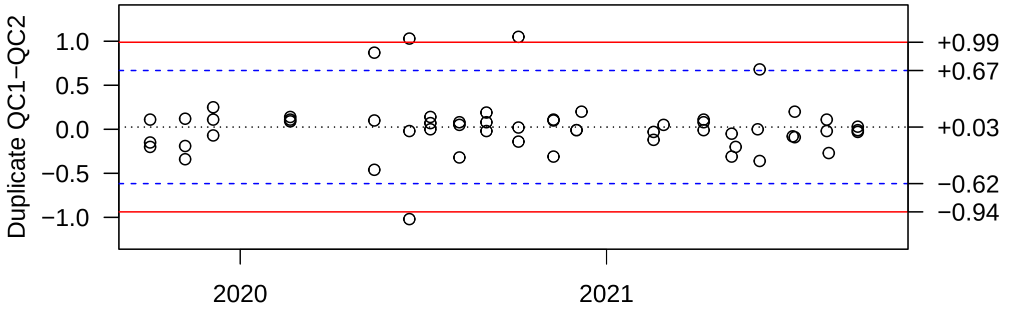


Alkalinity Check Standards, Training Data

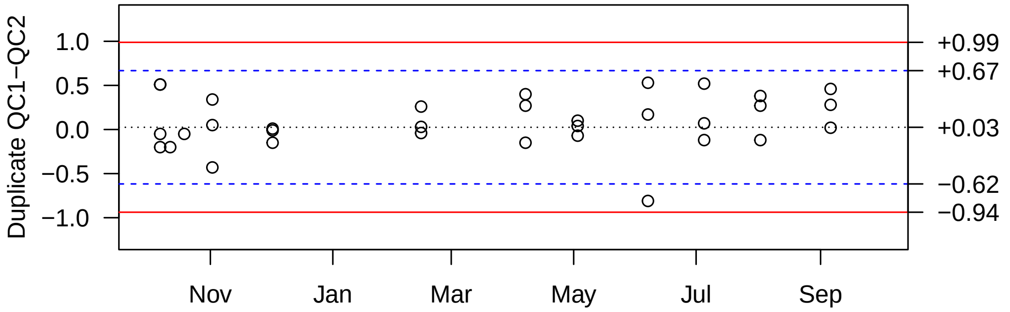


Alkalinity Check Standards, Test Data

Figure C3: Alkalinity low-range check standards (mg/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

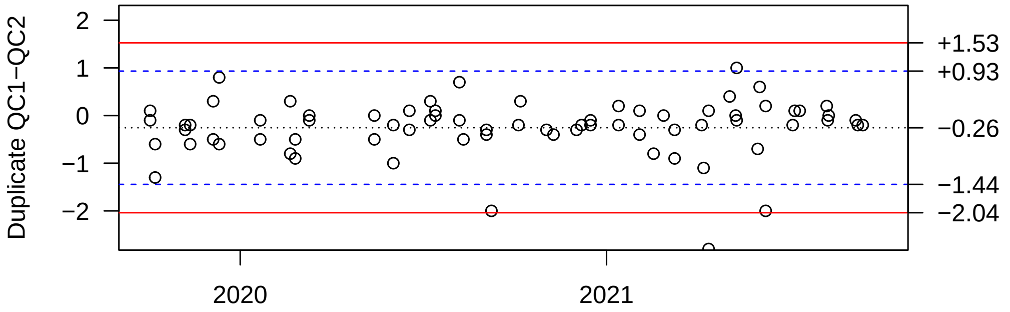


Chlorophyll Laboratory Duplicates, Training Data

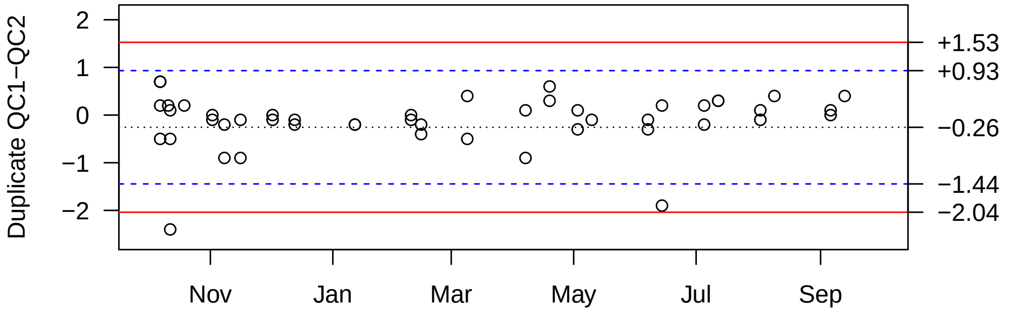


Chlorophyll Laboratory Duplicates, Test Data

Figure C4: Chlorophyll laboratory duplicates (μg/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

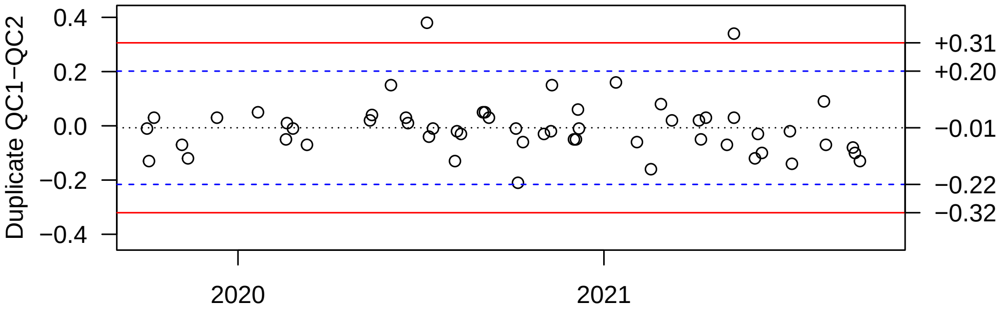


Conductivity Laboratory Duplicates, Training Data

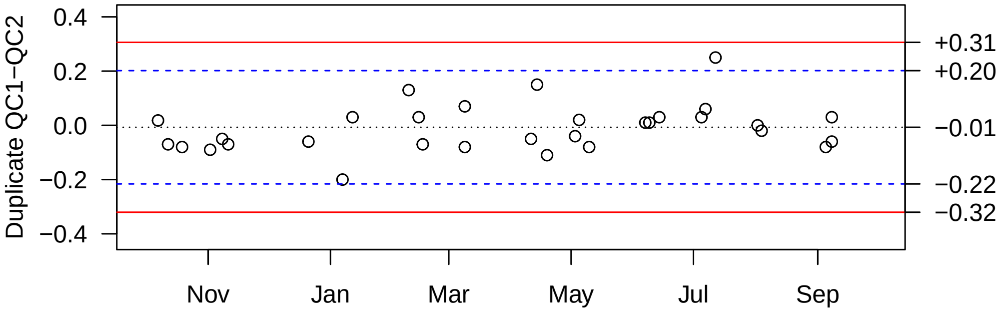


Conductivity Laboratory Duplicates, Test Data

Figure C5: Conductivity laboratory duplicates (μS/cm) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

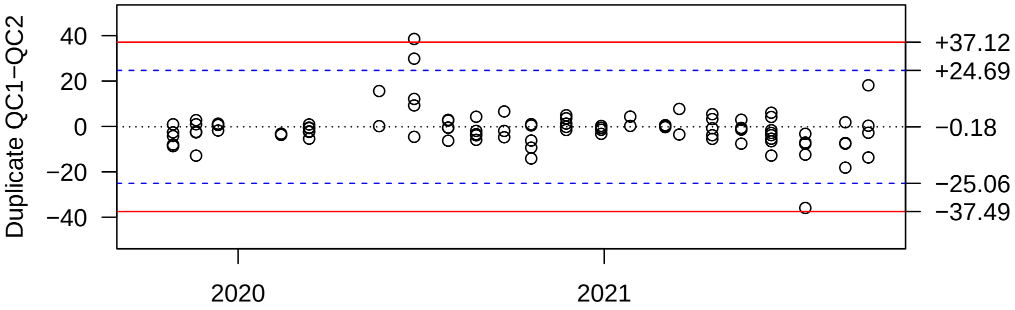


Dissolved Oxygen Laboratory Duplicates, Training Data

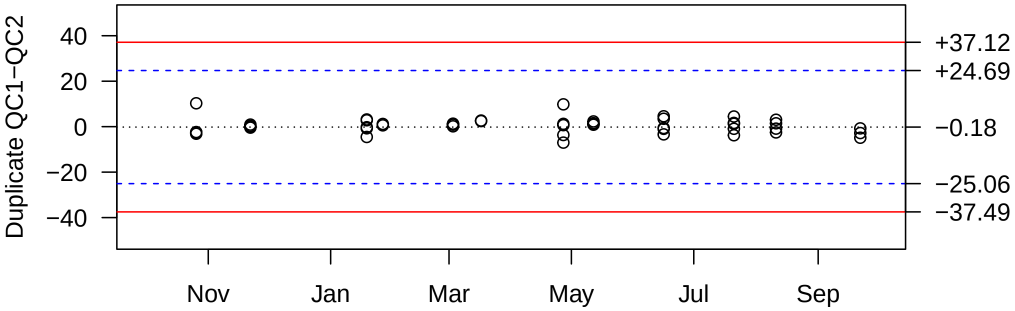


Dissolved Oxygen Laboratory Duplicates, Test Data

Figure C6: Dissolved oxygen laboratory duplicates (mg/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

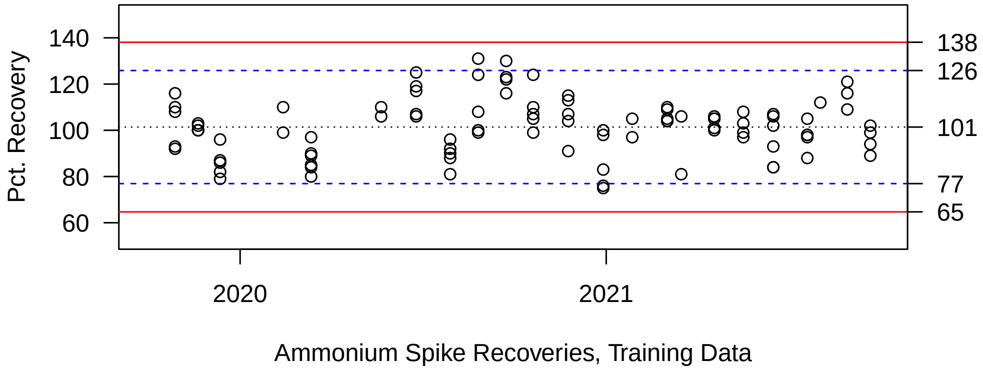


Ammonium Laboratory Duplicates, Training Data



Ammonium Laboratory Duplicates, Test Data

Figure C7: Nitrogen (ammonium) laboratory duplicates (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.



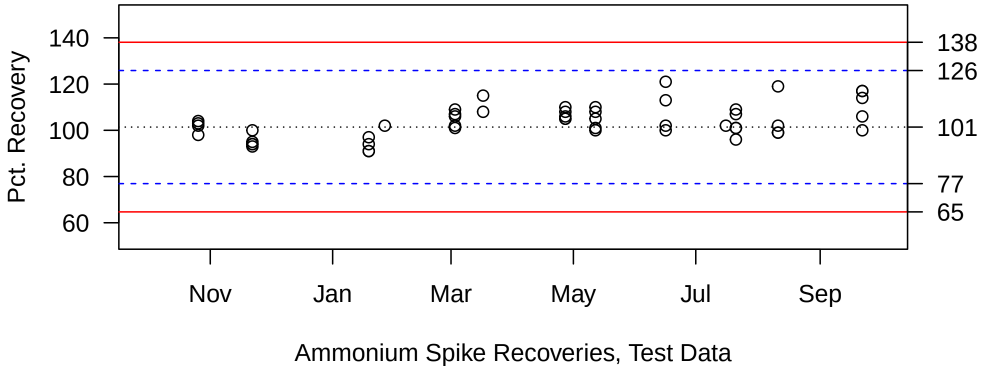
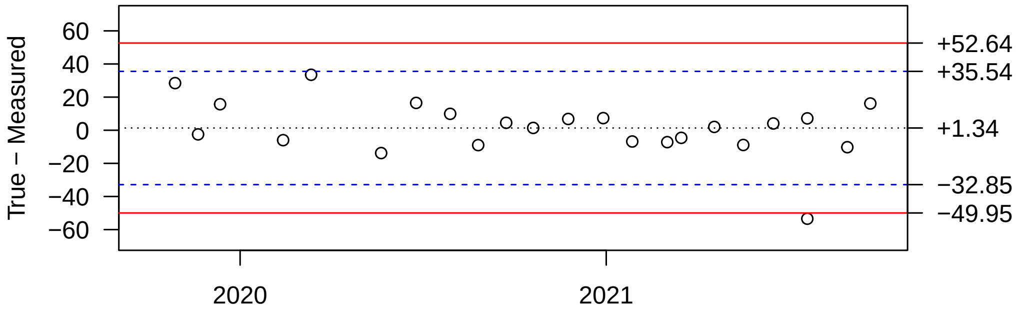
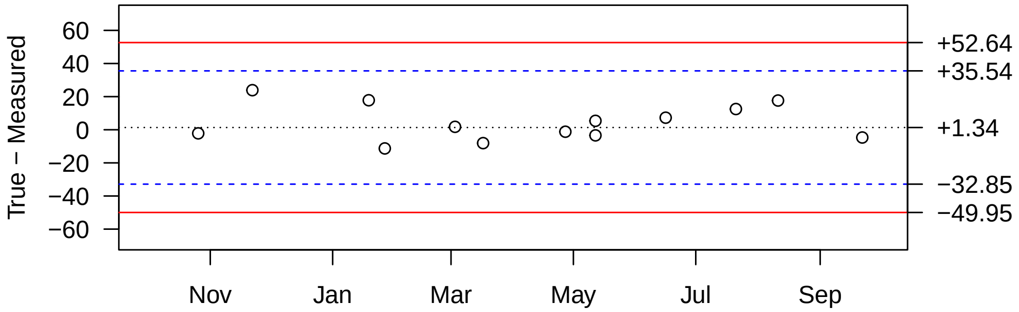


Figure C8: Nitrogen (ammonium) spike recoveries (%) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of spike data.

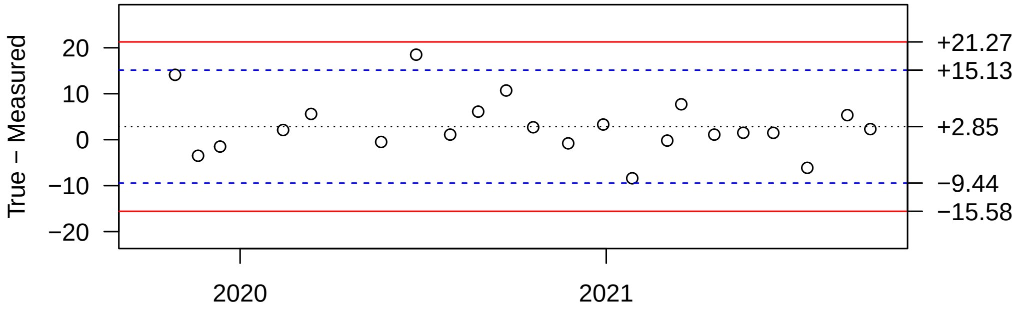


Ammonium Check Standards, Training Data

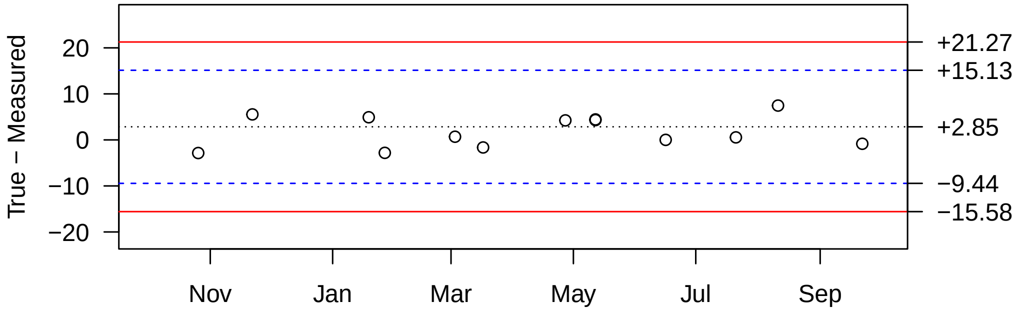


Ammonium Check Standards, Test Data

Figure C9: Nitrogen (ammonium) high-range check standards (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

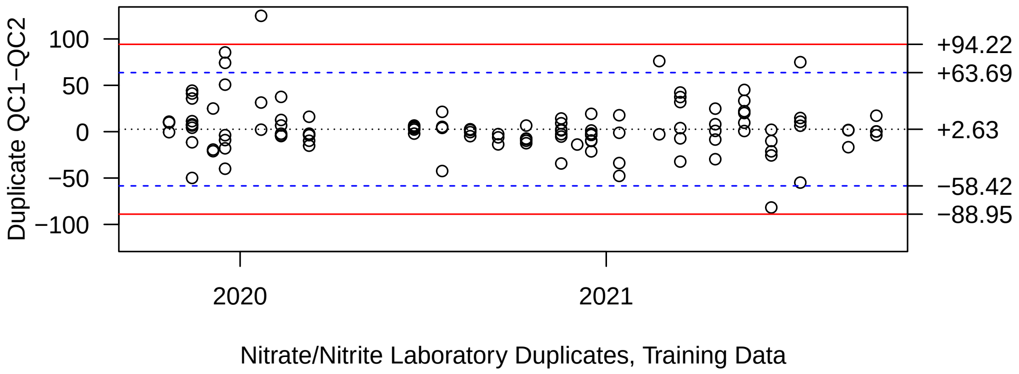


Ammonium Check Standards, Training Data



Ammonium Check Standards, Test Data

Figure C10: Nitrogen (ammonium) low-range check standards (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.



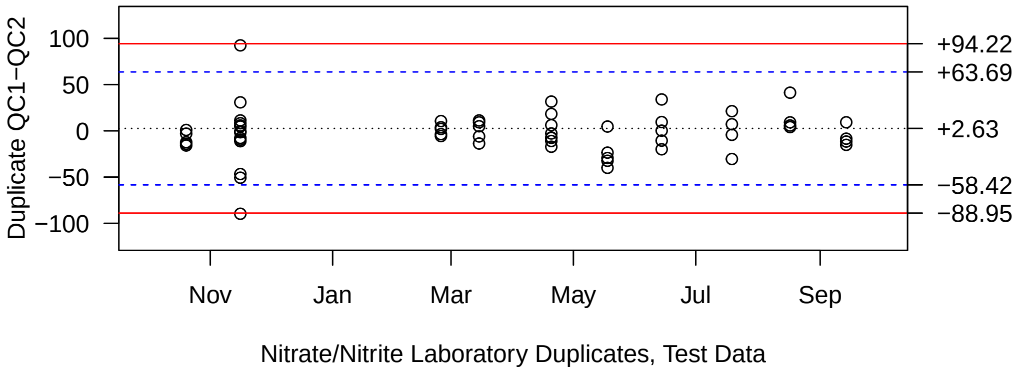
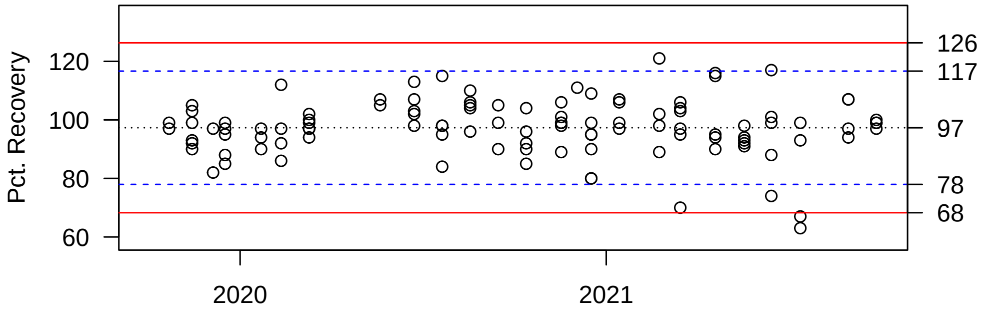
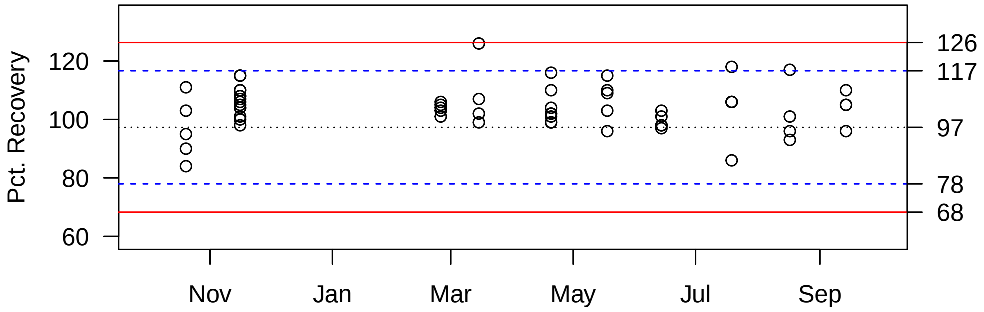


Figure C11: Nitrogen (nitrate/nitrite) laboratory duplicates (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

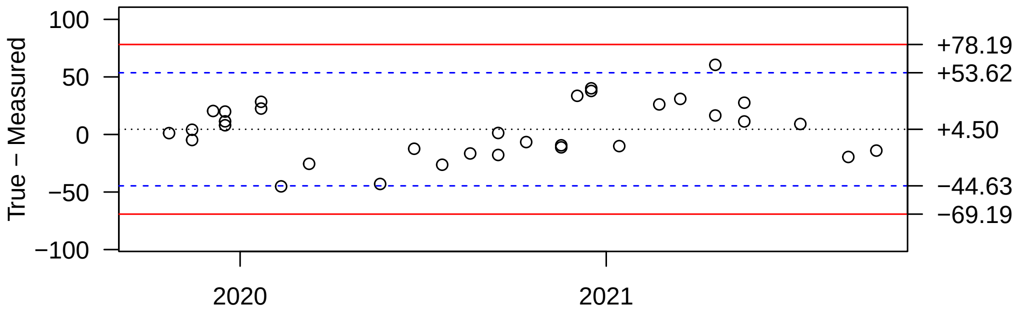


Nitrate/Nitrite Spike Recoveries, Training Data

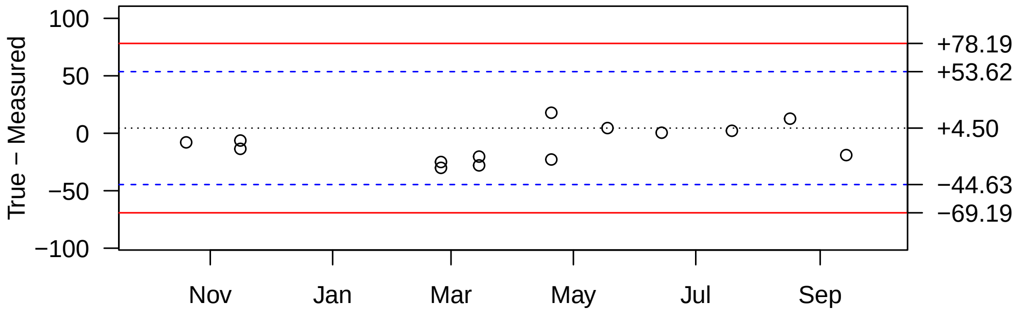


Nitrate/Nitrite Spike Recoveries, Test Data

Figure C12: Nitrogen (nitrate/nitrite) spike recoveries (%) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of spike data.

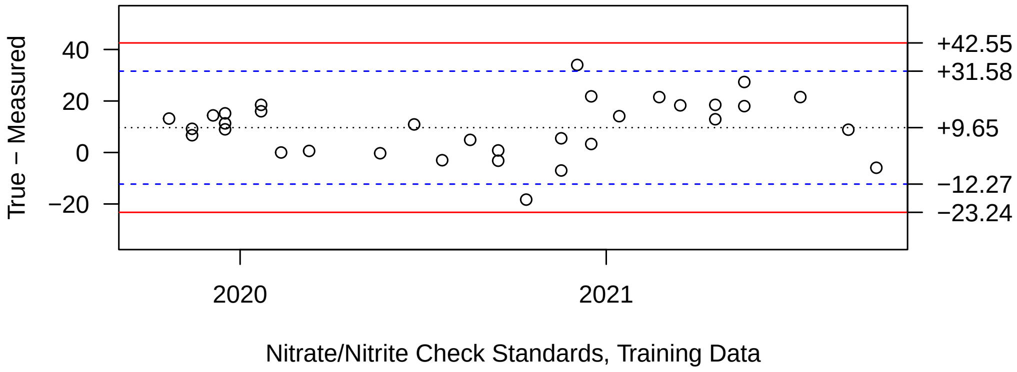


Nitrate/Nitrite Check Standards, Training Data



Nitrate/Nitrite Check Standards, Test Data

Figure C13: Nitrogen (nitrate/nitrite) high-range check standards (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.



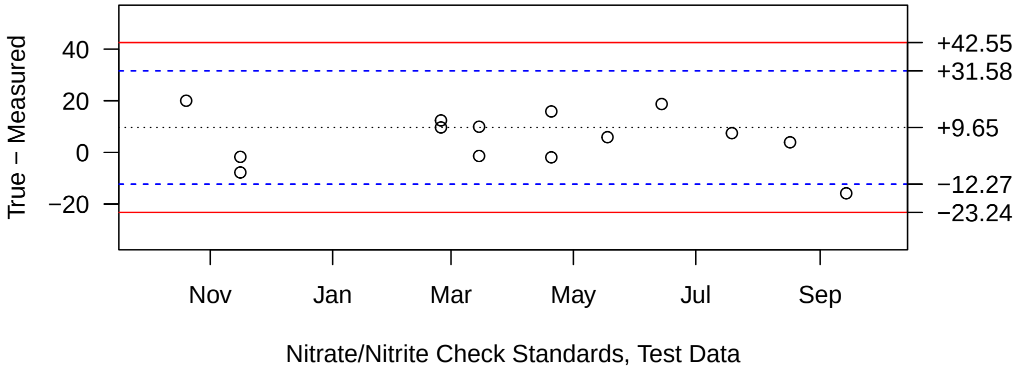
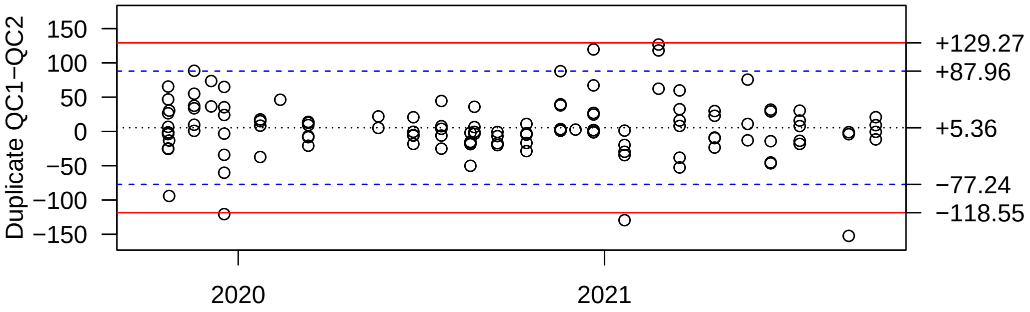
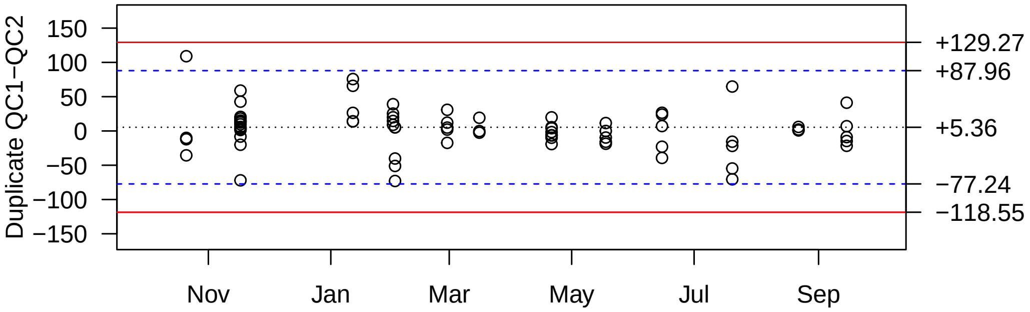


Figure C14: Nitrogen (nitrate/nitrite) low-range check standards (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

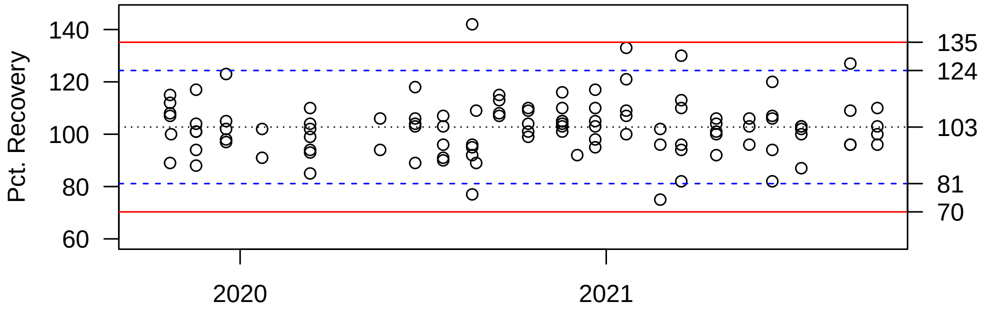


Total Nitrogen Laboratory Duplicates, Training Data

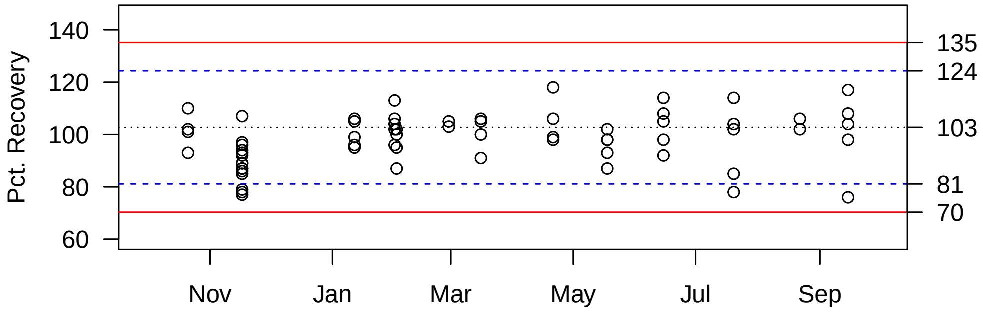


Total Nitrogen Laboratory Duplicates, Test Data

Figure C15: Nitrogen (total) laboratory duplicates (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

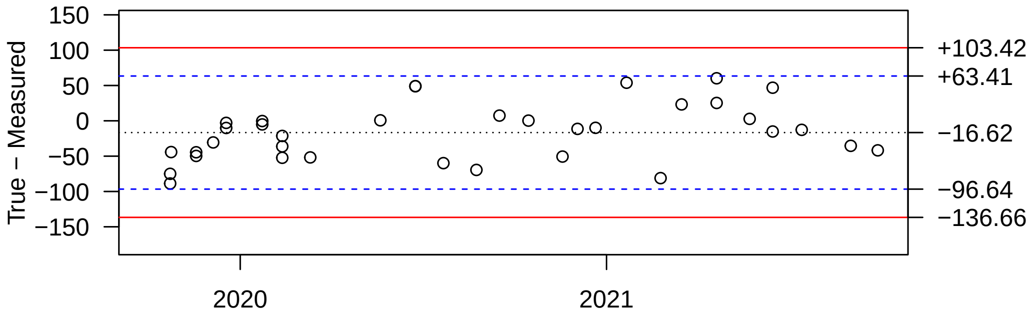


Total Nitrogen Spike Recoveries, Training Data

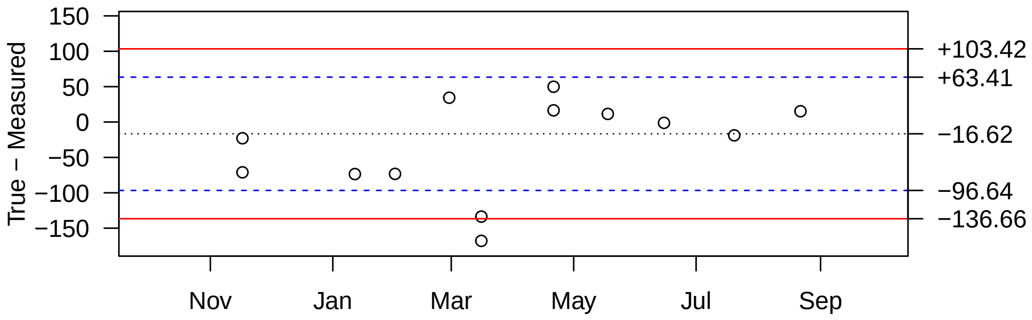


Total Nitrogen Spike Recoveries, Test Data

Figure C16: Nitrogen (total) spike recoveries (%) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of spike data.

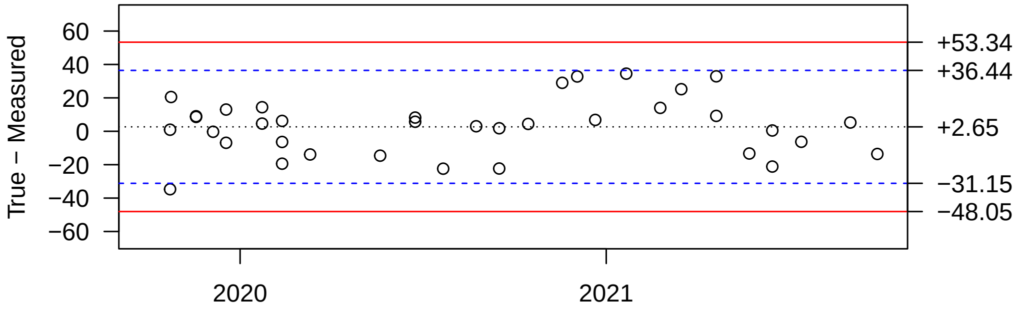


Total Nitrogen Check Standards, Training Data

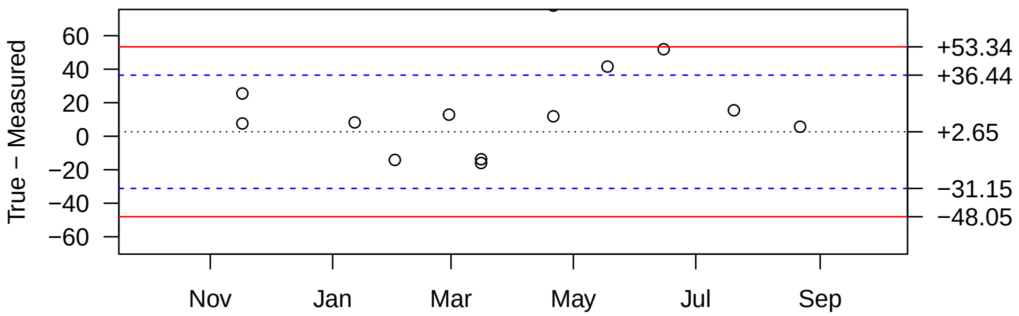


Total Nitrogen Check Standards, Test Data

Figure C17: Nitrogen (total) high-range check standards (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

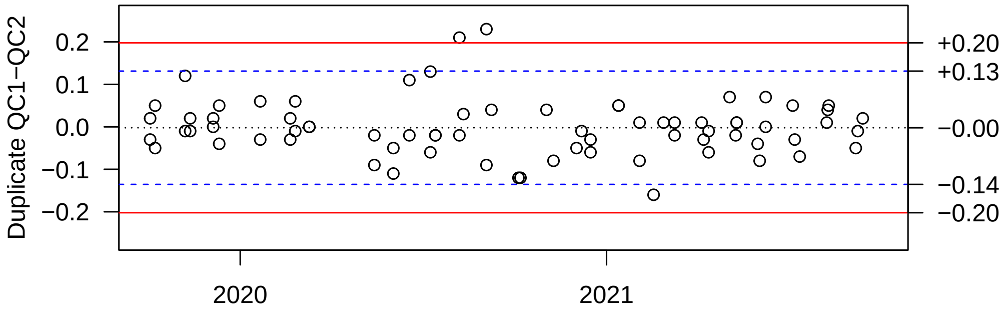


Total Nitrogen Check Standards, Training Data

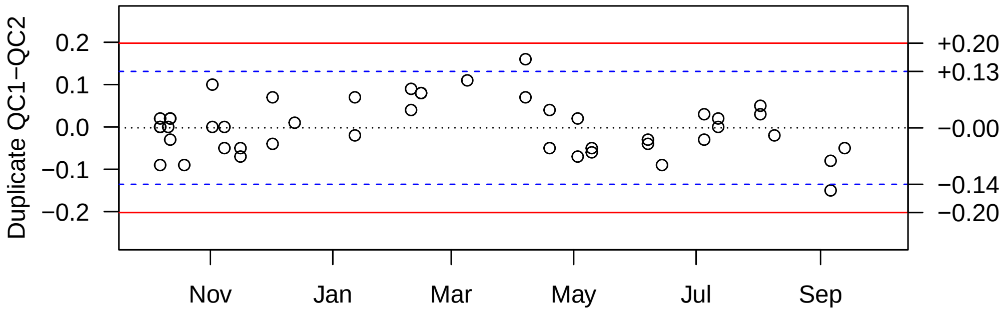


Total Nitrogen Check Standards, Test Data

Figure C18: Nitrogen (total) low-range check standards (μg-N/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

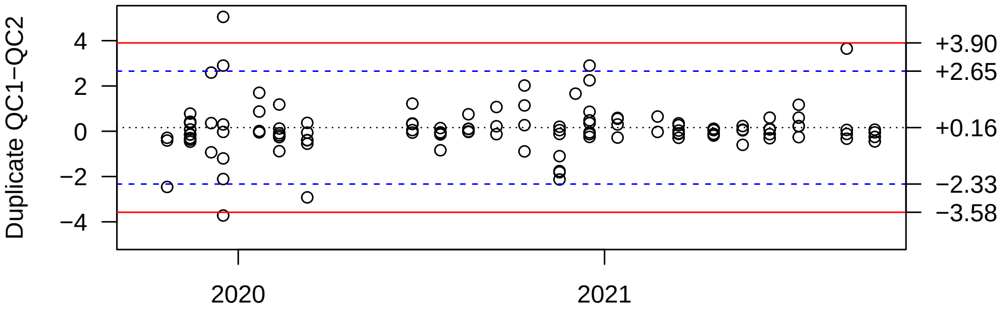


pH Laboratory Duplicates, Training Data

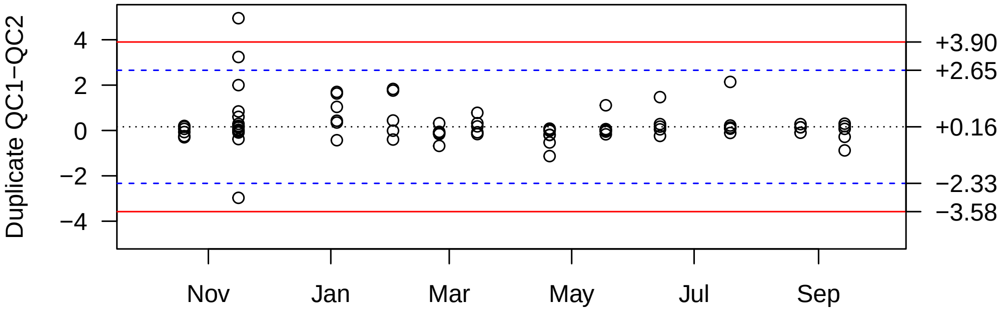


pH Laboratory Duplicates, Test Data

Figure C19: Laboratory pH duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

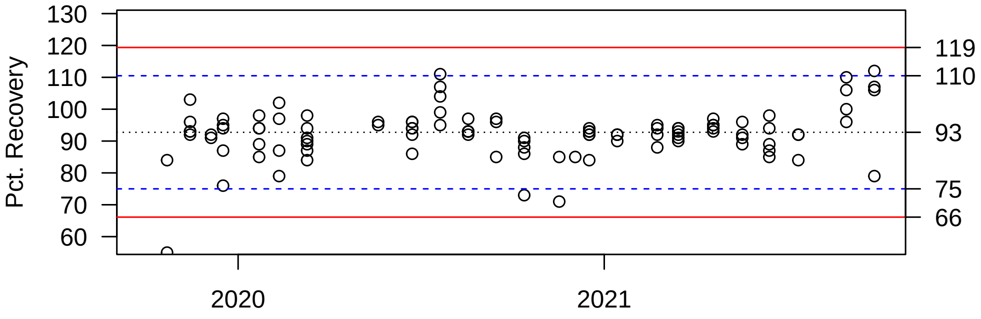


Soluble Reactive Phosphate Laboratory Duplicates, Training Data

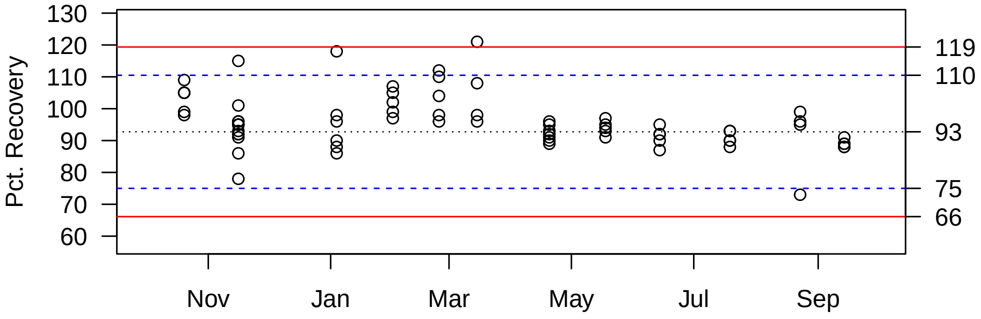


Soluble Reactive Phosphate Laboratory Duplicates, Test Data

Figure C20: Phosphorus (soluble reactive phosphate) laboratory duplicates (μg-P/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

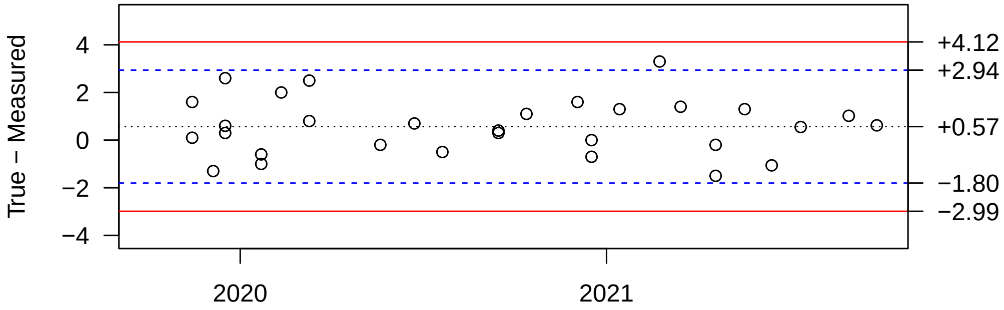


Soluble Reactive Phosphate Spike Recoveries, Training Data

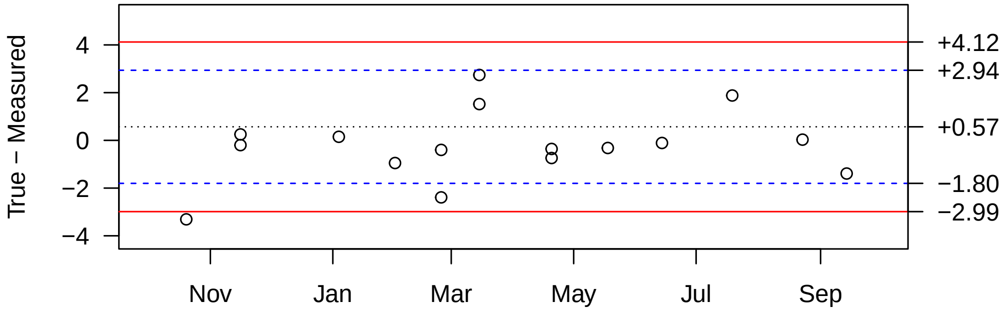


Soluble Reactive Phosphate Spike Recoveries, Test Data

Figure C21: Phosphorus (soluble reactive phosphate) spike recoveries (%) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of spike data.

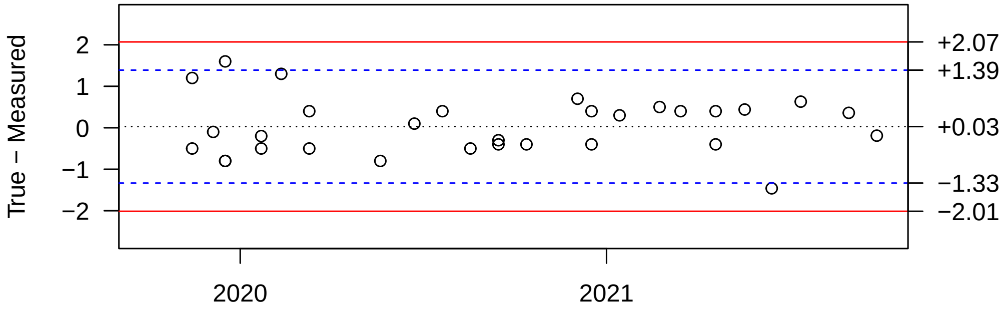


Soluble Reactive Phosphate Check Standards, Training Data

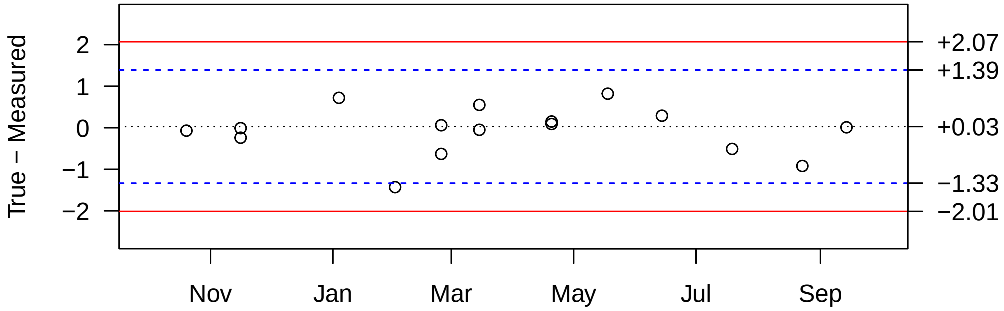


Soluble Reactive Phosphate Check Standards, Test Data

Figure C22: Phosphorus (soluble reactive phosphate) high-range check standards (μg-P/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

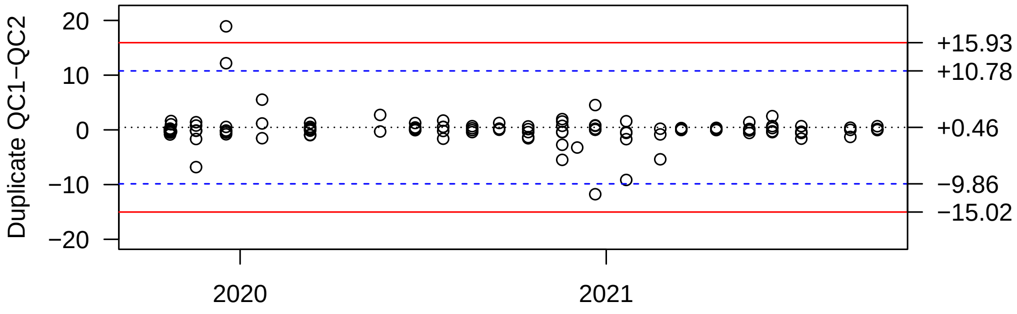


Soluble Reactive Phosphate Check Standards, Training Data

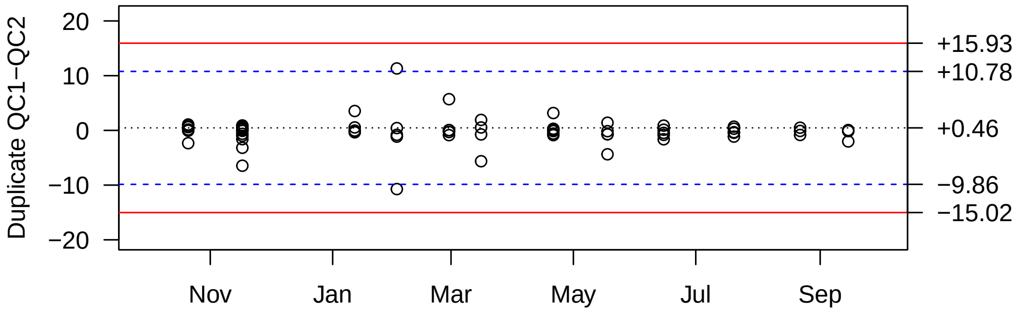


Soluble Reactive Phosphate Check Standards, Test Data

Figure C23: Phosphorus (soluble reactive phosphate) low-range check standards (μg-P/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

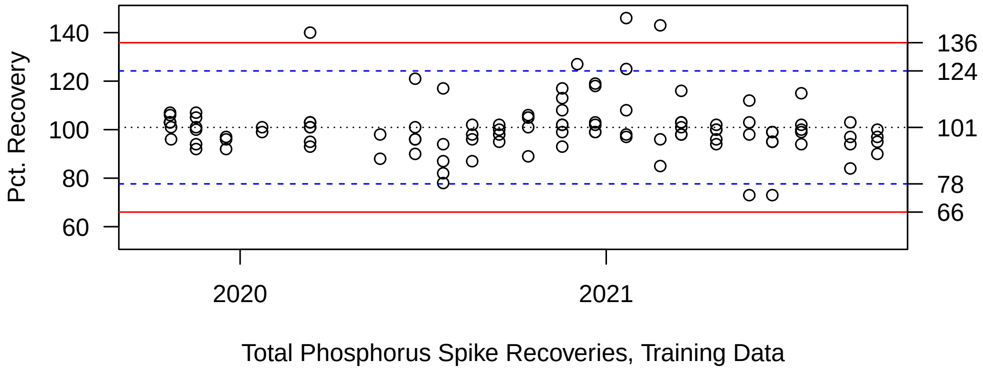


Total Phosphorus Laboratory Duplicates, Training Data



Total Phosphorus Laboratory Duplicates, Test Data

Figure C24: Phosphorus (total) laboratory duplicates (μg-P/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.



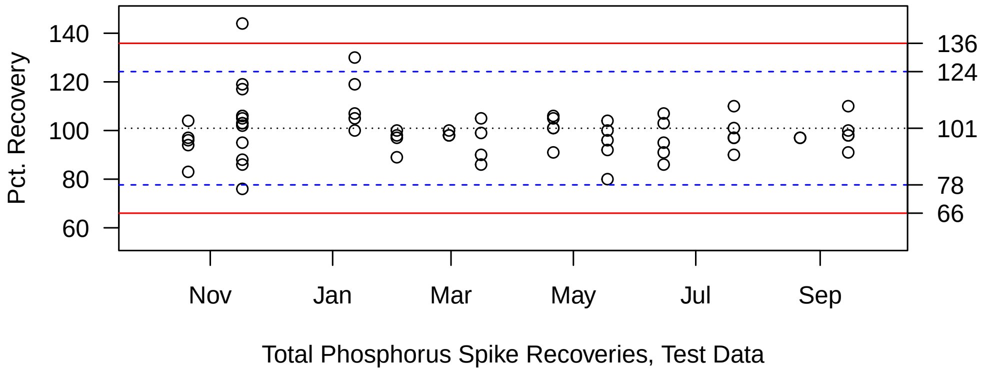
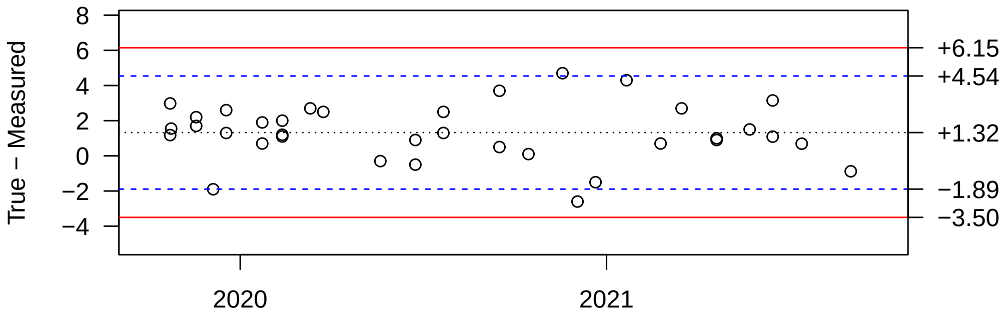
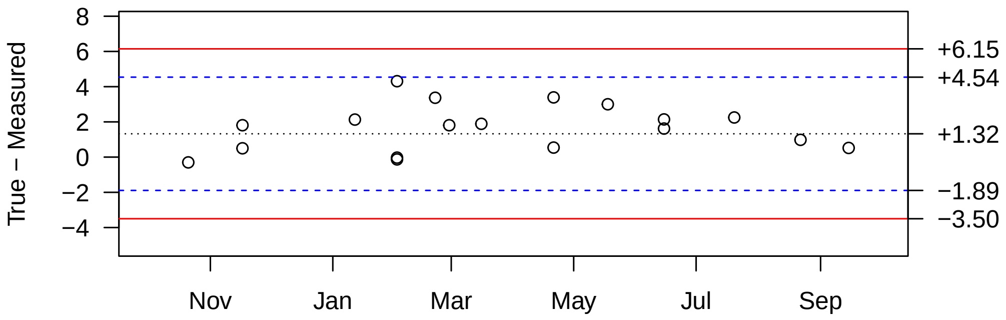


Figure C25: Phosphorus (total) spike recoveries (%) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of spike data.

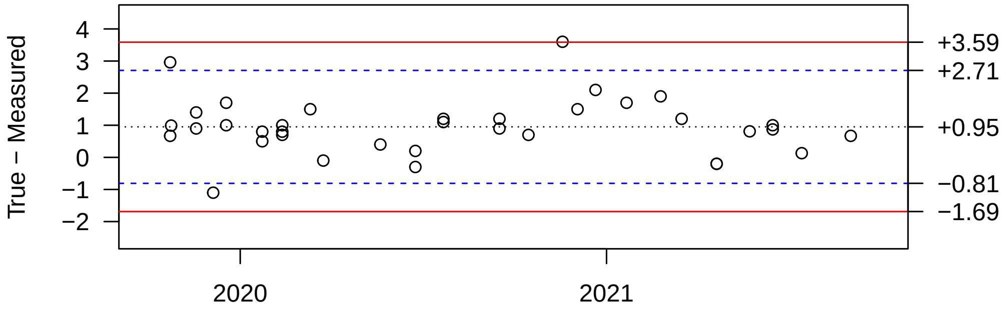


Total Phosphorus Check Standards, Training Data

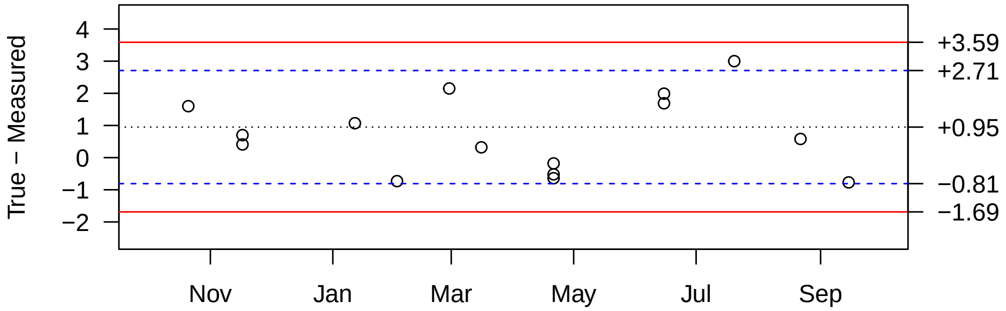


Total Phosphorus Check Standards, Test Data

Figure C26: Phosphorus (total) high-range check standards (μg-P/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

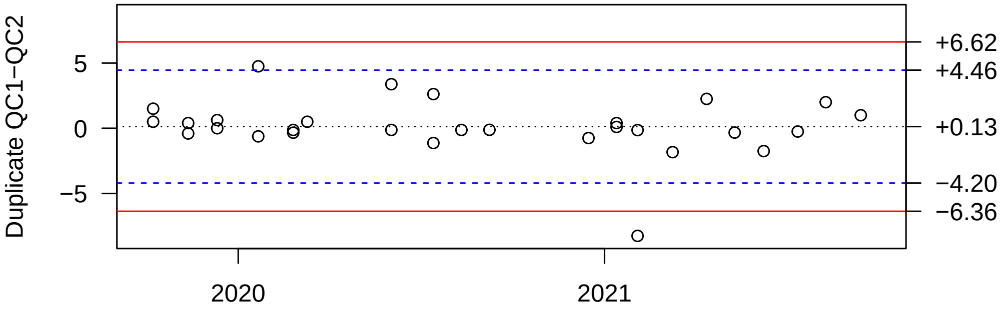


Total Phosphorus Check Standards, Training Data

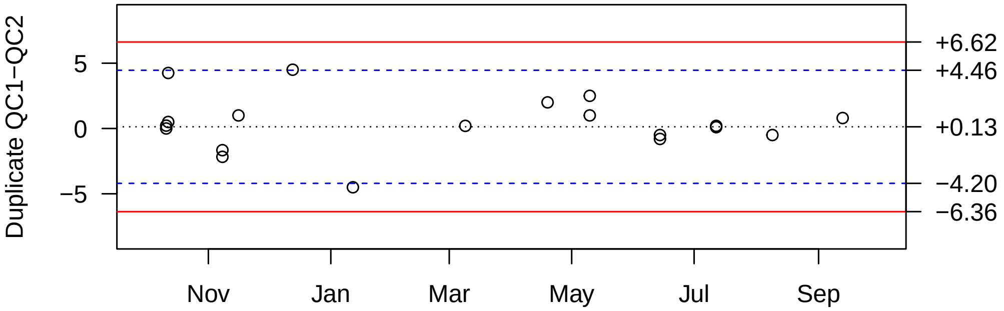


Total Phosphorus Check Standards, Test Data

Figure C27: Phosphorus (total) low-range check standards (μg-P/L) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.

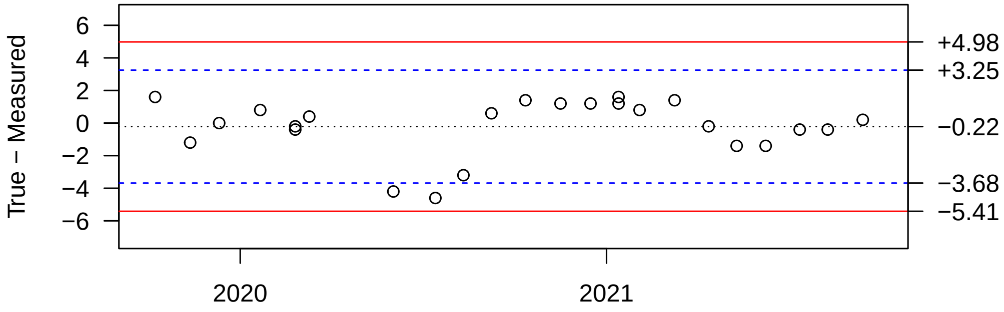


Total Suspended Solids Laboratory Duplicates, Training Data

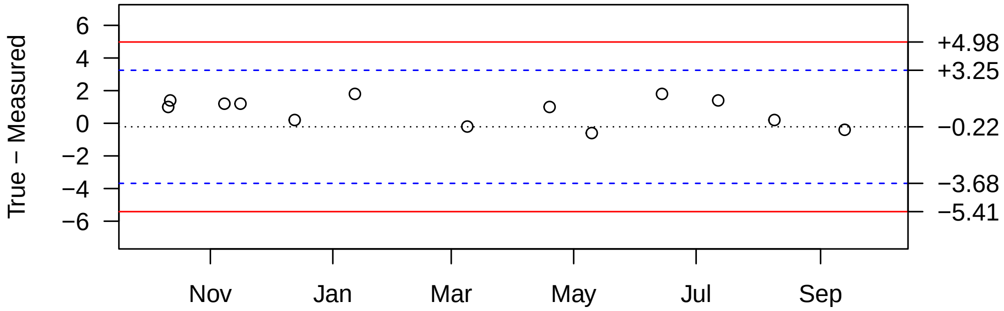


Total Suspended Solids Laboratory Duplicates, Test Data

Figure C28: Total suspended solids laboratory duplicates (mg/L) for the Lake Whatcom monitoring program (tributary and storm water samples). Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

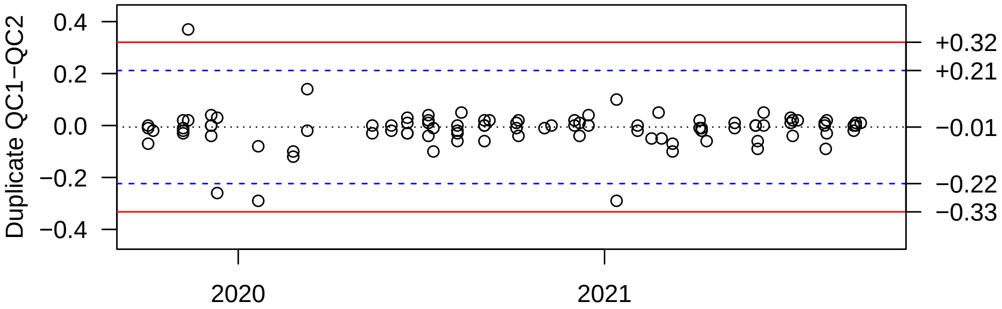


Total Suspended Solids Check Standards, Training Data

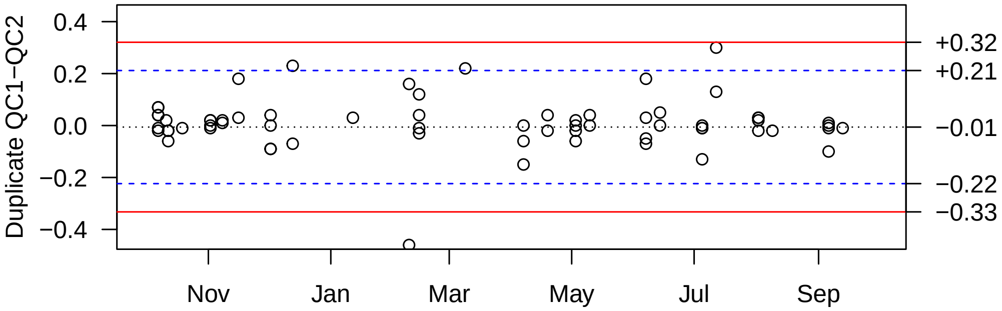


Total Suspended Solids Check Standards, Test Data

Figure C29: Total suspended solids check standards (mg/L) for the Lake Whatcom monitoring program (tributary and storm water samples). Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of check standard data.



Turbidity Laboratory Duplicates, Training Data



Turbidity Laboratory Duplicates, Test Data

Figure C30: Turbidity laboratory duplicates (NTU) for the Lake Whatcom monitoring program. Upper/lower acceptance limits (±2 std. dev. from mean pair difference) and upper/lower warning limits (±3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

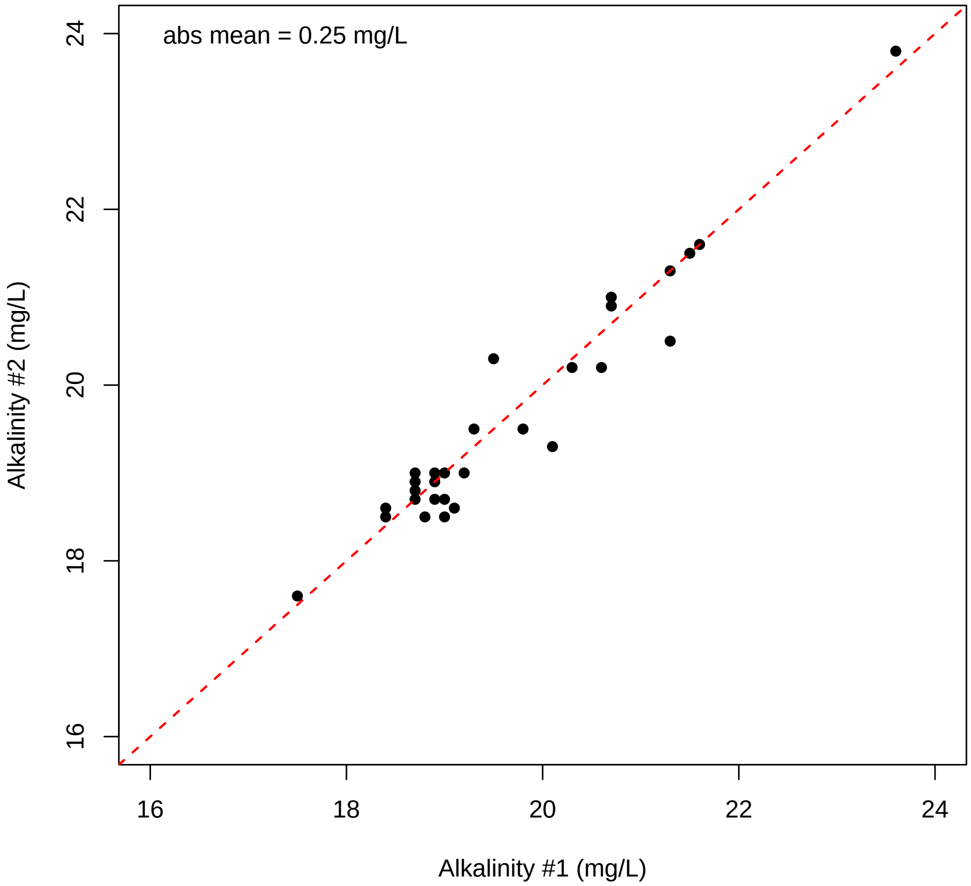


Figure C31: Alkalinity field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship.

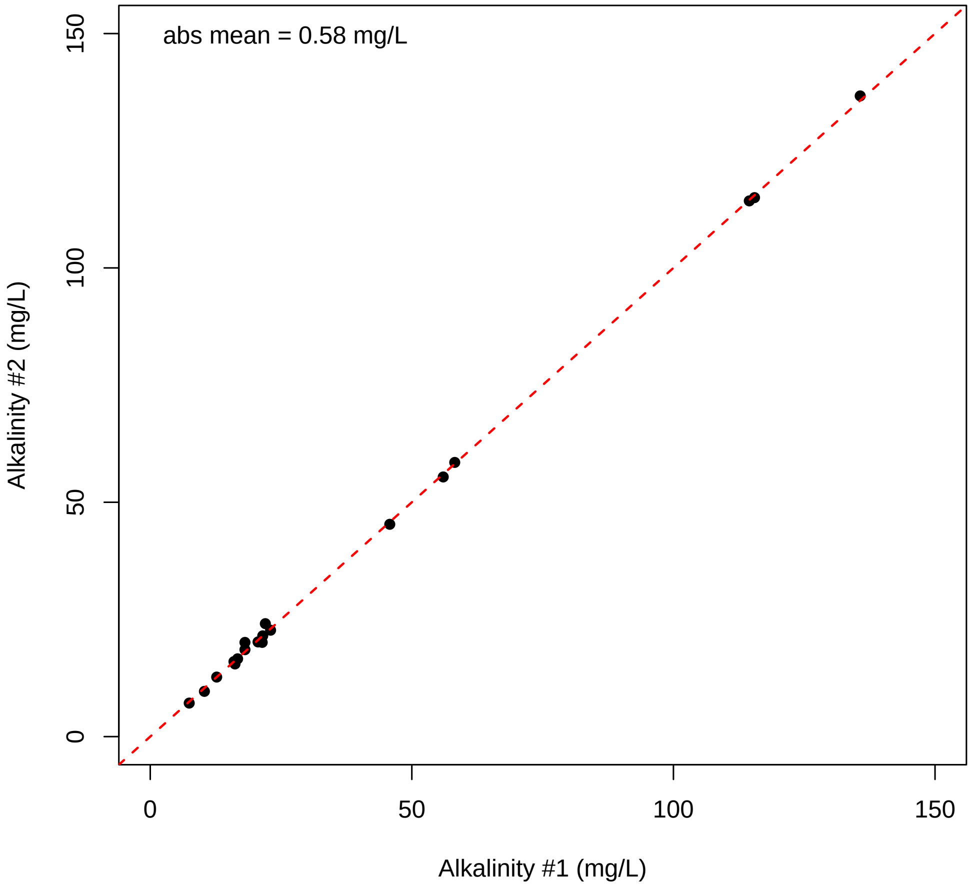


Figure C32: Alkalinity field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship.

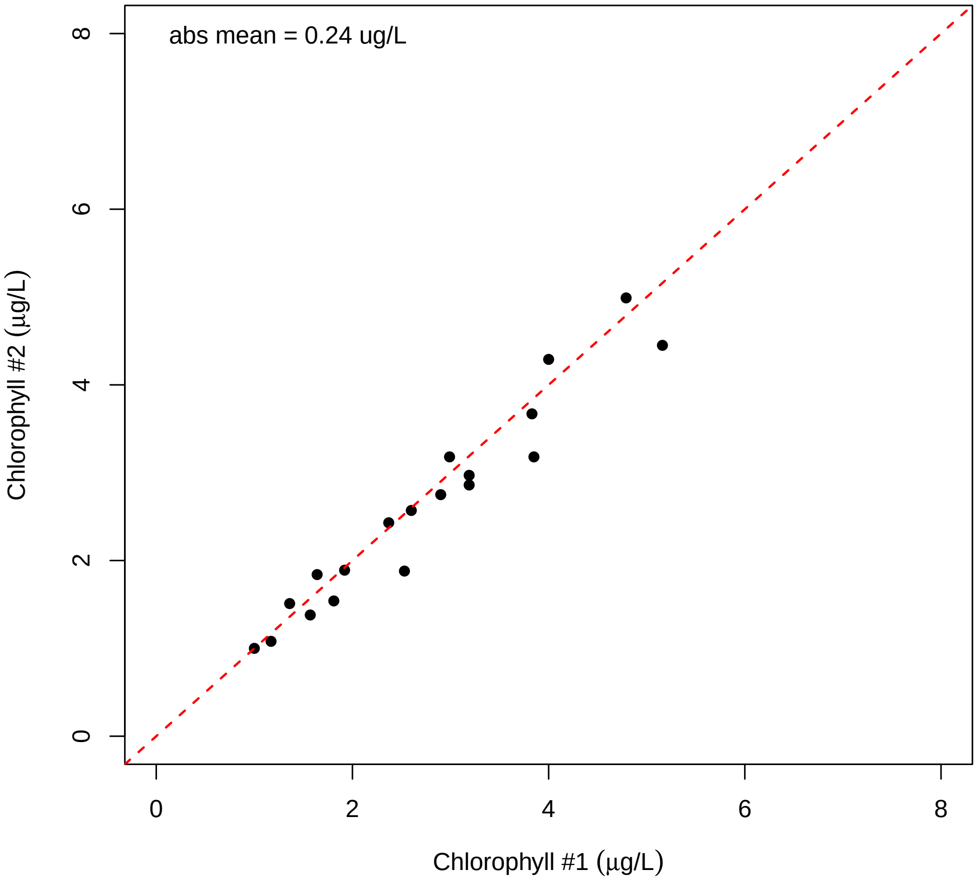


Figure C33: Chlorophyll field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship.

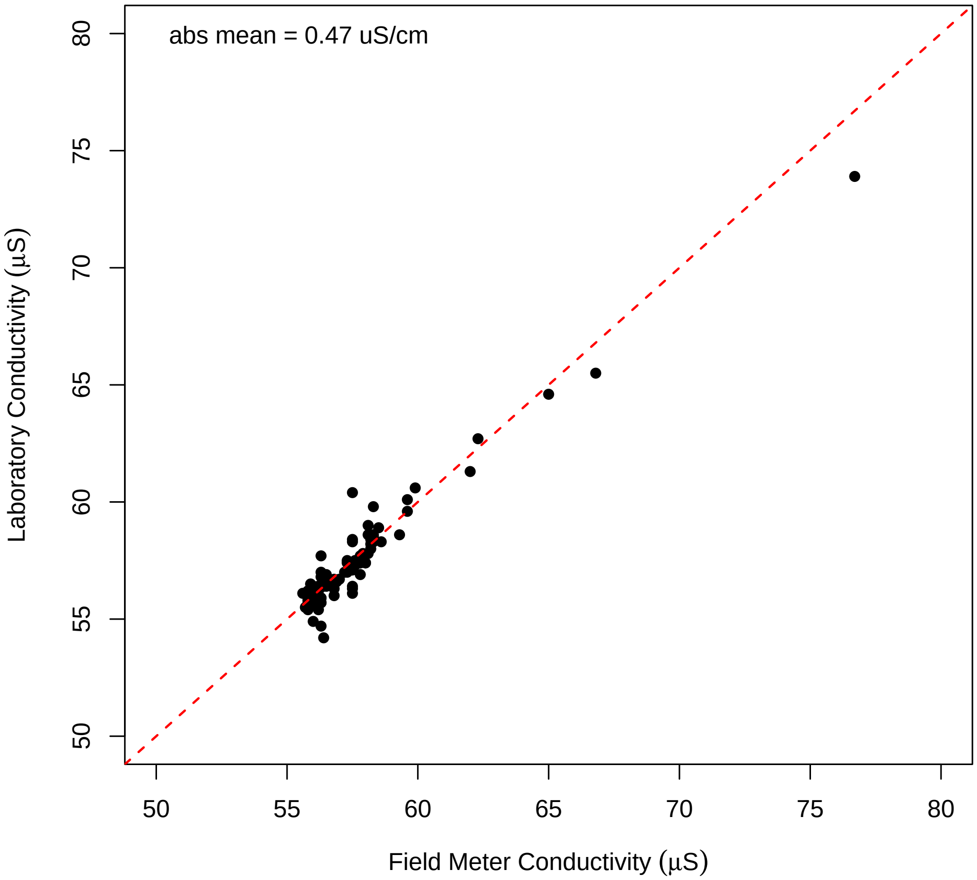


Figure C34: Conductivity field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship.

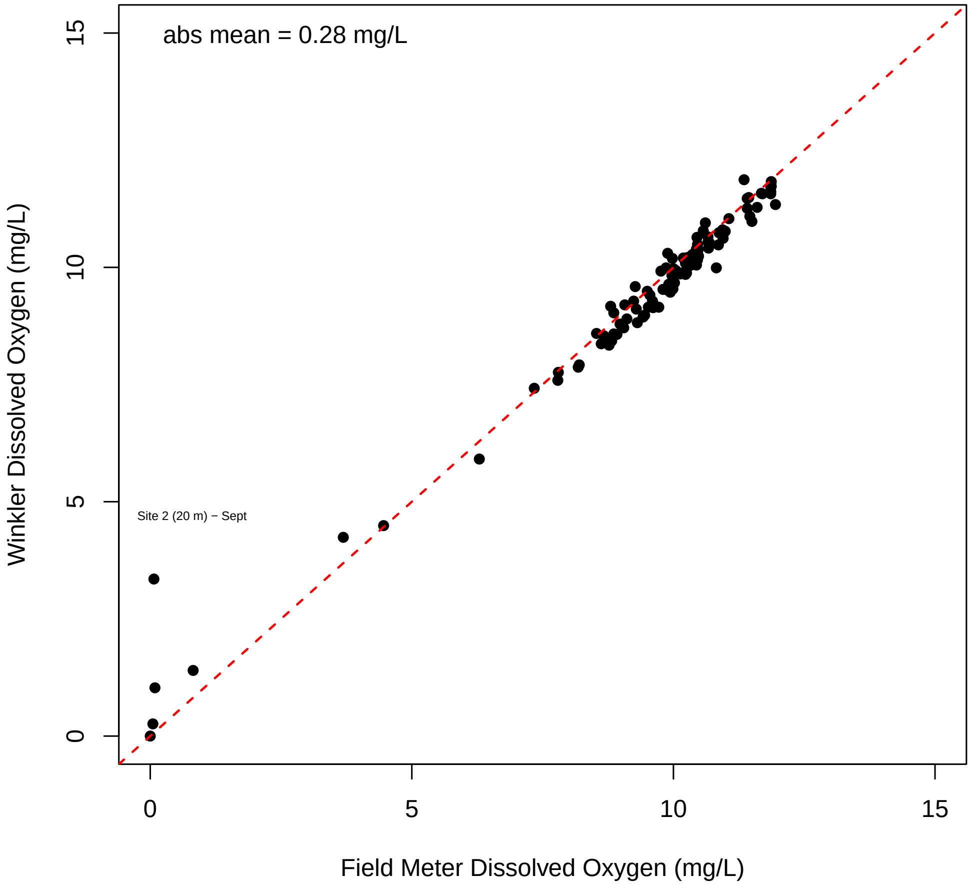


Figure C35: Dissolved oxygen field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship. The labeled outlier likely represents laboratory error with reagent concentrations. There was a systematic bias between the Winkler and field meter results, with the Winkler results ∼0.5 mg/L lower than the field meter. This is within typical ranges for Winkler vs. field meter comparisons (Johengen, et al., 2016).

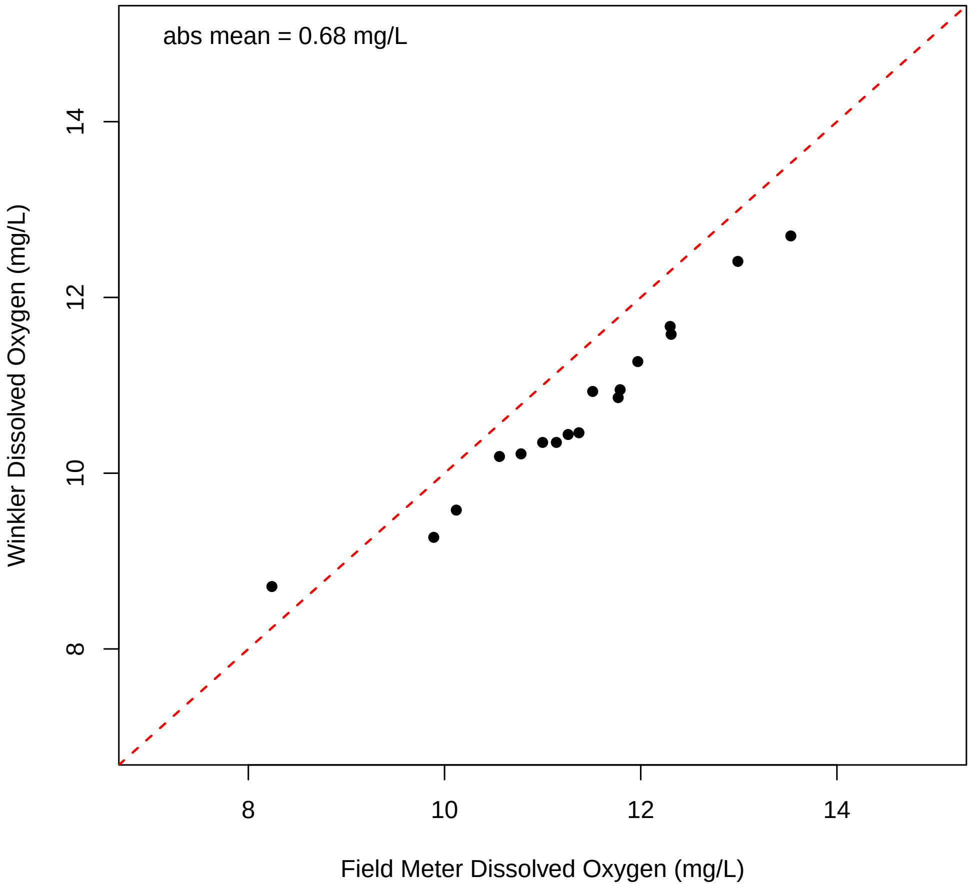


Figure C36: Dissolved oxygen field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship. There was a systematic bias between the Winkler and field meter results, with the Winkler results ∼0.5 mg/L lower than the field meter. This is within typical ranges for Winkler vs. field meter comparisons (Johengen, et al., 2016).

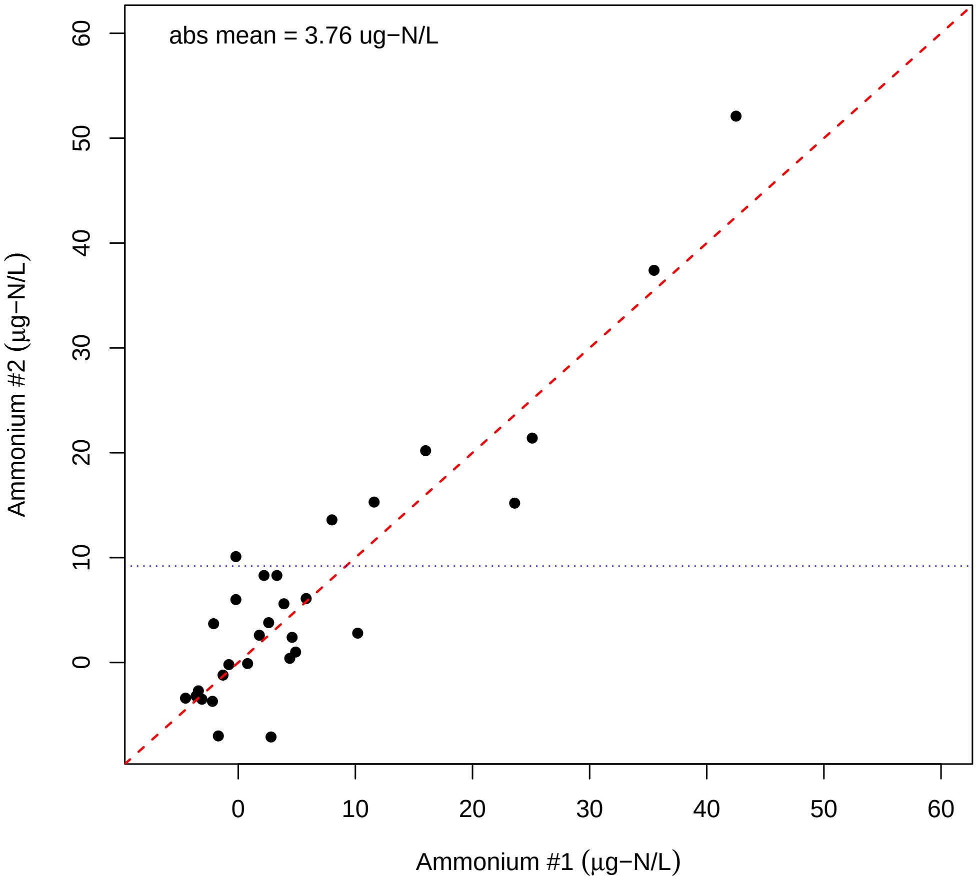


Figure C37: Nitrogen (ammonium) field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit.

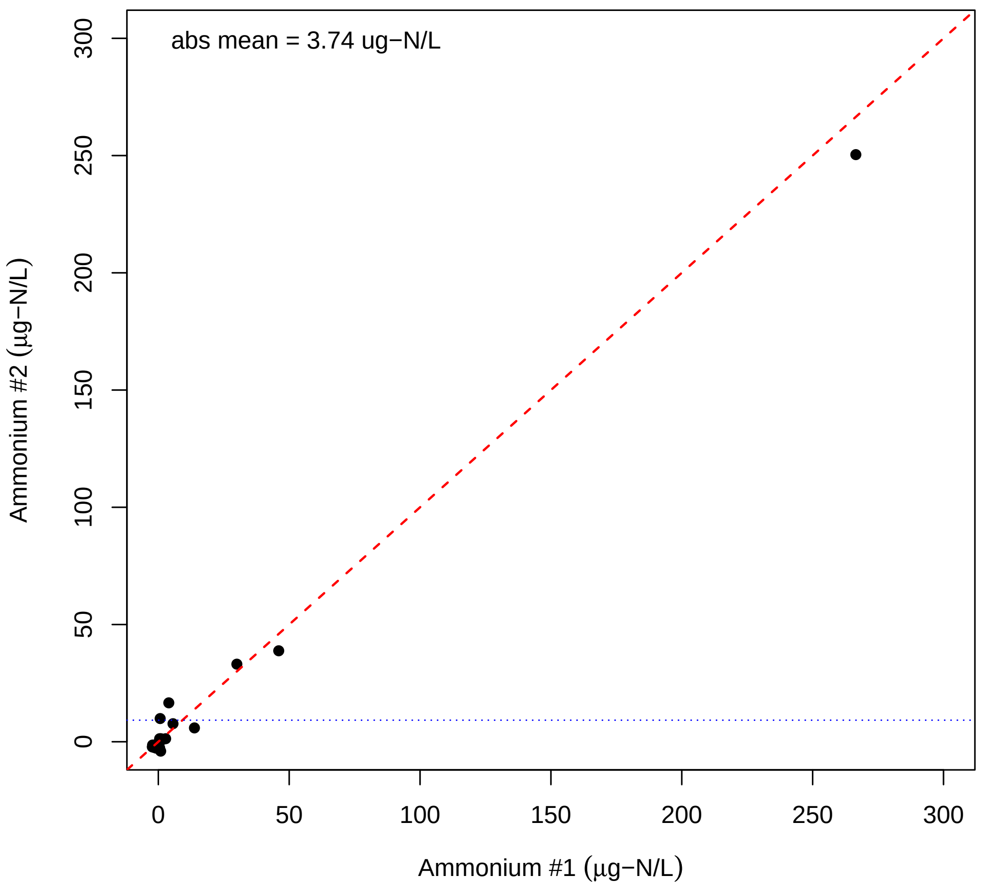


Figure C38: Nitrogen (ammonium) field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit.

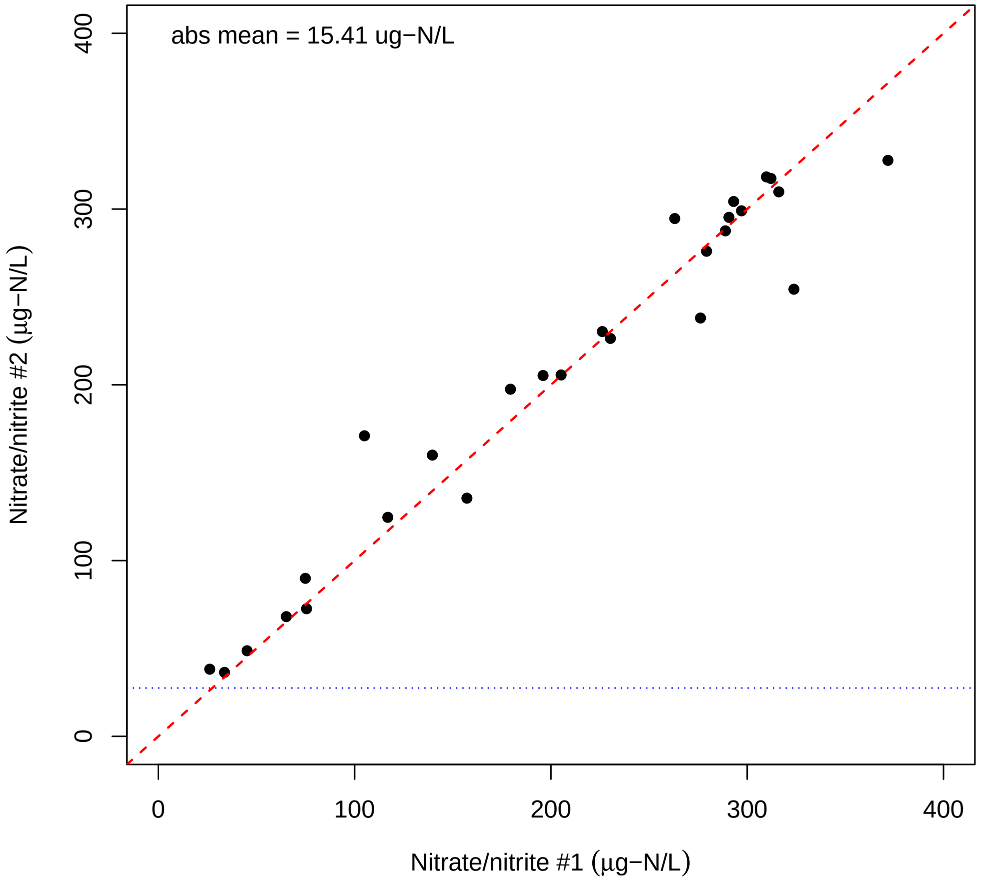


Figure C39: Nitrogen (nitrate/nitrite) field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit.

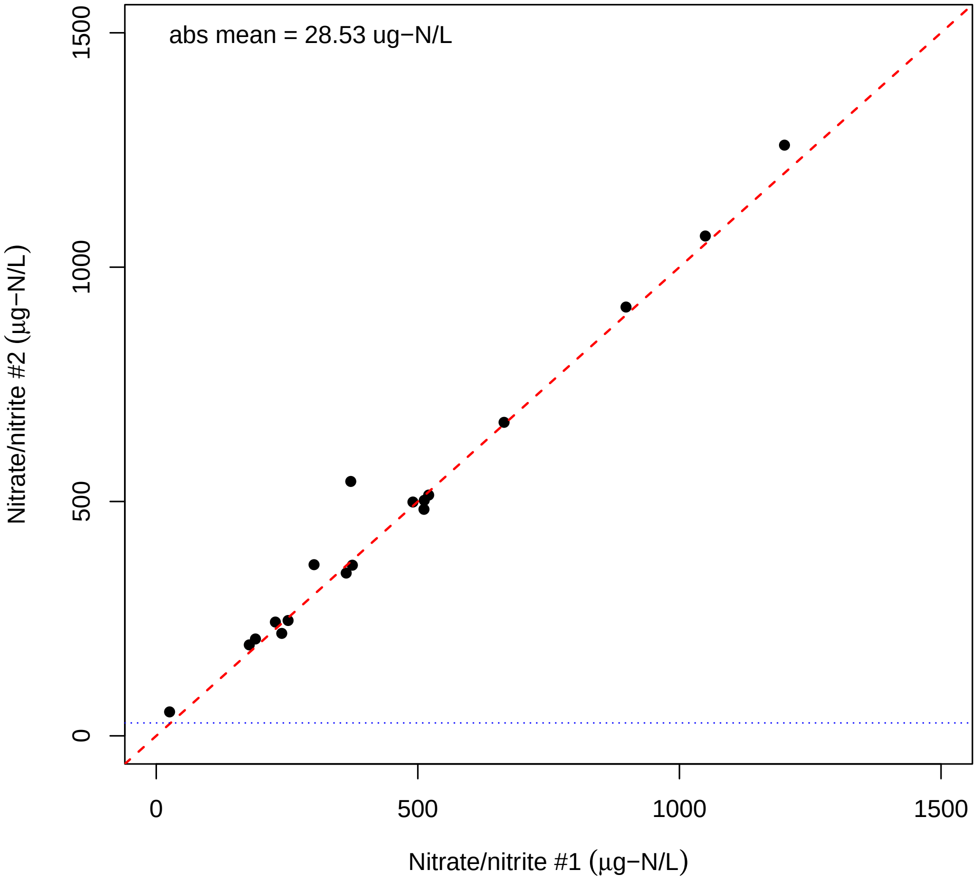


Figure C40: Nitrogen (nitrate/nitrite) field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit.

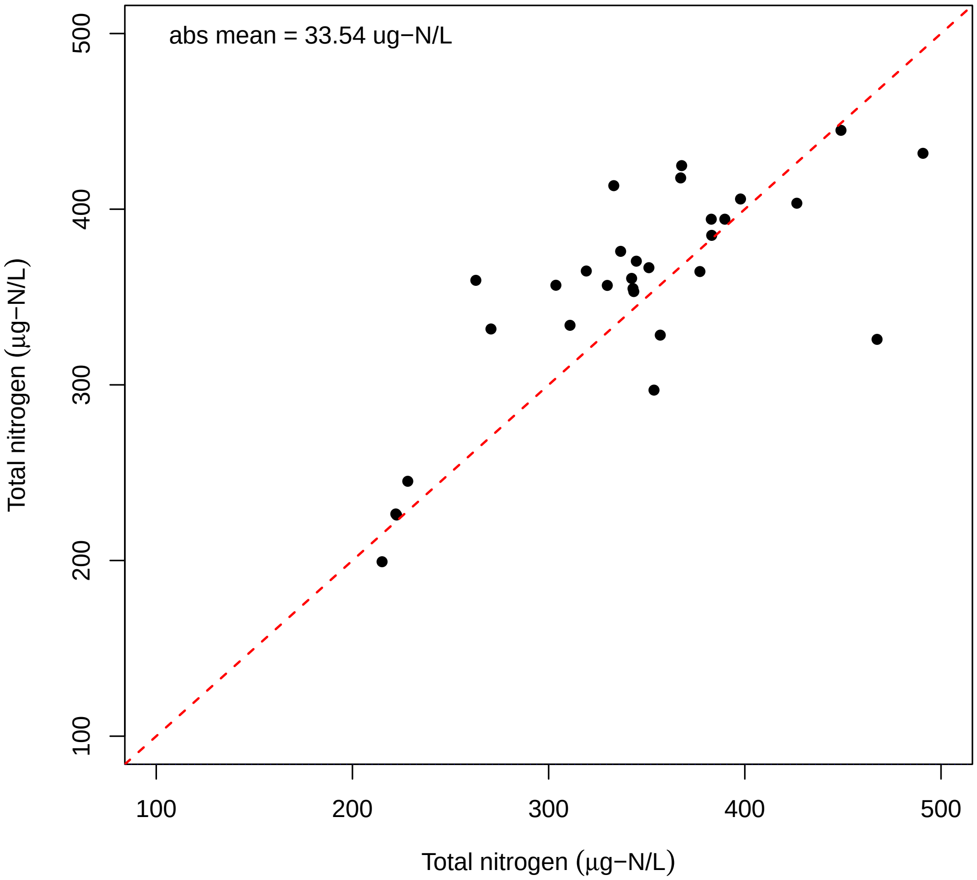


Figure C41: Nitrogen (total) field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship. The scatter around the line is within the range of the laboratory QC standards (Figure C15).

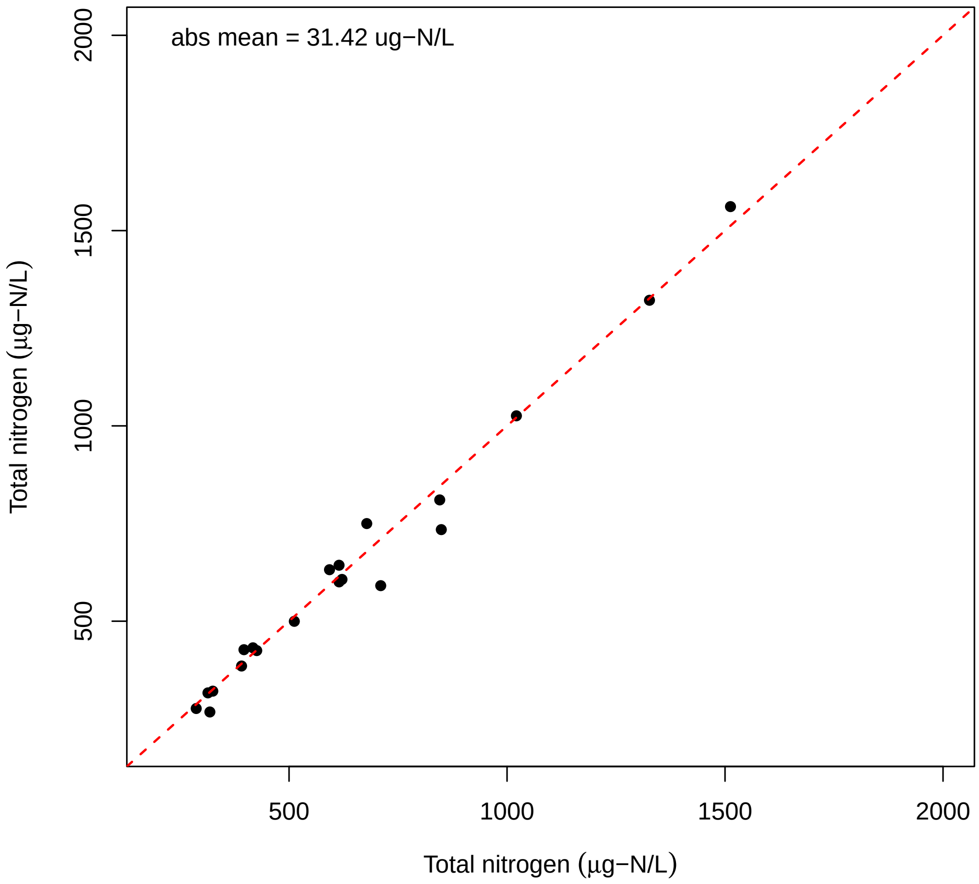


Figure C42: Nitrogen (total) field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship.

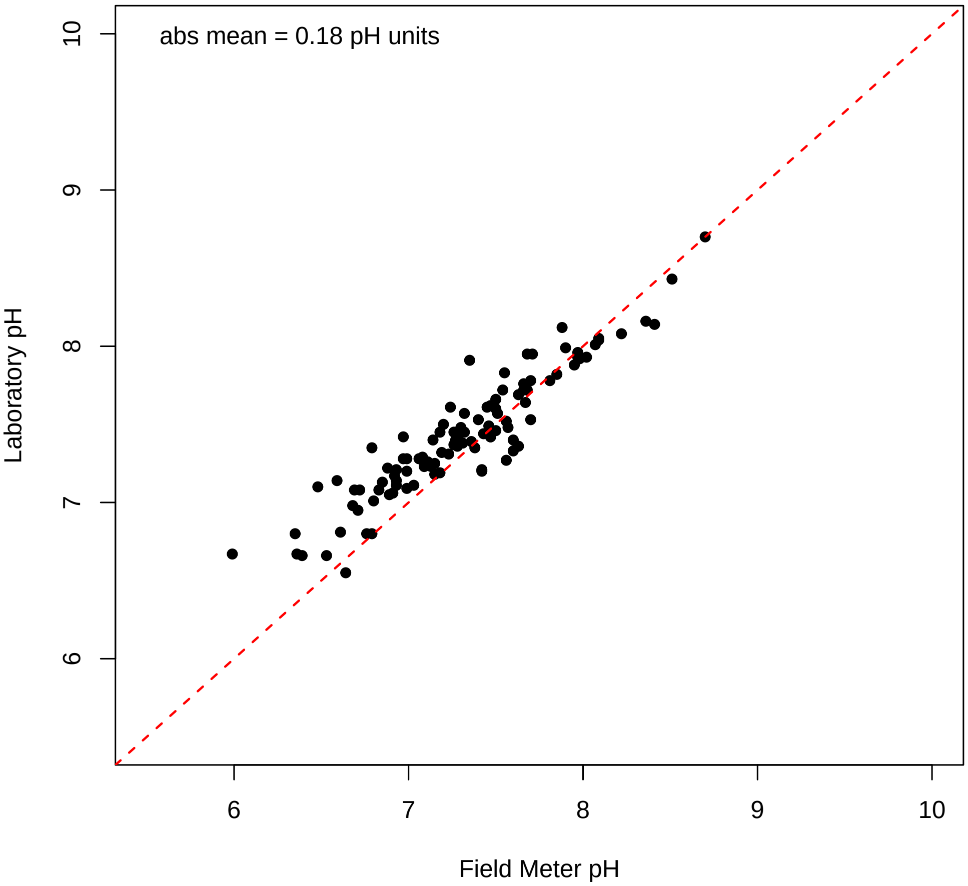


Figure C43: Field duplicates for pH from the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship. A systematic bias was observed for pH values ≤ 7.0. This bias may be the result of the time lag between field sampling and laboratory measurements, temperature differences, and/or the effects of gas exchange once the sample is exposed to air.

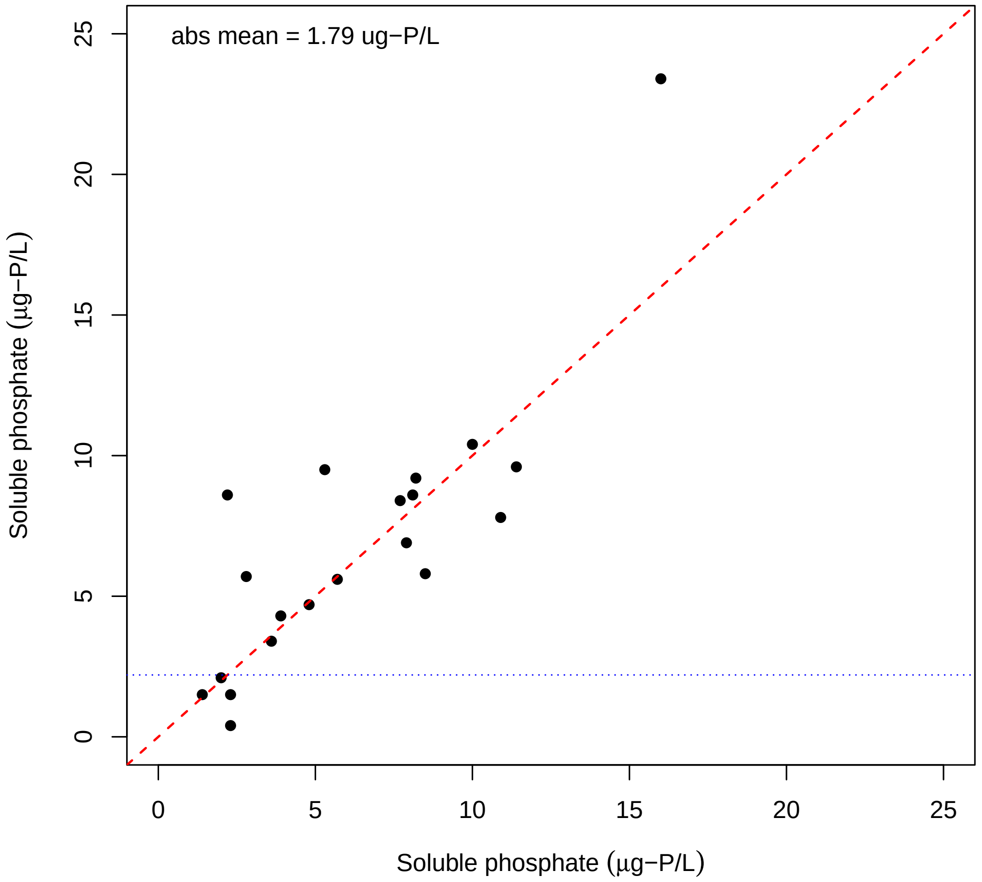


Figure C44: Phosphorus (soluble reactive phosphate) field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit. The high degree of scatter is due to the low concentrations of the samples.

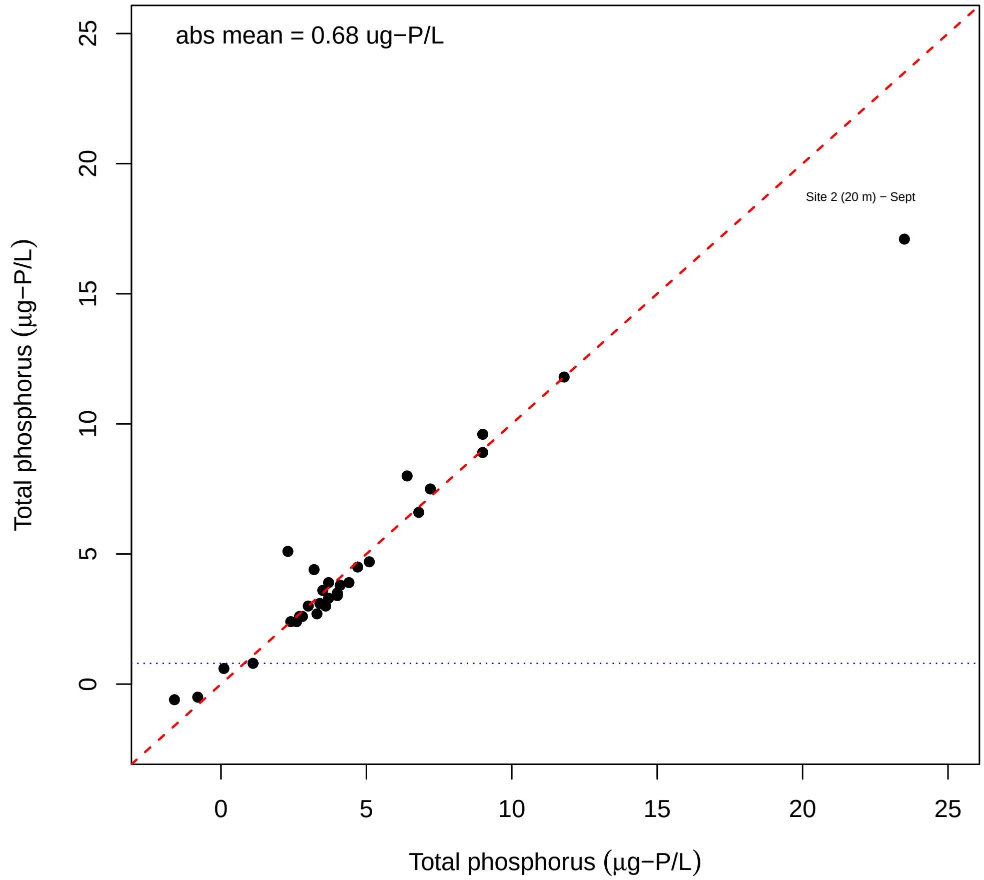


Figure C45: Phosphorus (total) field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit. The outlier identified likely represents sediment contamination from the lake bottom.

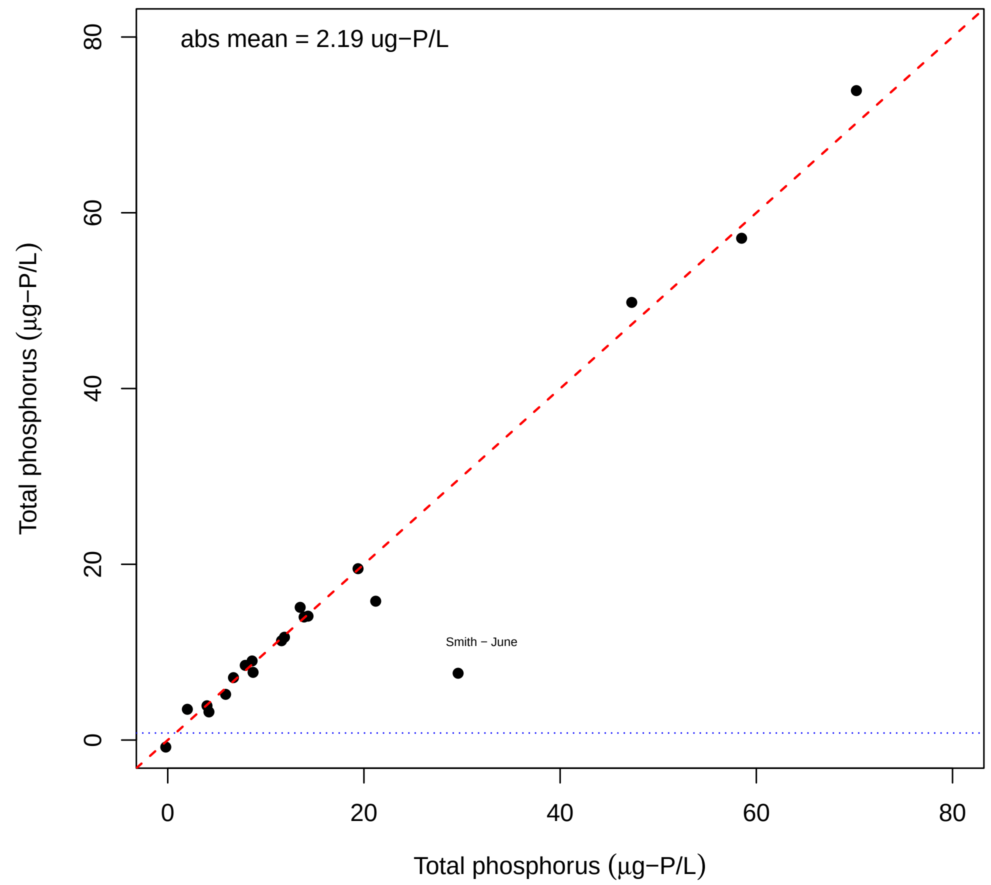


Figure C46: Phosphorus (total) field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit. The outlier identified likely represents sediment contamination of the duplicate sample during low flow conditions.

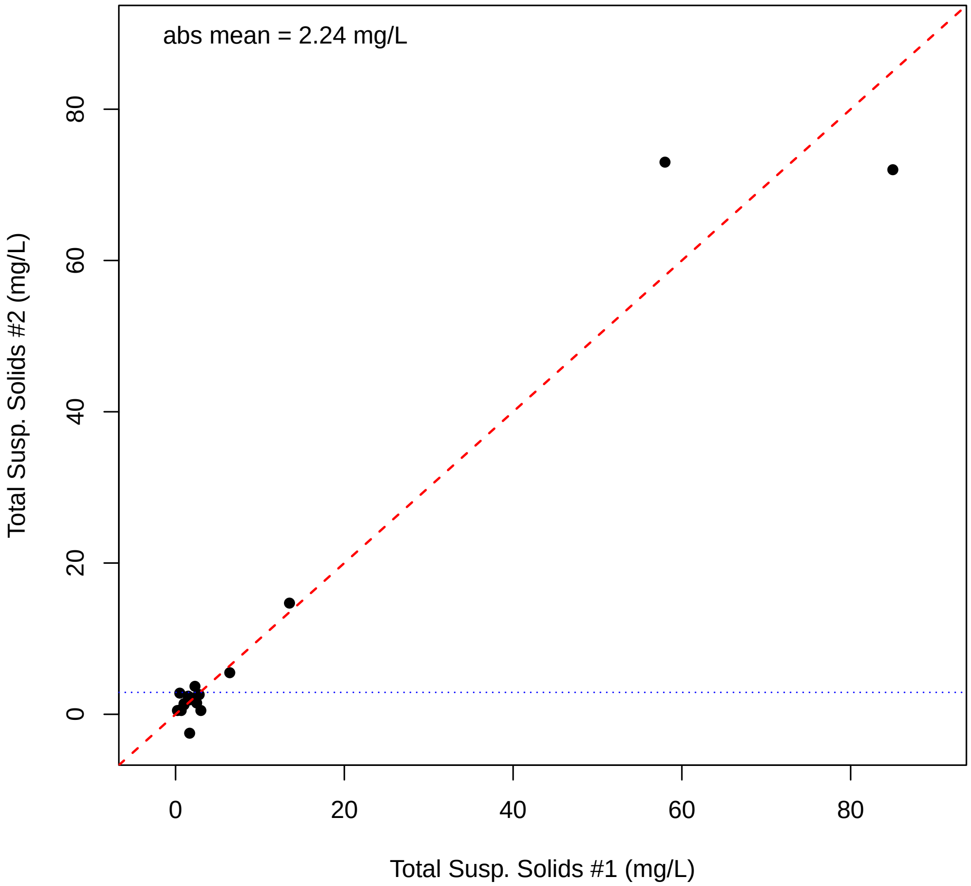


Figure C47: Total suspended solids field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit. The scatter at extremely high concentrations is expected.

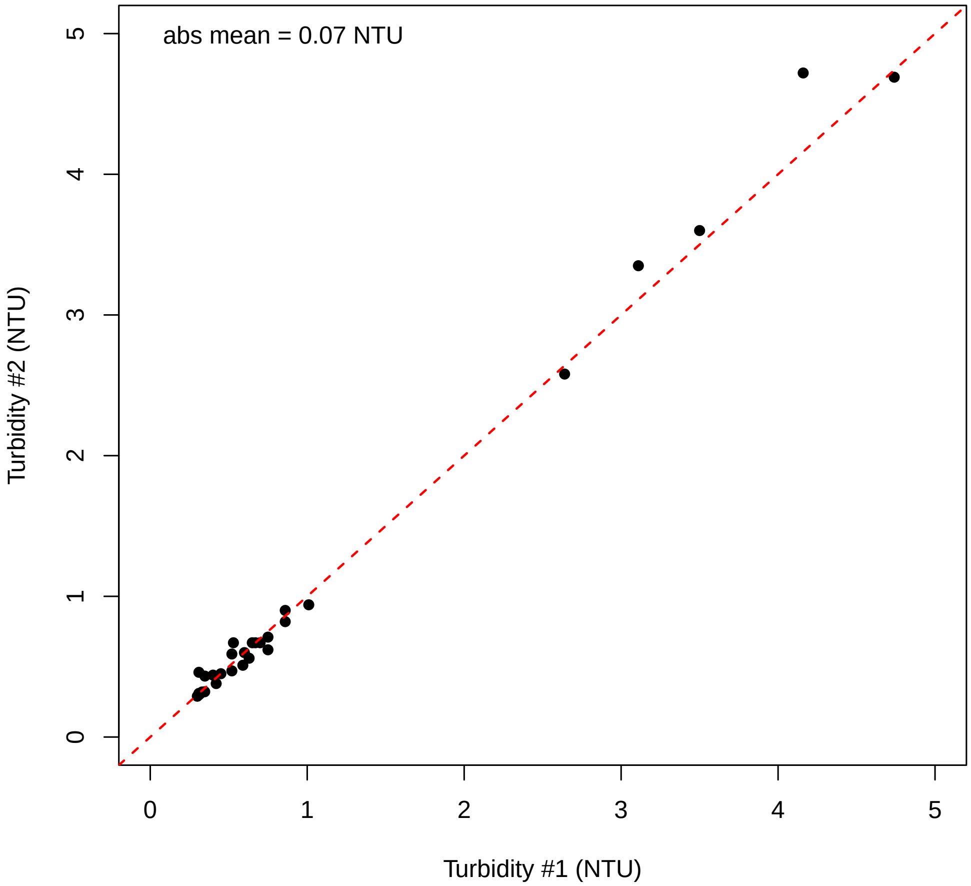


Figure C48: Turbidity field duplicates for the 2021/2022 Lake Whatcom monitoring program (lake samples). Diagonal reference line shows 1:1 relationship.

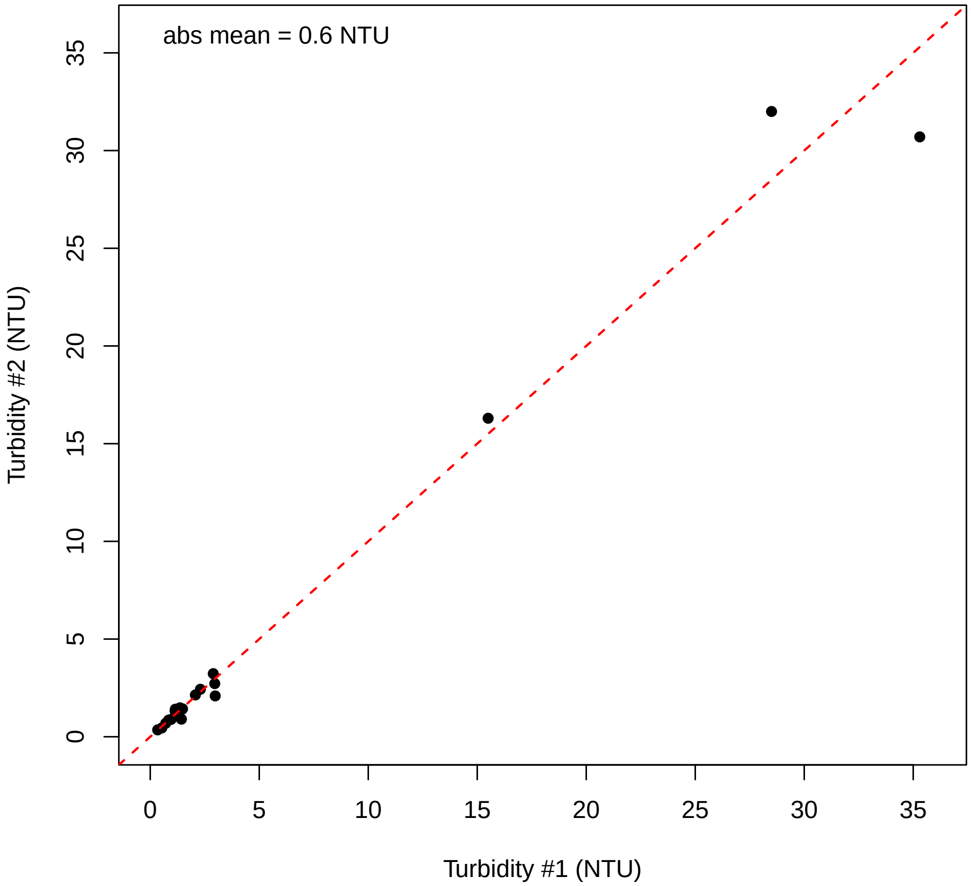


Figure C49: Turbidity field duplicates for the 2021/2022 Lake Whatcom monitoring program (tributary samples). Diagonal reference line shows 1:1 relationship. The scatter at extremely high concentrations is expected.

D Lake Whatcom Online Data

The following **readme** file describes the electronic data posted at the IWS web site (`www.wwu.edu/iws`) and additional data available from IWS. Please contact the Director of the Institute for Watershed Studies if you have questions or trouble accessing the online data.

```
**************************************************************
* README FILE - LAKE WHATCOM ONLINE DATA
* THIS FILE WAS UPDATED JANUARY 4, 2023
**************************************************************
Most of the Lake Whatcom water quality data are available in
electronic format at the IWS website (http://www.wwu.edu/iws) or from
the IWS Director.

The historic and current detection limits and abbreviations for each
parameter are listed in the annual reports.  The historic detection
limits for each parameter were estimated based on recommended lower
detection ranges, instrument limitations, and analyst judgment on the
lowest repeatable concentration for each test.  Over time, some
analytical techniques have improved so that current detection limits
are usually lower than historic detection limits.  Because the Lake
Whatcom data set includes long-term monitoring data, which have been
collected using a variety of analytical techniques, this report sets
conservative detection limits to allow comparisons between years.

All files are comma-separated ascii data files.  The code "NA" has
been entered into all empty cells in the ascii data files to fill in
unsampled dates and depths, missing data, etc.  Questions about
missing data should be directed to the IWS Director.

Unless otherwise indicated, the electronic data files have NOT been
censored to flag or otherwise identify below detection and above
detection values.  As a result, the ascii files may contain negative
values due to linear extrapolation of the standards regression curve
for below detection data.  It is essential that any statistical or
analytical results that are generated using these data be reviewed by
someone familiar with statistical uncertainty associated with
uncensored data.
```

```
*************************************************************
* ONLINE LAKE DATA FILES:
*************************************************************
Hydrolab/YSI data
1988_hl.csv, 1989_hl.csv, 1990_hl.csv, 1991_hl.csv, 1992_hl.csv
1993_hl.csv, 1994_hl.csv, 1995_hl.csv, 1996_hl.csv, 1997_hl.csv
1998_hl.csv, 1999_hl.csv, 2000_hl.csv, 2001_hl.csv, 2002_hl.csv
2003_hl.csv, 2004_hl.csv, 2005_hl.csv, 2006_hl.csv, 2007_hl.csv
2008_hl.csv, 2009_hl.csv, 2010_hl.csv, 2011_hl.csv, 2012_hl.csv
2013_hl.csv, 2014_hl.csv, 2015_hl.csv, 2016_hl.csv, 2017_hl.csv
2018_hl.csv, 2019_hl.csv, 2020_hl.csv, 2021_hl.csv, 2022_hl.csv

Water quality data
1988_wq.csv, 1989_wq.csv, 1990_wq.csv, 1991_wq.csv, 1992_wq.csv
1993_wq.csv, 1994_wq.csv, 1995_wq.csv, 1996_wq.csv, 1997_wq.csv
1998_wq.csv, 1999_wq.csv, 2000_wq.csv, 2001_wq.csv, 2002_wq.csv
2003_wq.csv, 2004_wq.csv, 2005_wq.csv, 2006_wq.csv, 2007_wq.csv
2008_wq.csv, 2009_wq.csv, 2010_wq.csv, 2011_wq.csv, 2012_wq.csv
2013_wq.csv, 2014_wq.csv, 2015_wq.csv, 2016_wq.csv, 2017_wq.csv
2018_wq.csv, 2019_wq.csv, 2020_wq.csv, 2021_wq.csv, 2022_wq.csv

Plankton counts
plankton.csv

The *_hl.csv files include: site, depth (m), month, day, year, temp
(temperature, C), pH, cond (conductivity, uS/cm), do (dissolved
oxygen, mg/L), lcond (lab conductivity qc, uS/cm), secchi (secchi
depth, m).

The *_wq.csv files include: site, depth (m), month, day, year, alk
(alkalinity, mg/L as CaCO3), turb (turbidity. NTU), nh3 (ammonium,
ug-N/L), tn (total persulfate nitrogen, ug-N/L), nos (nitrate/
nitrite, ug-N/L), srp (soluble reactive phosphate, ug-P/L), tp (total
persulfate phosphorus, ug-P/L), chl (chlorophyll, ug/L).

The plankton.csv file includes: site, depth (m), month, day, year,
zoop (zooplankton, #/L), chry (chrysophyta, #/L), cyan (cyano-
bacteria, #/L), chlo (chlorophyta, #/L), pyrr (pyrrophyta, #/L).

*************************************************************
* ONLINE HYDROGRAPH DATA FILES:
*************************************************************
WY1998.csv, WY1999.csv, WY2000_rev.csv (rev. 3/8/2012), WY2001.csv,
WY2002.csv, WY2003.csv, WY2004_rev.csv (rev. 6/21/2006), WY2005.csv,
WY2006.csv, WY2007.csv (rev. July 31, 2008), WY2008.csv, WY2009.csv,
```

```
WY2010.csv, WY2011.csv, WY2012.csv, WY2013.csv, WY2014.csv, WY2015.csv
WY2016.csv, WY2017.csv, WY2018.csv, WY2019.csv, WY2020.csv, WY2021.csv,
WY2022.csv

The WY*.csv files include: month, day, year, hour, min, sec, ander.g
(anderson gauge height, ft), ander.cfs(anderson discharge, cfs),
austin.g (austin gauge height, ft), austin.cfs (austin discharge,
cfs), smith.g (smith gauge height, ft), smith.cfs (smith discharge,
cfs).  Anderson Creek hydrograph data were deleted in WY2000_rev.csv
due to uncertainty about the gauge height; Anderson Creek data are
available for WY1998, WY1999, and WY2001-WY2007. Beginning with
WY2002, the variable "time" replaced "hour, min, sec," with time
reported daily on a 24-hr basis. Data are reported as Pacific
Standard Time without Daylight Saving Time adjustment. In WY2022.csv,
there is an additional column for DHSVM modeled data in Smith Creek
(smith.dhsvm.cfs) - these data are provided for the period of time
when the Smith Creek gauge was damaged during winter storms. See Section 4
for further detail.

*************************************************************
* STORM WATER AND TRIBUTARY DATA FILES
*************************************************************
The storm water and tributary data include composite and grab samples
from numerous sites in the Lake Whatcom watershed (1994--present),
representing a variety of study objectives and sampling intensities
over time.  The electronic data files are not posted online, but may
be obtained by contacting the Institute for Watershed Studies.

*************************************************************
* SITE CODES
* ALL FILES - INCLUDES DISCONTINUED SITES AND OFF-LINE DATA
*************************************************************
The site codes in the data are as follows:
    11  = Lake Whatcom Site 1
    21  = Lake Whatcom Intake site
    22  = Lake Whatcom Site 2
    31  = Lake Whatcom Site 3
    32  = Lake Whatcom Site 4
    33  = Strawberry Sill site S1
    34  = Strawberry Sill site S2
    35  = Strawberry Sill site S3

    AlabamaVault inlet     = Alabama canister vault inlet
    AlabamaVault outlet    = Alabama canister vault outlet
    Brentwood inlet        = Brentwood wet pond inlet
```

Brentwood outlet = Brentwood wet pond outlet
ParkPlace cell1 = Park Place wet pond cell 1
ParkPlace cell2 = Park Place wet pond cell 2
ParkPlace cell3 = Park Place wet pond cell 3
ParkPlace inlet = Park Place wet pond inlet
ParkPlace outlet = Park Place wet pond outlet
Parkstone_swale inlet = Parkstone grass swale inlet
Parkstone_swale outlet = Parkstone grass swale outlet
Parkstone_pond inlet = Parkstone wet pond inlet
Parkstone_pond outlet = Parkstone wet pond outlet
SouthCampus inlet = South Campus storm water facility inlet
SouthCampus outletE = South Campus storm water facility east outlet
SouthCampus outletW = South Campus storm water facility west outlet
Sylvan inlet = Sylvan storm drain inlet
Sylvan outlet = Sylvan storm drain outlet
Wetland outlet = Grace Lane wetland

CW1 = Smith Creek (see alternate code below)
CW2 = Silver Beach Creek (see alternate code below)
CW3 = Park Place drain (see alternate code below)
CW4 = Blue Canyon Creek (see alternate code below)
CW5 = Anderson Creek (see alternate code below)
CW6 = Wildwood Creek (discontinued in 2004)
CW7 = Austin Creek (see alternate code below)

The following tributary site codes were used for the expanded 2004-2006 tributary monitoring project

AND = Anderson Creek (same location as CW5 above)
BEA1 = Austin.Beaver.confluence
AUS = Austin.lower (same location as CW7 above)
BEA2 = Austin.upper
BEA3 = Beaver.upper
BLU = BlueCanyon (same location as CW4 above)
BRA = Brannian
CAR = Carpenter
EUC = Euclid
MIL = Millwheel
OLS = Olsen
PAR = ParkPlace (same location as CW3 above)
SIL = SilverBeach (same location as CW2 above)
SMI = Smith (same location as CW1 above)
WHA = Whatcom

****
* VERIFICATION PROCESS FOR THE LAKE WHATCOM DATA FILES
****

During the summer of 1998 the Institute for Watershed Studies began creating an electronic data file that would contain long term data records for Lake Whatcom. These data were to be included with annual Lake Whatcom monitoring reports. This was the first attempt to make a long-term Lake Whatcom data record available to the public. Because these data had been generated using different quality control plans over the years, a comprehensive re-verification process was done.

The re-verification started with printing a copy of the entire data file and checking 5% of all entries against historic laboratory bench sheets and field notebooks. If an error was found, the entire set of values for that analysis were reviewed for the sampling period containing the error. Corrections were noted in the printed copy and entered into the electronic file; all entries were dated and initialed in the archive copy.

Next, all data were plotted and descriptive statistics (e.g., minimum, maximum) were computed to identify outliers and unusual results. All outliers and unusual data were verified against original bench sheets. A summary of decisions pertaining to these data is presented below. All verification actions were entered into the printed copy, dated, and initialed by the IWS director.

The following is a partial list of the changes made to the verified Lake Whatcom data files. For detailed information refer to the data verification archive files in the IWS library.

Specific Deletions: 1) Rows containing only missing values were deleted. 2) All lab conductivity for February 1993 were deleted for cause: meter inadequate for low conductivity readings (borrowed Huxley’s student meter). 3) All Hydrolab conductivity from April - December 1993 were deleted for cause: Hydrolab probe slowly lost sensitivity. Probe was replaced and Hydrolab was reconditioned prior to the February 1994 sampling. 4) All 1993 Hydrolab dissolved oxygen data less than or equal to 2.6 mg/L were deleted for cause: Hydrolab probe lost sensitivity at low oxygen concentrations. Probe was replaced and Hydrolab was reconditioned prior to February 1994 sampling. 5) All srp and tp data were deleted (entered as "missing" in 1989) from the July 10, 1989 wq data due to sample contamination in at least three samples. 6) December 2, 1991, Site 3, 0 m conductivity point deleted due to inconsistency with adjacent points. 7) December 15, 1993, Site 4, 80 m lab conductivity point deleted because matching field conductivity data are absent and point is inconsistent with all other lab conductivity points. 8) November 4, 1991, Site 2, 17-20 m, conductivity points deleted due to evidence of equipment problems related to depth. 9) February 2, 1990, Site 1, 20 m, soluble reactive phosphate and total phosphorus points deleted due to evidence of sample contamination. 10) August 6, 1990, Site 1, 0 m, soluble reactive phosphate and total phosphorus points deleted due to evidence of sample contamination. 11) October 5, 1992, Site 3, 80 m, all data deleted due to evidence of sample contamination in turbidity, ammonium, and total phosphorus results. 12) August 31, 1992, Site 3, 5 m, soluble reactive phosphate and total phosphorus data deleted due to probable coding error. 13) All total Kjeldahl nitrogen data were removed from the historic record. This was not due to errors with the data but rather on-going confusion over which records contained total persulfate nitrogen and which contained total Kjeldahl nitrogen. The current historic record contains only total persulfate nitrogen. Total Kjeldahl nitrogen data were retained in the IWS data base, but not in the long-term Lake Whatcom data files.

****
* ROUTINE DATA VERIFICATION PROCESS
****

1994-present: The Lake Whatcom data are verified using a four step method: 1) The results are reviewed as they are generated. Outliers are checked for possible analytical or computational errors. This step is completed by the Laboratory Analyst and IWS Laboratory Supervisor. 2) The results are reviewed monthly or quarterly and sent to the City. Unusual results are identified. This step is completed by the IWS Director. 3) The results are reviewed on an annual basis and discussed in the Lake Whatcom Monitoring Program Final Report. Unusual results are identified, and explained, if possible. This step is completed by the IWS Director, IWS Laboratory Supervisor, and Laboratory Analyst. 4) Single-blind quality control samples, laboratory duplicates, and field duplicates are analyzed as specified in the Lake Whatcom Monitoring Program contract and in the IWS Laboratory Certification requirements. Unusual results that suggest instrumentation or analytical problems are reported to the IWS Director and City. The results from these analyses are summarized in the annual report.

1987-1993: The lake data were reviewed as above except that the IWS Director’s responsibilities were delegated to the Principle Investigator in charge of the lake monitoring contract.

Prior to 1987: Data were informally reviewed by the Laboratory Analyst and IWS Director. Laboratory and field duplicates were commonly included as part of the analysis process, but no formal (i.e., written) quality control program was in place. Laboratory logs were maintained for most analyses, so it is possible to verify data against original analytical results. It is also possible to review laboratory quality control results for some analyses.