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Lake Whatcom Monitoring Project 2014/2015 Report

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Lake Whatcom Monitoring Project 2014/2015 Report

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Executive Summary

Background for the Lake Whatcom Annual Reports

- This report describes the results from the 2014/2015 Lake Whatcom monitoring program conducted by the Institute for Watershed Studies at Western Washington University (www.wwu.edu/iws).
- The major objectives in 2014/2015 were to continue long-term baseline water quality monitoring in Lake Whatcom; collect storm runoff water quality data from Anderson, Austin, and Brannian Creeks; 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 4.2, beginning on page 76, 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 2014/2015 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). The surface water temperatures were warmer than historic medians from February through July, and the entire water column was relatively warm from February through May.
- The levels of [hypolimnetic oxygen](#) have declined over time at Site 1, causing the lake to be listed by the Department of Ecology on the 1998 303d list of impaired waterbodies in the state of Washington. Following the onset of stratification, the hypolimnetic oxygen concentrations dropped very rapidly. By July 8, 2015 the oxygen concentration was <1 mg/L from 12 meters to the bottom.
- In February 2015, [incomplete mixing](#) of the water column was observed at Sites 3–4, which contributed to a slight oxygen deficit in the hypolimnion at these sites, along with atypical patterns in conductivity and pH.
- [Nitrate depletion](#) was evident at all sites in the photosynthetic zone during the summer due to algal uptake of this essential nutrient. Low nitrate in the photosynthetic zone favors the growth of Cyanobacteria. 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](#) and [chlorophyll concentrations](#) have increased significantly over time at most sites. The patterns continue to be somewhat variable, but it appears that the chlorophyll concentrations have stabilized since 2004, with medians ranging from 3.8–6.7 µg/L at Site 1 and 2.9–4.6 µg/L at Sites 2–4.
- The concentrations of [trihalomethanes and haloacetic acids](#) (TTHMs and HAAs) in Bellingham's treated drinking water have been increasing over time, but the concentrations of both types of disinfection by-products remained below the recommended maximum contaminant levels of 0.080 mg/L and 0.060 mg/L, respectively.
- All of the mid-basin [fecal coliforms counts](#) were less than 10 cfu/100 mL. 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 *Extraordinary Primary Contact Recreational* bacteria standard for Washington.

- [Hydrograph data](#) were collected at Austin and Smith Creeks using rating curves developed with Aquarius software to calculate discharge.
- Due to the unusually dry weather conditions in 2014/2015, only [four storm events](#) were sampled. Samples were collected in Anderson, Austin, and Brannian Creeks using automated samplers to collect time-paced discrete samples. The storm runoff contained elevated levels of total suspended solids, total phosphorus, and total nitrogen.

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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 4.2, beginning on page 76.

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 supplemental water source to various consecutive systems to the City of Bellingham, including the Lummi Nation and the Puget Sound Energy Co-Generation Plant, which is located at the former Georgia-Pacific Corporation site.¹

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.

In January 22, 2014, approximately 8,800 acres of forest lands formerly managed by the Department of Natural Resources was reconveyed to Whatcom County to be managed as low impact park lands. The Lake Whatcom reconveyance planning process is summarized online at www.whatcomcounty.us/625/Lake-Whatcom-Reconveyance.

¹The Georgia-Pacific Corporation closed its Bellingham pulp mill operations in 2001, reducing its water requirements from 30–35 MGD to 7–12 MGD. By 2007 the water requirements had been reduced to 0.6–3.88 MGD; the mill closed its operations in December 2007.

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 1981, 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 2014/2015 Lake Whatcom monitoring program were to continue long-term baseline water quality monitoring in Lake Whatcom; collect storm runoff water quality data from Anderson, Austin, and Brannian Creeks; and continue collection of hydrologic data from Austin and Smith Creeks.

Detailed site descriptions can be found in Appendix A. The historic 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 261). Table 2.1 (page 16) lists abbreviations and units used to describe water quality analyses in this document.

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 84 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 1 & 2, November 4 & 5, and December 2 & 4 2014; and February 3 & 4, April 9 & 14, May 7 & 12, June 2 & 4, July 6 & 8, August 3 & 6, and September 1 & 3 2015. Each sampling event is a multi-day task; all samples were collected during daylight hours, typically between 10:00 am and 3:00 pm.

A YSI multiparameter field meter² was used to measure temperature, pH, dissolved oxygen, and conductivity. Raw water samples were collected using a Van-Dorn sampler. All water samples (including bacteriological samples) collected in the field were stored on ice and in the dark until they reached the laboratory, and were analyzed as described in Table 2.1 (page 16). Total organic carbon analyses were done by AmTest.³ 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. 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 (ammonium⁴, nitrate/nitrite, total nitrogen, soluble phosphate, total phosphorus, alkalinity, turbidity, chlorophyll); plankton and bacteria counts; and total organic carbon measurements.

Tables 2.2–2.6 (pages 17–21) summarize the current field measurements, ambient water quality, and coliform data. The raw data are available online at www.wvu.edu/iws as described in Appendix D (page 261). The monthly profiles for temperature, dissolved oxygen, conductivity, and pH are plotted in Figures B1–B50 (pages 88–137).

²YSI Inc., Yellow Springs, Ohio

³AmTest, 13600 Northeast 126th Place, Suite C, Kirkland, WA, 98034–8720.

⁴Ammonium (NH_4^+) is ionized ammonia (NH_3). Nearly all ammonia is ionized in surface water. Earlier IWS reports used the term ammonia and ammonium interchangeably to describe ammonium concentrations because it is generally understood that ammonia is usually ionized. To improve clarity, IWS has switched to the term “ammonium” to indicate that we are reporting the concentration of ionized ammonia. This does not represent any change in analytical methods.

The 2014/2015 lake data are plotted with historic lake data in Figures B51–B130 (pages 139–219). 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.

2.3.1 Water temperature

The 2015 surface water temperatures were warmer than historic median values from February through July (Figure 2.1, page 24), and the entire water column was relatively warm from February through April or May (Figure 2.2, page 25).

The summer temperature profiles (e.g., Figures B46–B50, pages 133–137) show how the lake stratifies into a warm surface layer (*epilimnion*), and cool bottom layer (*hypolimnion*). The transition zone between the epilimnion and hypolimnion (the *metalimnion*), is a region of rapidly changing water temperature. When stratified, the profiles show distinct differences between surface and bottom temperatures. 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 are usually stratified by late spring or early summer. (The Intake is too shallow to develop stable stratification.) 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 ($\Delta T \geq 5^\circ\text{C}$), it is unlikely that the lake will destratify.⁵

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, but basin 3 (Sites 3–4) is often still stratified in November or early December. Complete thermal destratification of basin 3 usually occurs in December or early January, so by February the temperatures are uniform throughout the water column at all sites.

⁵The ΔT is the difference between the epilimnion and hypolimnion temperatures.

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: Figures B.7 in Matthews, et al., 2015).

In February 2015, incomplete mixing was observed at Sites 3–4 (Figures B19–B20, pages 106–107). The temperature profiles were essentially uniform throughout the water column, indicating that the lake was thermally destratified. But the oxygen profiles indicated that the water column was not completely mixed in February. This could be partly due to late destratification in basin 3; Sites 3–4 were still stratified in December, 2014. But basin 3 is often weakly stratified in December, so this feature by itself does not explain the incomplete mixing.

The lack of mixing observed in basin 3 is usually associated with a chemical gradient where the water near the bottom is saline, which is denser than fresh water. But Lake Whatcom does not have a strong salinity gradient. Instead, the lack of mixing is probably due to the shape of basin 3 and weak winter storms. Wind energy creates the internal waves that mix the water column. The amount of internal wave movement is related to the duration, intensity, and direction of the wind storm, as well as the length of lake surface that is impacted by the wind (fetch). Deep, steep-sided lakes with a small surface area-to-volume ratio may not receive enough wind energy to generate strong internal waves, which can result in failure to mix the entire water column, despite uniform surface-to-bottom water temperatures. This lack of winter mixing has been observed frequently in the west arm of Lake Samish (Matthews and Vandersypen, 2011), but was not observed in Lake Whatcom until 2015 (based on 1988–2015 temperature data).

2.3.2 Dissolved oxygen

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.

As in previous years, Sites 1–2 developed severe hypolimnetic oxygen deficits by mid-summer (Figures B41–B42 and B56–B57, pages 128–129 and 144–145). 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, biological respiration usually has little influence on hypolimnetic oxygen concentrations except occasionally in the deepest samples from Site 3 (Figures B49–B50 and B59–B60, pages 136–137 and 147–148). In contrast, there is rapid depletion of the hypolimnetic oxygen concentrations at Sites 1–2 (Figures B46–B47, and B56–B57, pages 133–134 and 144–145). These two sites are in shallow basins that have small hypolimnions compared to their photic zones, so decomposition of algae and other organic matter causes a measurable drop in hypolimnetic oxygen over the summer.⁶

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).⁷ The increasing rate of oxygen loss is most apparent during July and August, after the lake develops stable stratification but before oxygen levels drops 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 2.3–2.6 (pages 26–29), there were significant negative correlations between dissolved oxygen and time for all hypolimnetic samples collected during July and August.⁸ In 2015, the rate of hypolimnetic oxygen loss at Site 1 was much faster than expected, resulting in anaerobic conditions throughout the hypolimnion by early July (Figures 2.3–2.6 and B36, pages 26–29 and 124).

⁶The photic zone is the portion of the lake with enough light to support algal photosynthesis, which extends to about 10 meters below the surface in Lake Whatcom. Assuming a photic zone of 0–10 meters, the photic zones for basins 1, 2, and 3 would be 75%, 70%, and 17%, respectively (Mitchell, et al., 2010).

⁷www.ecy.wa.gov/programs/wq/303d.

⁸ 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 .

In addition to the rapid loss of hypolimnetic oxygen at Site 1, the lake developed atypical oxygen patterns at Sites 3–4 that seemed to be related to incomplete mixing in February 2015 (see temperature discussion on page 5 and Figures 2.7–2.14, pages 30–37). Usually, biological respiration has very little effect on the hypolimnetic oxygen concentrations in basin 3, so oxygen concentrations remain high throughout the period of stratification. Based on past data, the only exception we expect to find will be in the deepest samples from Site 3, where low oxygen concentrations are common just prior to destratification (Figure B59, page 147). In 2015, however, the water column at Sites 3–4 did not mix completely in February. As a result, the lower portion of the water column entered into stratification with an oxygen deficit of about 2 mg/L (Figure 2.7, page 30 and Figures B19–B20, page 106–107). As stratification developed, internal mixing within the hypolimnion redistributed the low oxygen water throughout the entire hypolimnion, but because the lake was stratified, the lower oxygen concentrations will persist until the water column mixes in late December or January.

A region of supersaturated oxygen was evident in the metalimnion at Site 1 in June and July, and smaller peaks were evident at Sites 2–4 in July (Figures B31–B40, pages 118–127). 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). Sites 3 and 4 developed small oxygen sags near the thermocline (e.g., Figures B4 and B5, pages 91 and 92), which are caused by respiration of heterotrophic bacteria that accumulate along the density gradient between the epilimnion and hypolimnion (Matthews and DeLuna, 2008).

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 alternate electron acceptors.⁹ First, bacteria will use nitrate as an alternate to oxygen, converting nitrate to ammonium or 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

⁹For a more complete discussion of anaerobic decomposition in lakes, see Wetzel, 2001.

the all of the above electron acceptors 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 2.7, page 22). 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. In 2015, the entire hypolimnion at Site 1 was anaerobic by early July, so by October the hydrogen sulfide concentrations were the highest levels recorded at that site in 17 years. Although Site 2 presumably stratified at about the same time as Site 1, the entire hypolimnion was not anaerobic until August, which may be why the site didn't develop unusually high levels of hydrogen sulfide in 2015.

2.3.3 Conductivity and pH

The pH and conductivity data followed trends that were fairly typical for Lake Whatcom (Figures B1–B50 and B61–B70, pages 88–137 and 149–158). Surface pH values increased during the summer due to photosynthetic activity. Hypolimnetic pH values decreased and conductivities increased due to decomposition and the release of dissolved compounds from the sediments. The most important exceptions were probably caused by incomplete water column mixing in basin 3 (see page 5), which was associated with elevated conductivities near the bottom of Site 3 in February and April (Figures B19 and B24, pages 106 and 111)

There was a significant long-term trend in the conductivity data that 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). The conductivity concentrations were elevated in deep samples at Sites 1–2, and occasionally Site 3, coinciding with periods of low oxygen near the bottom. (Figures B66, B67, and B69, pages 154, 155, and 157).

2.3.4 Alkalinity and turbidity

Because Lake Whatcom is a soft water lake, the alkalinity values were fairly low at most sites and depths (Figures B71–B75, pages 160–164). During the summer the alkalinity values at the bottom of Sites 1–2, and occasionally Site 3, increased due to decomposition and the release of dissolved compounds in the lower waters.

Turbidity values in the lake were usually low (1–3 NTU) except during late summer in samples from 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 Site 3 (Figures B76–B80, pages 165–169).

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 basin 3 because there are fewer distracting late summer hypolimnetic turbidity peaks (see February 2009 storm-related turbidity peaks in Figures B78 and B79–B80; pages 167 and 168–169).

2.3.5 Nitrogen and phosphorus

The nitrogen and phosphorus data for Lake Whatcom are illustrated in Figures B81–B105 (pages 170–194). 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.¹⁰

Nitrogen: Most algae require inorganic nitrogen in the form of nitrate or ammonium for growth, but some types of algae can use organic nitrogen or even dissolved nitrogen gas.¹¹ Nitrate depletion was evident at all sites in the photosynthetic zone during the summer (Figures B86–B90, pages 175–179), particu-

¹⁰Organic nitrogen and phosphorus comes from living or decomposing plants and animals, and may include bacteria, algae, leaf fragments, and other organic particles.

¹¹Only Cyanobacteria and a few uncommon species of diatoms can use nitrogen gas.

larly at Site 1, where the epilimnetic nitrate concentrations usually drop below $20 \mu\text{g-N/L}$ by the end of the summer. Epilimnetic nitrogen depletion is an indirect measure of phytoplankton productivity, and because algal densities have been increasing throughout the lake, epilimnetic dissolved inorganic nitrogen concentrations (DIN)¹² have been declining over time (Figure 2.15, page 38). Low epilimnetic DIN concentrations favor the growth of Cyanobacteria because many types of Cyanobacteria can use dissolved N_2 gas as a nitrogen source.

Hypolimnetic nitrate concentrations dropped below $20 \mu\text{g-N/L}$ at Sites 1–2 (Figures B86–B87, pages 175–176). In anaerobic environments, bacteria reduce nitrate (NO_3^-) to nitrite (NO_2^-) and nitrogen gas (N_2). The historic 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 B87, page 176). Since then, the only year that Site 2 hypolimnetic nitrate concentrations did not drop below $20 \mu\text{g-N/L}$ 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.¹³ 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 nitrite and 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 B81 & B82, pages 170 & 171). 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 B82, page 171). By October 2015, the extended anoxia in the hypolimnion at Sites 1–2 resulted in unusually high ammonium concentrations at 20 meters ($467 \mu\text{g-N/L}$ and $688 \mu\text{g-N/L}$, respectively). Site 1 was destratified by early November, so the ammonium concentrations dropped to $<25 \mu\text{g-N/L}$ at all depths, but Site 2 was still slightly stratified, with an ammonium concentration of $978 \mu\text{g-N/L}$ at 20 meters. By December, both sites were destratified and ammonium concentrations were low throughout the water column

¹²Dissolved inorganic nitrogen includes ammonium, nitrate, and nitrite. Usually, epilimnetic concentrations of ammonium and nitrite are low, so DIN is nearly equivalent to nitrate.

¹³Ammonium 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.

Sites 3–4 often have slightly elevated ammonium concentrations in the metalimnion at 20 m, or near the bottom at 80–90 m (Figures B84–B85, pages 173–174). 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).

When hypolimnetic oxygen concentrations are low, sediment-bound phosphorus becomes soluble and leaches into the overlying water. 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 mixed 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, similar to the epilimnetic DIN reduction that was described for nitrogen. But, since this uptake simply moves the phosphorus into the “live-algae” fraction of organic phosphorus, total phosphorus concentrations may actually increase in the epilimnion.

In Lake Whatcom, total phosphorus and soluble phosphate concentrations were usually low except in the hypolimnion at Sites 1–2 just prior to destratification (Figures B96–B100, pages 185–189 and B101–B105, pages 190–194). Epilimnetic total phosphorus concentrations are usually lower than late-summer hypolimnetic peaks. Prior to 2000, the median epilimnetic phosphorus concentrations were $<5 \mu\text{g-P/L}$ at Sites 2–4 and approximately $5\text{--}8 \mu\text{g-P/L}$ at Site 1 (Figure 2.16, page 39). The epilimnetic phosphorus levels have increased significantly at most sites (Figure 2.16, page 39); however, the pattern is quite erratic, reflecting the complicated nature of phosphorus movement in the water column.

2.3.6 Chlorophyll, plankton, and Secchi depth

Site 1 continued to have the highest chlorophyll concentrations of all the sites (Figures B106–B110, pages 195–199). 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 Lake Whatcom plankton counts were usually dominated by Chrysophyta, primarily *Dinobryon*, *Mallomonas*, and diatoms (Figures B121–B130, pages 210–219). Substantial blooms of bluegreen bacteria (Cyanobacteria) and green algae (Chlorophyta) 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, Cyanobacteria and Chlorophyta often dominate the plankton biomass, particularly in late summer and early fall (Ashurst, 2003; Matthews, et al., 2002b). Most of the Cyanobacteria in the lake samples are counted by colony rather than as individual cells because of the tiny cell size. When all cells are counted, the plankton counts are dominated by Cyanobacteria (Matthews, et al. 2012).

Secchi depths (Figures B111–B115, pages 200–204) showed no clear seasonal pattern because transparency in Lake Whatcom is affected by particulates from 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 eutrophica-

tion and Matthews, et al., 2005, for a description of the chemical and biological indicators of eutrophication in Lake Whatcom).

The median near-surface summer chlorophyll concentrations have increased significantly at all sites since 1994 (Figure 2.17, page 40). 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 $\tau = 0.538$; Sites 2–4 Kendalls $\tau = 0.599$, 0.671, 0.694, respectively).¹⁴ Although the annual chlorophyll concentrations are quite variable, they seem to have stabilized since 2004, ranging from 3.8–6.7 $\mu\text{g/L}$ at Site 1 and 2.9–4.6 $\mu\text{g/L}$ at Sites 2–4.

Chlorophyll is a direct measure of algal biomass and is best used to evaluate trophic changes in the lake (e.g., is the lake becoming more biologically productive?). We used algal counts rather than chlorophyll to look for trends within the same type of algae (e.g., are the numbers of Cyanobacteria increasing?). The actual relationship between chlorophyll concentration and the algae cell count is complex. The amount of chlorophyll in an algal 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. Even if the amount of chlorophyll was constant in each cell, it would take many tiny cells to equal the chlorophyll biomass in one large colony.

Except for the dinoflagellates,¹⁵ the algae counts have increased significantly since 1994 (Figure 2.18, page 41). Similarly, there was a steady increase in the number of Cyanobacteria at all sites (Figure 2.19, page 42). However, as with the chlorophyll concentrations, the algae and Cyanobacteria counts appear to have stabilized around 2004.

2.3.7 Coliform bacteria

The current surface water standards are based on “designated use” categories, which for Lake Whatcom is “Extraordinary Primary Contact Recreation.” The standard for bacteria is described in Chapter 173–201A–200 of the Washington Administrative Code, Water Quality Standards for Surface Waters of the state of

¹⁴See discussion of correlation in footnote on page 6

¹⁵Dinoflagellates are small single-cell algae that are common in Lake Whatcom, but rarely have high densities in the plankton counts.

Washington:

Fecal coliform organism levels must not exceed a geometric mean value of 50 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten sample points exist) obtained for calculating the geometric mean value exceeding 100 colonies/100 mL.

All of the mid-basin (Sites 1–4) and Intake values for fecal coliforms were less than 10 cfu¹⁶/100 mL (Figures B116–B120, pages 205–209) and passed the freshwater *Extraordinary Primary Contact Recreation* bacteria standard.

Coliform samples collected offshore from the Bloedel-Donovan swimming area had slightly higher counts than at Site 1 (mid-basin). None of the Bloedel-Donovan counts exceeded 100 cfu/100 mL and the geometric mean was 2 cfu/100 mL, so this site passed both parts of the freshwater *Extraordinary Primary Contact Recreation* bacteria standard.

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).

The 2014/2015 total organic carbon concentrations ranged from 0.6–2.4 mg/L, with slightly lower concentrations in February than in August (Table 2.8, page 23). The long-term data show that the median total organic carbon concentrations have increased over time, but the pattern is inconsistent from year to year (Figure 2.20, page 43). 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 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).

¹⁶Colony forming unit/100 mL; cfu/100 mL is sometimes labeled “colonies/100 mL.”

The sampling requirement doubled under Phase II; currently the City samples eight locations in the water distribution system.¹⁷

The THMs have been increasing in Bellingham's treated drinking water, particularly during the summer and fall (second and third quarters; Figures 2.21–2.22, pages 44–45), when algal densities are higher. Haloacetic acids (HAAs), another type of disinfection by-product, also show a significant increase over time (Figure 2.23, page 46). The annual results are a little misleading because the trend is confined to winter and spring quarters (Quarters 1–2); the summer and fall data were not significantly correlated with year (Figure 2.24, page 47). 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). As a result, the HAAs trend is not easily explained, and is not a simple response to increasing summer/fall algae.

The total THMs and HAAs remained below the recommended 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.

¹⁷P. Wendling, pers. comm., City of Bellingham Public Works Dept.

Abbrev.	Parameter	Method	Historic DL [†]	2014/2015 MDL [†]	Sensitivity or Confidence limit
IWS field measurements:					
cond	Conductivity	YSI (2010)	–	–	± 2 µS/cm
do	Dissolved oxygen	YSI (2010)	–	–	± 0.1 mg/L
ph	pH	YSI (2010)	–	–	± 0.1 pH unit
temp	Temperature	YSI (2010)	–	–	± 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 (2012) #2320; SOP-IWS-8	–	–	± 0.7 mg/L
cond	Conductivity	APHA (2012) #2510; SOP-IWS-8	–	–	± 2.1 µS/cm
do	Dissolved oxygen	APHA (2012) #4500-O.C.; SOP-IWS-8	–	–	± 0.1 mg/L
ph	pH-lab	APHA (2012) #4500-H ⁺ ; SOP-IWS-8	–	–	± 0.1 pH unit
tss	T. suspended solids	APHA (2012) #2540 D; SOP-IWS-13	2 mg/L	2.7 mg/L	± 2.9 mg/L
turb	Turbidity	APHA (2012) #2130; SOP-IWS-8	–	–	± 0.2 NTU
nh4	Ammonium (auto)	APHA (2012) #4500-NH ₃ H; SOP-IWS-19	10 µg-N/L	9.6 µg-N/L	± 9.6 µg-N/L
no3	Nitrite/nitrate (auto)	APHA (2012) #4500-NO ₃ I; SOP-IWS-22	20 µg-N/L	7.9 µg-N/L	± 16.2 µg-N/L
tn	T. nitrogen (auto)	APHA (2012) #4500-N C; SOP-IWS-22	100 µg-N/L	14.2 µg-N/L	± 20.4 µg-N/L
srp	Sol. phosphate (auto)	APHA (2012) #4500-P G; SOP-IWS-22	5 µg-P/L	2.0 µg-P/L	± 2.1 µg-P/L
tp	T. phosphorus (auto)	APHA (2012) #4500-P J; SOP-IWS-22	5 µg-P/L	2.8 µg-P/L	± 2.7 µg-P/L
IWS plankton analyses:					
chl	Chlorophyll	APHA (2012) #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 (2012) #9222 D	1 cfu/100 mL	1 cfu/100 mL	–
Edge Analytical analyses:					
H ₂ S	Hydrogen sulfide	APHA (2012) #4500-S ²	–	0.100 mg/L	–
AmTest analyses:					
TOC	T. organic carbon	APHA (2012) #5310 B	1.0 mg/L	0.5 mg/L	–

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

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

Variable	Min.	Med.	Mean [†]	Max.
Alkalinity (mg/L CaCO ₃)	18.6	20.9	21.6	28.7
Conductivity (μS/cm)	59.0	60.0	62.3	79.0
Dissolved oxygen (mg/L)	0.2	9.3	7.9	12.5
pH	6.1	7.5	7.4	9.0
Temperature (°C)	7.2	11.5	12.8	23.6
Turbidity (NTU)	0.5	1.0	1.3	7.8
Nitrogen, ammonium (μg-N/L)	<10	<10	36.7	300.4
Nitrogen, nitrate/nitrite (μg-N/L)	<20	174.1	164.8	346.6
Nitrogen, total (μg-N/L)	187.9	349.0	345.9	471.8
Phosphorus, soluble (μg-P/L)	<5	<5	<5	35.0
Phosphorus, total (μg-P/L)	<5	8.9	10.8	62.0
Chlorophyll (μg/L)	0.8	4.4	4.7	15.1
Secchi depth (m)	3.0	4.5	4.4	6.0
Coliforms, fecal (cfu/100 mL) [‡]	<1	1	1	7

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

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

Table 2.2: Summary of Site 1 water quality data, Oct. 2014 – Sept. 2015.

Variable	Min.	Med.	Mean [†]	Max.
Alkalinity (mg/L CaCO ₃)	17.3	19.3	19.7	21.1
Conductivity (μS/cm)	57.0	59.0	59.1	62.0
Dissolved oxygen (mg/L)	8.8	10.2	10.1	11.5
pH	7.4	7.8	7.9	8.6
Temperature (°C)	7.4	15.8	15.3	23.2
Turbidity (NTU)	0.4	0.5	0.6	0.9
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	23.4
Nitrogen, nitrate/nitrite (μg-N/L)	94.2	236.4	227.3	380.0
Nitrogen, total (μg-N/L)	225.7	329.1	344.0	470.6
Phosphorus, soluble (μg-P/L)	<5	<5	<5	<5
Phosphorus, total (μg-P/L)	<5	5.0	5.0	10.0
Chlorophyll (μg/L)	1.4	2.9	3.0	4.9
Secchi depth (m)	4.5	5.9	5.8	7.0
Coliforms, fecal (cfu/100 mL) [‡]	<1	1	1	2

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

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

Table 2.3: Summary of Intake water quality data, Oct. 2014– Sept. 2015.

Variable	Min.	Med.	Mean [†]	Max.
Alkalinity (mg/L CaCO ₃)	18.1	19.3	20.3	28.9
Conductivity (μS/cm)	57.0	59.0	60.4	85.0
Dissolved oxygen (mg/L)	0.2	9.6	8.7	11.6
pH	5.9	7.5	7.5	8.4
Temperature (°C)	7.3	12.4	13.5	23.2
Turbidity (NTU)	0.4	0.6	0.9	6.2
Nitrogen, ammonium (μg-N/L)	<10	<10	40.7	554.9
Nitrogen, nitrate/nitrite (μg-N/L)	<20	250.4	228.8	396.4
Nitrogen, total (μg-N/L)	227.8	396.8	395.0	738.9
Phosphorus, soluble (μg-P/L)	<5	<5	<5	22.4
Phosphorus, total (μg-P/L)	<5	5.5	8.0	41.8
Chlorophyll (μg/L)	0.8	2.5	2.8	7.2
Secchi depth (m)	4.0	6.2	5.9	7.0
Coliforms, fecal (cfu/100 mL) [‡]	<1	1	1	3

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

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

Table 2.4: Summary of Site 2 water quality data, Oct. 2014 – Sept. 2015.

Variable	Min.	Med.	Mean [†]	Max.
Alkalinity (mg/L CaCO ₃)	17.3	18.6	18.9	21.0
Conductivity (μS/cm)	58.0	59.0	59.4	102.0
Dissolved oxygen (mg/L)	0.4	9.2	9.1	11.6
pH	6.3	7.3	7.3	8.7
Temperature (°C)	6.3	8.3	11.0	23.9
Turbidity (NTU)	0.2	0.4	0.5	1.4
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	61.3
Nitrogen, nitrate/nitrite (μg-N/L)	111.2	392.2	342.2	468.5
Nitrogen, total (μg-N/L)	147.6	468.6	422.2	542.7
Phosphorus, soluble (μg-P/L)	<5	<5	<5	<5
Phosphorus, total (μg-P/L)	<5	<5	<5	7.8
Chlorophyll (μg/L)	0.6	2.3	2.6	4.6
Secchi depth (m)	5.5	6.5	6.7	8.5
Coliforms, fecal (cfu/100 mL) [‡]	<1	1	1	2

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

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

Table 2.5: Summary of Site 3 water quality data, Oct. 2014 – Sept. 2015.

Variable	Min.	Med.	Mean [†]	Max.
Alkalinity (mg/L CaCO ₃)	17.0	18.5	18.7	20.8
Conductivity (μS/cm)	58.0	59.0	59.4	61.0
Dissolved oxygen (mg/L)	6.7	9.2	9.2	11.6
pH	6.2	7.1	7.2	8.2
Temperature (°C)	6.3	7.6	10.5	23.3
Turbidity (NTU)	0.2	0.4	0.4	0.7
Nitrogen, ammonium (μg-N/L)	<10	<10	<10	14.1
Nitrogen, nitrate/nitrite (μg-N/L)	124.1	394.1	351.6	471.7
Nitrogen, total (μg-N/L)	188.3	466.4	427.0	517.7
Phosphorus, soluble (μg-P/L)	<5	<5	<5	<5
Phosphorus, total (μg-P/L)	<5	<5	<5	9.4
Chlorophyll (μg/L)	0.3	2.0	2.3	4.7
Secchi depth (m)	6.0	6.6	6.8	8.0
Coliforms, fecal (cfu/100 mL) [‡]	<1	1	1	2

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

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

Table 2.6: Summary of Site 4 water quality data, Oct. 2014 – Sept. 2015.

Year	H ₂ S (mg/L)		Year	H ₂ S (mg/L)	
	Site 1	Site 2		Site 1	Site 2
1999 [†]	0.03–0.04	0.40	2008	0.28	0.38
2000 [†]	0.27	0.53	2009	0.15	0.47
2001 [†]	0.42	0.76	2010	0.38	0.40
2002 [†]	0.09	0.32	2011	0.12	0.16
2003 [†]	0.05	0.05	2012	na	na
2004 [†]	0.25	0.25	2013	0.20 [§]	0.16
2005 [‡]	0.13, 0.12	0.25, 0.42	2014	0.28	0.66
2006	0.20	0.42	2015	0.51	0.41
2007	0.40	0.20			

[†]H₂S samples analyzed by HACH test kit.

[‡]HACH (first value) vs. Edge Analytical (second value)

[§]Corrected value (1.20 in Matthews, et al., 2015)

Table 2.7: October hypolimnetic hydrogen sulfide concentrations at Sites 1 and 2 (20 m). The H₂S samples have been analyzed by Edge Analytical since 2005. Earlier samples were analyzed using a HACH field test kit. The 2012 samples were lost during processing.

Site	Date	Depth (m)	TOC (mg/L)	Date	Depth (m)	TOC (mg/L)
Site 1	Feb 4, 2015	0	1.1	Aug 3, 2014	0	2.3
	Feb 4, 2015	20	1.4	Aug 3, 2014	20	2.4
Intake	Feb 4, 2015	0	0.9	Aug 3, 2014	0	2.3
	Feb 4, 2015	10	1.0	Aug 3, 2014	10	2.1
Site 2	Feb 4, 2015	0	1.1	Aug 3, 2014	0	2.1
	Feb 4, 2015	20	1.1	Aug 3, 2014	20	2.2
Site 3	Feb 3, 2015	0	1.3	Aug 6, 2015	0	2.3
	Feb 3, 2015	80	0.6	Aug 6, 2015	80	1.8
Site 4	Feb 3, 2015	0	0.8	Aug 6, 2-15	0	2.3
	Feb 3, 2015	90	0.7	Aug 6, 2015	90	1.6

Table 2.8: Lake Whatcom 2014/2015 total organic carbon data.

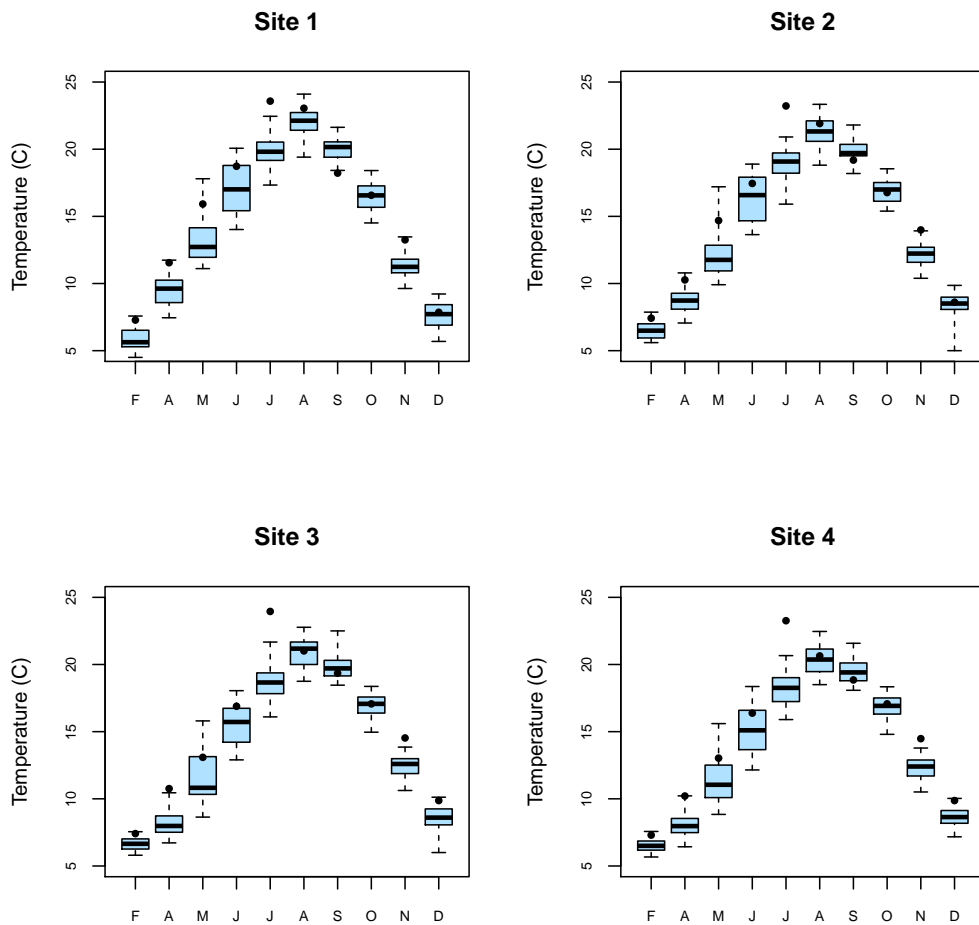


Figure 2.1: Boxplots showing monthly 1988–2014 water temperatures (surface only) vs. surface temperatures in 2015 (●). Boxplots show medians and upper/lower quartiles; whiskers extend to maximum/minimum values.

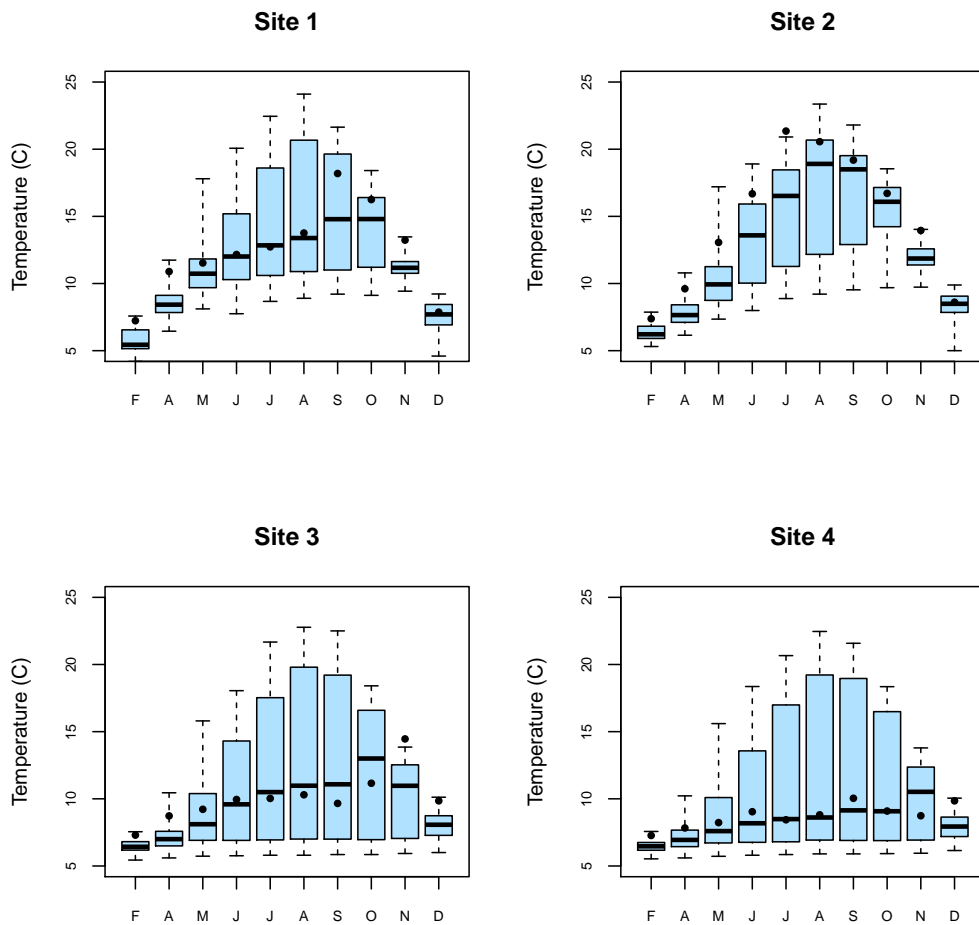


Figure 2.2: Boxplots showing monthly 1988–2014 water temperatures (all depths) vs. median monthly temperatures in 2015 (●). Boxplots show medians and upper/lower quartiles; whiskers extend to maximum/minimum values.

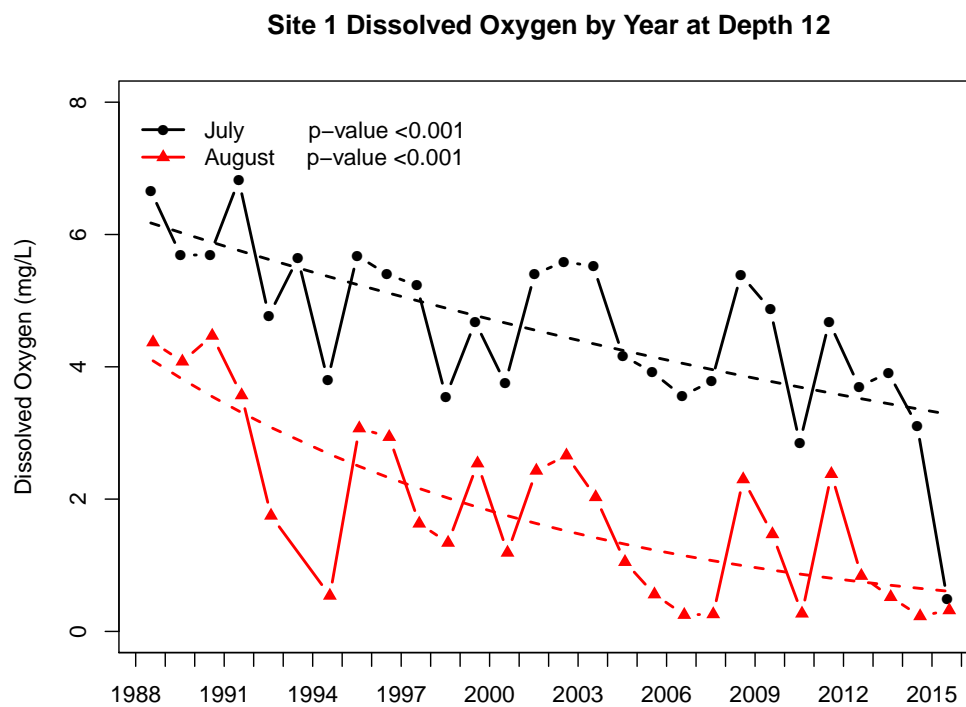


Figure 2.3: Relationship between dissolved oxygen and time at Site 1, 12 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

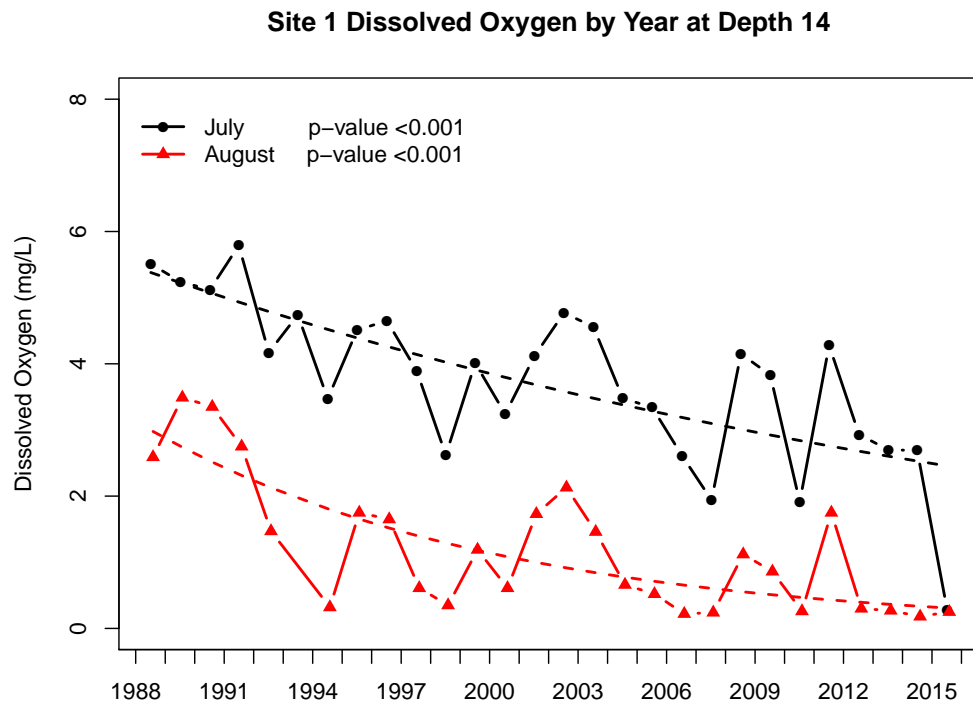


Figure 2.4: Relationship between dissolved oxygen and time at Site 1, 14 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

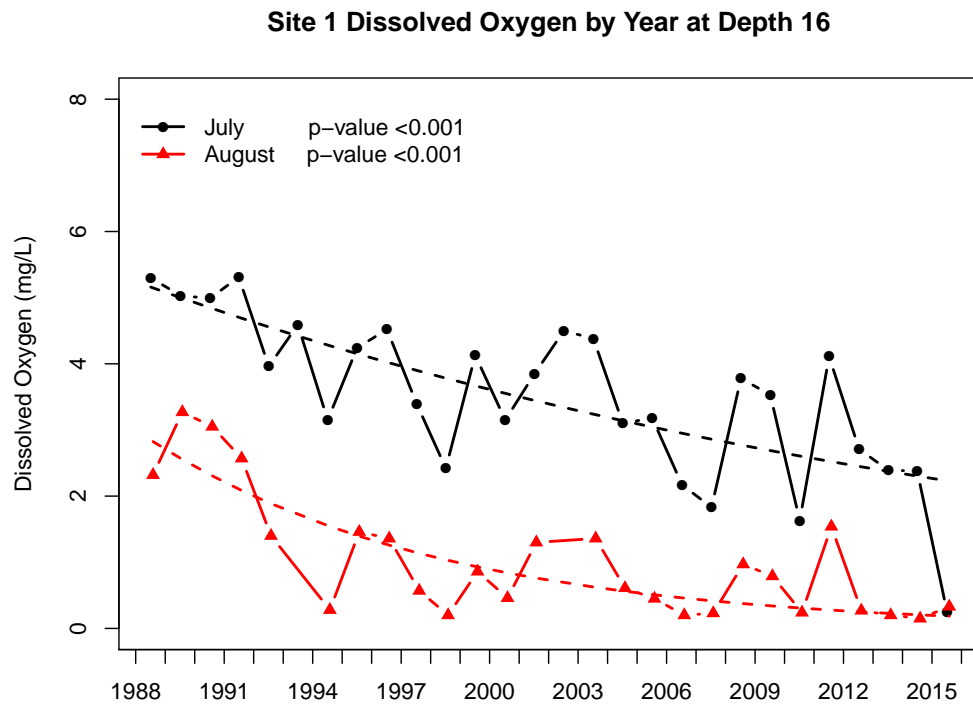


Figure 2.5: Relationship between dissolved oxygen and time at Site 1, 16 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

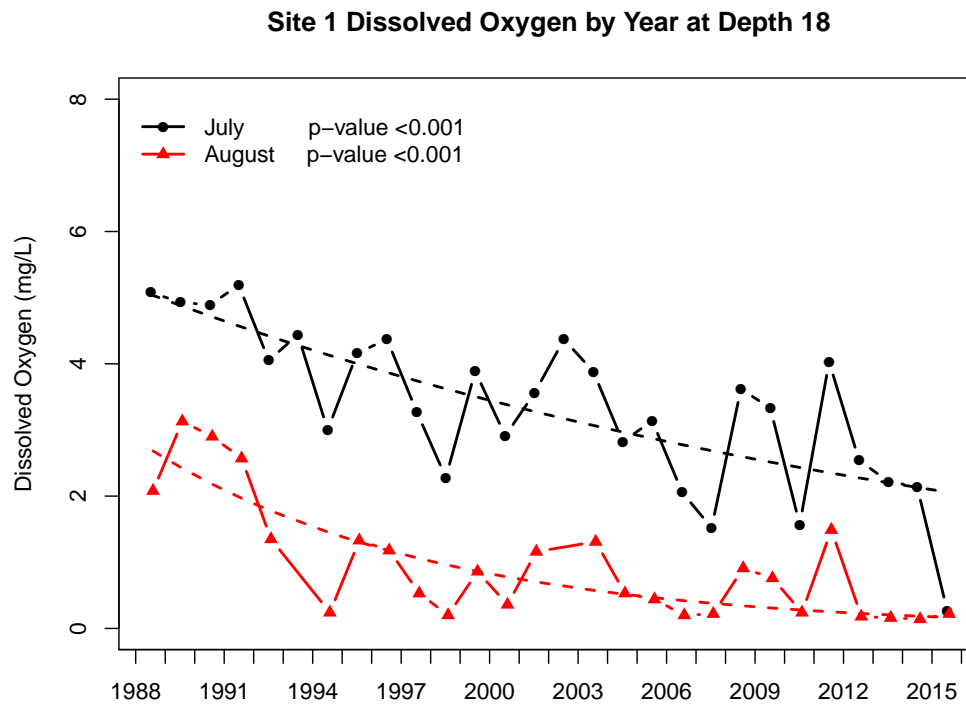


Figure 2.6: Relationship between dissolved oxygen and time at Site 1, 18 m. Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

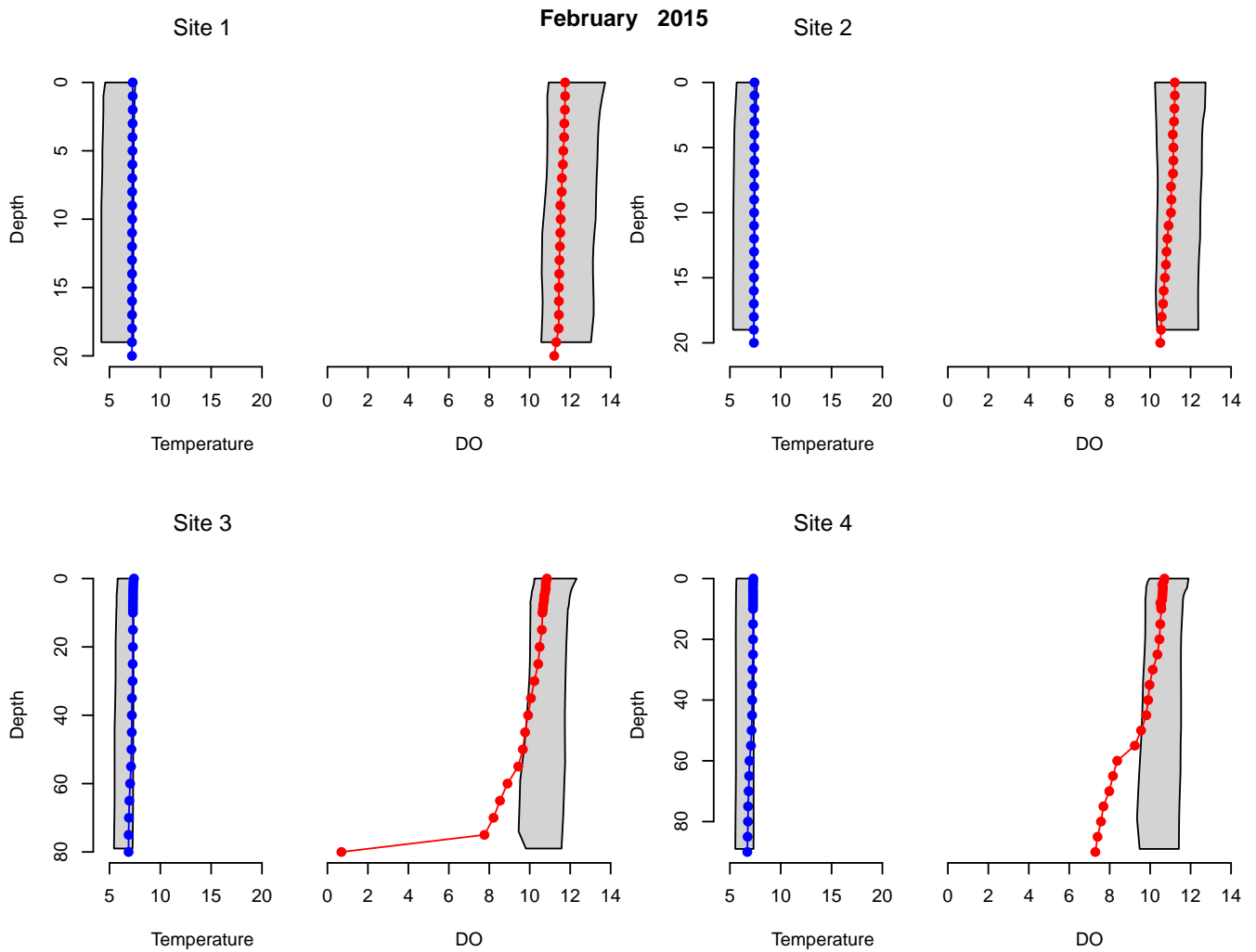


Figure 2.7: February 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

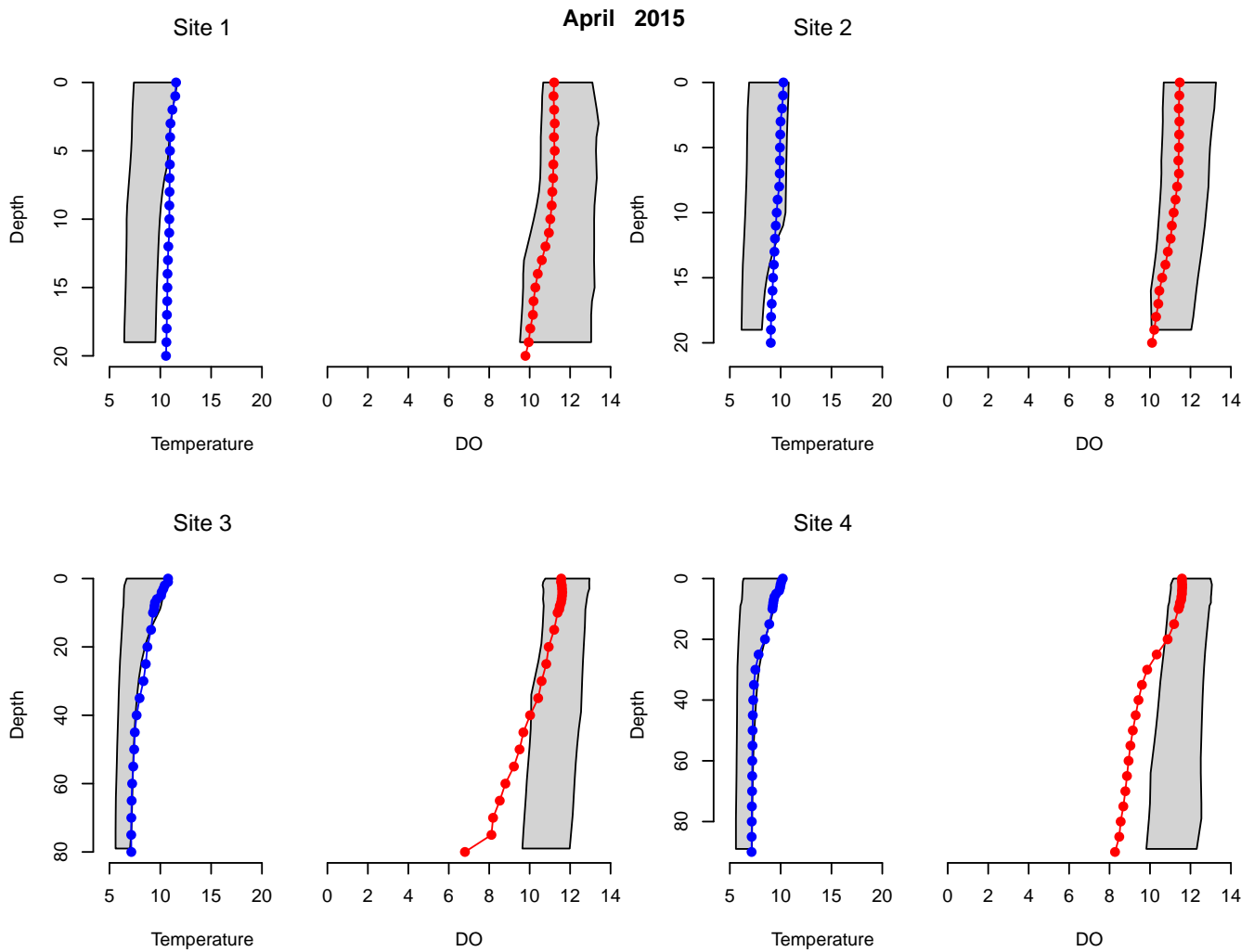


Figure 2.8: April 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

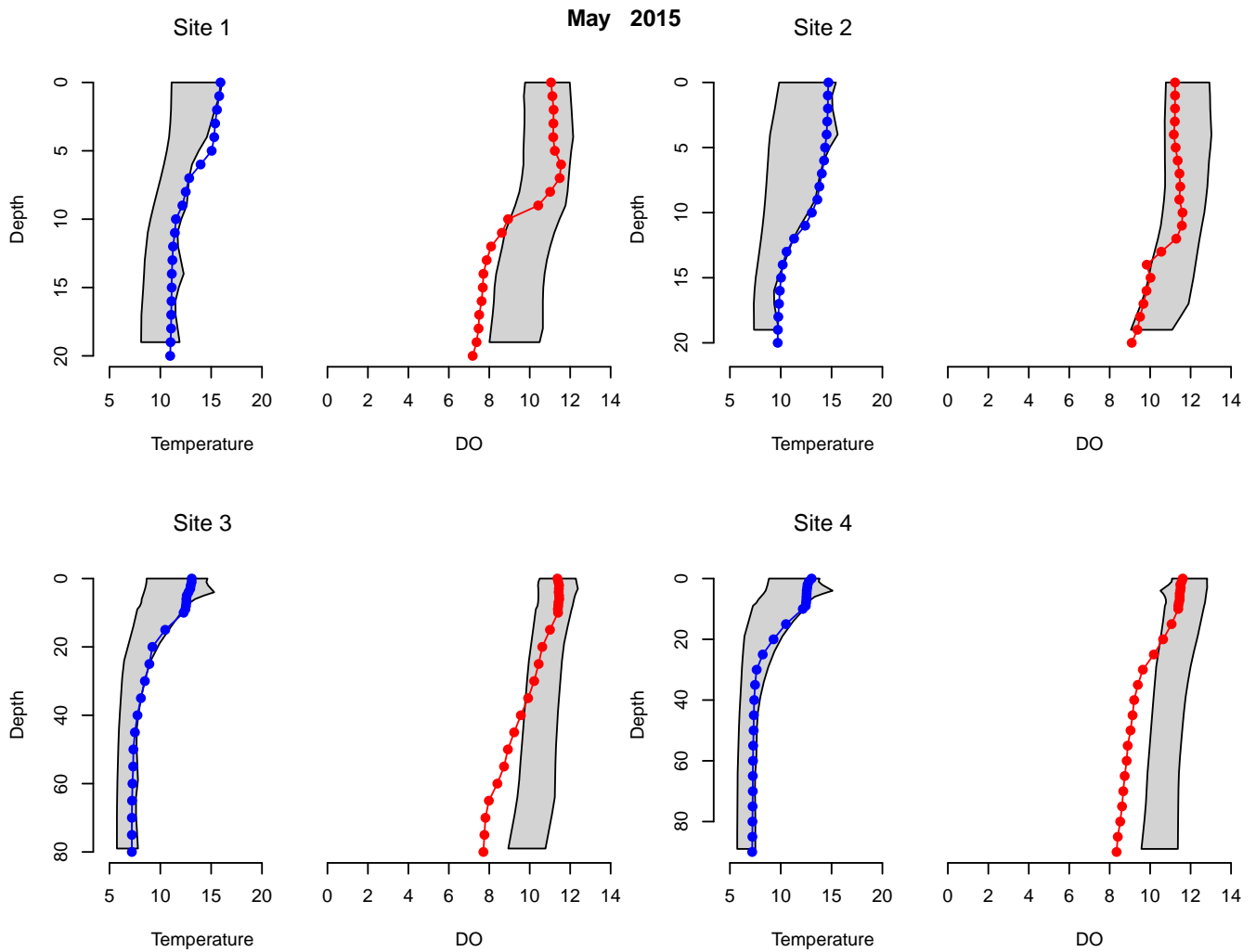


Figure 2.9: May 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

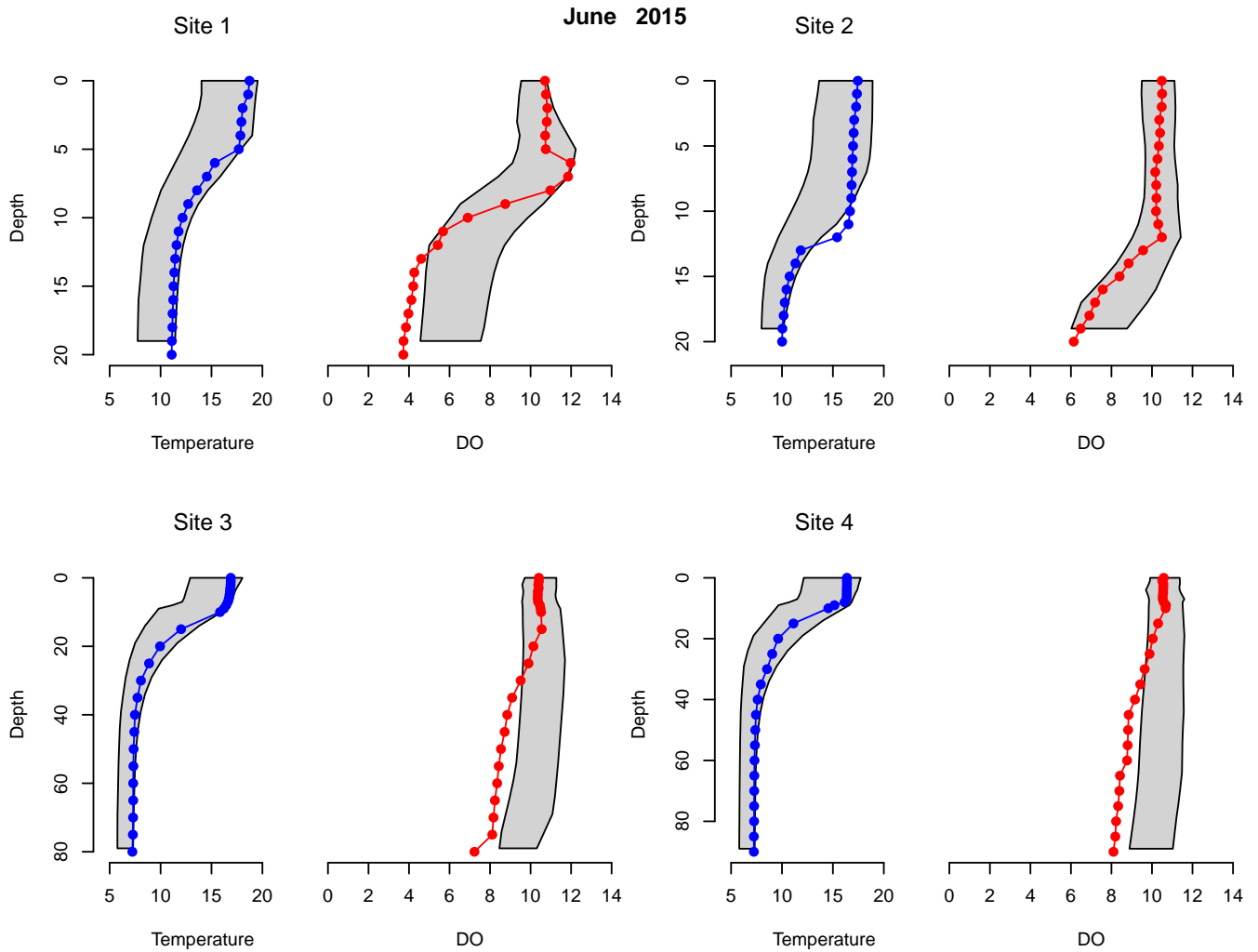


Figure 2.10: June 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

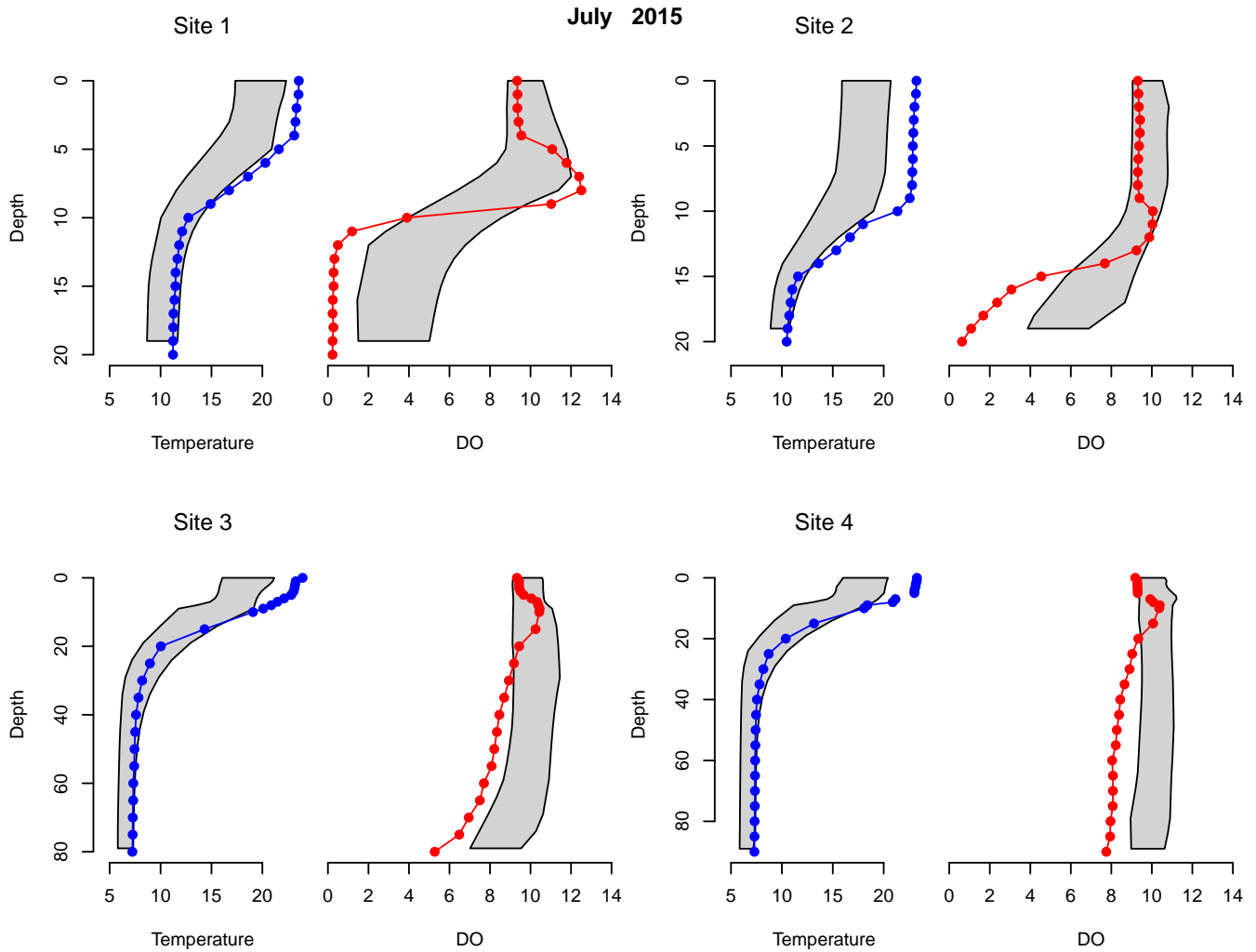


Figure 2.11: July 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

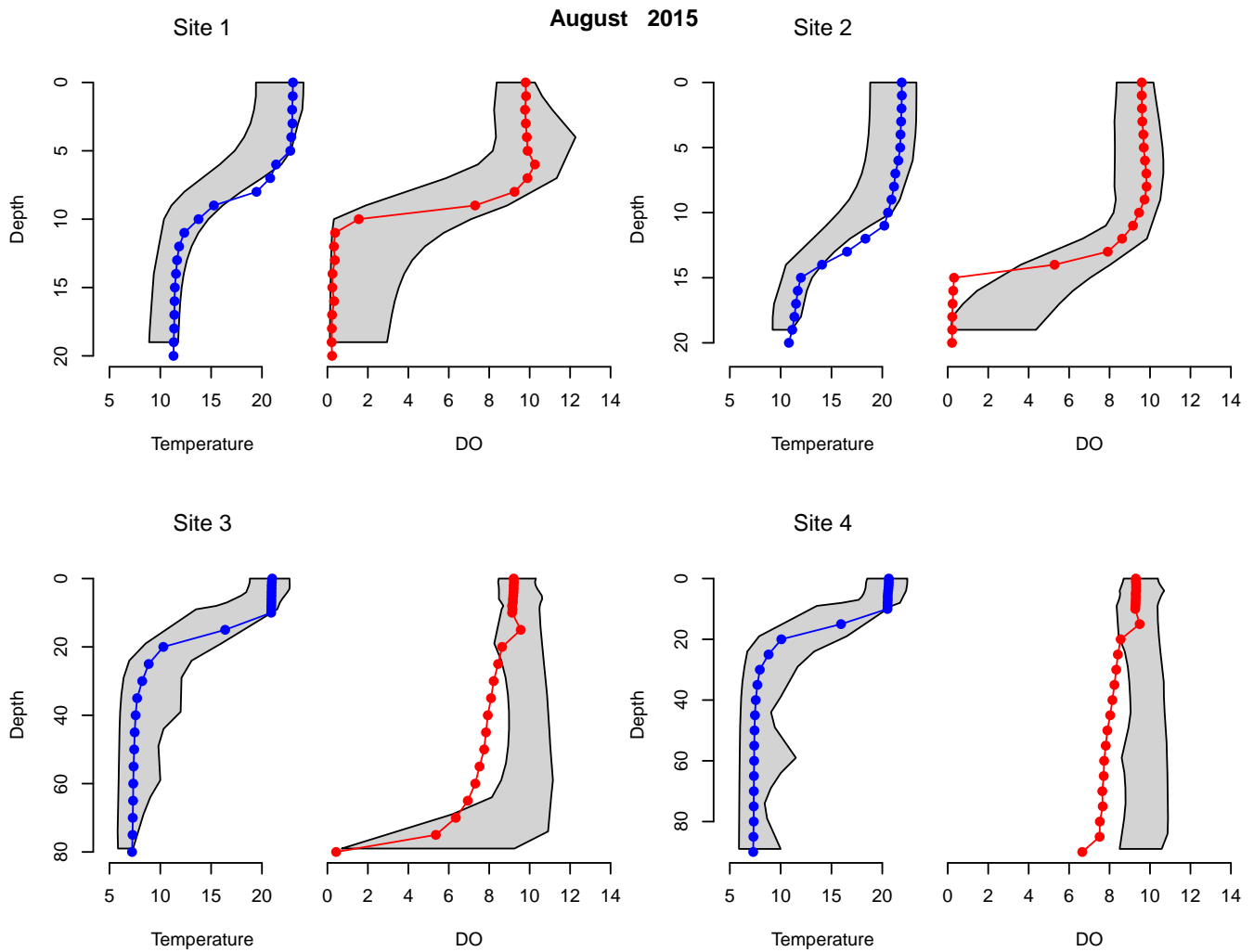


Figure 2.12: August 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

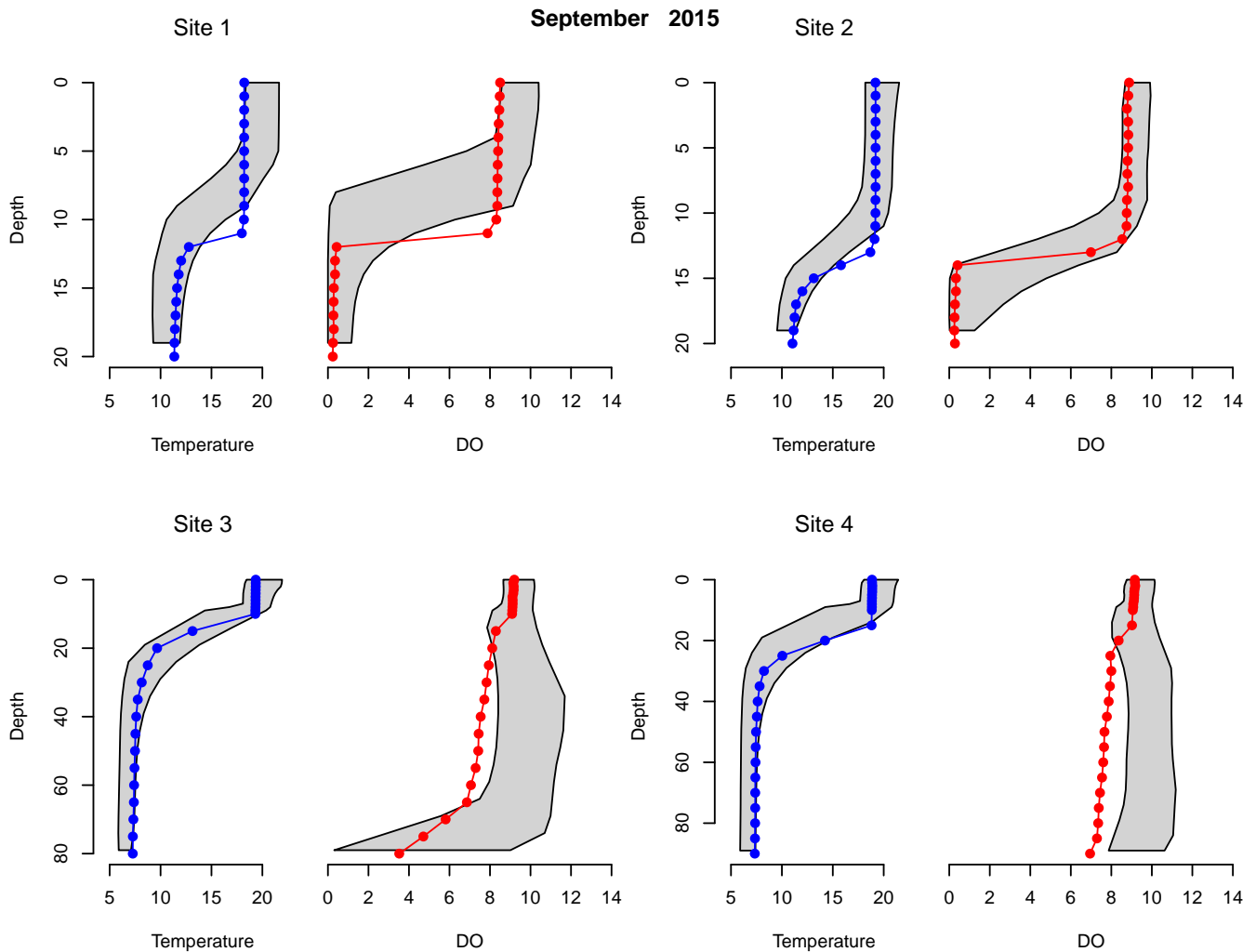


Figure 2.13: September 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

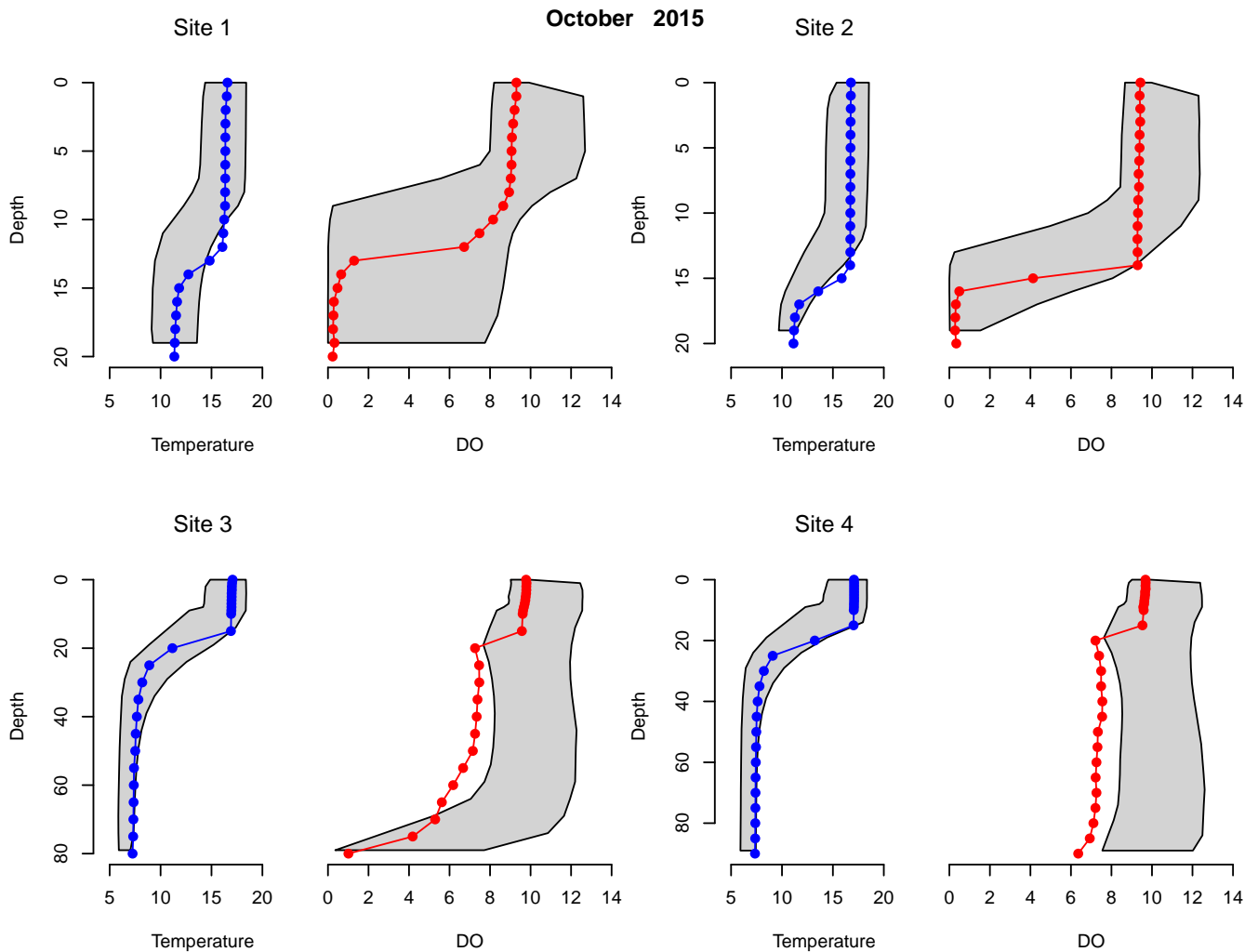


Figure 2.14: October 2015 temperature (blue line) and dissolved oxygen (red line) compared to 1988–2014 minimum/maximum ranges (gray shaded polygons); historic data were smoothed to adjust for minor differences in sampling depths in different years.

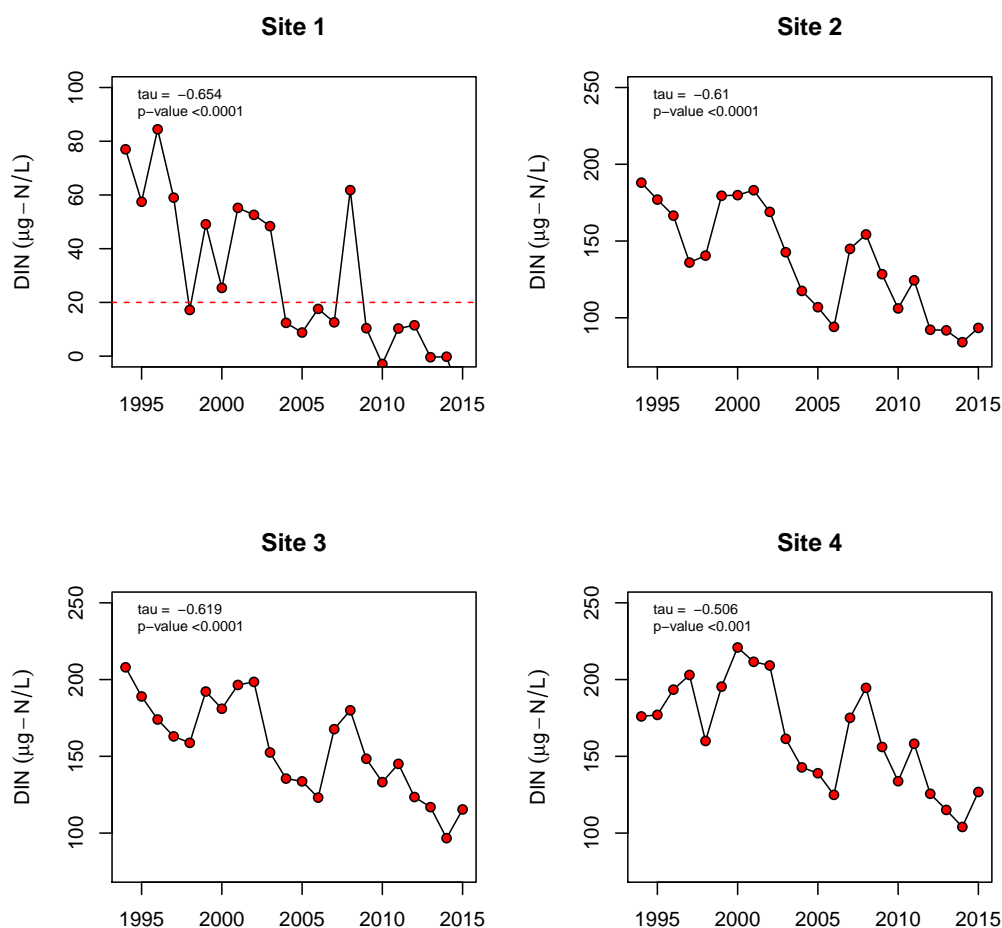


Figure 2.15: Minimum summer, near-surface dissolved inorganic nitrogen (DIN) concentrations (1994–2015, June–Oct, depths ≤ 5 m). Uncensored (raw) data were used to illustrate that minimum values are dropping below analytical detection limits (dashed red line). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

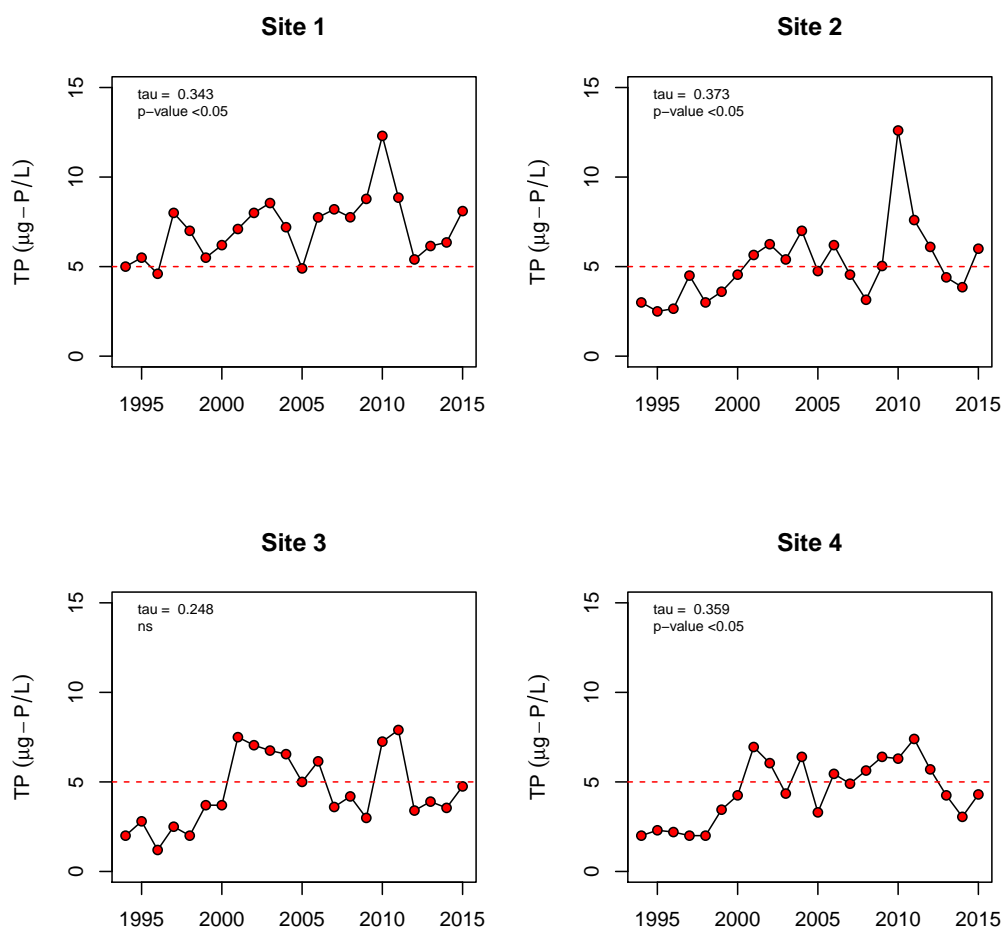


Figure 2.16: Median summer, near-surface total phosphorus concentrations (1994–2015, June–Oct, depths ≤ 5 m). Uncensored (raw) data were used to illustrate that median values are increasingly above analytical detection limits (dashed red line). Kendall's τ correlations were used because the data were not monotonic-linear; the correlations were significant at Sites 1, 2, and 4.



Figure 2.17: Median summer near-surface chlorophyll concentrations (1994–2015, June–October, depths ≤ 5 m). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

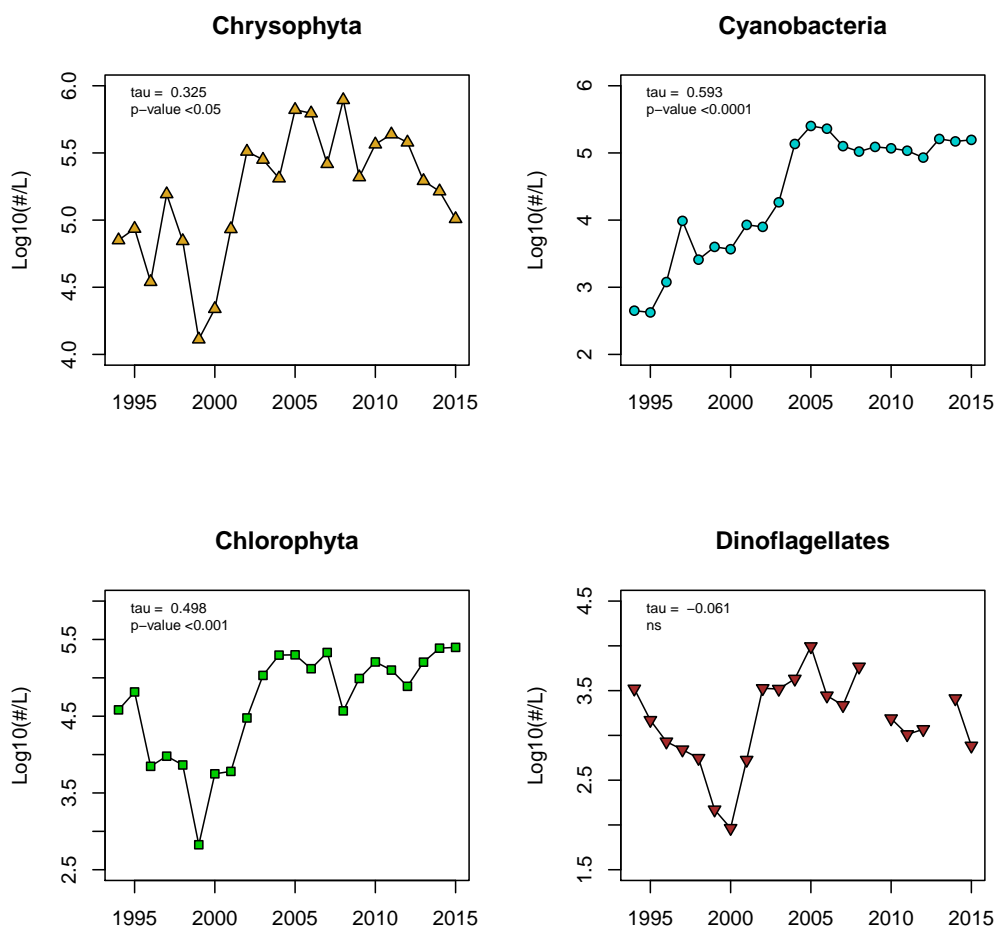


Figure 2.18: Log_{10} plots of median summer, near-surface algae counts (1994-2015, June-October, all sites and depths). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations except Dinoflagellates were significant.

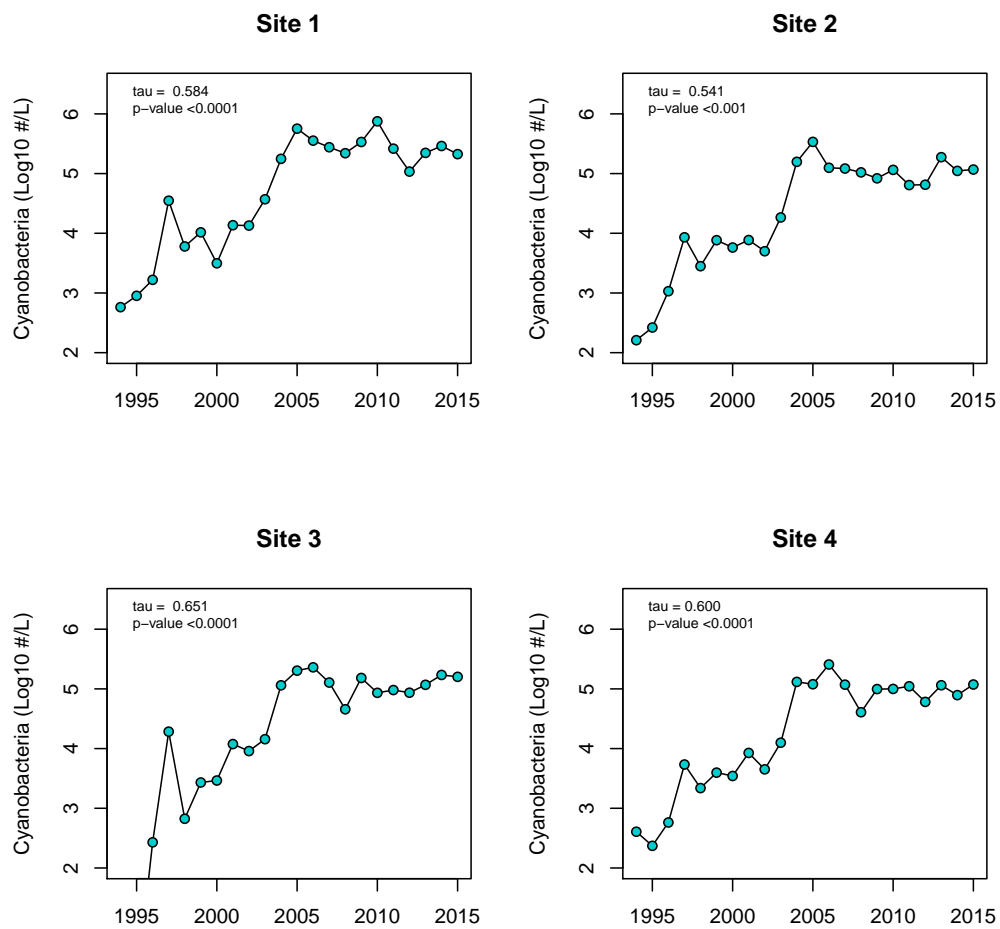


Figure 2.19: Log₁₀ plots of median summer, near-surface Cyanobacteria counts (1994–2015, June–October, depths ≤ 5 m). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

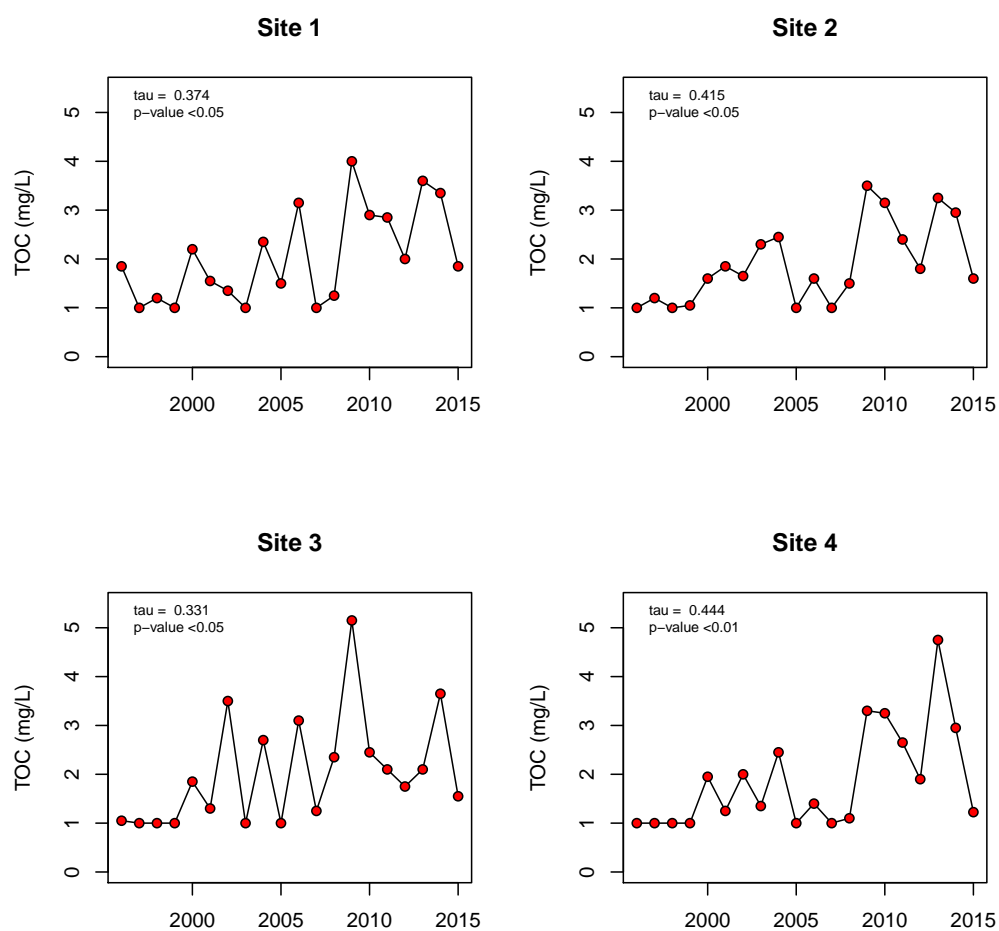


Figure 2.20: Median annual total organic carbon concentrations (surface/bottom, winter/summer, 1996–2015). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

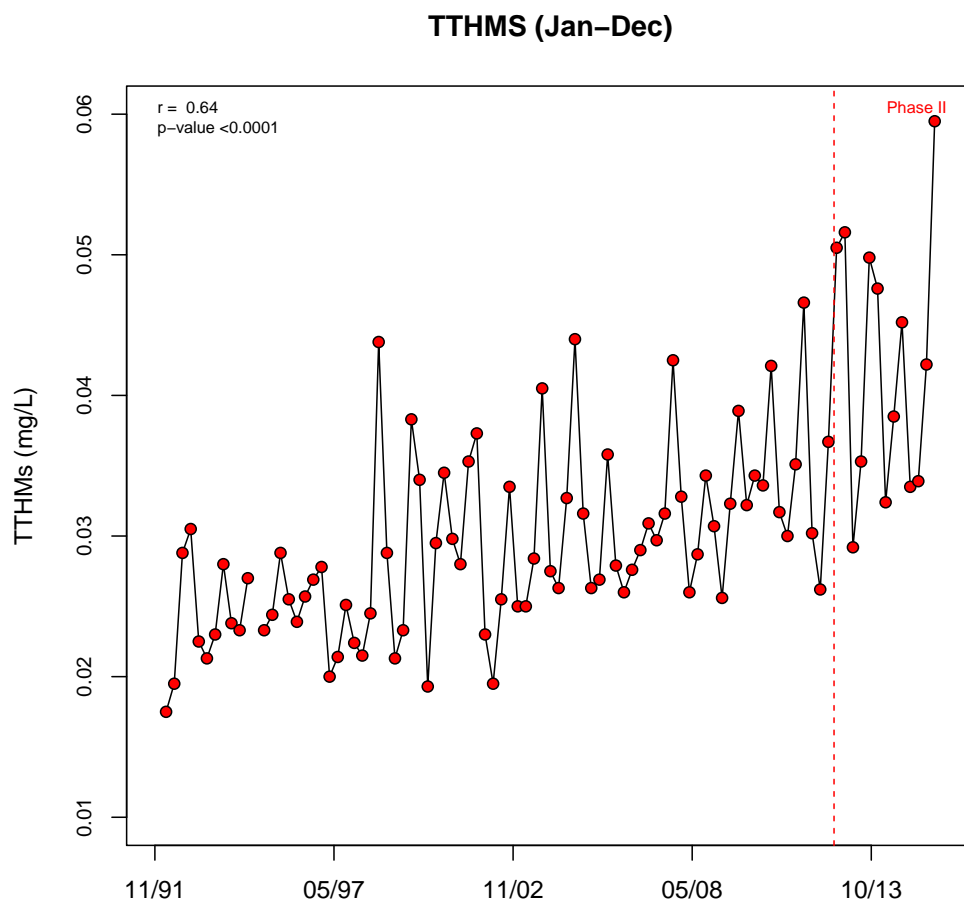


Figure 2.21: Total trihalomethanes (TTHMs) concentrations in the Bellingham water distribution system (data provided by the City of Bellingham Public Works Department). The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlation was used because the data were not monotonic-linear; the correlation was significant.

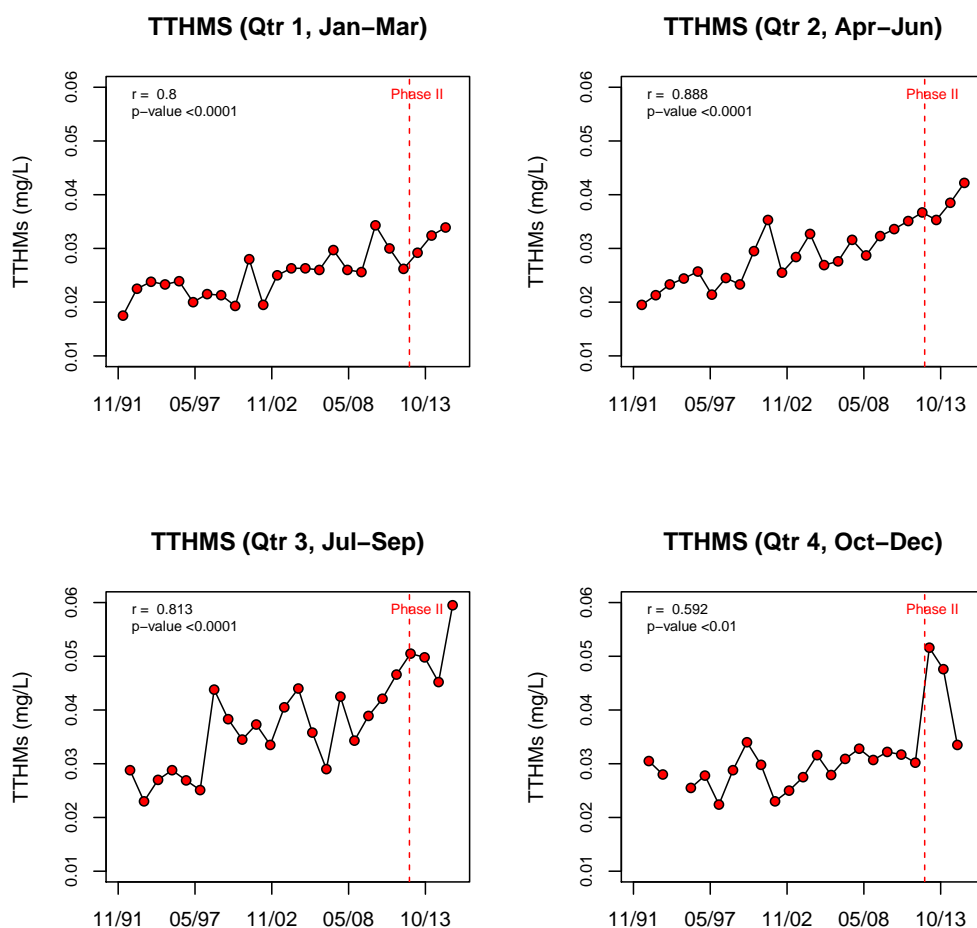


Figure 2.22: Quarterly total trihalomethanes (TTHMs) concentrations in the Bellingham water distribution system (data provided by the City of Bellingham Public Works Department). The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlations were used because the data were not monotonic-linear; all correlations were significant.

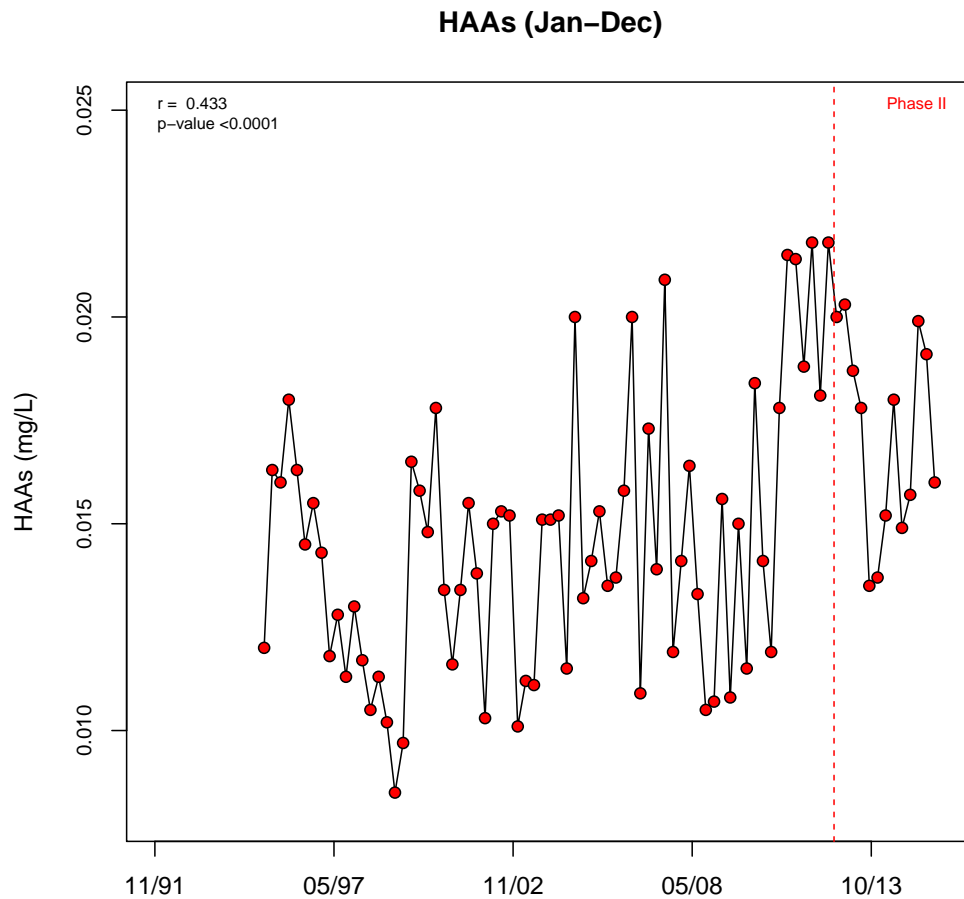


Figure 2.23: Haloacetic acids (HAAs) concentrations in the Bellingham water distribution system (data provided by the City of Bellingham Public Works Department). The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlation was used because the data were not monotonic-linear; the correlation was significant.

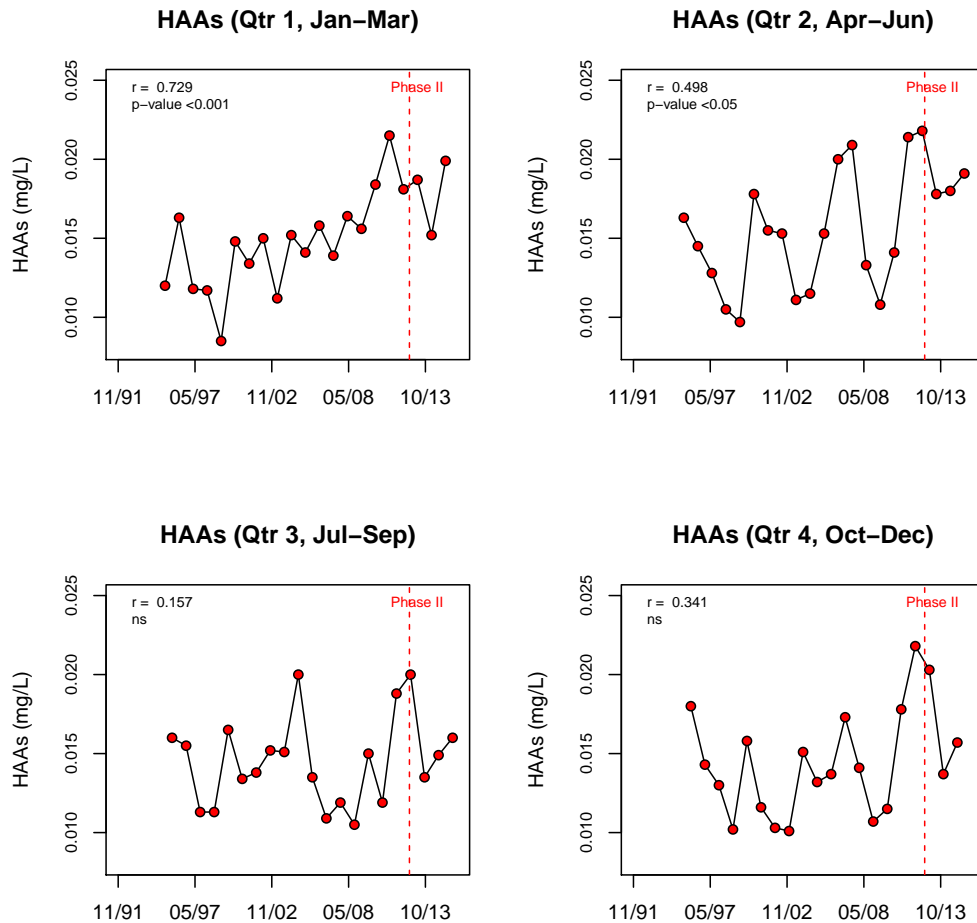


Figure 2.24: Quarterly haloacetic acids (HAAs) concentrations in the Bellingham water distribution system (data provided by the City of Bellingham Public Works Department). The number of sites used to calculate the quarterly averages increased from four to eight in the fourth quarter of 2012 (vertical red line). Kendall's τ correlations were used because the data were not monotonic-linear; the Quarter 1 and Quarter 2 correlations were significant.

3 Storm Water Monitoring

3.1 Hydrograph Data

Recording hydrographs are installed in Austin Creek and Smith Creek; the data are plotted in Figures 3.1–3.2 (pages 54–55). The location of each hydrograph is described in Appendix A.2 (page 80). All hydrograph data, including data from previous years, are online at www.wvu.edu/iws. Field notes and rating curves for each water year are available from the Institute for Watershed Studies. The rating curves were generated using Aquarius rating curve software (Aquatic Informatics, 2014). The field discharge and stage height measurements are plotted in Figures 3.3–3.4 (pages 56–57) and the Aquarius rating curve equations are listed in Tables 3.1–3.2 (pages 51–52). All results are reported as Pacific Standard Time, without Daylight Saving Time adjustment.

3.2 Storm Event Data

Beginning in January 2013, storm water sampling has focused on Anderson, Austin, and Brannian Creeks (Figure A2, page 85). A total of sixteen events were sampled at these sites between January 2013 and March 2015. Events 1–14 were described by Matthews et al. (2014; 2015). Events 13–14 have also been included in the discussion below because they were collected in October 2014, which is part of the 2014/2015 monitoring period. Due to extremely dry conditions, only two additional (Events 15–16) were collected during early 2015. Beginning in October, 2015, the sampling effort was relocated to collect storm water from Carpenter, Olsen, and Silver Beach Creeks. Data from these new sites will be included in next year's annual report. For information about other storm water sites that were monitored by IWS, refer to Section 4.2 (page 76).

3.2.1 Field sampling and analytical methods

Four storm events were sampled in Anderson, Austin, and Brannian Creeks between October 2014 and March 2015 (Table 3.3, page 53; Figures 3.5–3.19, pages 58–72). Time-paced discrete samples were collected at the gauging sites in Anderson, Austin, and Brannian Creeks using ISCO automated samplers provided by

the City of Bellingham. Extremely dry weather conditions persisted throughout most of the sampling period, so there were relatively few storm events that could be sampled between January and September 2015.

Water samples were collected at regular intervals during each event, and were analyzed for total suspended solids, total phosphorus, soluble reactive phosphorus, total nitrogen, and nitrate/nitrite following the methods summarized in Table 2.1 (page 16).

3.2.2 Results and discussion

The amount and intensity of precipitation varied between storm events (Table 3.3, page 53). The event precipitation totals ranged from 1.60 cm to 5.36 cm, and all four events met the precipitation goal (≥ 1 cm in 24 hours). But because of the unusual weather patterns, only two of the events (Event 13 and Event 16) displayed classic hydrograph profiles with distinct peaks and rising/falling legs.

Total suspended solids, total phosphorus, and total nitrogen usually increased with stage height, with maximum concentrations occurring just prior to the hydrograph peak (Figures 3.5–3.13, pages 58–66).¹⁸ This relationship was most clearly demonstrated in storm events that produced distinct hydrograph peaks (e.g., Events 13 and 16). Some of the events contained outliers, such as the high total suspended solids concentration and matching high total phosphorus concentration in Austin Creek during Event 14. Outliers such as these are common during storm events, and can be caused by stream bank collapse or any other types of upstream disturbance. Event 14 had a very shallow hydrograph rise and fall, with no distinct peaks at any of the sites. Not surprisingly, the total suspended solids and total phosphorus concentrations were also relatively uniform, showing only small changes related to stage height.

¹⁸Stage height is used for Figures 3.5–3.19 rather than estimated stream flow because stage height is measured directly by the ISCO sampler so it is a more accurate indicator of the rise and fall of the water level during sample collection. Stream flow data are available from IWS (Austin Creek) or from USGS (Anderson and Brannian Creeks).

Soluble phosphorus concentrations were relatively low ($\leq 10 \mu\text{g-P/L}$), but tended to follow the hydrograph profile during most events. Nitrate concentrations are often difficult to predict in storm samples. Soluble forms of nitrogen like nitrate can be transported with storm runoff, which would produce results that followed the hydrograph profile. But nitrate can also be diluted by precipitation, so it is common to see lower concentrations as the storm event progressed. Most of the nitrate concentrations from Anderson, Austin, and Brannian Creeks increased during the storm event, but the dilution effect is evident in Event 16 at Brannian Creek.

Stage Height (ft)	Discharge Equations
0.17–0.37	$\text{discharge} = 27.023 \times \text{stage}^{3.286}$
0.37–0.49	$\text{discharge} = 13.260 \times \text{stage}^{2.570}$
0.49–0.76	$\text{discharge} = 14.908 \times \text{stage}^{2.734}$
0.76–1.03	$\text{discharge} = 14.330 \times \text{stage}^{2.590}$
1.03–1.41	$\text{discharge} = 14.237 \times \text{stage}^{2.807}$
1.41–1.96	$\text{discharge} = 15.648 \times \text{stage}^{2.532}$
1.96–2.64	$\text{discharge} = 20.138 \times \text{stage}^{2.157}$
2.64–4.66	$\text{discharge} = 24.224 \times \text{stage}^{1.967}$

Table 3.1: Austin Creek rating curves for WY2015 (October 1, 2014–September 30, 2014); equations generated by Aquarius software (Aquatic Informatics, 2014).

Stage Height (ft)	Discharge Equations
1.44–1.52	discharge = $0.002 \times \text{stage}^{11.057}$
1.52–1.65	discharge = $0.003 \times \text{stage}^{10.149}$
1.65–1.78	discharge = $0.001 \times \text{stage}^{11.496}$
1.78–1.95	discharge = $0.003 \times \text{stage}^{10.398}$
1.95–2.14	discharge = $0.015 \times \text{stage}^{7.846}$
2.14–2.35	discharge = $0.017 \times \text{stage}^{7.682}$
2.35–2.62	discharge = $0.258 \times \text{stage}^{4.503}$
2.62–2.91	discharge = $0.060 \times \text{stage}^{6.015}$
2.91–3.28	discharge = $0.202 \times \text{stage}^{4.880}$
3.28–3.85	discharge = $0.420 \times \text{stage}^{4.264}$
3.85–4.82	discharge = $1.442 \times \text{stage}^{3.349}$

Table 3.2: Smith Creek rating curves for WY2015 (October 1, 2014-September 30, 2015); equations generated by Aquarius software (Aquatic Informatics, 2014).

Event	Sampling Period		Event Precip [†]
13	Anderson	16:00 Oct 13 to 08:00 Oct 14, 2014	1.24 in (3.15 cm)
	Austin	17:30 Oct 13 to 08:30 Oct 14, 2014	
	Brannian	16:00 Oct 13 to 08:00 Oct 14, 2014	
	<i>Event duration</i>	16:00 Oct 13 to 08:30 Oct 14, 2014	
14	Anderson	03:00 Oct 22 to 09:00 Oct 24, 2014	1.14 in (2.90 cm)
	Austin	03:00 Oct 22 to 10:55 Oct 24, 2014	
	Brannian	03:00 Oct 22 to 09:00 Oct 24, 2014	
	<i>Event duration</i>	03:00 Oct 22 to 10:45 Oct 24, 2014	
15	Anderson	04:00 Feb 5 to 14:00 Feb 5, 2015	0.42 in (1.07 cm)
	Austin	04:00 Feb 5 to 16:00 Feb 5, 2015	
	Brannian	04:00 Feb 5 to 14:00 Feb 5, 2015	
	<i>Event duration</i>	04:00 Feb 5 to 16:00 Feb 5, 2015	
16	Anderson [‡]	02:00 Mar 14 to 10:00 Mar 16, 2015	2.11 in (5.36 cm)
	Austin	02:00 Mar 14 to 10:30 Mar 16, 2015	
	Brannian	02:00 Mar 14 to 10:00 Mar 16, 2015	
	<i>Event duration</i>	02:00 Mar 14 to 10:30 Mar 16, 2015	

[†]Precipitation data obtained from the Northshore rain gage.

[‡]Nooksack River diversion was open during Event 16, but not during Events 13–15.

Table 3.3: Summary of storm events for Anderson, Austin, and Brannian Creeks and maximum 24-hr precipitation totals. Precipitation and diversion data were provided by the City of Bellingham.

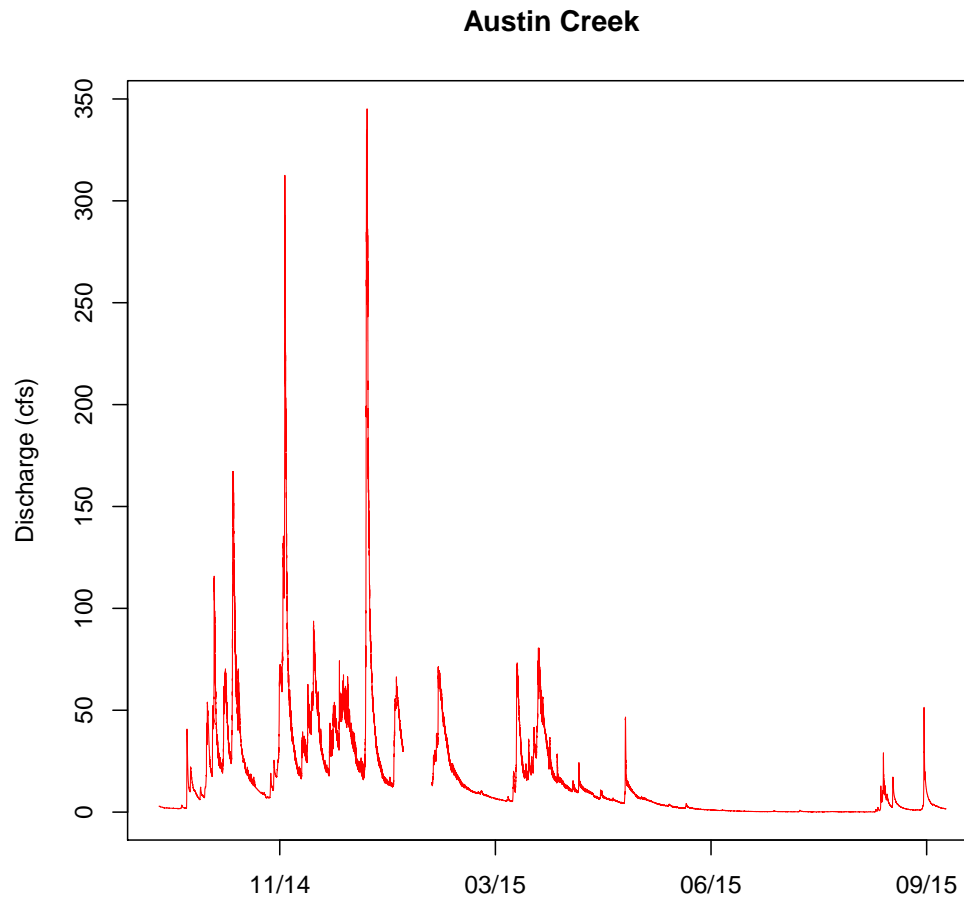


Figure 3.1: Austin Creek hydrograph for WY2015 (October 1, 2014–September 30, 2015). Data were recorded at 15 minute intervals.

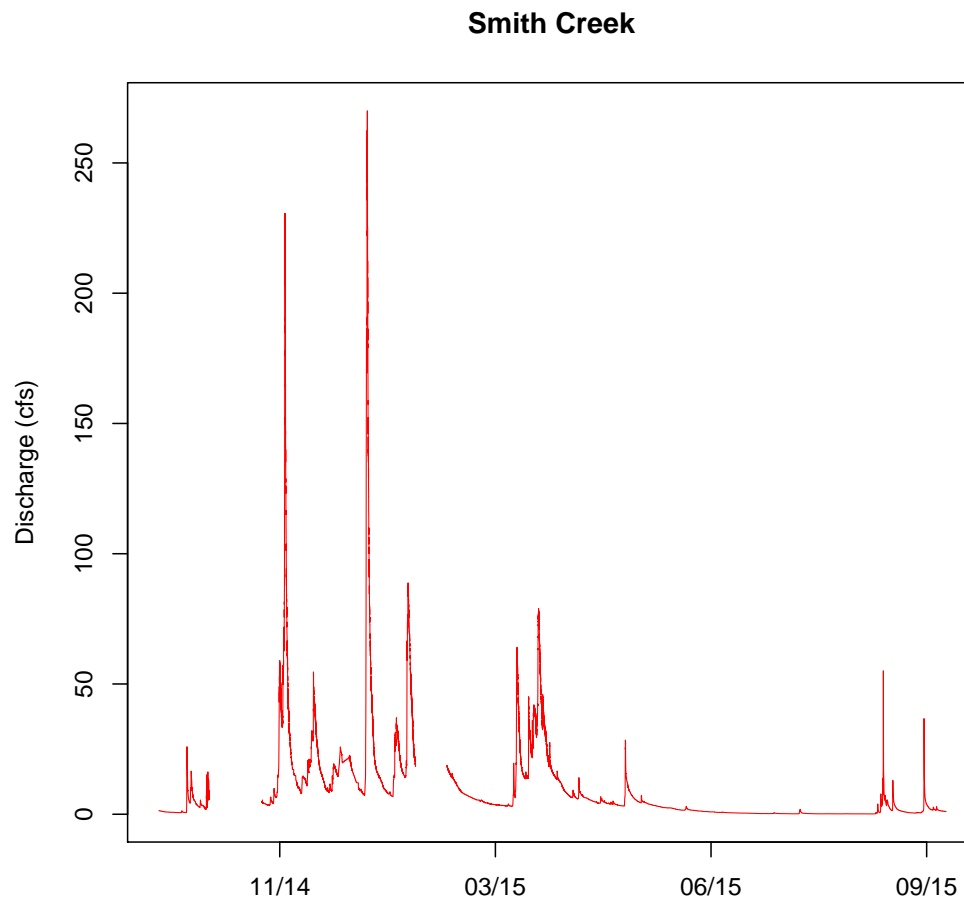


Figure 3.2: Smith Creek hydrograph for WY2015 (October 1, 2014–September 30, 2015). Data were recorded at 15 minute intervals.

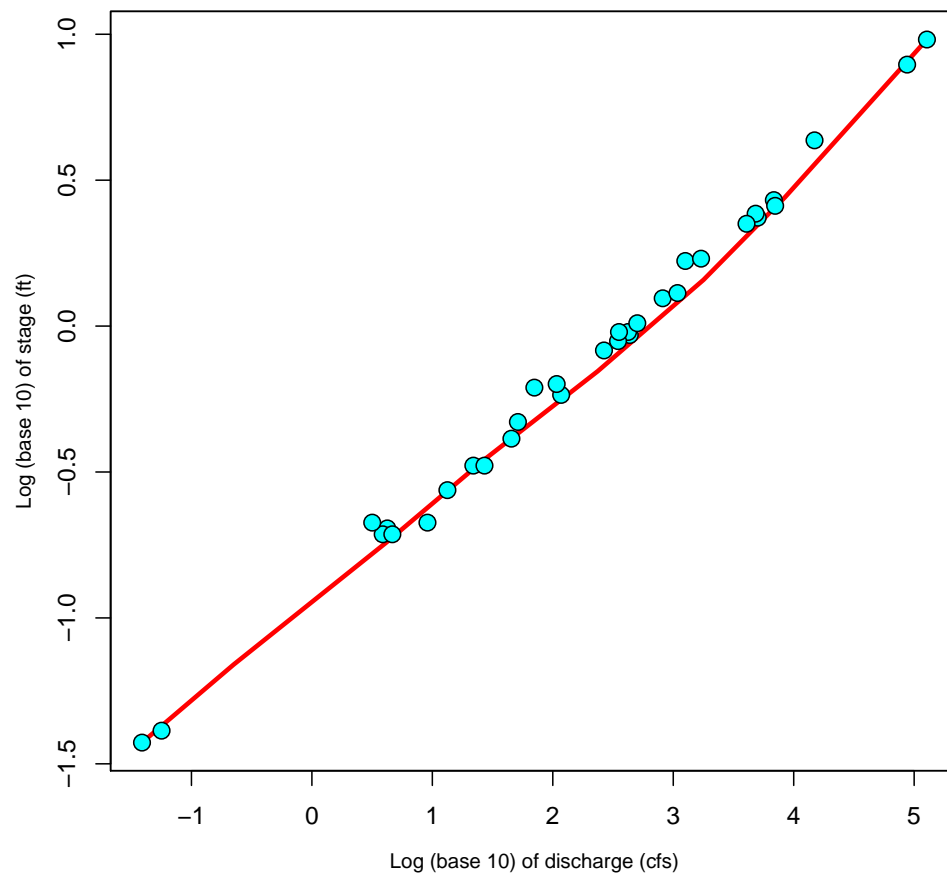


Figure 3.3: Aquarius rating curve for Austin Creek.

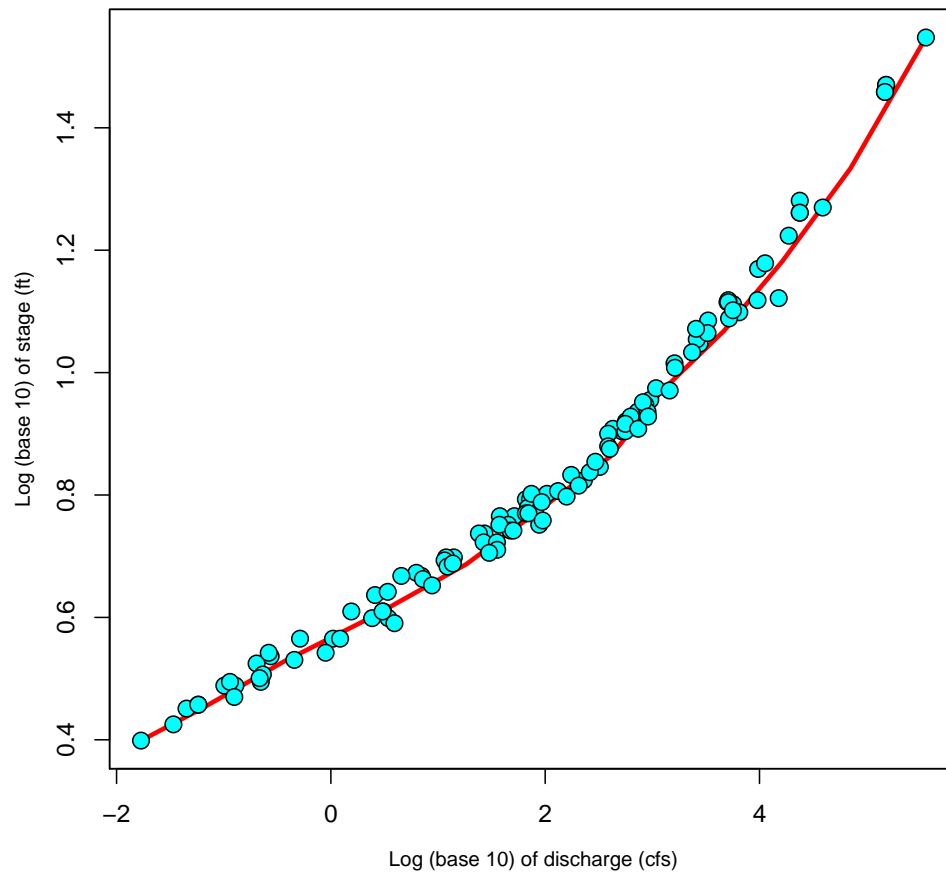


Figure 3.4: Aquarius rating curve for Smith Creek.

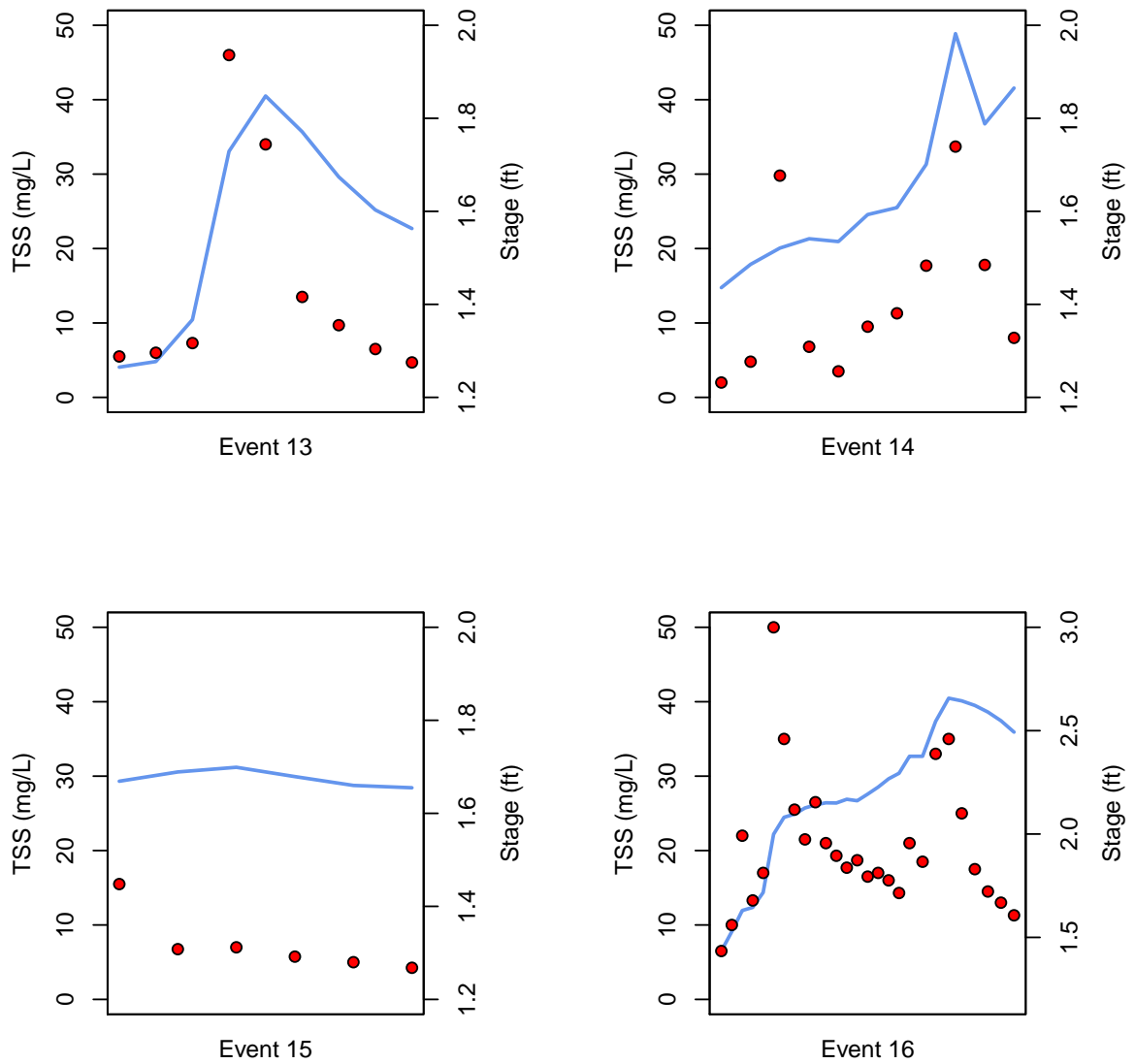


Figure 3.5: Anderson Creek storm water monitoring results: total suspended solids (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

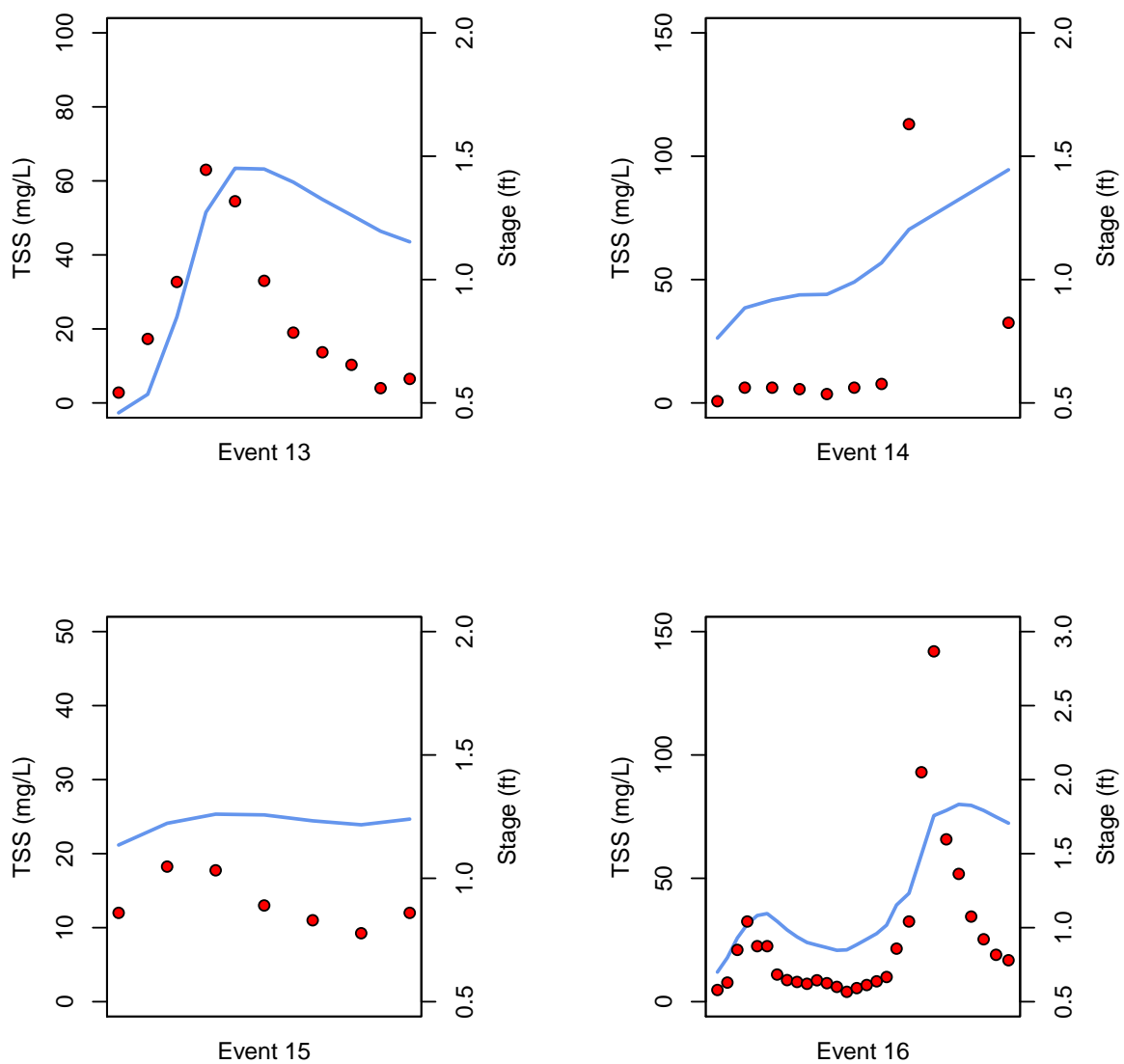


Figure 3.6: Austin Creek storm water monitoring results: total suspended solids (•) vs. ISCO stage height (—). Note differences in vertical axis scales.

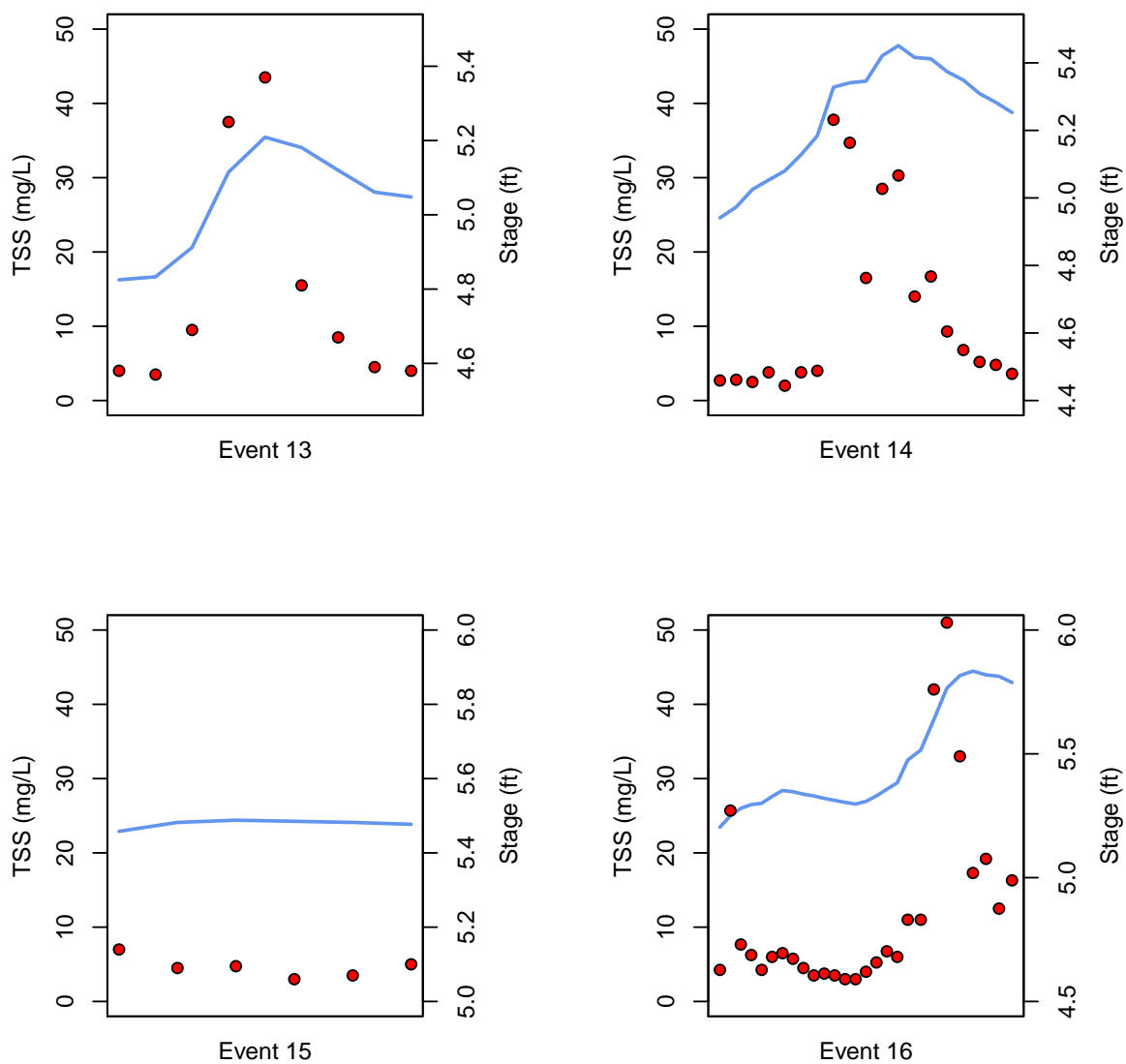


Figure 3.7: Brannian Creek storm water monitoring results: total suspended solids (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

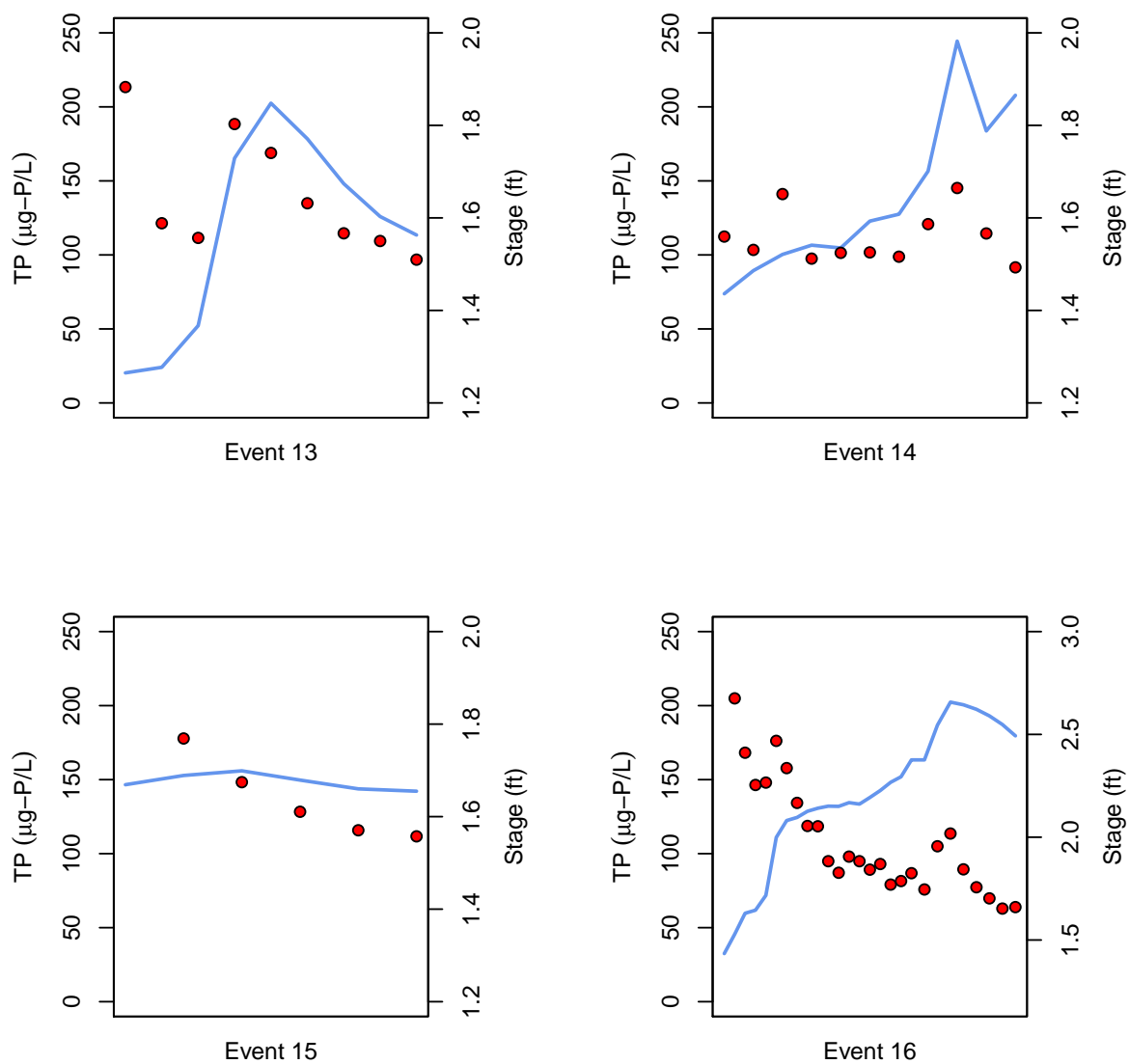


Figure 3.8: Anderson Creek storm water monitoring results: total phosphorus (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

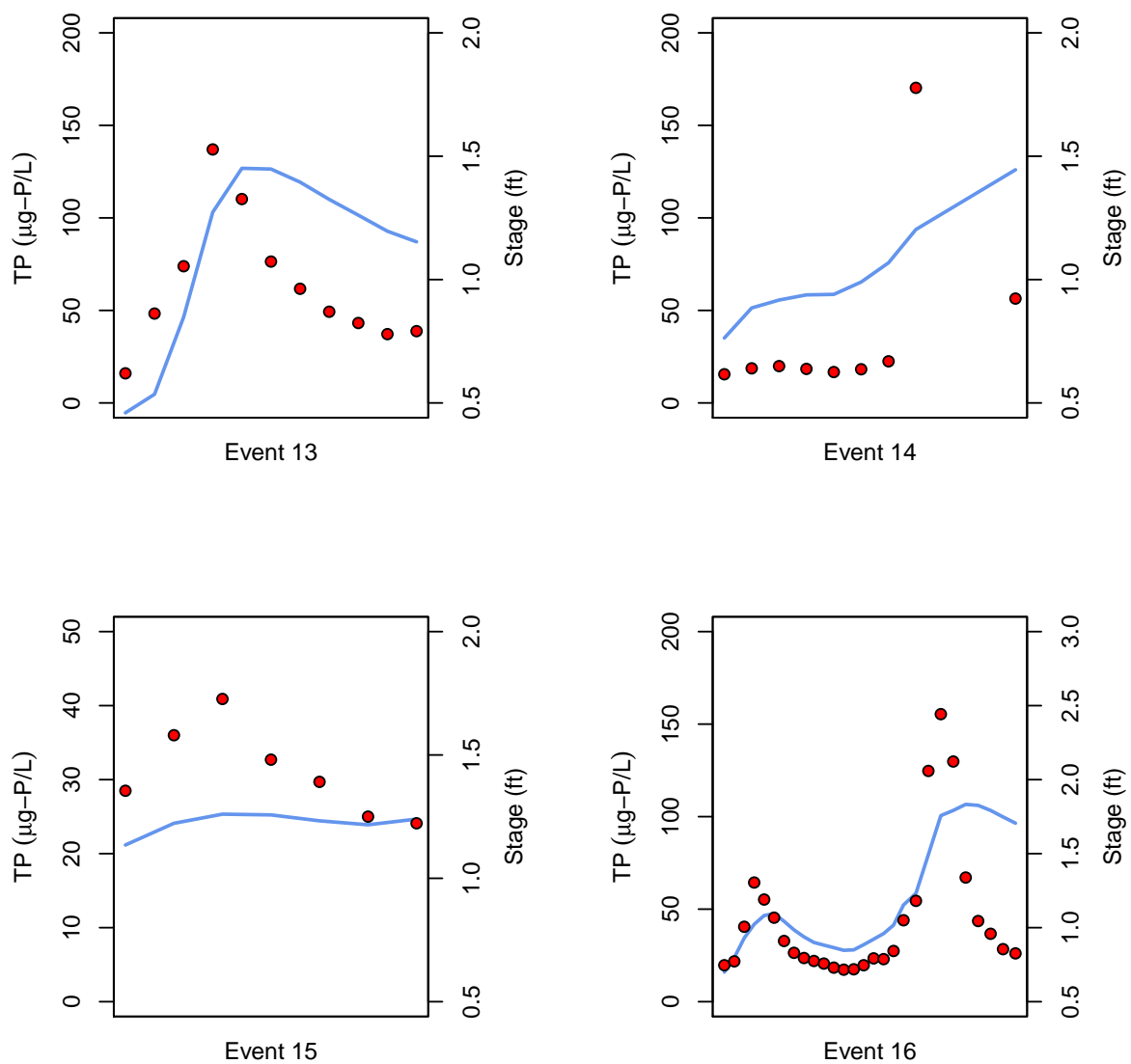


Figure 3.9: Austin Creek storm water monitoring results: total phosphorus (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

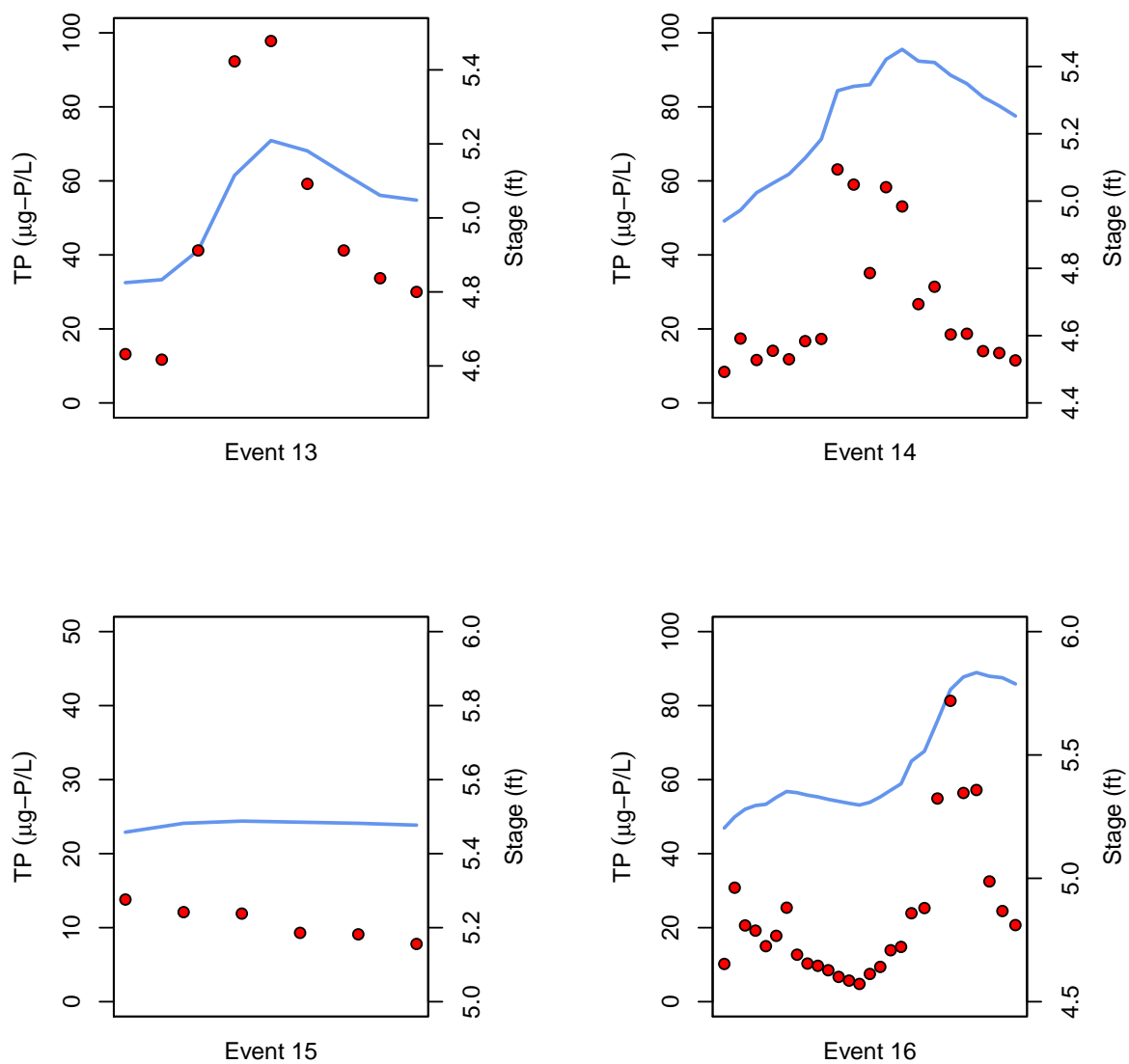


Figure 3.10: Brannian Creek storm water monitoring results: total phosphorus (•) vs. ISCO stage height (—). Note differences in vertical axis scales.

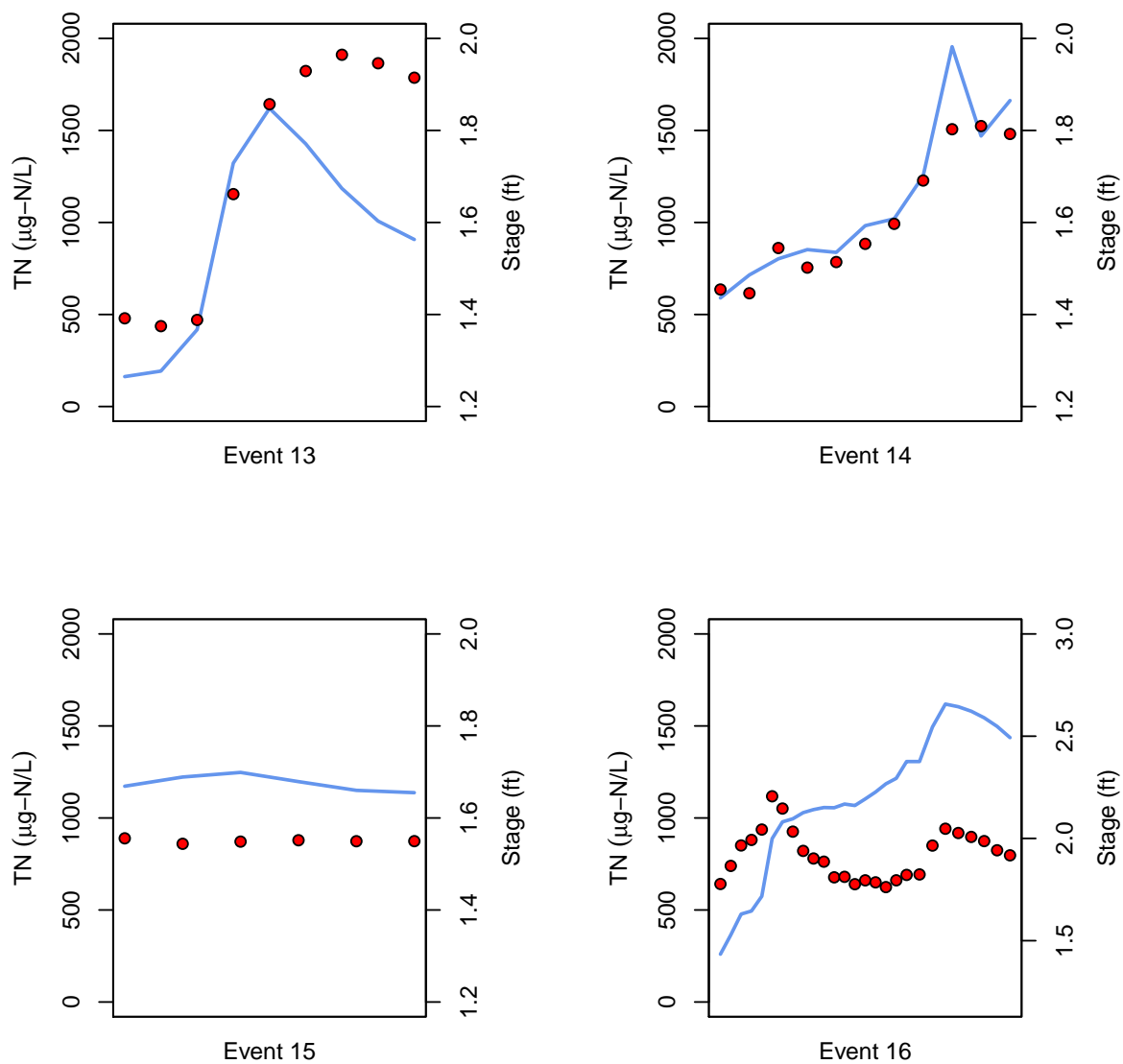


Figure 3.11: Anderson Creek storm water monitoring results: total nitrogen (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

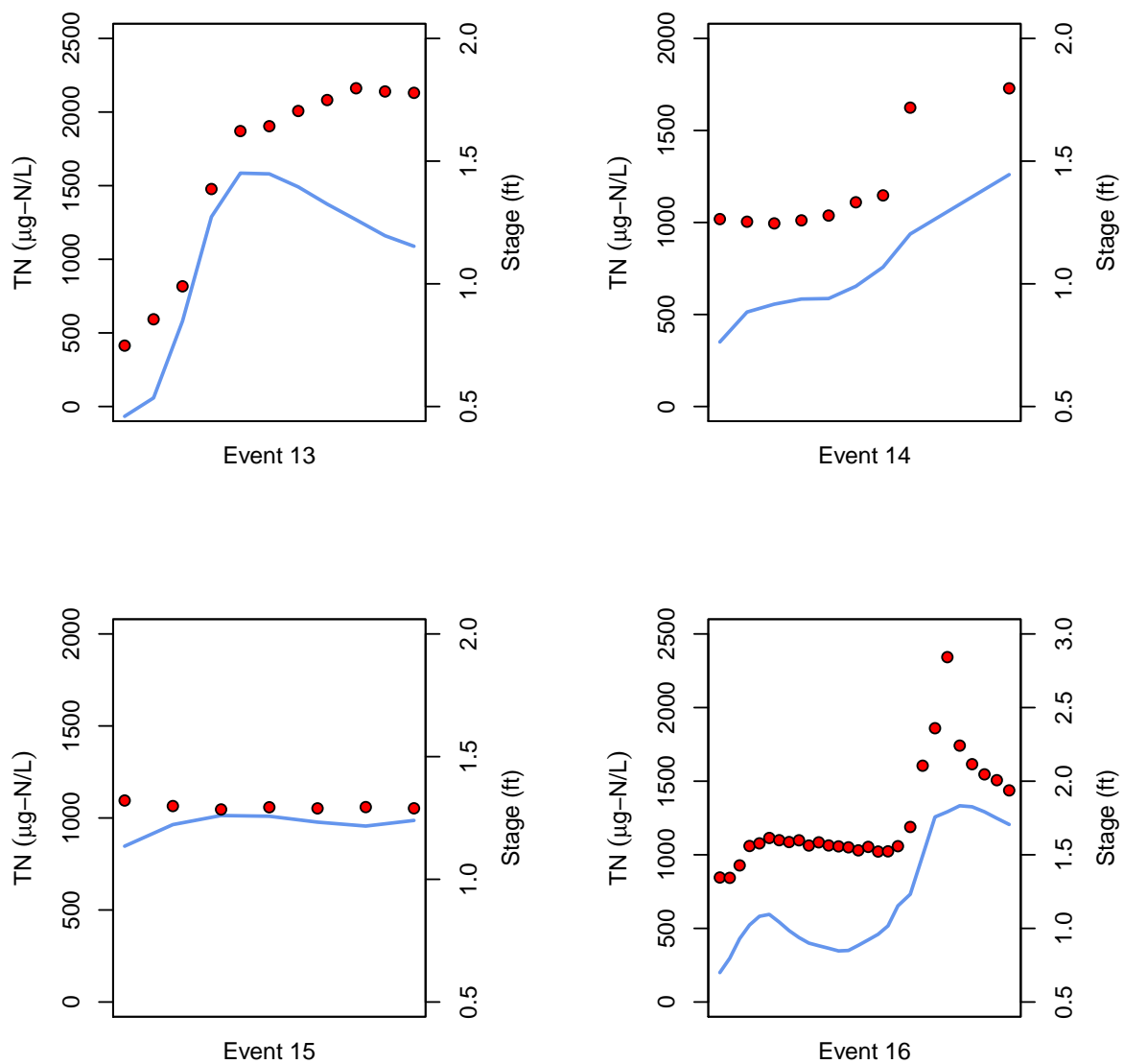


Figure 3.12: Austin Creek storm water monitoring results: total nitrogen (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

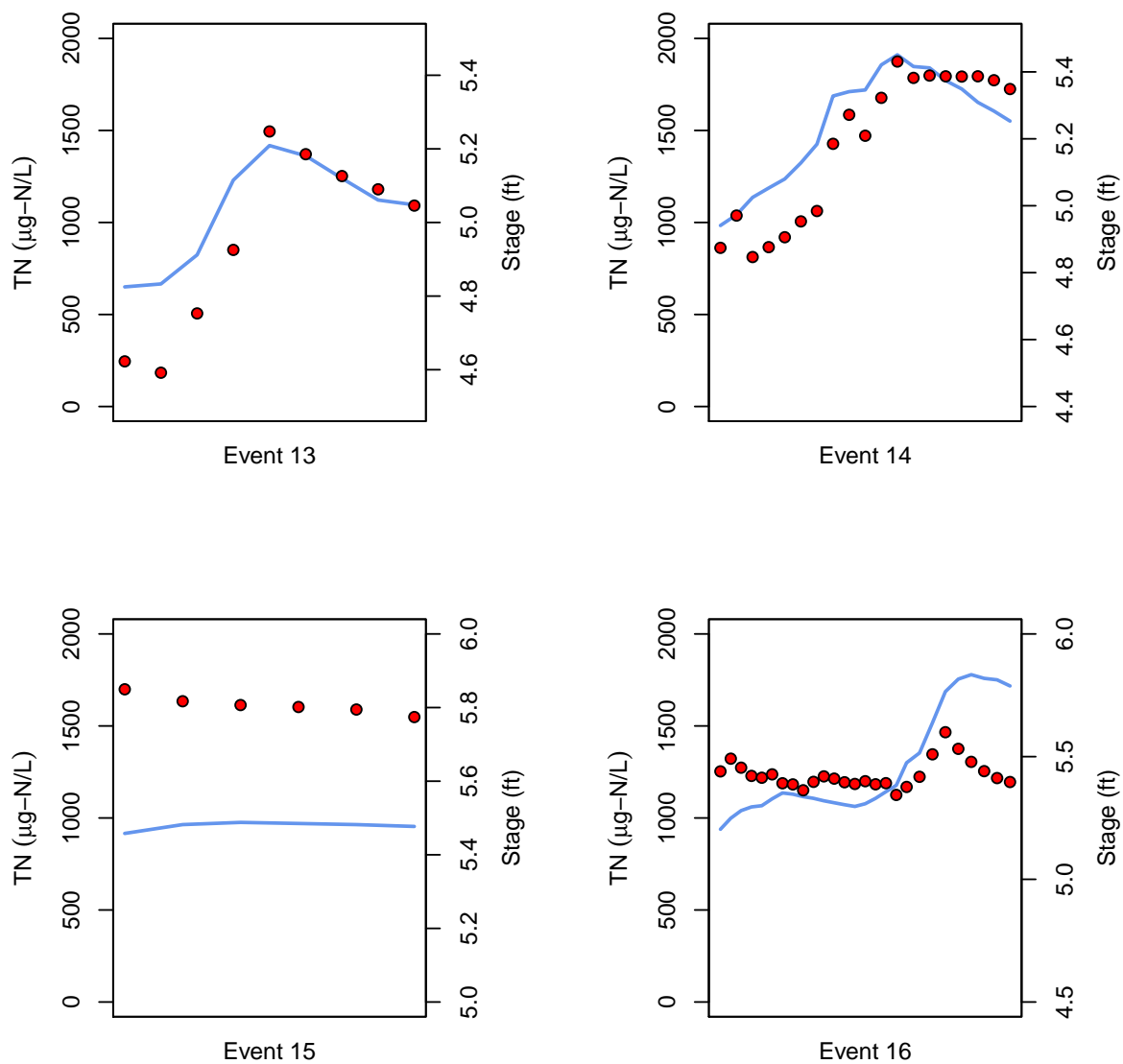


Figure 3.13: Brannian Creek storm water monitoring results: total nitrogen (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

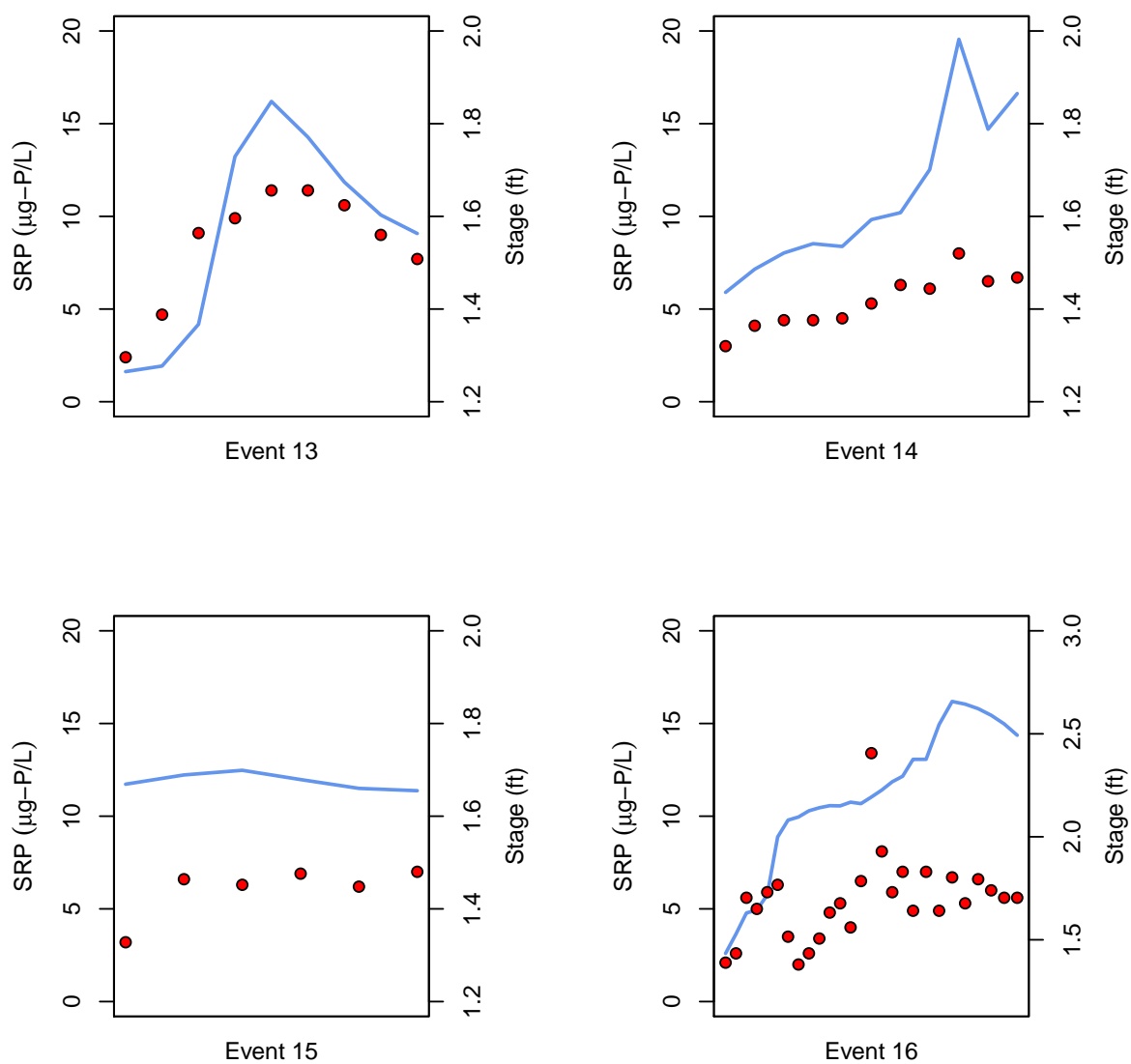


Figure 3.14: Anderson Creek storm water monitoring results: soluble phosphate (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

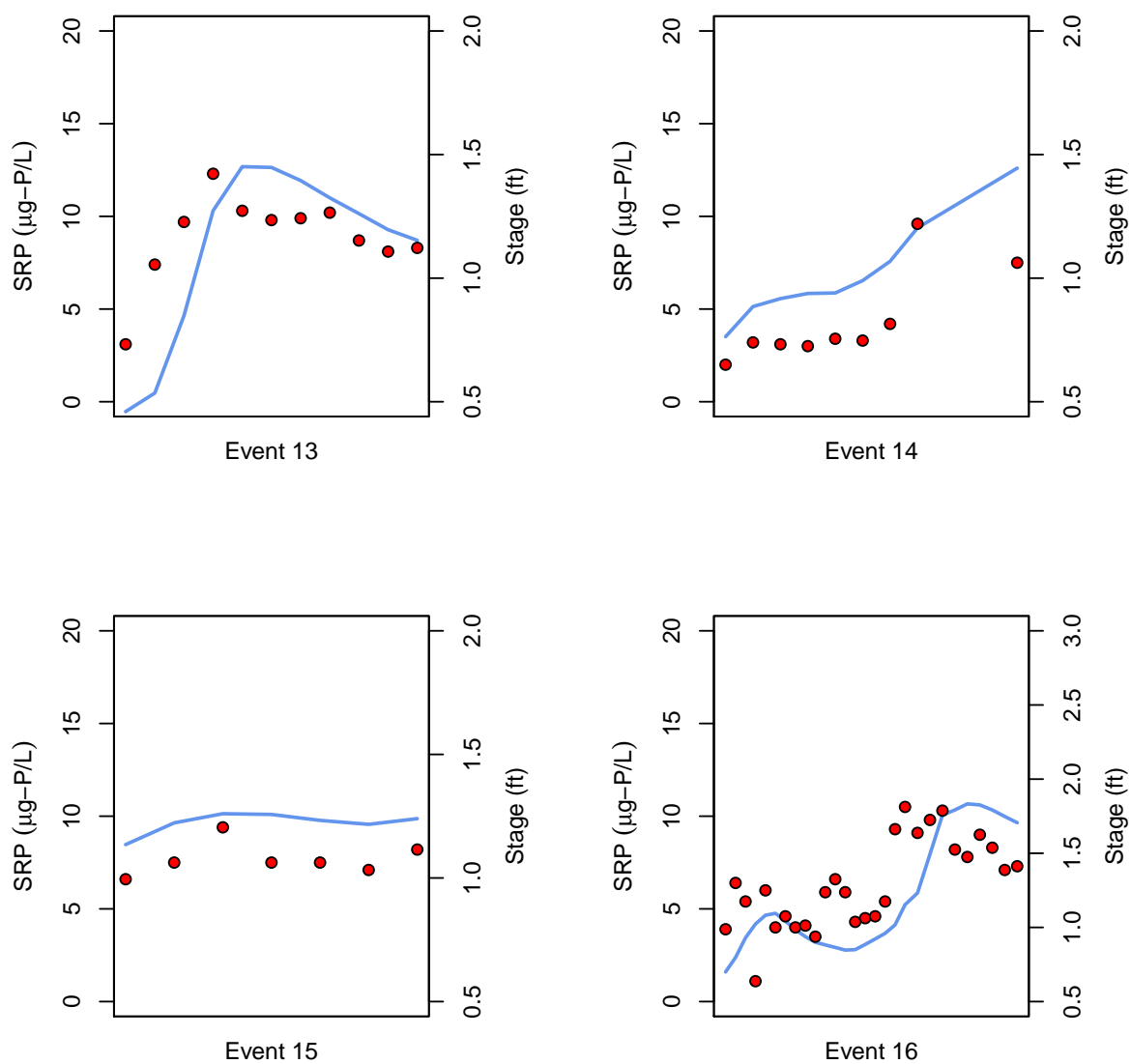


Figure 3.15: Austin Creek storm water monitoring results: soluble phosphate (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

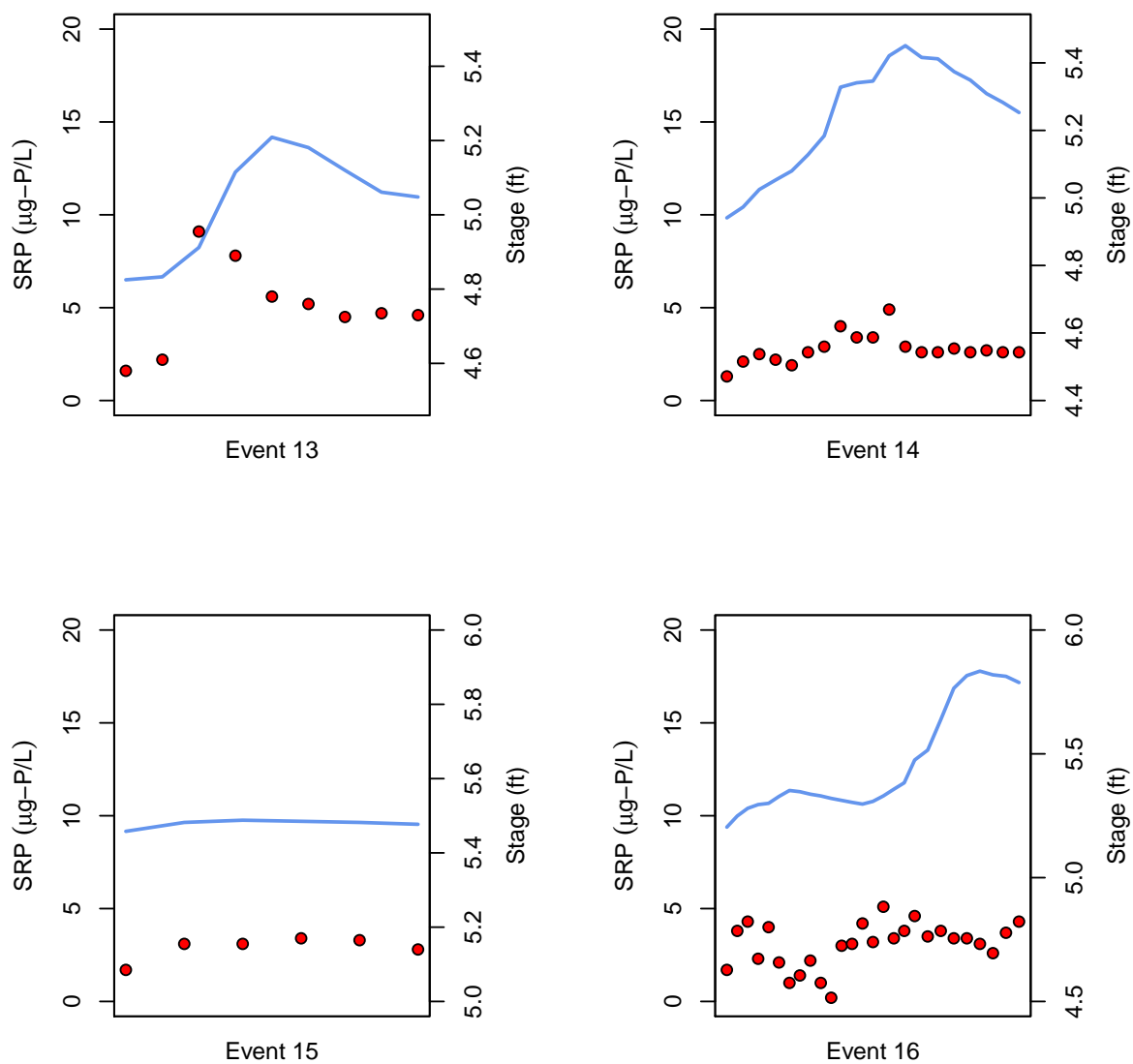


Figure 3.16: Brannian Creek storm water monitoring results: soluble phosphate (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

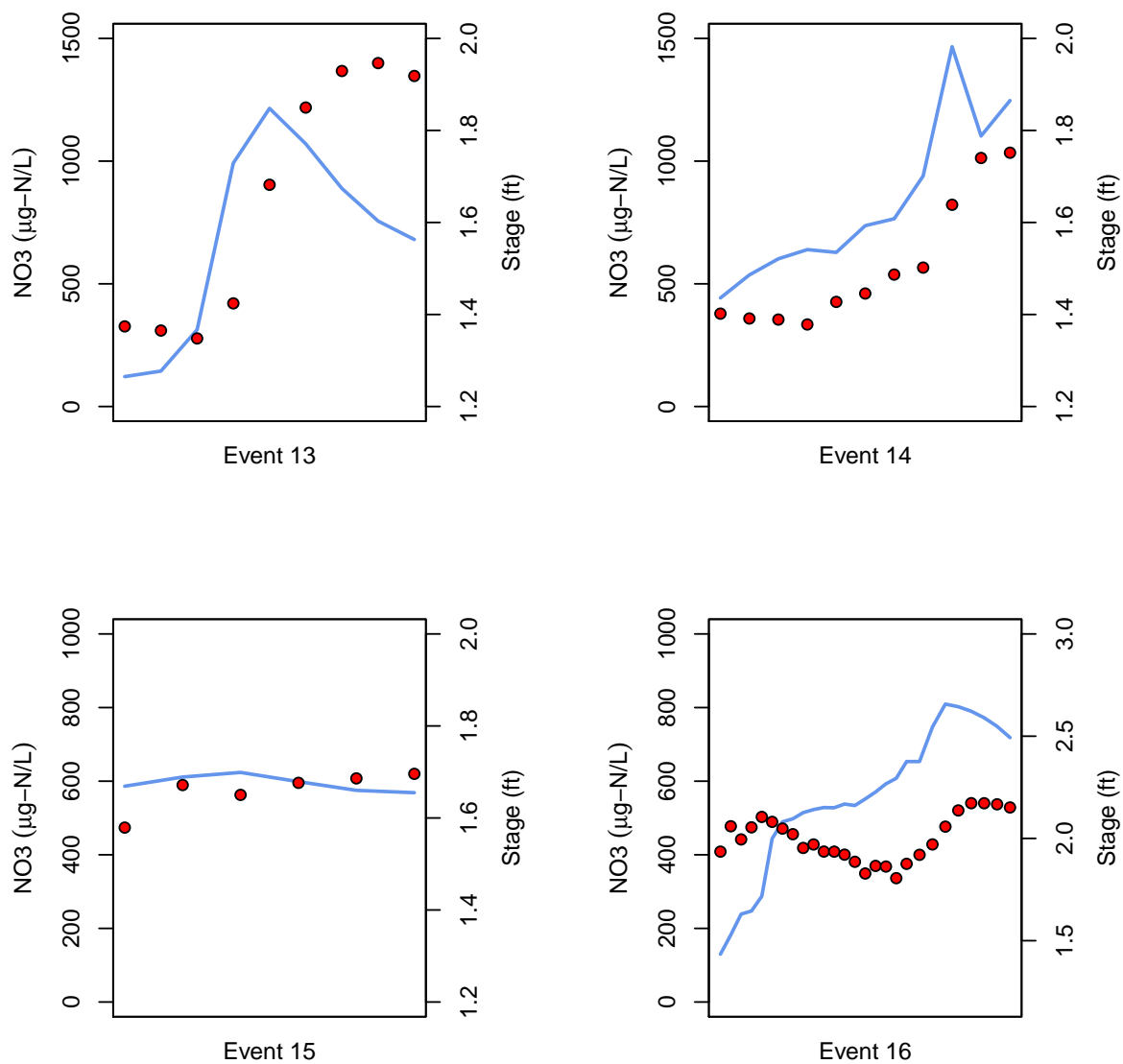


Figure 3.17: Anderson Creek storm water monitoring results: nitrate/nitrite (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

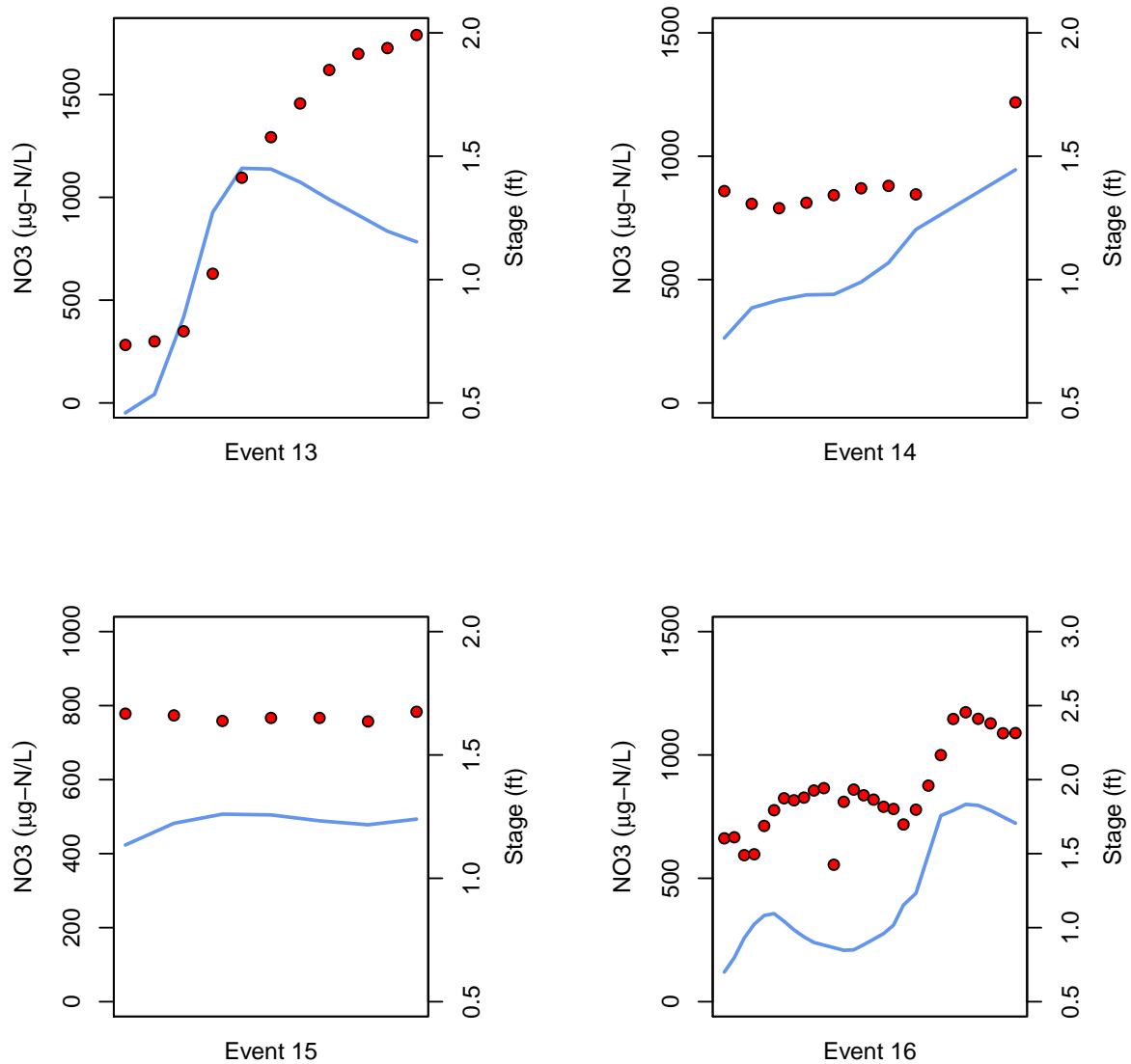


Figure 3.18: Austin Creek storm water monitoring results: nitrate/nitrite (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

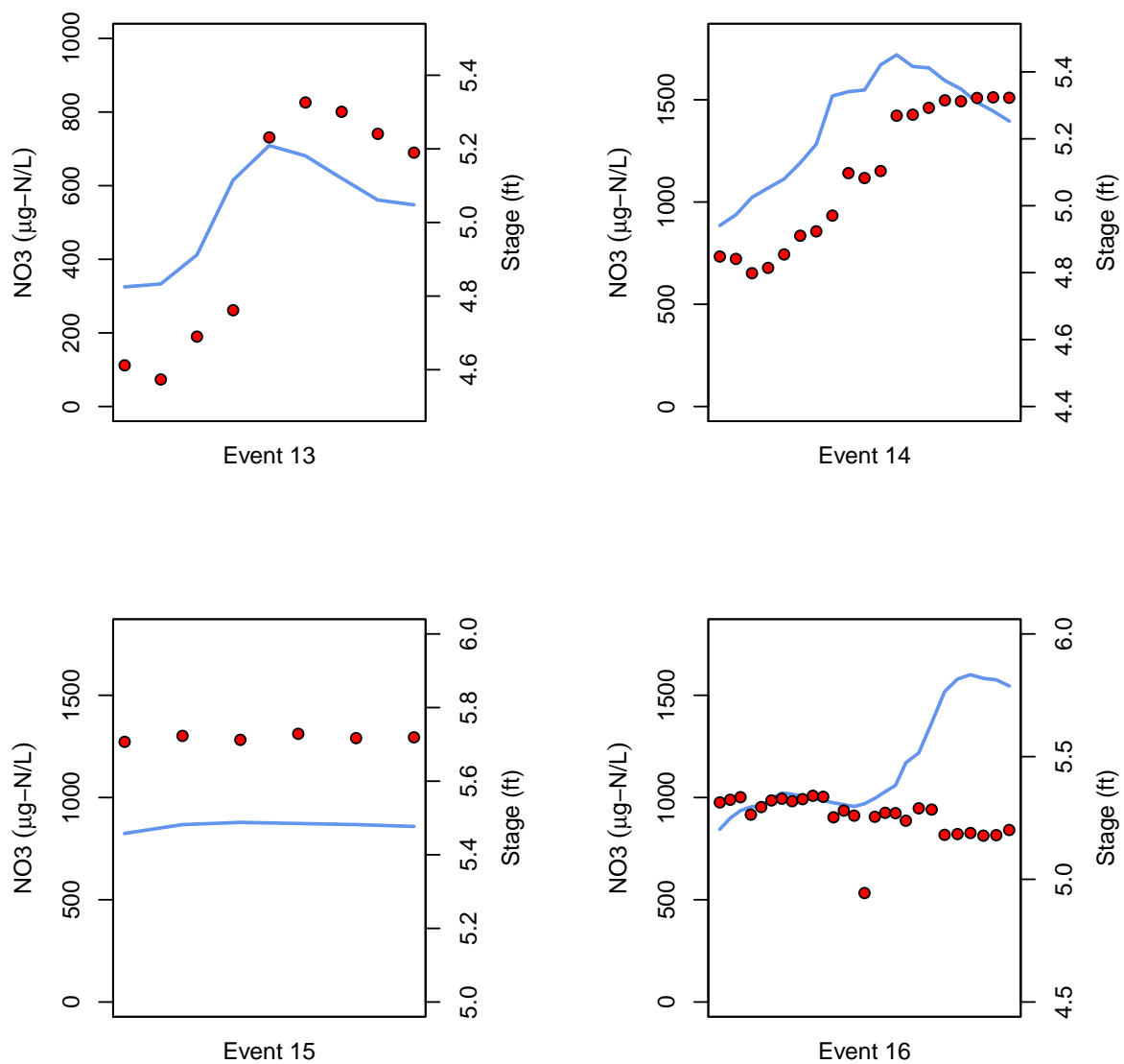


Figure 3.19: Brannian Creek storm water monitoring results: nitrate/nitrite (●) vs. ISCO stage height (—). Note differences in vertical axis scales.

4 References and Related Reports

4.1 References

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4.2 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.wvu.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:

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, K. Beeler, and G. B. Matthews. 2015. Lake Whatcom Monitoring Project, 2013/2014 Final Report, February 26, 2015. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. 2014. Lake Whatcom Monitoring Project, 2012/2013 Final Report, March 6, 2014. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. 2013. Lake Whatcom Monitoring Project, 2011/2012 Final Report, March 8, 2013. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. 2012. Lake Whatcom Monitoring Project, 2010/2011 Final Report, February 24, 2012. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. Lake Whatcom Monitoring Project, 2009/2010 Final Report, March 1, 2011. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. Lake Whatcom Monitoring Project, 2008/2009 Final Report, March 10, 2010. 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, 2002/2003 Final Report, April 5, 2004. 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, 1999/2000 Final Report, March 23, 2001. Report to the City of Bellingham, WA.
- Matthews, R. A., M. Hilles, J. Vandersypen, R. Mitchell, and G. B. Matthews. Lake Whatcom Monitoring Project, 1998/99 Final Report, March 15, 2000. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles and G. B. Matthews. Lake Whatcom Monitoring Project, 1997/98 Final Report, April 12, 1999. Report to the City of Bellingham, WA.

Matthews, R. A., M. Hilles and G. B. Matthews. Lake Whatcom Monitoring Project, 1996/97 Final Report, February 10, 1998. Report to the City of Bellingham, WA.

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Matthews, R. and G. Matthews. Lake Whatcom Monitoring Project, 1991–1992 Final Report, March 19, 1993. Report to the City of Bellingham, WA.

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:

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.
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A Site Descriptions

Figures A1–A2 (pages 84–85) show the locations of the current monitoring sites and Table A1 (page 83) 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 at 20 m 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.

Site 2 is located at 18–20 m 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.

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.

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.

A.2 Tributary Monitoring Sites

Anderson Creek samples are collected 15 m upstream from South Bay Rd. Water samples and discharge measurements are collected upstream from the bridge. The Anderson Creek hydrograph¹⁹ is mounted in the stilling well on the east side of Anderson Creek, directly adjacent to the bridge over Anderson Creek (South Bay Rd.), approximately 0.5 km from the mouth of the creek.

¹⁹This 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.

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. This site can be difficult to locate and may be dry or have minimal flow during drought conditions; contact IWS for detailed information about the site location.

Brannian Creek samples are collected approximately 40 m downstream from South Bay Rd. near 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 an unnamed tributary located off Decator Rd. near the USGS hydrograph gauge. The site is named for its proximity to Euclid Ave., and 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 just downstream 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.

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 15 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 at the gaging station approximately 15 m downstream from North Shore Dr.

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 2013/2014 storm water monitoring program focused on collecting storm runoff data from Anderson, Austin, and Brannian Creeks. For information about other storm water sites that have been monitored by IWS, refer to the annual reports listed in Section 4.2 (page 76).

Anderson Creek samples are collected 15 m upstream from South Bay Rd. Water samples and discharge measurements are collected upstream from the bridge. The Anderson Creek hydrograph²⁰ is mounted in the stilling well on the east side of Anderson Creek, directly adjacent 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**.

Brannian Creek samples are collected approximately 40 m downstream from South Bay Rd. near the USGS hydrograph gauge.

²⁰This 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.

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.

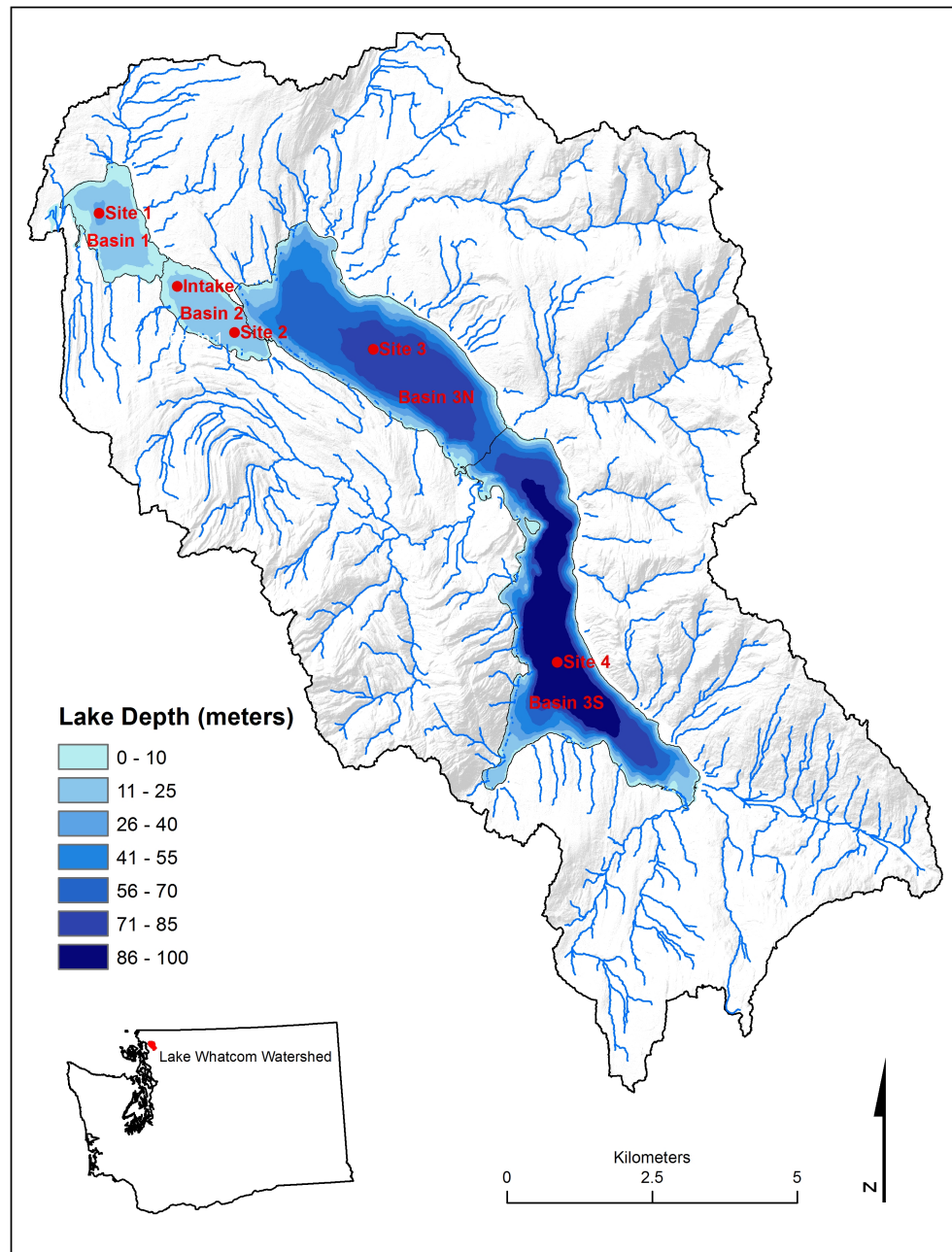


Figure A1: Lake Whatcom lake sampling sites. Basemap created using data from Western Washington University, Skagit County, the Nooksack Tribe, and the City of Bellingham.

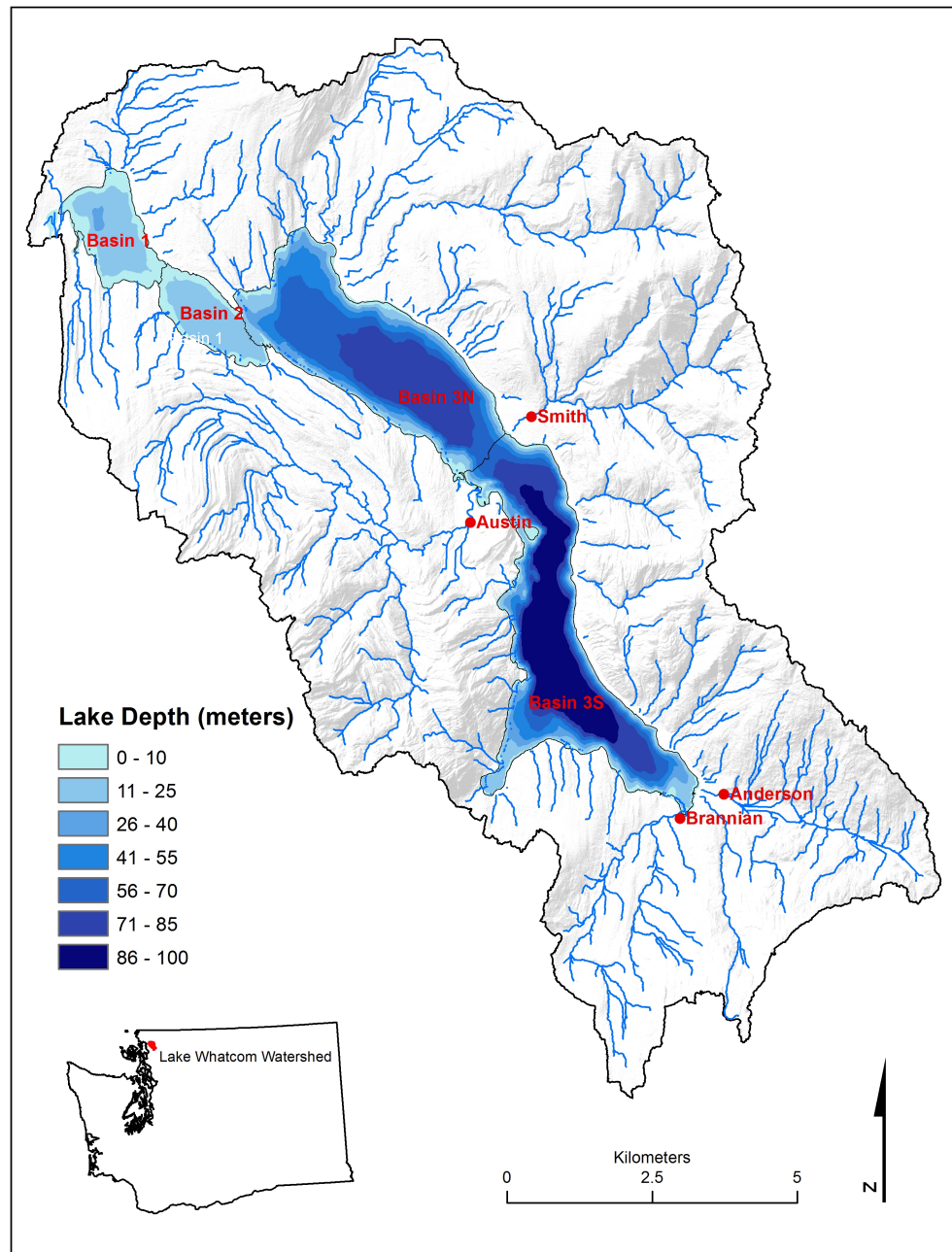


Figure A2: Lake Whatcom hydrograph and storm water sampling sites. Basemap created using data from Western Washington University, Skagit County, the Nooksack Tribe, and the City of Bellingham.

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 16).

The historic detection limits for each parameter were estimated based on recommended lower detection ranges (APHA, 1998; Hydrolab, 1997; Lind, 1985), 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 defined below (see current detection limits in Table 2.1, page 16). 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 introduction of increasingly sensitive field equipment (see, for example, Figures B66–B70, pages 154–158, 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

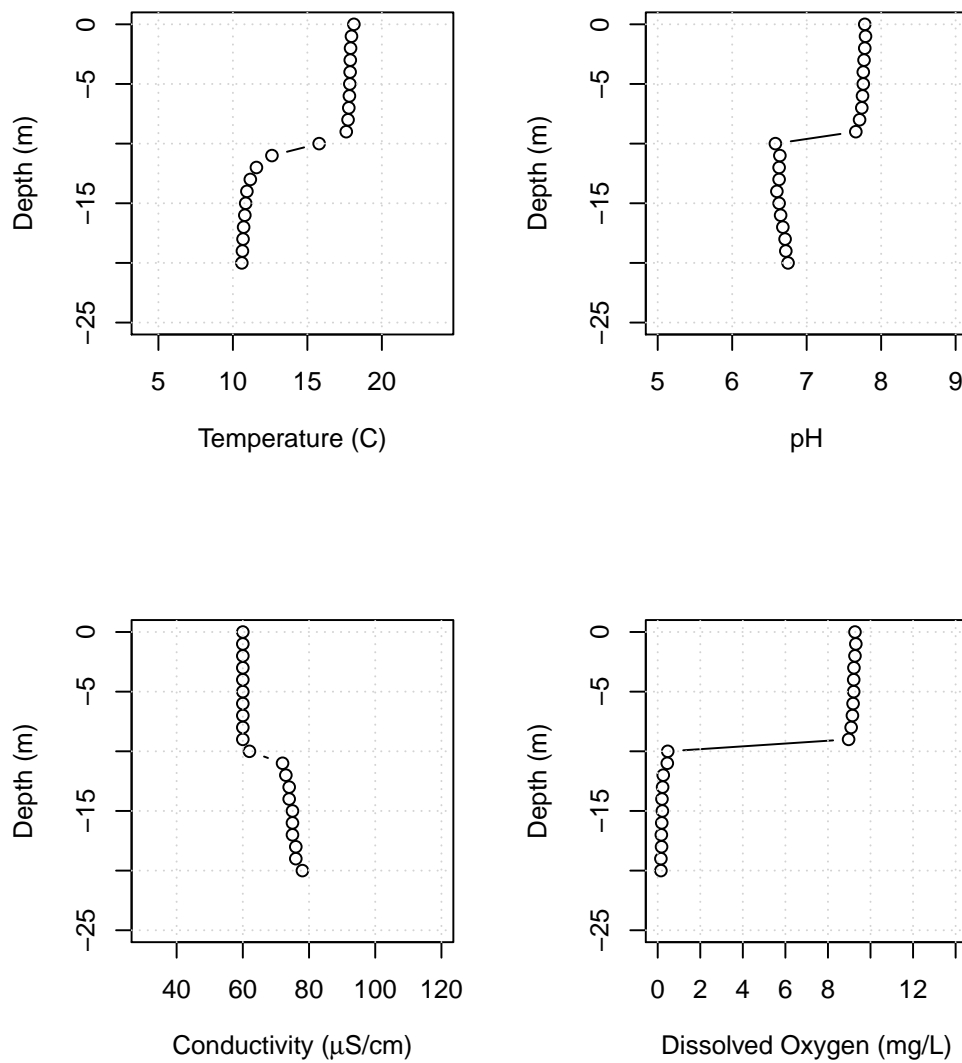


Figure B1: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, October 2, 2014.

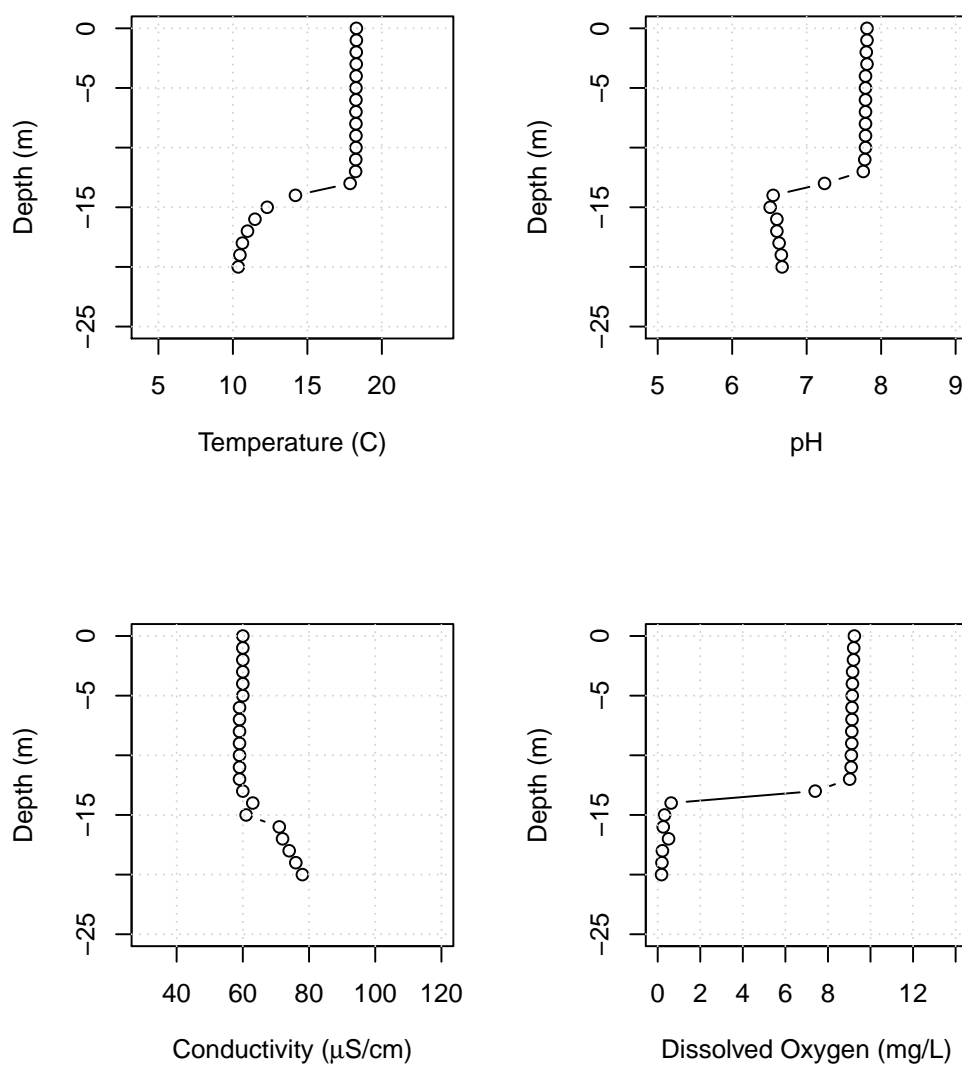


Figure B2: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, October 2, 2014.

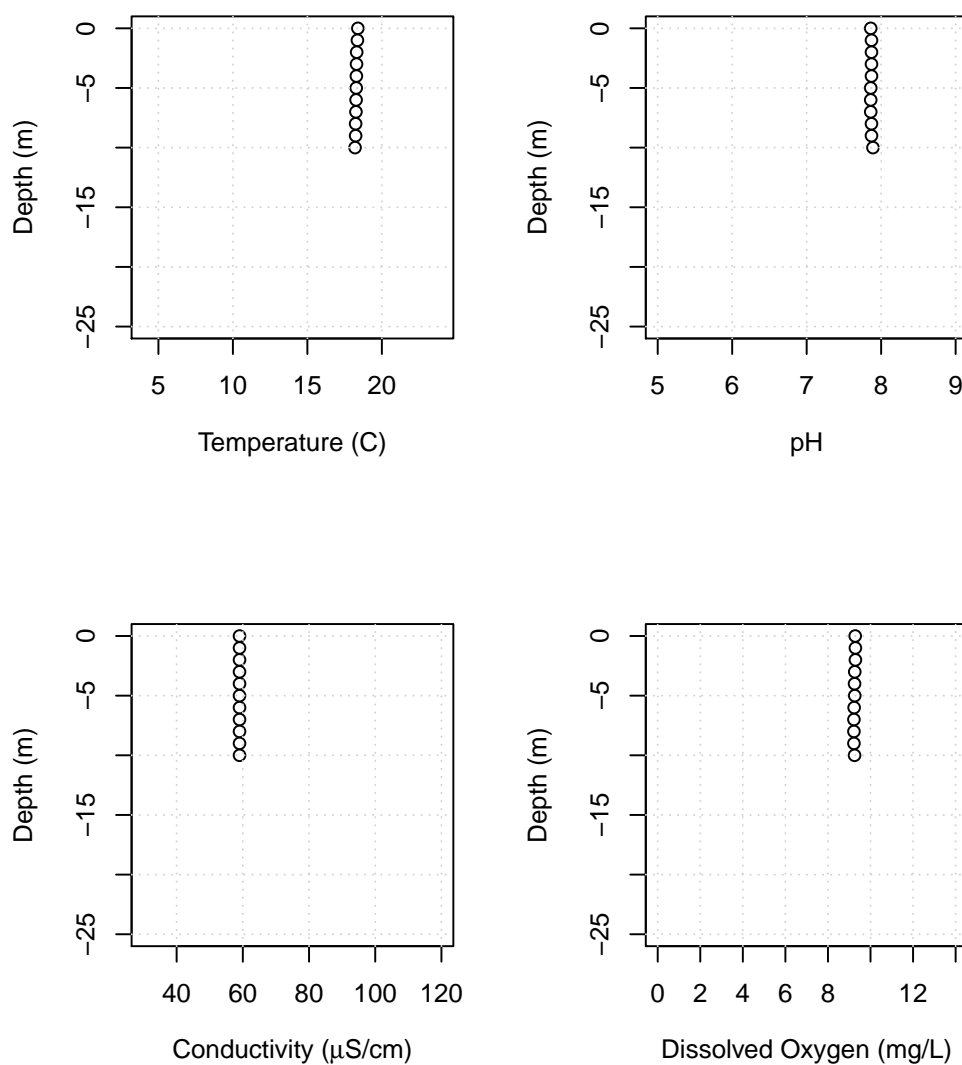


Figure B3: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, October 2, 2014.

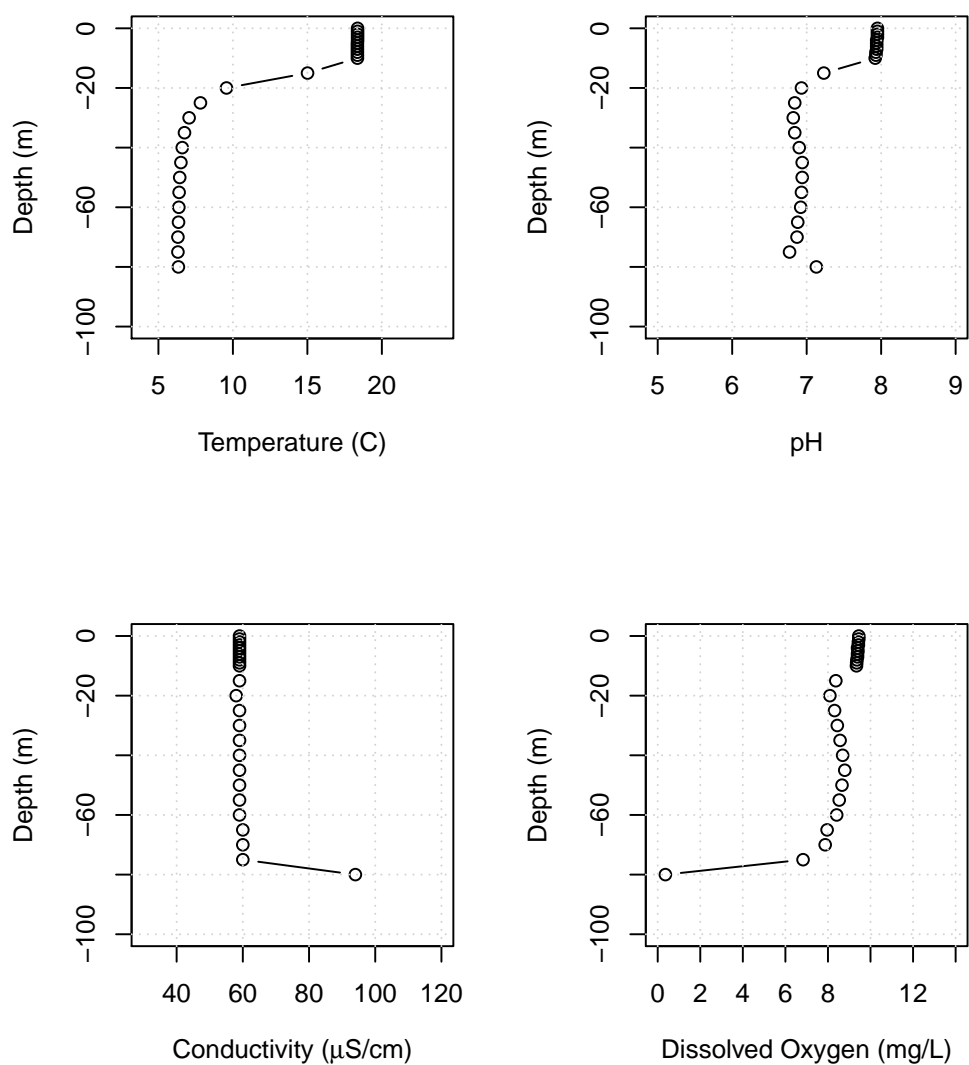


Figure B4: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, October 1, 2014.

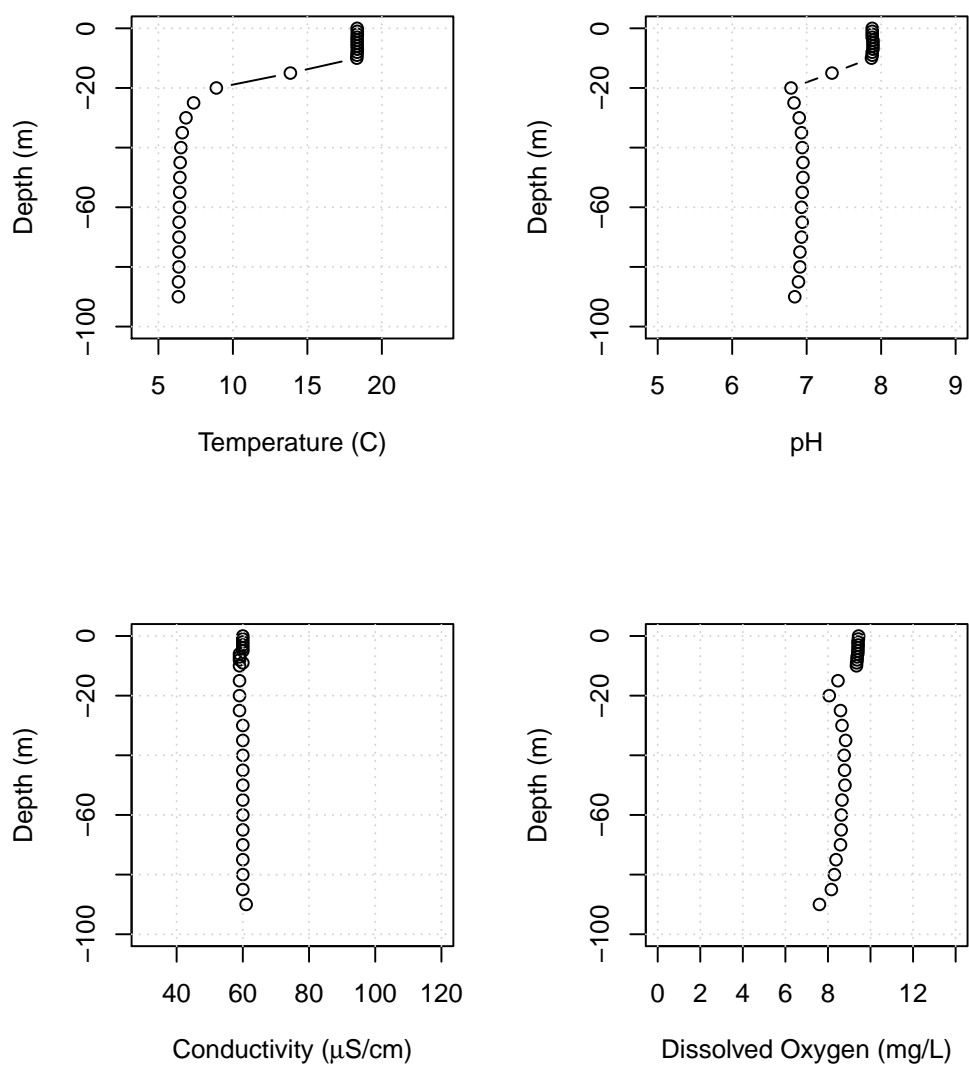


Figure B5: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, October 1, 2014.

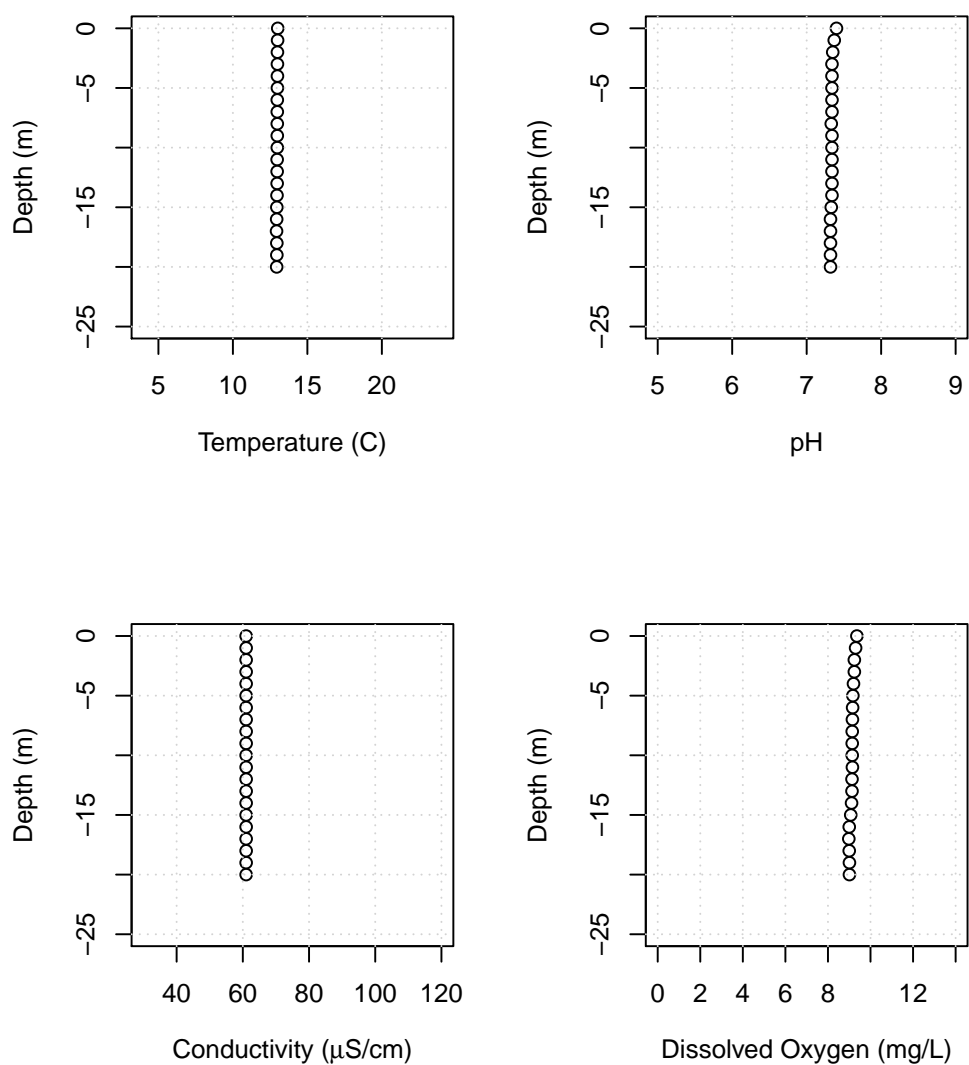


Figure B6: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, November 5, 2014.

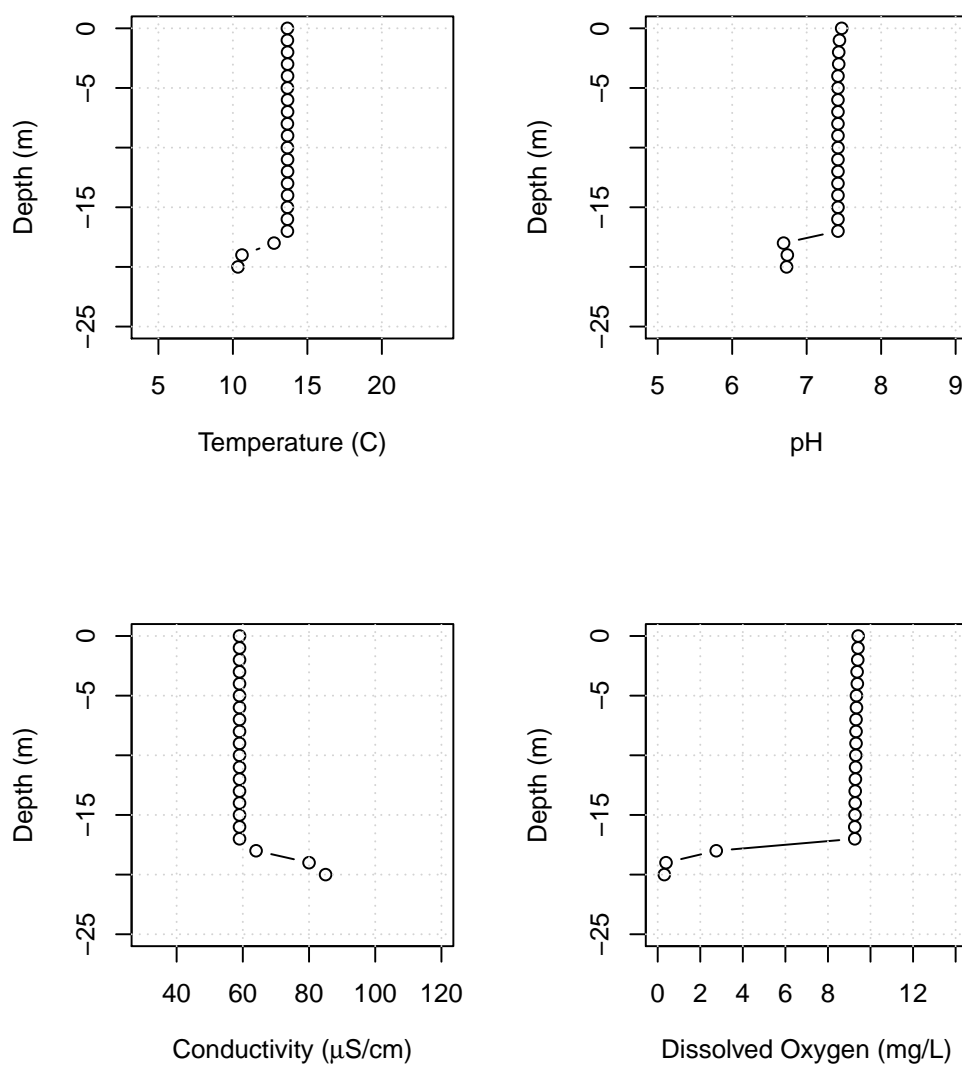


Figure B7: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, November 5, 2014.

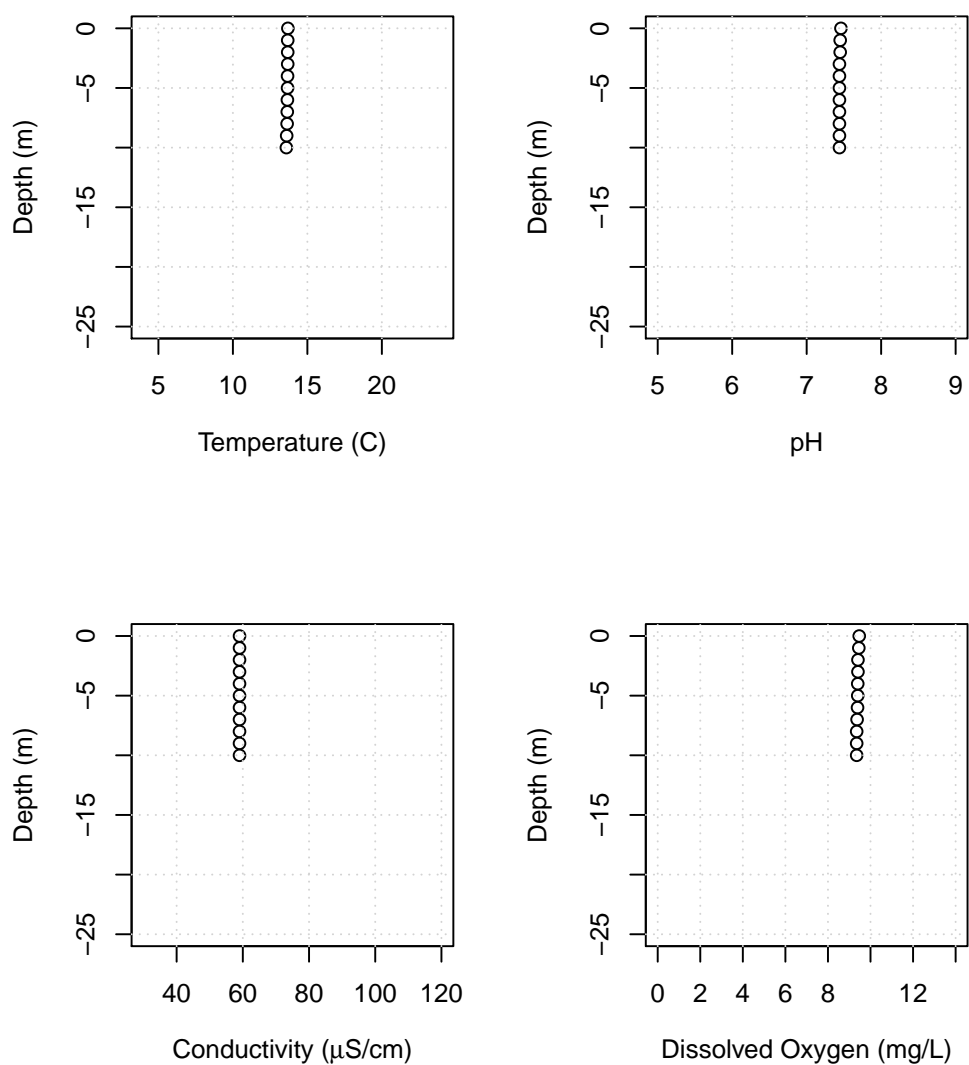


Figure B8: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, November 5, 2014.

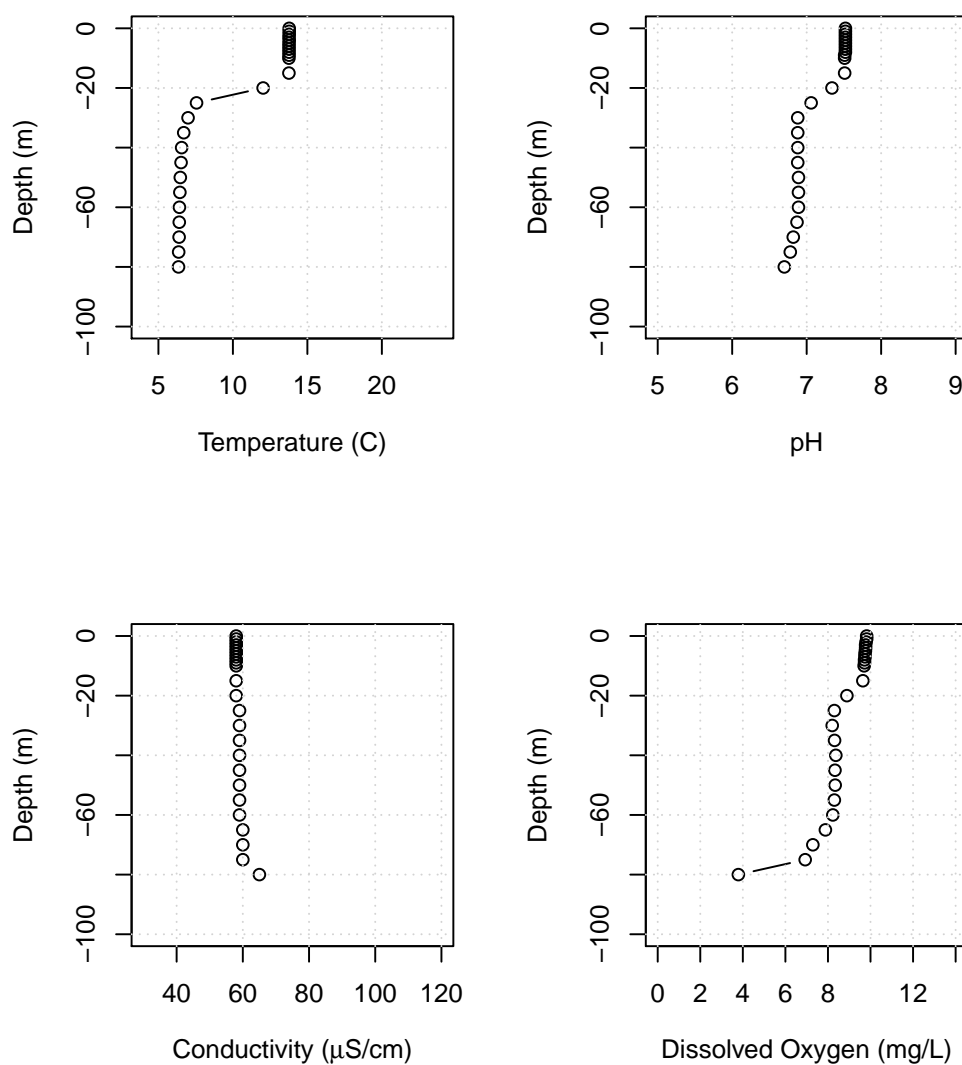


Figure B9: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, November 4, 2014.

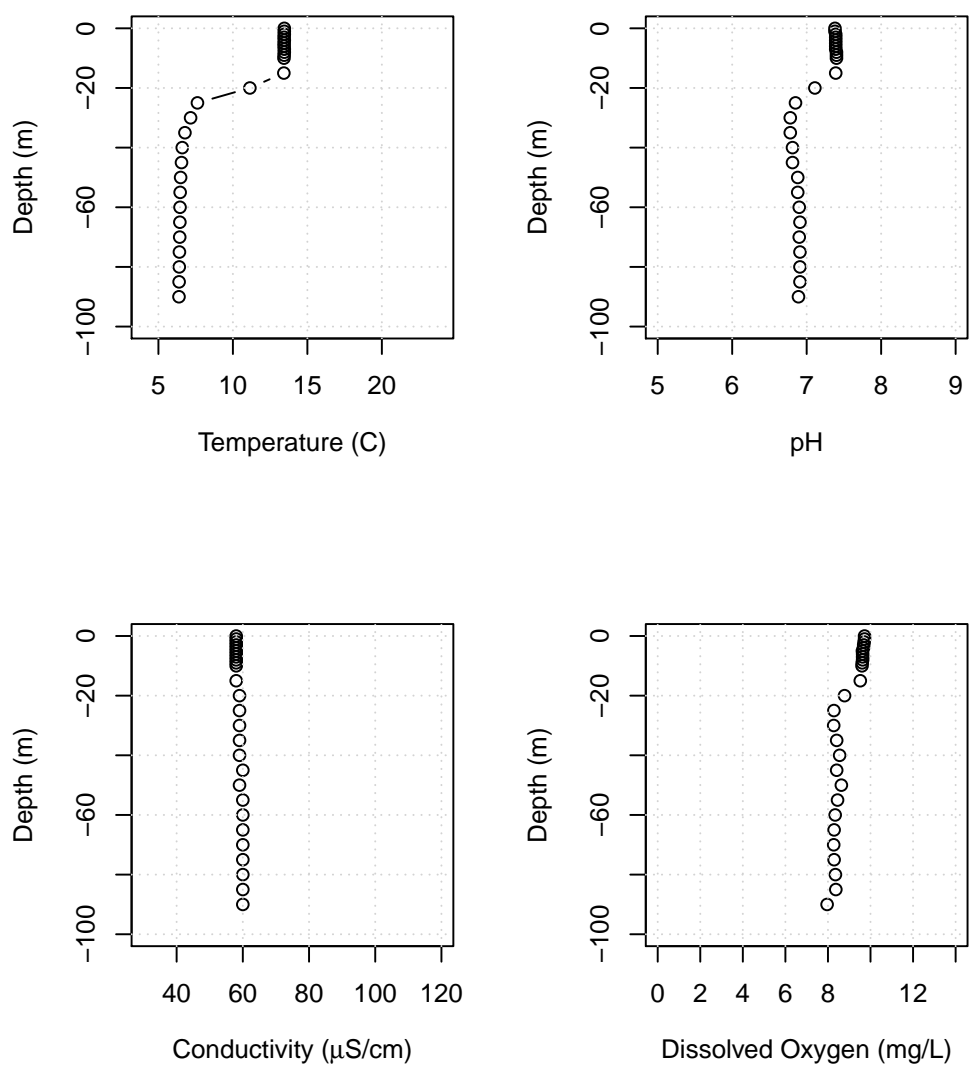


Figure B10: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, November 4, 2014.

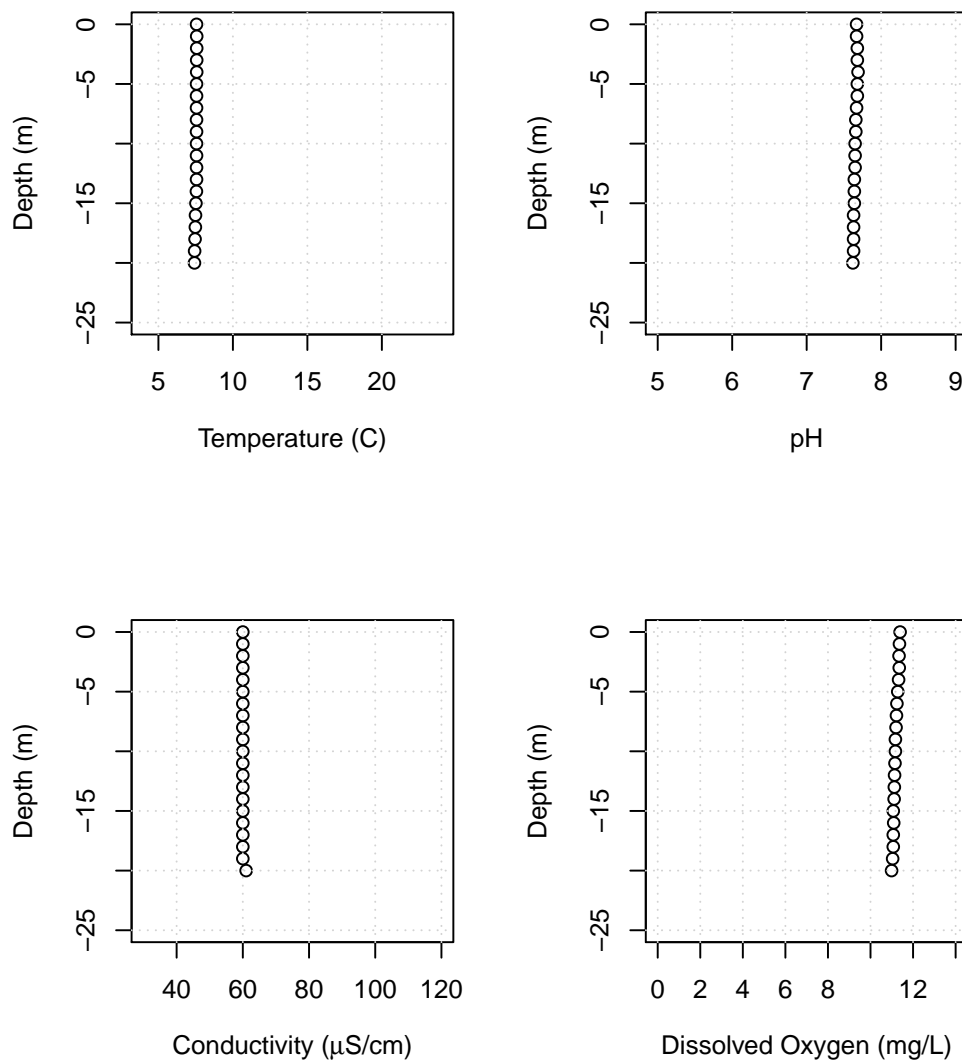


Figure B11: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, December 4, 2014.

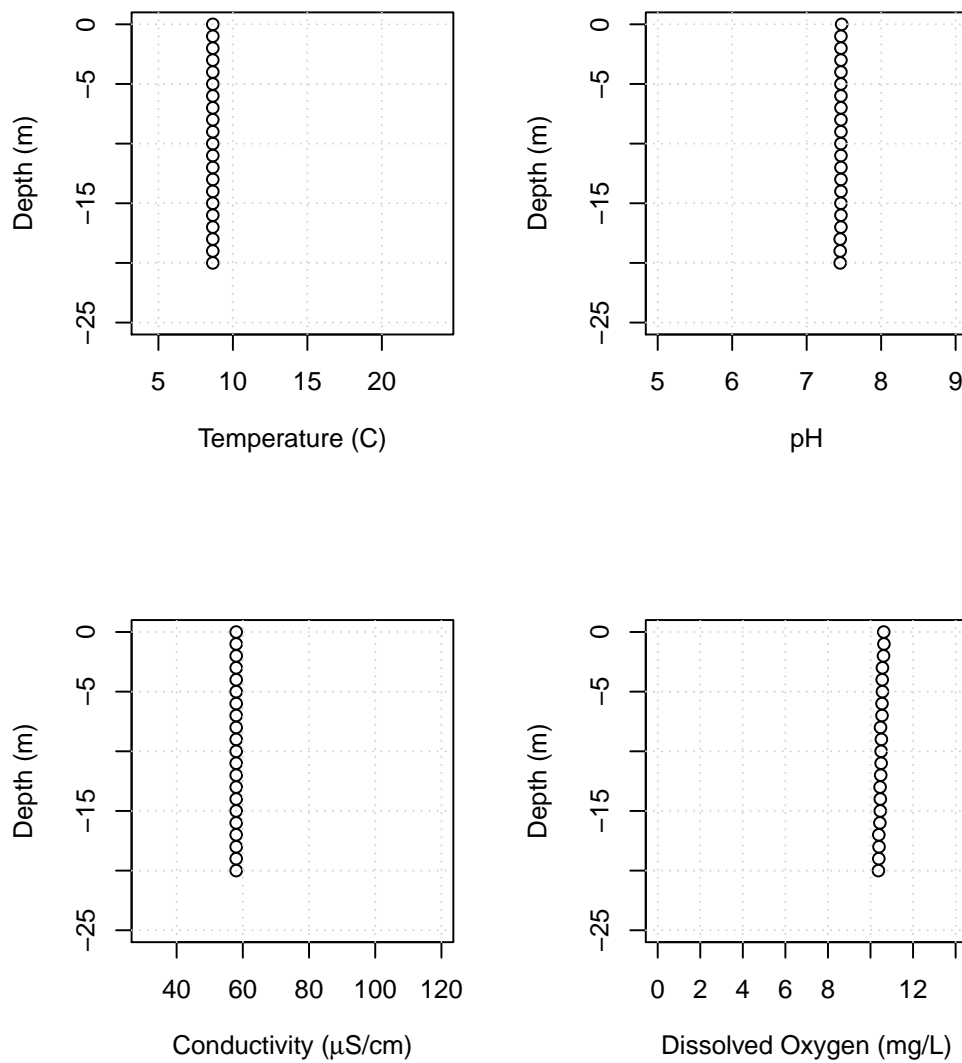


Figure B12: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, December 4, 2014.

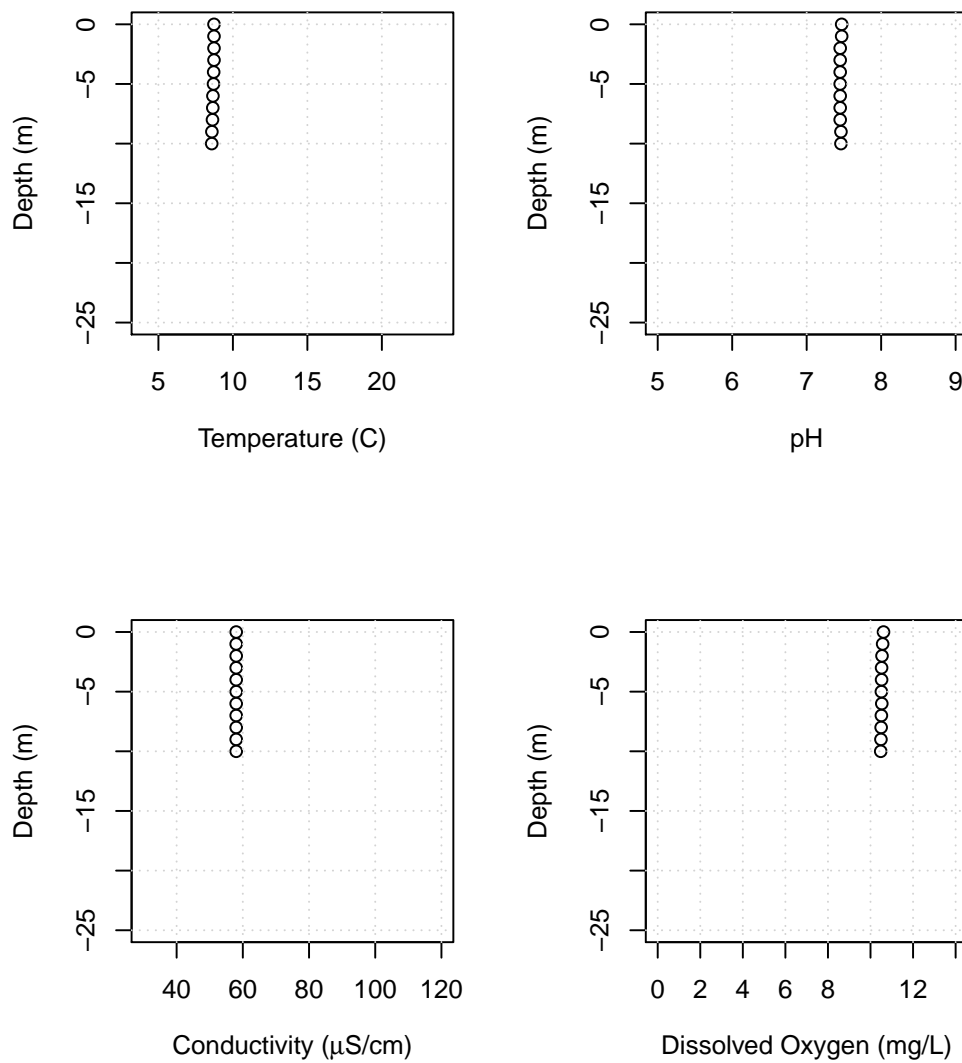


Figure B13: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, December 4, 2014.

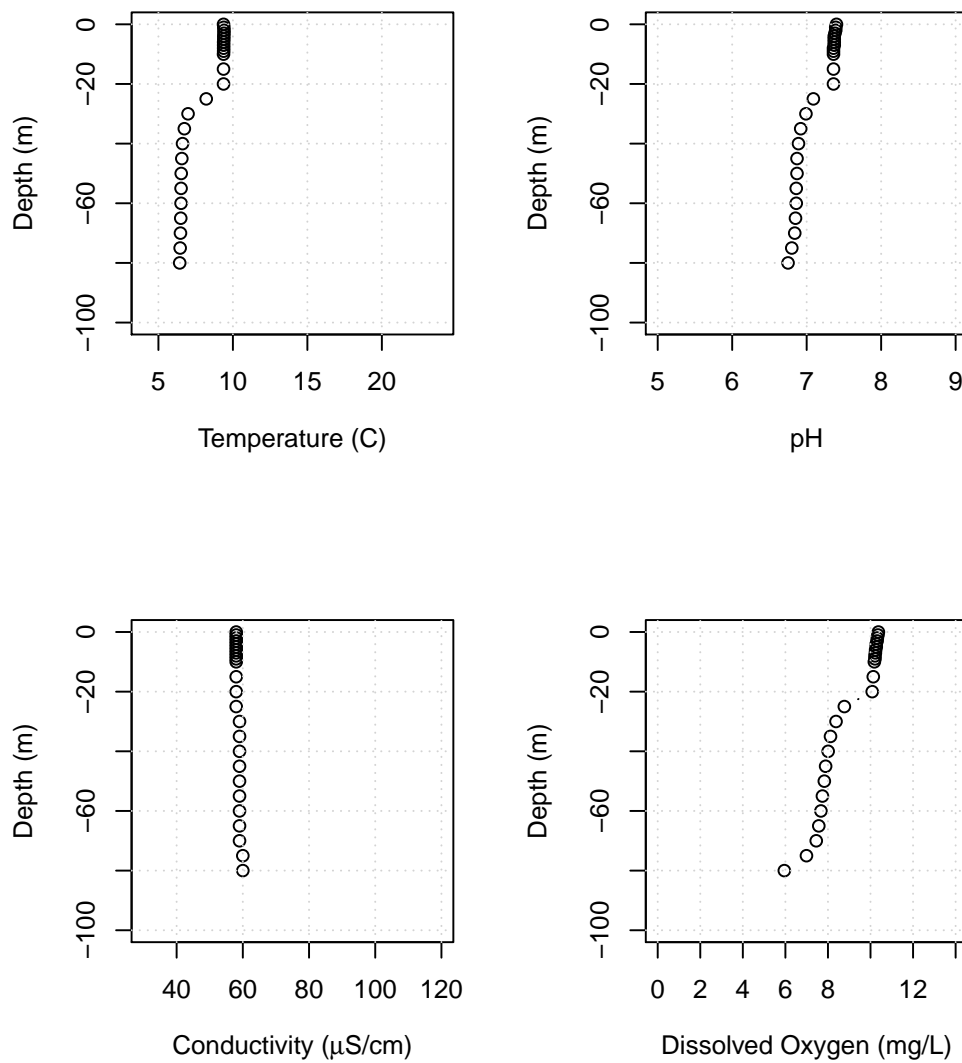


Figure B14: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, December 2, 2014.

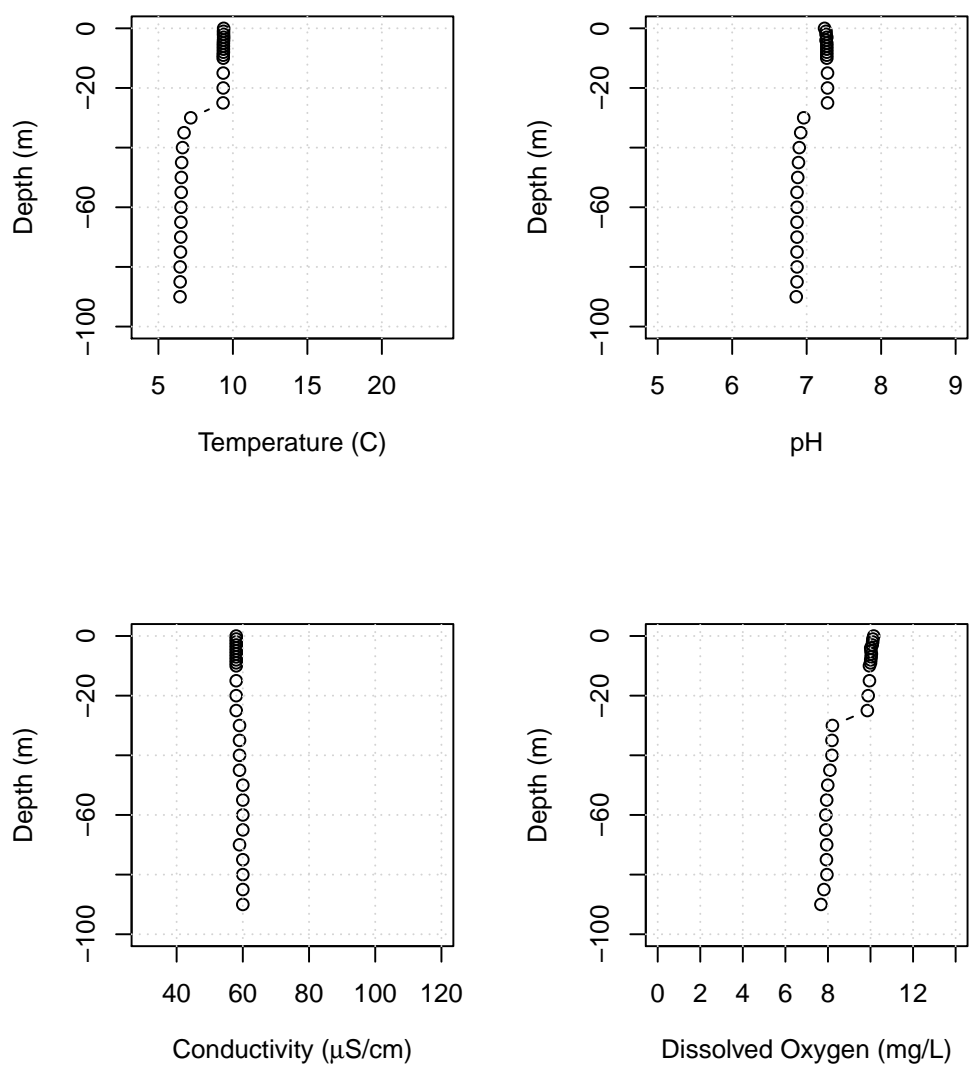


Figure B15: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, December 2, 2014.

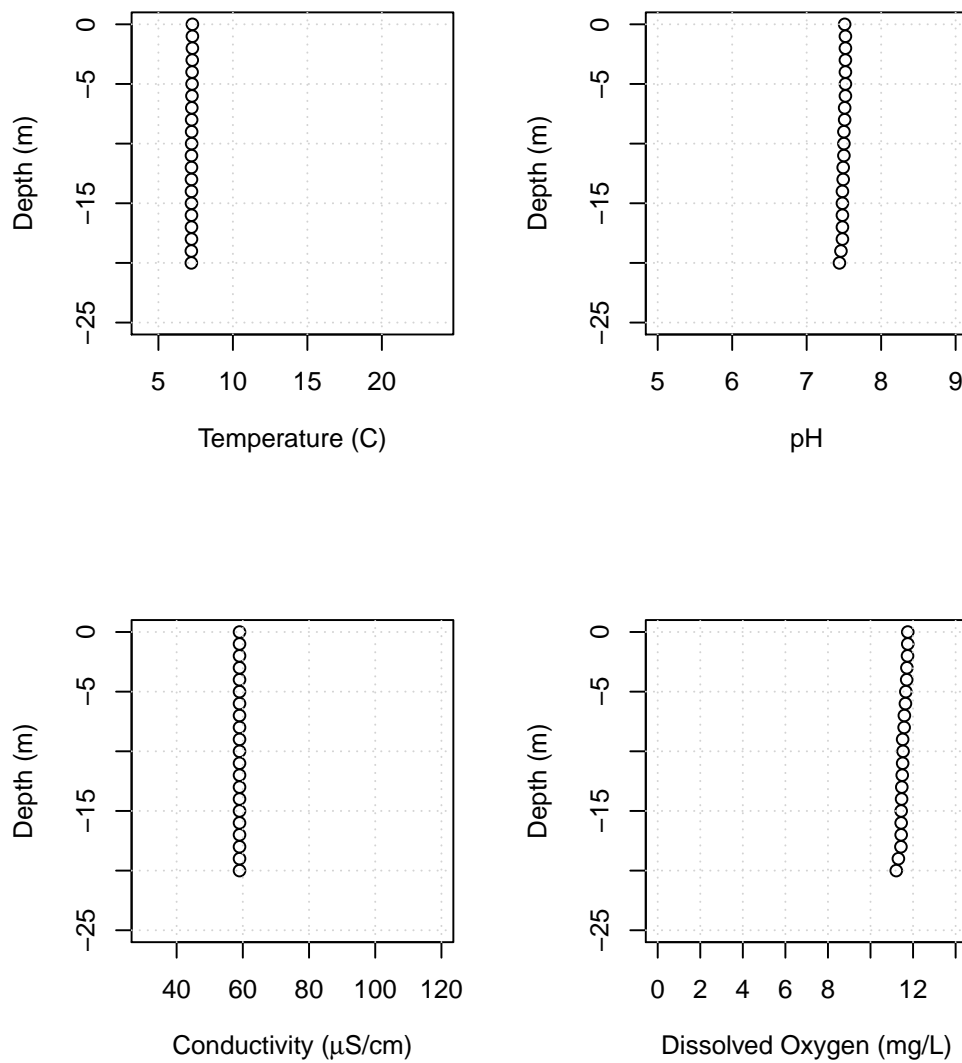


Figure B16: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, February 4, 2015.

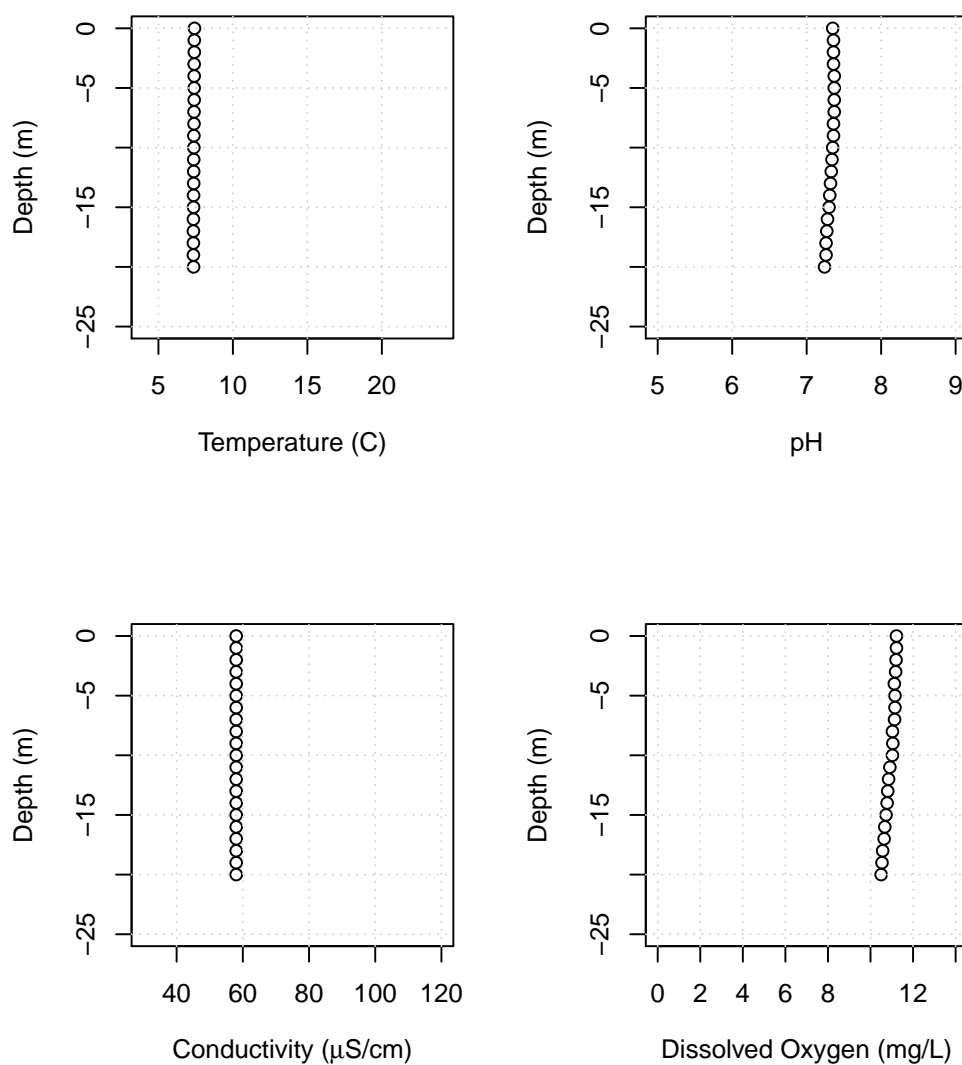


Figure B17: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, February 4, 2015.

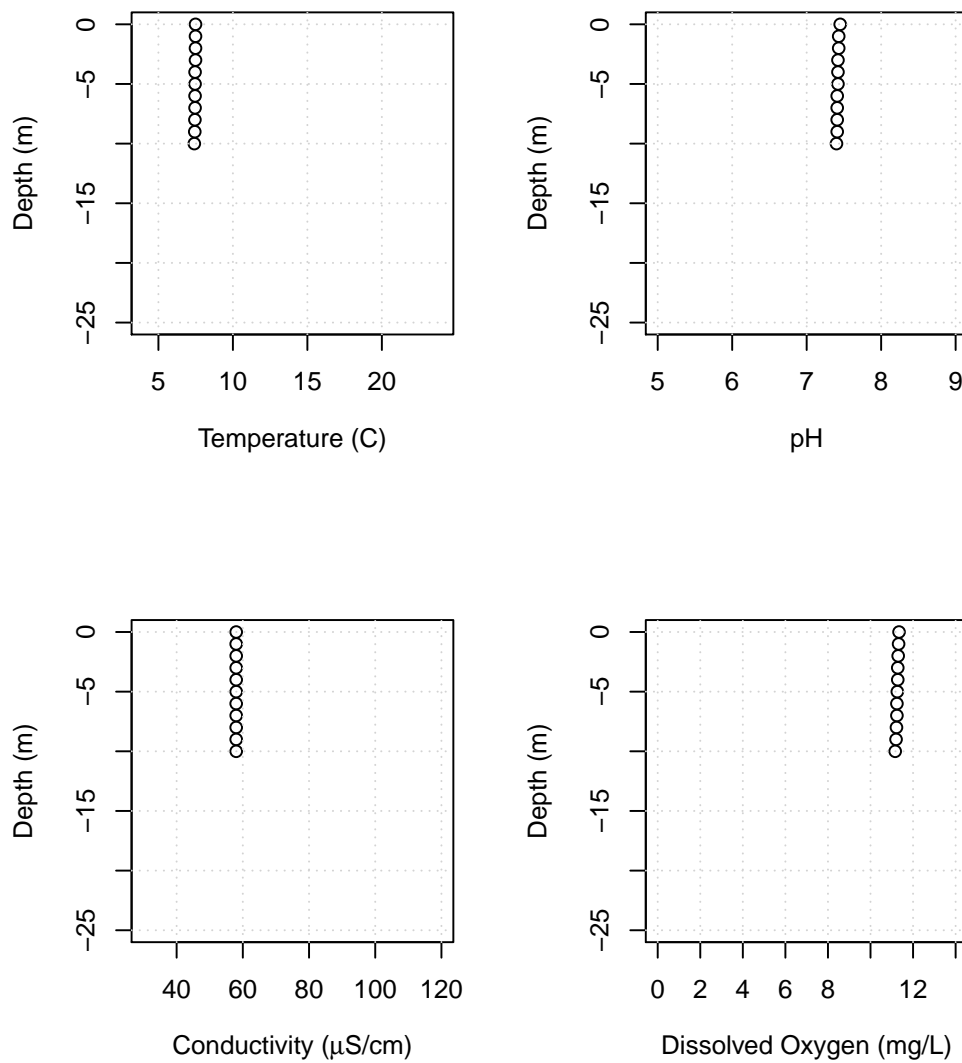


Figure B18: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, February 4, 2015.

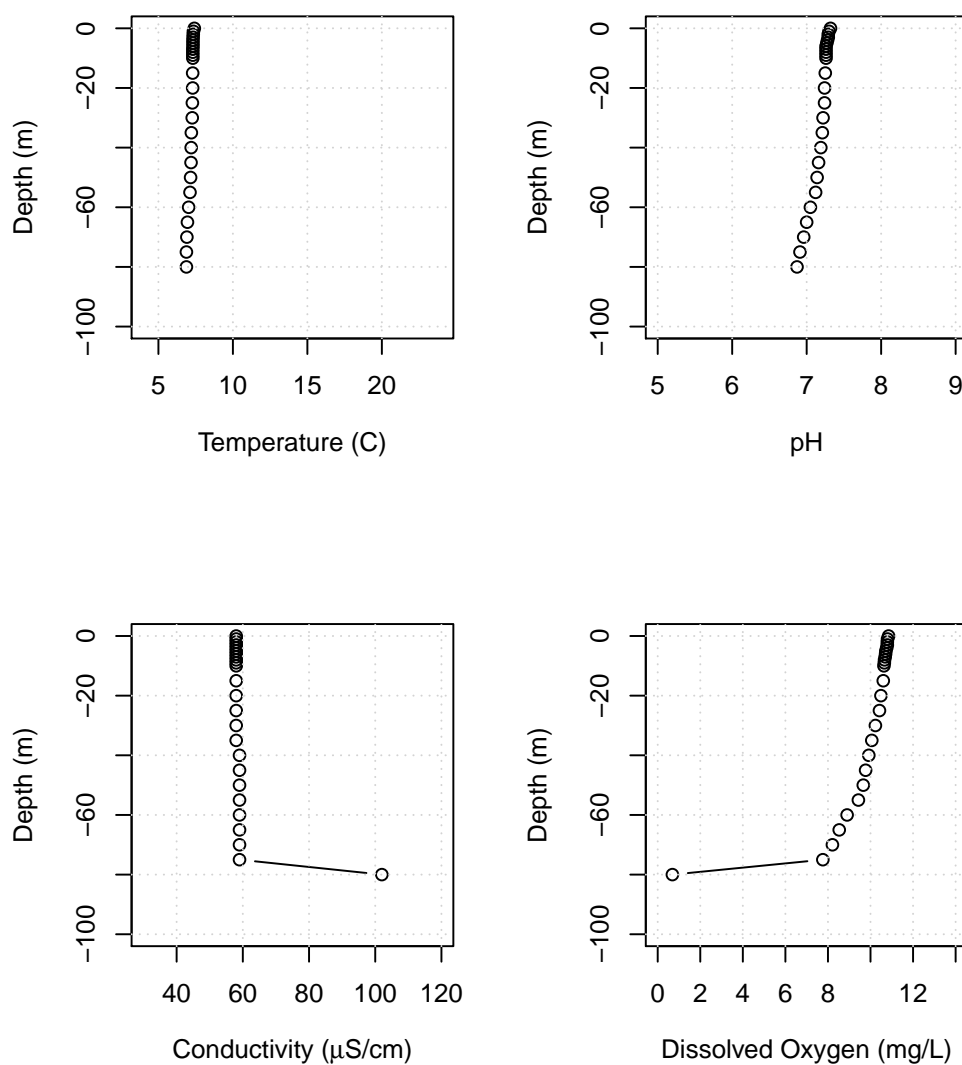


Figure B19: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, February 3, 2015.

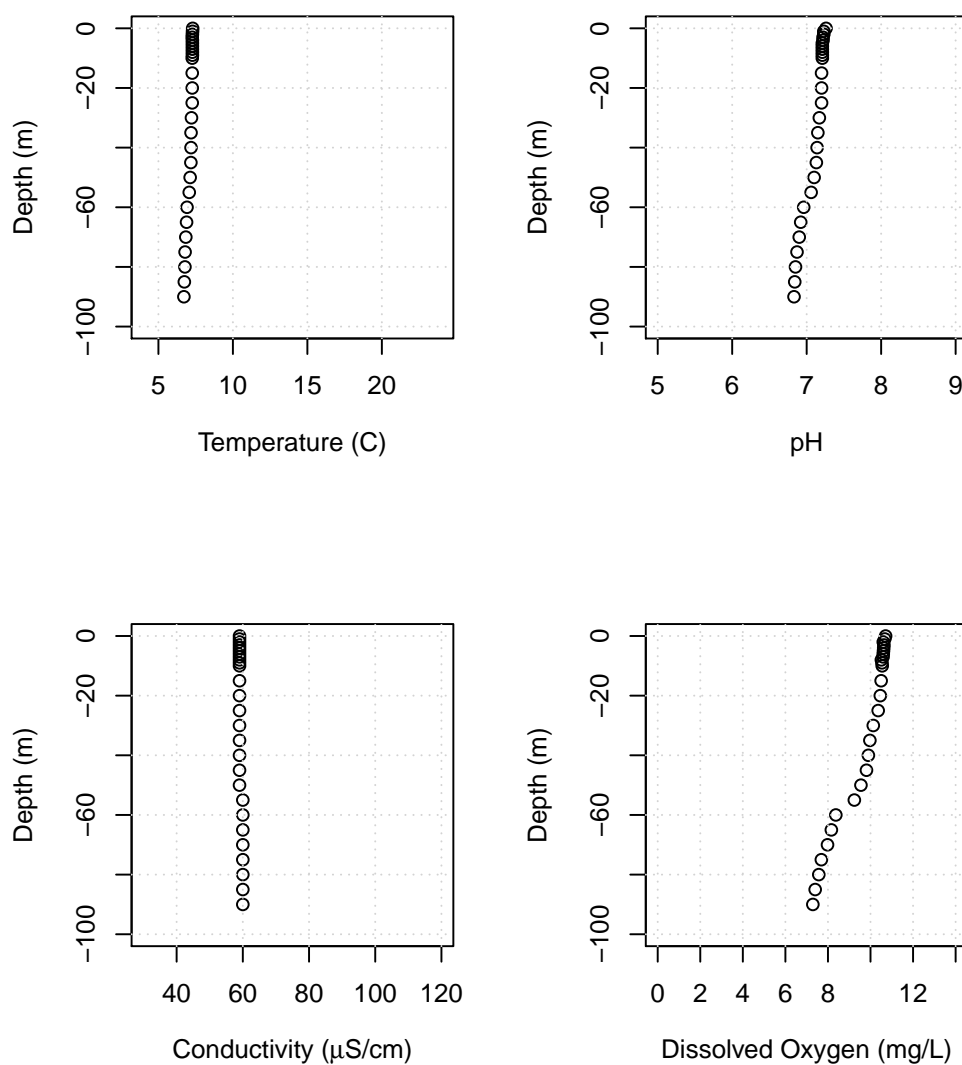


Figure B20: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, February 3, 2015.

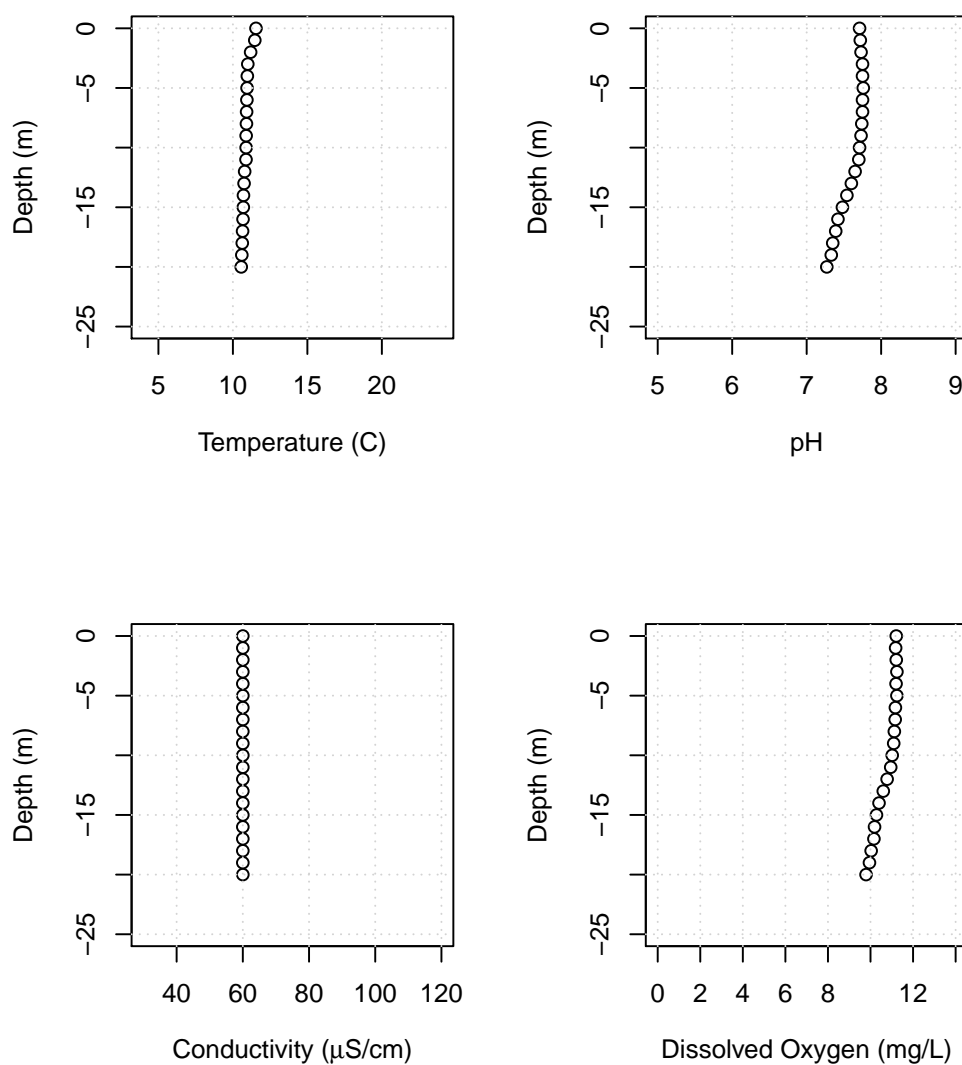


Figure B21: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, April 14, 2015.

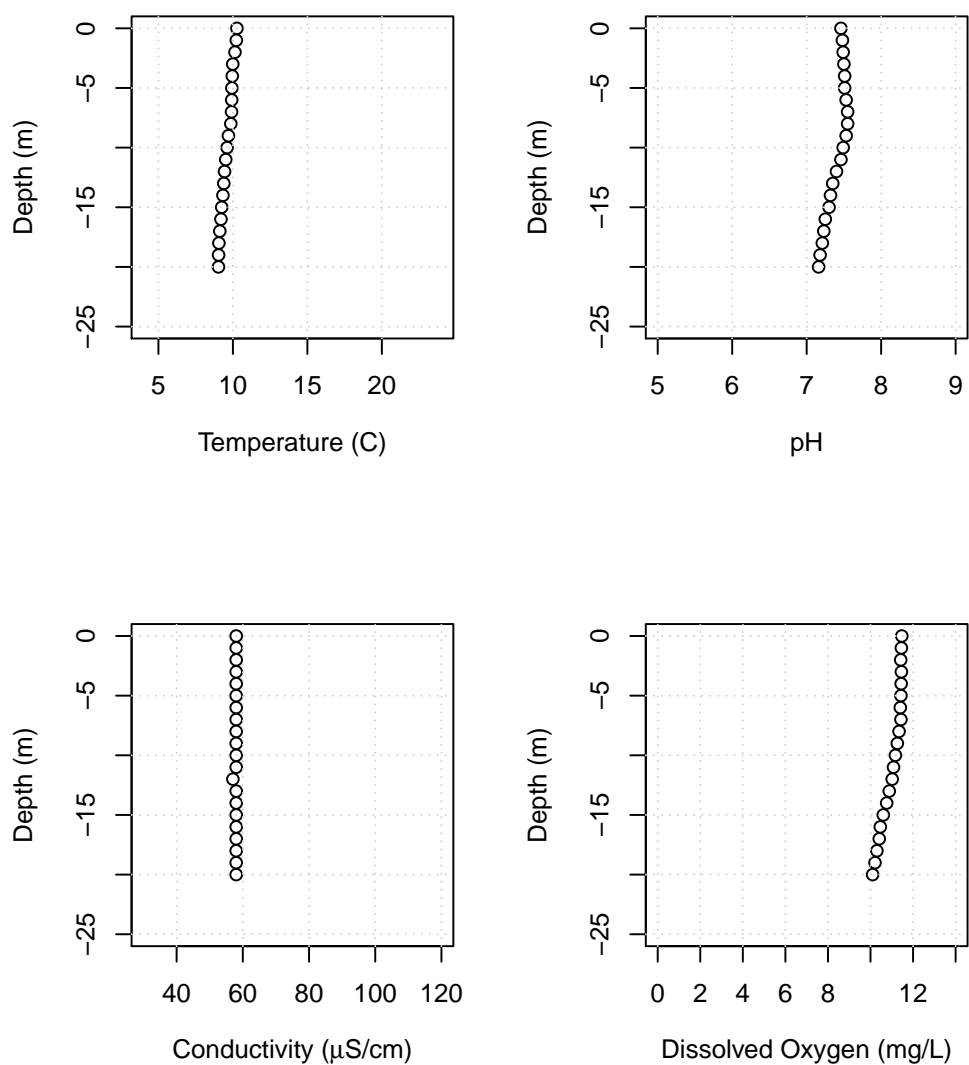


Figure B22: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, April 14, 2015.

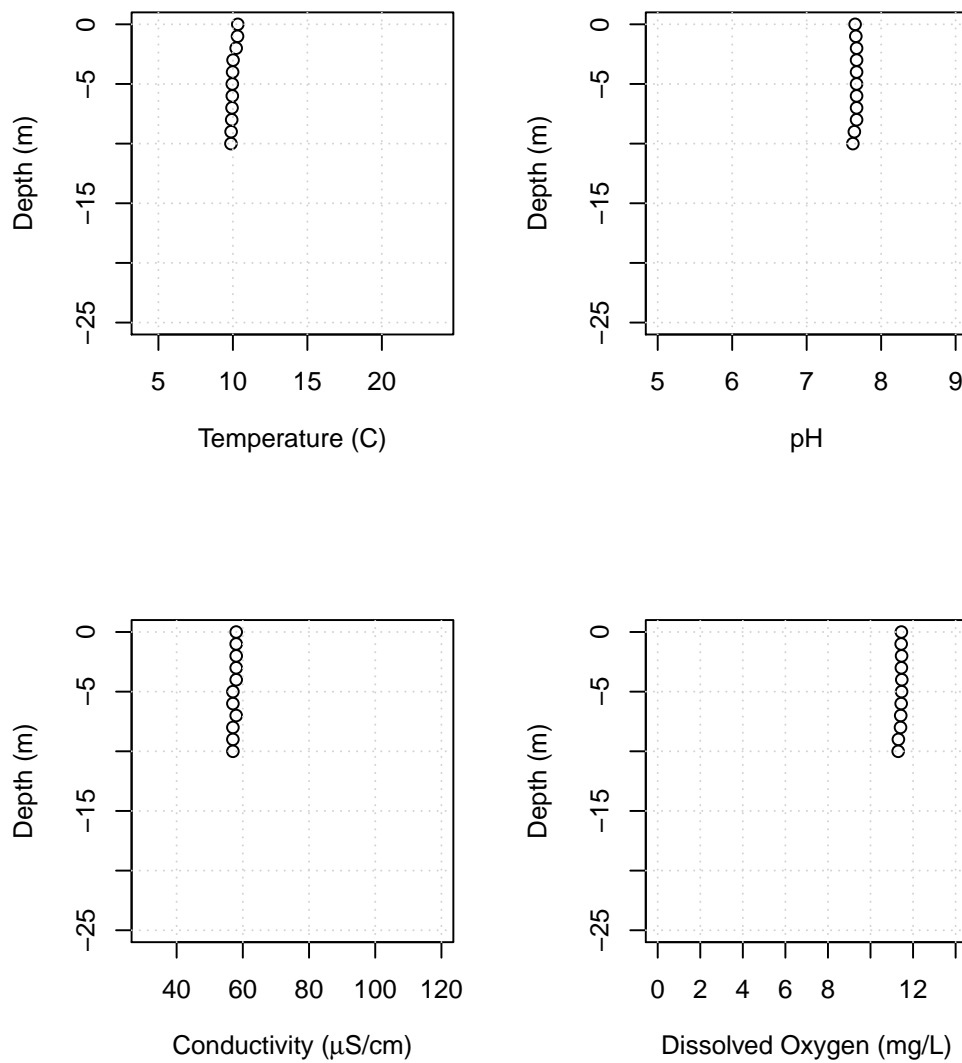


Figure B23: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, April 14, 2015.

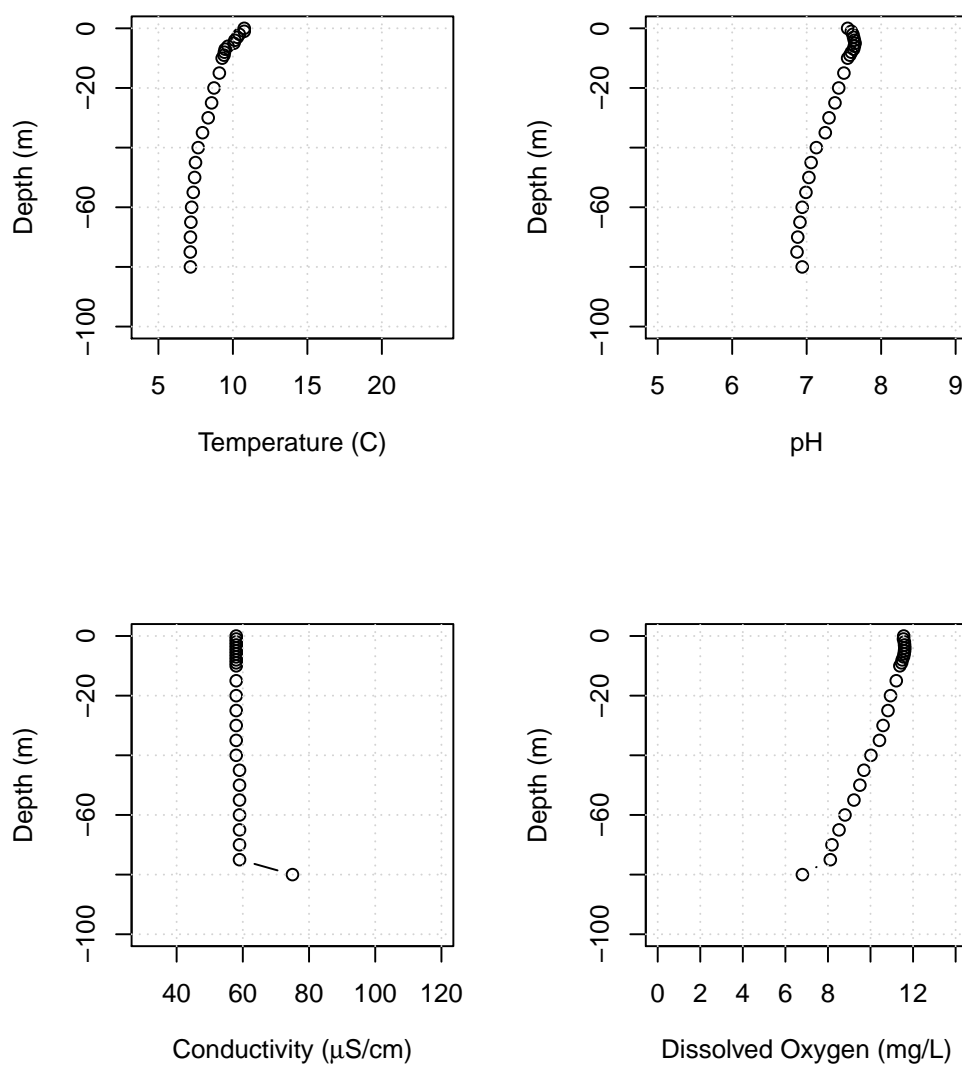


Figure B24: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, April 9, 2015.

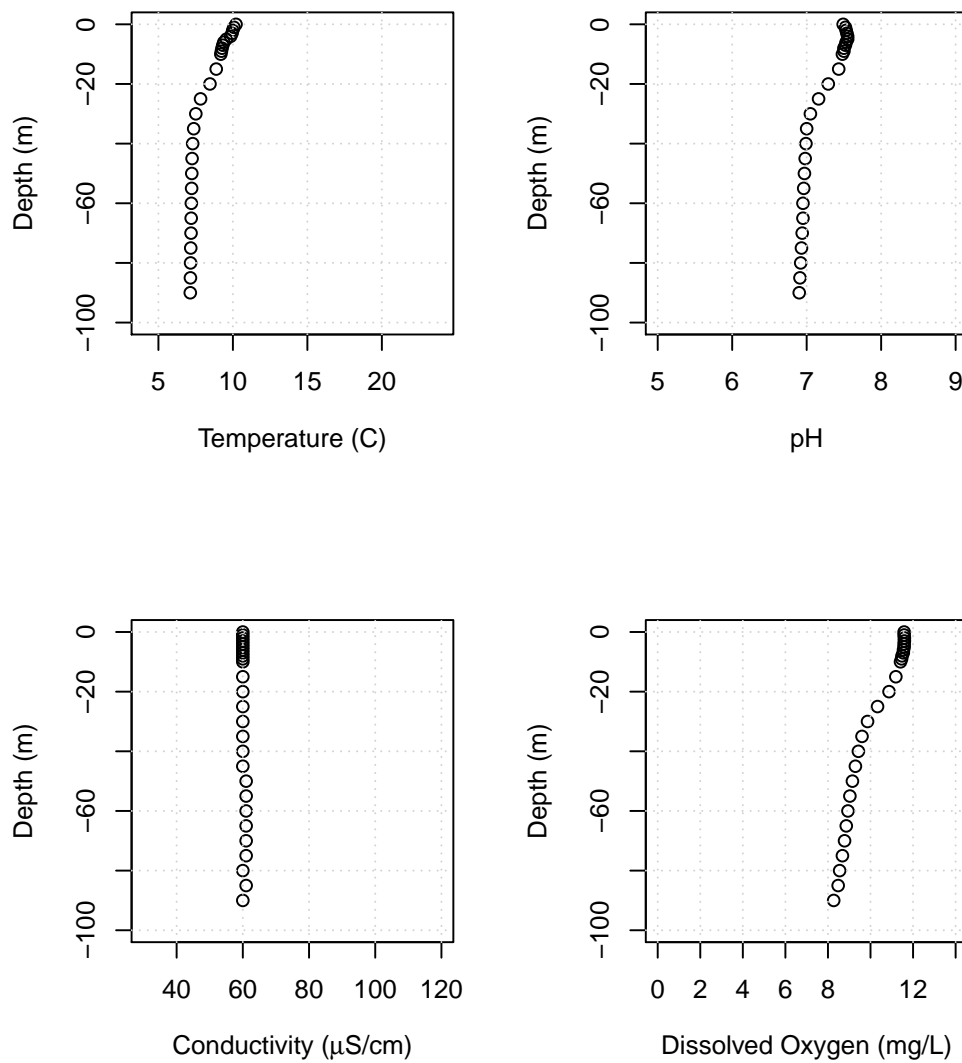


Figure B25: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, April 9, 2015.

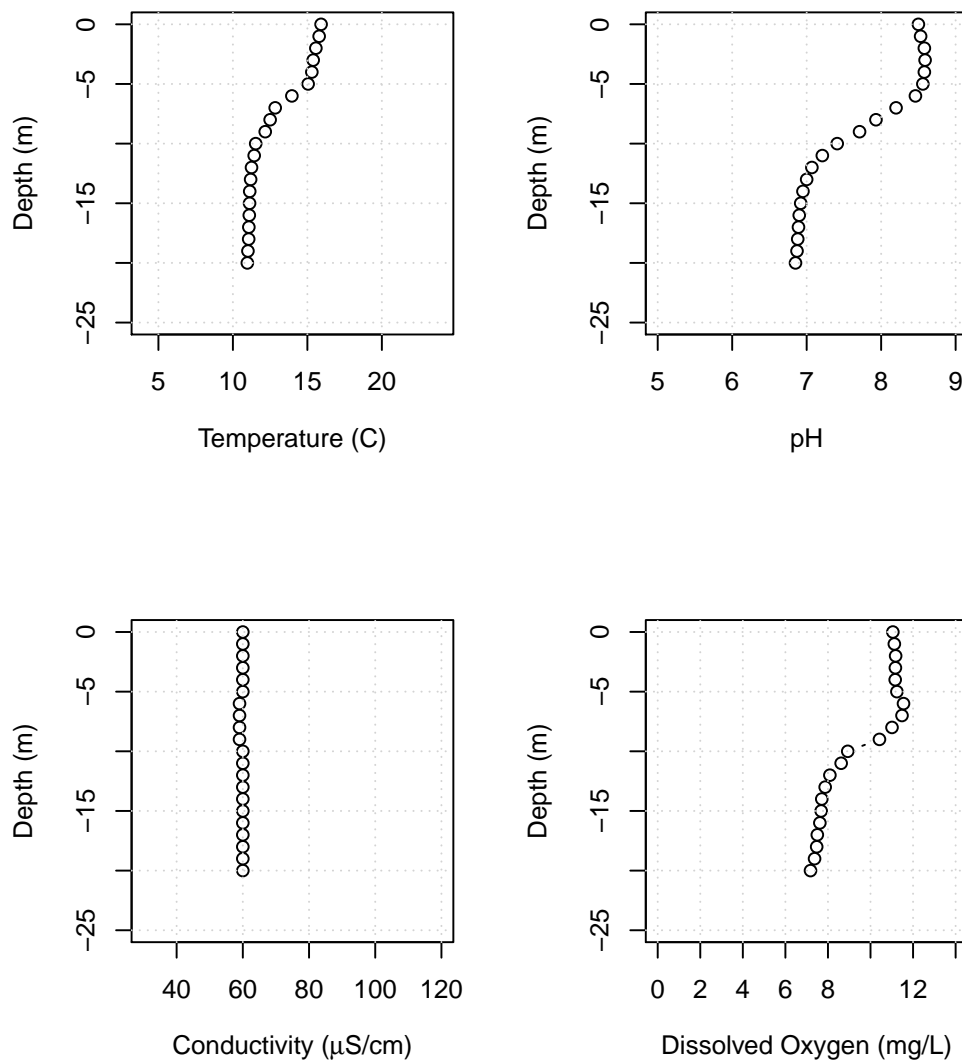


Figure B26: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, May 12, 2015.

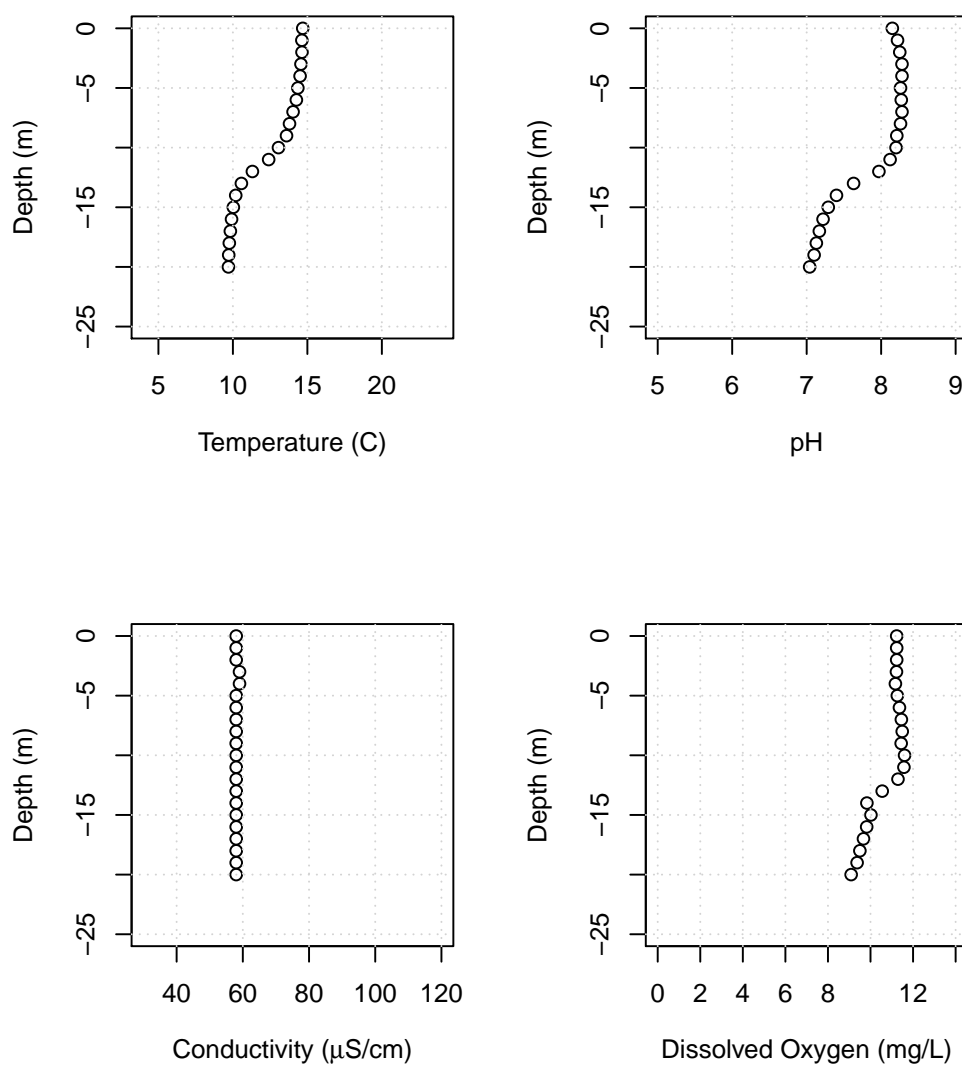


Figure B27: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, May 12, 2015.

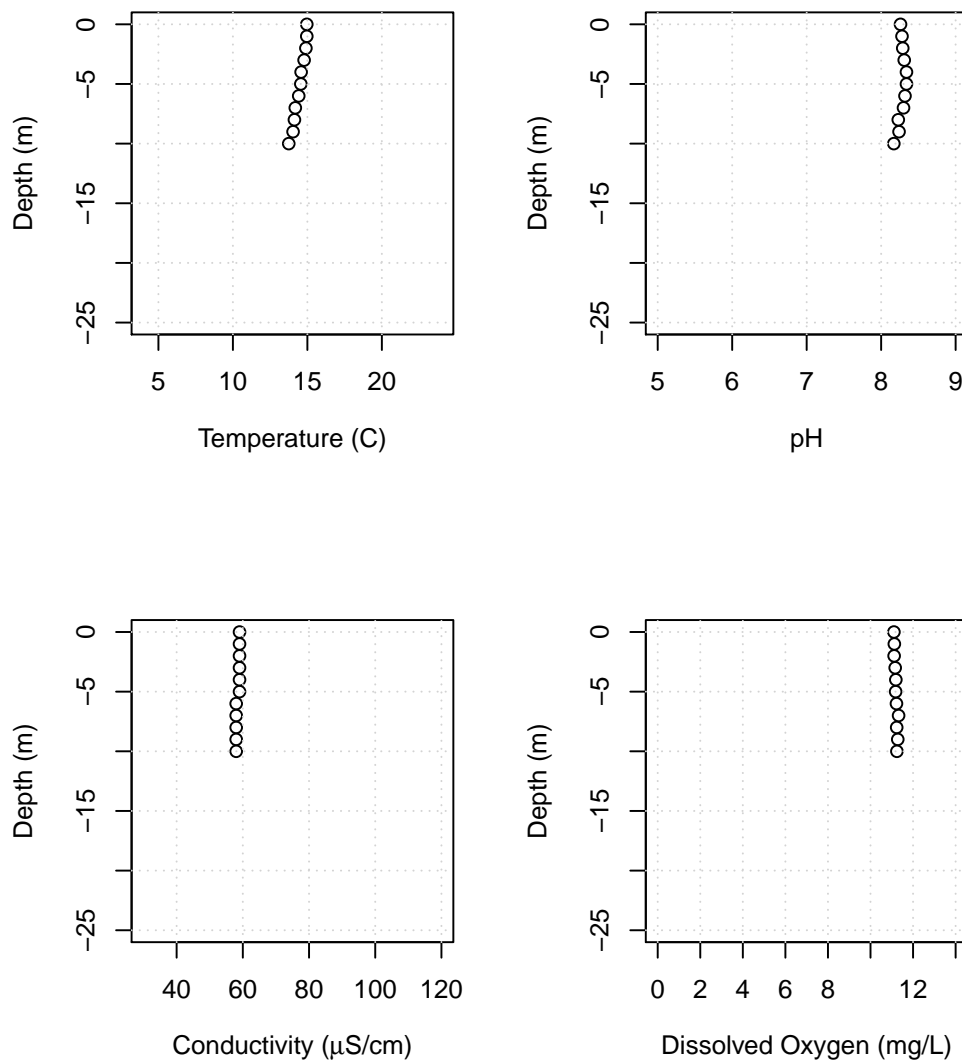


Figure B28: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, May 12, 2015.

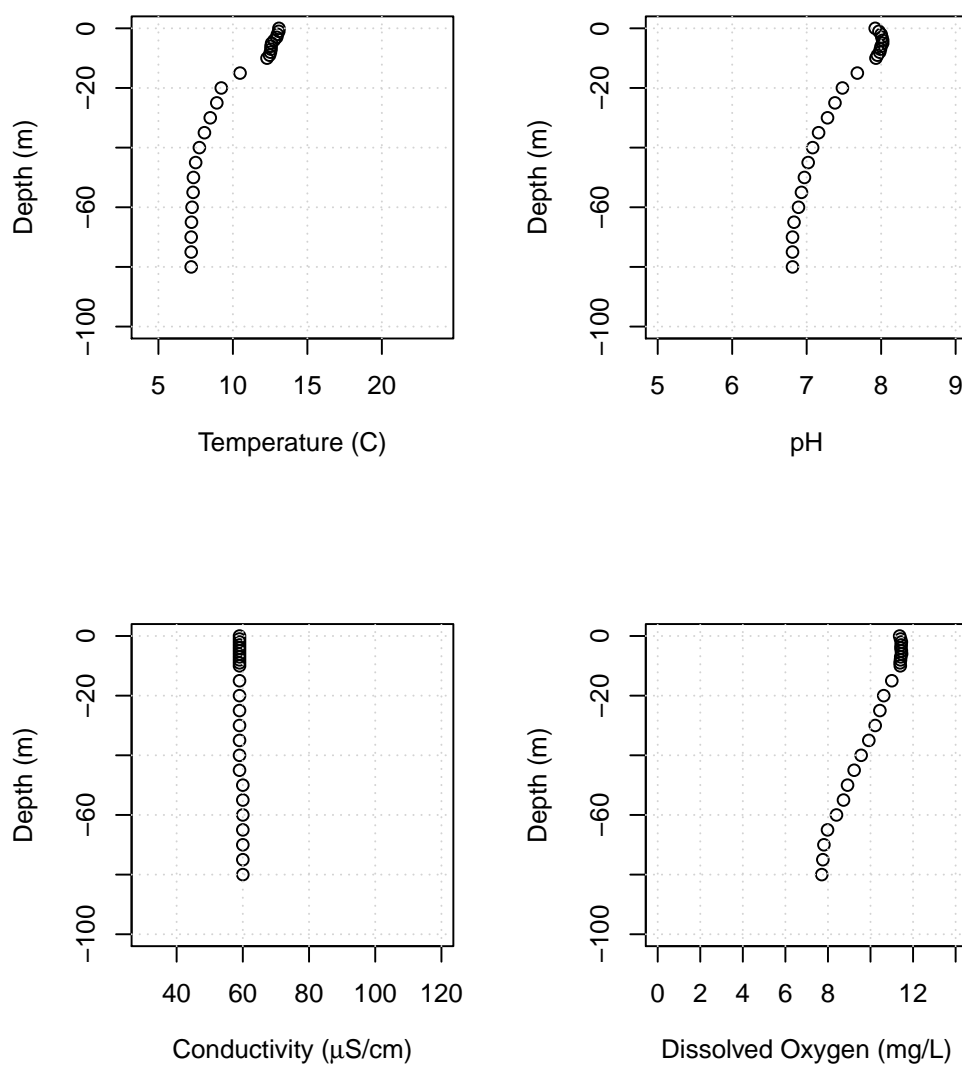


Figure B29: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, May 7, 2015.

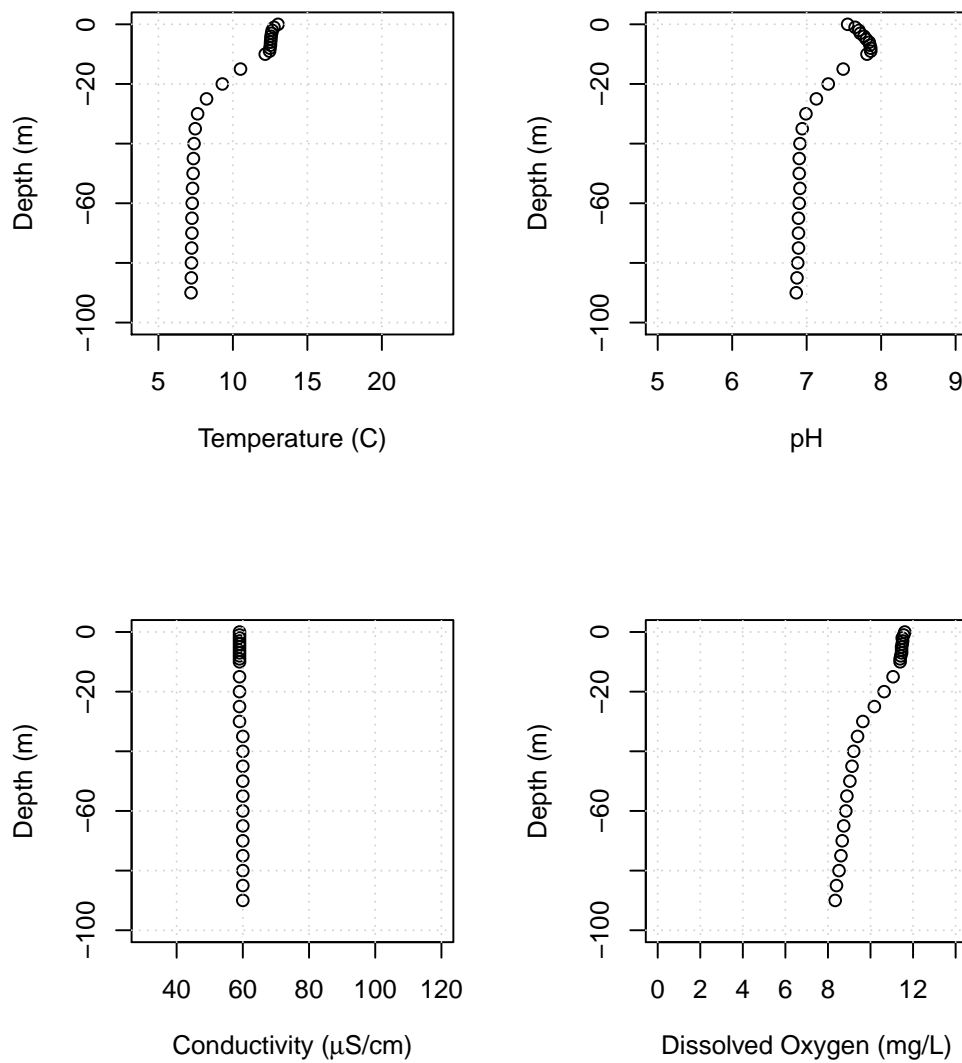


Figure B30: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, May 7, 2015.

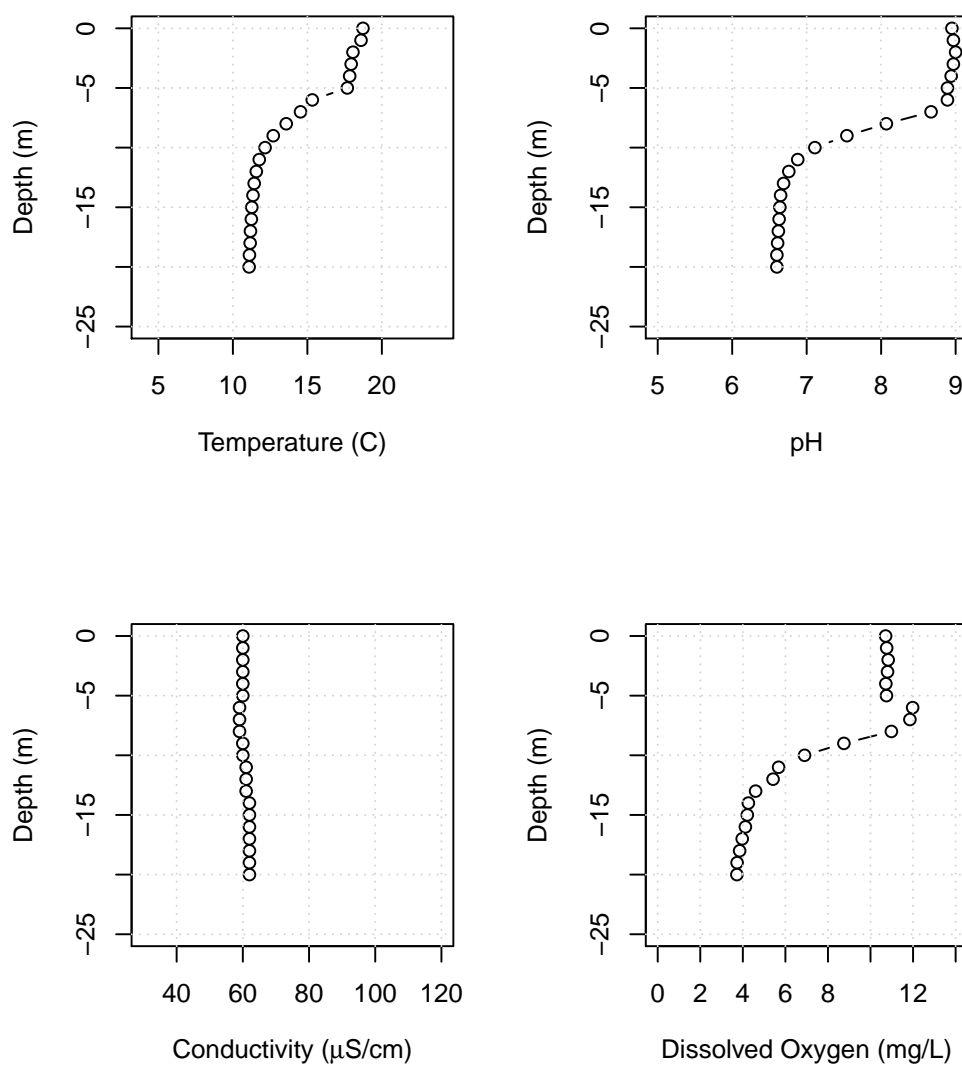


Figure B31: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, June 4, 2015.

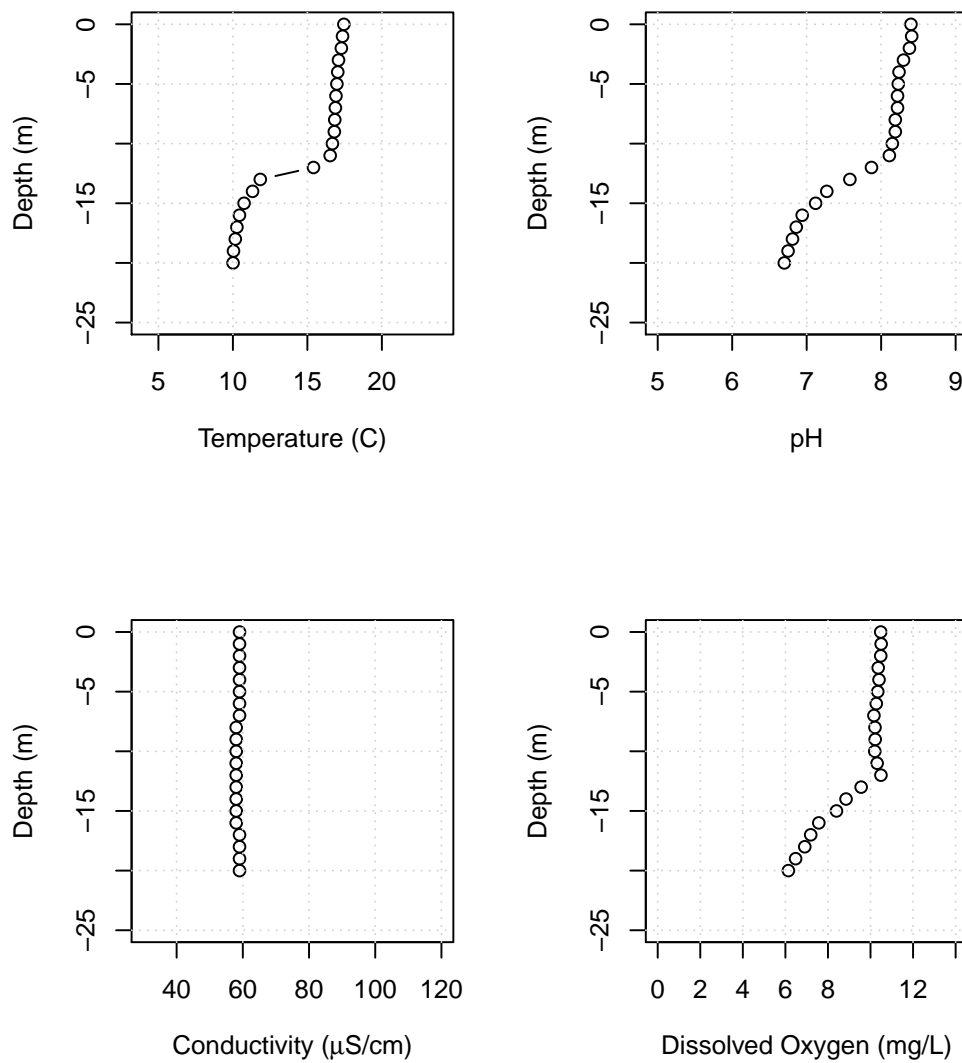


Figure B32: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, June 4, 2015.

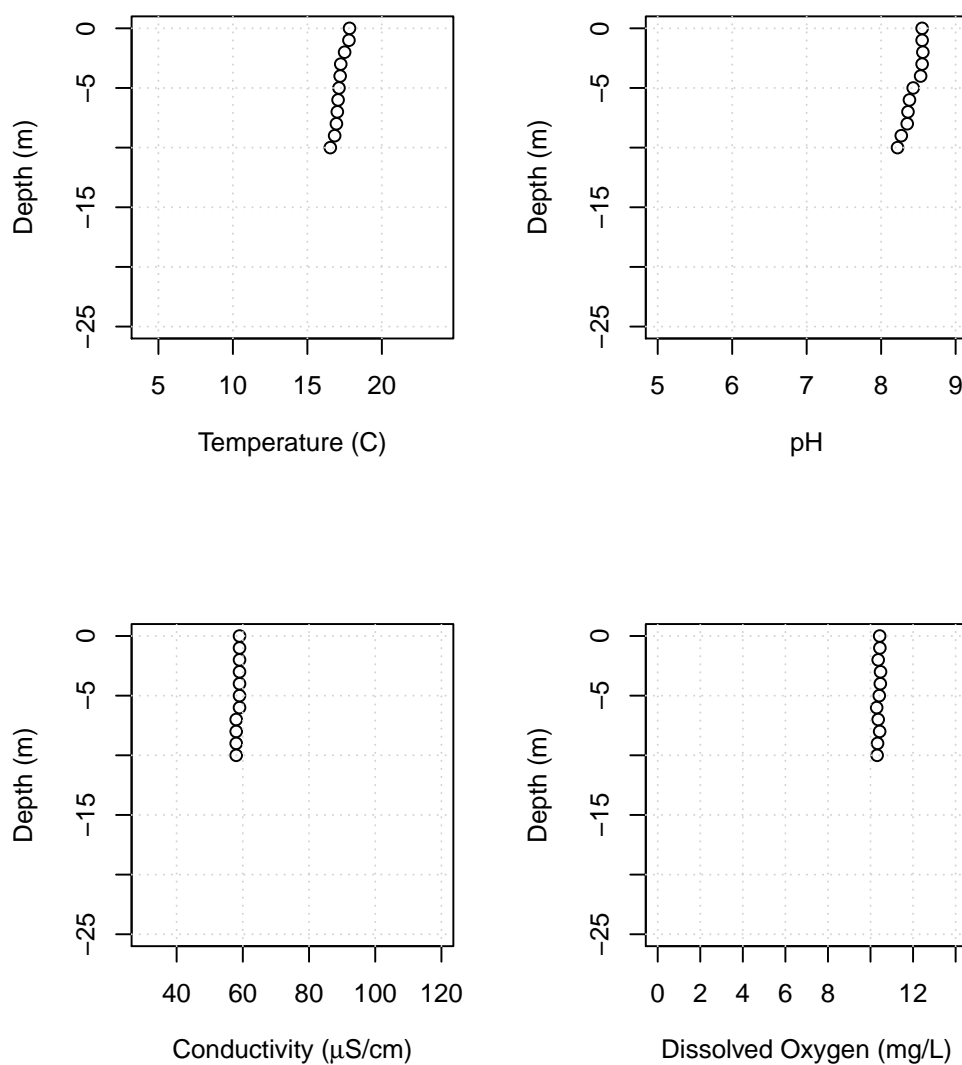


Figure B33: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, June 4, 2015.

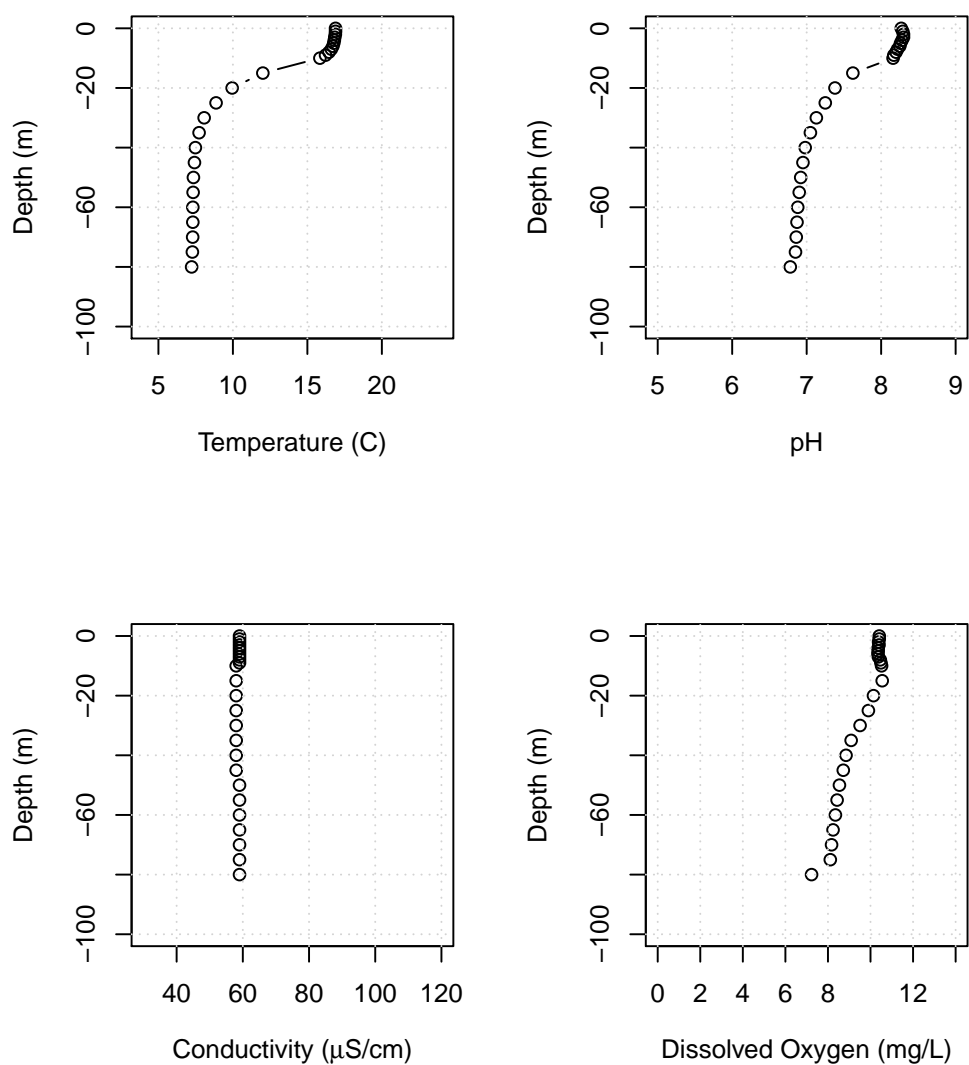


Figure B34: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, June 2, 2015.

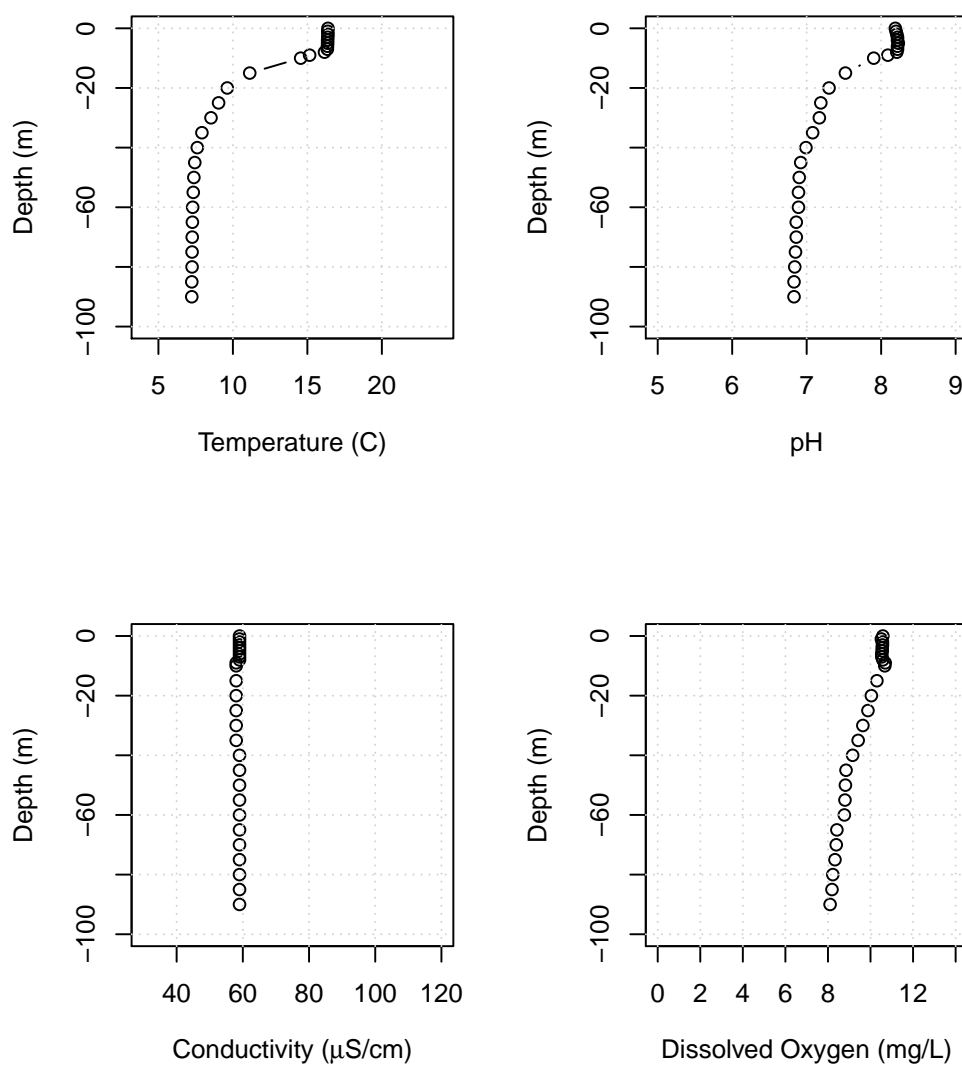


Figure B35: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, June 2, 2015.

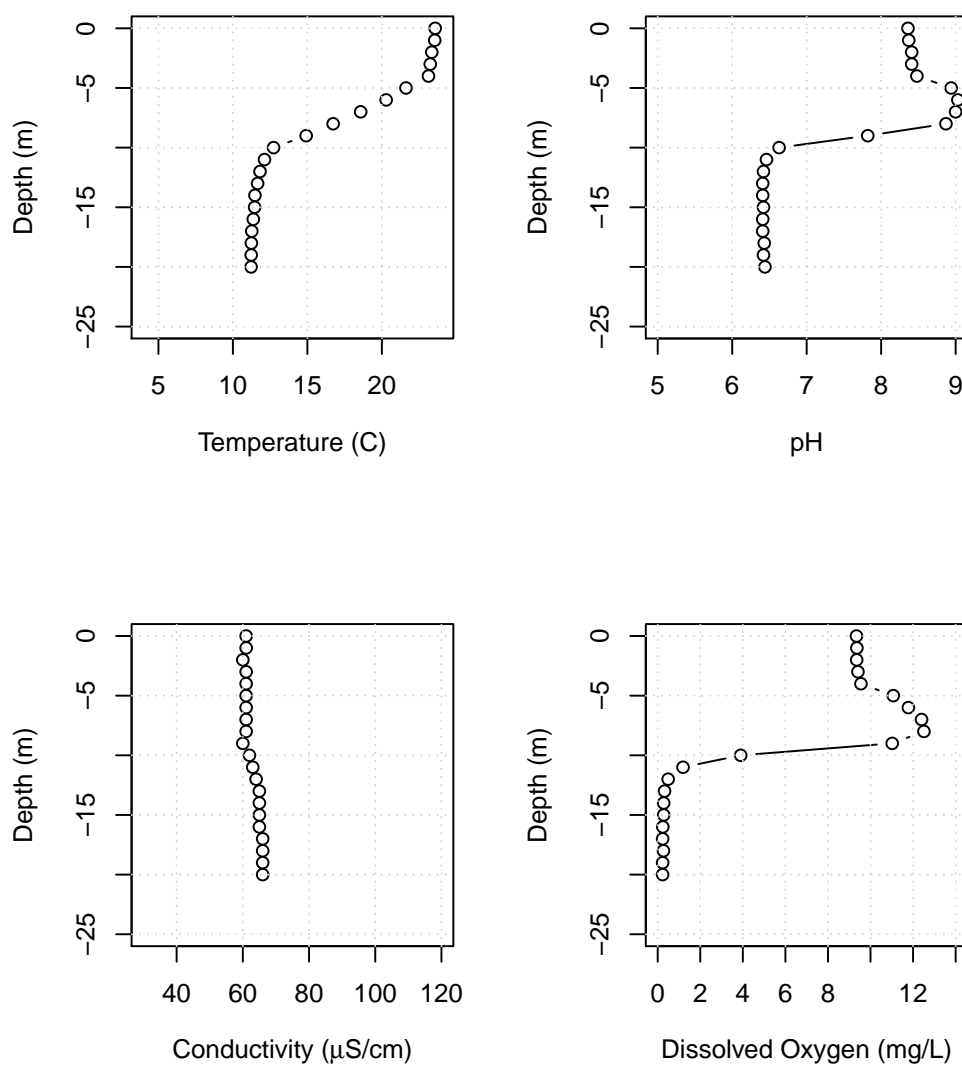


Figure B36: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, July 8, 2015.

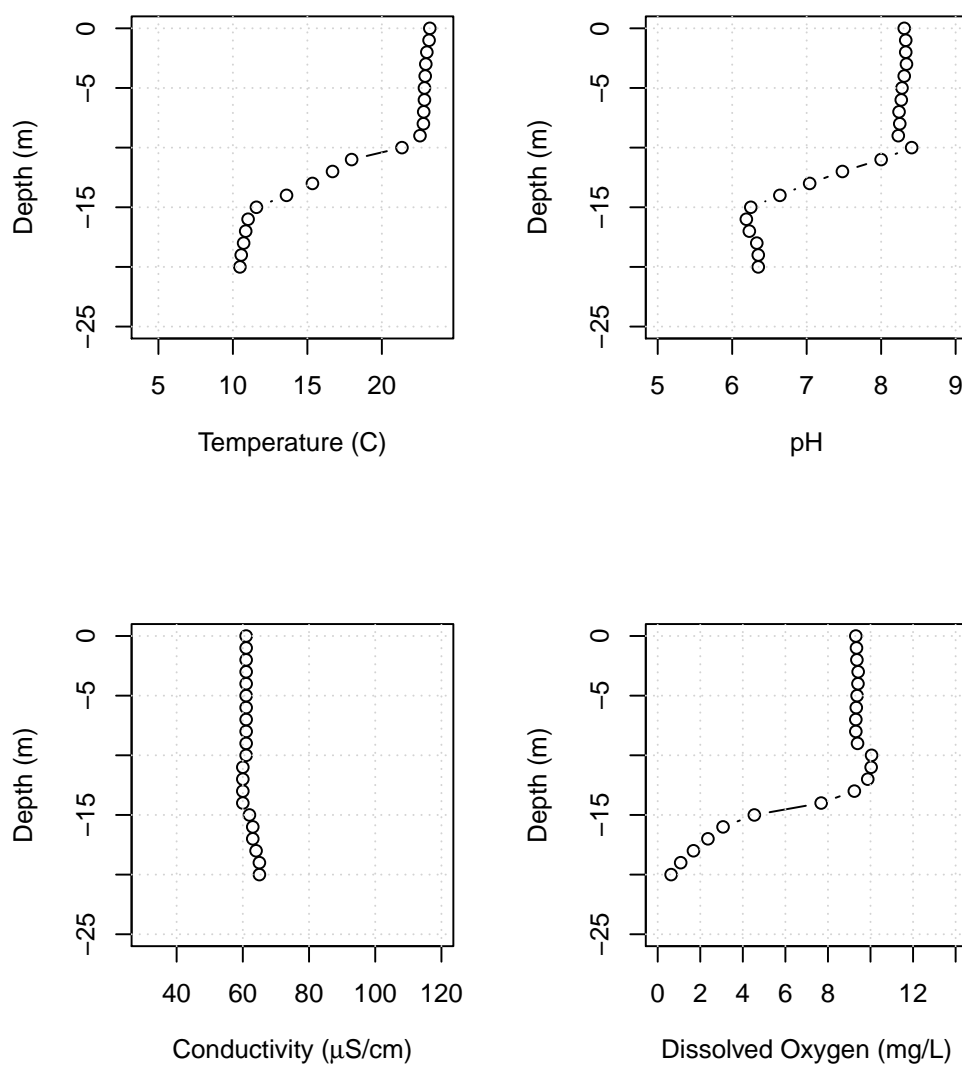


Figure B37: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, July 8, 2015.

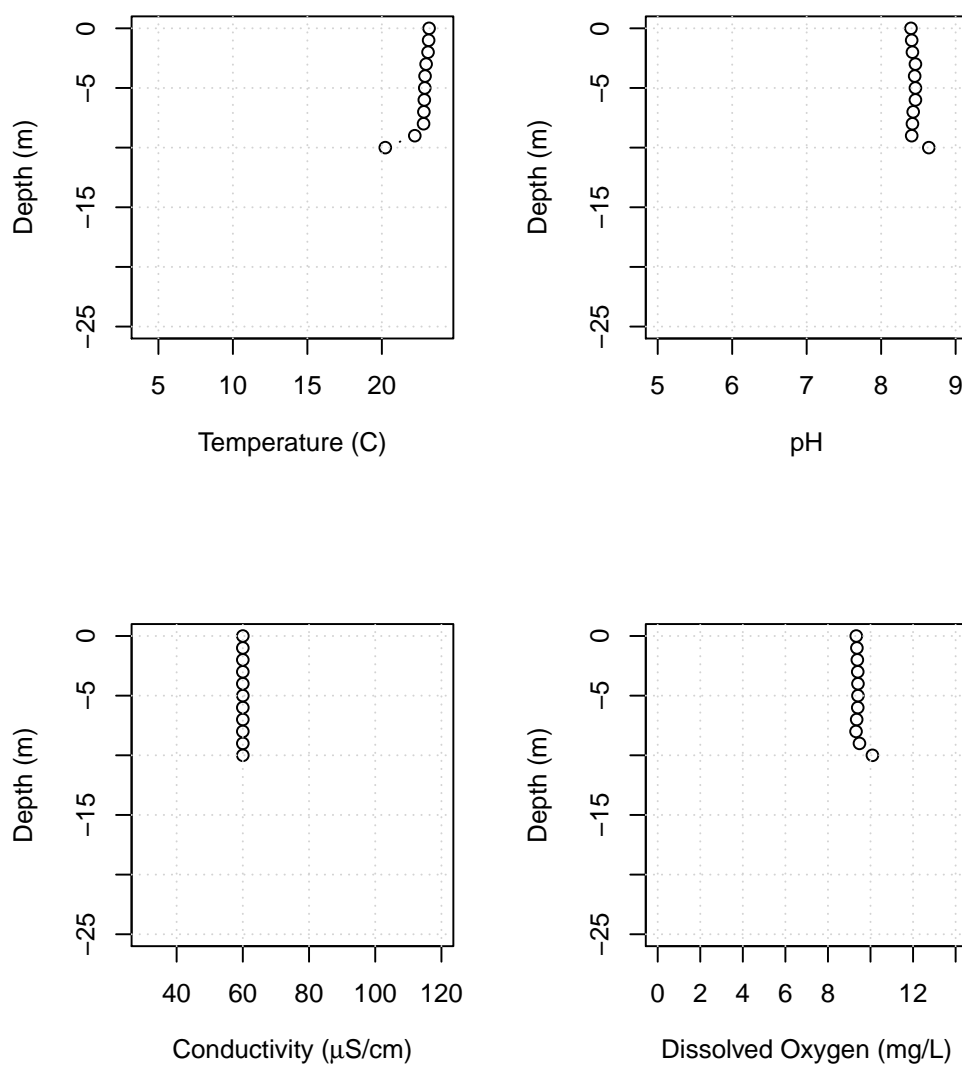


Figure B38: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, July 8, 2015.

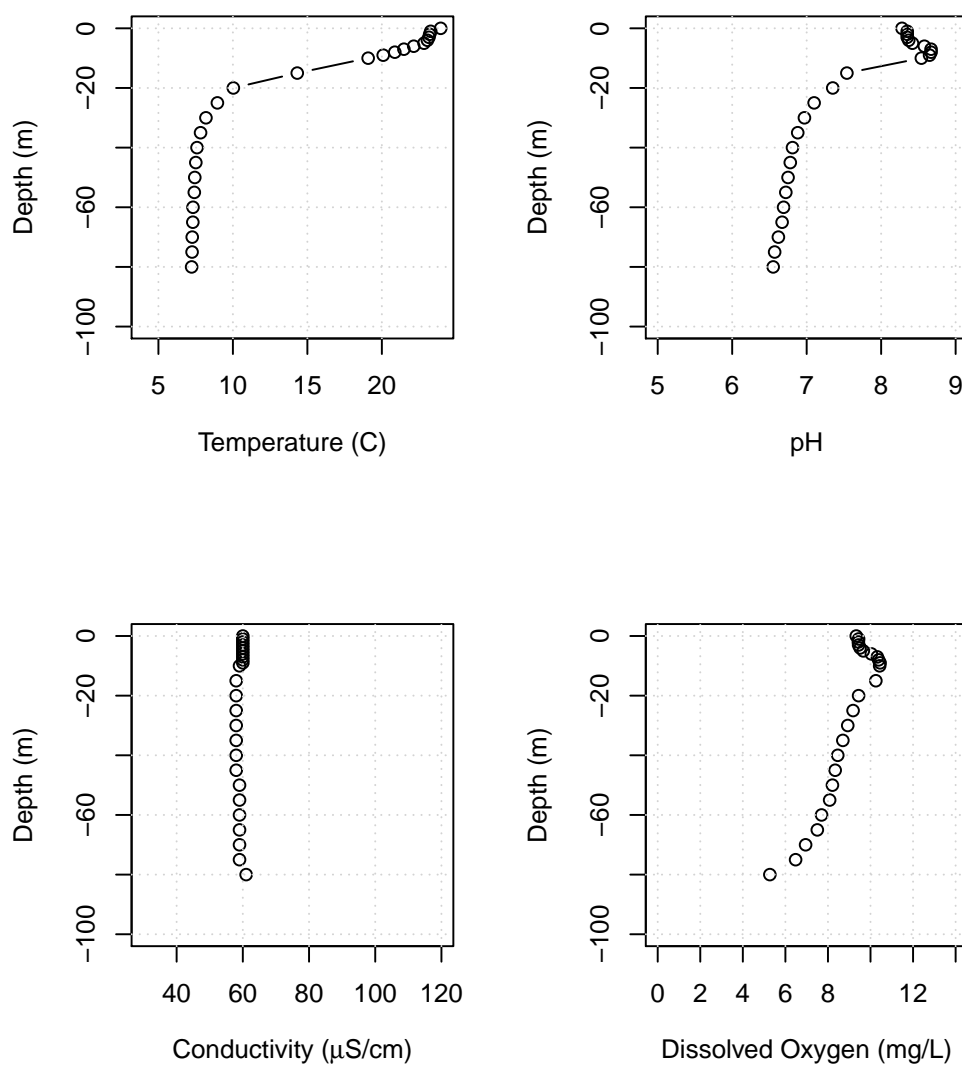


Figure B39: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, July 6, 2015.

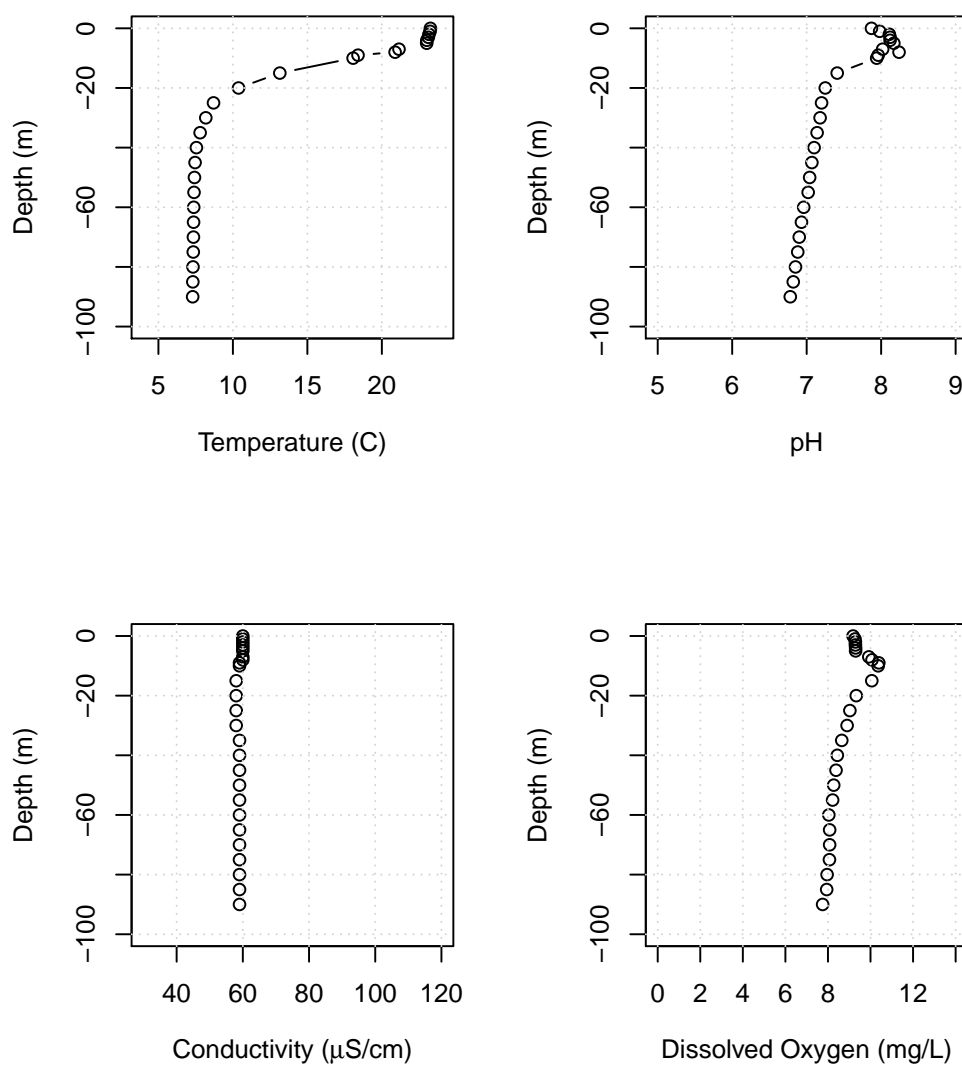


Figure B40: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, July 6, 2015.

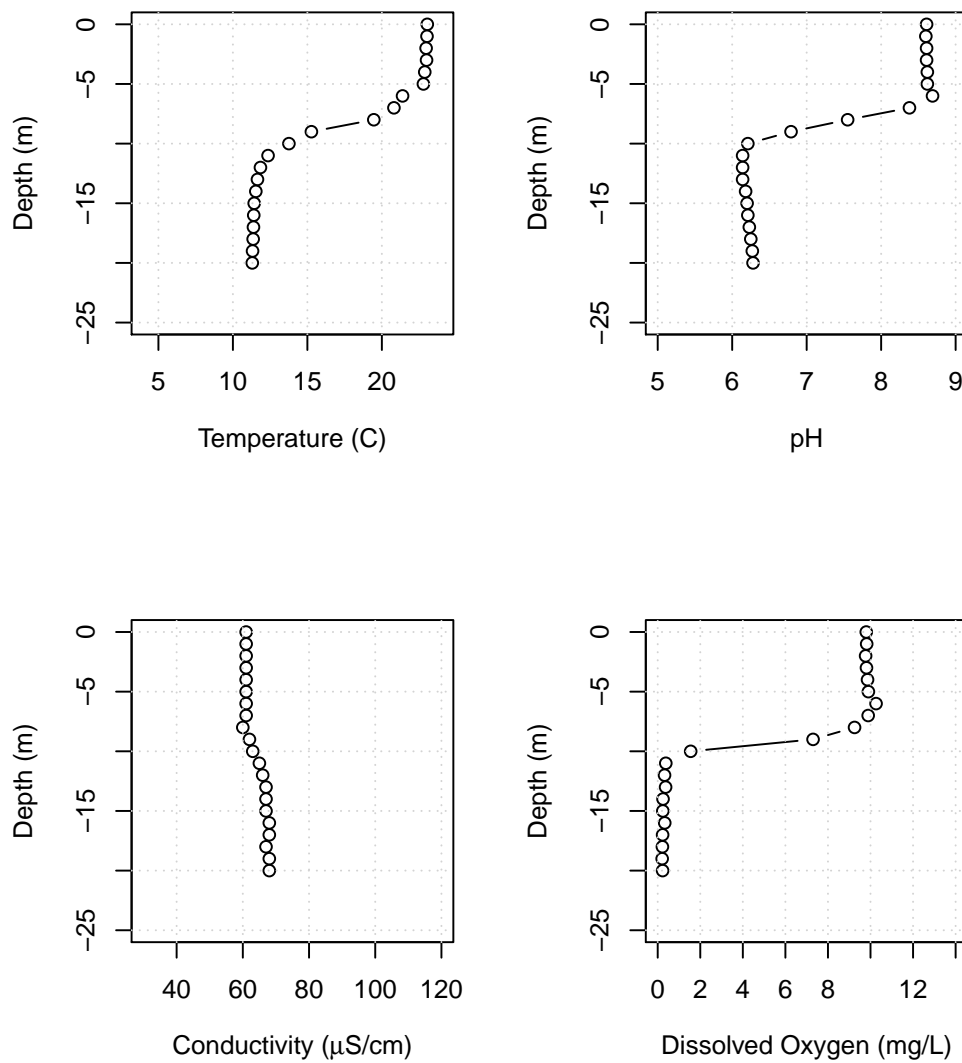


Figure B41: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, August 3, 2015.

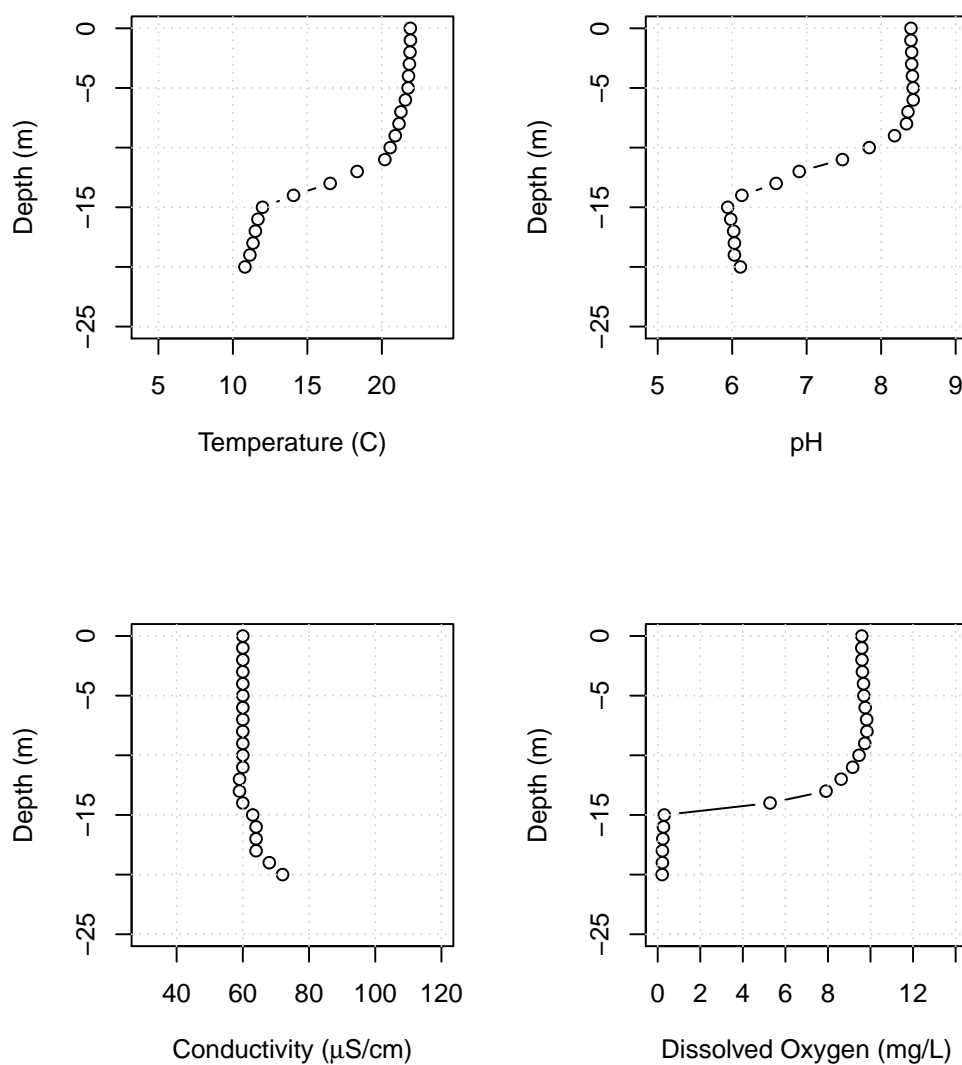


Figure B42: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, August 3, 2015.

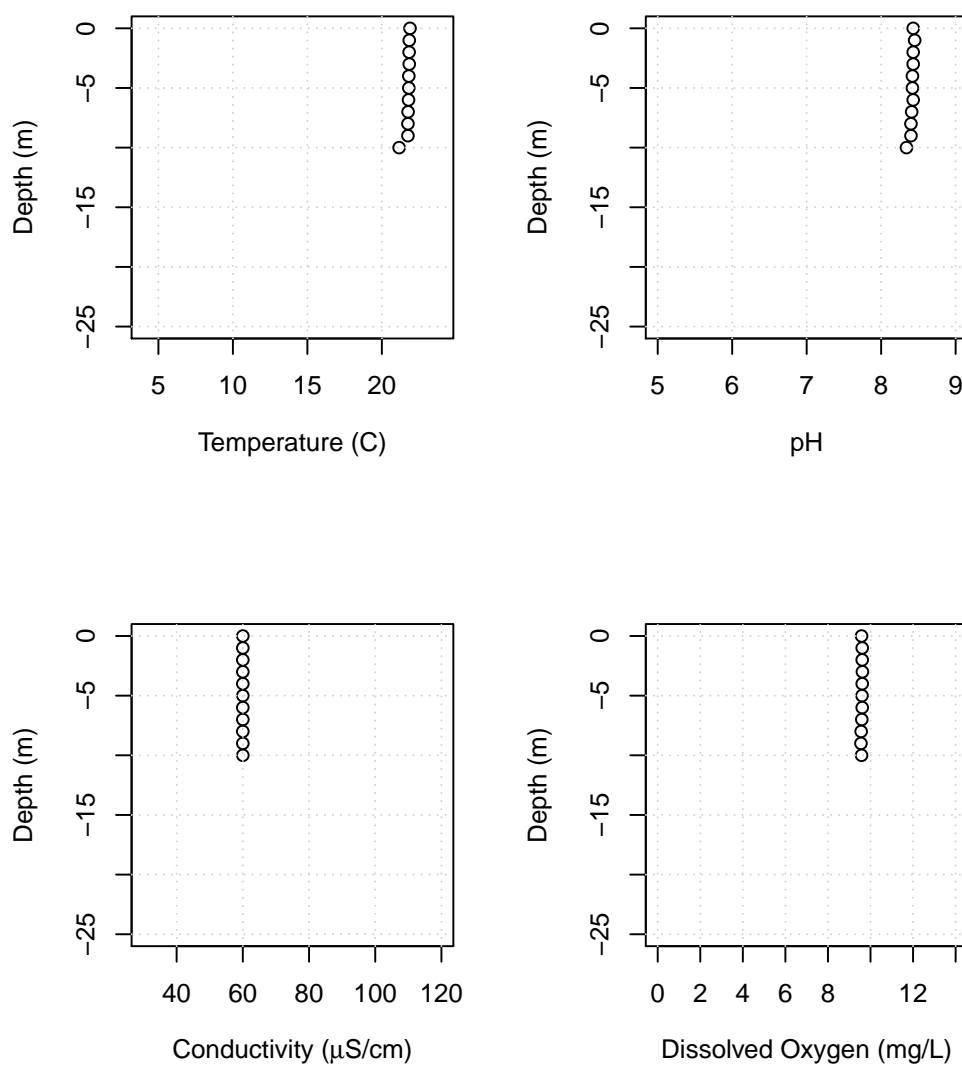


Figure B43: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, August 3, 2015.

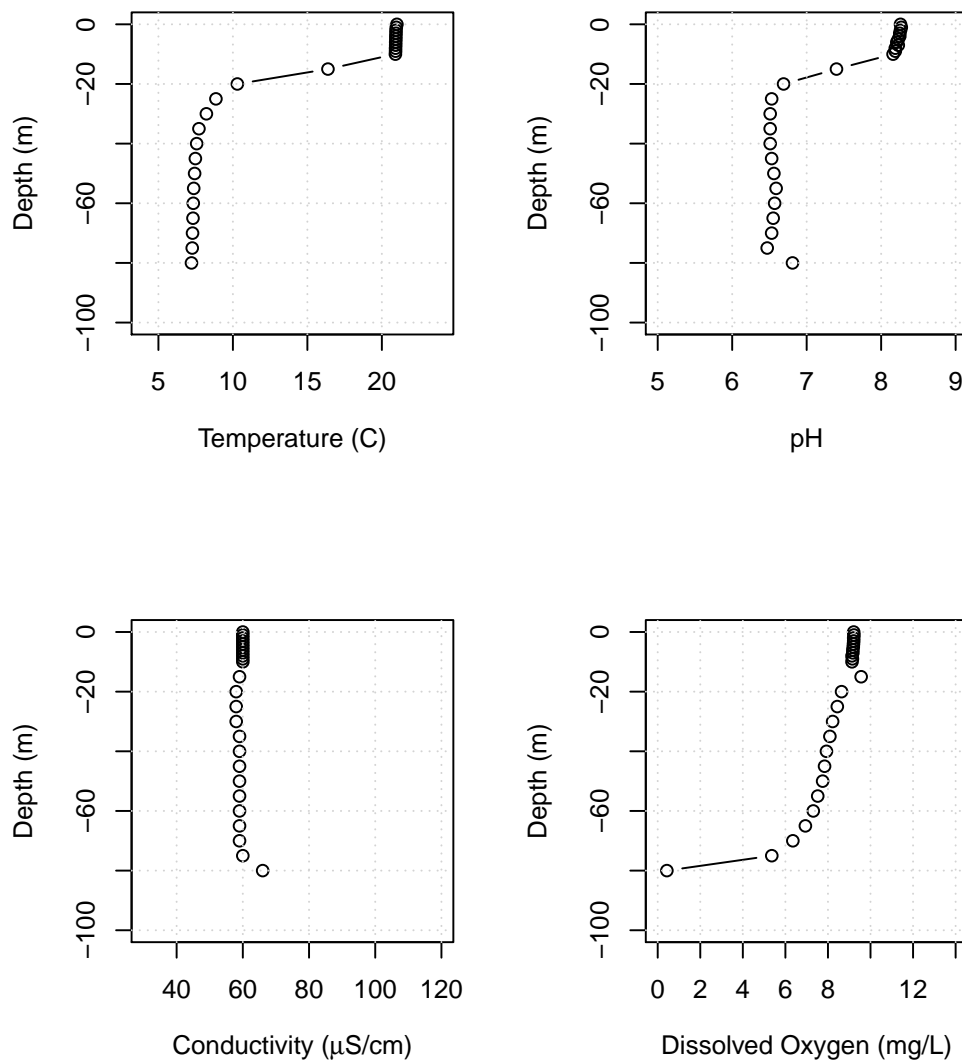


Figure B44: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, August 6, 2015.

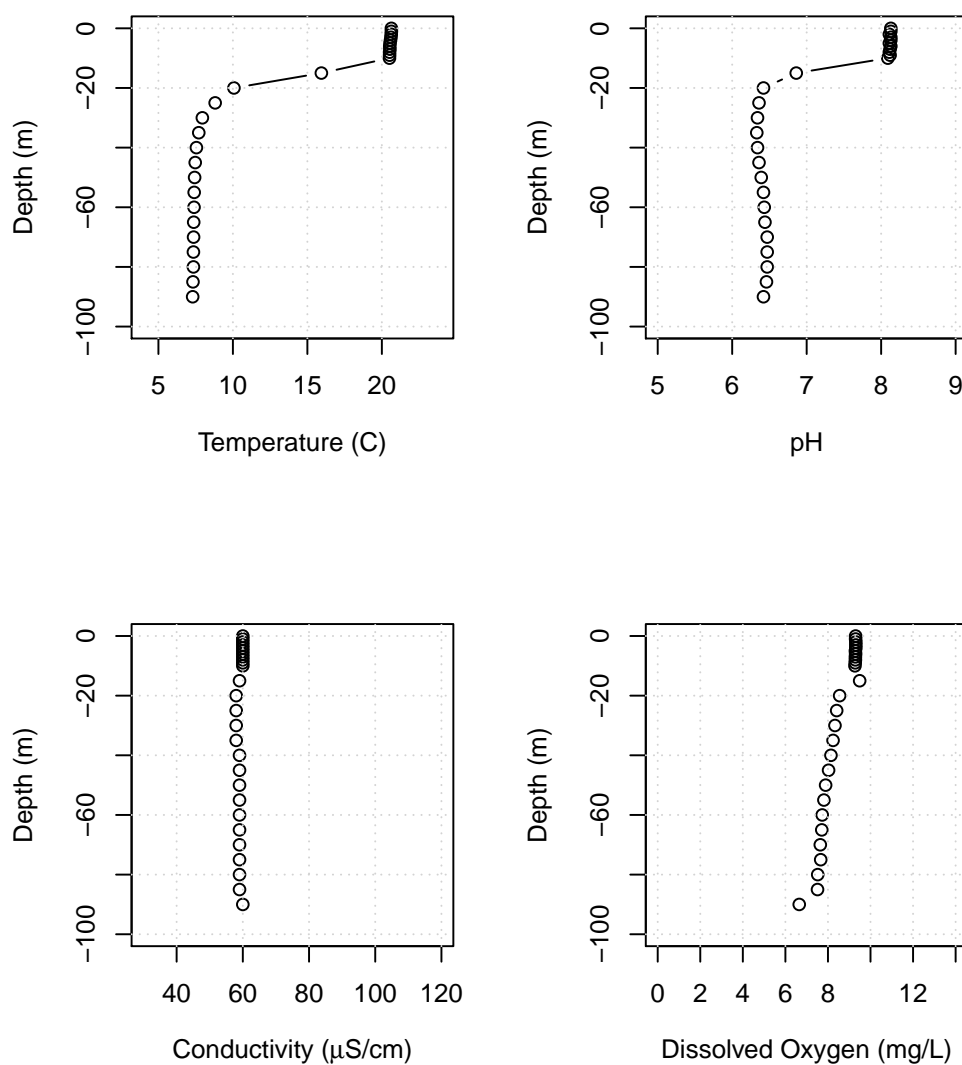


Figure B45: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, August 6, 2015.

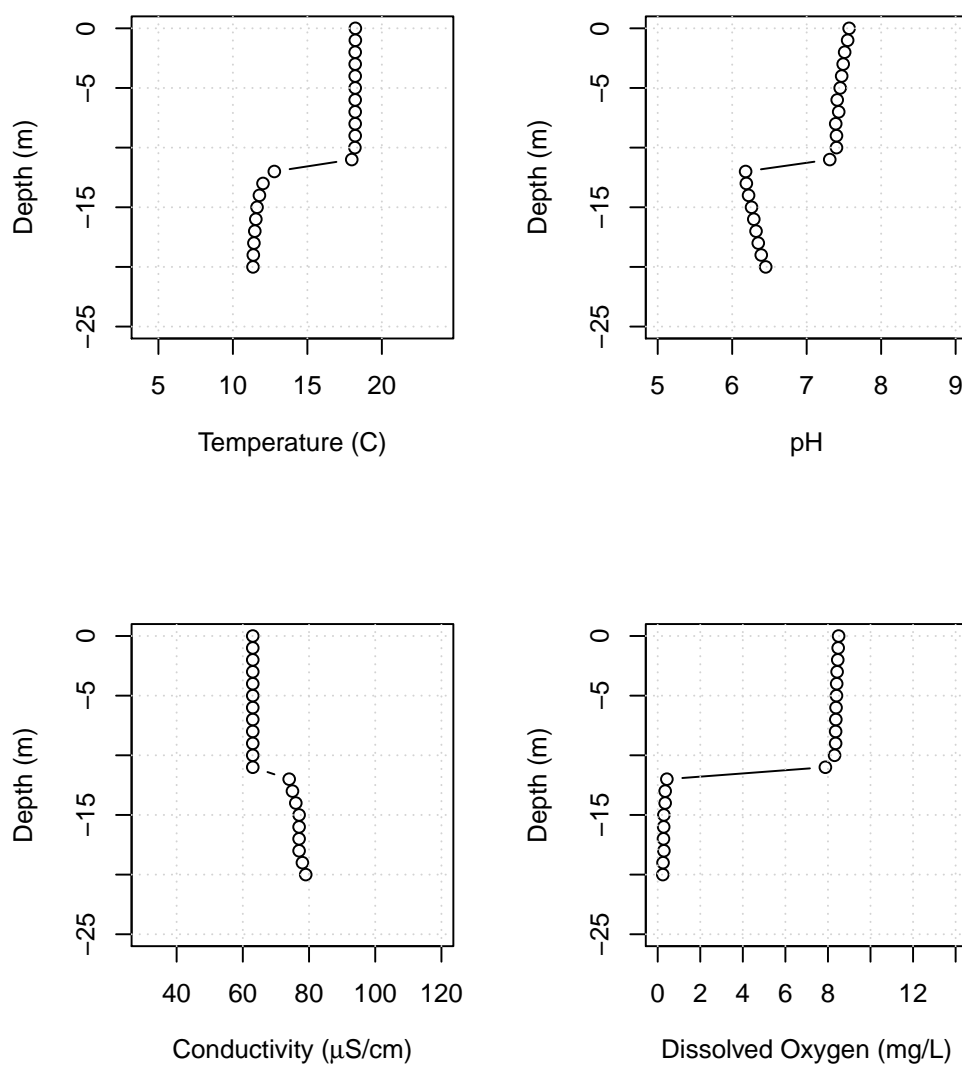


Figure B46: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 1, September 3, 2015.

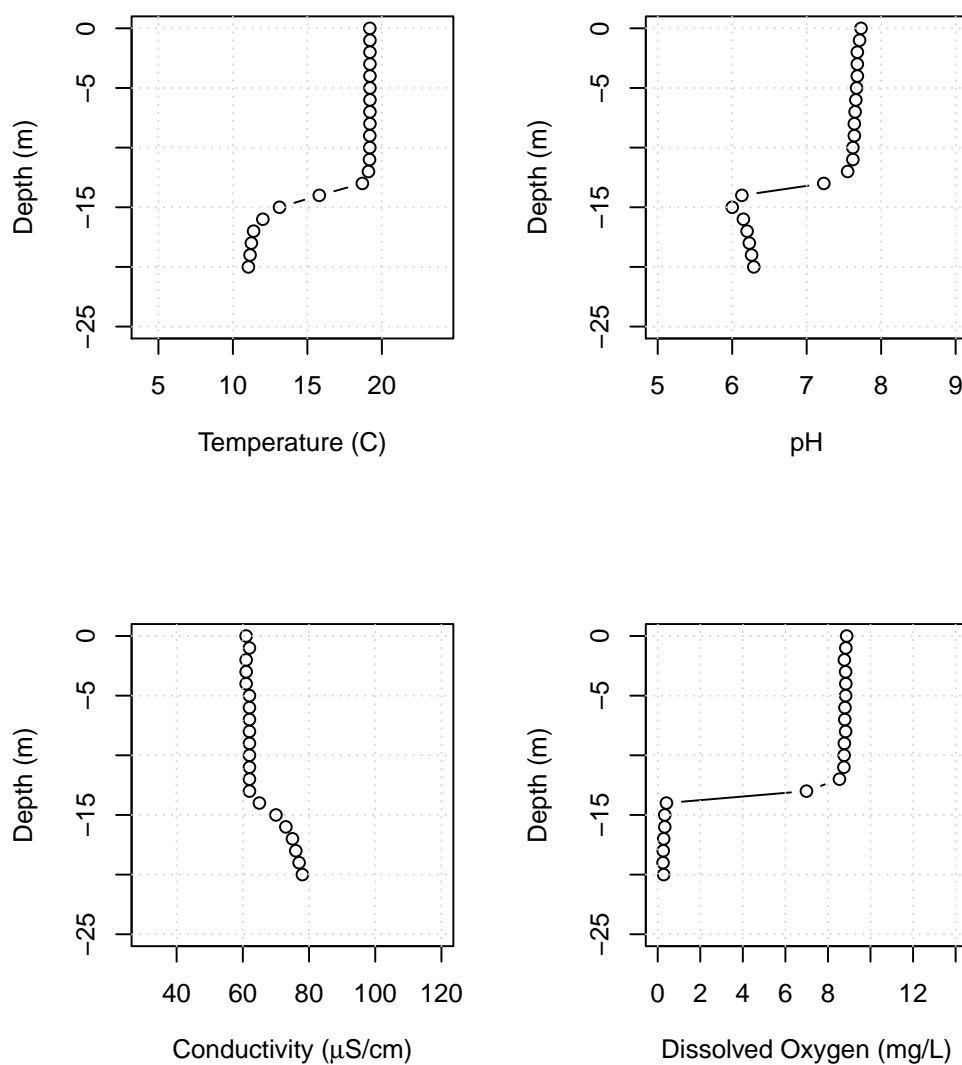


Figure B47: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 2, September 3, 2015.

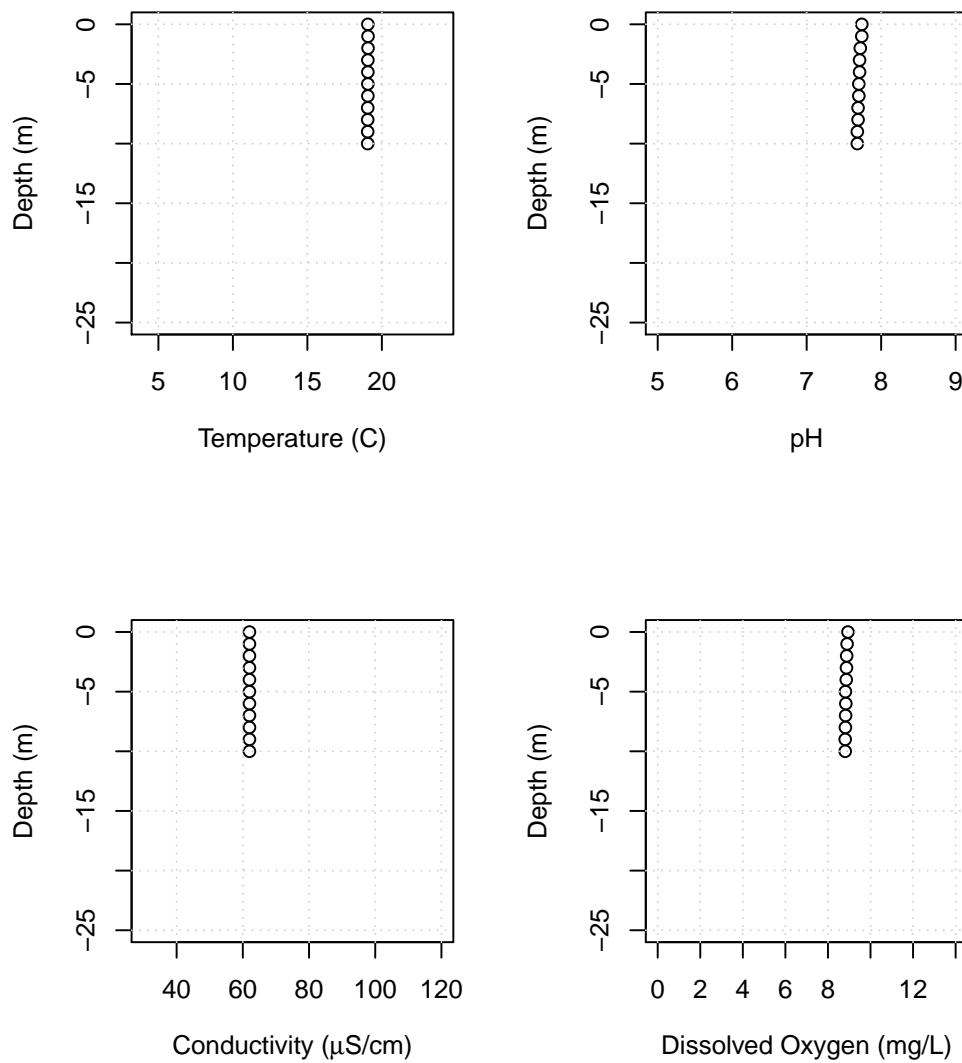


Figure B48: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for the Intake, September 3, 2015.

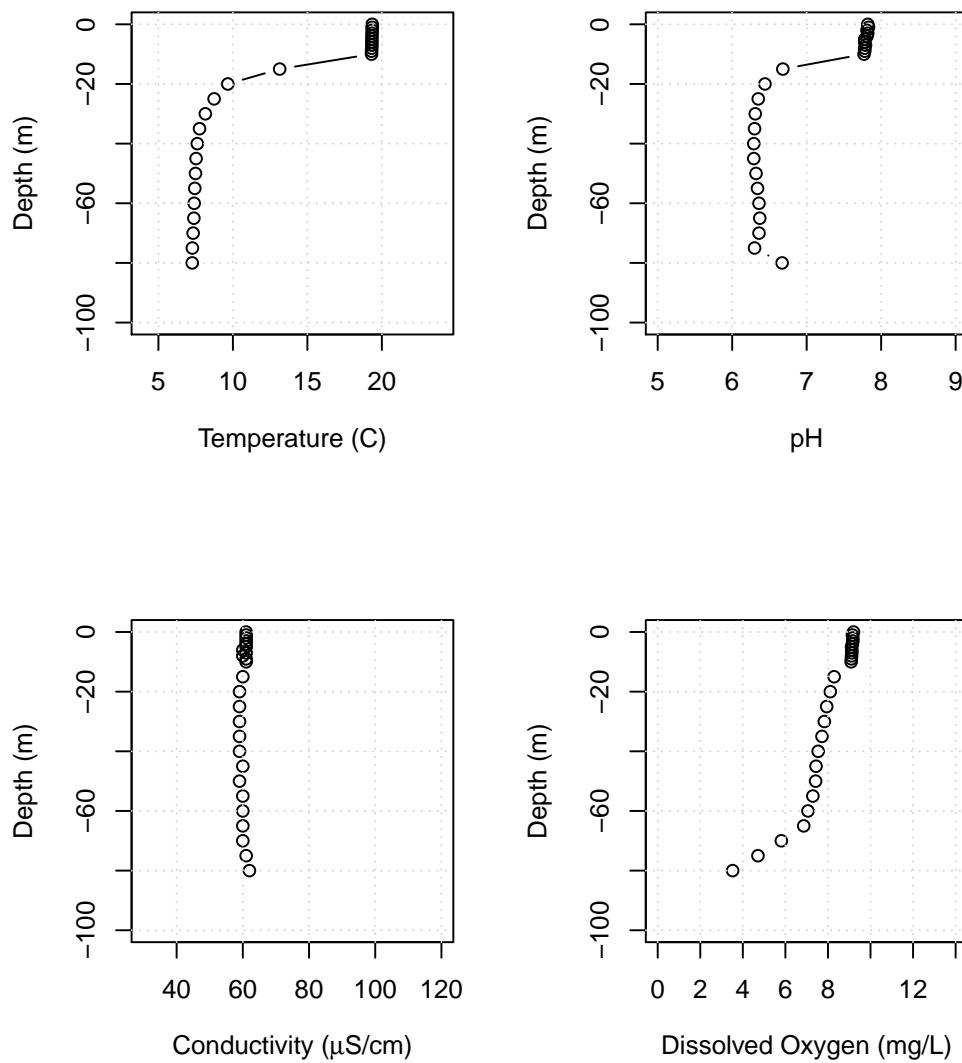


Figure B49: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 3, September 1, 2015.

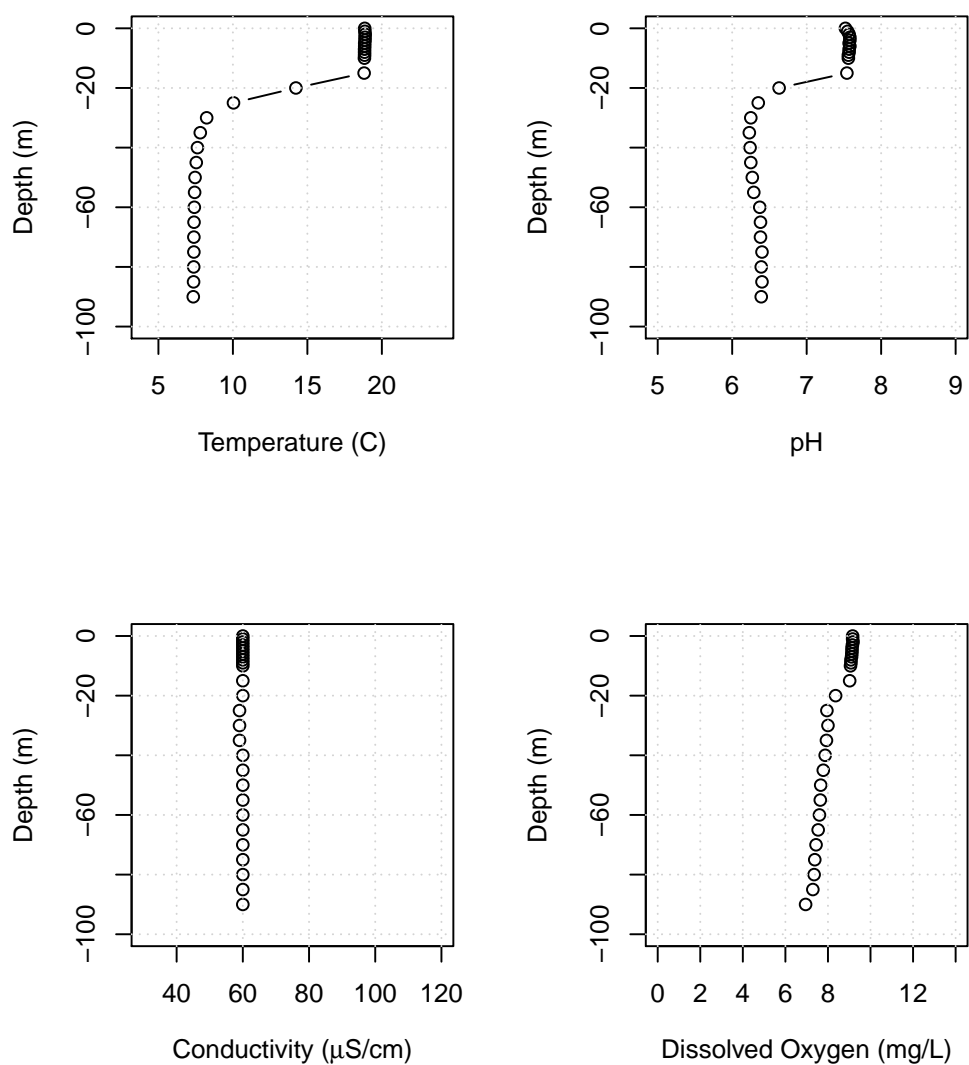


Figure B50: Lake Whatcom water column profiles showing temperature, pH, conductivity, and dissolved oxygen for Site 4, September 1, 2015.

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

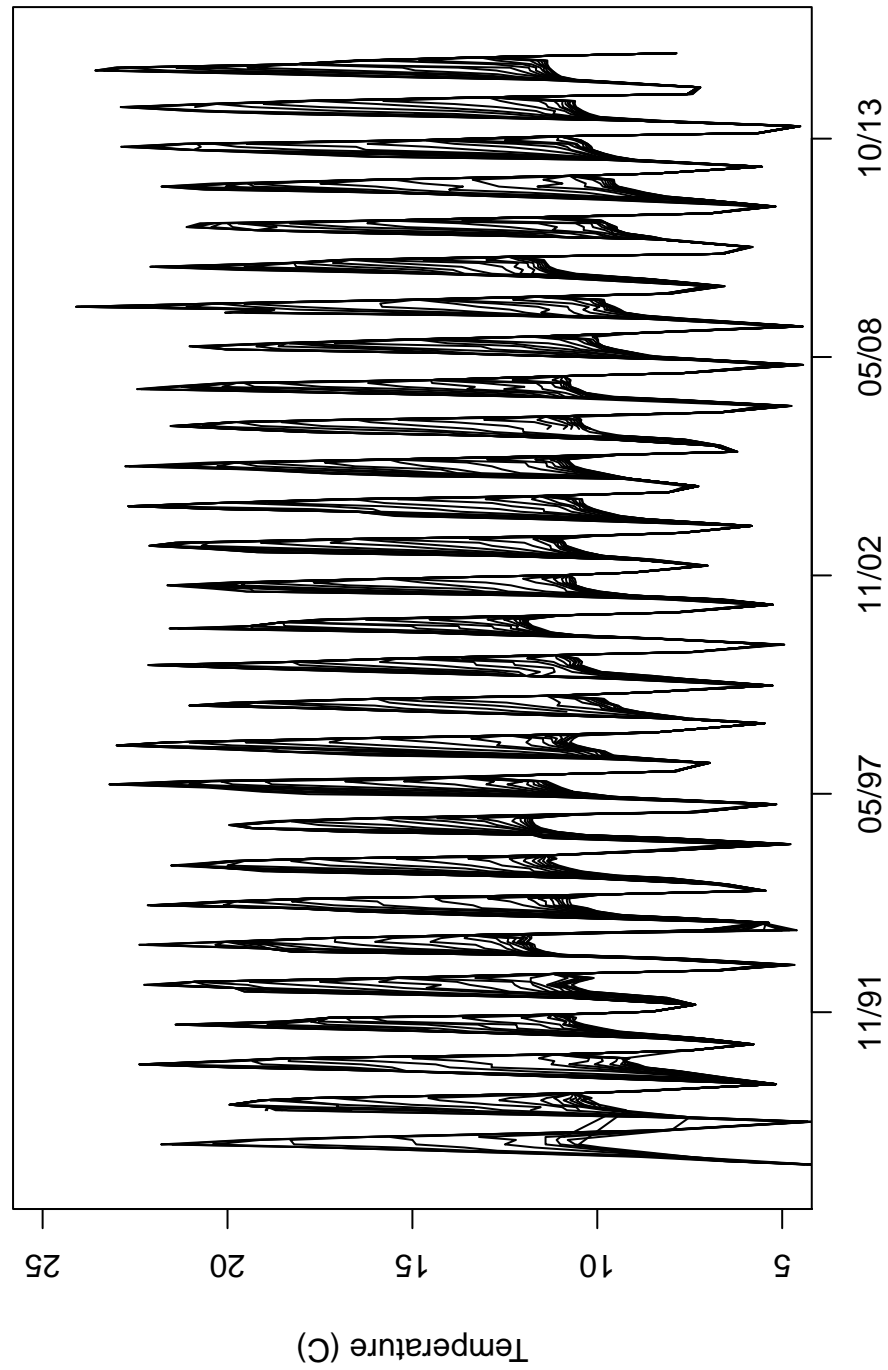


Figure B51: Lake Whatcom historic temperature data for Site 1.

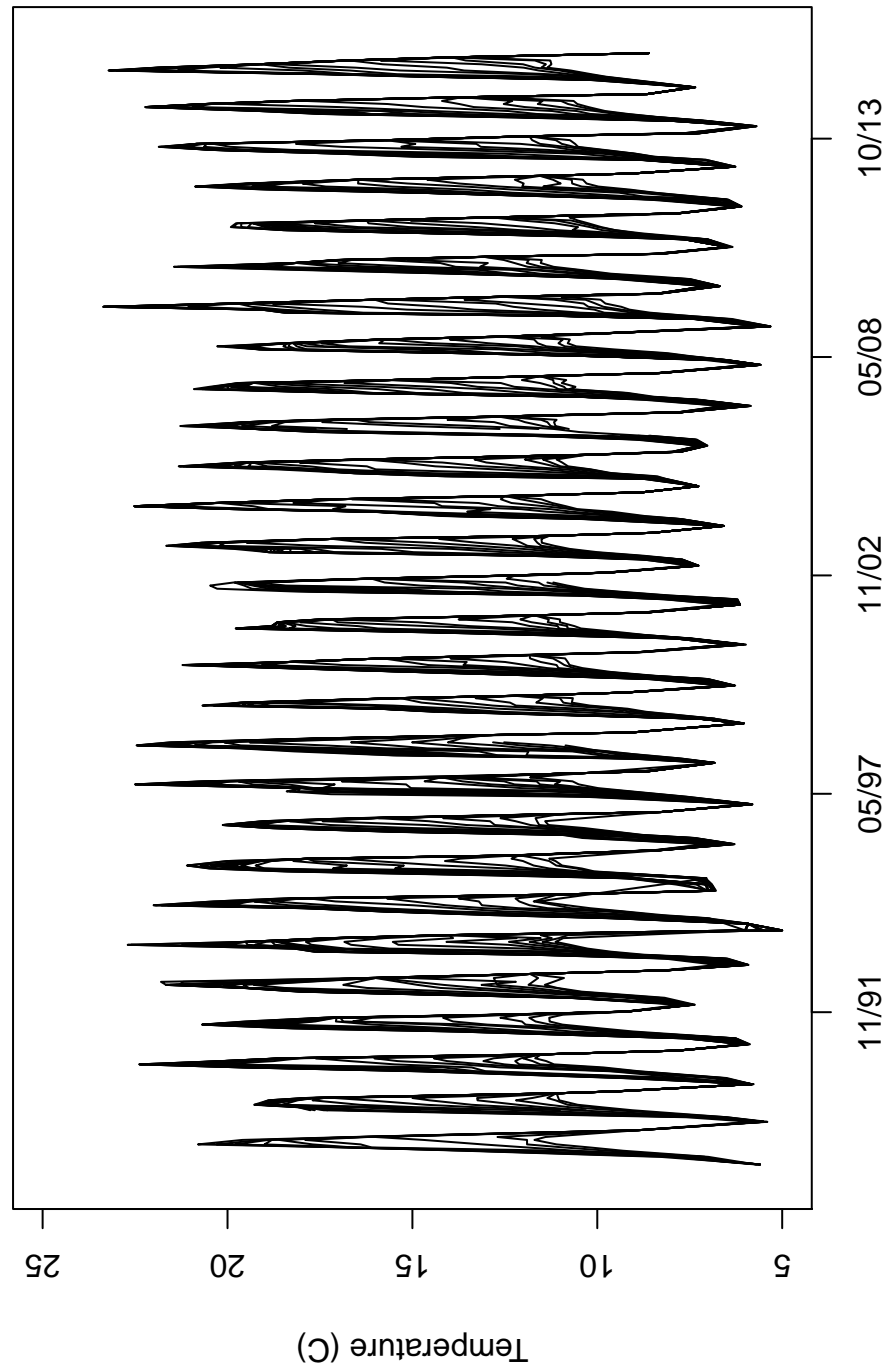


Figure B52: Lake Whatcom historic temperature data for Site 2.

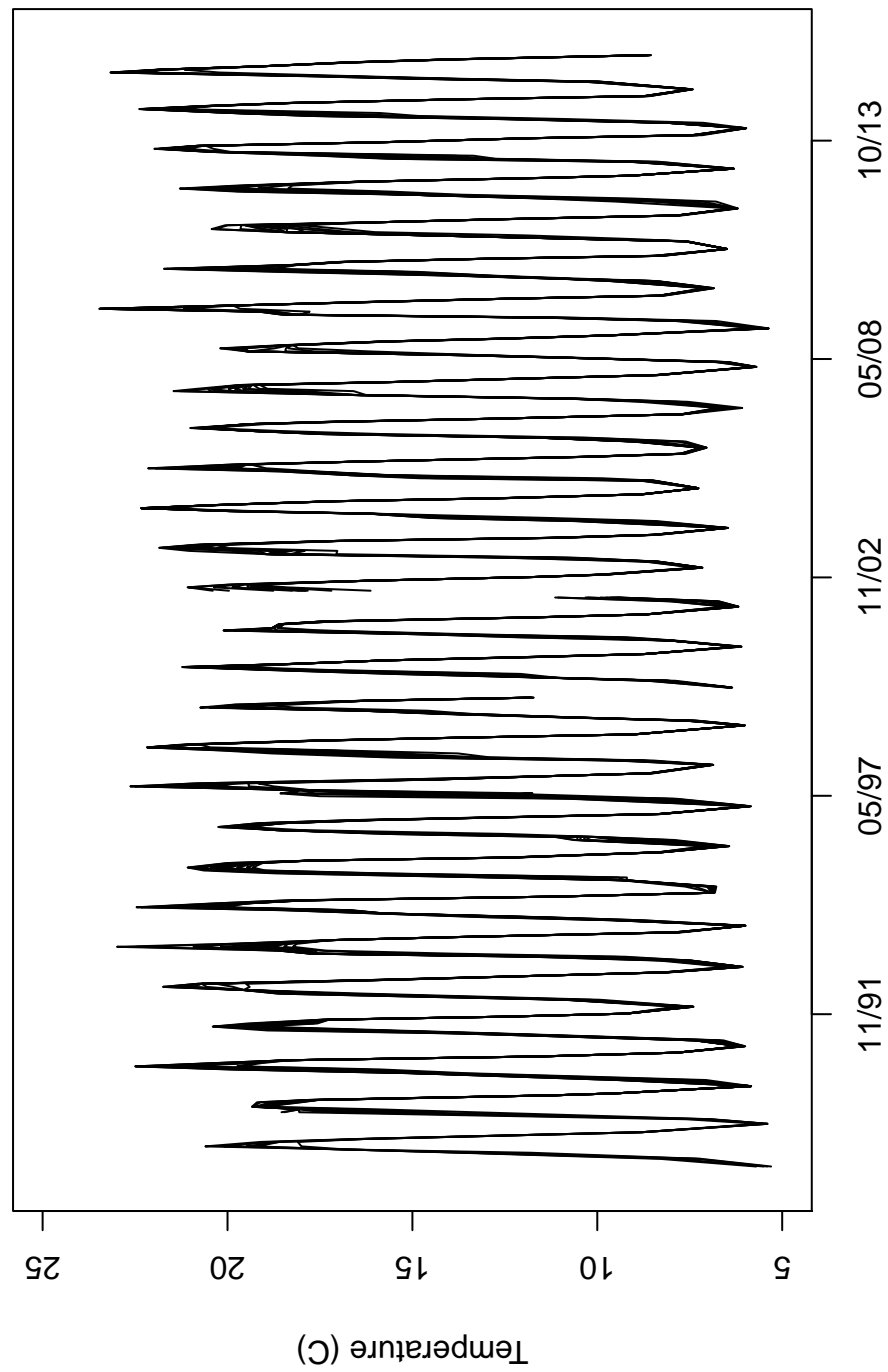


Figure B53: Lake Whatcom historic temperature data for the Intake.

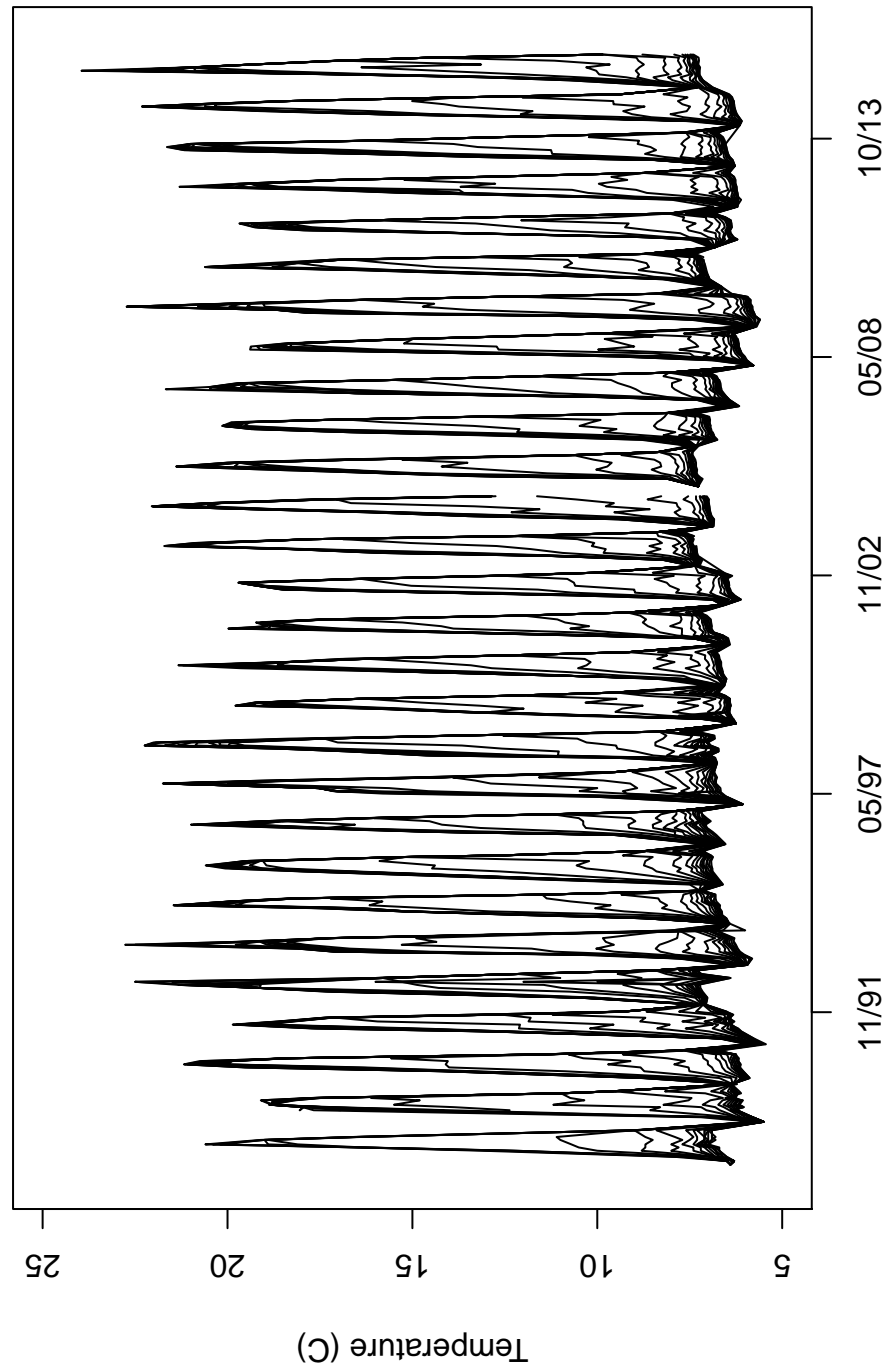


Figure B54: Lake Whatcom historic temperature data for Site 3.

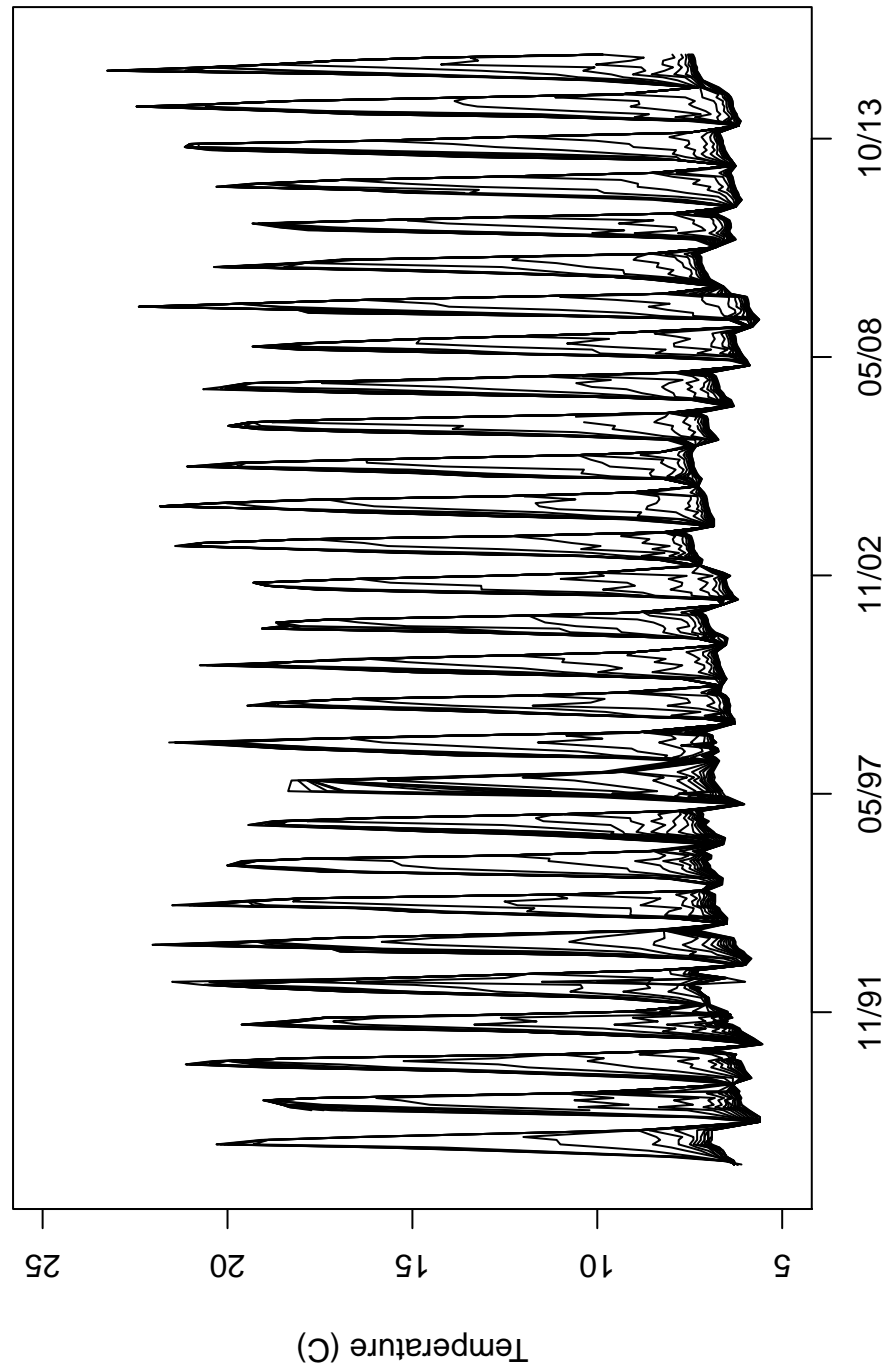


Figure B55: Lake Whatcom historic temperature data for Site 4.

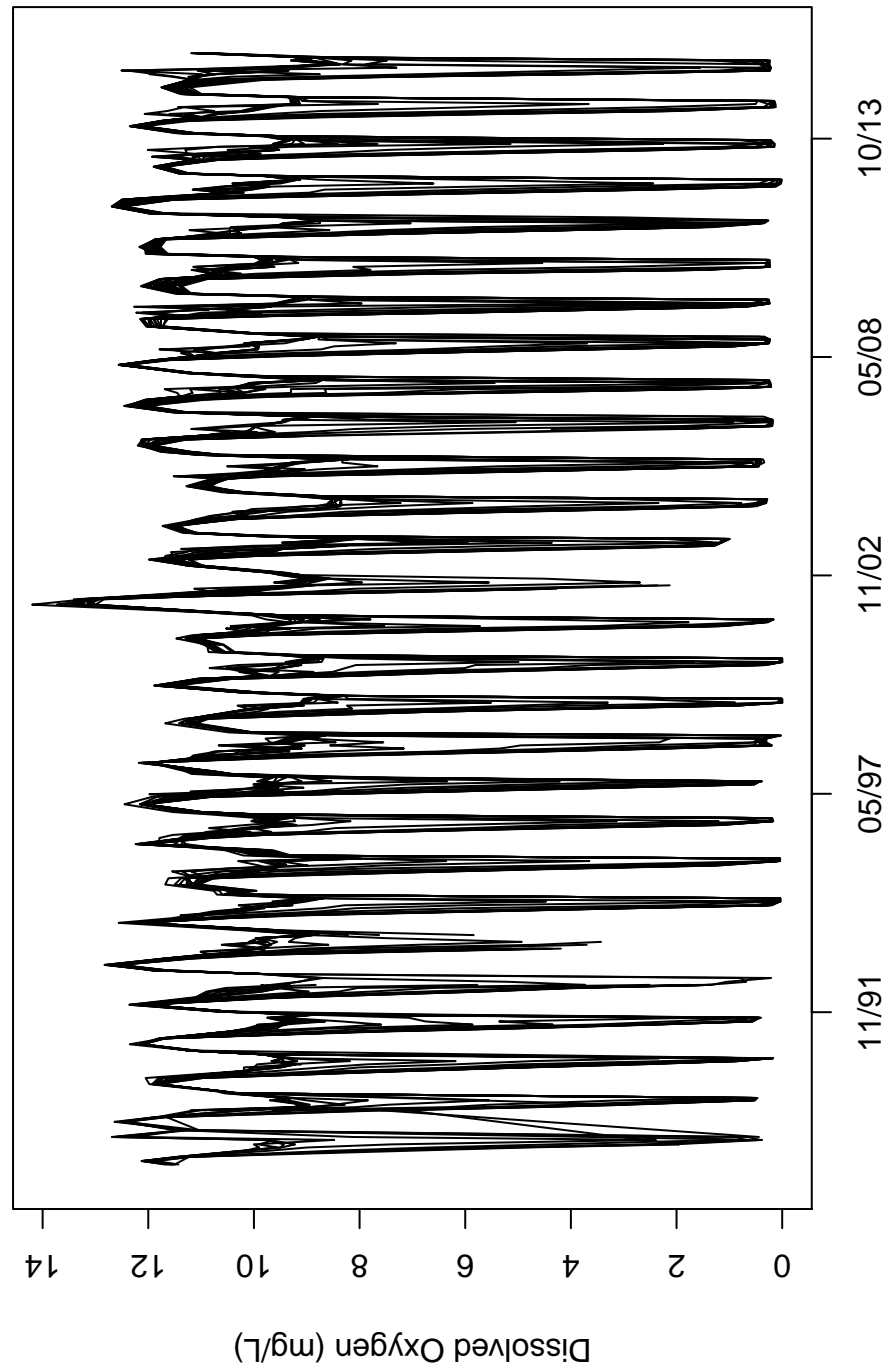


Figure B56: Lake Whatcom historic dissolved oxygen data for Site 1.

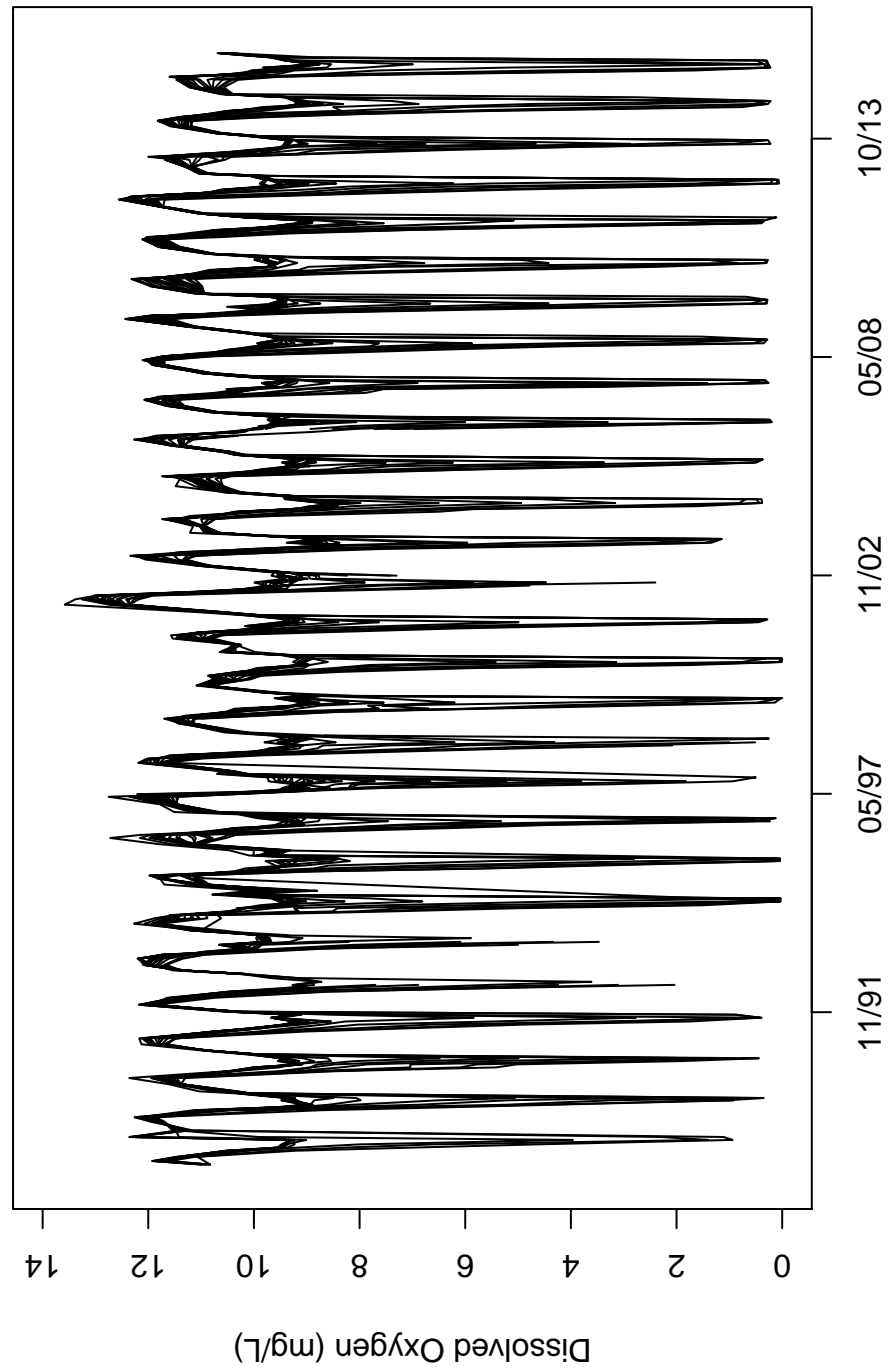


Figure B57: Lake Whatcom historic dissolved oxygen data for Site 2.

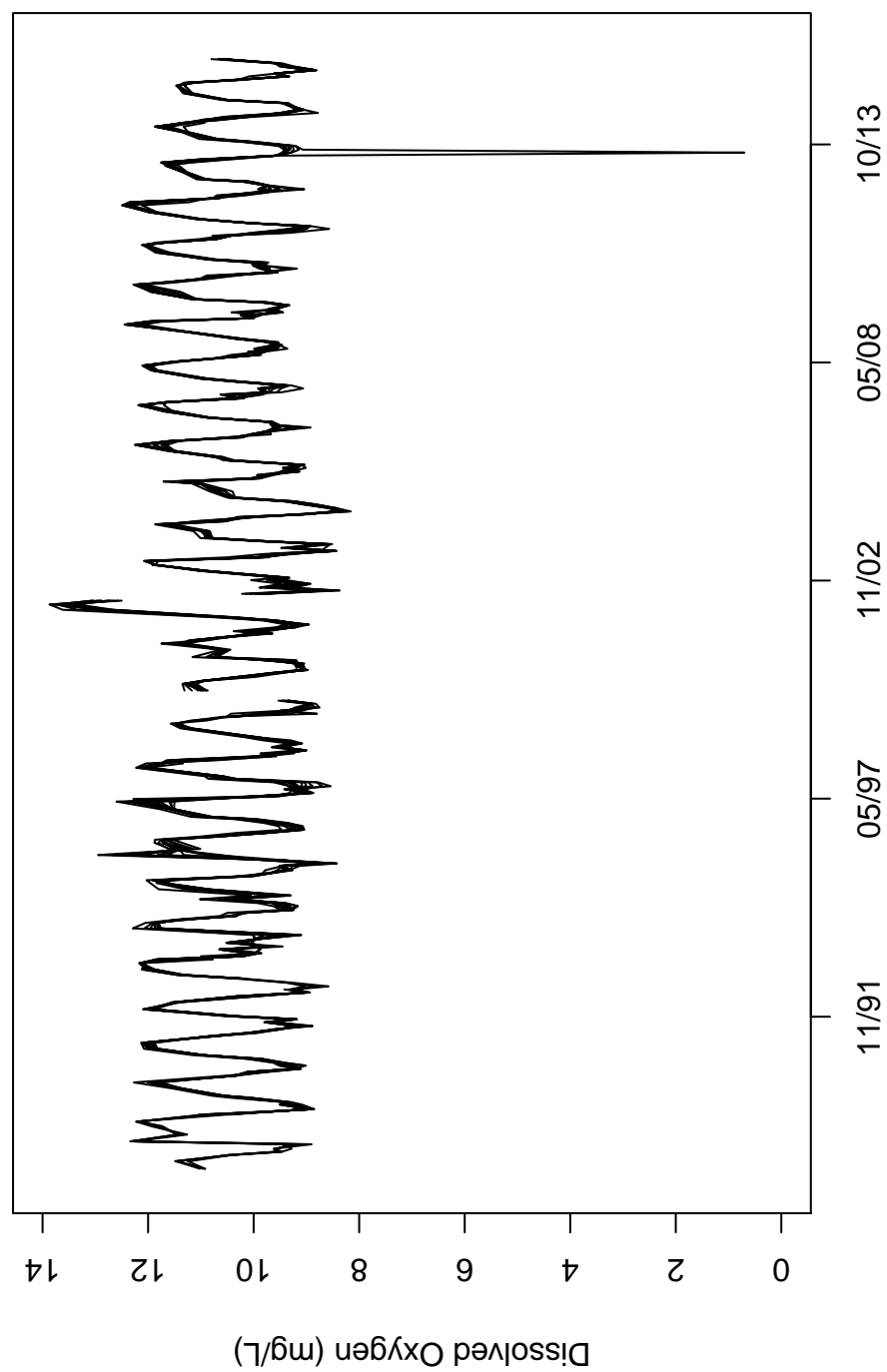


Figure B58: Lake Whatcom historic dissolved oxygen data for the Intake. See discussion of the low dissolved oxygen value in Matthews et al. (2014).

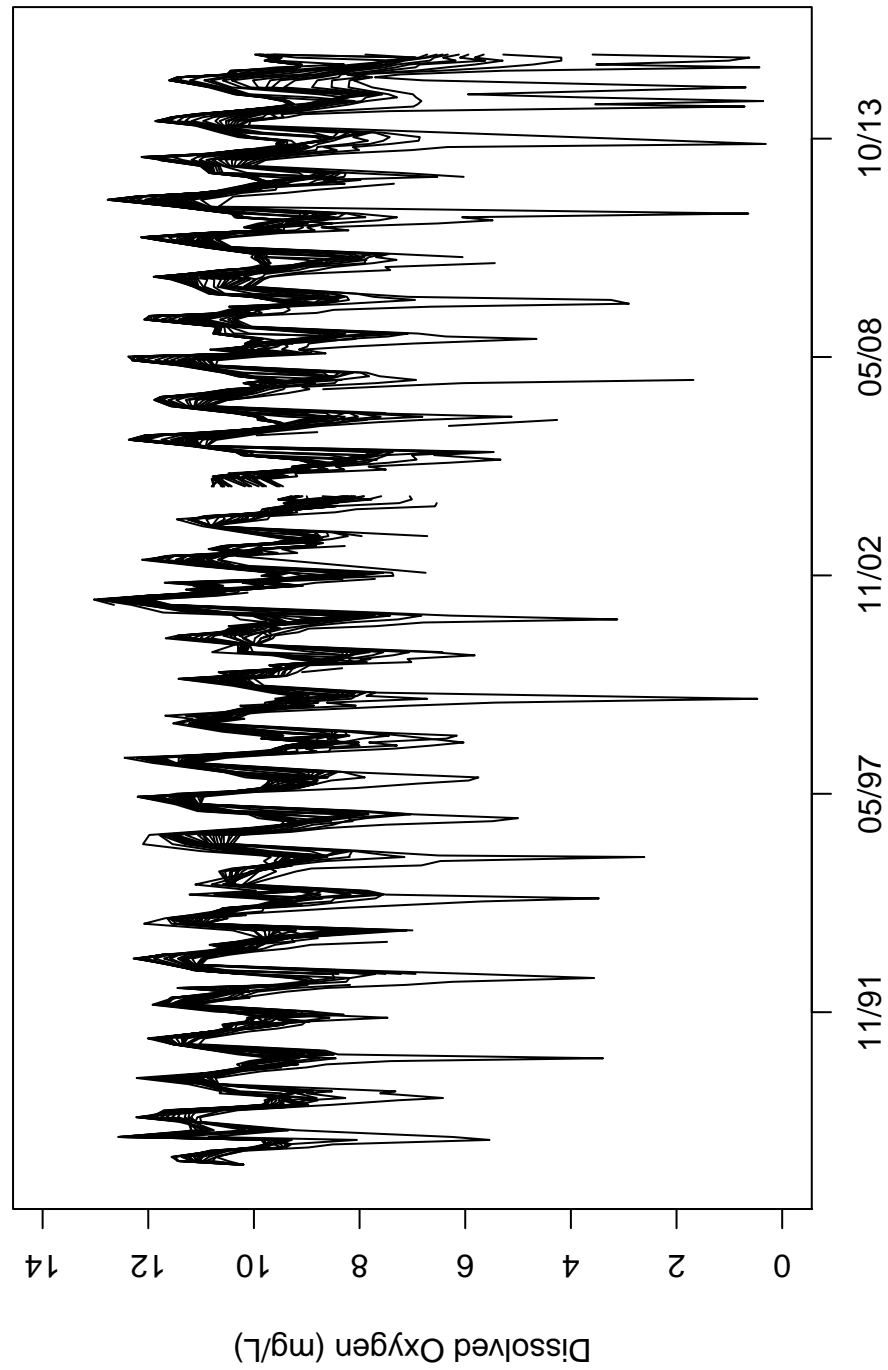


Figure B59: Lake Whatcom historic dissolved oxygen data for Site 3.

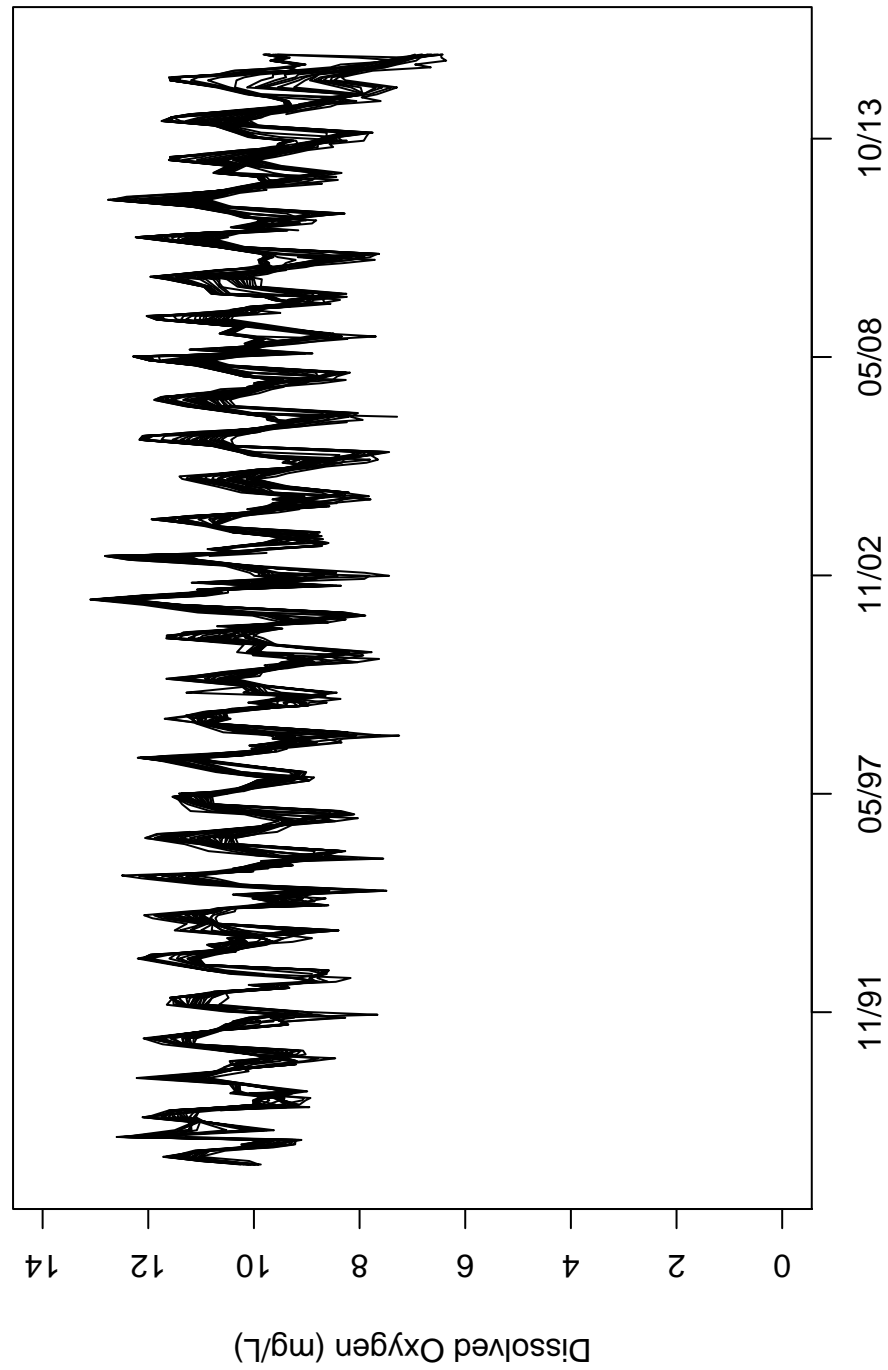


Figure B60: Lake Whatcom historic dissolved oxygen data for Site 4.

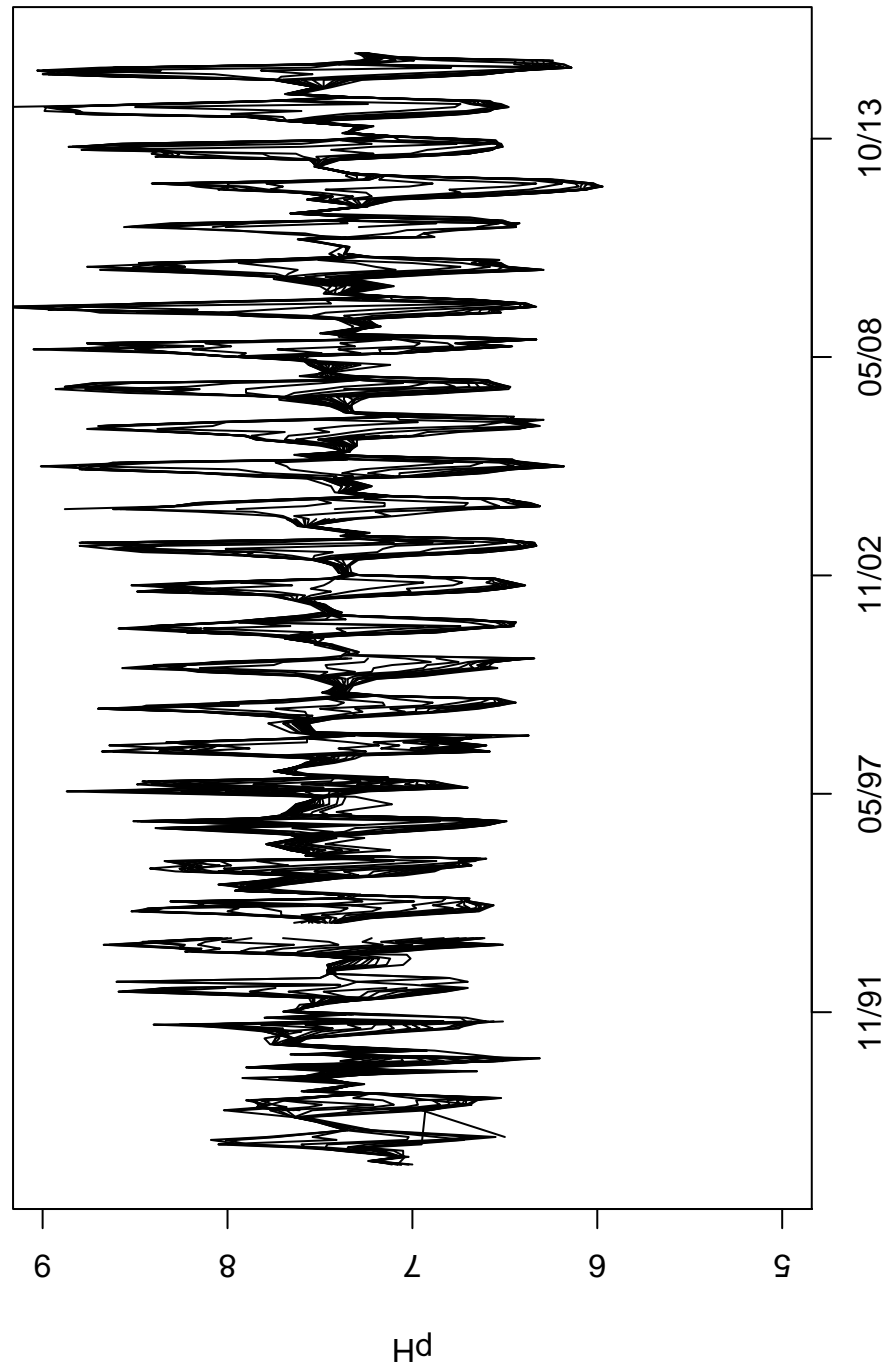


Figure B61: Lake Whatcom historic pH data for Site 1.

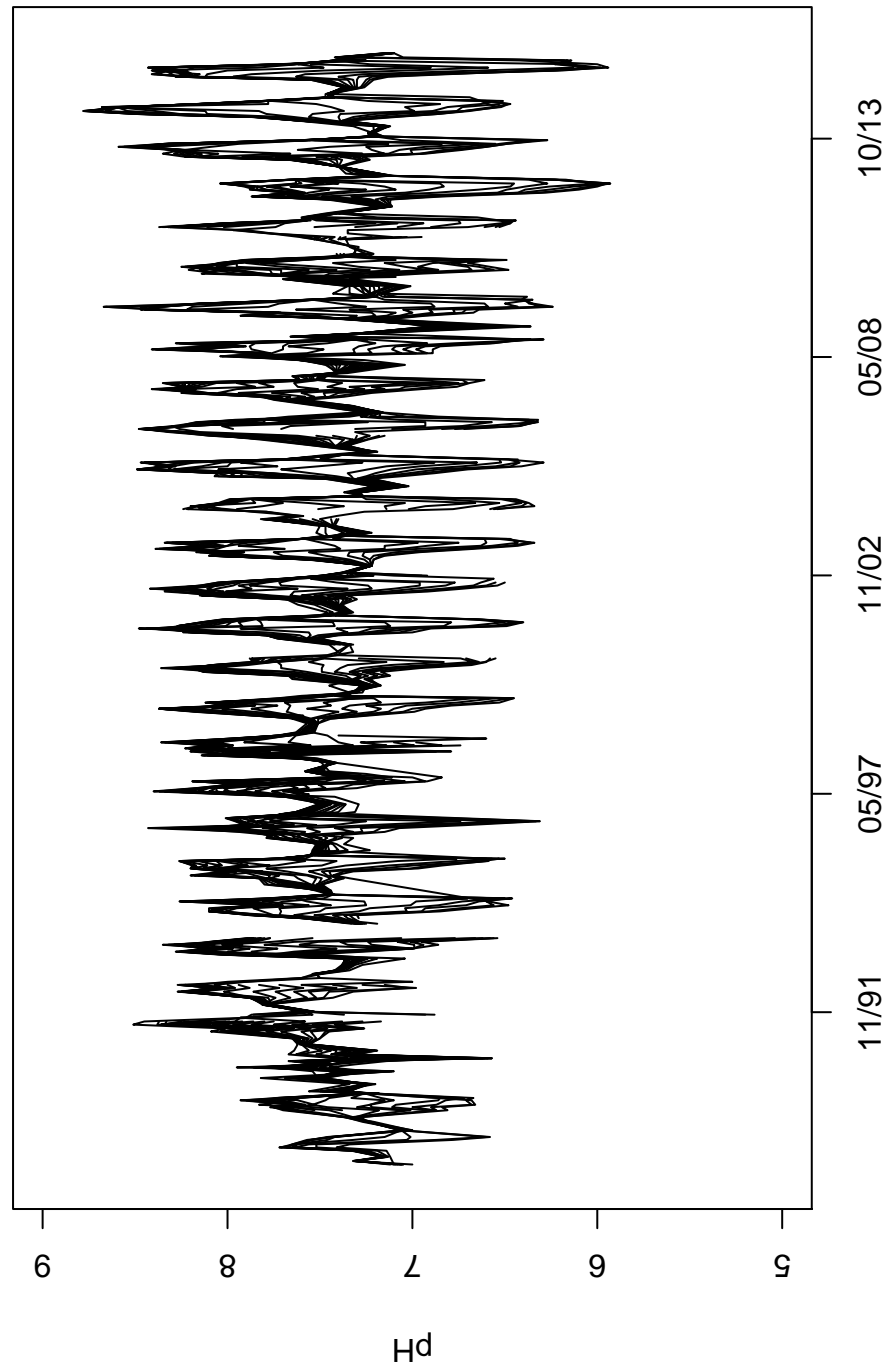


Figure B62: Lake Whatcom historic pH data for Site 2.

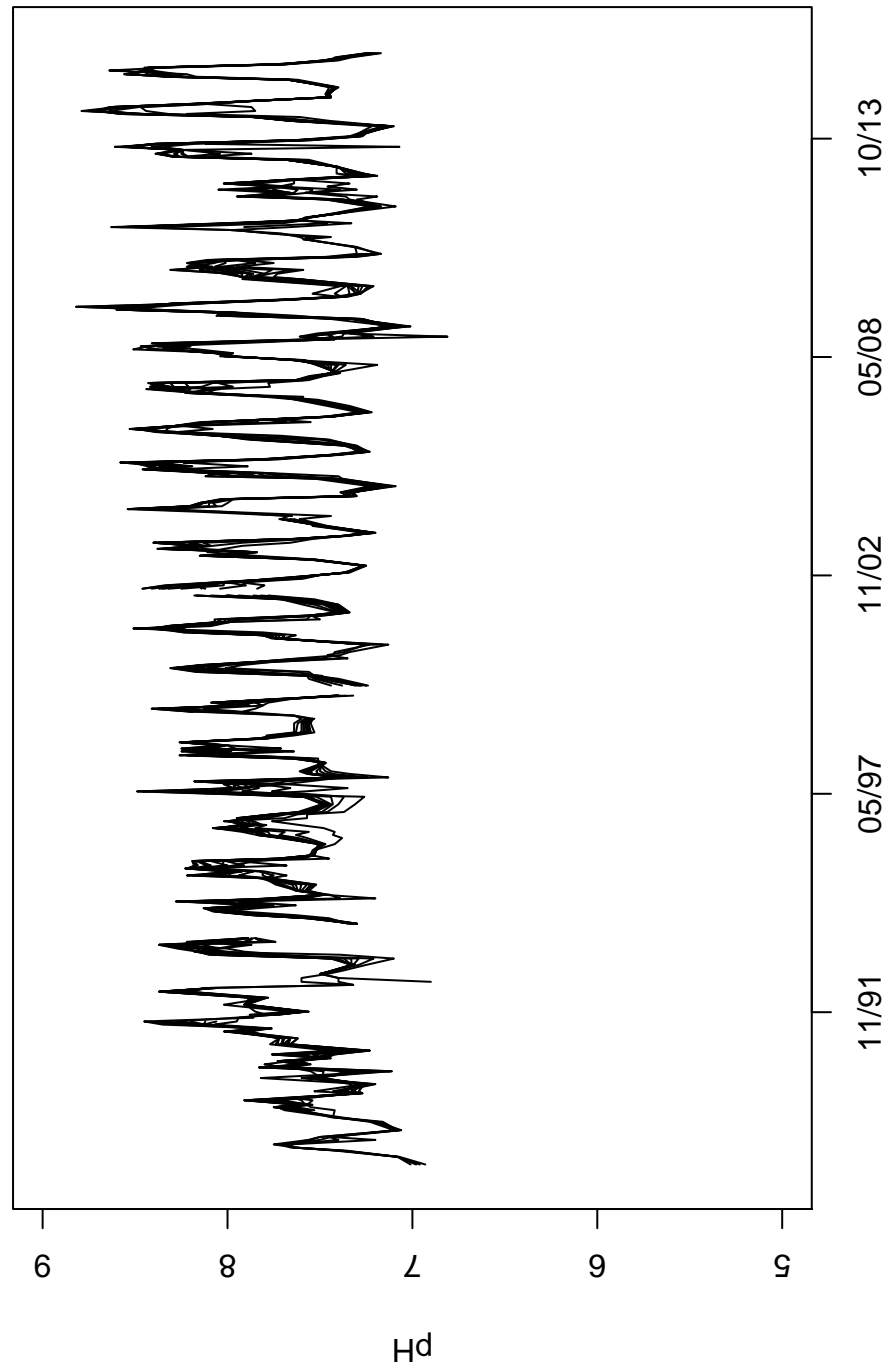


Figure B63: Lake Whatcom historic pH data for the Intake.

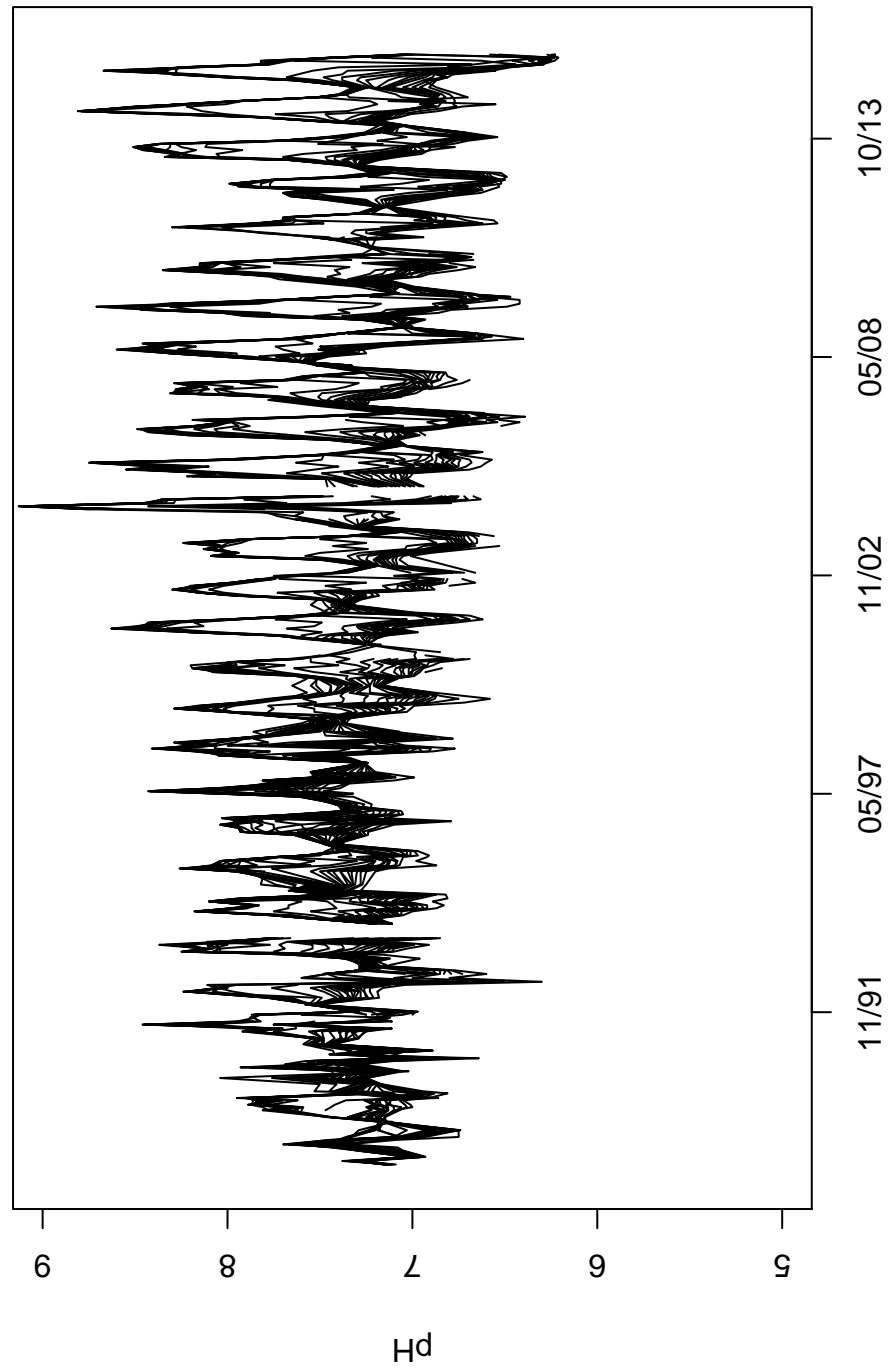


Figure B64: Lake Whatcom historic pH data for Site 3.

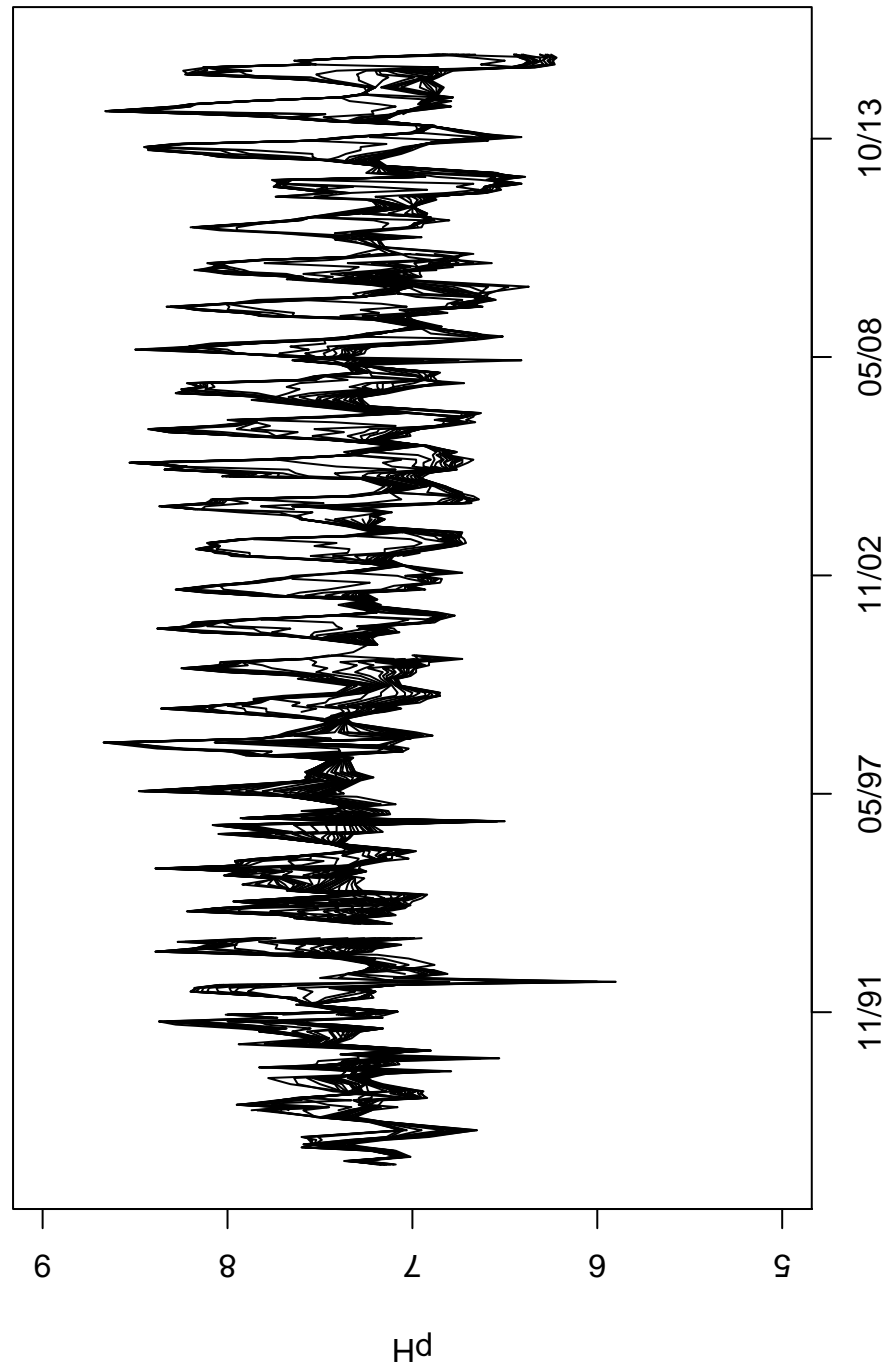


Figure B65: Lake Whatcom historic pH data for Site 4.

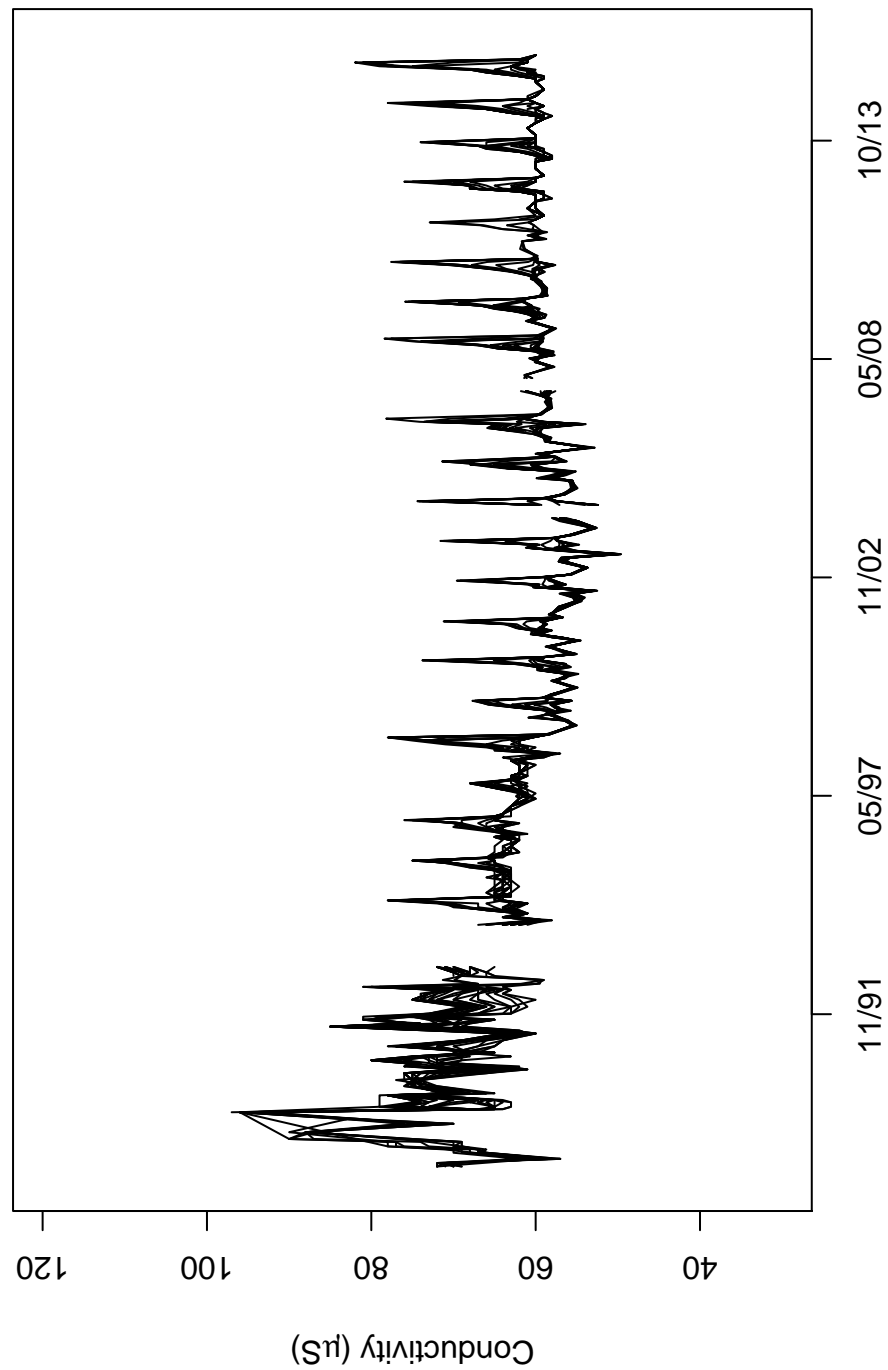


Figure B66: Lake Whatcom historic conductivity data for Site 1. The decreasing conductivity trend is the result of changing to more sensitive equipment.

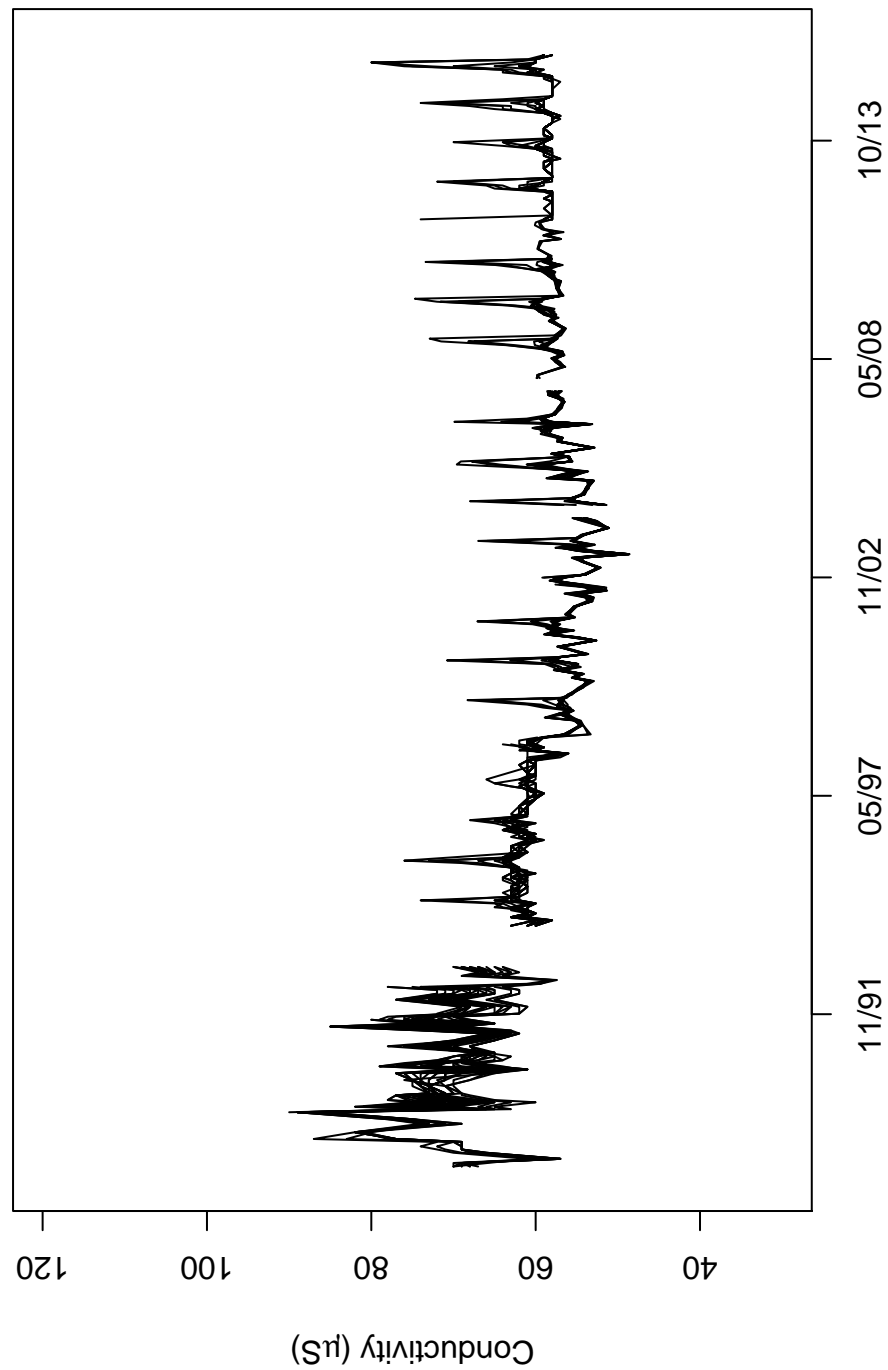


Figure B67: Lake Whatcom historic conductivity data for Site 2. The decreasing conductivity trend is the result of changing to more sensitive equipment.

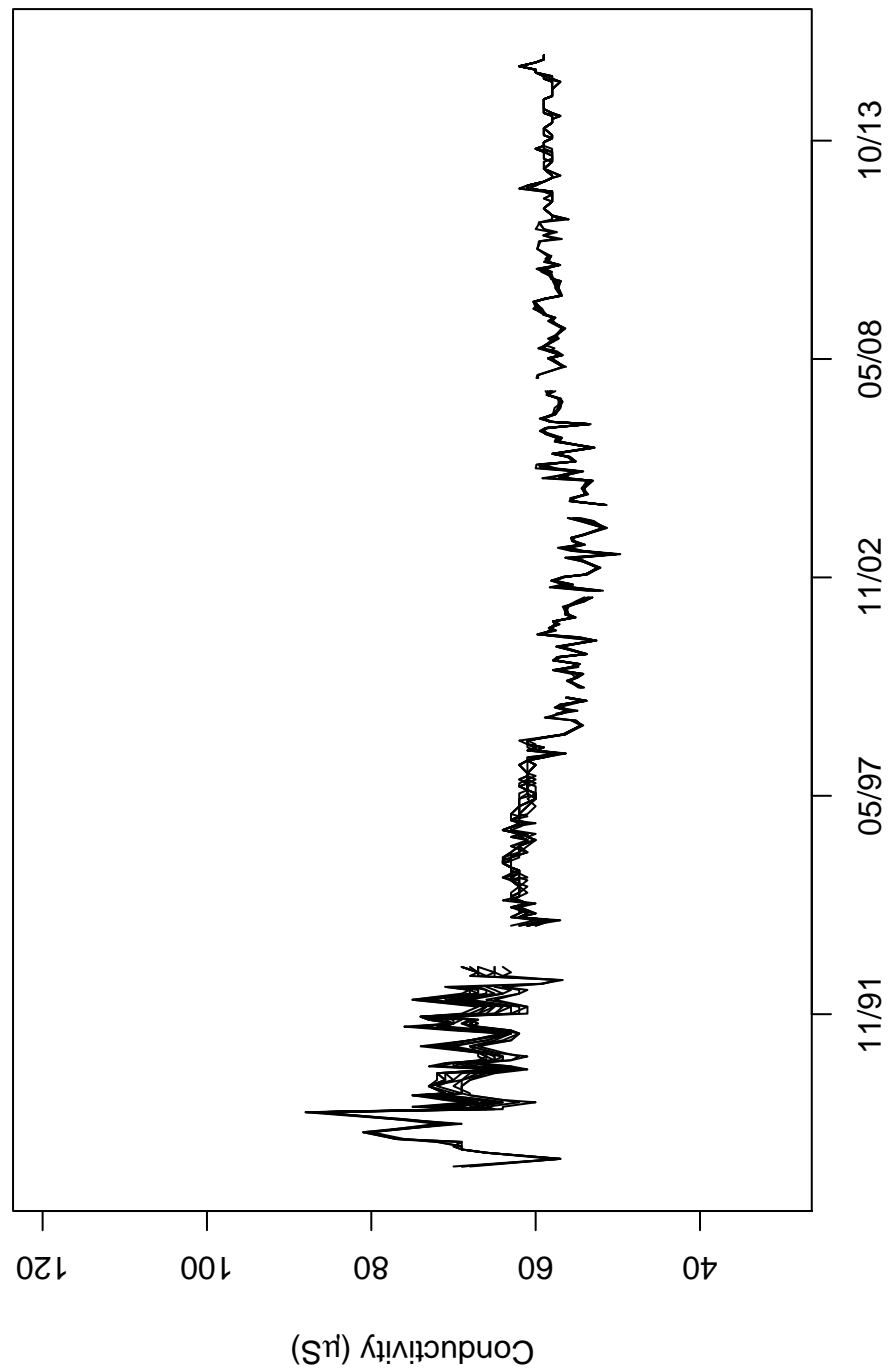


Figure B68: Lake Whatcom historic conductivity data for the Intake. The decreasing conductivity trend is the result of changing to more sensitive equipment.

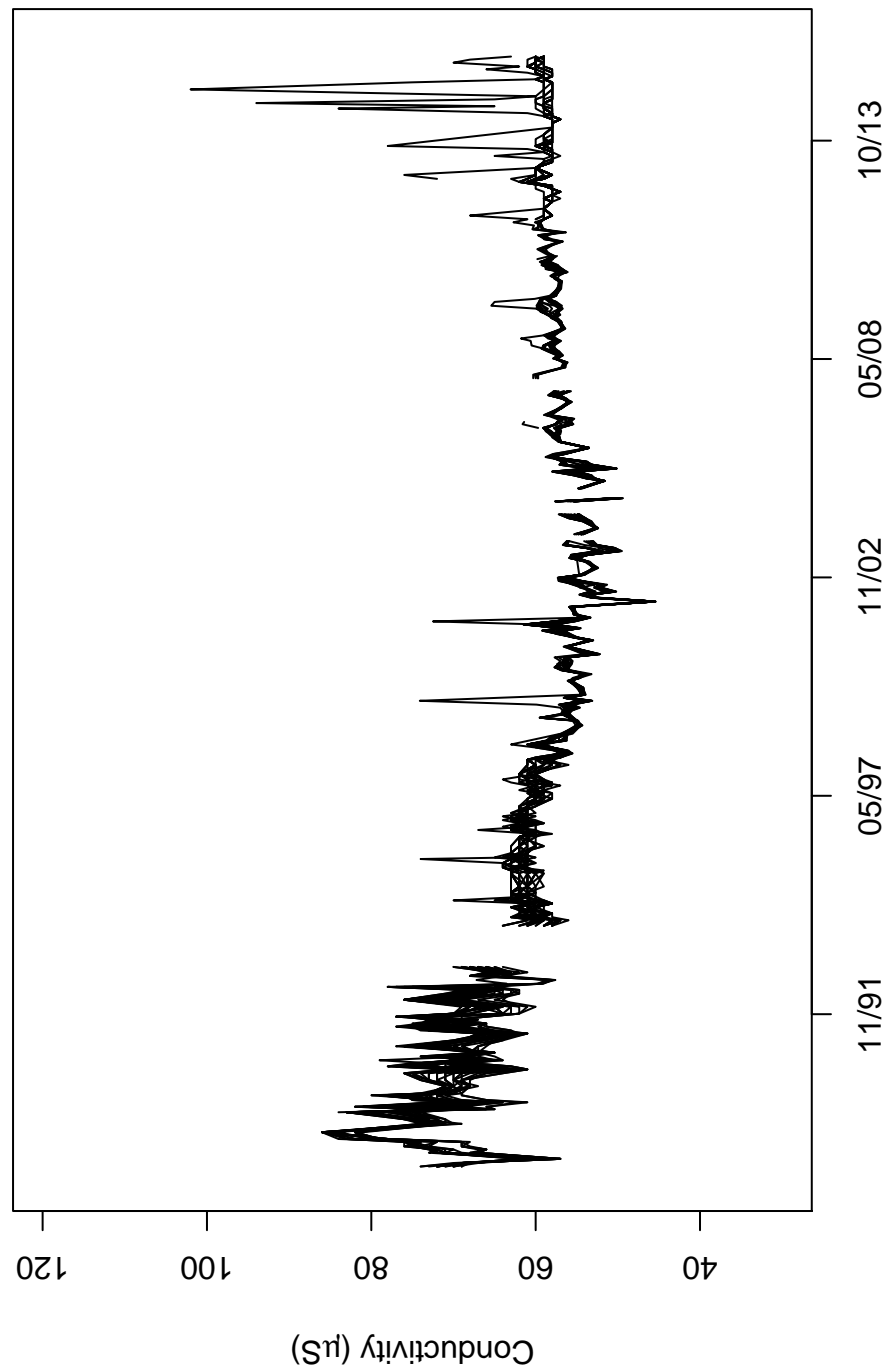


Figure B69: Lake Whatcom historic conductivity data for Site 3. The decreasing conductivity trend is the result of changing to more sensitive equipment.

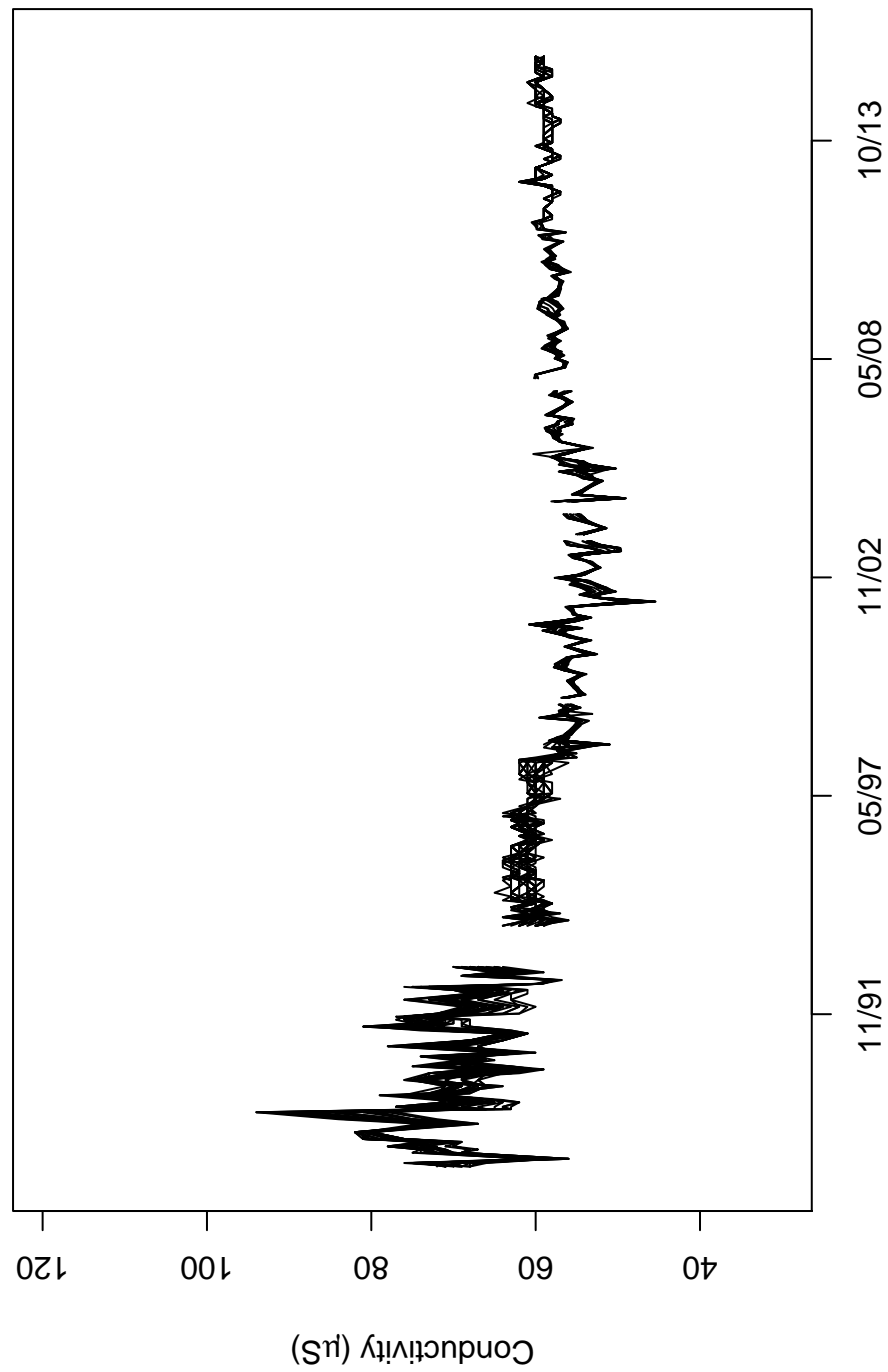


Figure B70: Lake Whatcom historic conductivity data for Site 4. The decreasing conductivity trend is the result of changing to more sensitive equipment.

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

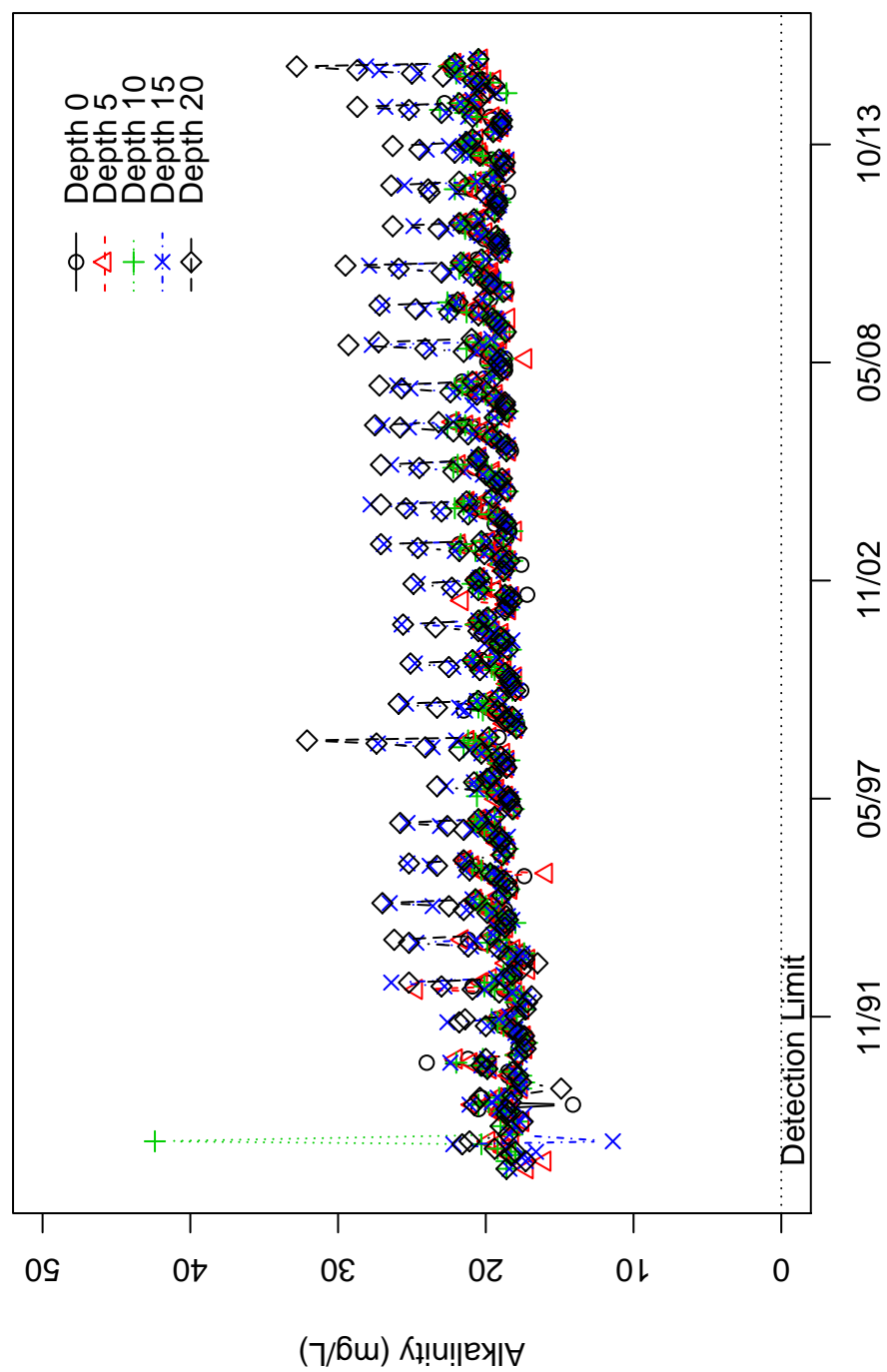


Figure B71: Lake Whatcom alkalinity data for Site 1.

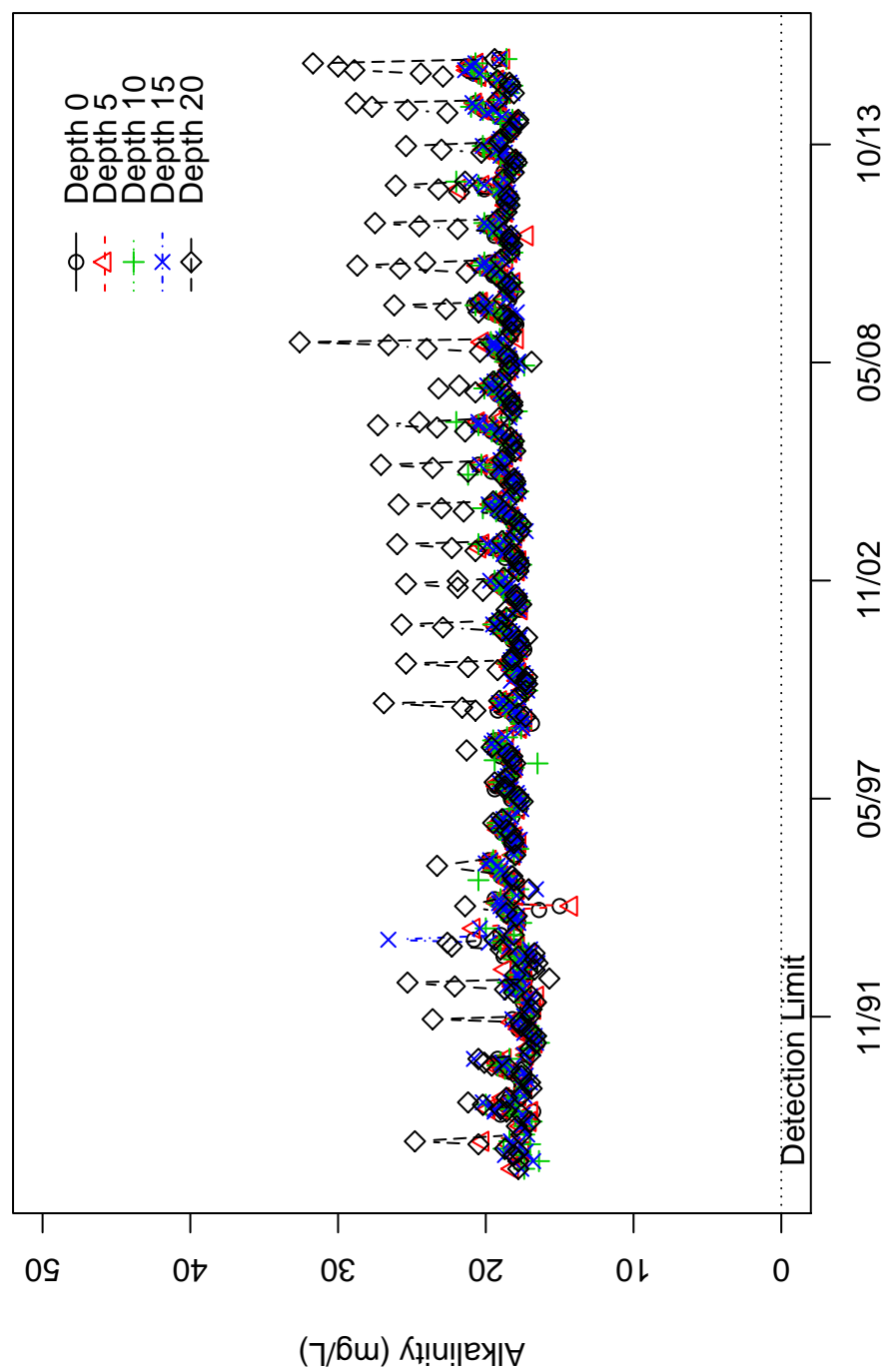


Figure B72: Lake Whatcom alkalinity data for Site 2.

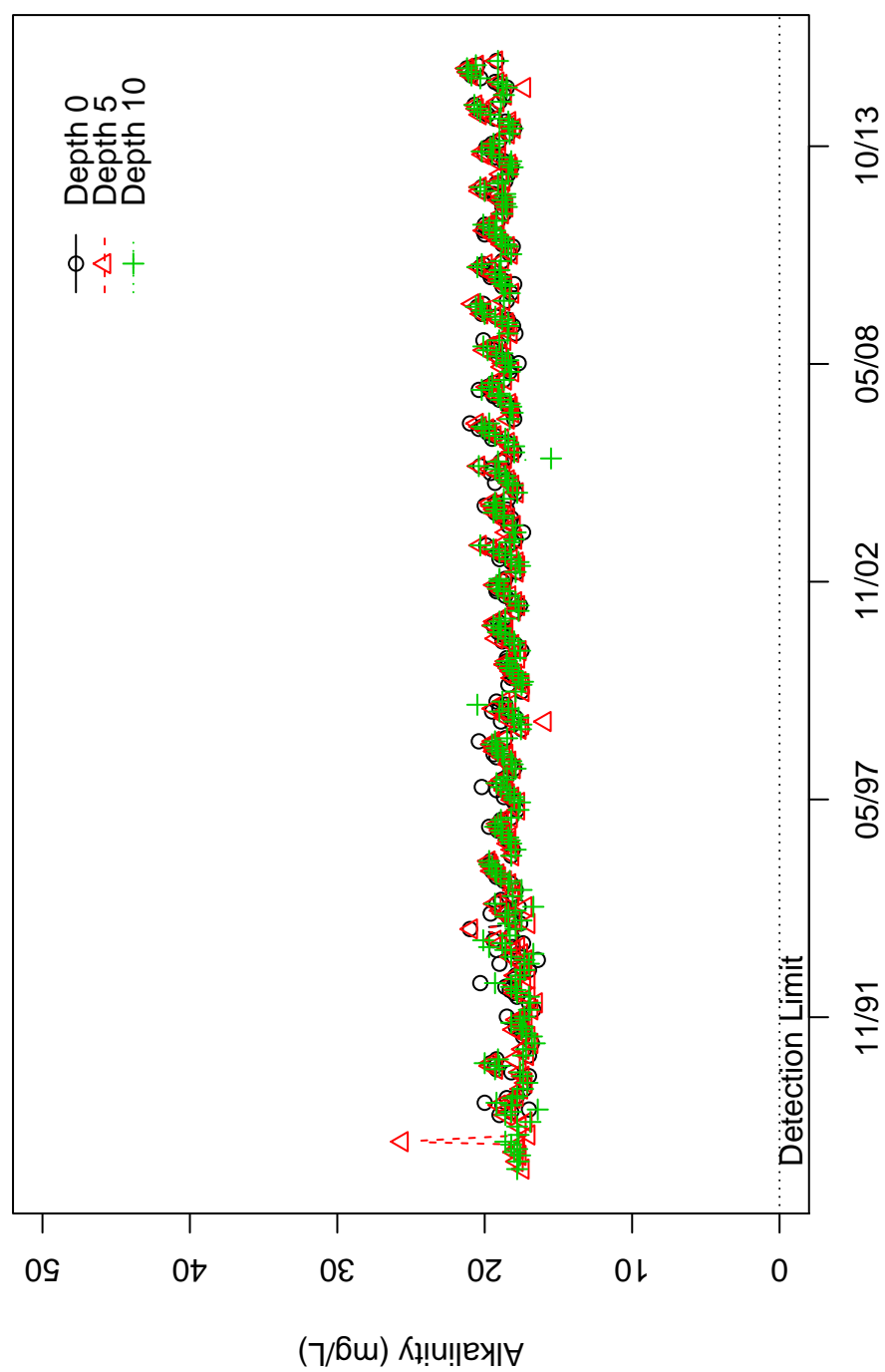


Figure B73: Lake Whatcom alkalinity data for the Intake site.

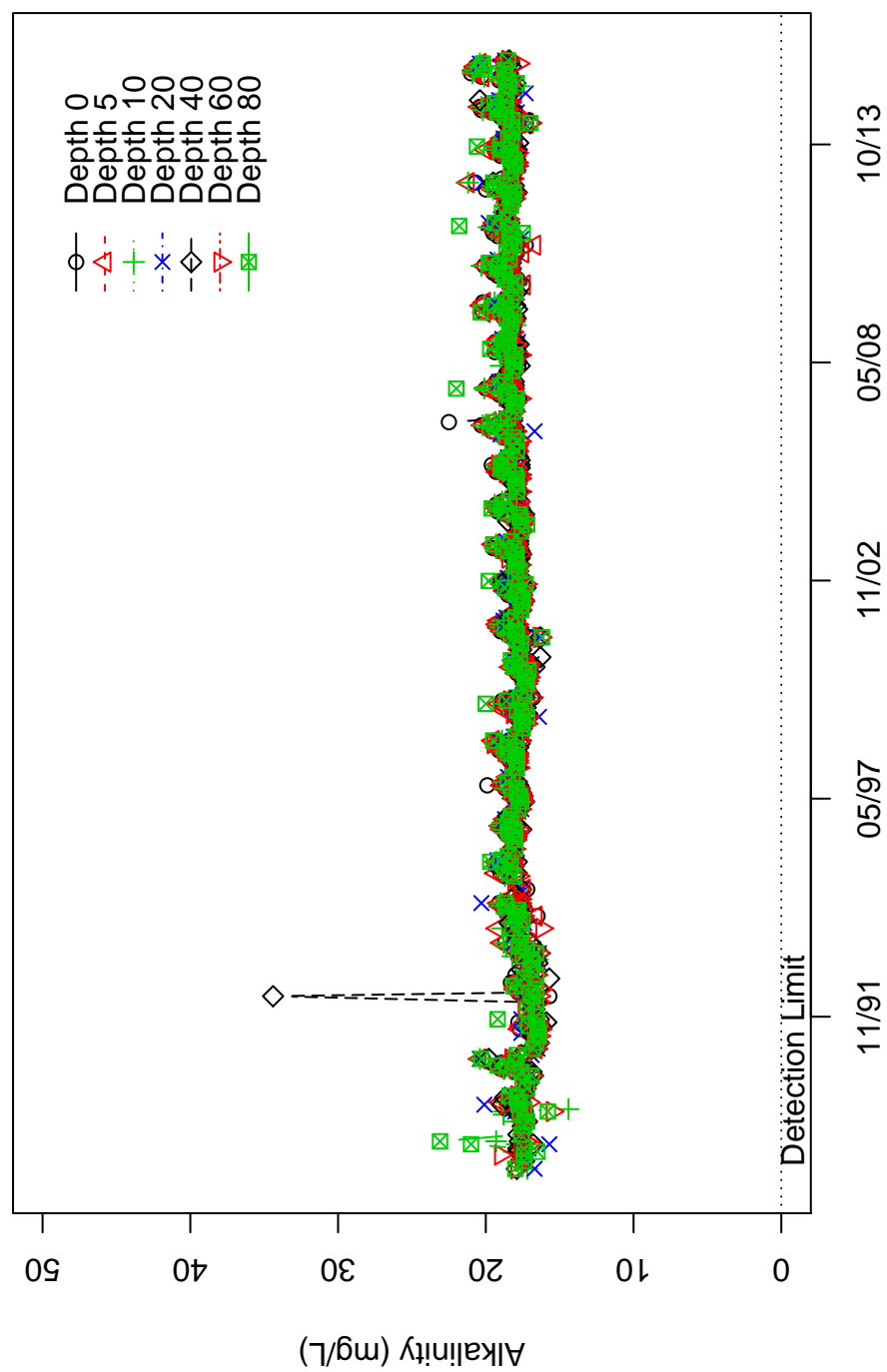


Figure B74: Lake Whatcom alkalinity data for Site 3.

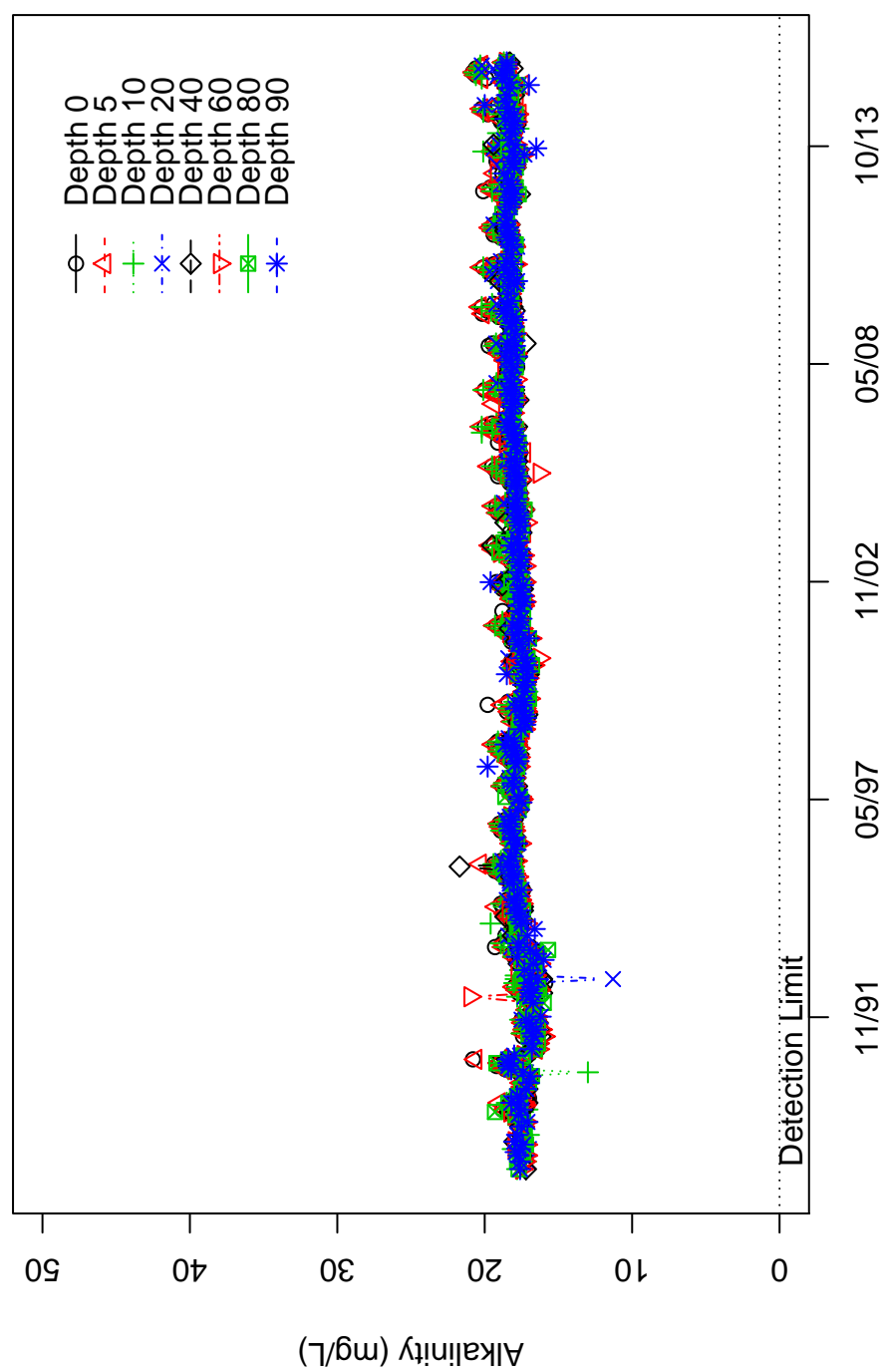


Figure B75: Lake Whatcom alkalinity data for Site 4.

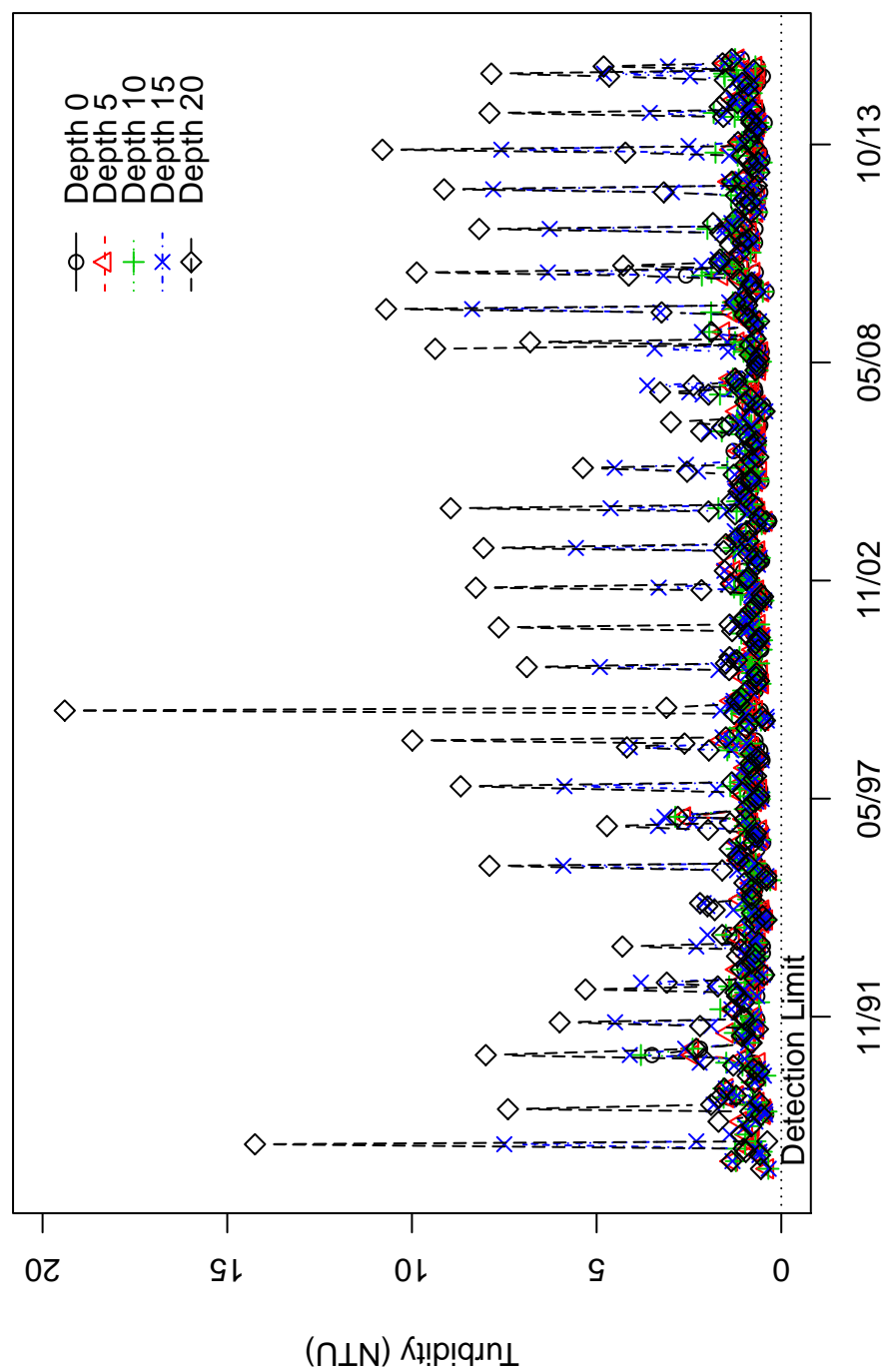


Figure B76: Lake Whatcom turbidity data for Site 1.

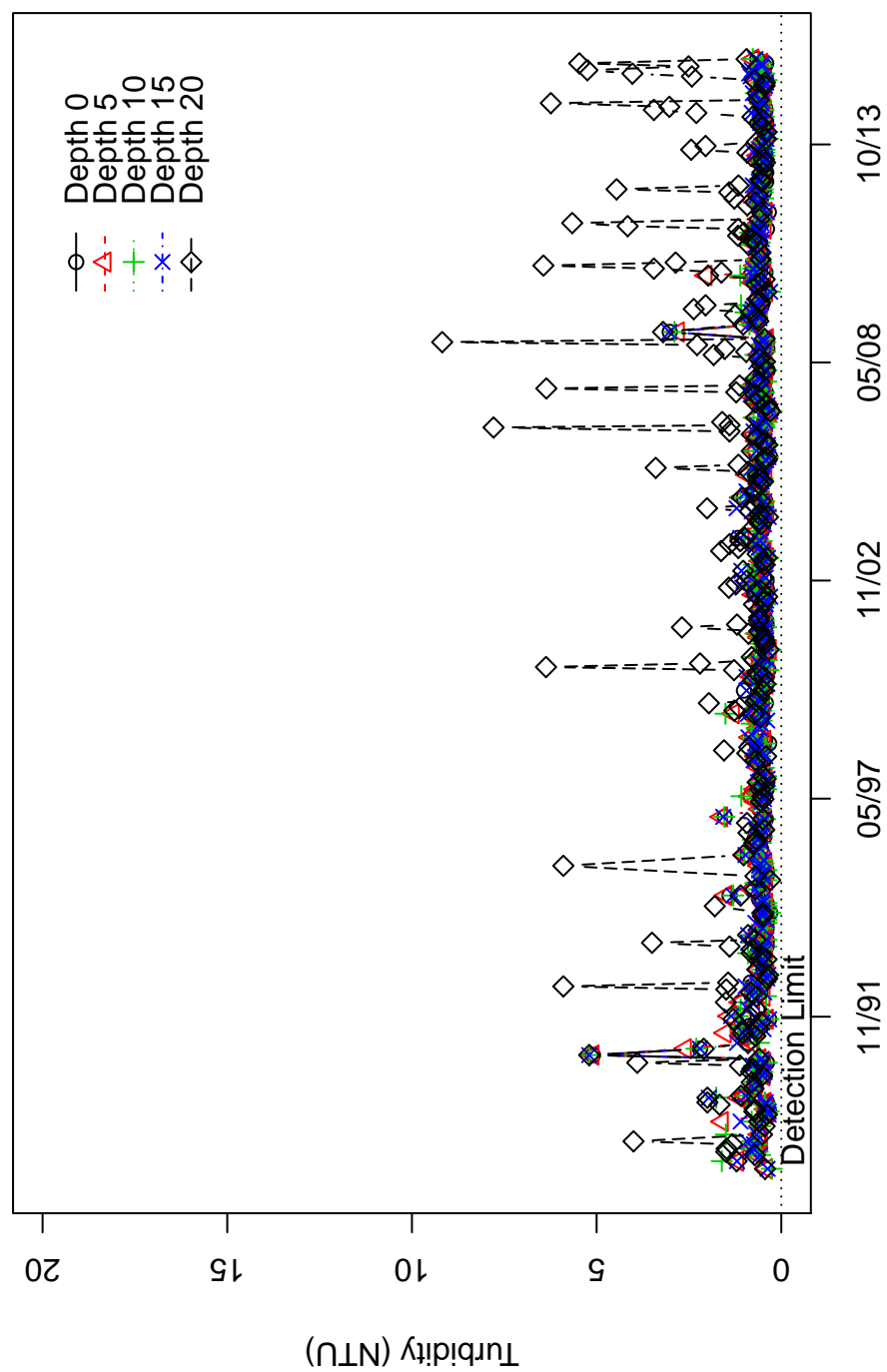


Figure B77: Lake Whatcom turbidity data for Site 2.

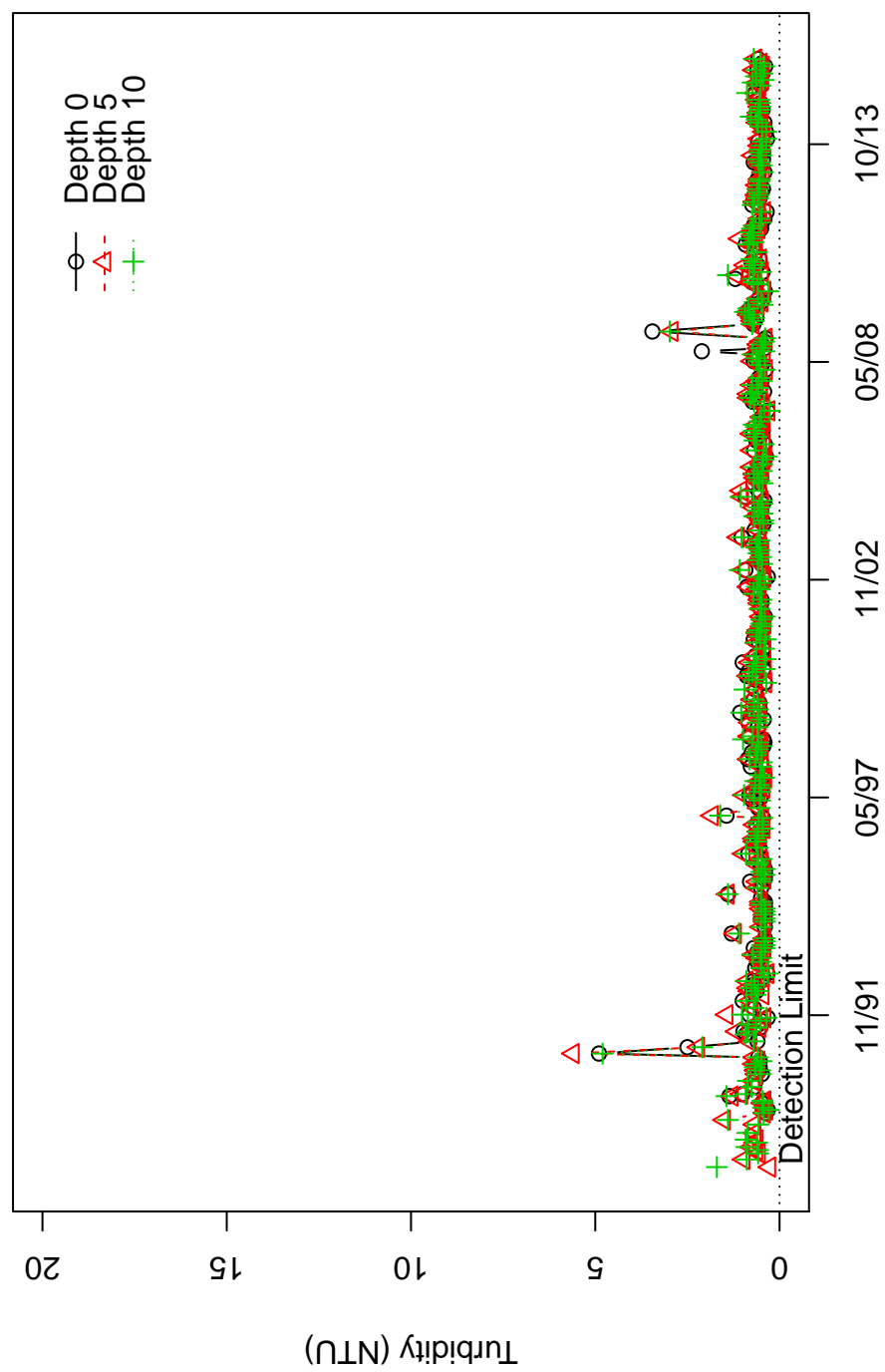


Figure B78: Lake Whatcom turbidity data for the Intake site.

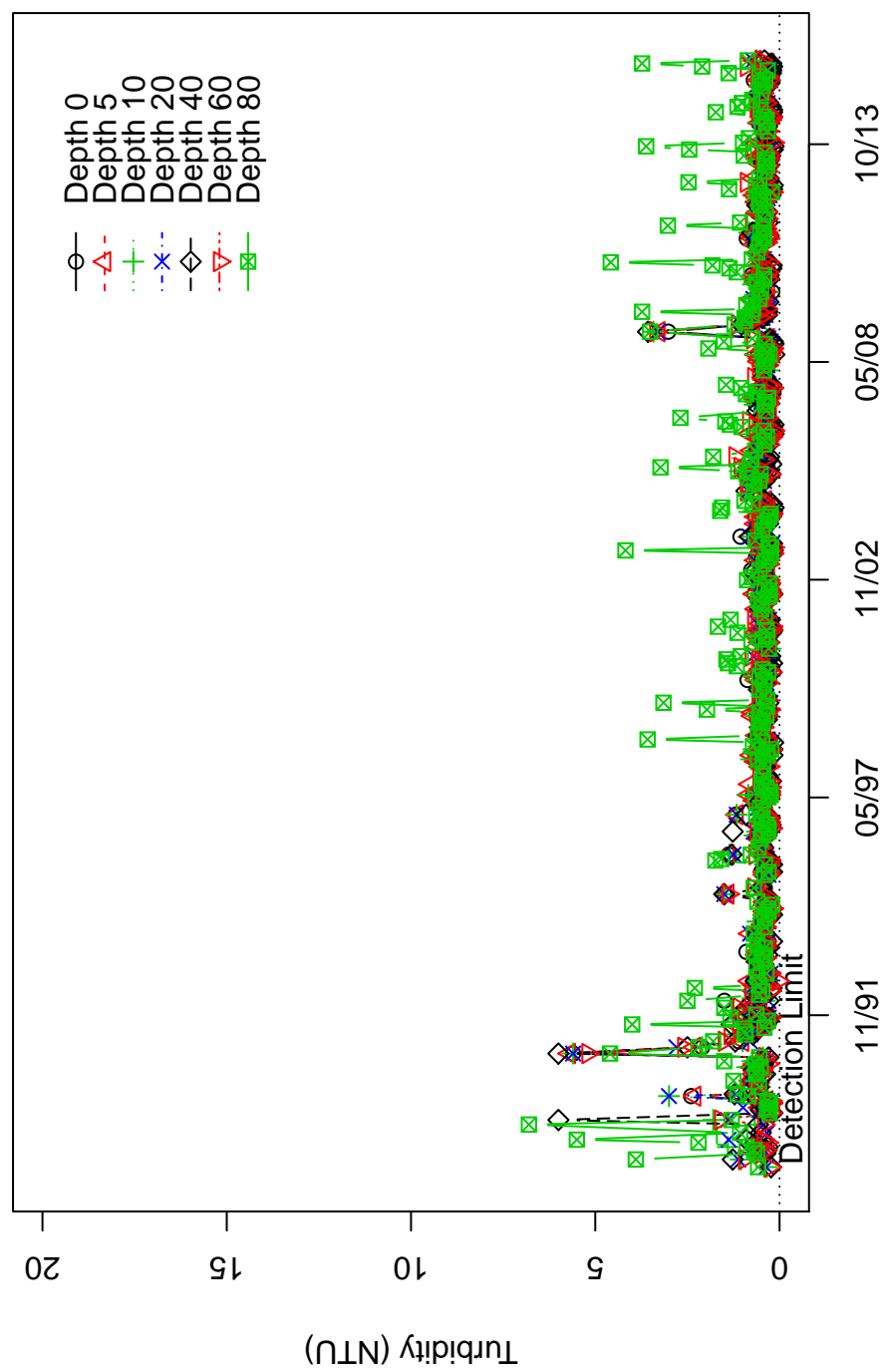


Figure B79: Lake Whatcom turbidity data for Site 3.

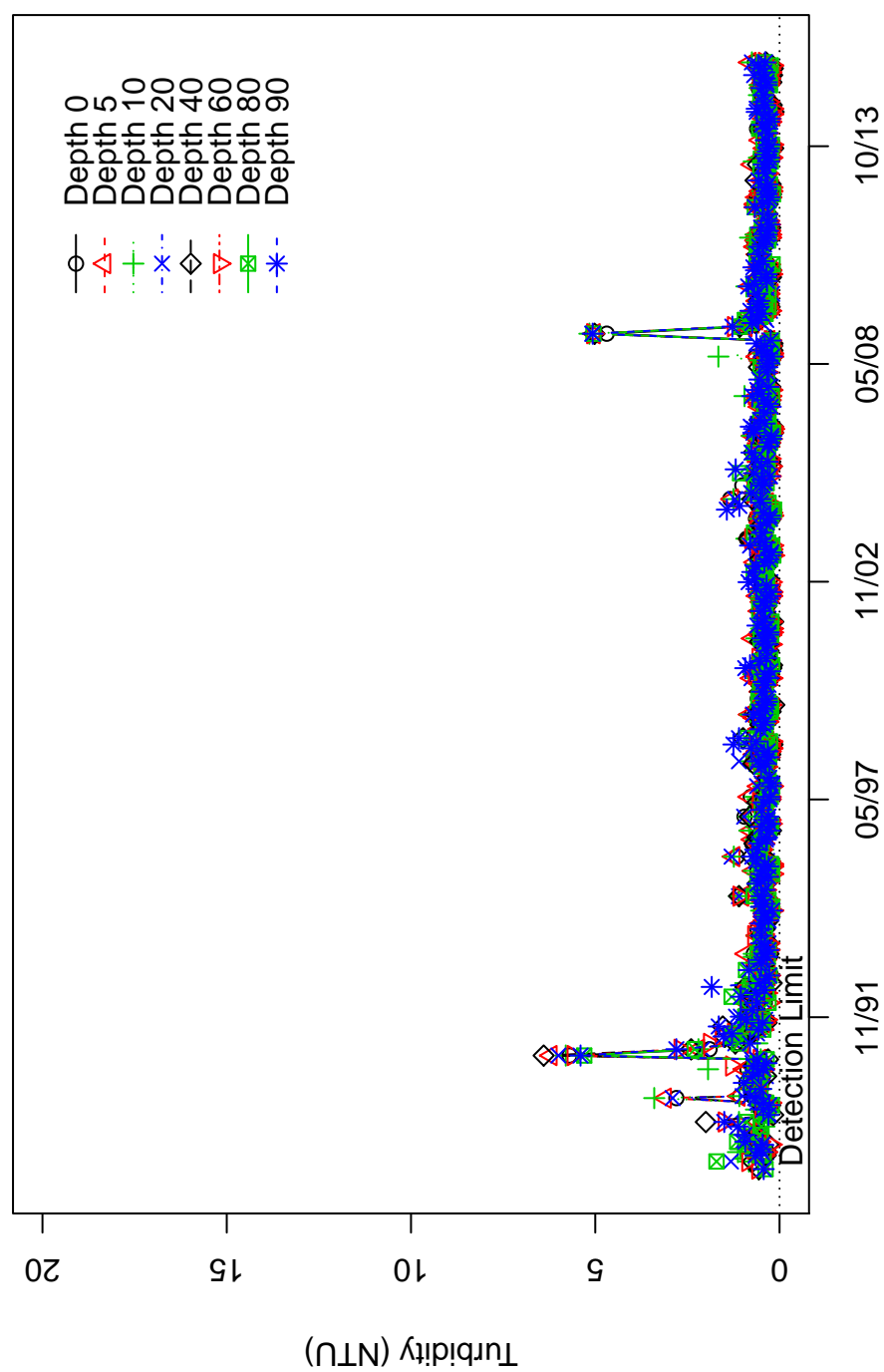


Figure B80: Lake Whatcom turbidity data for Site 4.

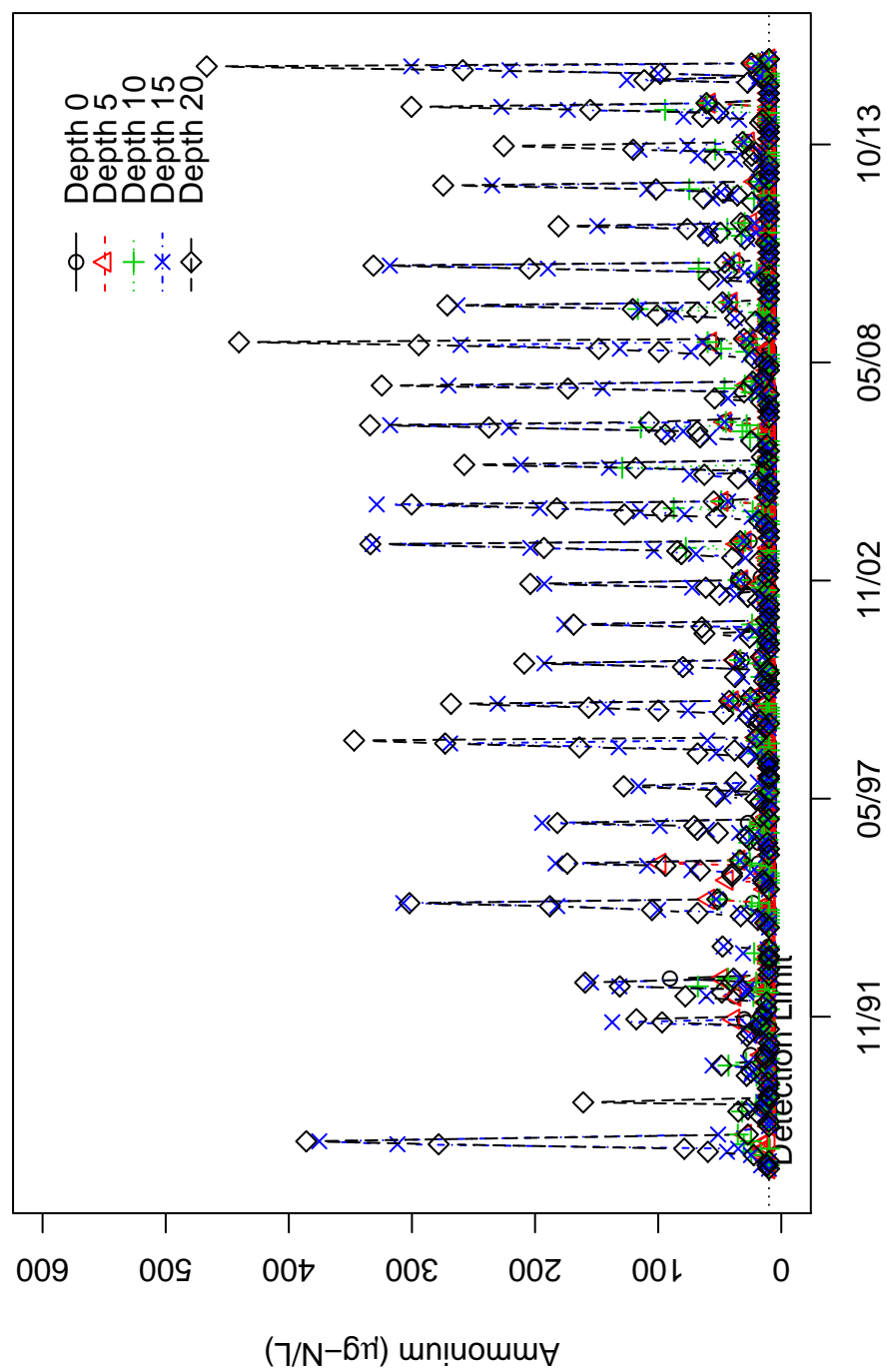


Figure B81: Lake Whatcom ammonium data for Site 1.

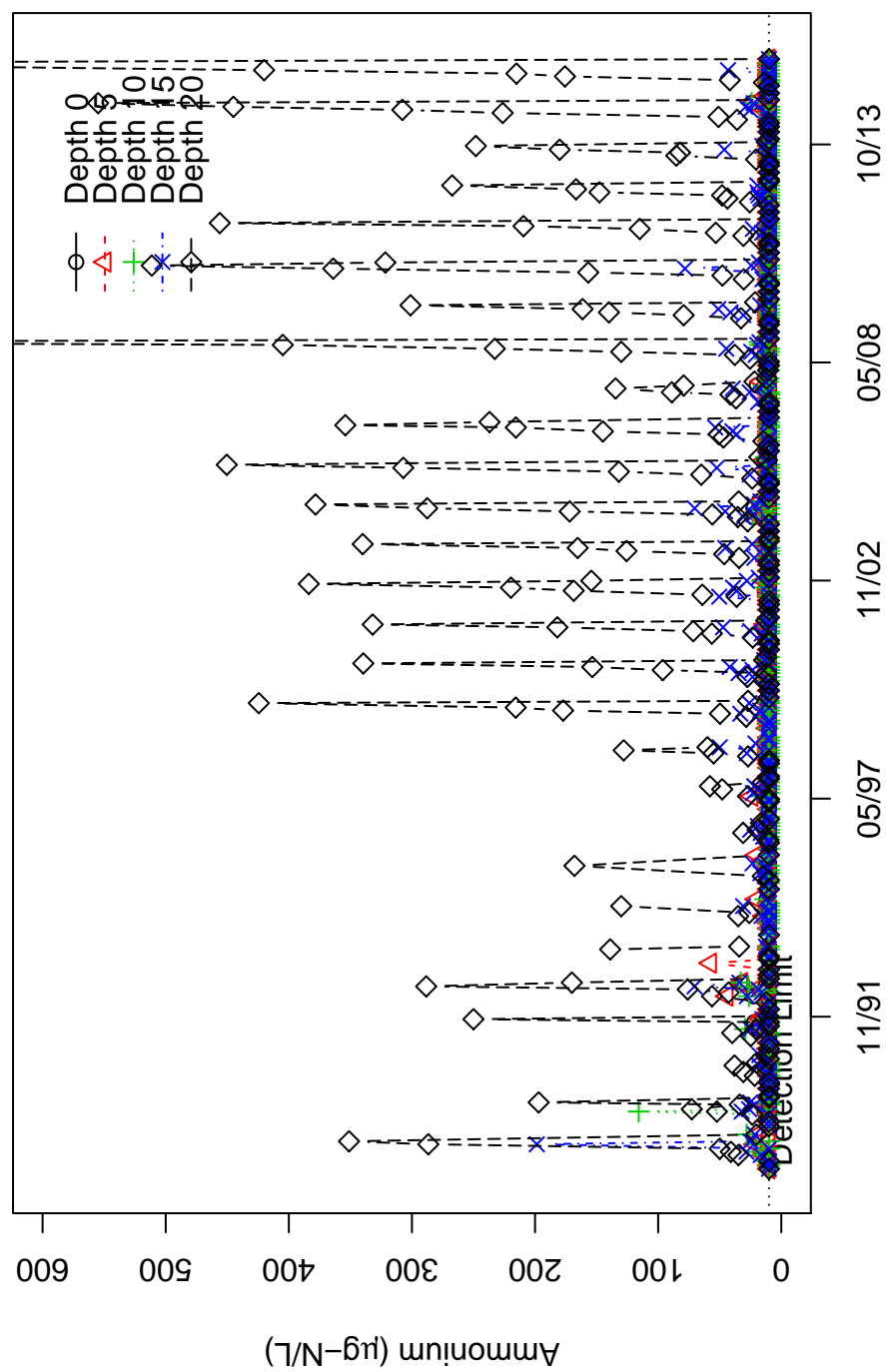


Figure B82: Lake Whatcom ammonium data for Site 2.

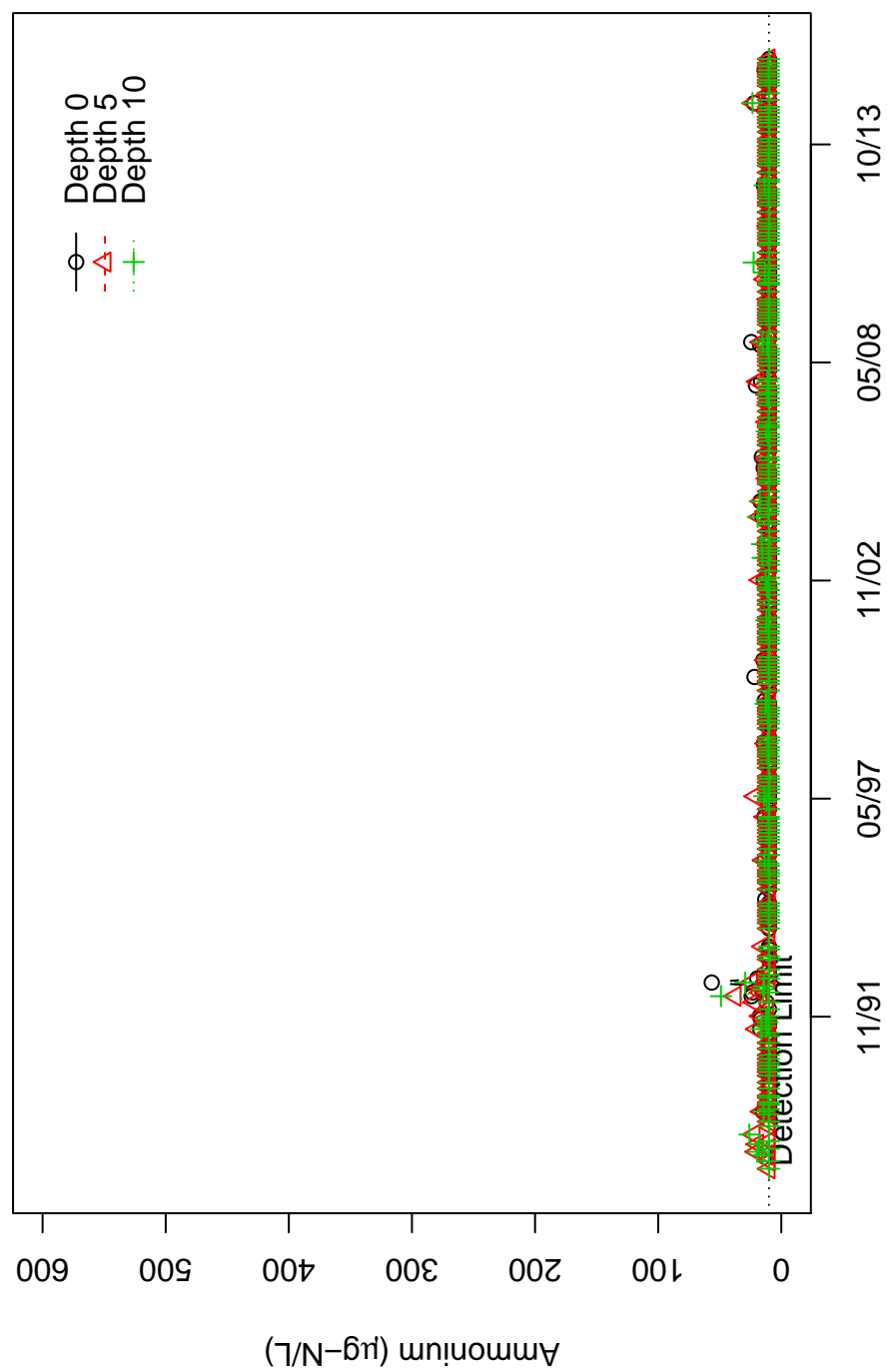


Figure B83: Lake Whatcom ammonium data for the Intake site.

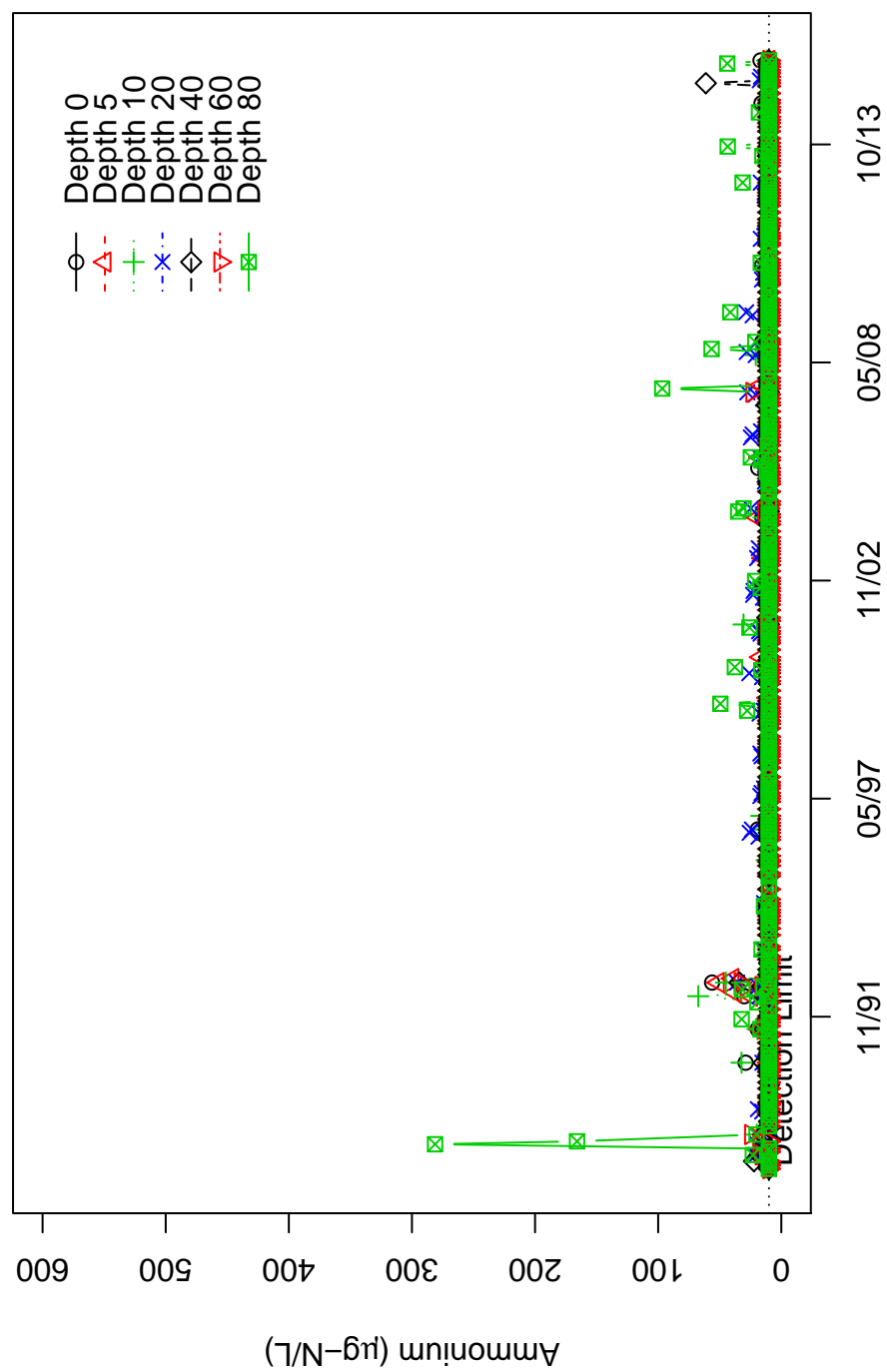


Figure B84: Lake Whatcom ammonium data for Site 3.

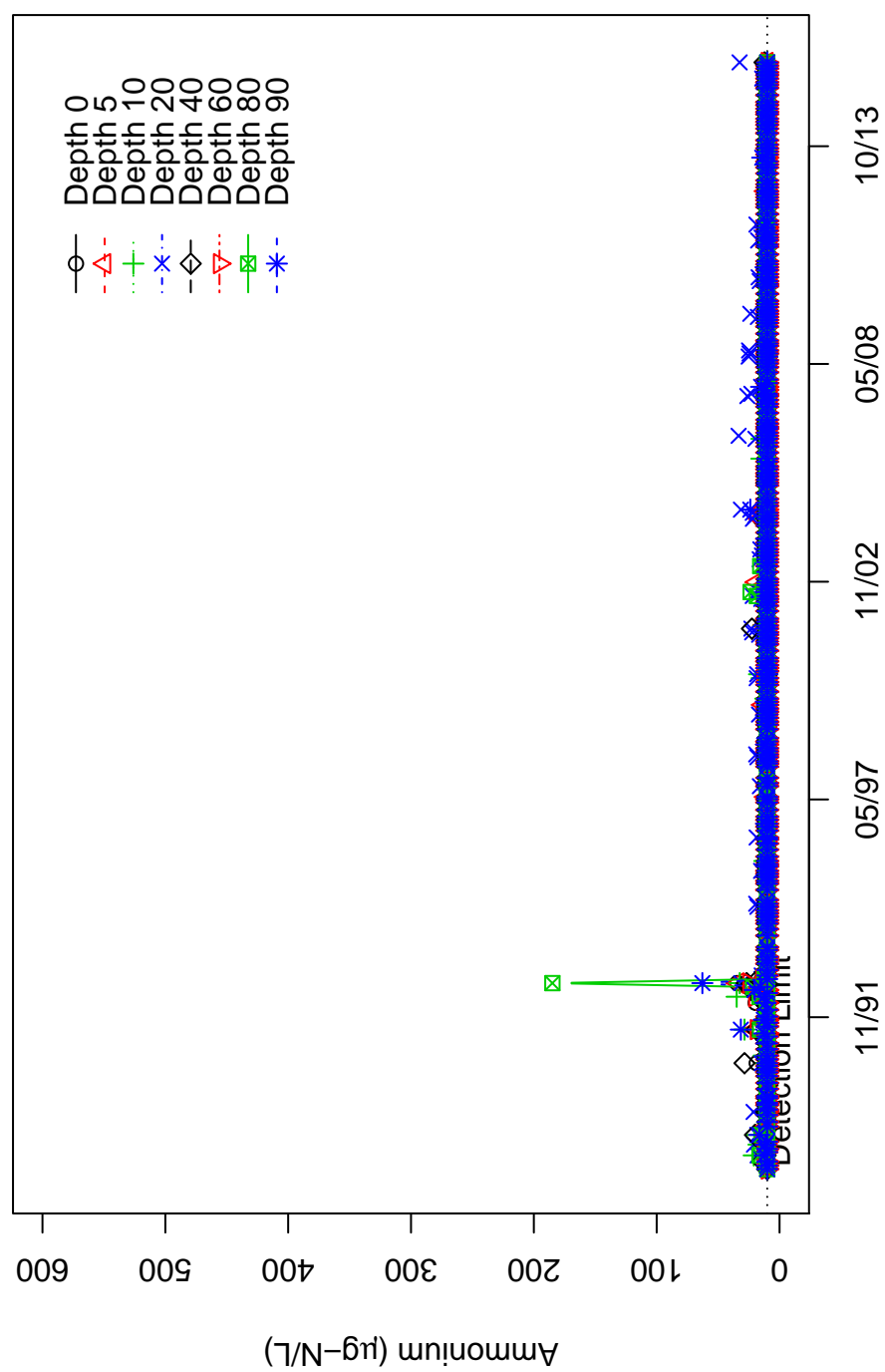


Figure B85: Lake Whatcom ammonium data for Site 4.

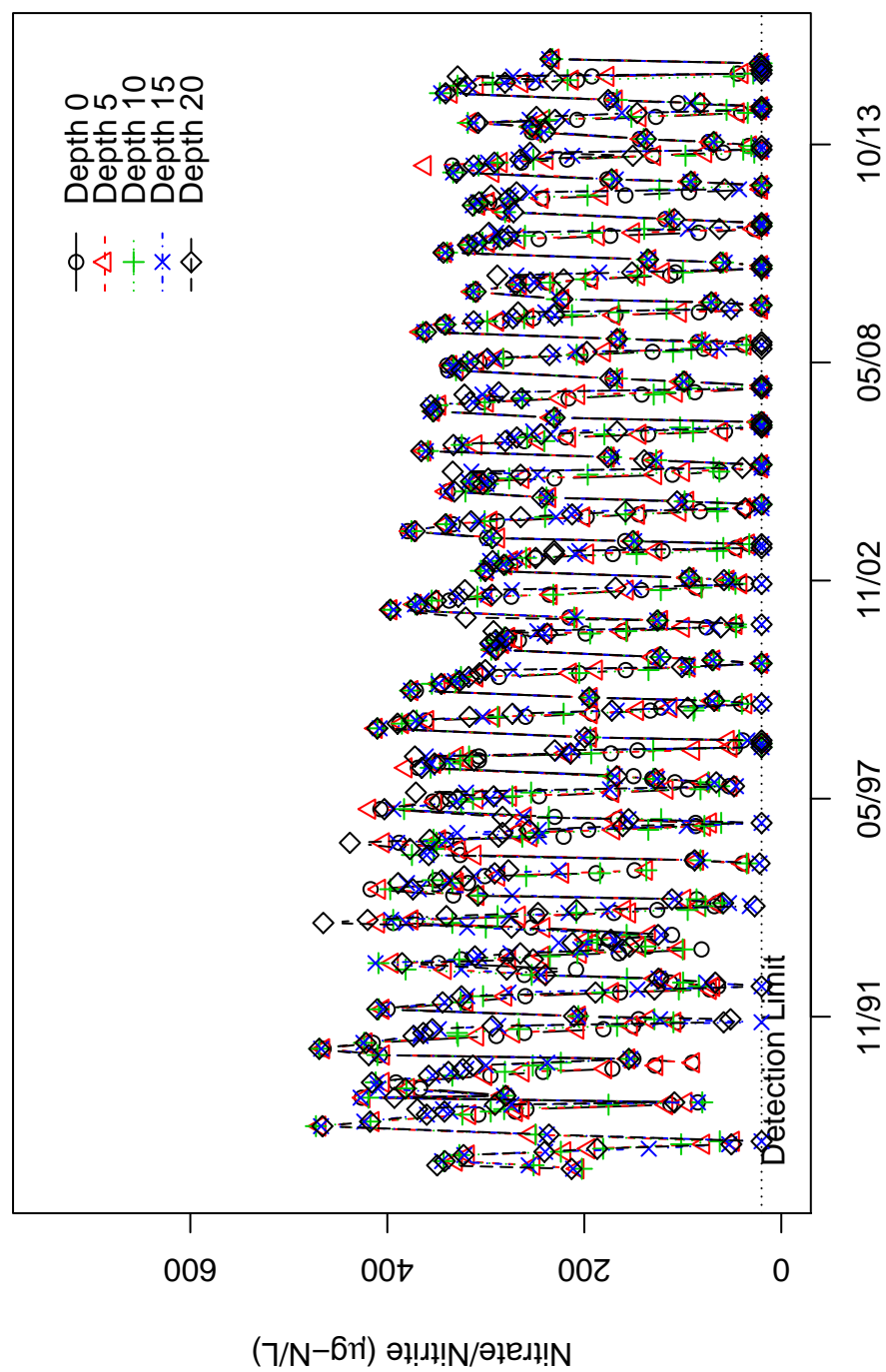


Figure B86: Lake Whatcom nitrate/nitrite data for Site 1.

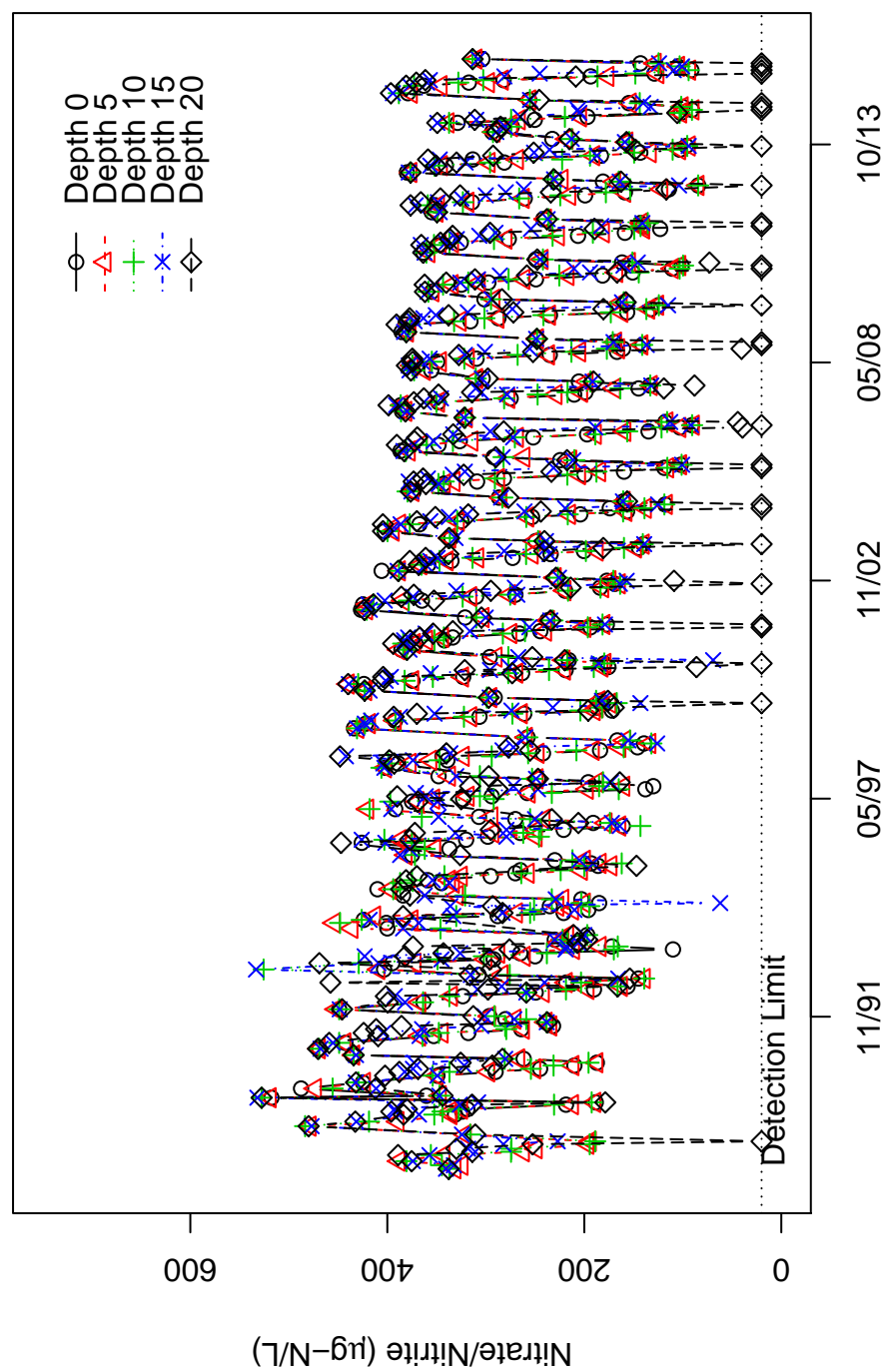


Figure B87: Lake Whatcom nitrate/nitrite data for Site 2.

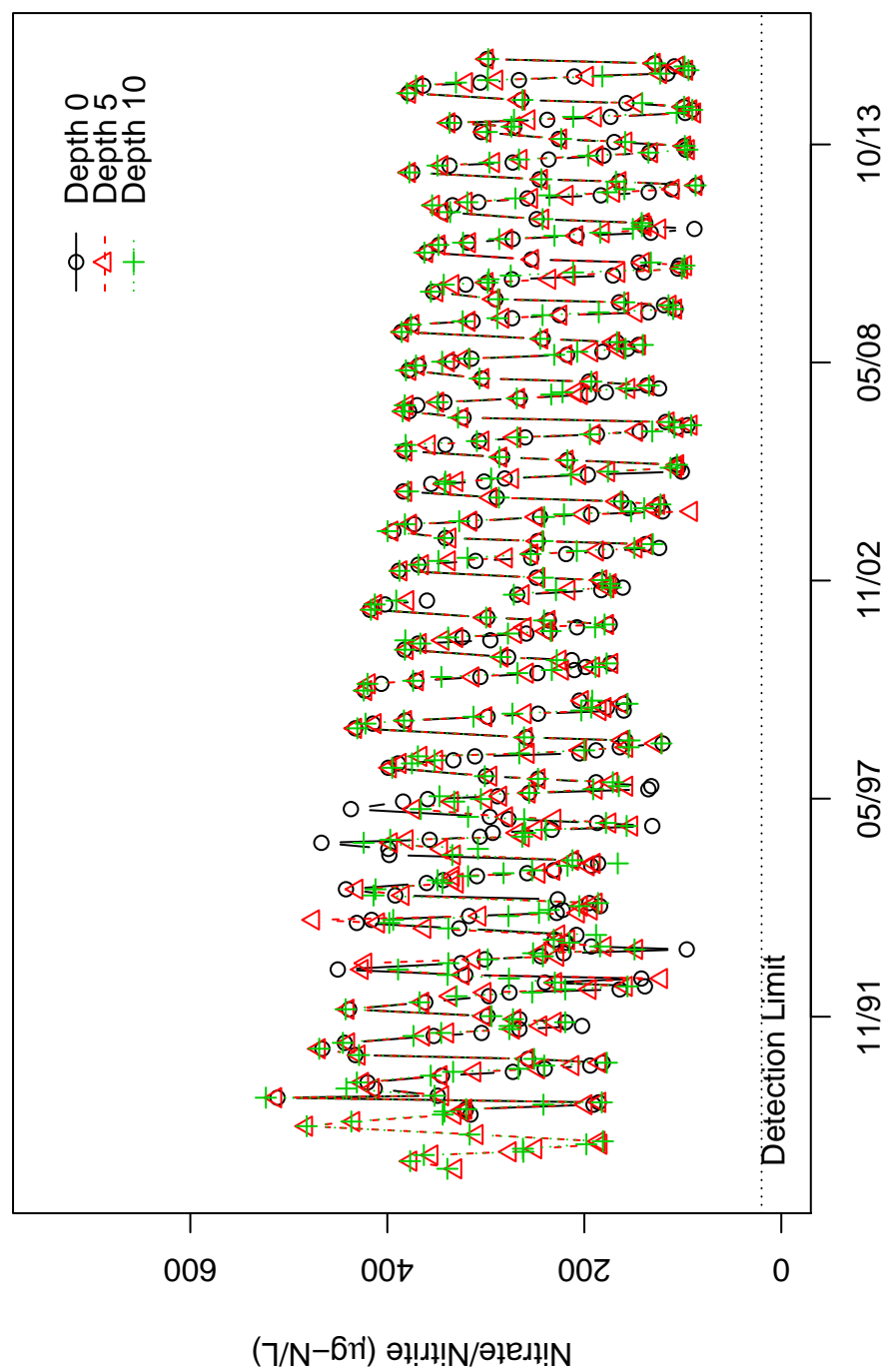


Figure B88: Lake Whatcom nitrate/nitrite data for the Intake site.

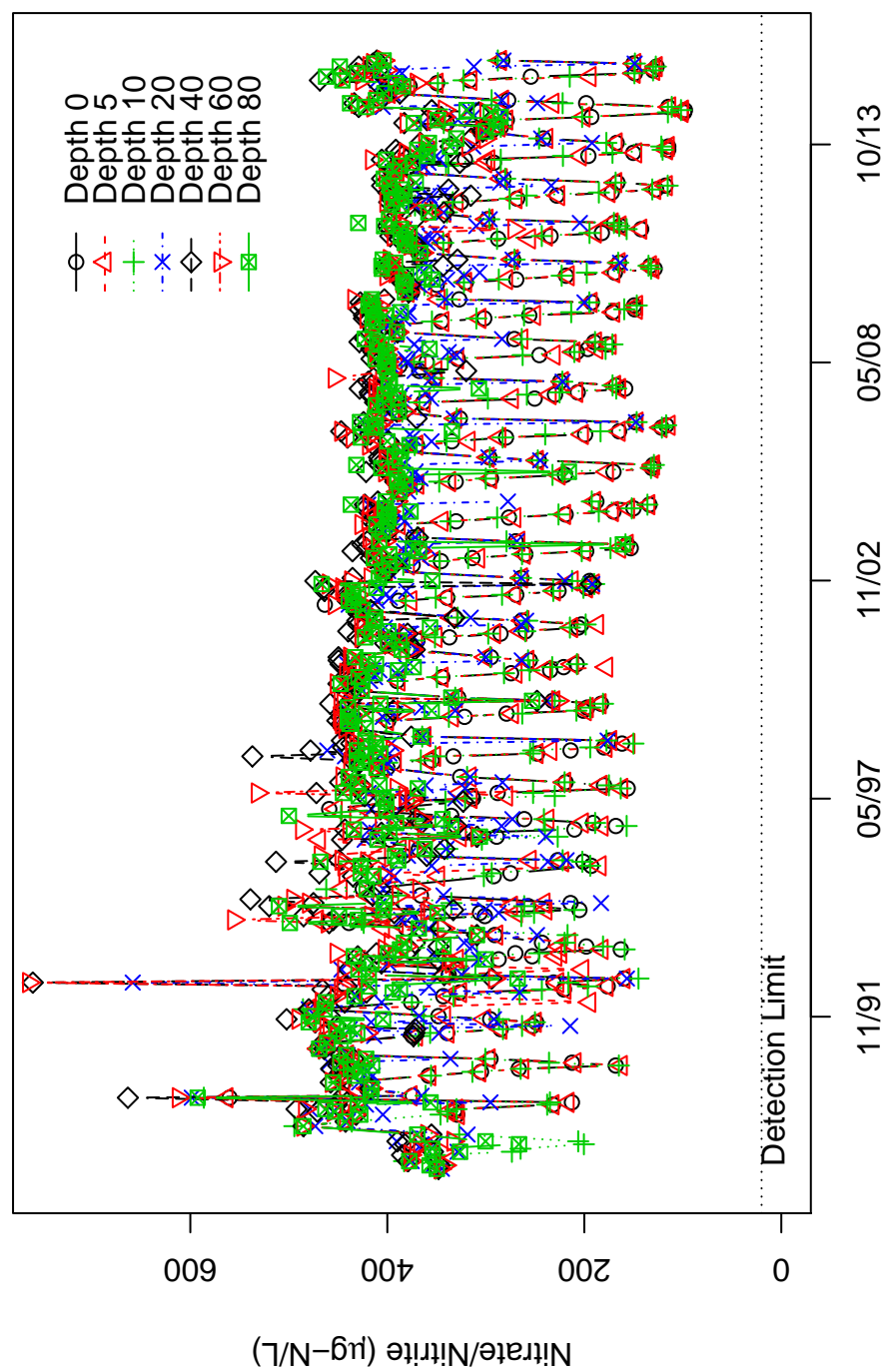


Figure B89: Lake Whatcom nitrate/nitrite data for Site 3.

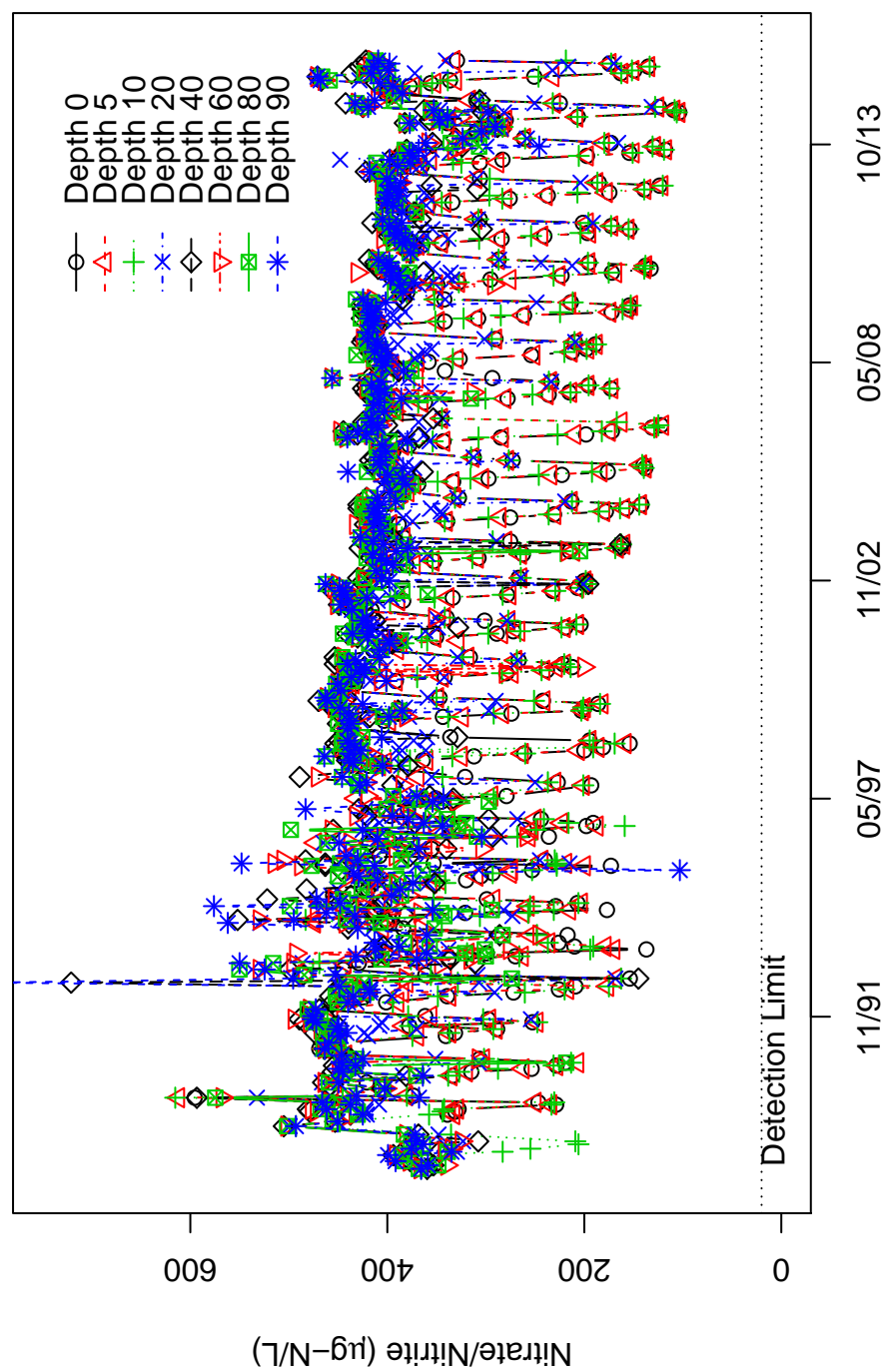


Figure B90: Lake Whatcom nitrate/nitrite data for Site 4.

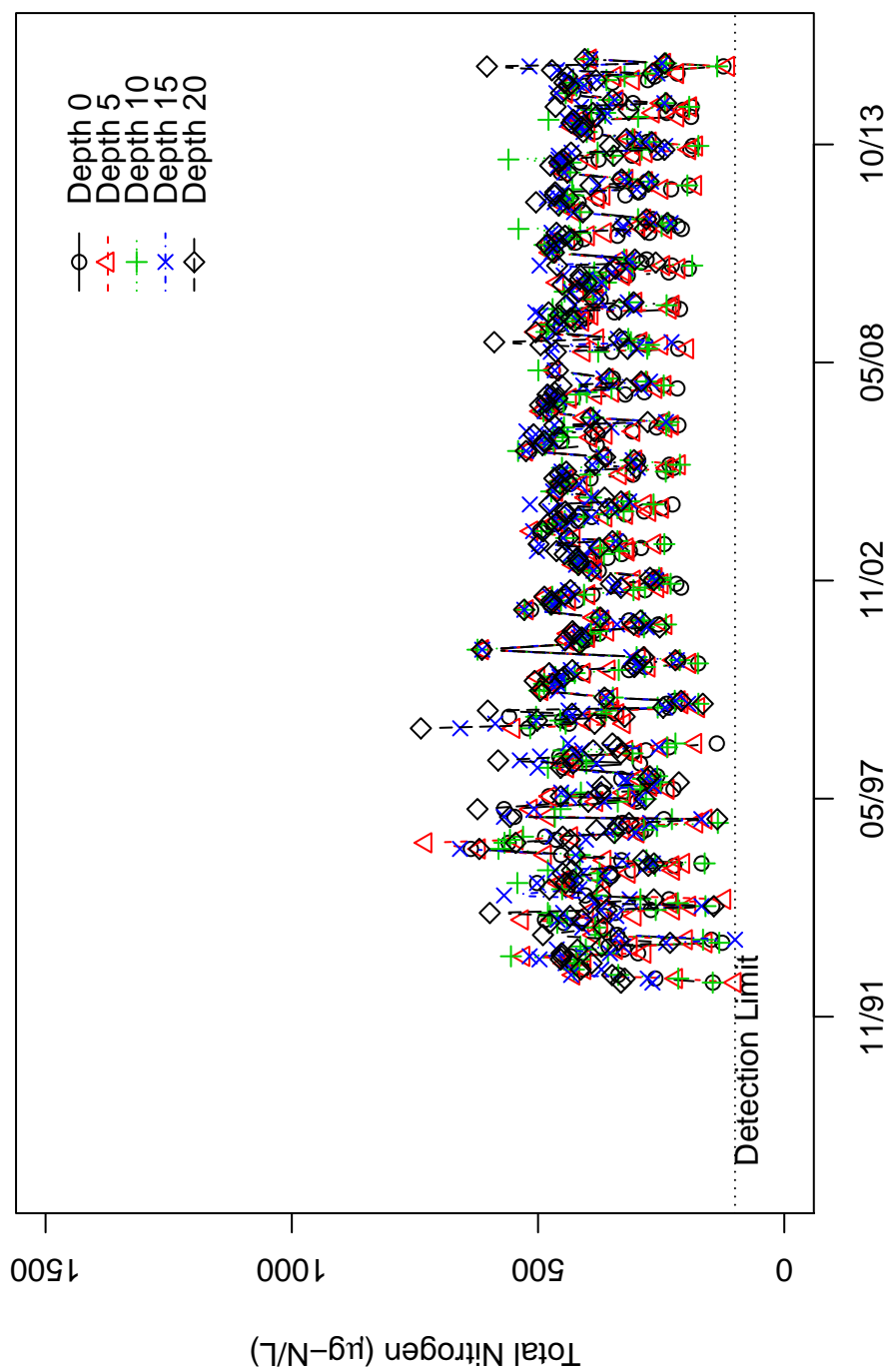


Figure B91: Lake Whatcom total nitrogen data for Site 1.

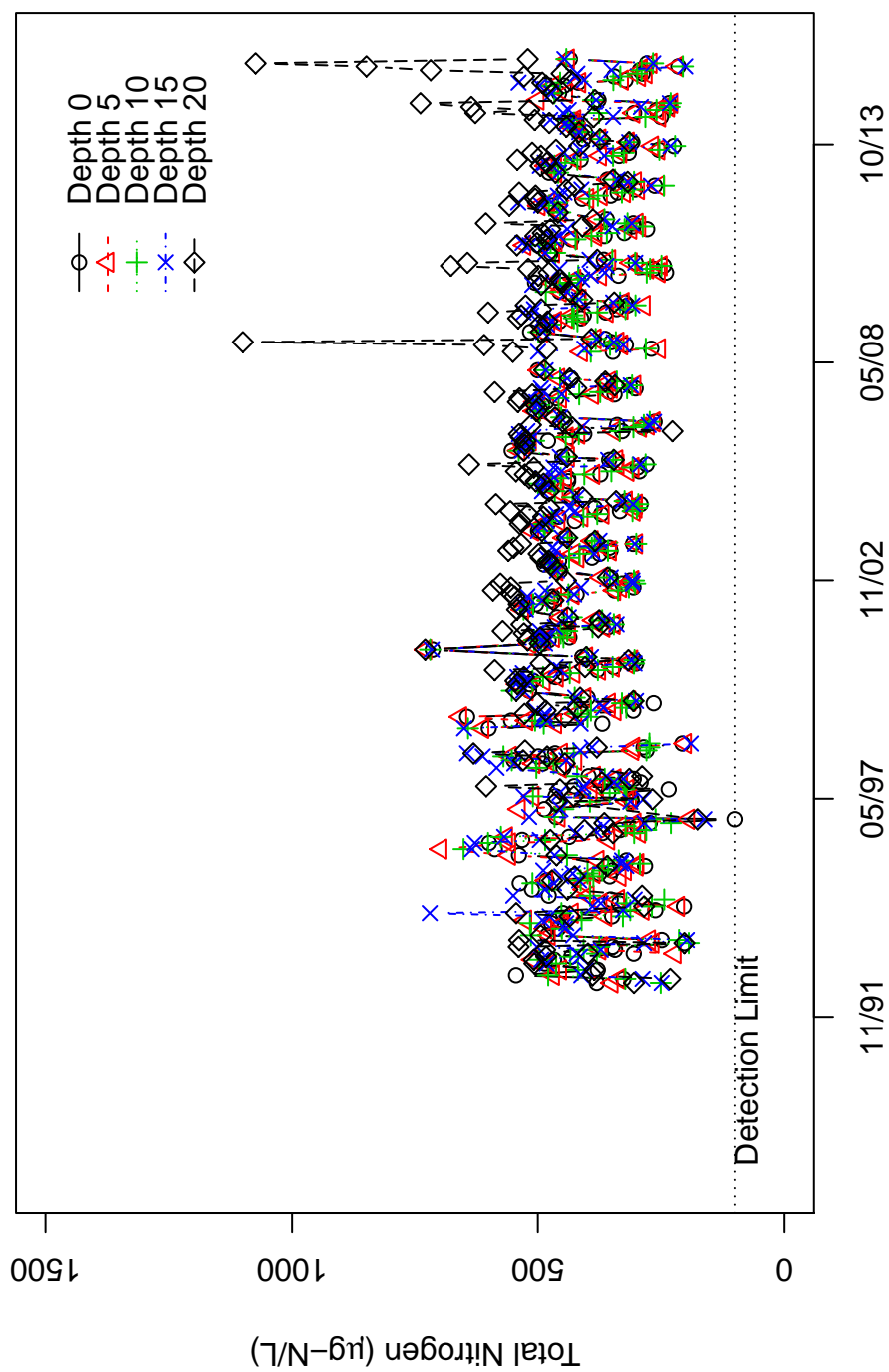


Figure B92: Lake Whatcom total nitrogen data for Site 2.

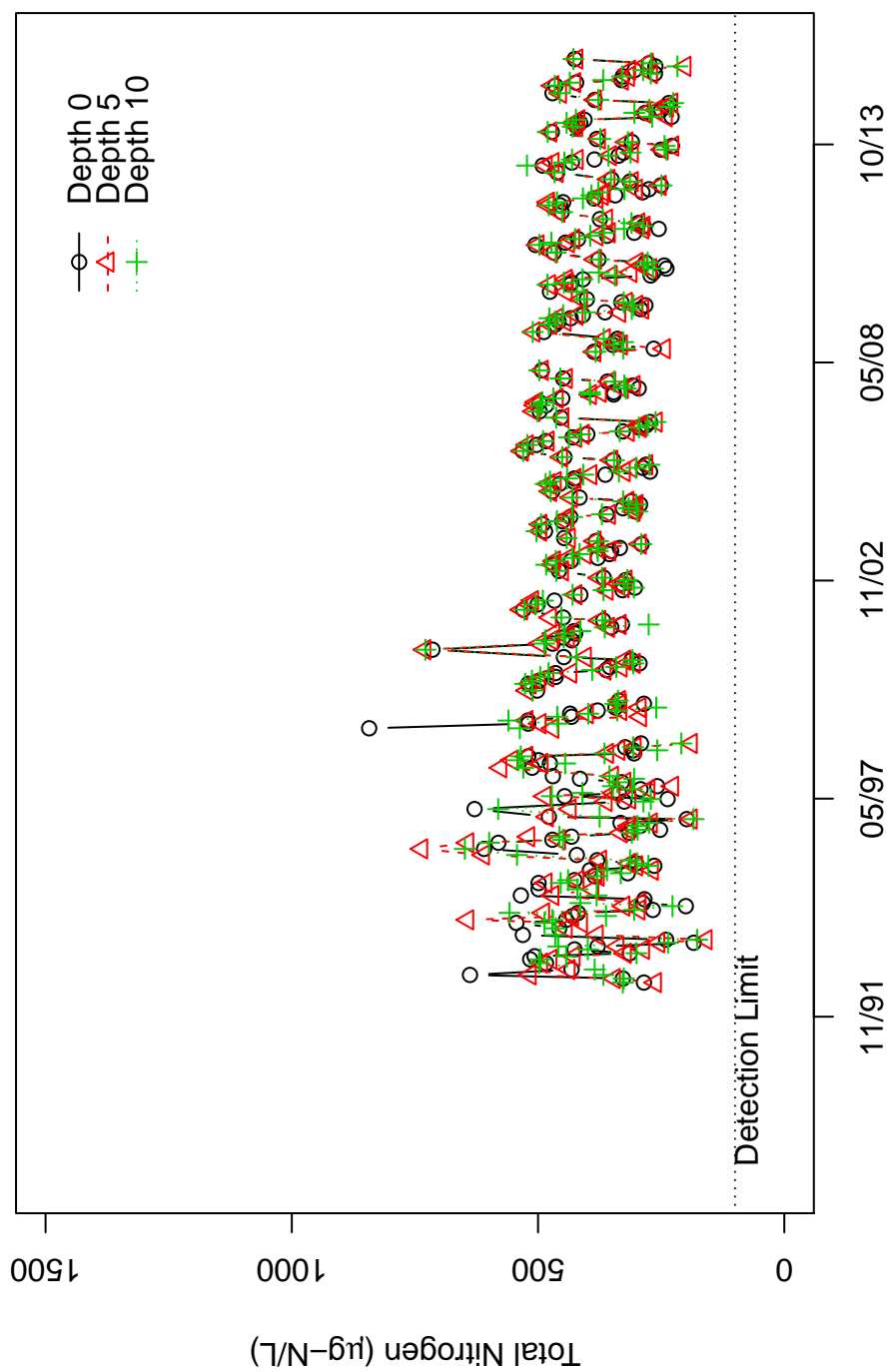


Figure B93: Lake Whatcom total nitrogen data for the Intake site.

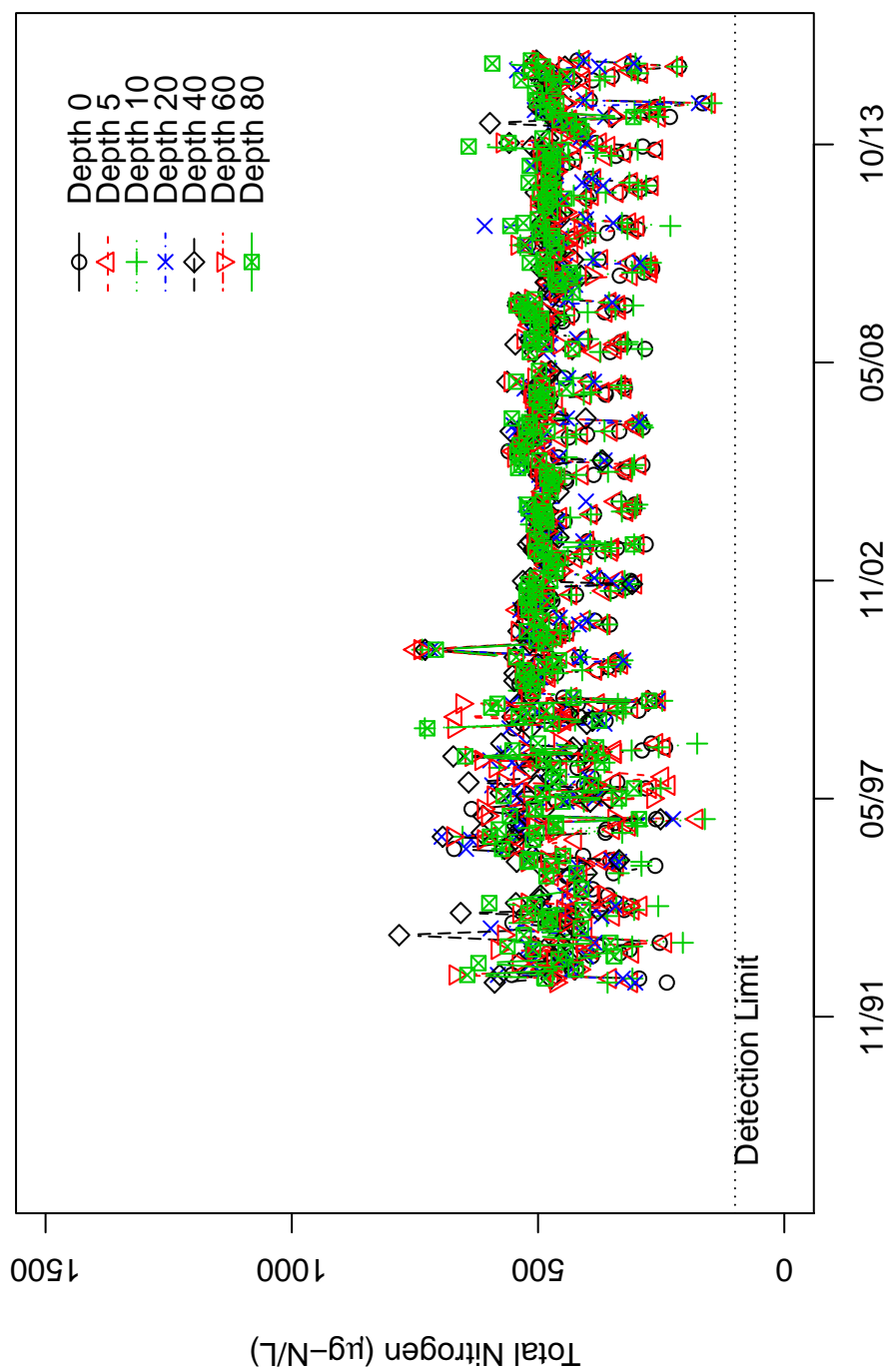


Figure B94: Lake Whatcom total nitrogen data for Site 3.

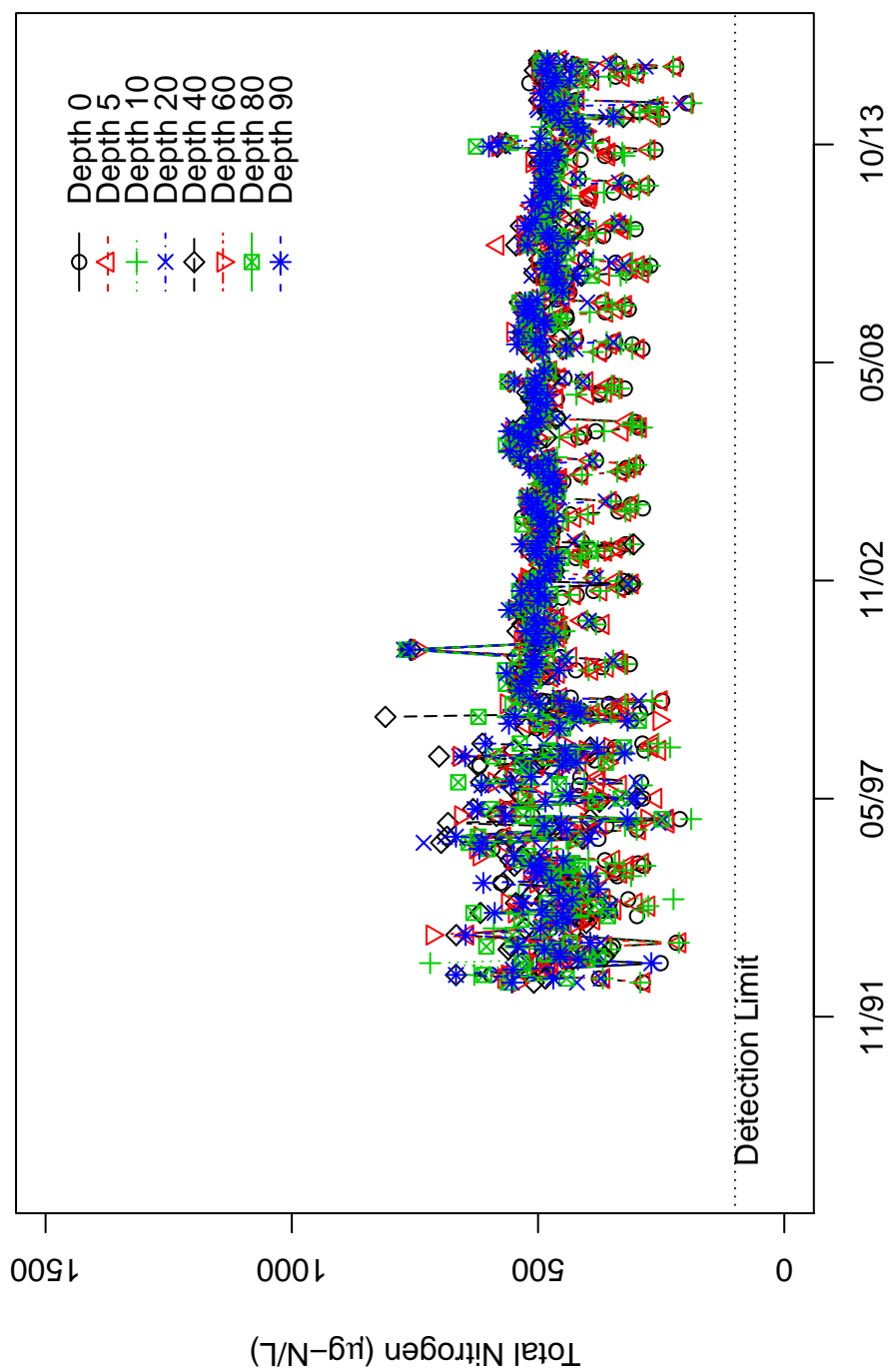


Figure B95: Lake Whatcom total nitrogen data for Site 4.

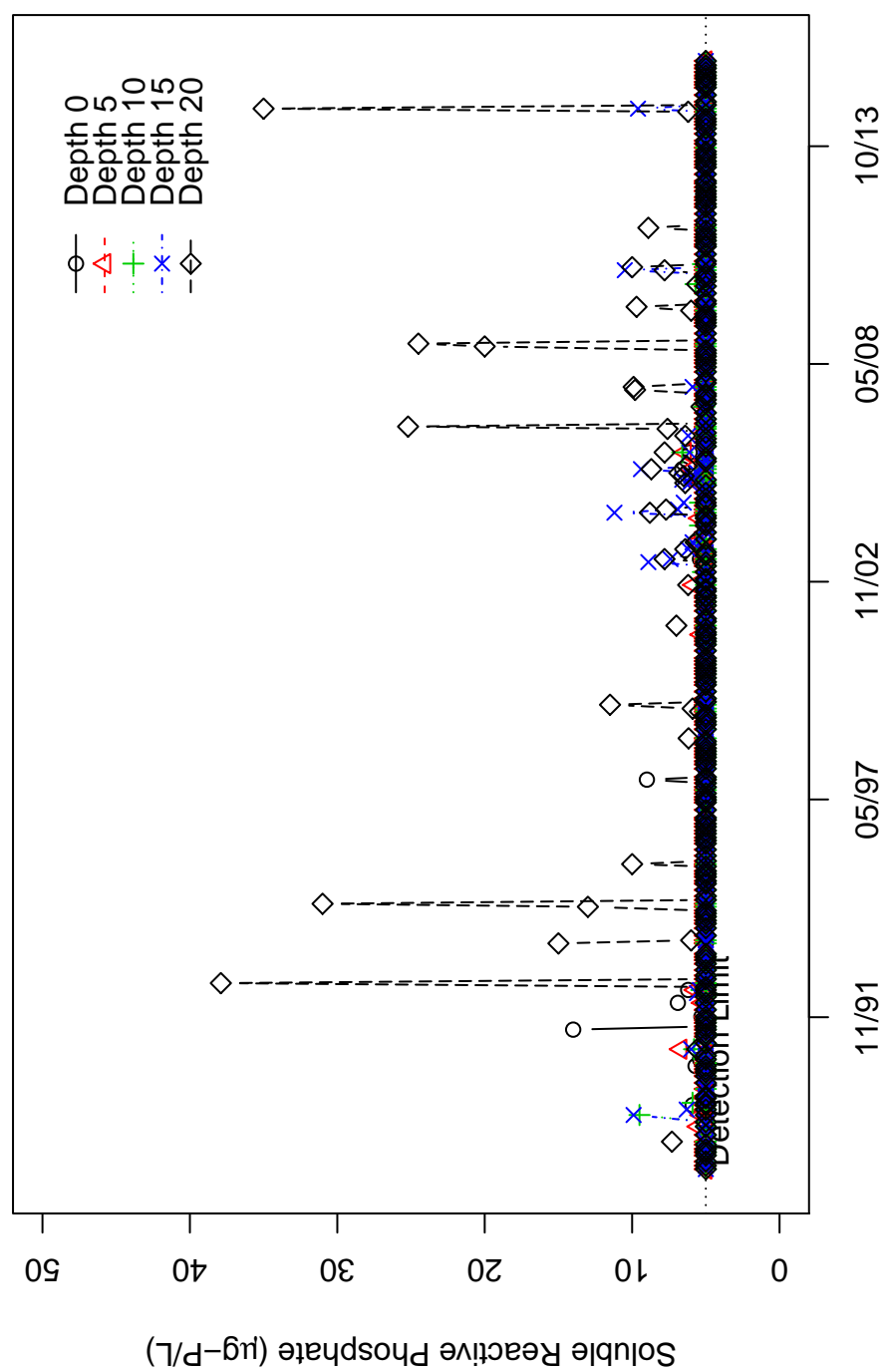


Figure B96: Lake Whatcom soluble phosphate data for Site 1.

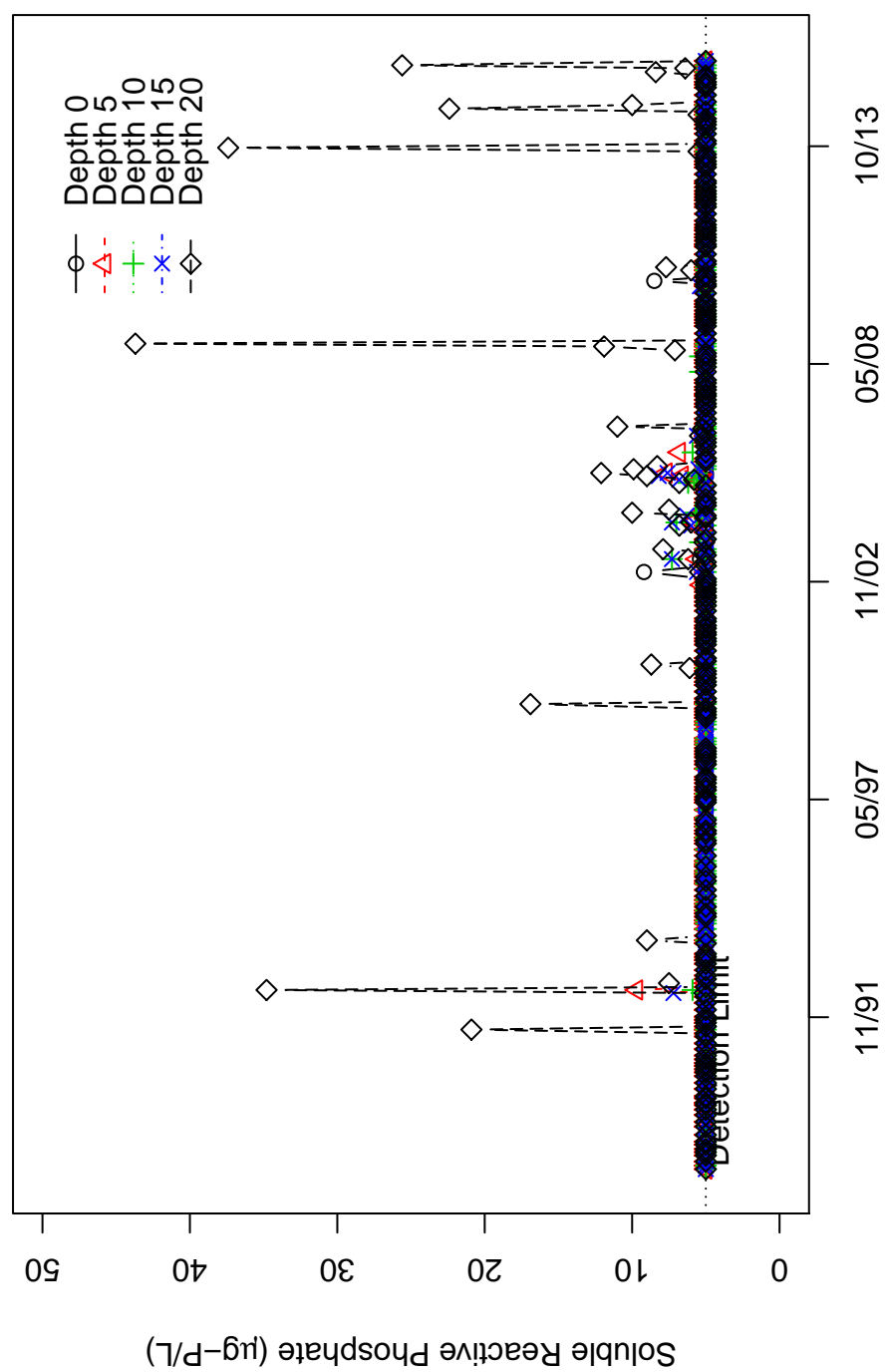


Figure B97: Lake Whatcom soluble phosphate data for Site 2.

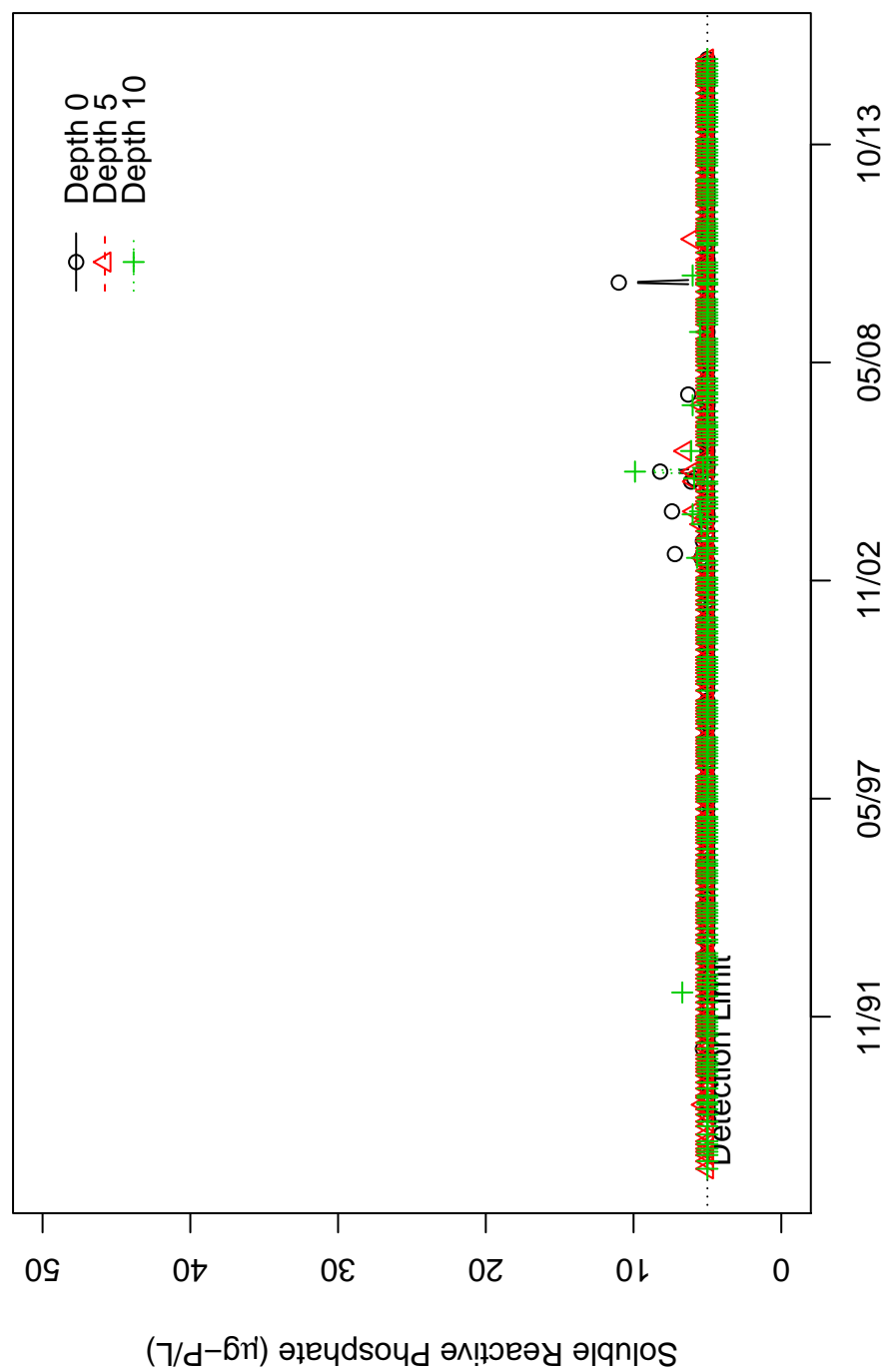


Figure B98: Lake Whatcom soluble phosphate data for the Intake site.

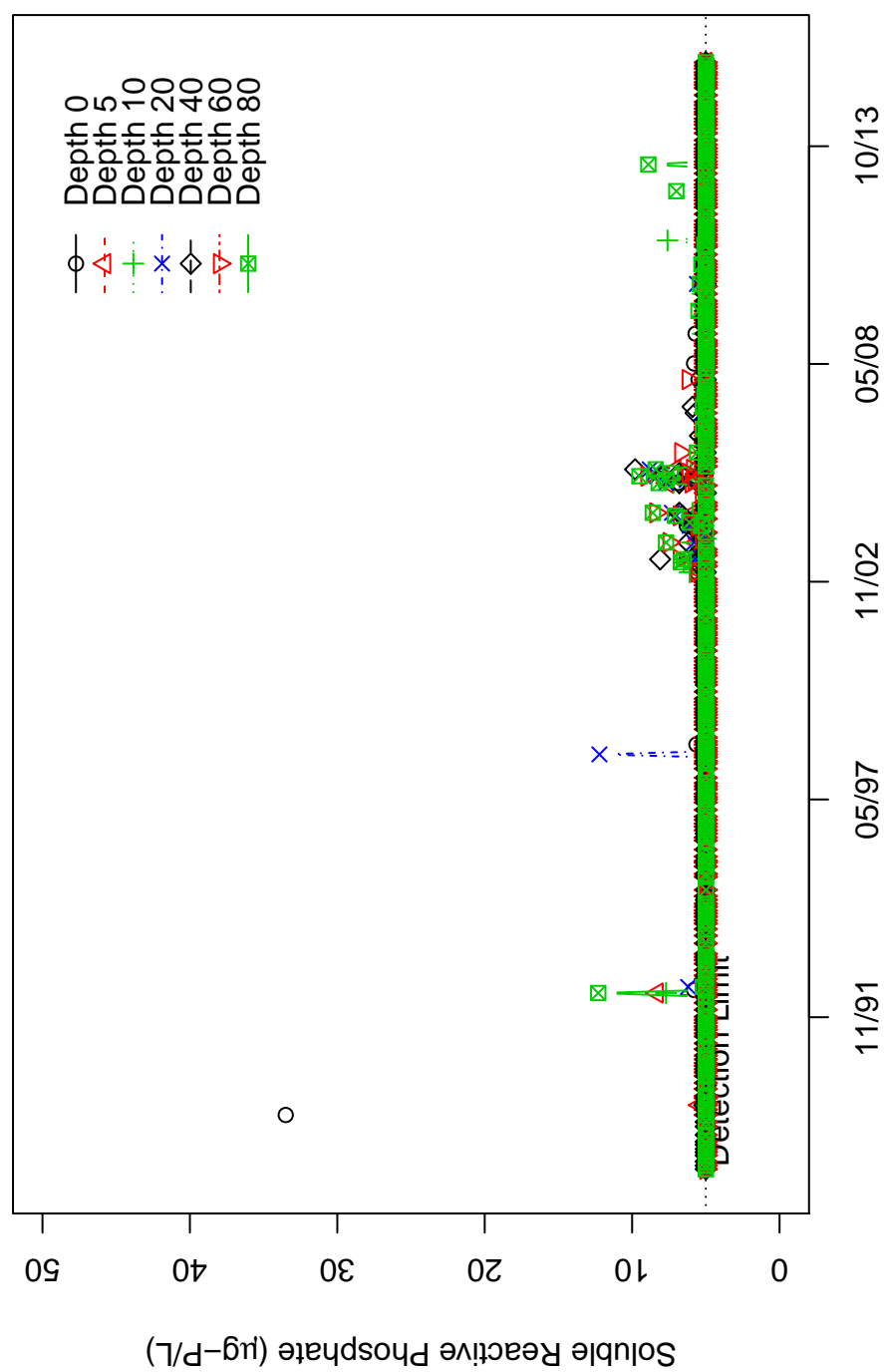


Figure B99: Lake Whatcom soluble phosphate data for Site 3.

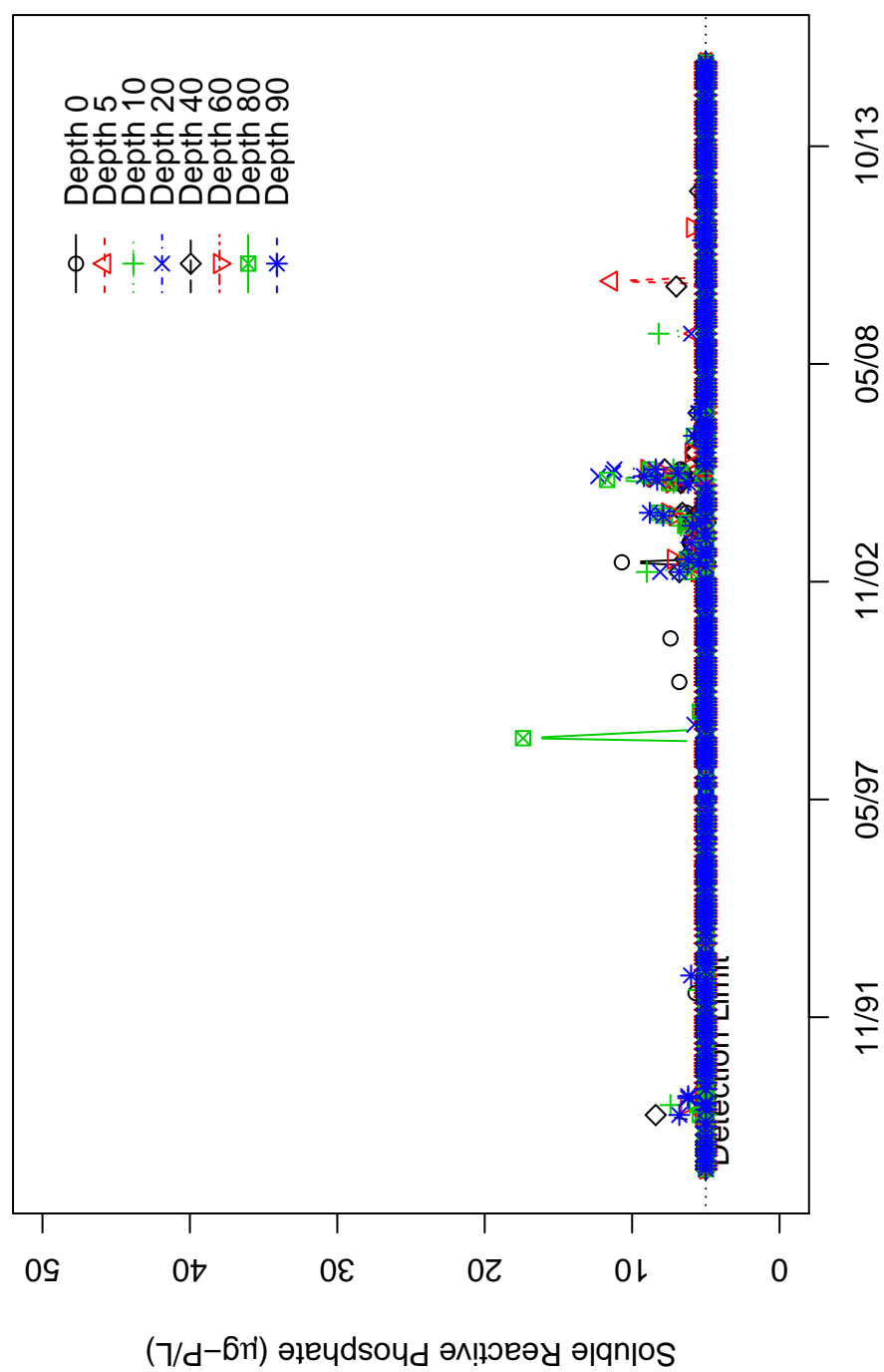


Figure B100: Lake Whatcom soluble phosphate data for Site 4.

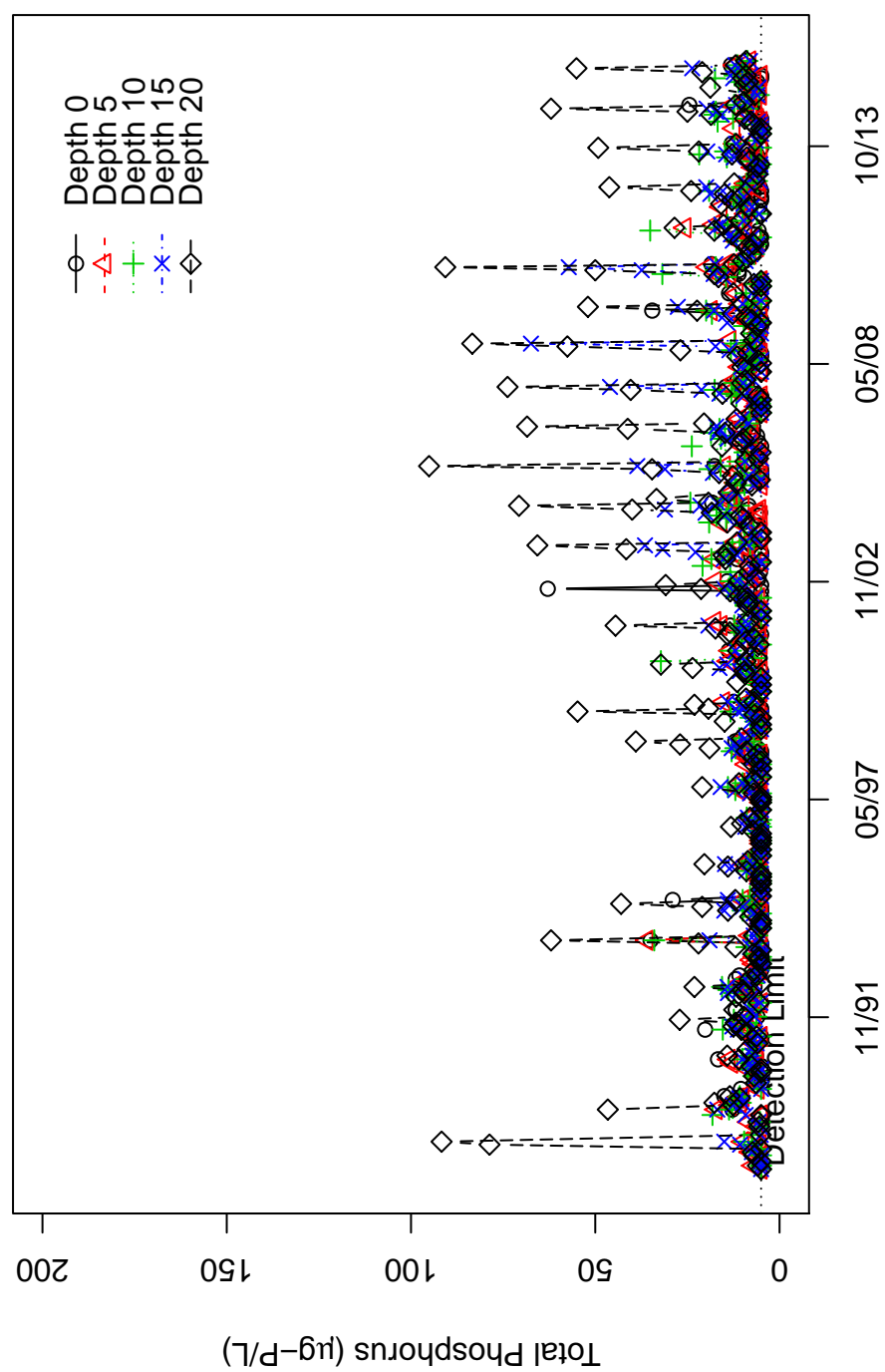


Figure B101: Lake Whatcom total phosphorus data for Site 1.

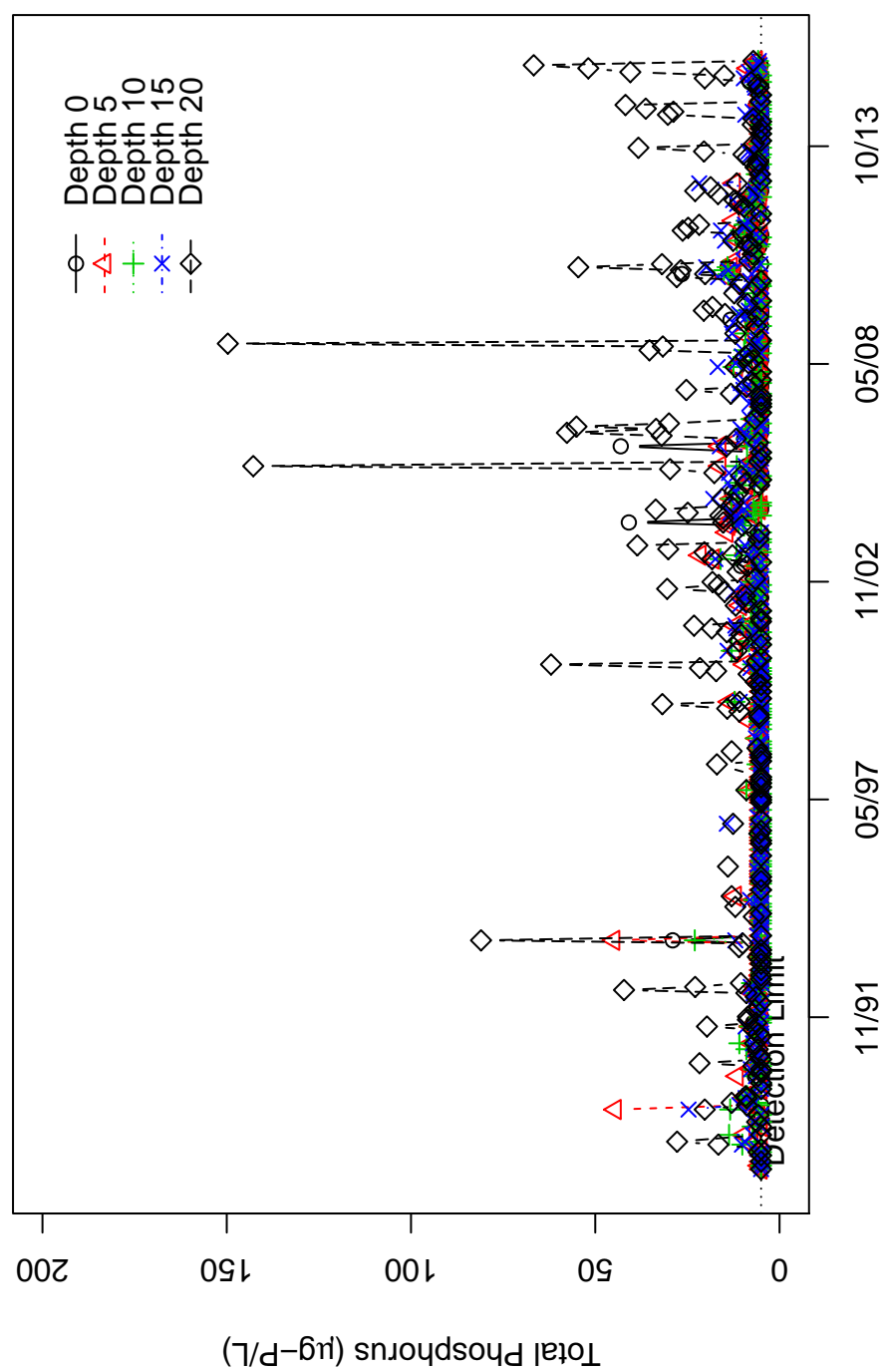


Figure B102: Lake Whatcom total phosphorus data for Site 2.

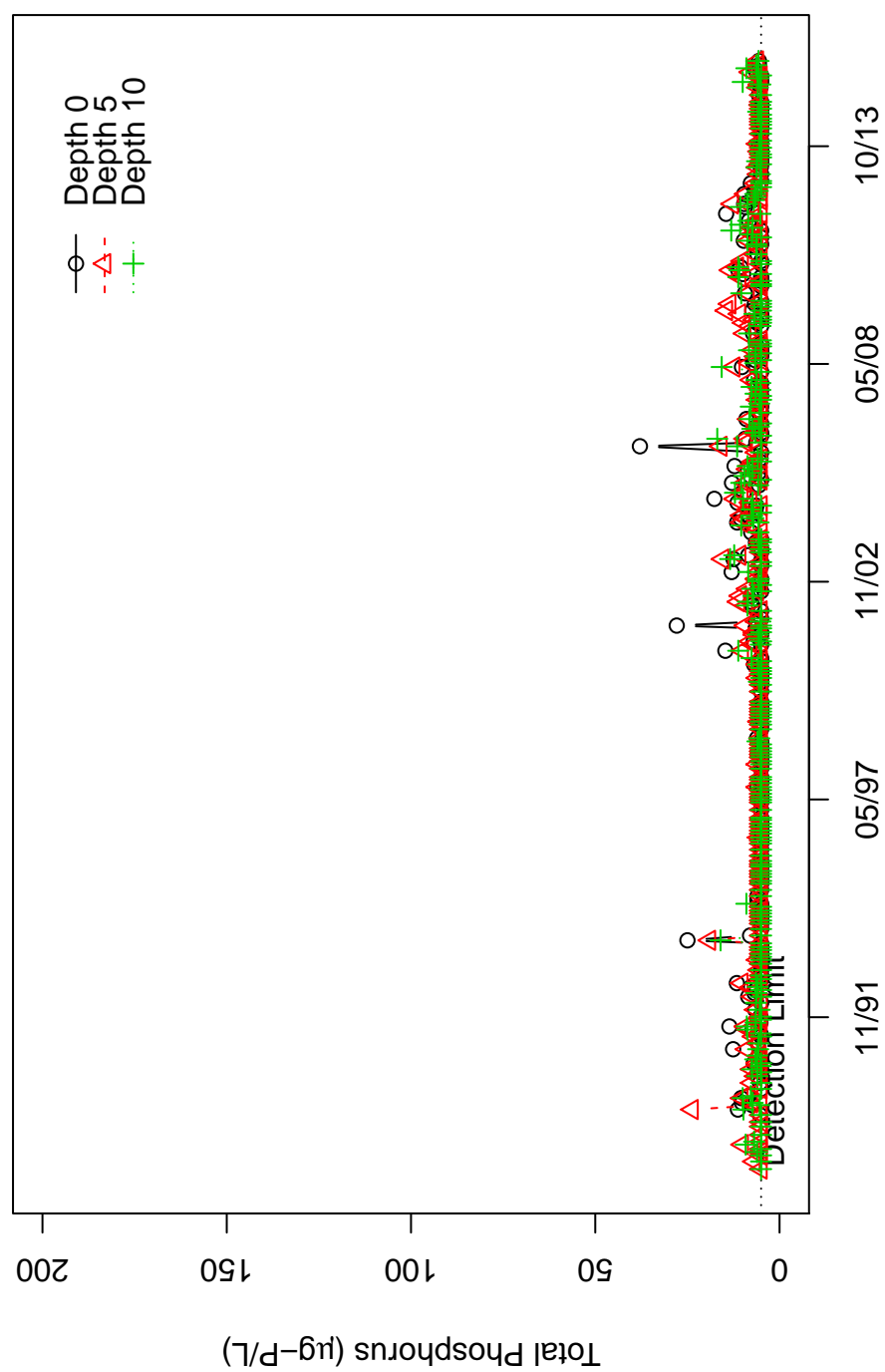


Figure B103: Lake Whatcom total phosphorus data for the Intake site.

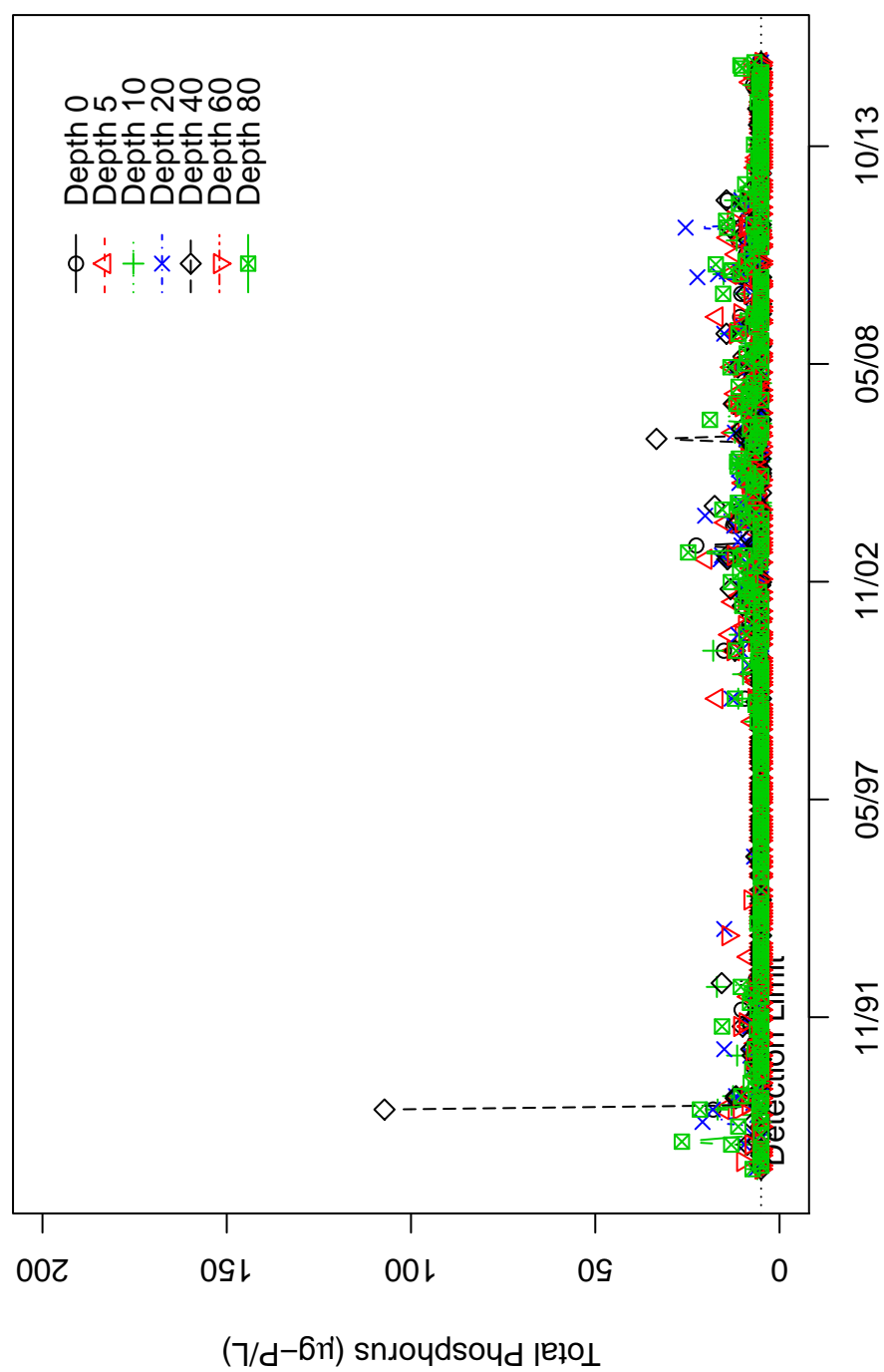


Figure B104: Lake Whatcom total phosphorus data for Site 3.

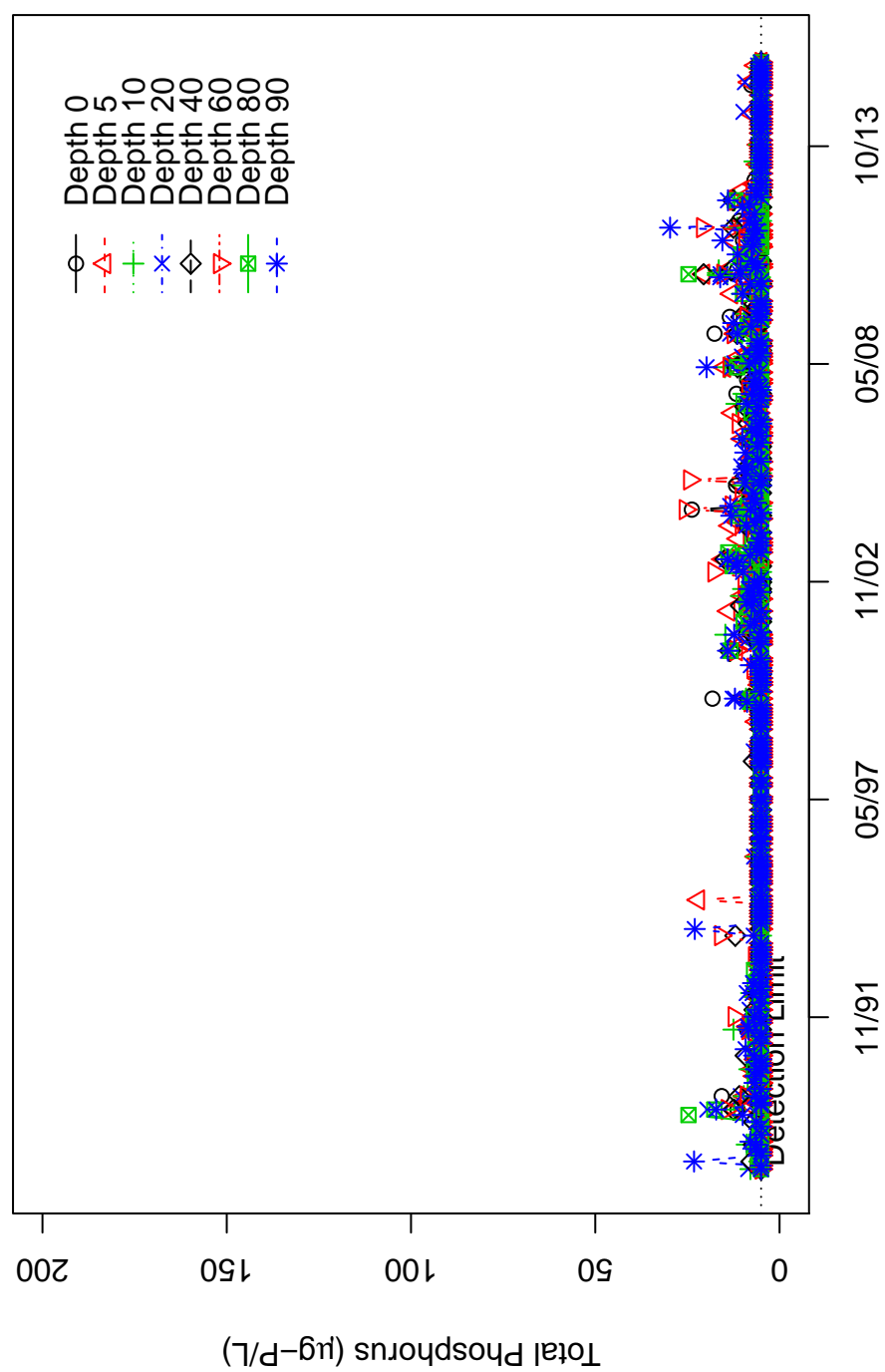


Figure B105: Lake Whatcom total phosphorus data for Site 4.

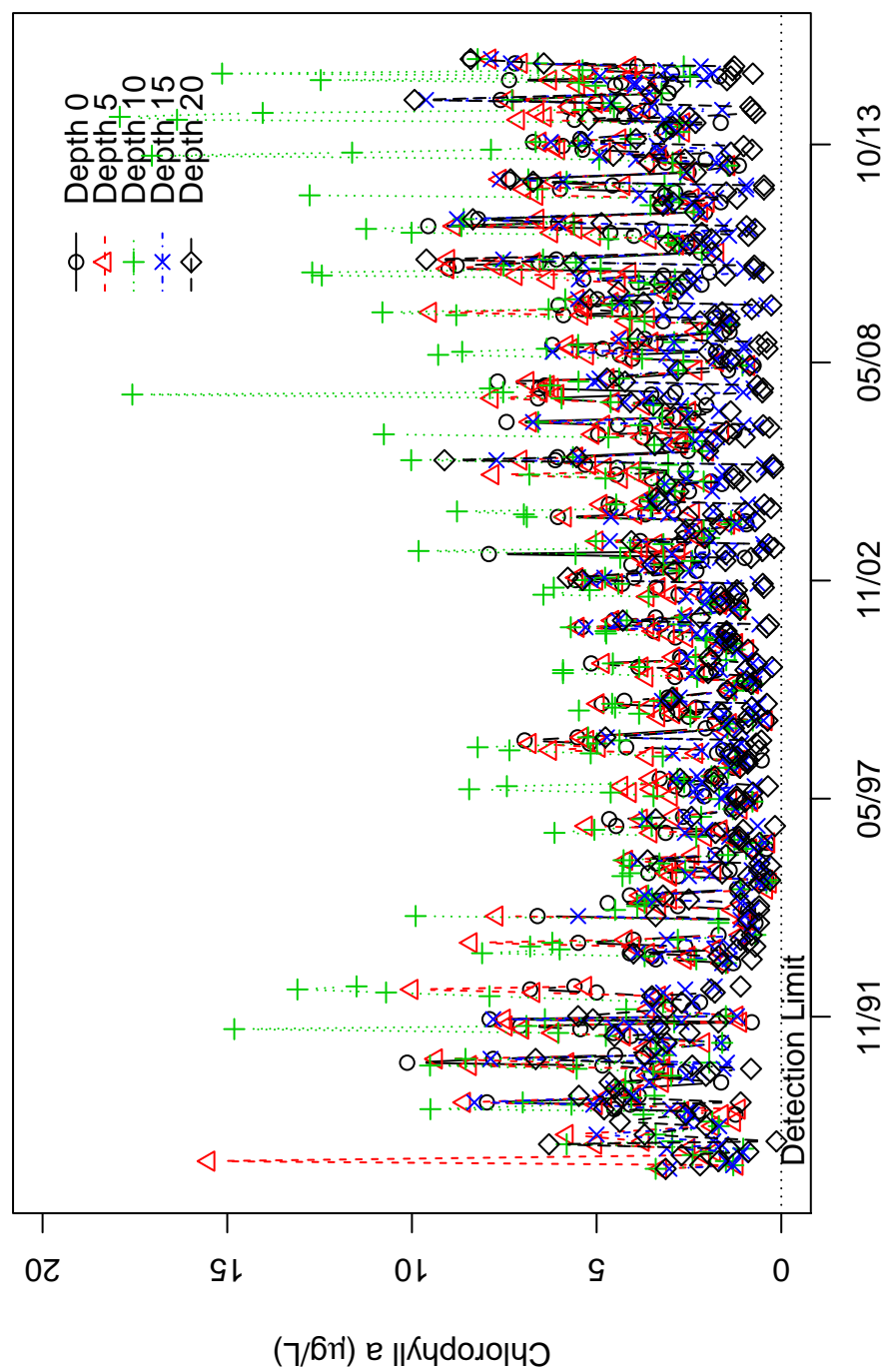


Figure B106: Lake Whatcom chlorophyll data for Site 1.

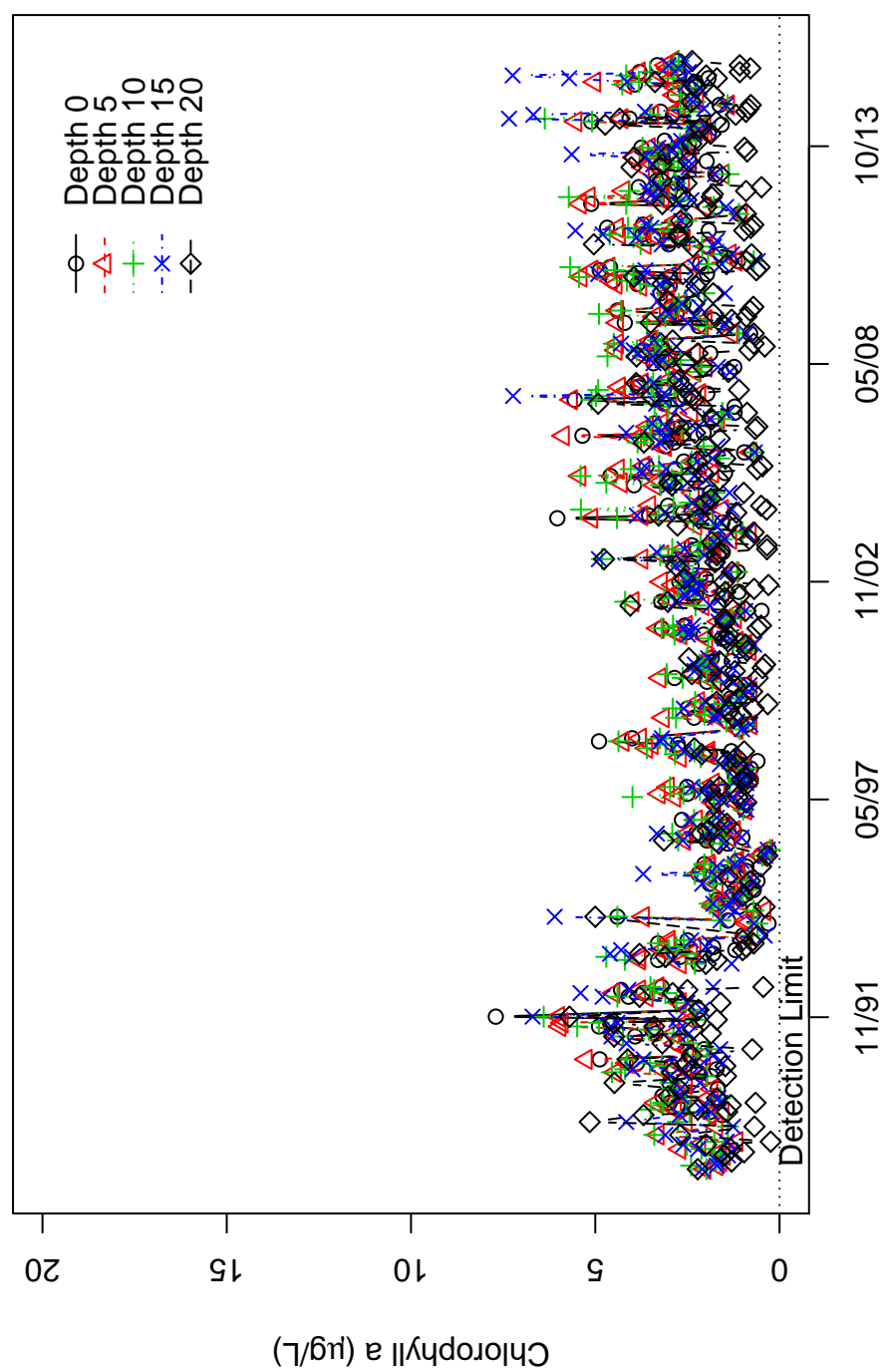


Figure B107: Lake Whatcom chlorophyll data for Site 2.

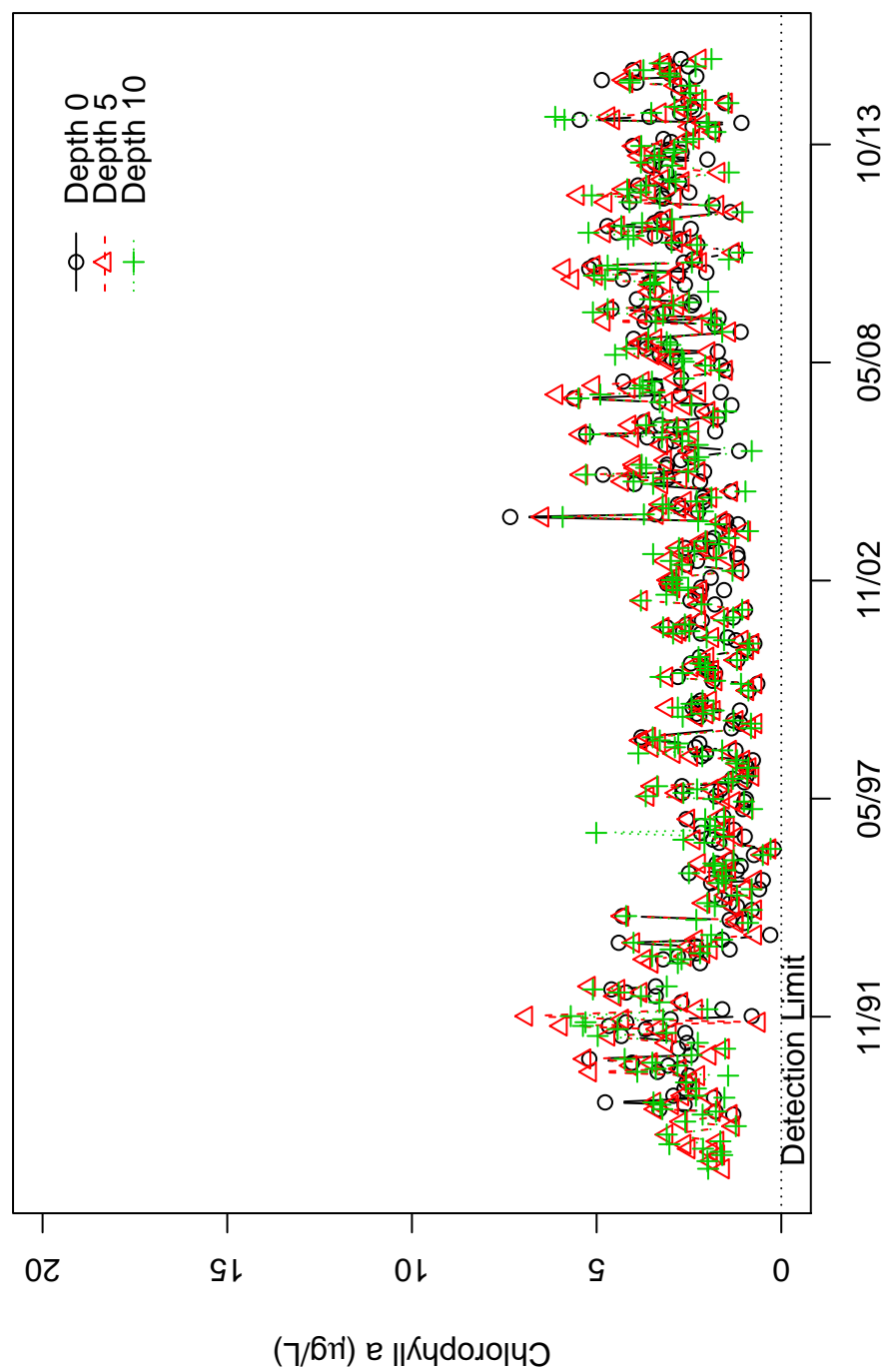


Figure B108: Lake Whatcom chlorophyll data for the Intake site.

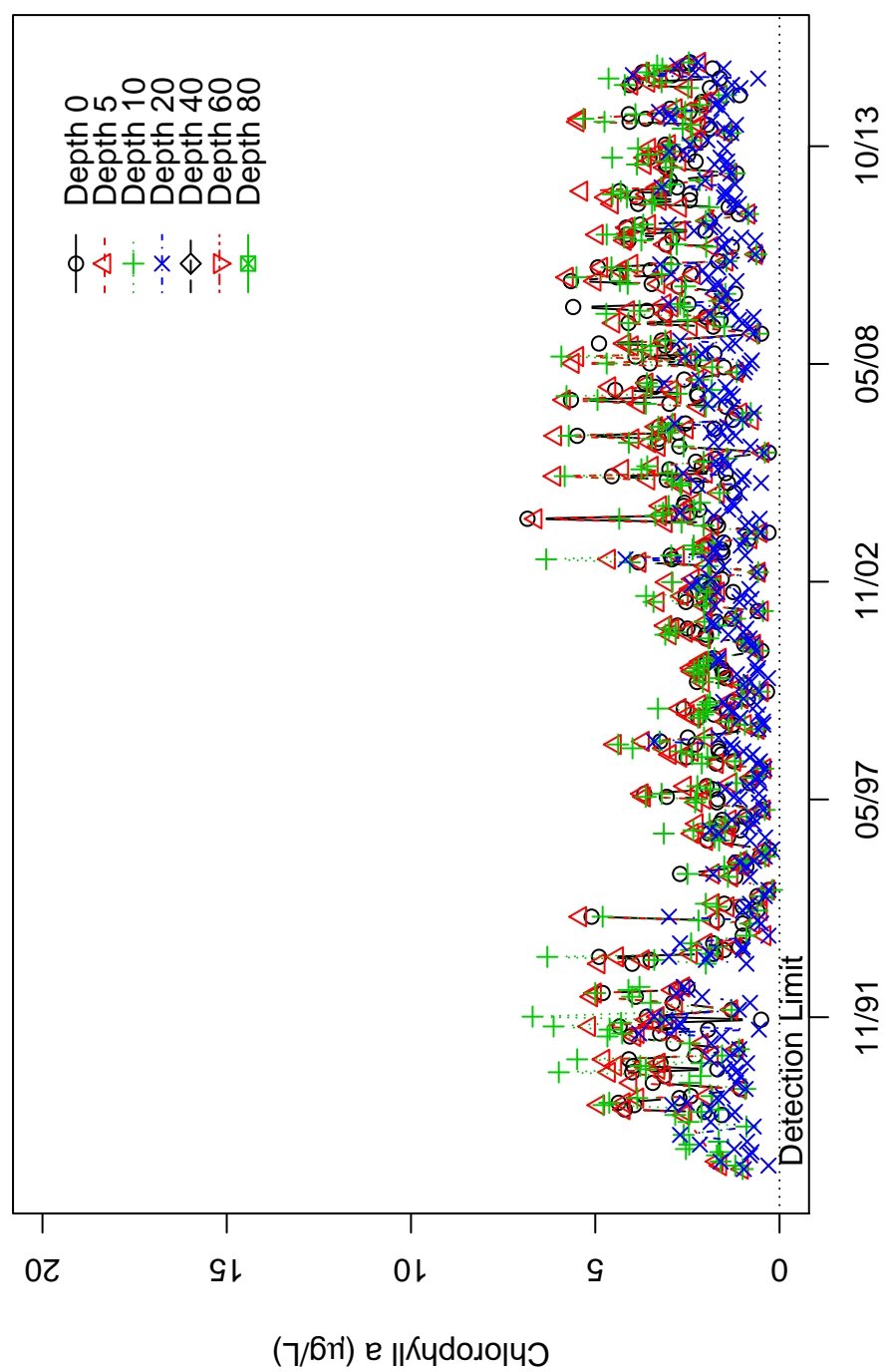


Figure B109: Lake Whatcom chlorophyll data for Site 3.

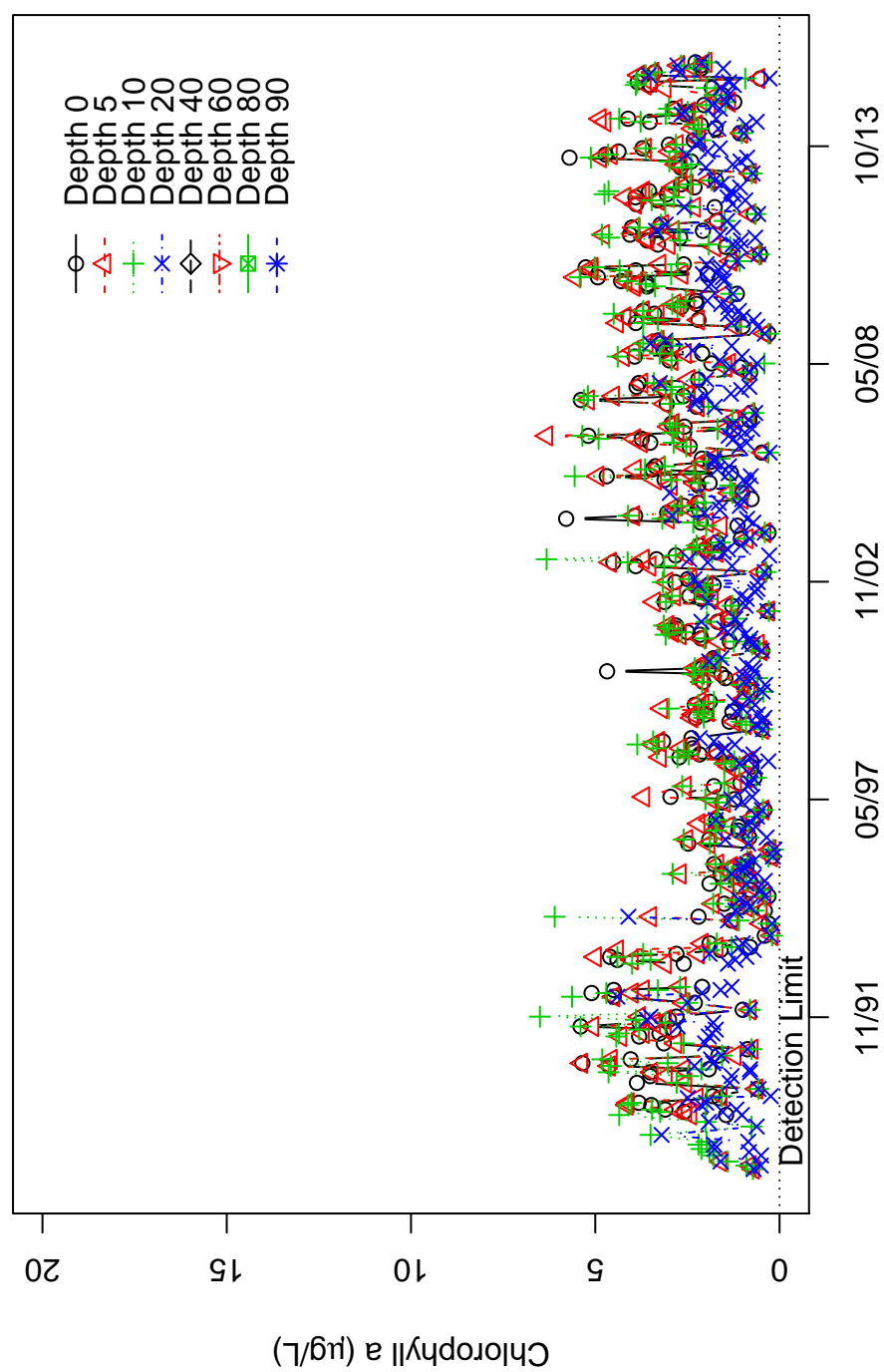


Figure B110: Lake Whatcom chlorophyll data for Site 4.

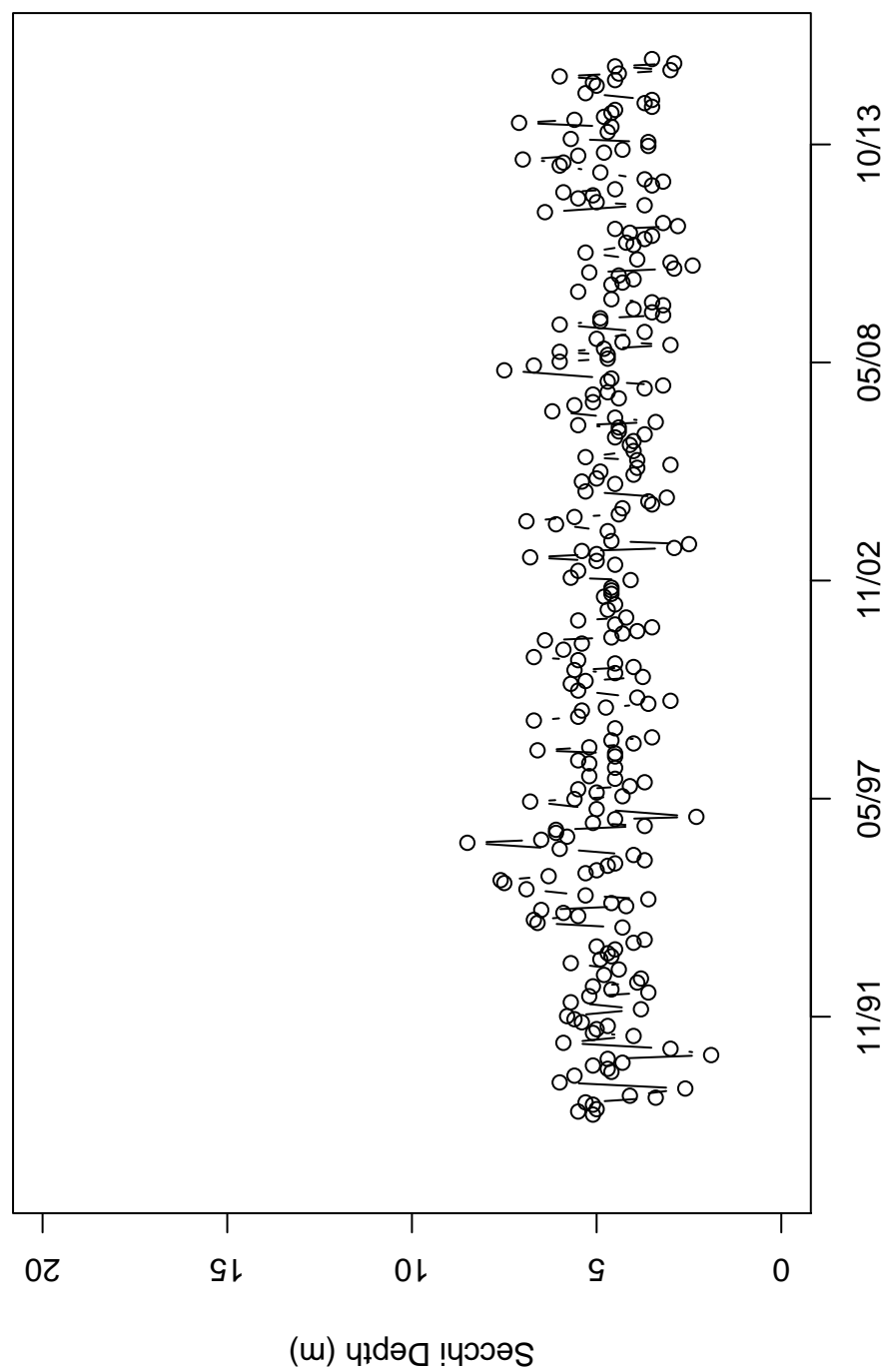


Figure B111: Lake Whatcom Secchi depths for Site 1.

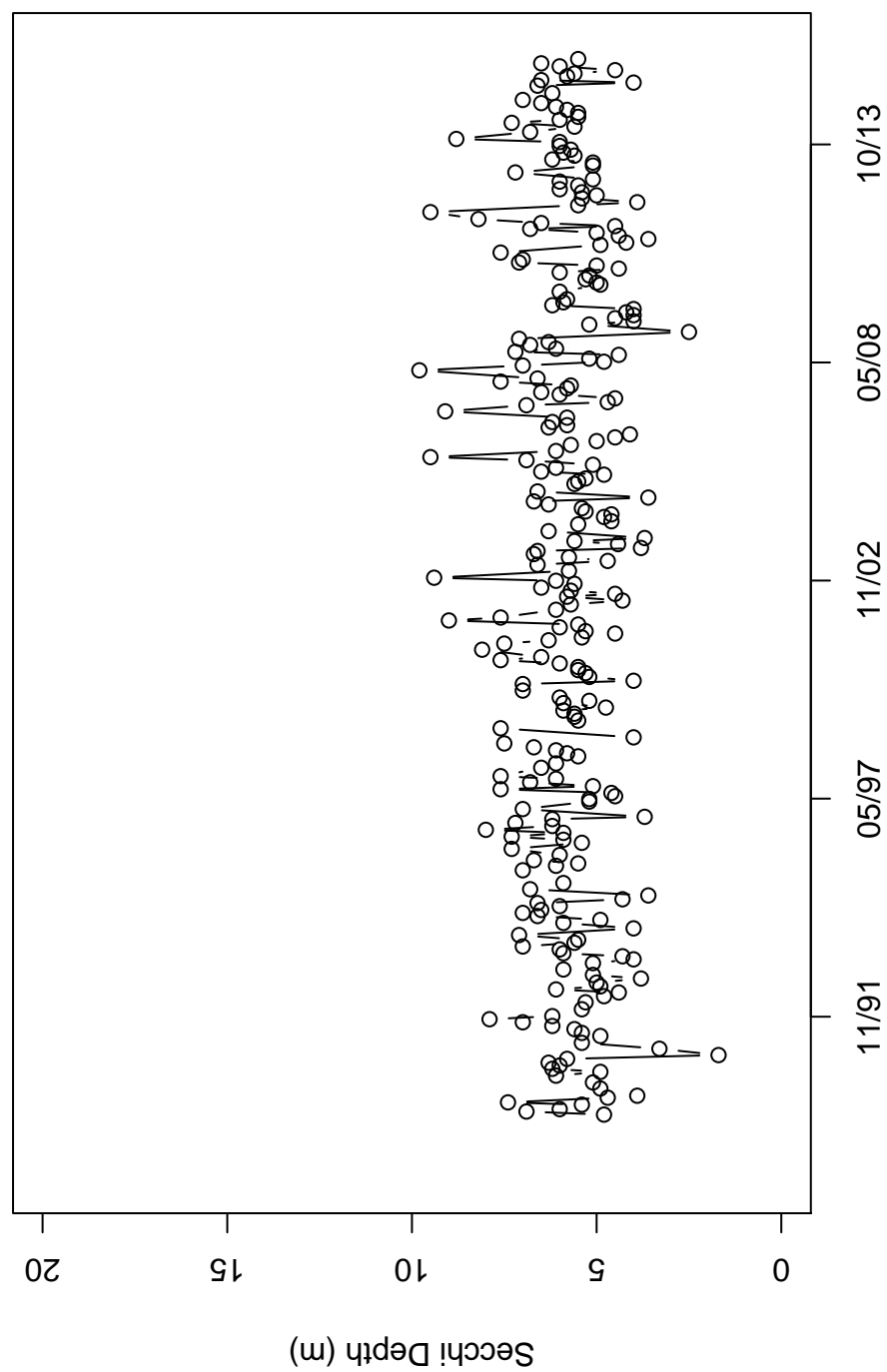


Figure B112: Lake Whatcom Secchi depths for Site 2.

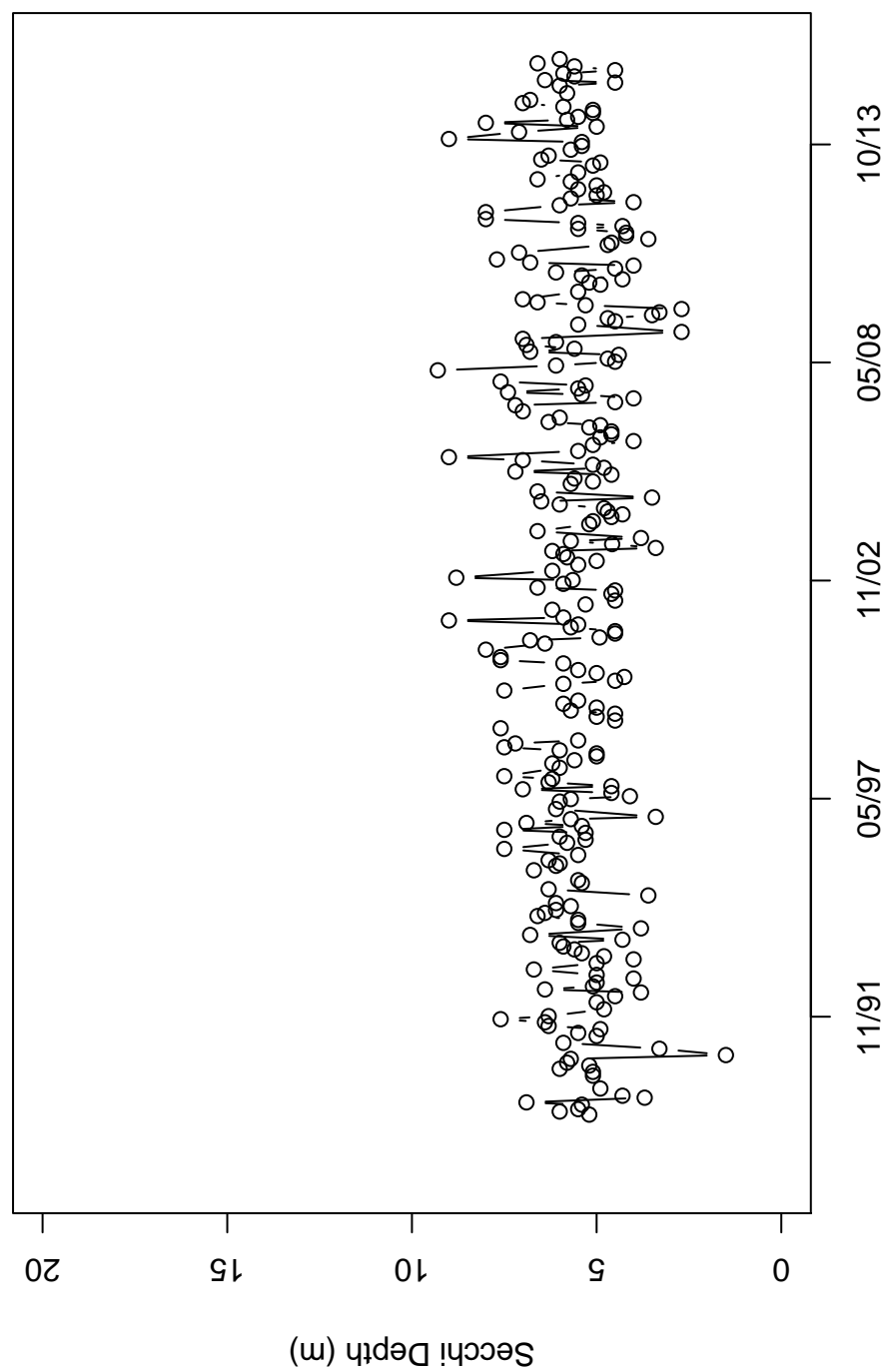


Figure B113: Lake Whatcom Secchi depths for the Intake site.

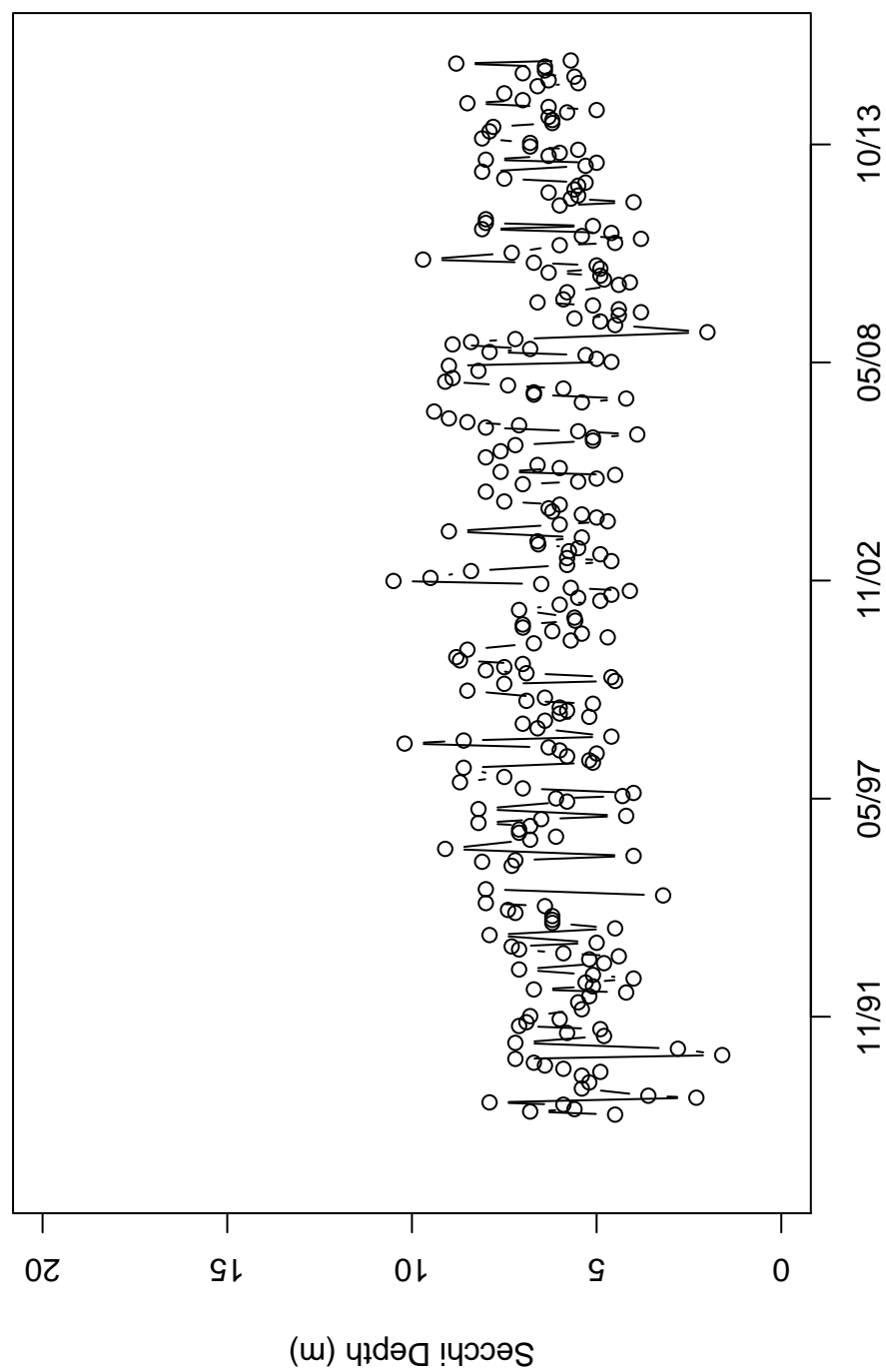


Figure B114: Lake Whatcom Secchi depths for Site 3.

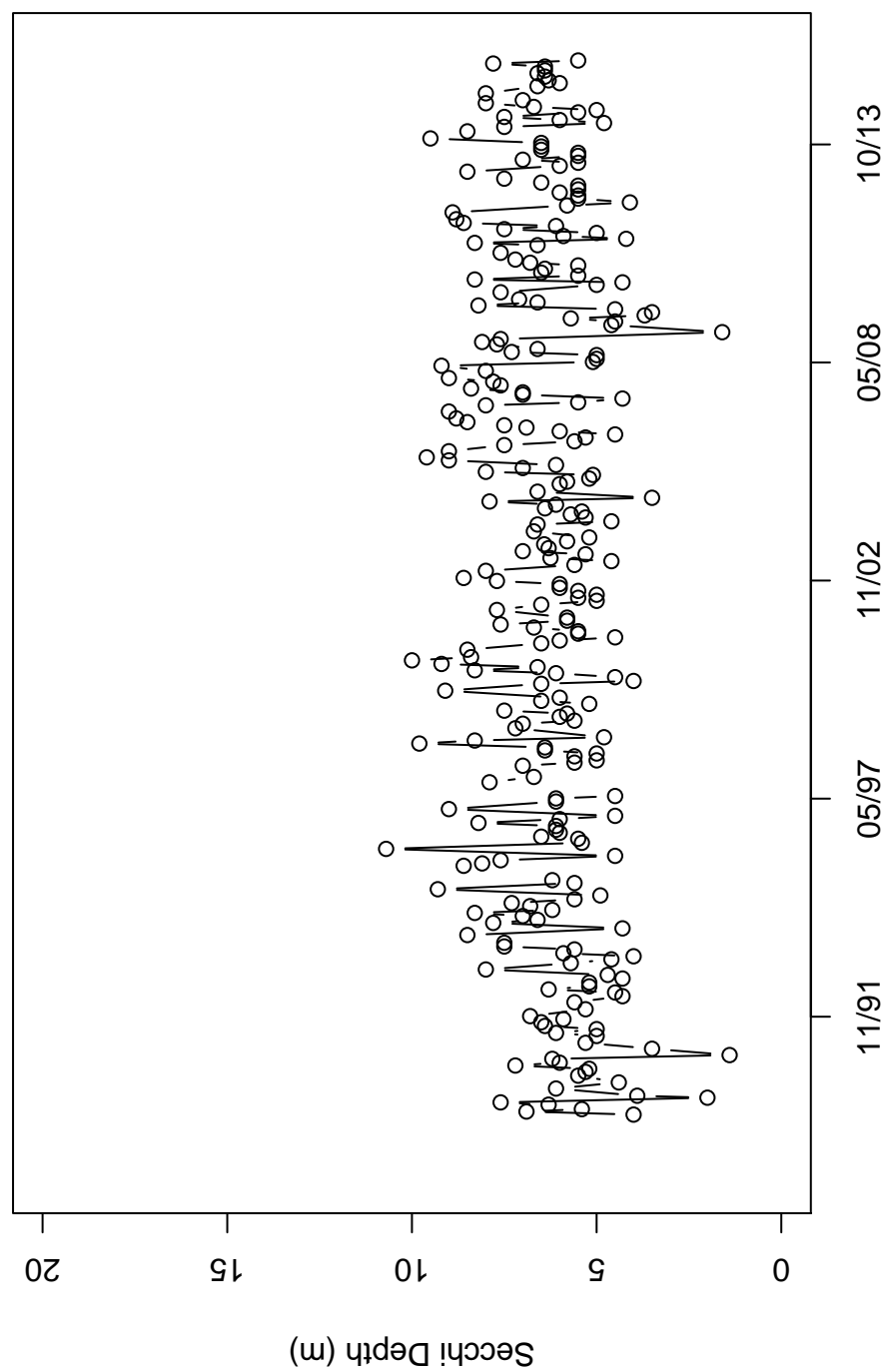


Figure B115: Lake Whatcom Secchi depths for Site 4.

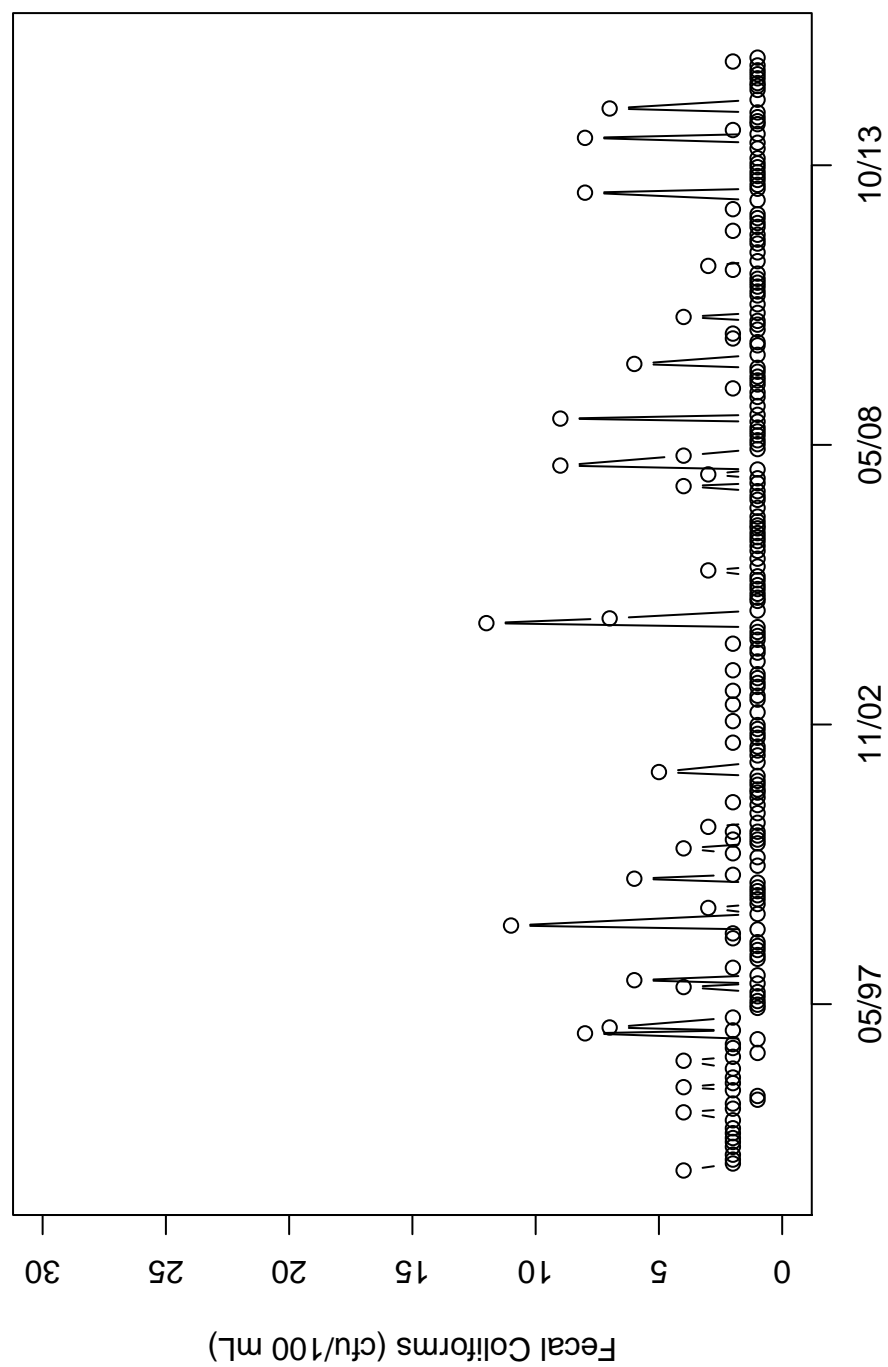


Figure B116: Lake Whatcom fecal coliform data for Site 1.

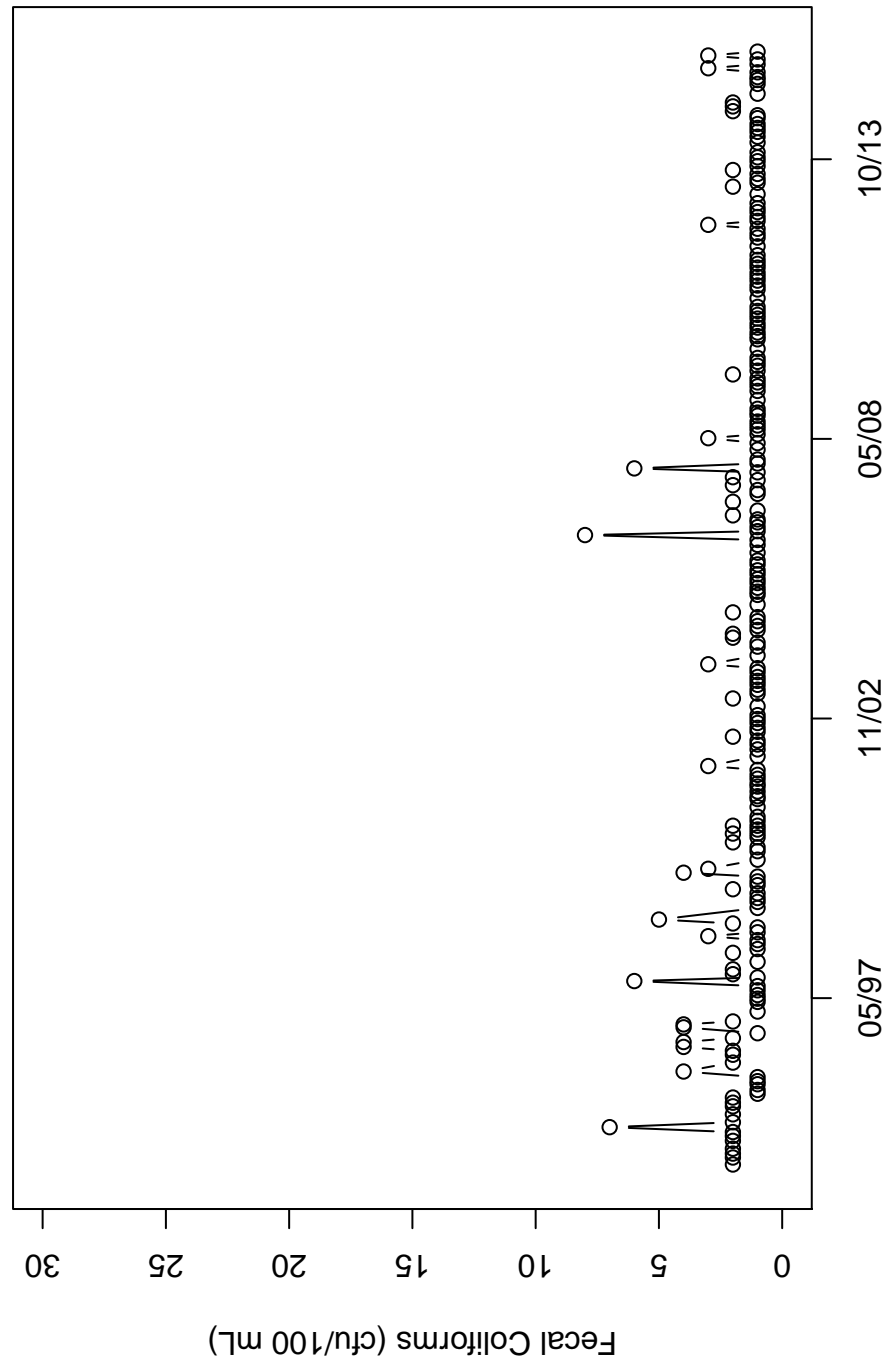


Figure B117: Lake Whatcom fecal coliform data for Site 2.

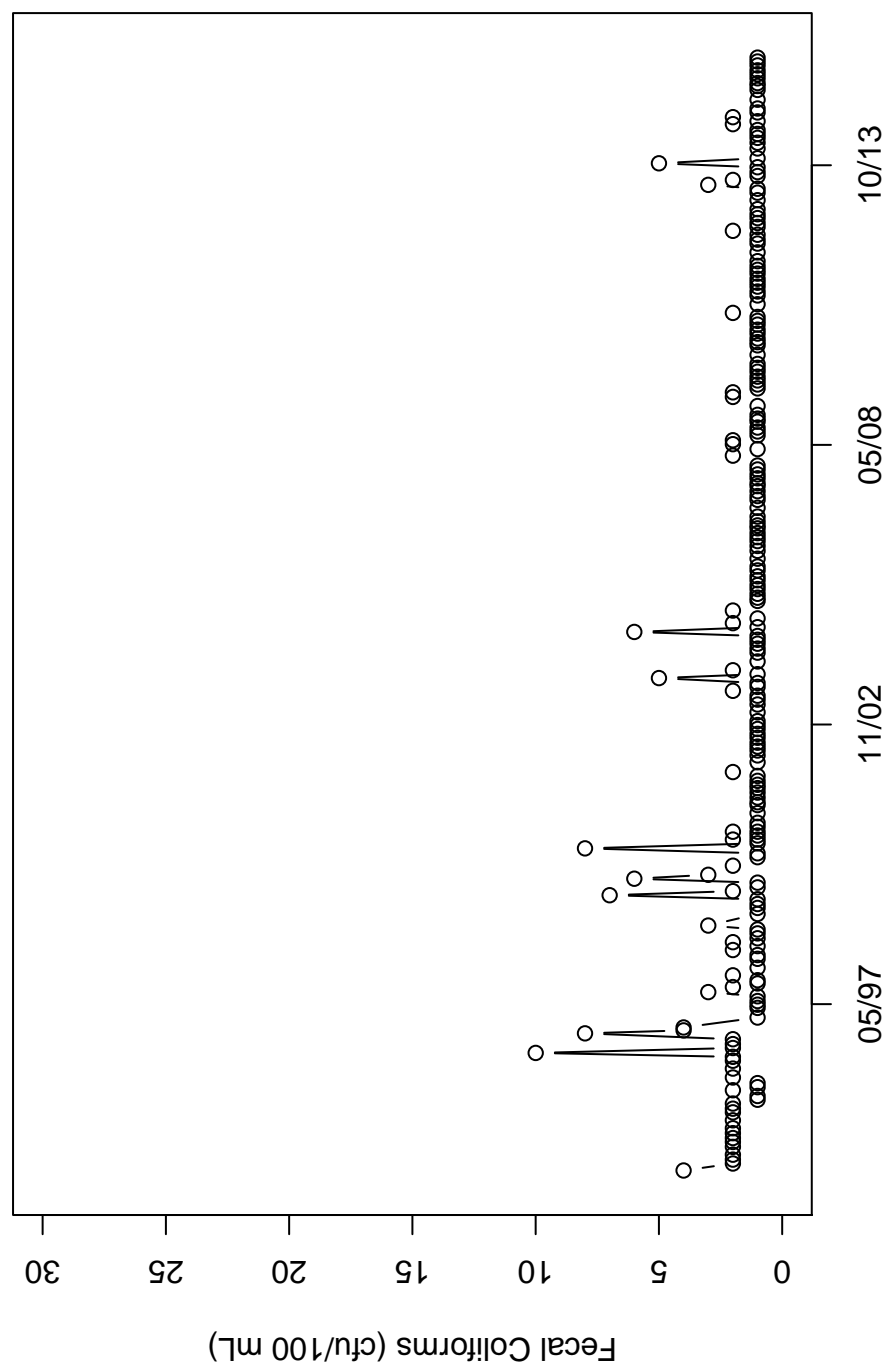


Figure B118: Lake Whatcom fecal coliform data for the Intake site.

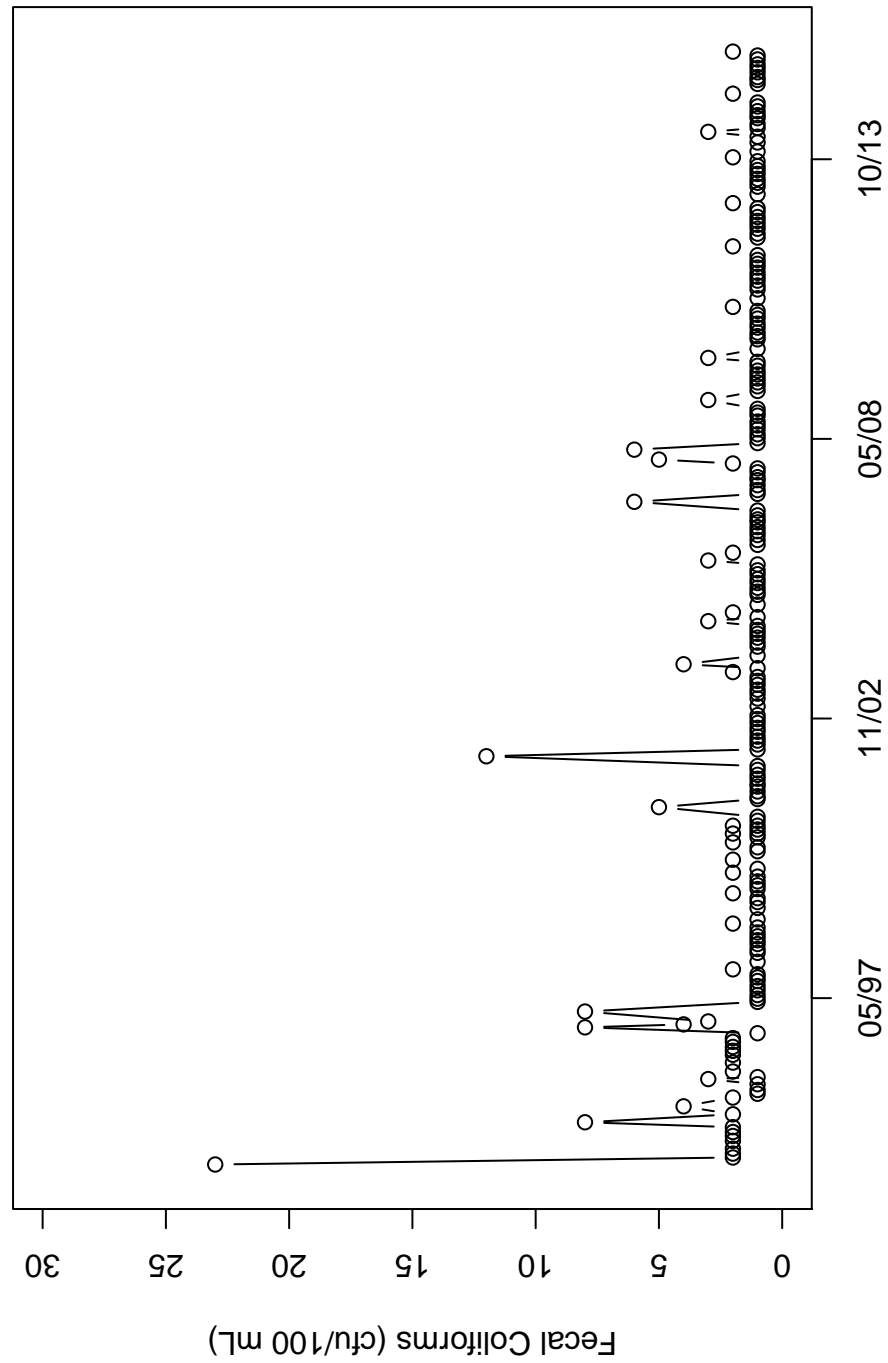


Figure B119: Lake Whatcom fecal coliform data for Site 3.

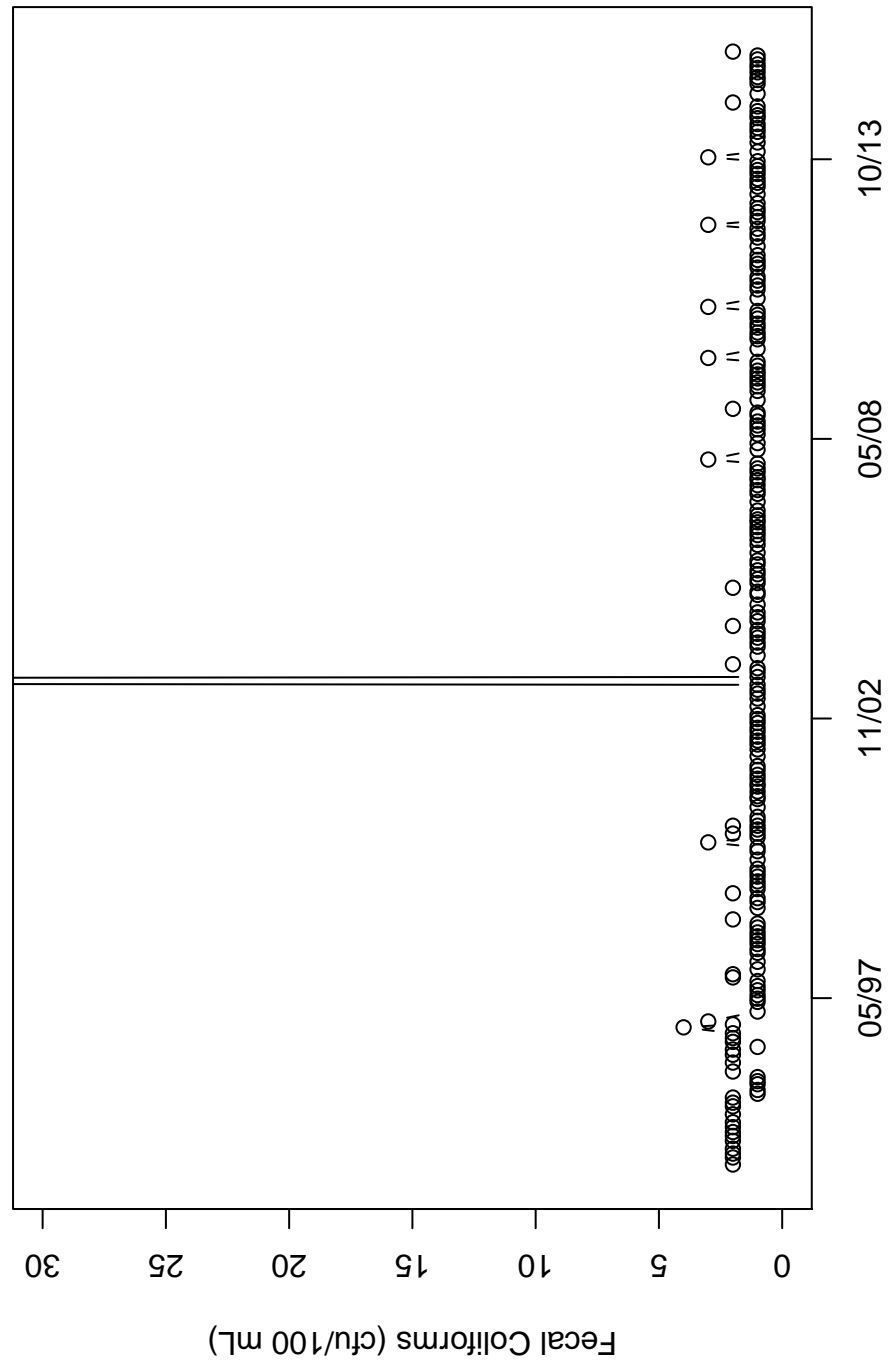


Figure B120: Lake Whatcom fecal coliform data for Site 4.

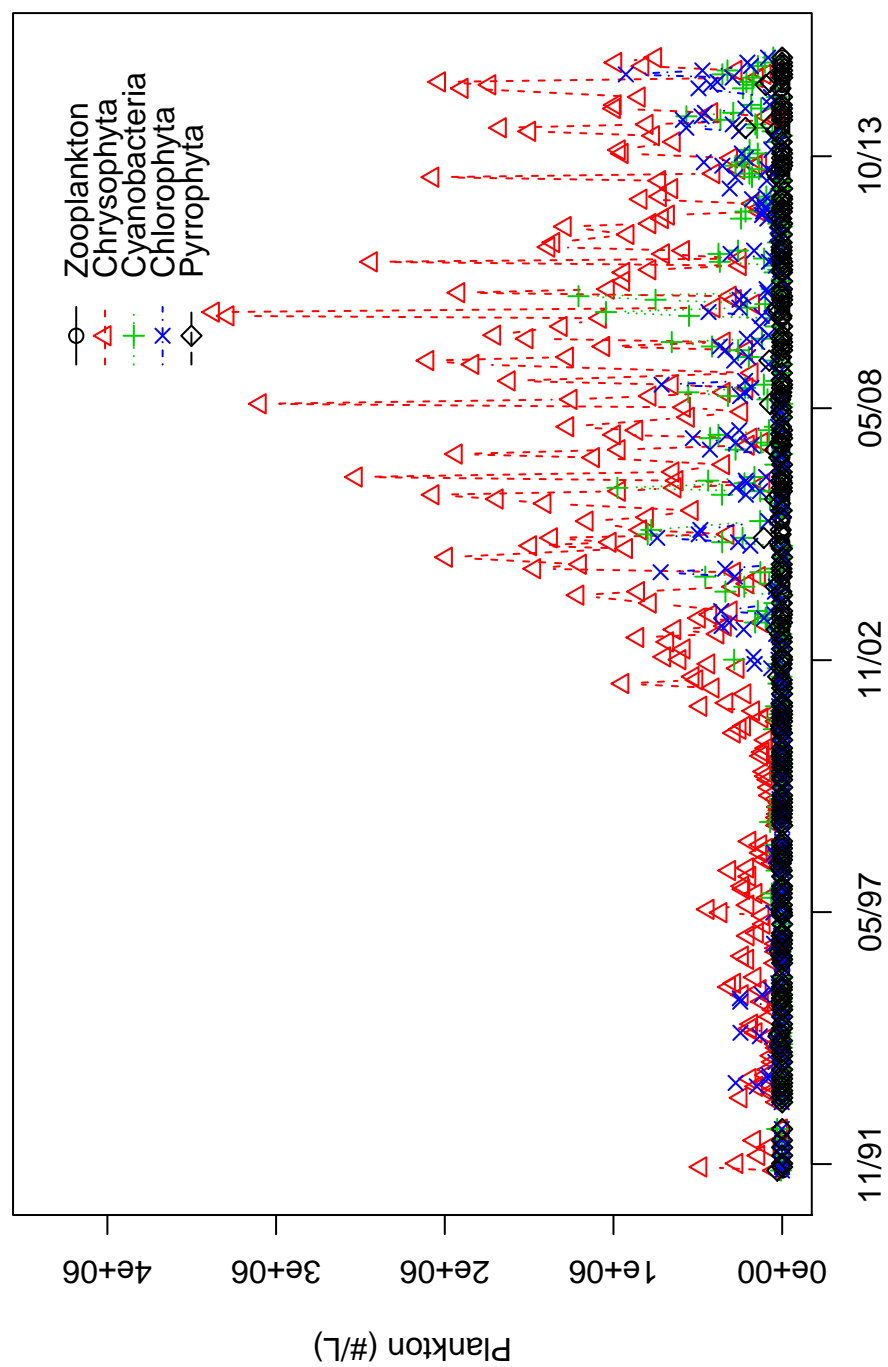


Figure B121: Lake Whatcom plankton data for Site 1.

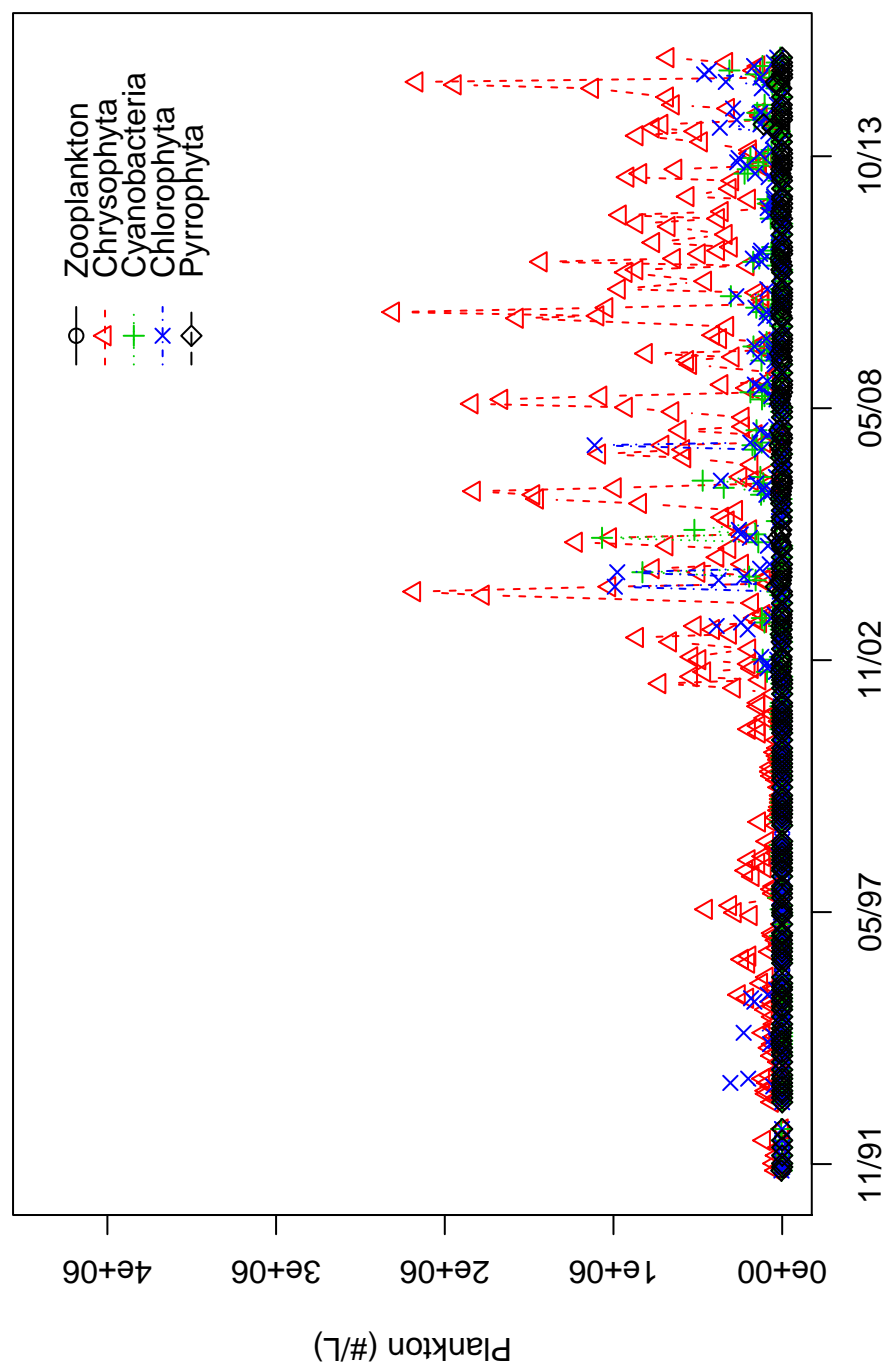


Figure B122: Lake Whatcom plankton data for Site 2.

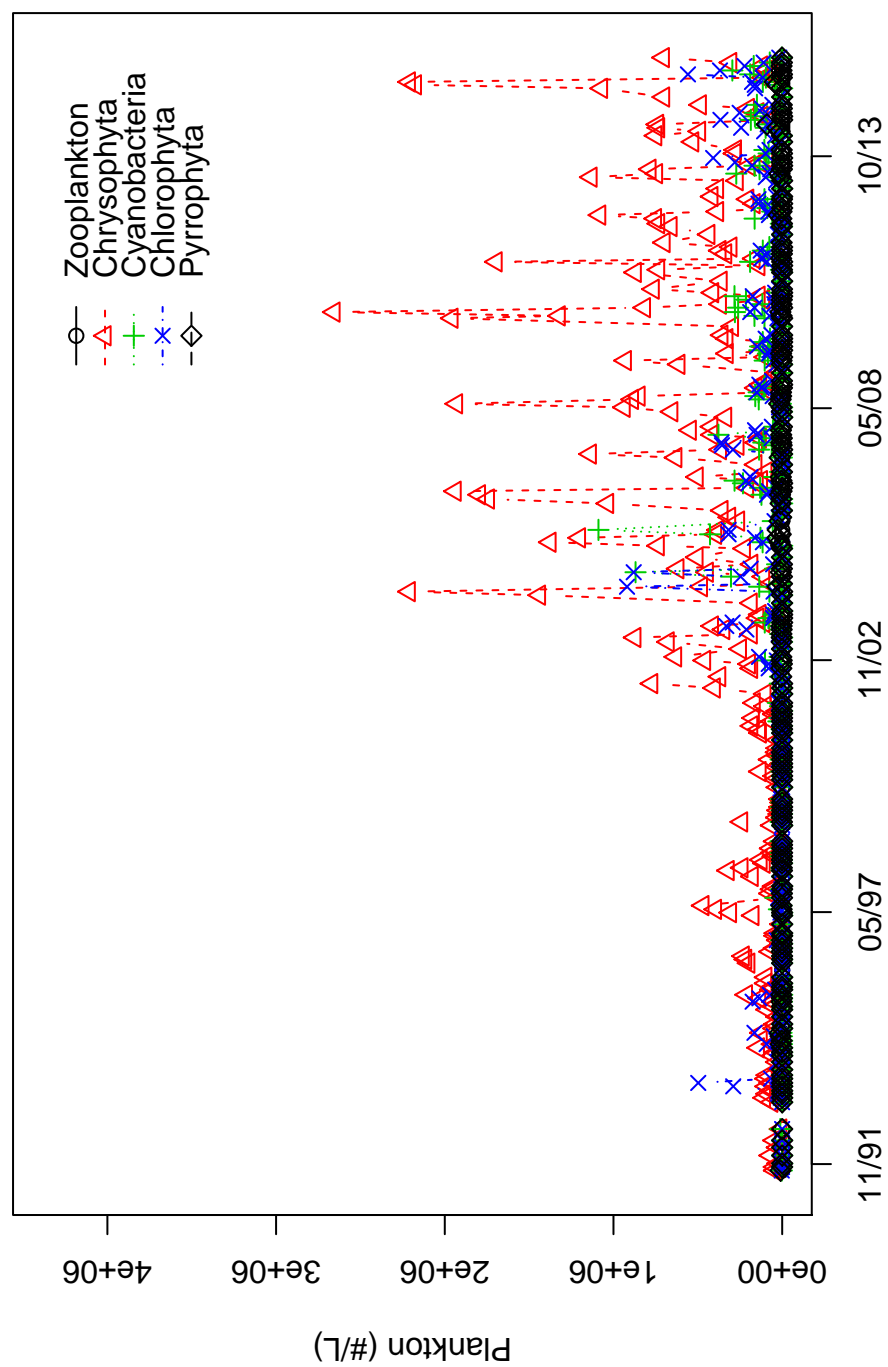


Figure B123: Lake Whatcom plankton data for the Intake Site.

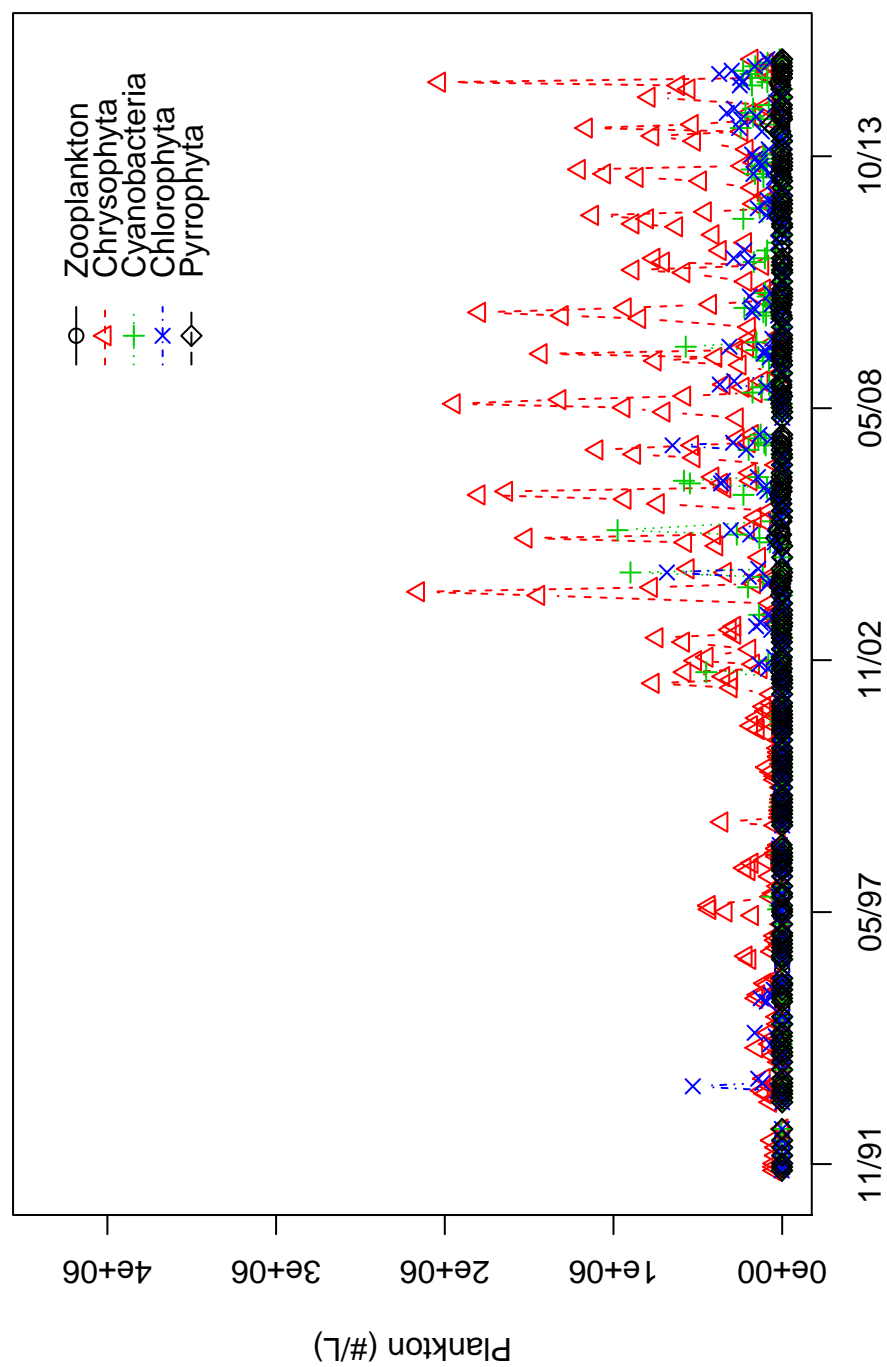


Figure B124: Lake Whatcom plankton data for Site 3.

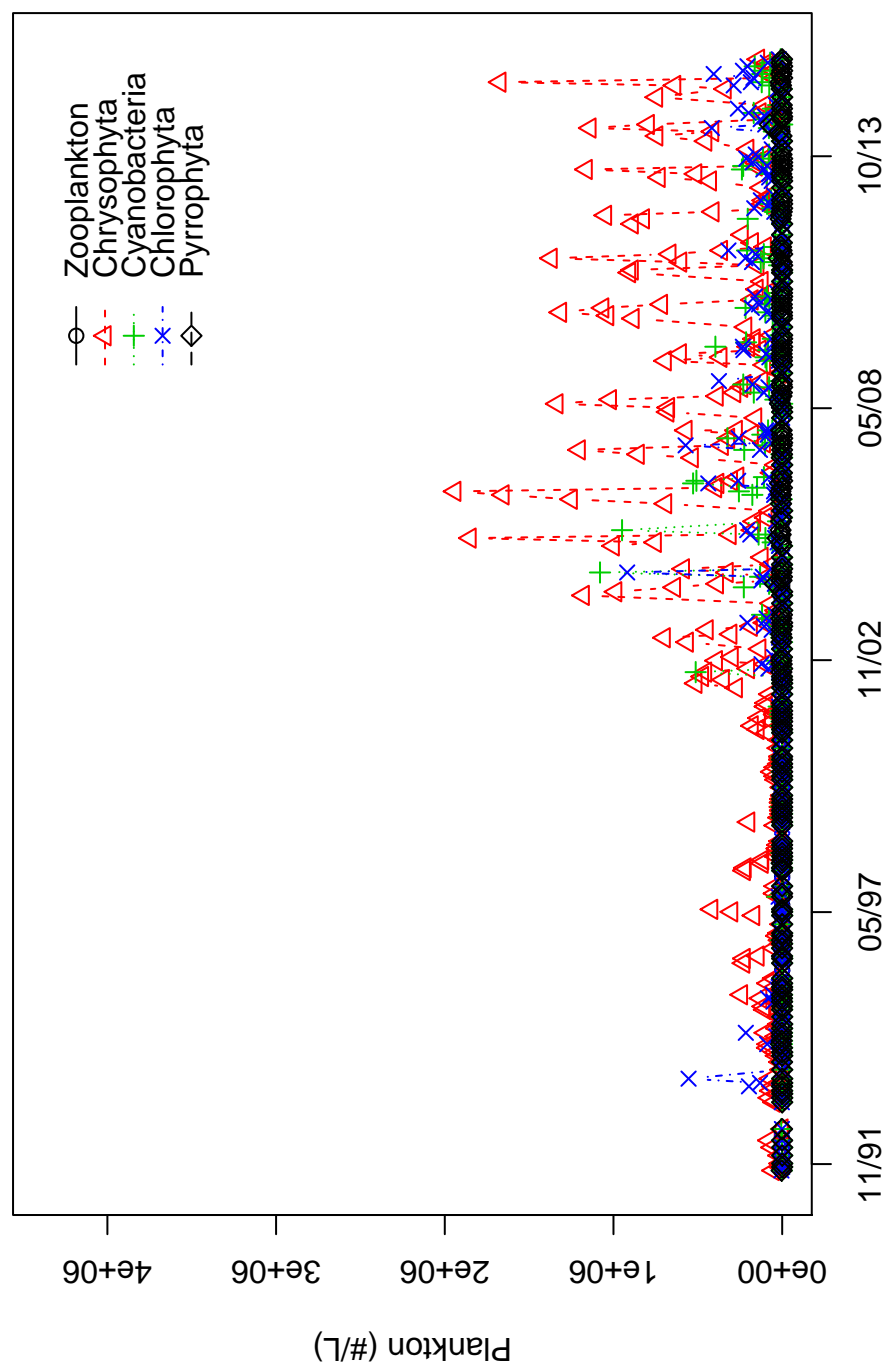


Figure B125: Lake Whatcom plankton data for Site 4.

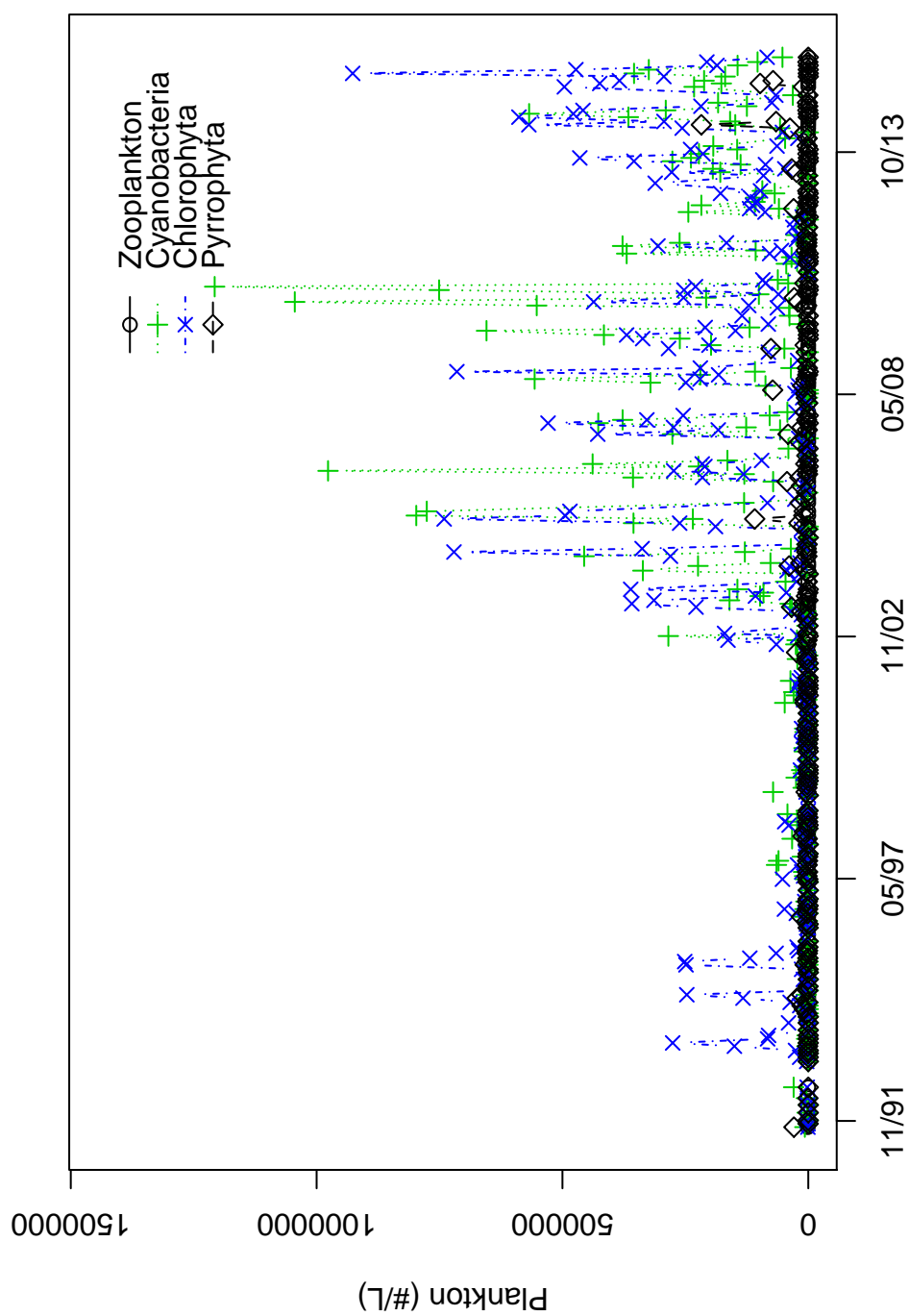


Figure B126: Lake Whatcom plankton data for Site 1, with Chrysophyta omitted to show remaining plankton groups.

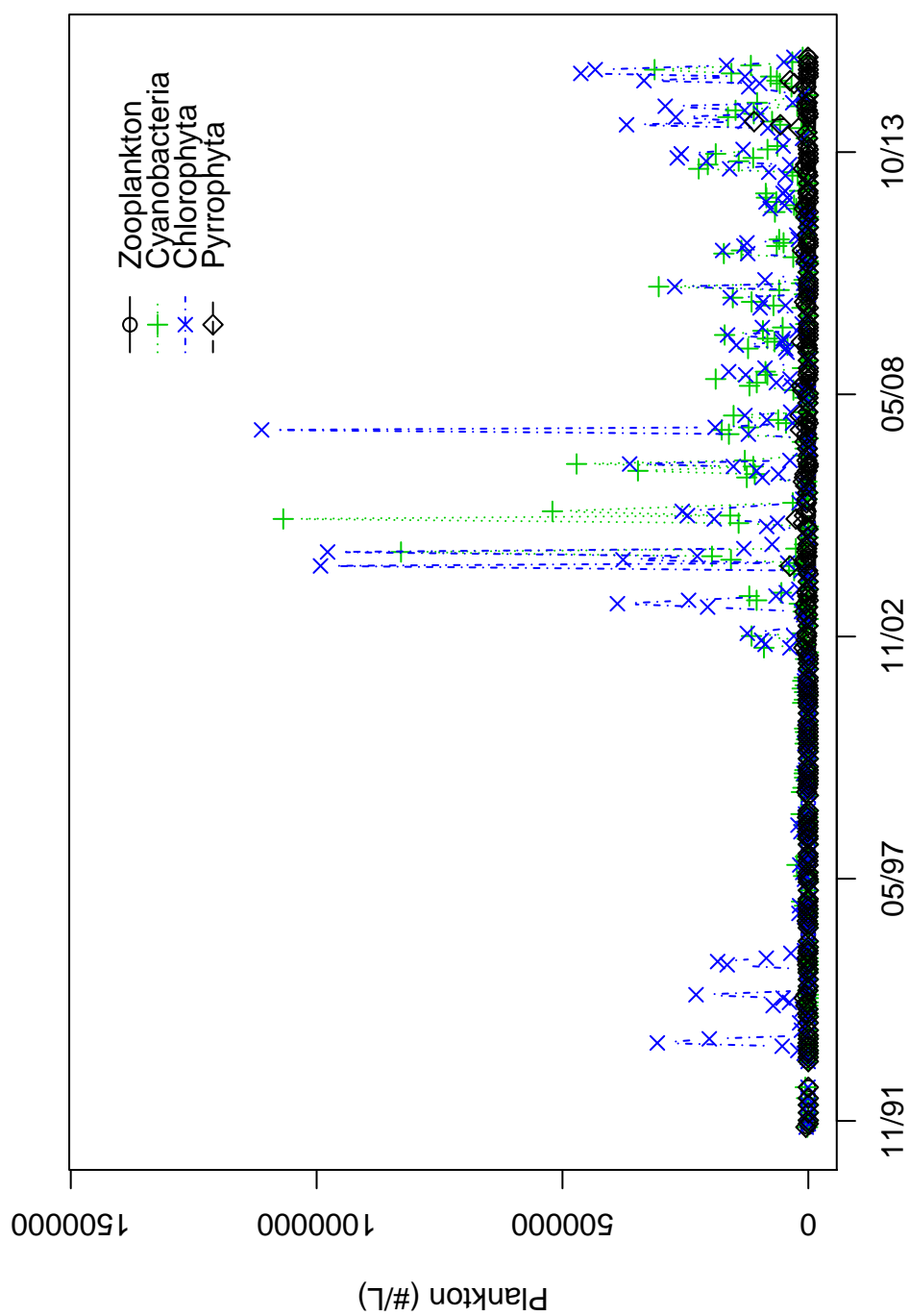


Figure B127: Lake Whatcom plankton data for Site 2, with Chrysophyta omitted to show remaining plankton groups.

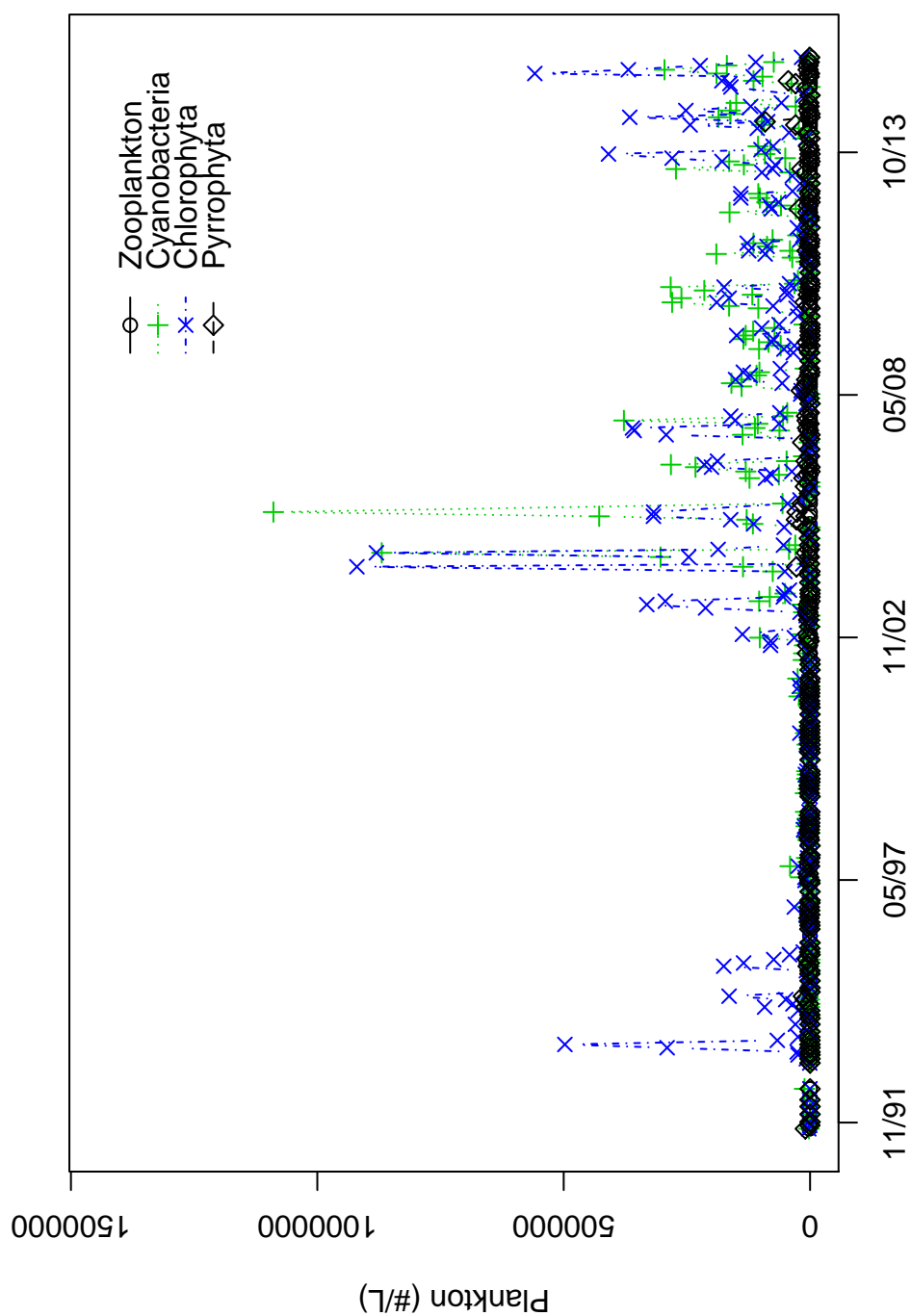


Figure B128: Lake Whatcom plankton data for the Intake Site, with Chrysophyta omitted to show remaining plankton groups.

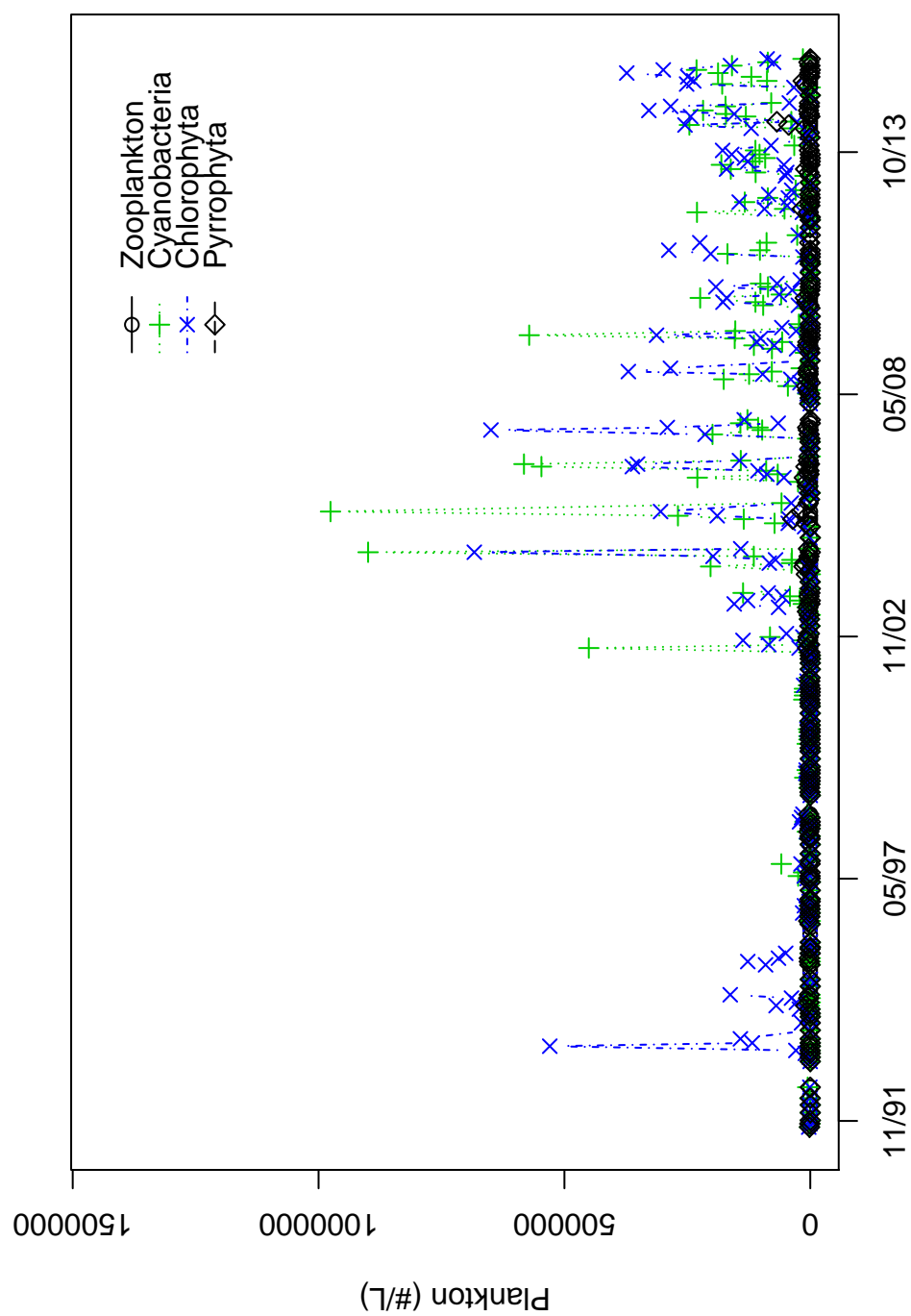


Figure B129: Lake Whatcom plankton data for Site 3, with Chrysophyta omitted to show remaining plankton groups.

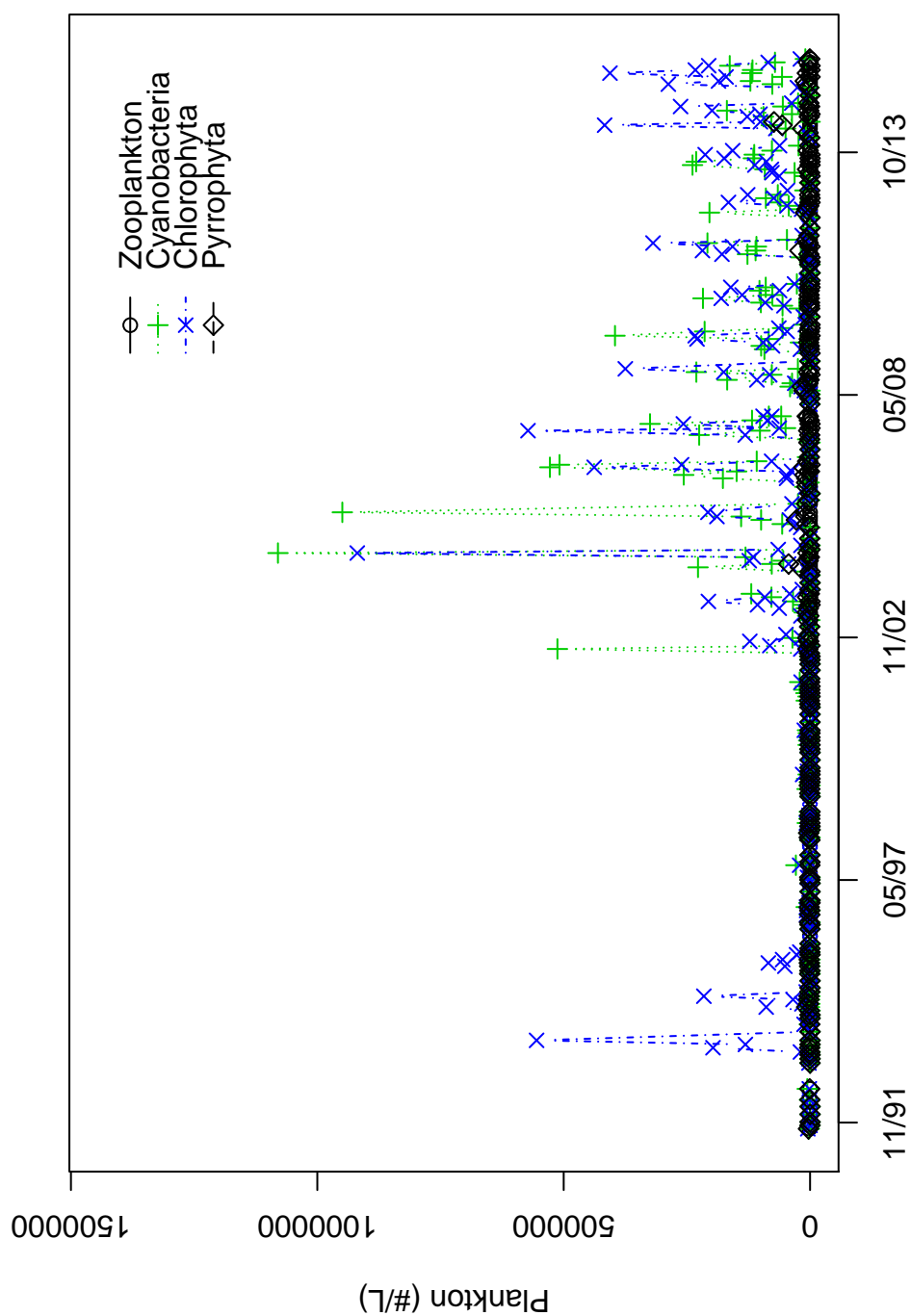


Figure B130: Lake Whatcom plankton data for Site 4, with Chrysophyta omitted to show remaining plankton groups.

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 16). 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). External check standards were analyzed during each analytical run to evaluate measurement precision and accuracy.²¹ The quality control results for laboratory duplicates, matrix spikes, and check standards are plotted in control charts (Figures C1–C29, pages 222–250).

C.3 Field Duplicates

Ten percent of all samples collected in the field were duplicated to measure sample replication (Figures C30–C39, pages 251–260). 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:

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

²¹External check standards are not available for all analytes.

	Reported Value	Assigned Value	Acceptance Limits	Test Result
Specific conductivity ($\mu\text{S}/\text{cm}$ at 25°C)	345	346	311–381	accept
Total alkalinity (mg/L as CaCO_3)	71.0	70.6	60.3–81.5	accept
Ammonium nitrogen, manual (mg-N/L)	8.20	8.36	6.62–10.1	accept
Ammonium nitrogen, auto (mg-N/L)	7.92	8.36	6.62–10.1	accept
Dissolved oxygen (mg/L)	8.59	8.51	7.65–8.96	accept
Nitrate/nitrite nitrogen, auto (mg-N/L)	8.10	8.36	6.93–9.72	accept
Nitrite nitrogen, auto (mg-N/L)	3.04	3.06	2.64–3.48	accept
Orthophosphate, manual (mg-P/L)	0.530	0.550	0.468–0.633	accept
Orthophosphate, auto (mg-P/L)	0.556	0.550	0.468–0.633	accept
Total phosphorus, manual (mg-P/L)	5.10	5.09	4.21–5.91	accept
Total phosphorus, auto (mg-P/L)	4.93	5.09	4.21–5.91	accept
pH	7.39	7.32	7.12–7.52	accept
Solids, non-filterable (mg/L)	46.9	52.6	41.1–60.0	accept
Turbidity (NTU)	8.88	9.59	7.75–11.4	accept

Table C1: Single-blind quality control results, WP-216 (06/19/2015) and WP-220 (10/16/2015; new parameter - dissolved oxygen). All results were within acceptance limits.

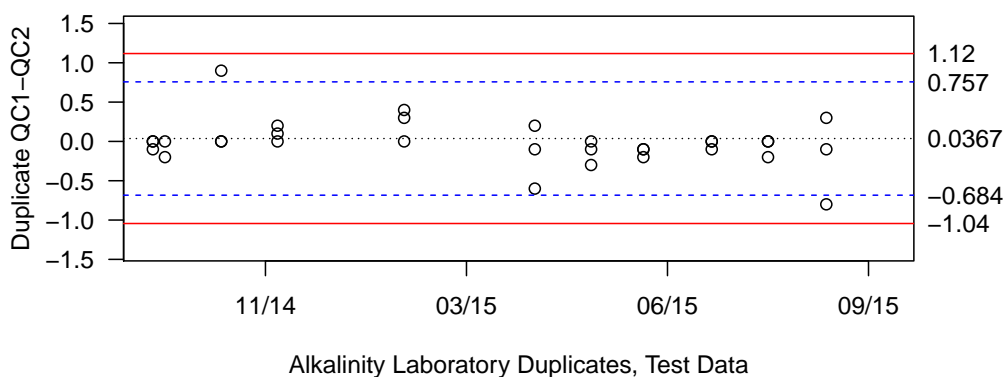
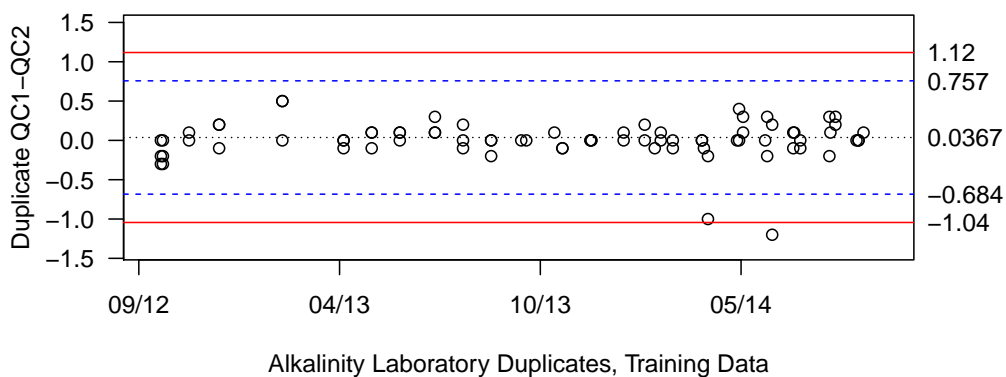


Figure C1: Alkalinity laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

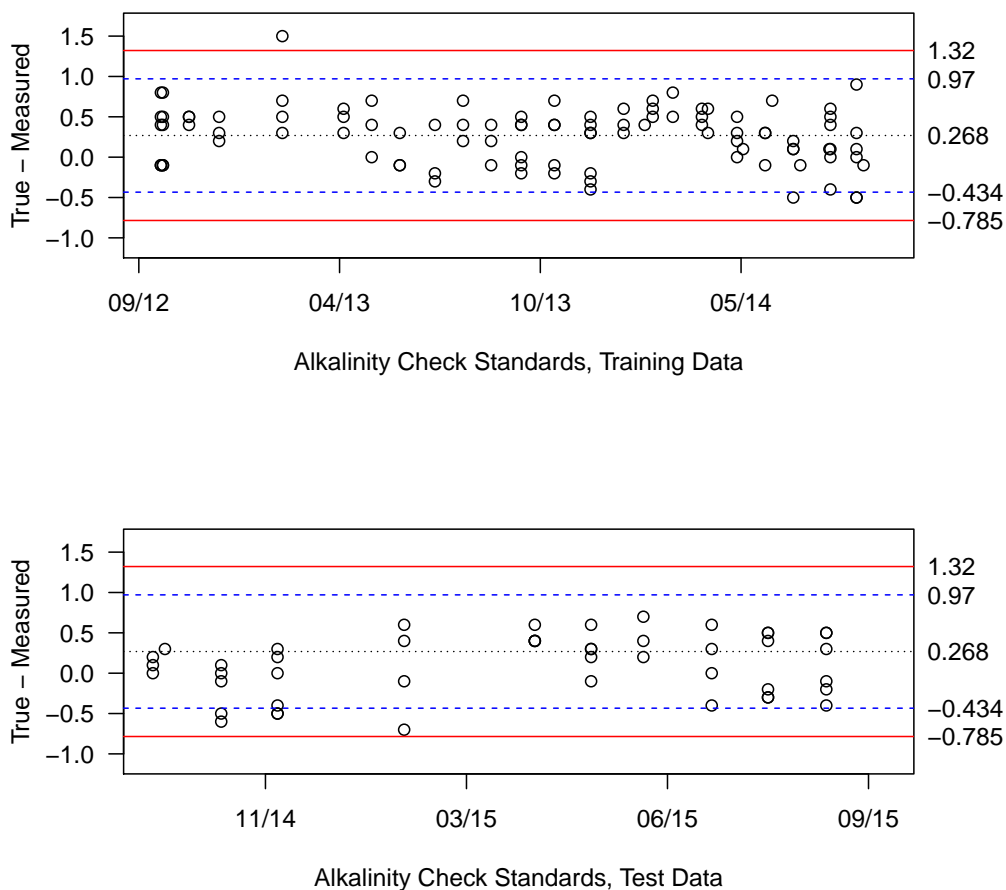


Figure C2: Alkalinity low-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

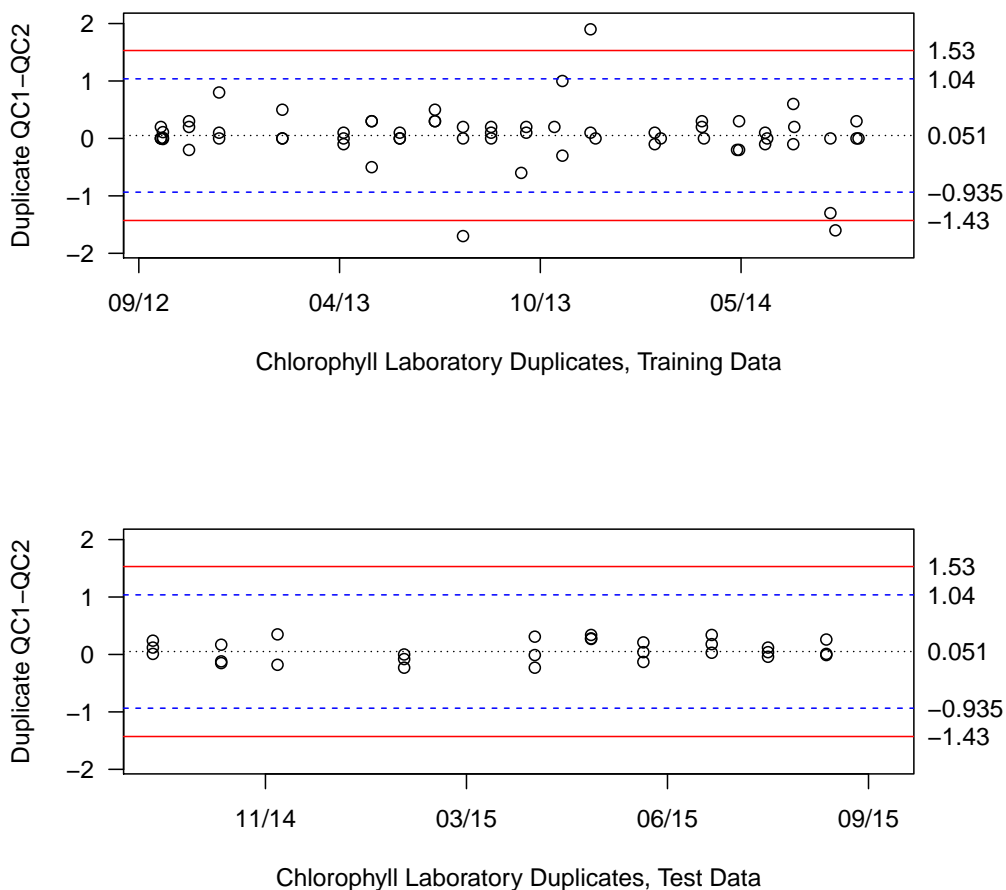


Figure C3: Chlorophyll laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

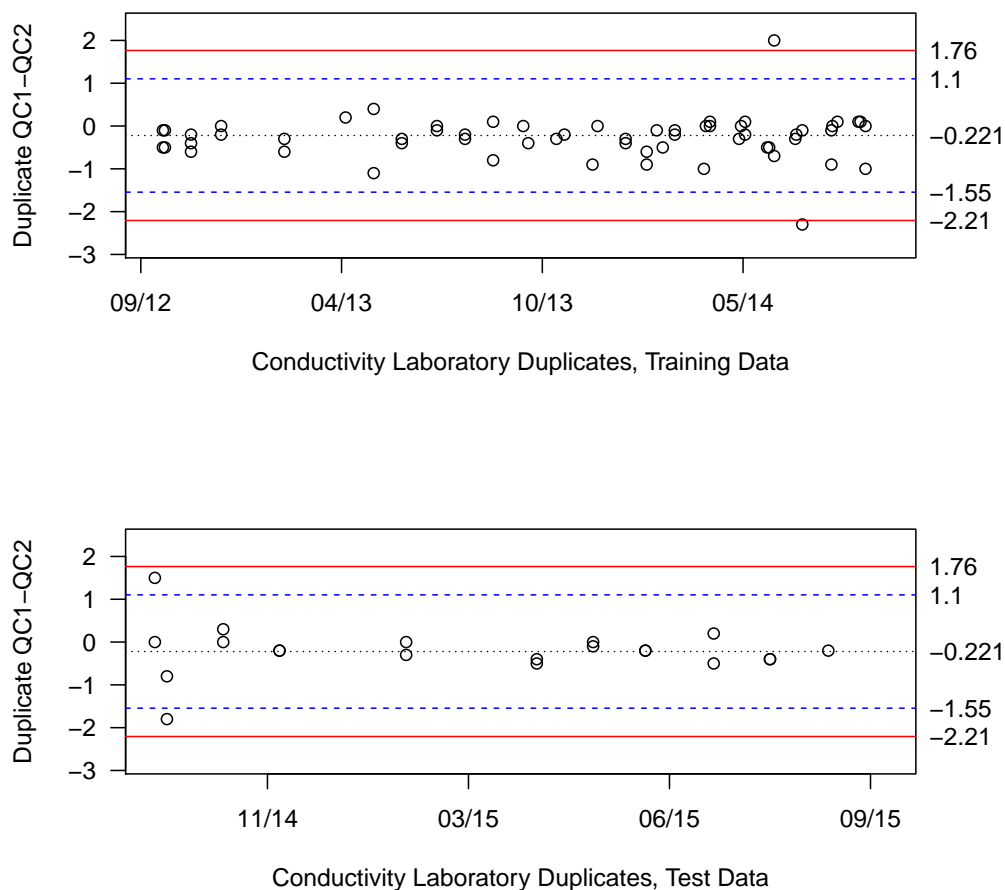


Figure C4: Conductivity laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

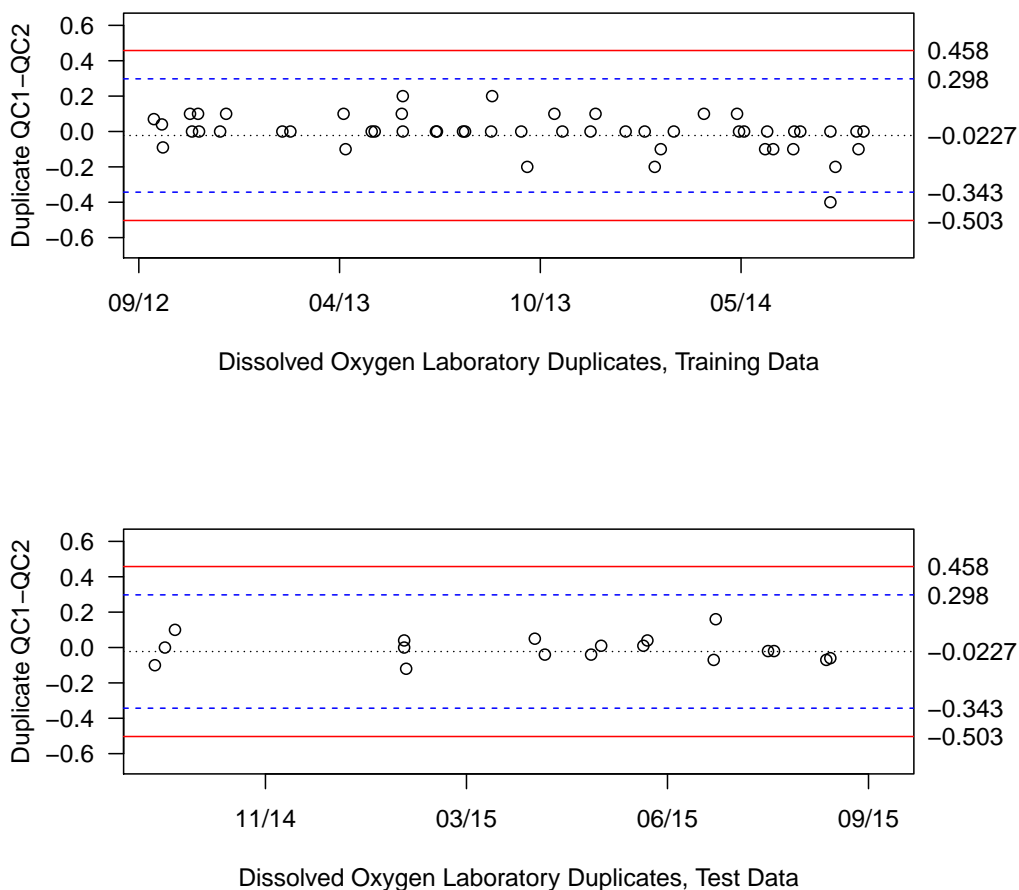


Figure C5: Dissolved oxygen laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate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

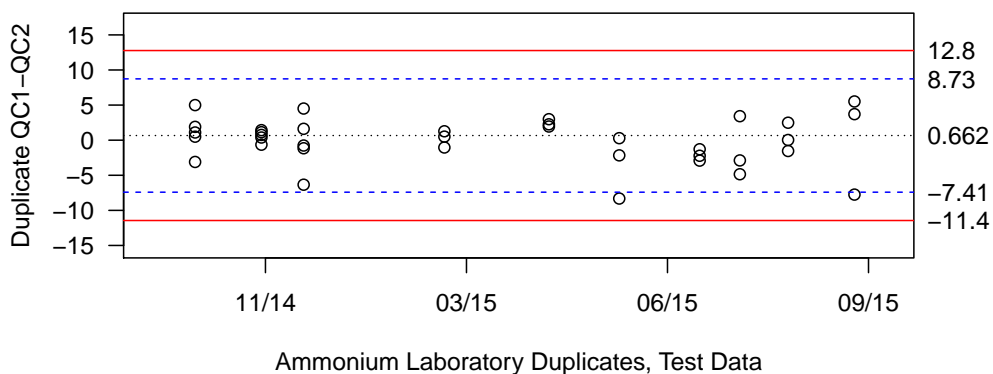
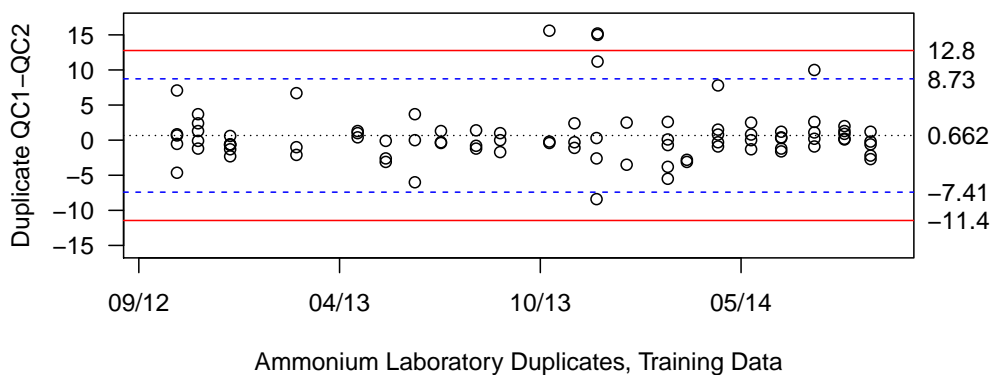


Figure C6: Ammonium laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

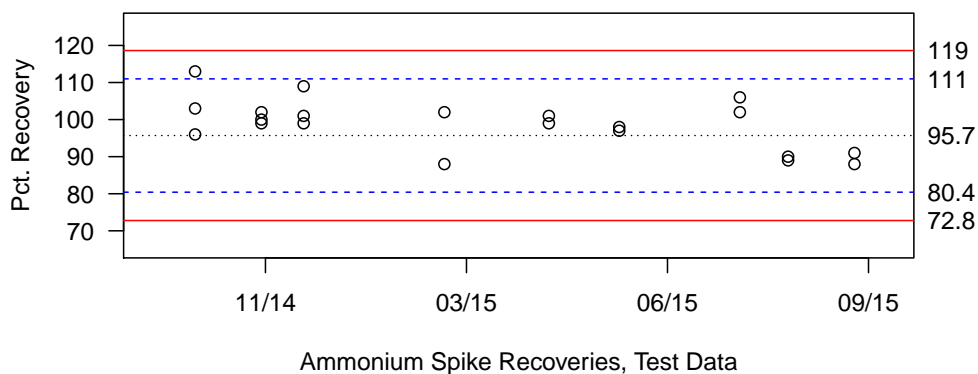
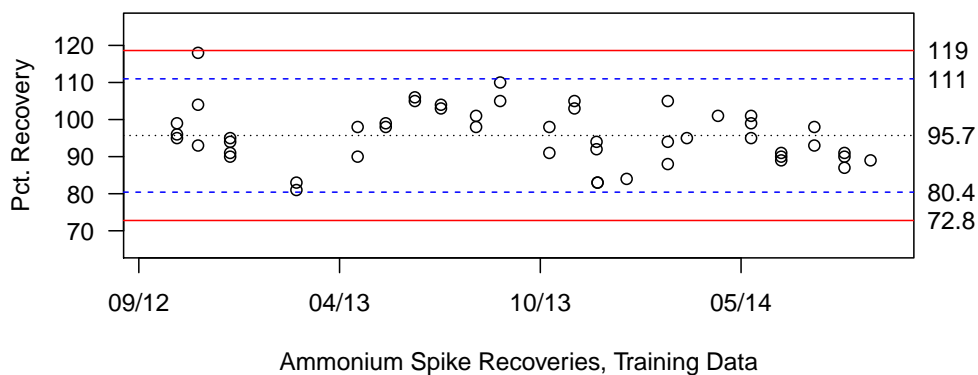


Figure C7: Ammonium spike recoveries for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

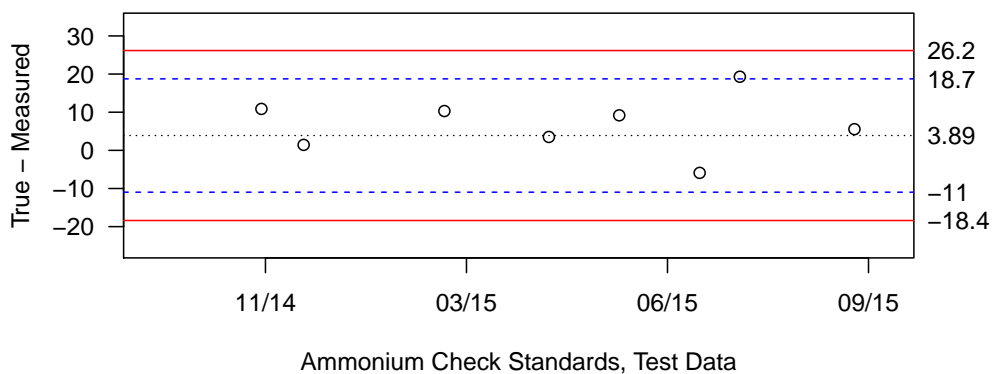
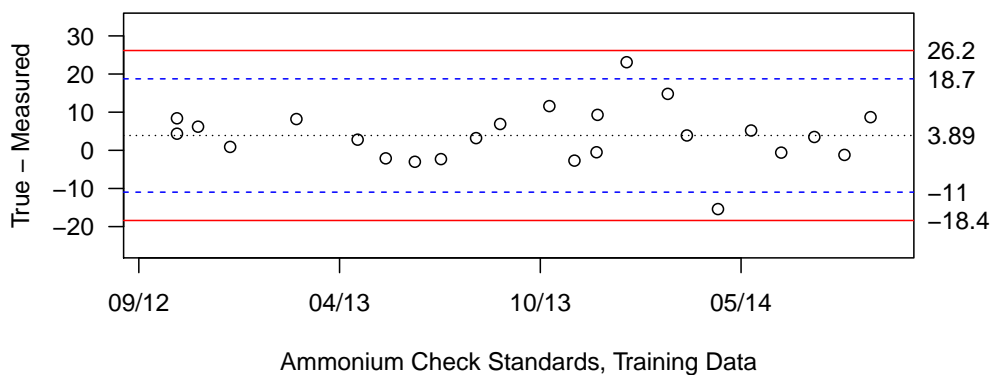
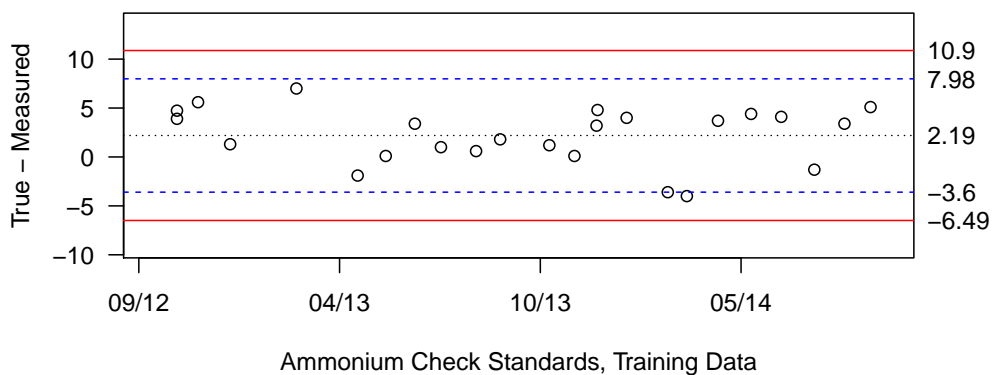


Figure C8: Ammonium high-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.



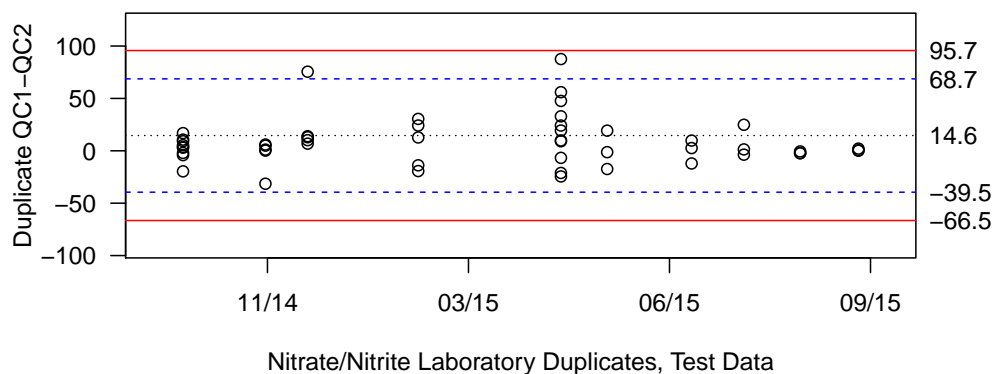
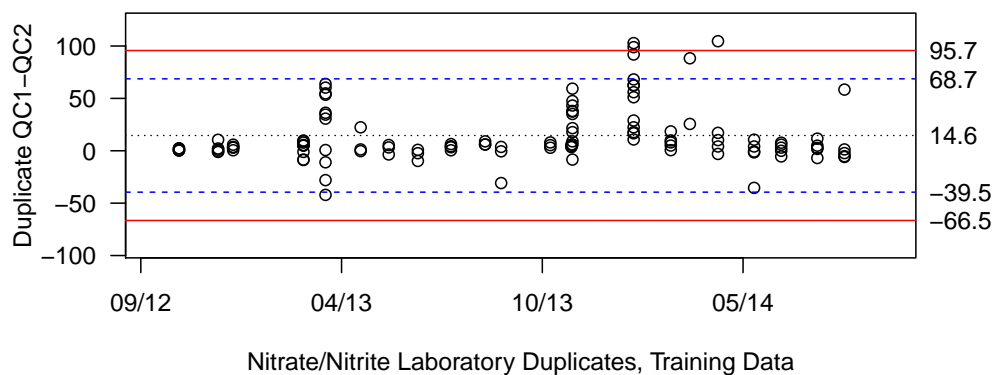


Figure C10: Nitrate/nitrite laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

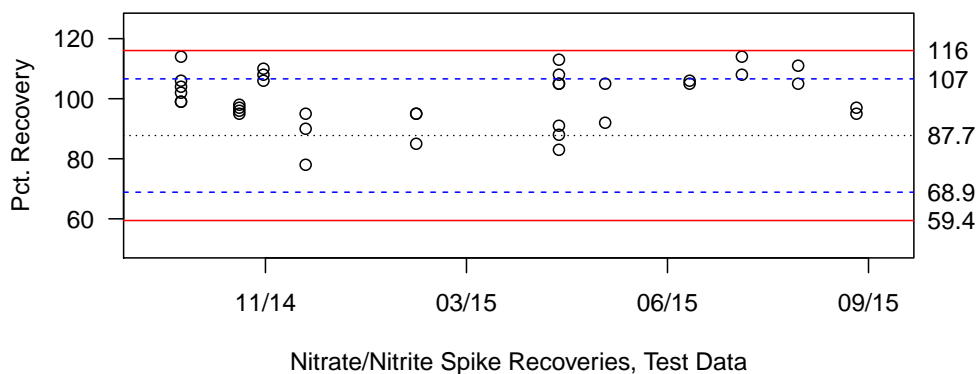
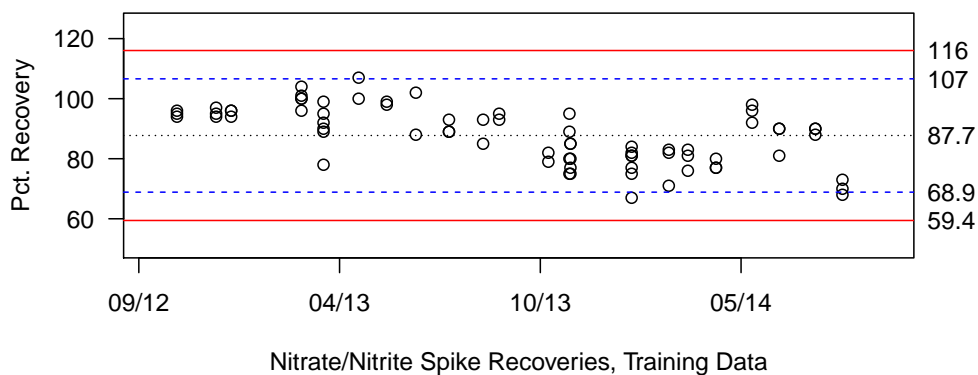


Figure C11: Nitrate/nitrite spike recoveries for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

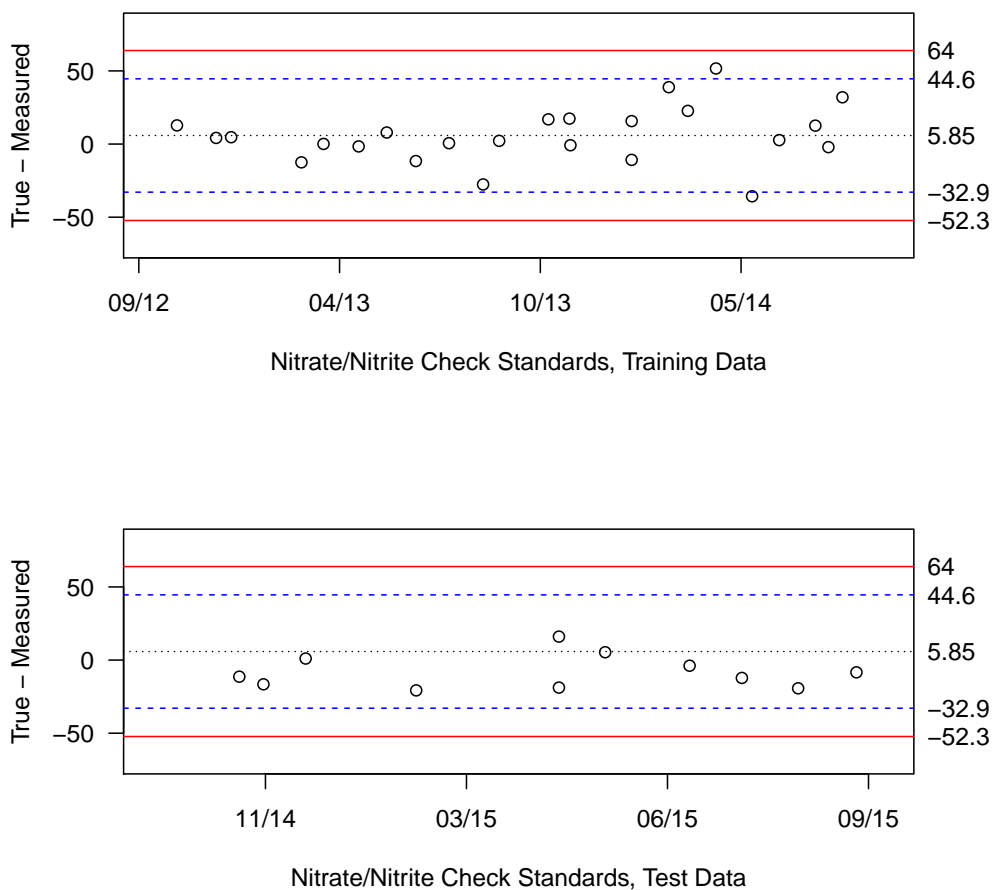


Figure C12: Nitrate/nitrite high-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

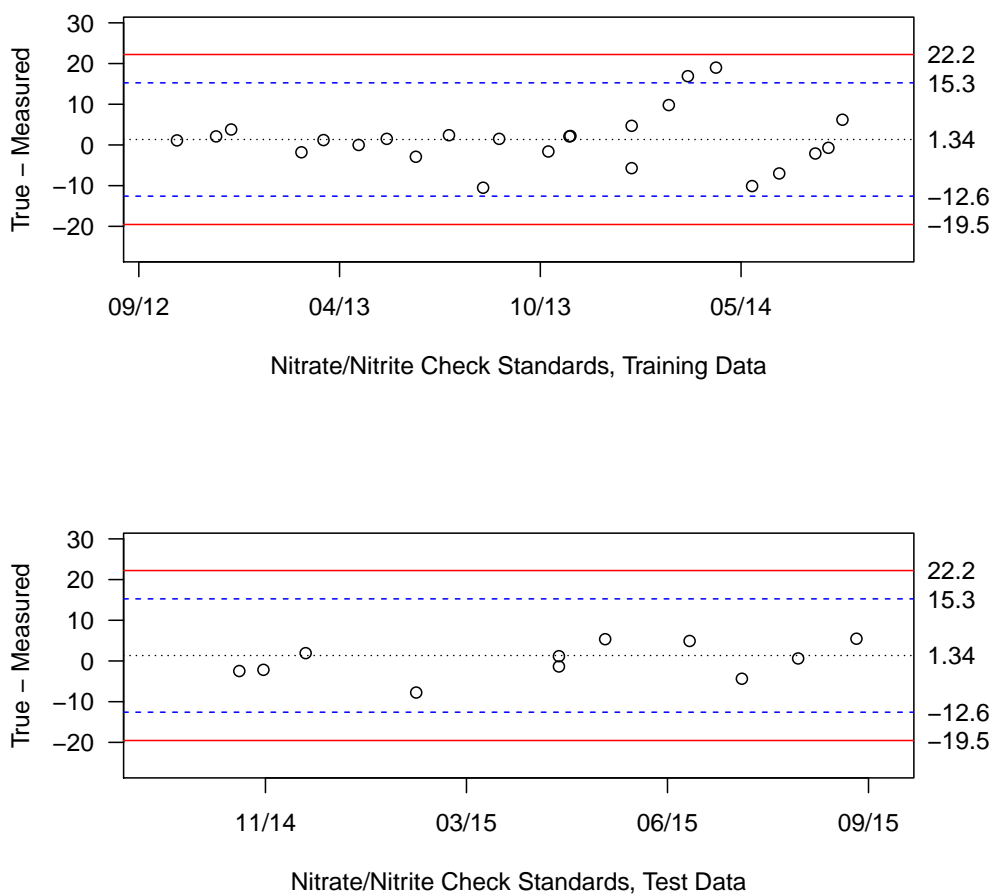


Figure C13: Nitrate/nitrite low-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

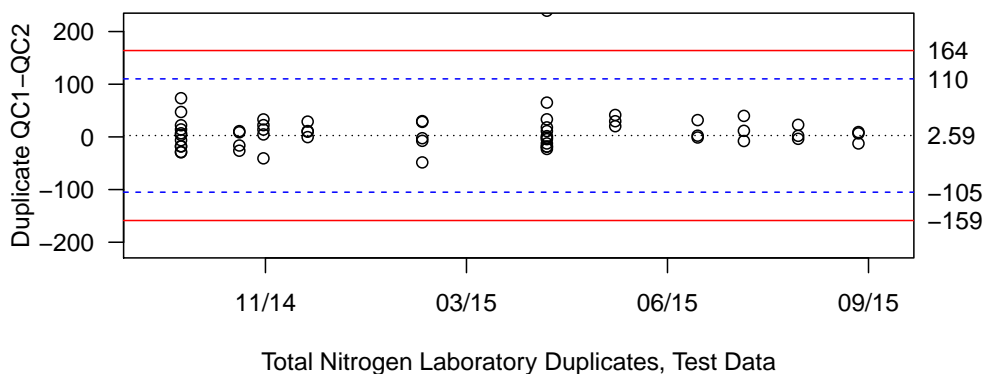
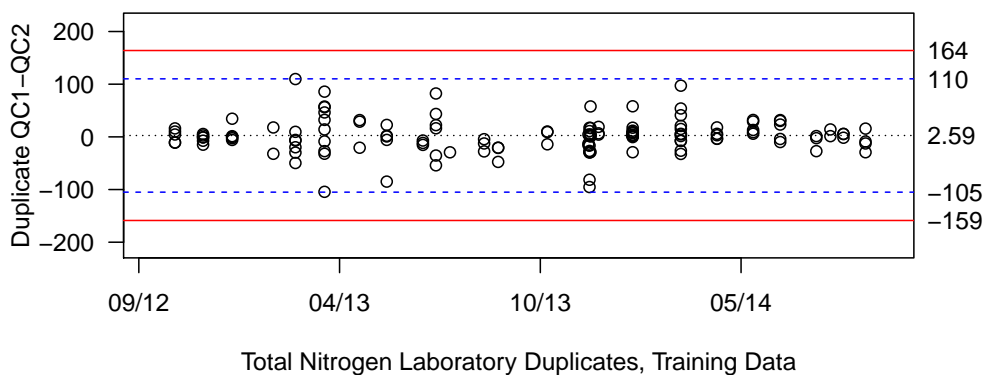
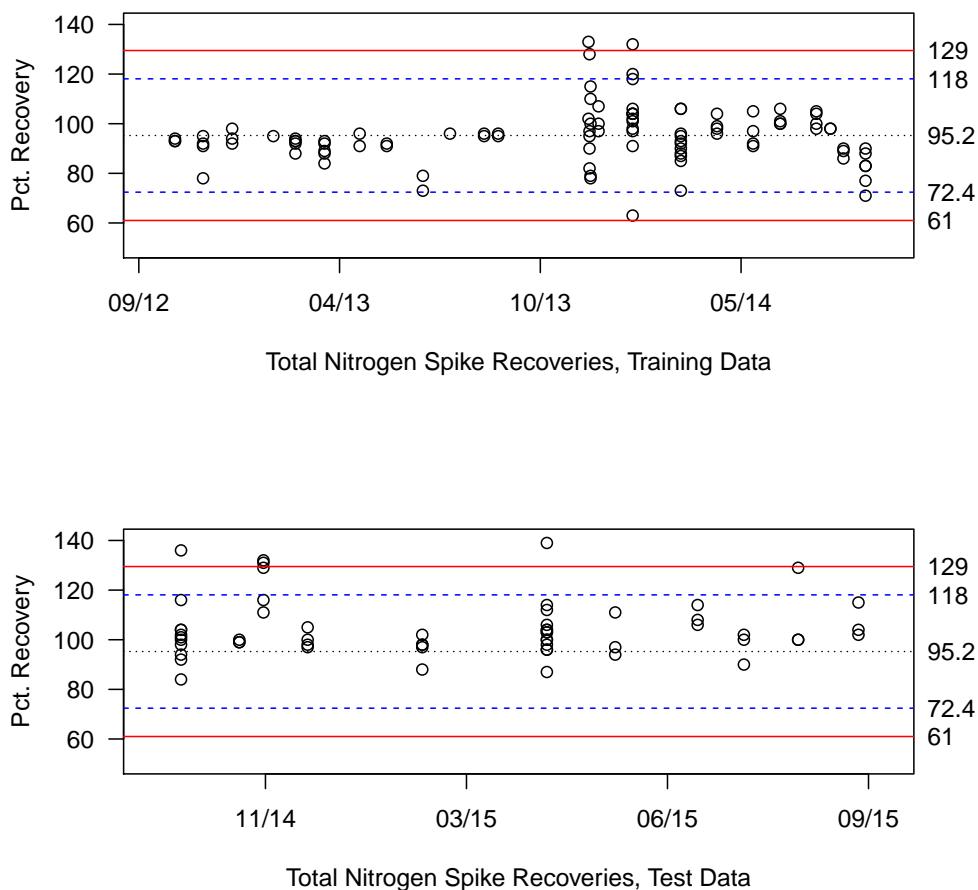


Figure C14: Total nitrogen laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.



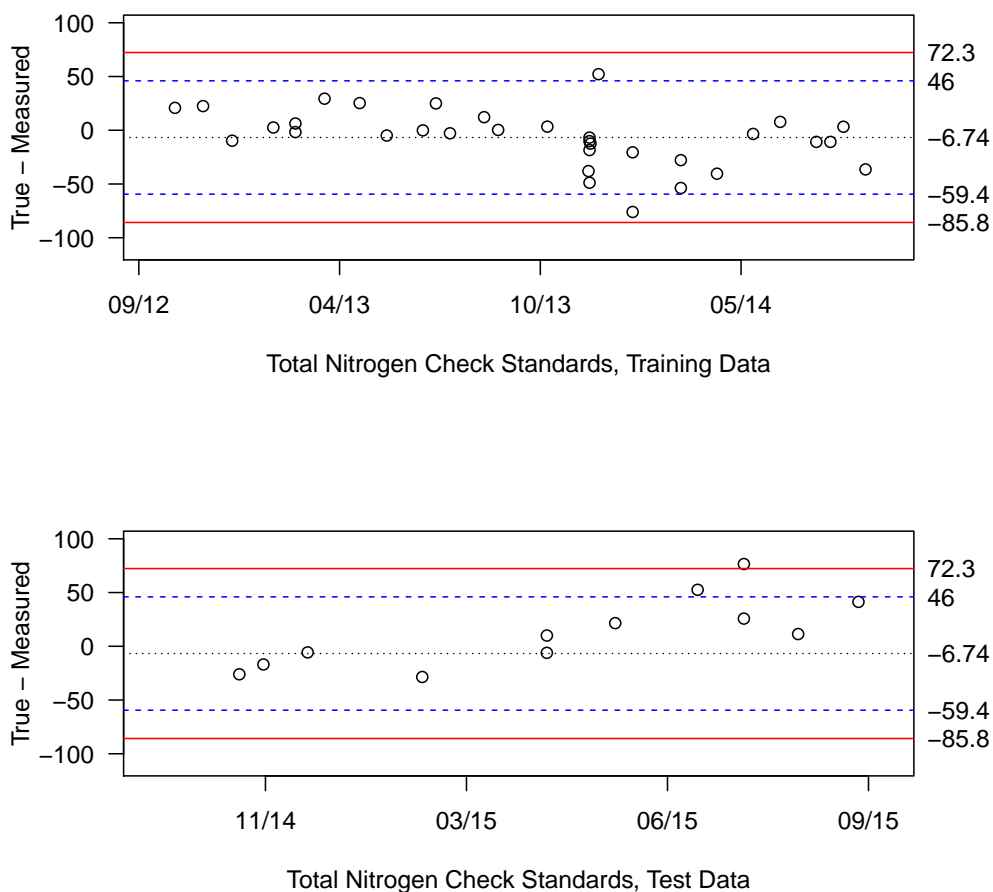


Figure C16: Total nitrogen high-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

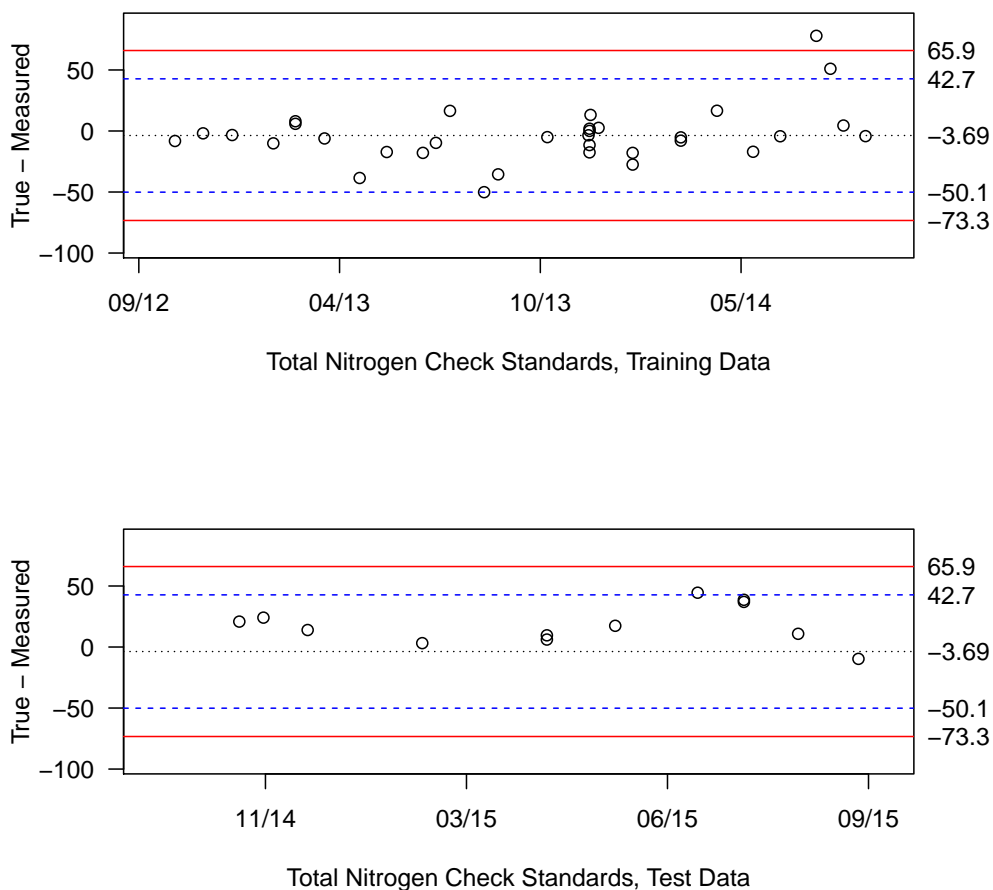


Figure C17: Total nitrogen low-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

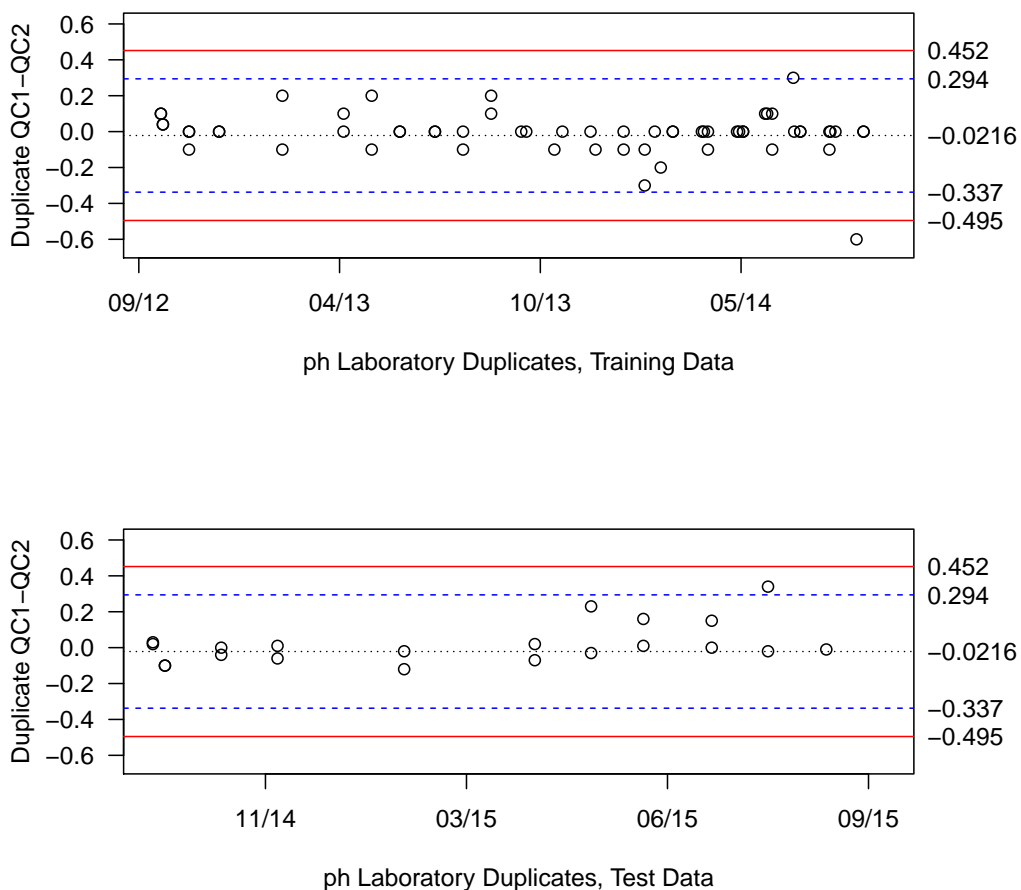


Figure C18: Laboratory pH duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

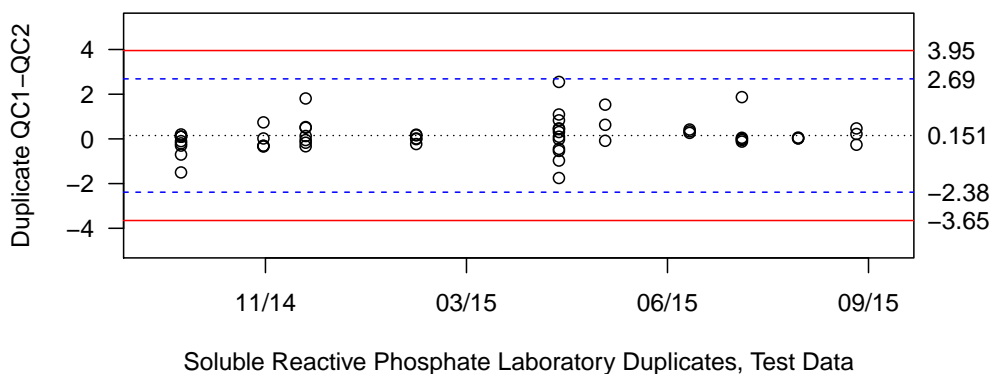
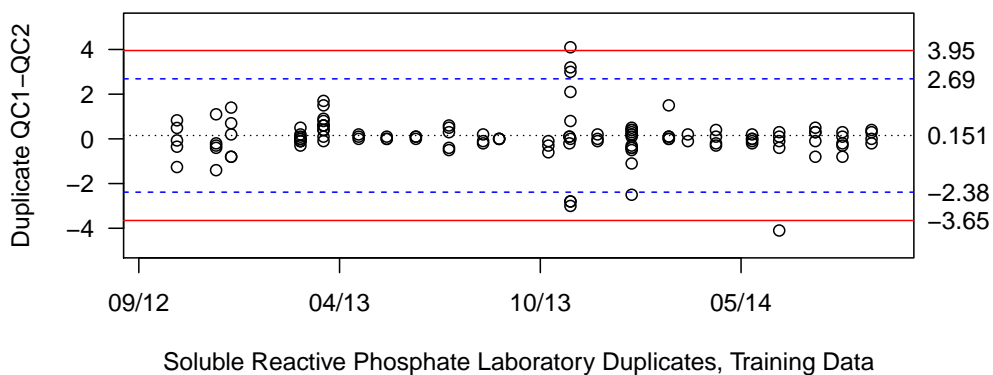


Figure C19: Soluble reactive phosphate laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab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

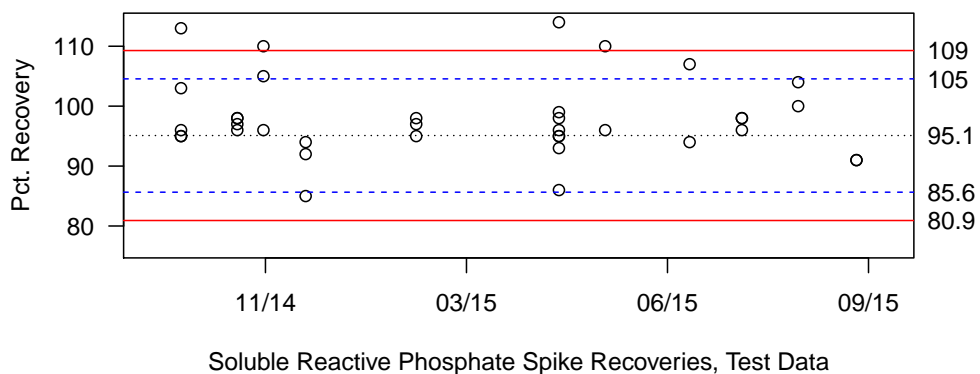
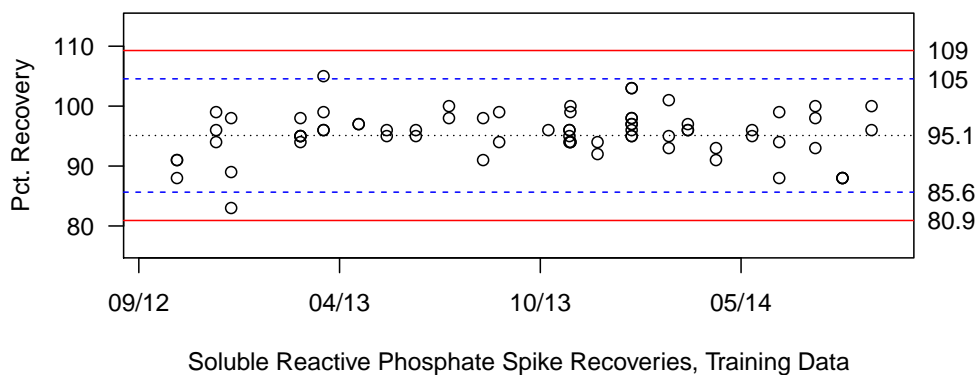


Figure C20: Soluble reactive phosphate spike recoveries for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

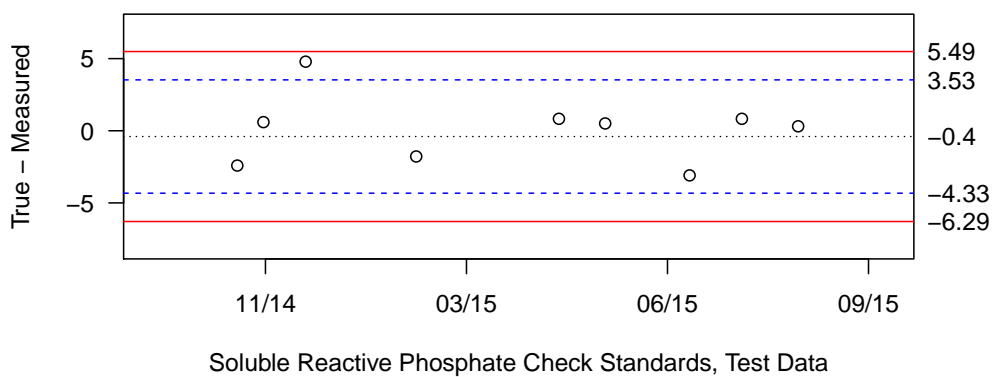
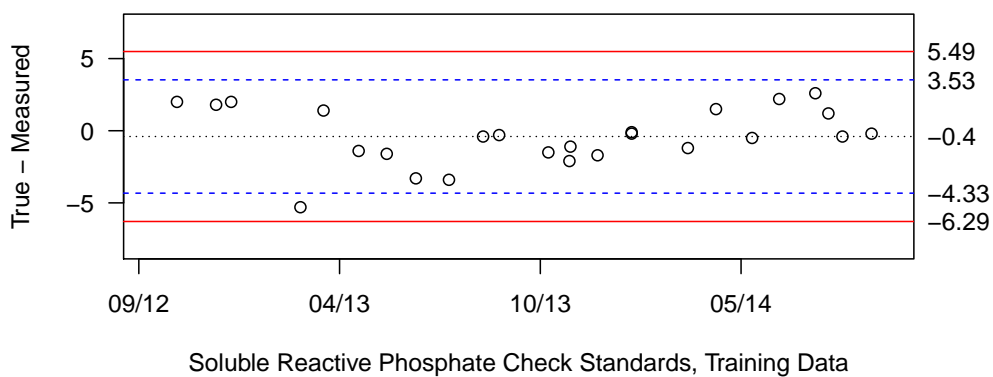


Figure C21: Soluble reactive phosphate high-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

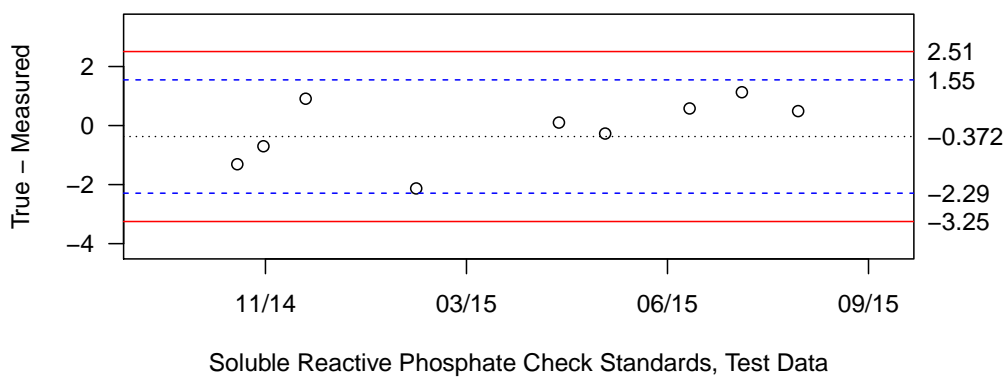
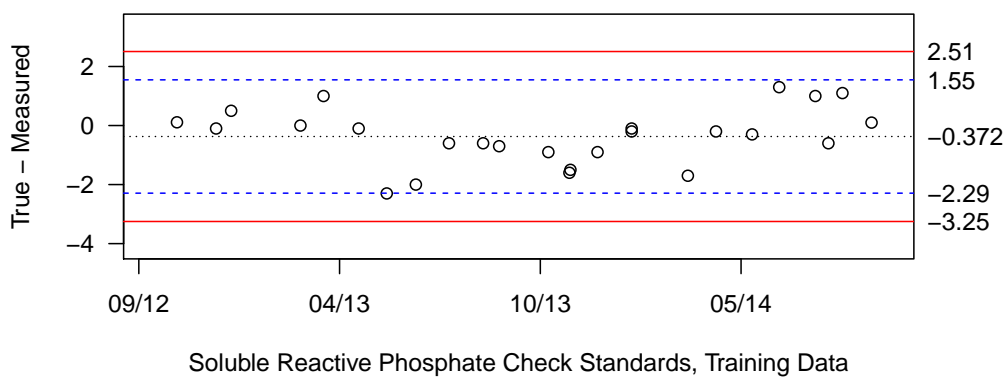


Figure C22: Soluble reactive phosphate low-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of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

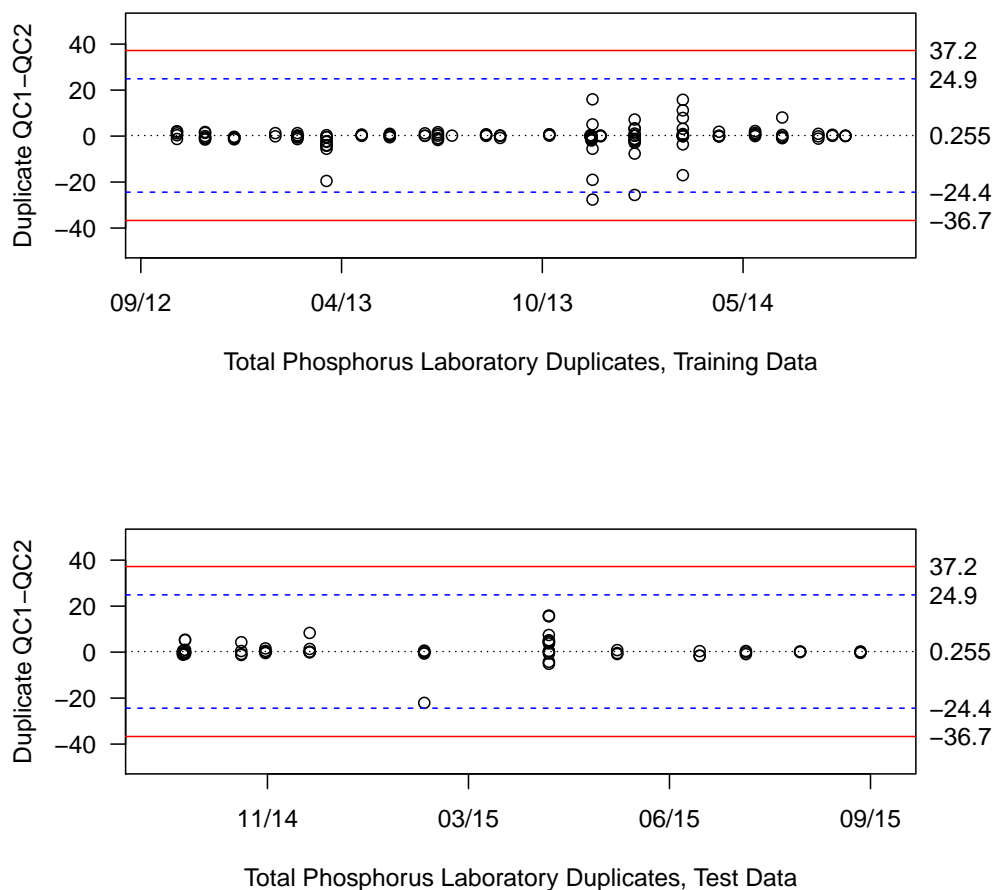


Figure C23: Total phosphorus laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

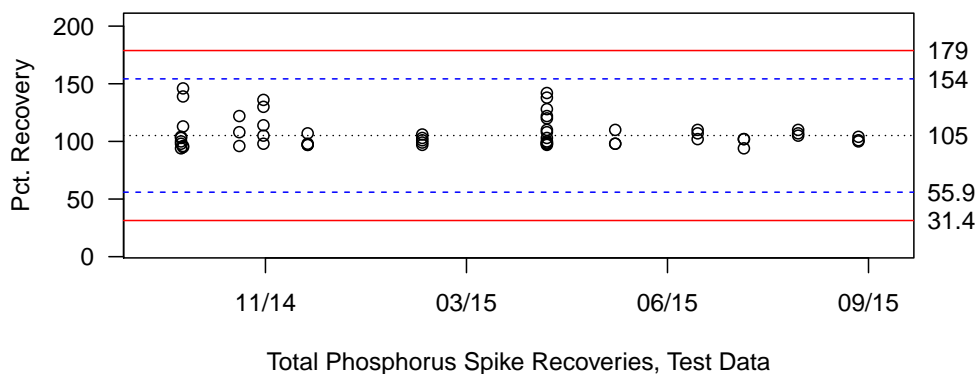
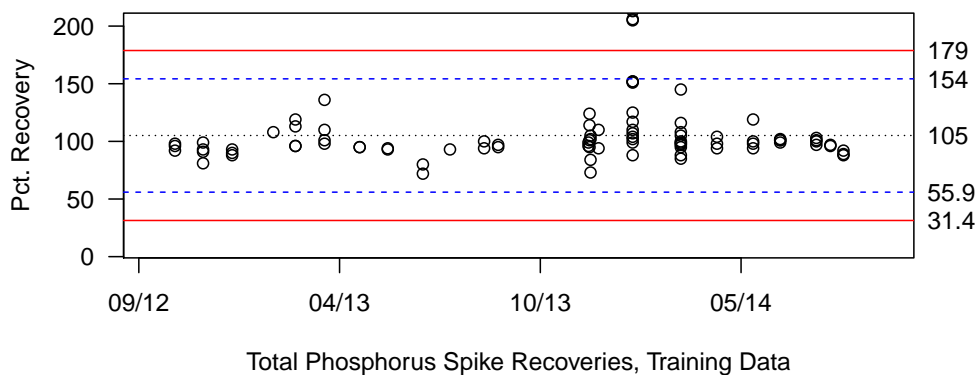


Figure C24: Total phosphorus spike recoveries for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

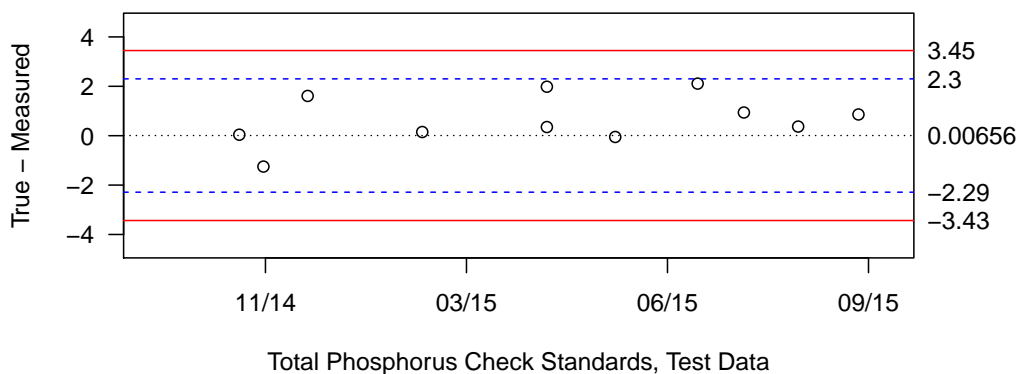
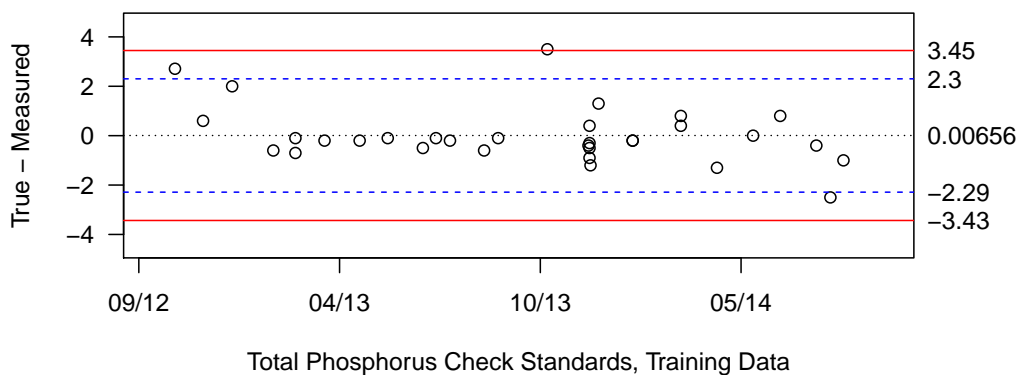


Figure C25: Total phosphorus high-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

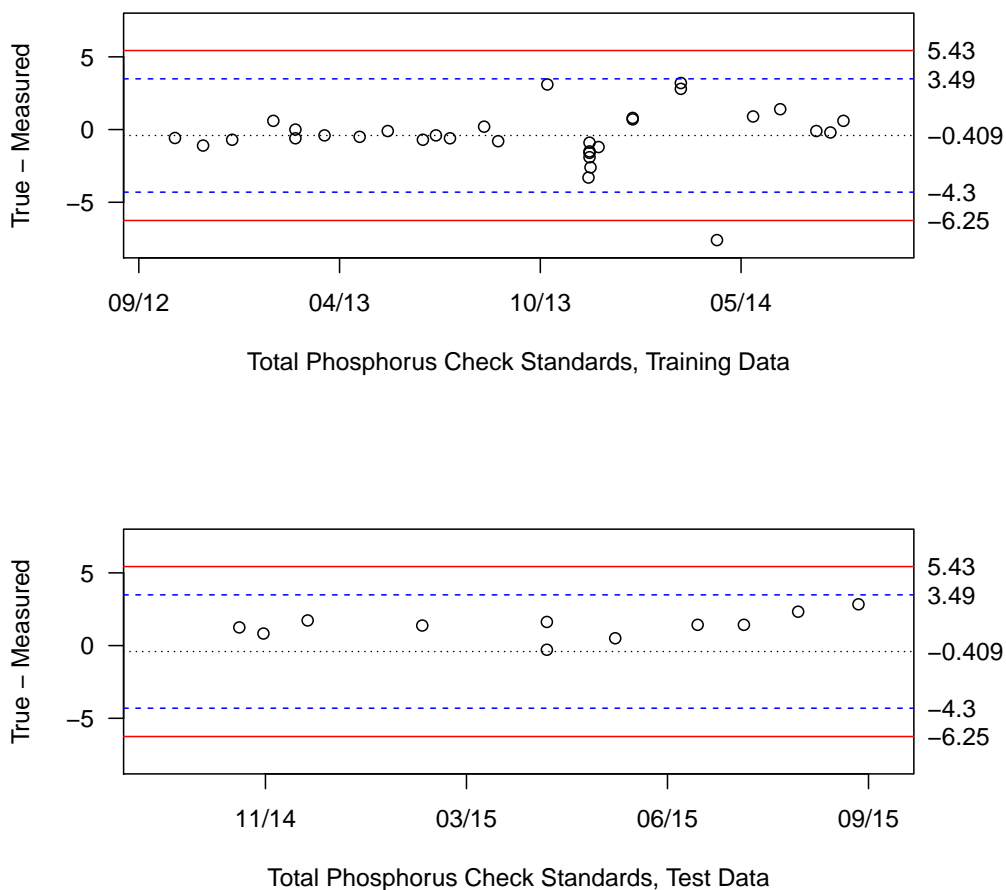


Figure C26: Total phosphorus low-range check standards for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

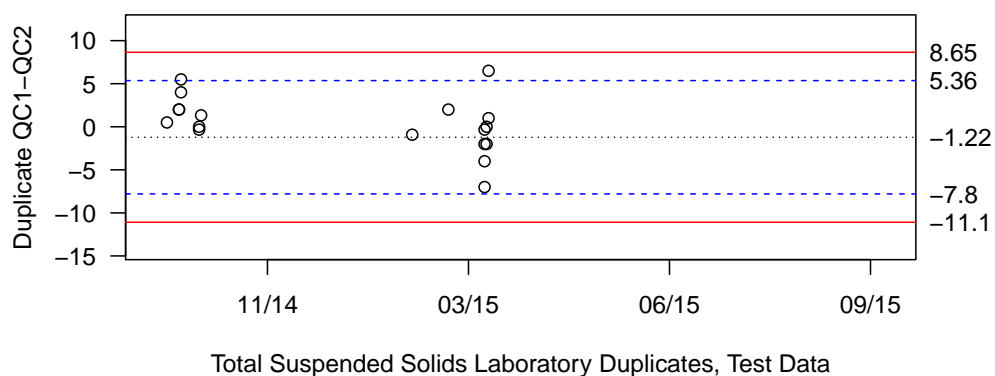
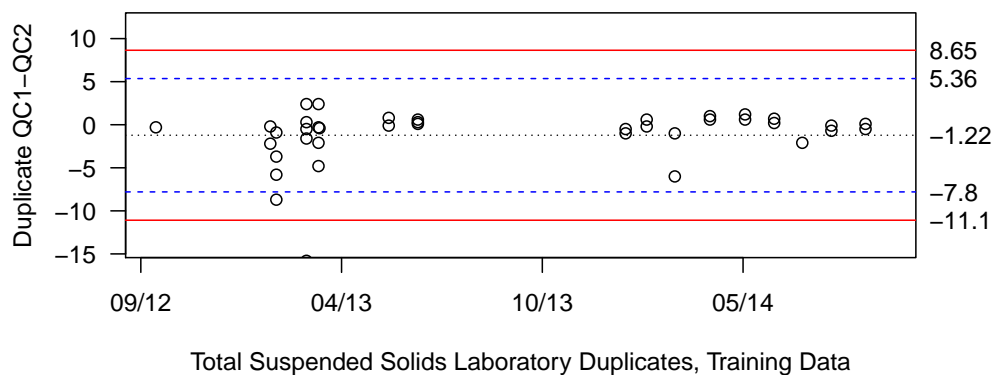


Figure C27: Total suspended solids laboratory duplicates for the Lake Whatcom monitoring program (storm water samples). Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

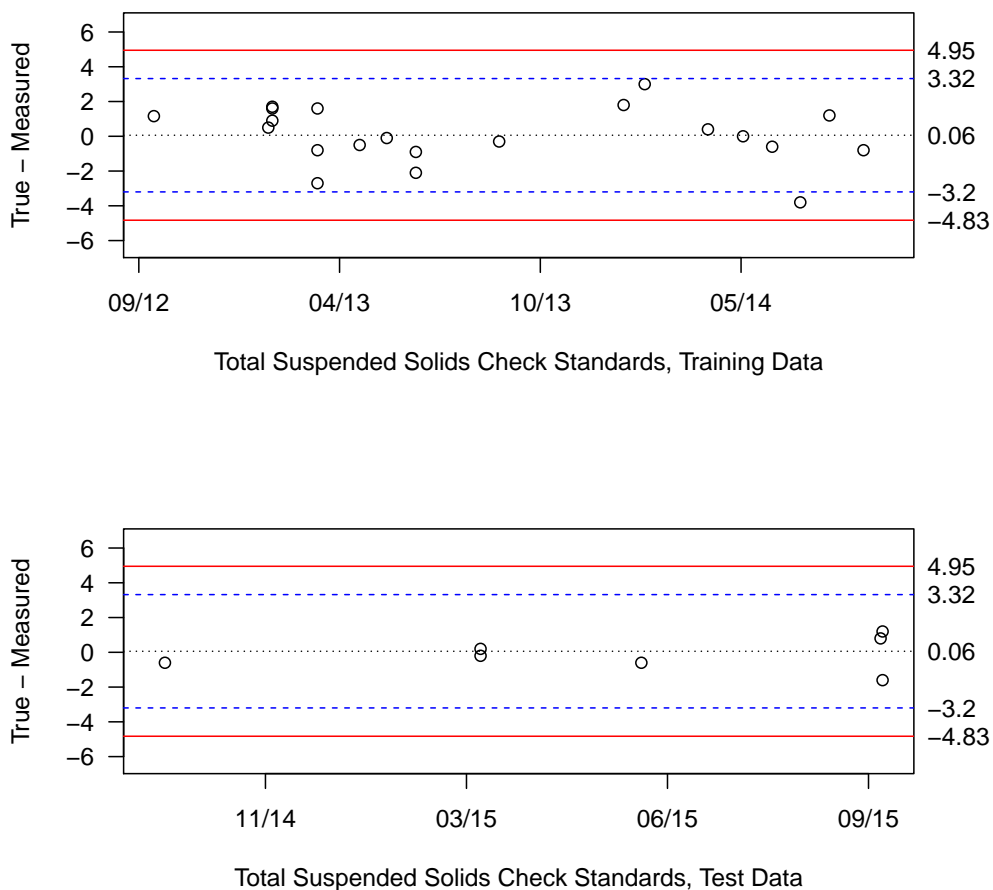


Figure C28: Total suspended solids check standards for the Lake Whatcom monitoring program (storm water samples). Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two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

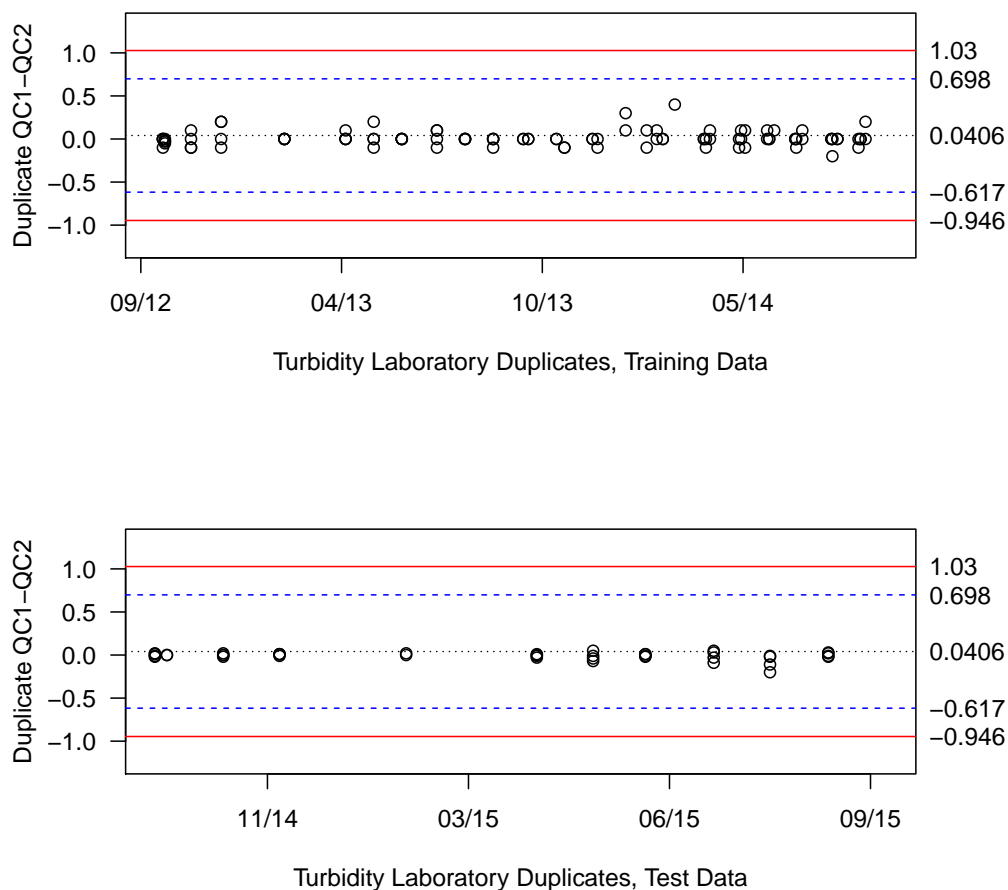


Figure C29: Turbidity laboratory duplicates for the Lake Whatcom monitoring program. Upper/lower acceptance limits (± 2 std. dev. from mean pair difference) and upper/lower warning limits (± 3 std. dev. from mean pair difference) were calculated based on the preceding two years of lab duplicate data.

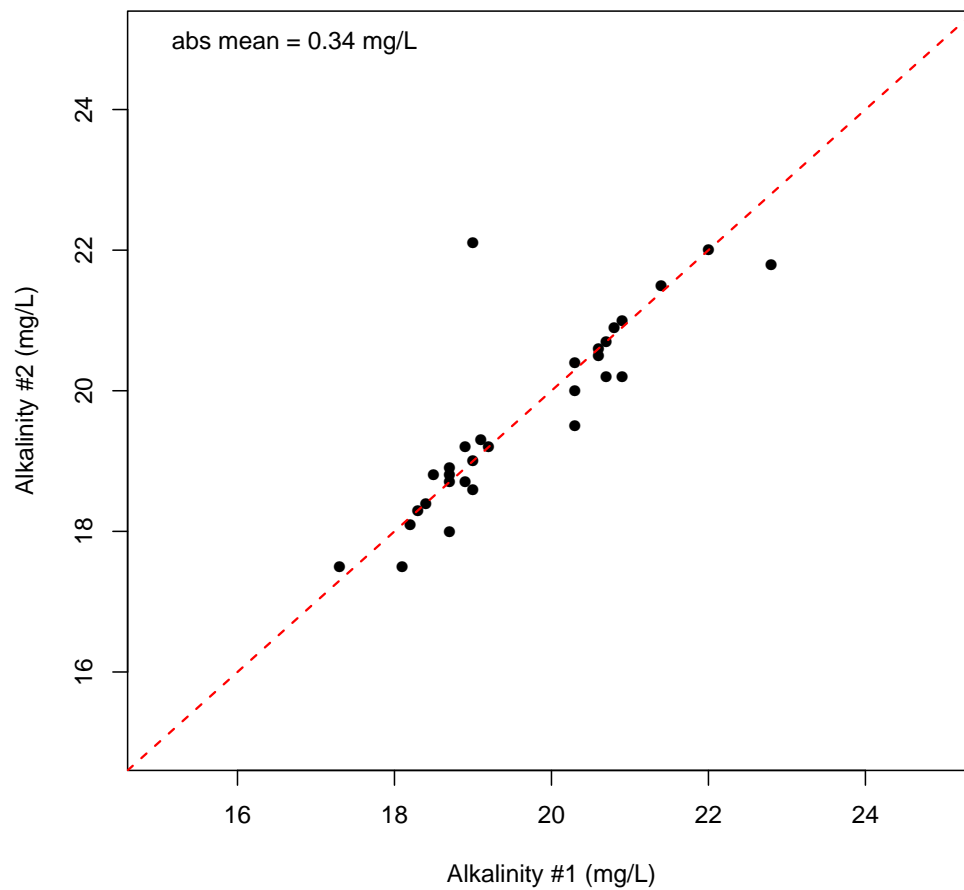


Figure C30: Alkalinity field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship.

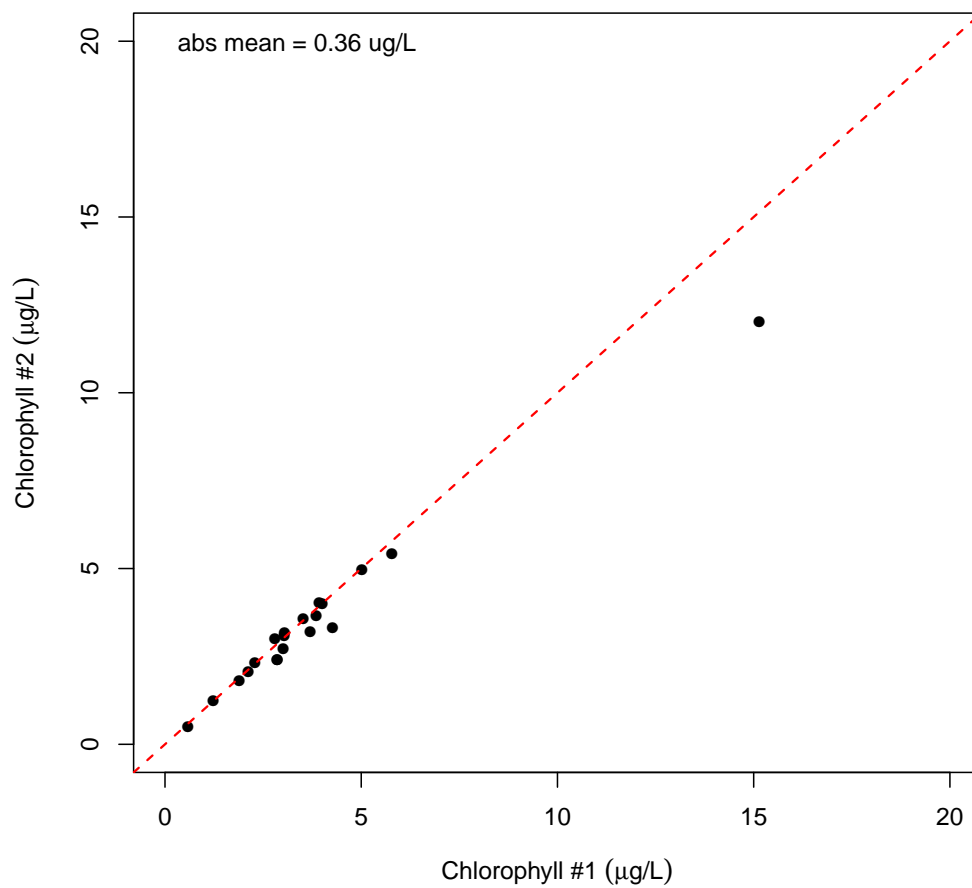


Figure C31: Chlorophyll field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship.

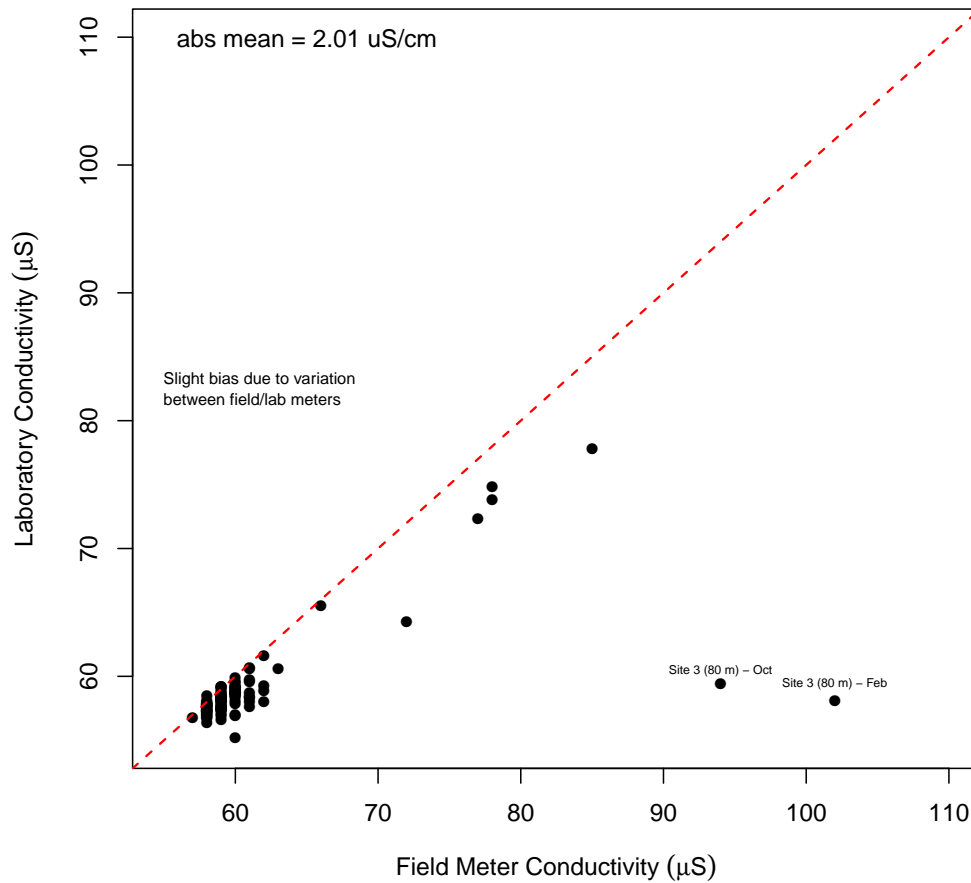


Figure C32: Conductivity field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship. The labeled outliers were collected Site 3 at 80 meters when extreme gradients were present. Field meter samples were collected at true depth; field duplicate samples were measured in the laboratory from samples collected using a marked line, which will be slightly shallower than true depth.

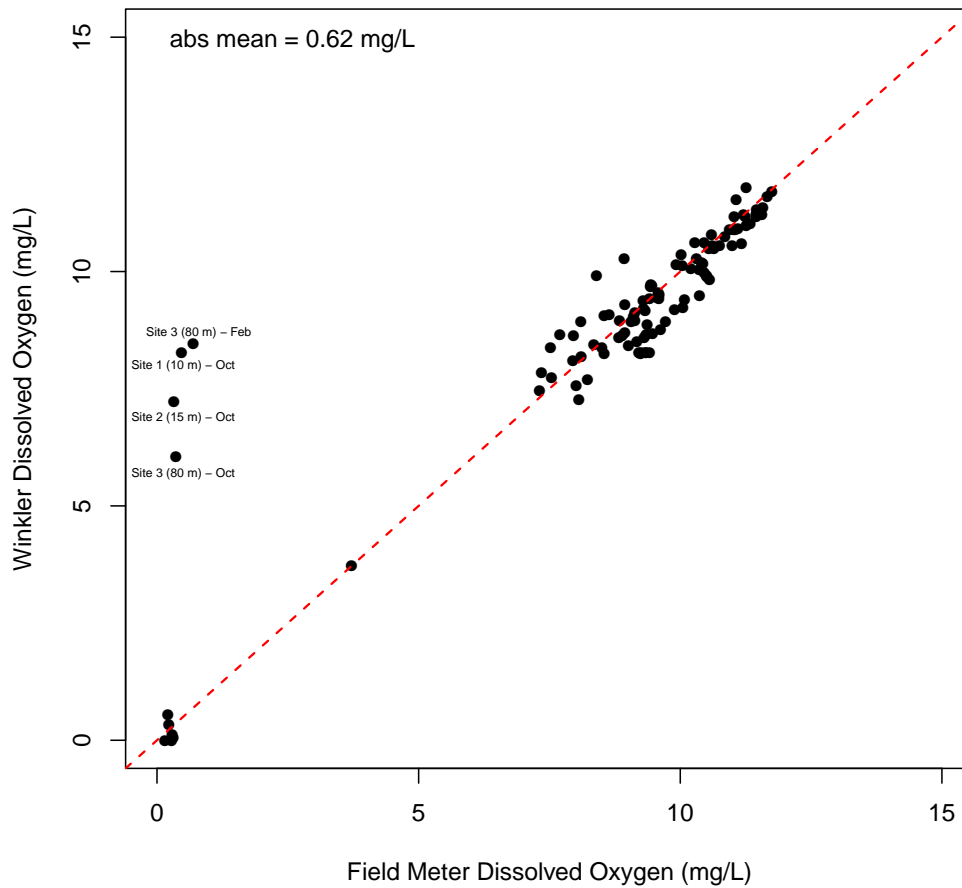


Figure C33: Dissolved oxygen field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship. The labeled outliers were collected Site 1 (10 m), Site 2 (15 m), and Site 3 (80 m) when extreme gradients were present. Field meter samples were collected at true depth; Winkler samples were measured in the laboratory from samples collected using a marked line, which will be slightly shallower than true depth.

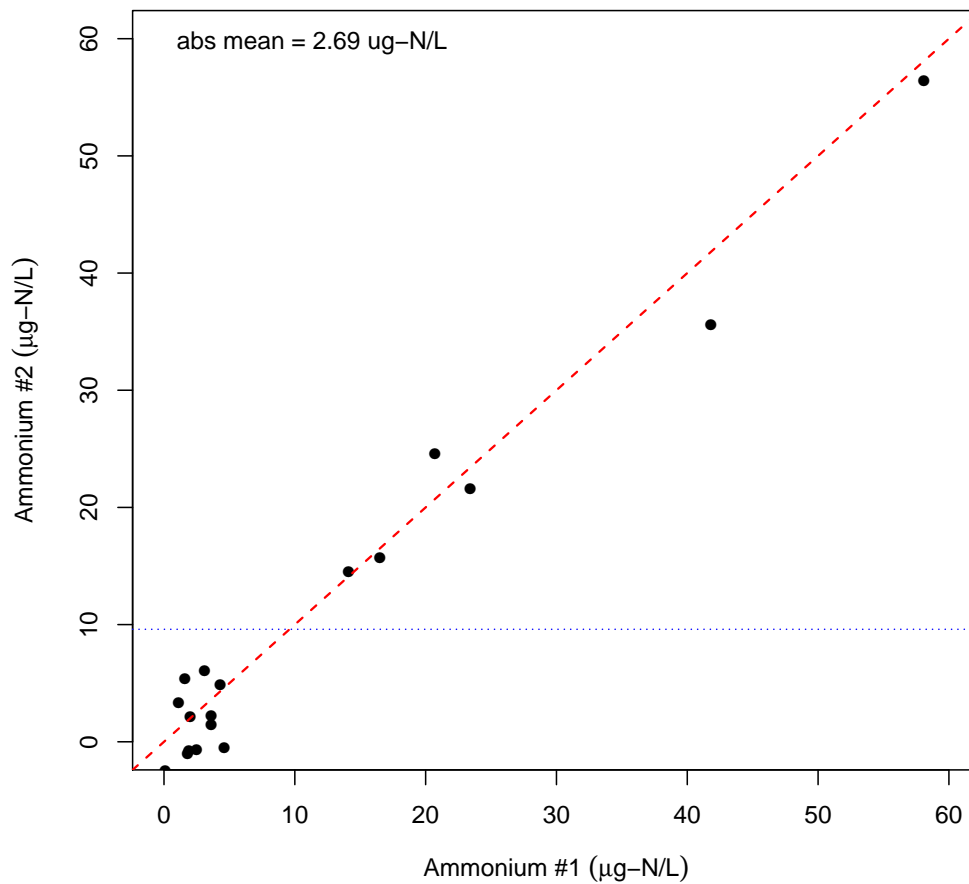


Figure C34: Ammonium field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit. The high degree of scatter is due to the low concentrations of the samples.

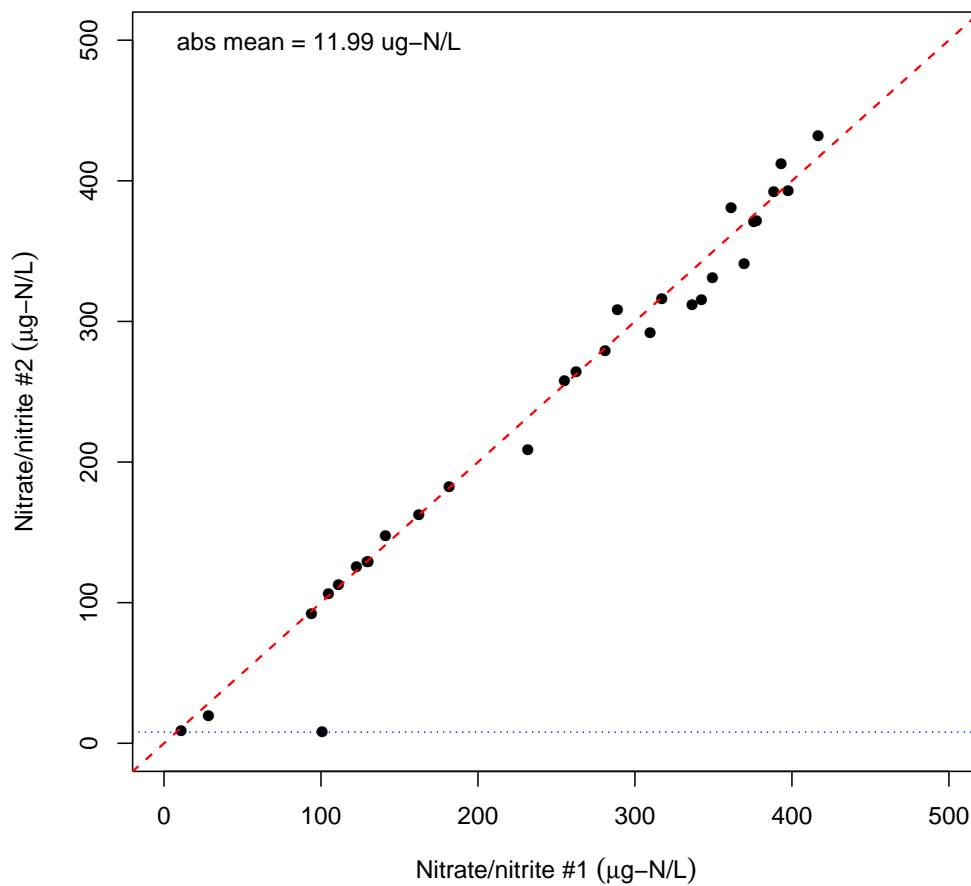


Figure C35: Nitrate/nitrite field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit.

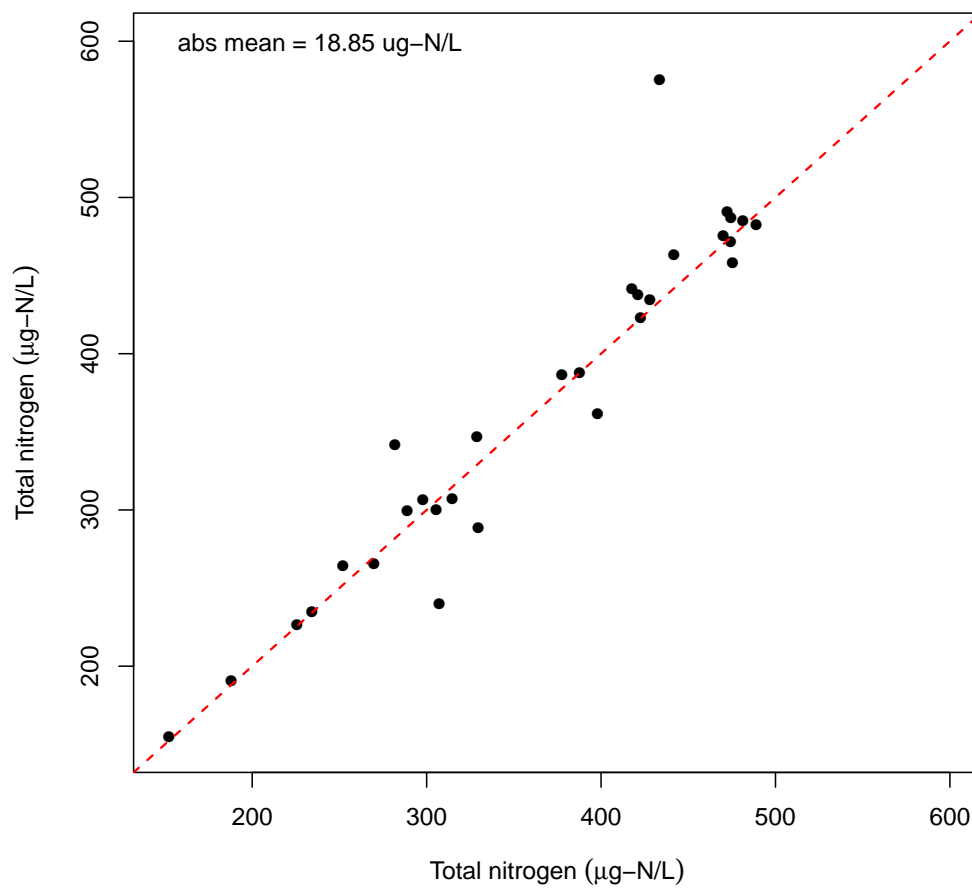


Figure C36: Total nitrogen field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship.

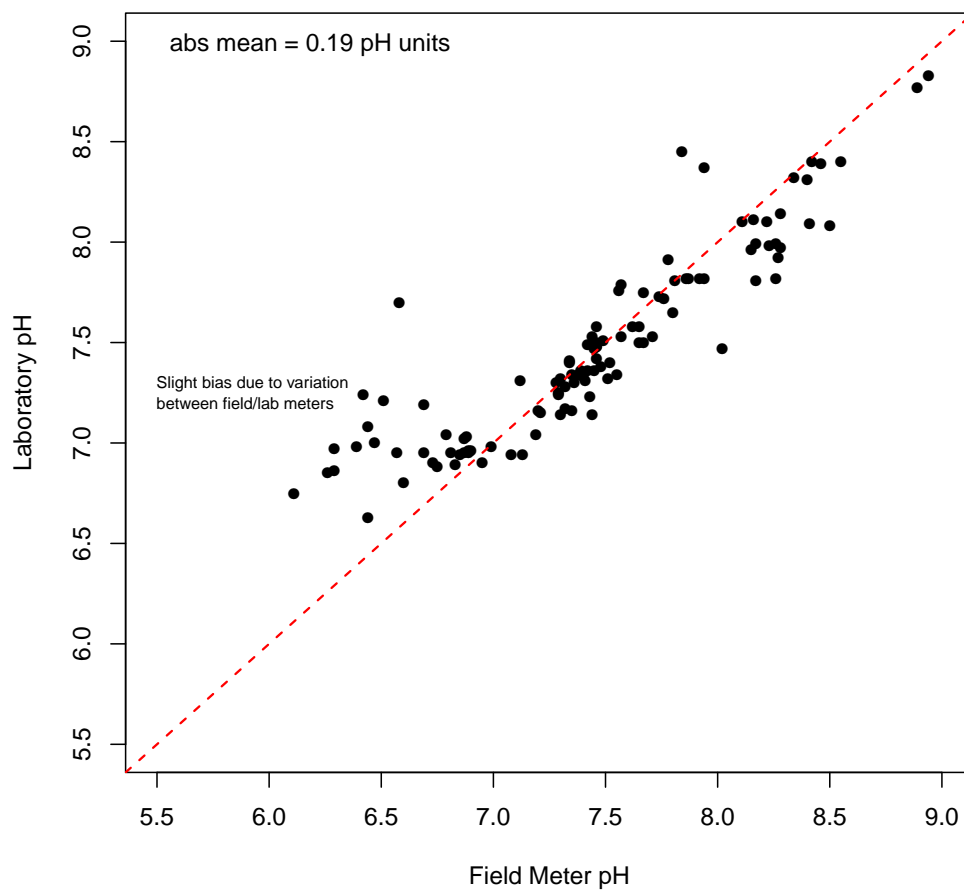


Figure C37: Field duplicates for pH from the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship.

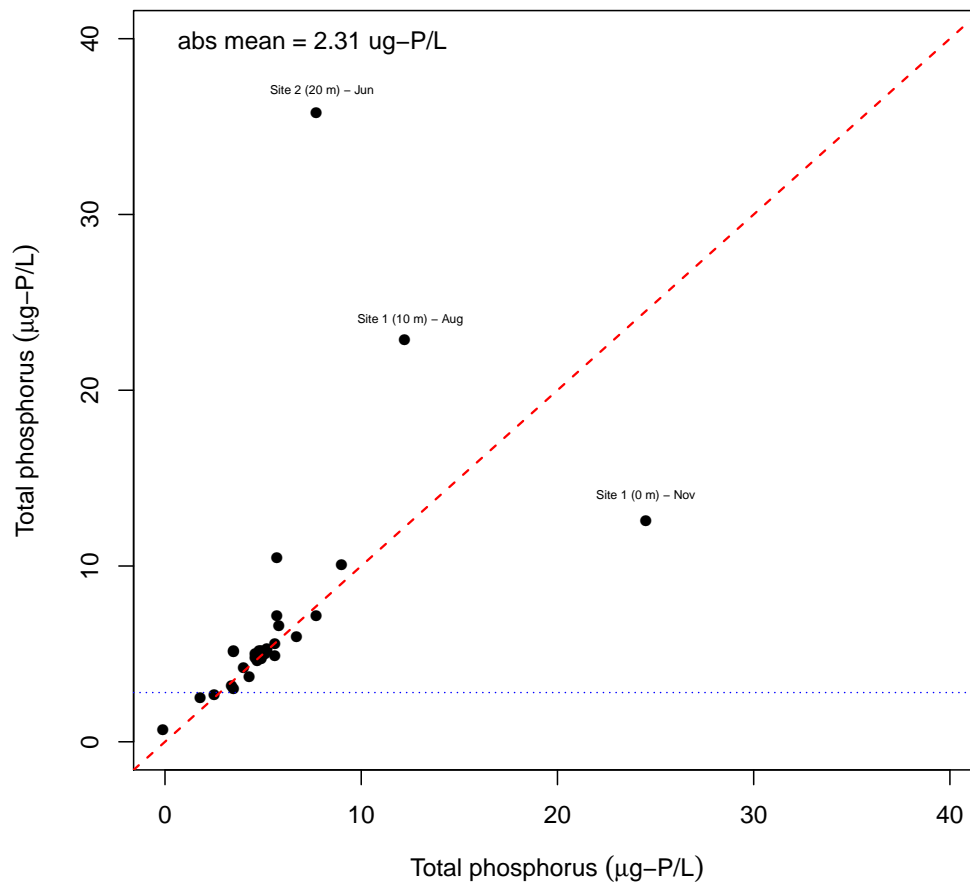


Figure C38: Total phosphorus field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship; horizontal reference line shows current detection limit. The labeled outliers may be due to the incorporation of suspended particles.

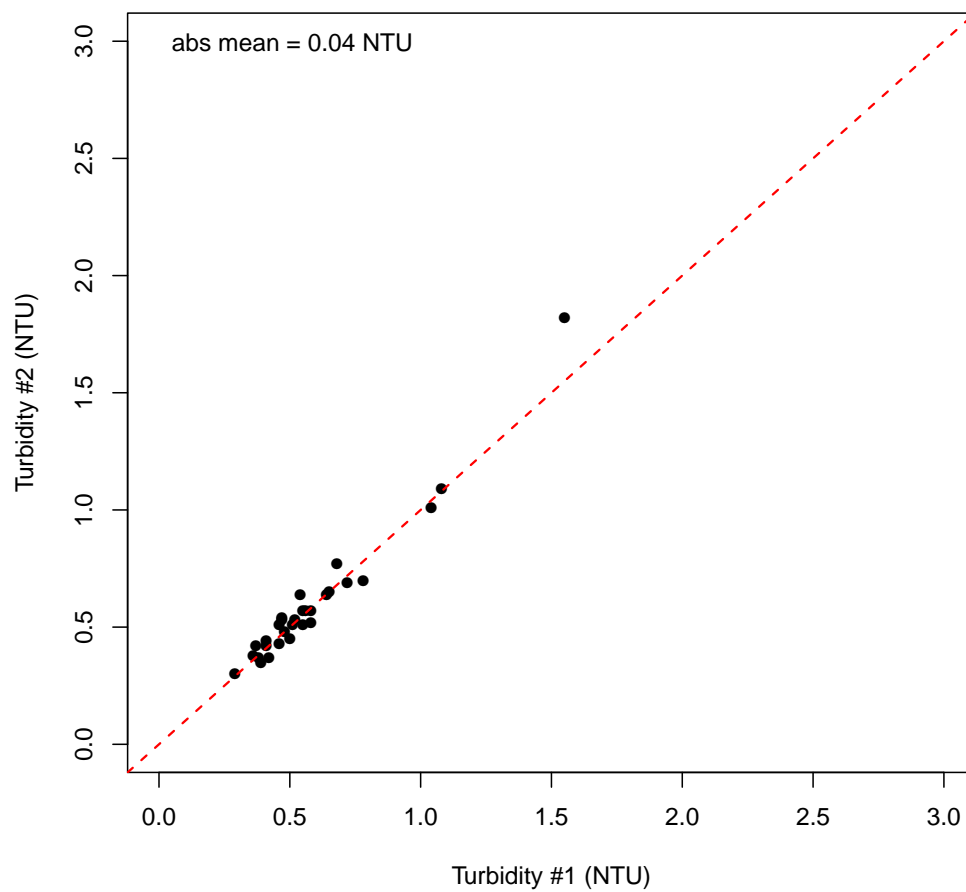


Figure C39: Turbidity field duplicates for the 2014/2015 Lake Whatcom monitoring program. Diagonal reference line shows 1:1 relationship.

D Lake Whatcom Online Data

The following **readme** file describes the electronic data posted at the IWS web site (www.wvu.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 DECEMBER 7, 2015
*****
Most of the Lake Whatcom water quality data are available in
electronic format at the IWS website (http://www.wvu.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

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

Plankton data

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

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.

* 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.