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Lake Samish Water Monitoring Project 2008 Final Report

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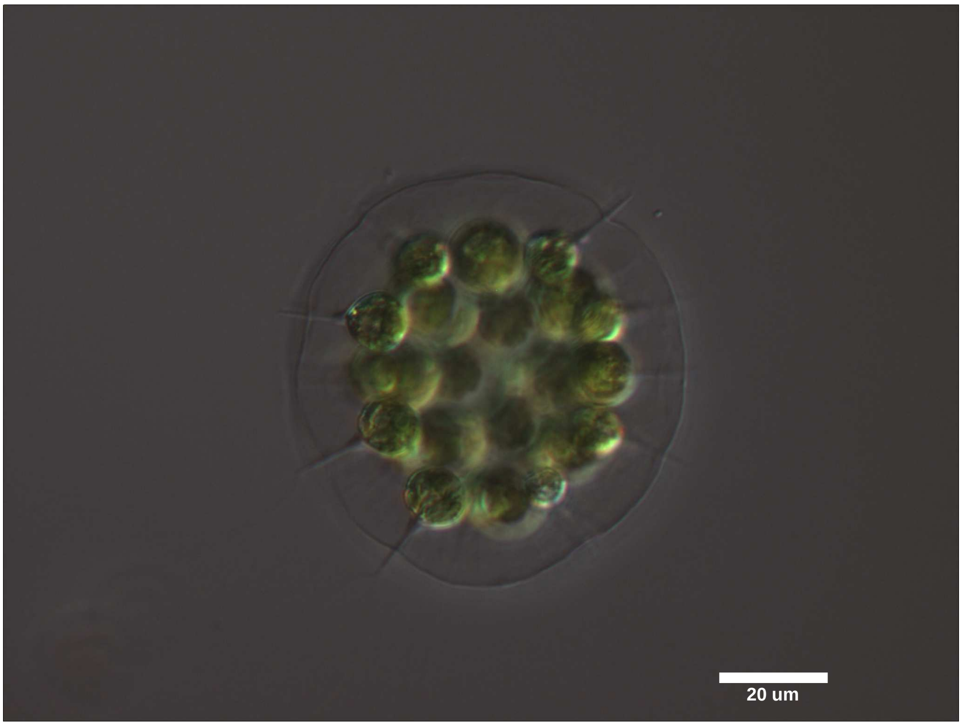

Lake Samish Water Monitoring Project
2008 Final Report

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1 Introduction

This report is a revised version of the 2006 and 2007 Final Reports by Matthews, et al., and contains most of the original text, updated figures, and additional discussion of all data collected from June 2005 through July 2008.

Lake Samish is a valuable aquatic resource, providing public access for boating, fishing, swimming, picnicking, and other water and lakeshore activities. Residents around the lake enjoy outstanding views of both the lake and its surrounding watershed, and the lake serves as a water supply for many of the lakeshore residents. Lake Samish is located in the Washington State Department of Ecology's water resource inventory area #3 (WRIA 3), and discharges into Friday Creek, a salmon spawning tributary of the Samish River.

The Lake Samish monitoring project was initiated in June 2005 to collect water quality data from the lake and from major tributaries in the watershed. Lake Samish experiences periodic algal blooms, including blooms of potentially toxic cyanobacteria. The major goal of the monitoring project was to collect data that would help identify the causes of the blooms, and possibly provide insight into how to protect the lake from water quality degradation.

2 Methods

2.1 Lake Sampling

Water samples were collected at representative sites in Lake Samish (Figure 1, page 24). The original scope of work specified monthly sampling at four sites (Sites A–D) from June 2005 through July 2006. This contract was amended through a no-cost extension to allow additional sampling at a reduced level of effort. During this extension, samples were collected as two sites (Sites A and B) from August through May 2006. In June 2007, under a new monitoring contract, the lake was again sampled at all four sites, but the sampling frequency was reduced to quarterly. Additional samples were collected at Sites A and B (at no cost) to provide supplemental water quality data for the lake. Table 1 (page 19) summarizes all samples collected from June 2005 through July 2008, Temperature and dissolved oxygen field measurements were collected at 1 meter depth intervals from the surface to the bottom at each site using a Hydrolab field meter. Beginning in March 2006, conductivity and pH profiles were also collected at 1 meter depth intervals using the Hydrolab field meter. Secchi depth was measured at each site by lowering a black and white disk into the water and recording the depth at which it was no longer visible from the lake surface. All field measurements followed the protocols summarized in Table 2 (page 20).

Surface and bottom water samples were collected at each lake site and transported to the laboratory to measure pH, conductivity, phosphorus (total phosphorus and soluble orthophosphate), nitrogen (total nitrogen, nitrate/nitrite[1], ammonium), turbidity, and alkalinity following the protocols listed in Table 2. Separate surface and bottom water samples were collected to measure fecal coliform counts; the coliform samples were delivered to the analytical laboratory the following morning.

From June 2005 through May 2007, chlorophyll fluorescence was measured in the field (*in vivo*) at 1 meter depth intervals from the surface to the bottom using a field fluorometer. Water samples were collected from approximately 10-20% of the depths where fluorescence was measured, and the water samples were used to measure chlorophyll biomass (Table 2). A linear regression between the paired *in vivo* fluorescence and chlorophyll biomass data was used to estimate chlorophyll biomass at all depths along the fluorescence profiles.[2] Due to equipment failure, field fluorometer data are not available after March 2007. Beginning in November 2007, chlorophyll biomass was measured directly (rather than estimated) using water samples collected at 5 meter depth intervals.

All water 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. All data for the Lake Samish monitoring project have been included in Appendix A.

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[1] Nitrate and nitrite were analyzed together because nitrite concentrations are usually very low in surface water and require low level analytical techniques to measure accurately.

[2] Chlorophyll biomass is more commonly used to describe lake trophic status than fluorescence, but fluorescence is easier to measure in the field.

2.2 Stream Sampling

Water samples were collected on the dates indicated in Table 1 from 4 tributaries flowing into Lake Samish and from the lake outlet at Friday Creek (Figure 1, page 24). Temperature and dissolved oxygen was measured using a field meter. Water samples were collected at each stream site and transported to the laboratory to measure pH, conductivity, phosphorus (total phosphorus and soluble orthophosphate), nitrogen (total nitrogen, nitrate/nitrite, ammonium), turbidity, and alkalinity. Separate water samples were collected to measure fecal coliform counts; the coliform samples were delivered on ice to the Samish Water District.

All water 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. All data for the Lake Samish monitoring project have been included in Appendix A.

3 Results and Discussion

3.1 Lake Samish

3.1.1 Water Temperature

Temperature profiles showed that much of the lake stratified from spring through early fall. Only Site D, which is very shallow, remained thermally unstratified throughout the year (Figures 2–33, pages 25–56).

Most lakes in our region will develop temperature stratification after the lake begins to warm during the spring. As the surface of the lake warms due to solar radiation, the surface water becomes less dense than the underlying cold water.[3] The surface water eventually forms a warm layer, the *epilimnion*, that is physically separated from the colder, denser lower layer, the *hypolimnion*. Once the lake is stratified, there is little exchange of dissolved chemicals between the layers. Algae and bacteria often accumulate in the transition zone between the layers, the *metalimnion*, where light is sufficient for photosynthesis and nutrients are often more available than at the surface.

[3]Water is most dense at 4°C; warmer water is less dense.

In the fall, the lake surface cools and the density difference between the epilimnion and hypolimnion decreases. Eventually, the surface and bottom water densities are sufficiently similar that wind-generated internal waves[4] mix the entire water column. This is called *turn-over* and is often accomplished within a few days (or hours) during the first major wind storm in the fall.

Based on the 2005–2008 data, the east arm of Lake Samish begins to stratify in April or May at locations where the water column is at least 12–15 meters deep (Sites B and C in Figures 11, 22, and 30). The lake remains stratified throughout the summer and early fall, and turns over in October or November, depending on weather conditions. In shallower areas (Site D), the water column does not maintain a stable stratification, and the water column mixed throughout the year.

Lake stratification in the west arm (Site A) is more complex. Site A develops temperature stratification by April (Figures 11 and 22) or earlier (see March 2008, Figure 31), and remains stratified throughout the summer and early fall. Destratification, however, does not follow the same pattern as at Sites B and C. Although Site A appears to reach uniform (cold) temperatures during the winter, the water column does not always mix completely. For examples, in February 2006, despite nearly uniform surface to bottom water temperatures, the water column at Site A was not completely mixed, and oxygen levels were near zero at the bottom of the lake (Figures 8–9). In 2007, the January temperature and oxygen profiles at Site A indicated complete water column mixing (Figure 19), while the January 2008 profile showed a very slight difference in oxygen in the surface and bottom samples (Figure 28), with uniform oxygen concentrations at all other depths.

This unusual pattern is called *intermittent meromixis*, and is probably the result of the relative isolation and protection of the west arm from prevailing winds, coupled with a small surface area and a deep, steep-sided basin (see discussion of meromixis by Hakala, 2004). When water temperatures are nearly uniform at Site A, a small amount of wind from the right direction will cause the water column to mix completely, creating uniform profiles for dissolved oxygen and other dissolved materials (e.g., Figure 19). If the right climate conditions do not occur, the water column will either maintain chemical stratification throughout the winter, or re-establish chemical stratification whenever the lake's slow water circulation rate is insufficient to replenish oxygen consumed by bacterial decomposition of organic matter.

[4]Wind energy generates many types of waves in lakes. See Wetzel (1983) for more information.

3.1.2 Dissolved Oxygen

All of the stratified sites in Lake Samish sites showed some degree of oxygen depletion in the hypolimnion during lake stratification (Figures 2–33). Epilimnetic oxygen concentrations were high during periods of stratification, and oxygen concentrations were high throughout the water column following lake turnover. Only Site A had low hypolimnetic oxygen concentrations during the winter.

Oxygen is required by most aquatic organisms, including fish, aquatic invertebrates, and most types of algae and bacteria. The primary source of dissolved oxygen in lakes is from the atmosphere. Although algae produce oxygen during daytime photosynthesis, they consume oxygen at night, and therefore have little effect on the net amount of dissolved oxygen in lakes. Hypolimnetic oxygen depletion can occur after a lake stratifies and the lower waters of the lake are isolated from the atmosphere. In nutrient-rich lakes, as bacteria decompose organic matter from dead algae or aquatic plants, they use up dissolved oxygen in the hypolimnion. Since the hypolimnion is isolated from the surface, no new supplies of oxygen are introduced into the hypolimnion until the lake turns over. Unproductive lakes that are low in plant nutrients, especially phosphorus, do not produce much organic matter. With less organic matter to decompose, bacteria may not use enough oxygen in unproductive lakes to cause a measurable drop in hypolimnetic oxygen concentrations.

Low oxygen conditions are associated with a number of unappealing water quality problems in lakes, including loss of aquatic habitat; release of phosphorus and nitrogen from the sediments; increased rates of algal production due to release of nutrients; unpleasant odors during lake overturn; fish kills, particularly during lake overturn; 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 byproducts created during the drinking water treatment process.

In addition to intermittent meromixis, Site A had another unusual feature that set it apart from the rest of the lake: it developed a region of supersaturated oxygen located in the transition zone between the epilimnion and hypolimnion (the *colorblue metalimnion*). This metalimnetic oxygen peak was evident at Site A every summer, usually by July (e.g., Figures 3, 14, and 33), but was not observed at the other sites until July 2008, when a clear metalimnetic oxygen peak developed at Site B (Figure 33). McNair (1995) reported similar metalimnetic oxygen peaks during the summer of 1993, but not in 1994. This pattern is commonly observed in the northern basin of Lake Whatcom (DeLuna, 2004; Matthews and DeLuna, 2008). Metalimnetic oxygen peaks are caused by an accumulation of rapidly photosynthesizing algae along the density gradient between the epilimnion and hypolimnion. Often, this is a region where algal nutrients are sufficient to support very high levels of photosynthesis. It is coupled with metalimnetic oxygen depletion at night as the dense band of algae consumes oxygen for metabolism.

3.1.3 Alkalinity, pH, and Specific Conductance

Alkalinity, pH, and specific conductance (conductivity) are related in surface water. Conductivity and pH both measure the amount of dissolved ions in water. Conductivity measures the resistance of water to flowing electrons, which is determined by the amount of dissolved ionic compounds in the water. Similarly, pH measures the acidity of water, which is determined by the availability of hydrogen ions. Alkalinity measures *buffering* or how resistant water is to pH changes. Alkalinity is measured analytically by adding hydrogen ions to see how fast pH is lowered.

The alkalinity, conductivity, and pH values in Lake Samish were all within the normal ranges for soft water lakes in this region (Figures 10–33 and 34–36, pages 33–56 and 57–59). Alkalinity concentrations were fairly low ($<$30 mg/L) throughout the sampling period (Figure 34). This means that Lake Samish is not well buffered against pH changes. When the water column in Lake Samish was stratified, surface alkalinities were often slightly lower than at the bottom and surface pH levels were often higher (Figures 34 and 35). During photosynthesis, algae remove dissolved CO_2 from the water, which can temporarily raise pH and lower alkalinity, especially in poorly buffered lakes like Lake Samish. The relationship between pH and photosynthesis is nicely illustrated when metalimnetic oxygen peaks occur, indicating high levels of photosynthesis (e.g., Figure 33).

As indicated above, the pH data showed the influence of photosynthesis and bacterial decomposition. During summer stratification, the surface pH levels increased due to the photosynthetic removal of CO_2. This caused a temporary reduction in the concentration of dissolved carbonic acid, which is formed when CO_2 reacts with water: $H_2O + CO_2 \leftrightarrow H_2CO_3$ (carbonic acid). Concurrently, the hypolimnetic pH levels decreased due to the accumulation of acidic decomposition products as bacteria broke down organic matter that settled to the bottom of the lake. This pattern is clearly illustrated in the summer Hydrolab profiles, which show high pH levels throughout the epilimnion and low pH levels throughout the hypolimnion (e.g., Figures 13–17).

Conductivity in lakes is determined by the types and amount of dissolved ions in the water. The soil type and land use in the watershed determine the potential amount of ionic compounds that can enter the lake from surface runoff and groundwater, while climate and hydrologic patterns determine the actual transport of dissolved ions. Surface runoff may have low conductivity levels when the runoff is significantly diluted by rain water, or high conductivity levels if there are soluble ionic compounds in the soils or on impervious surfaces. Groundwater will often have higher conductivity levels compared to surface runoff because water percolating through the soil has more time to pick up dissolved compounds.

From the Lake Samish tributary data (Section 3.2), the conductivity of surface water entering the lake during high flow (November 2005) was about 70–100 μS/cm, which was similar to the lake's surface conductivities ($\sim$60–80 μS/cm). Lake conductivities were usually higher in bottom samples, especially during stratification when low oxygen conditions at Sites A–C allowed dissolved ions to leak into the hypolimnion from the sediments.

3.1.4 Algal Nutrients: Nitrogen and Phosphorus

Nitrogen and phosphorus were measured in the laboratory from water samples collected at the surface and bottom of each site (Figures 37–41, paged 60–64). The samples were analyzed to measure total nitrogen, which includes organic and inorganic forms of nitrogen, as well as dissolved inorganic ammonium and nitrate/nitrite. Phosphorus was measured as total phosphorus (organic and inorganic phosphorus) and soluble, inorganic orthophosphate.

Nitrogen and phosphorus are important nutrients that influence algal growth in lakes. The type of nitrogen available in the water column often determines which species of algae will be abundant. Most algae can only use dissolved inorganic nitrogen for growth (DIN = ammonium, nitrite, and nitrate). During the summer, as algae take up dissolved nitrogen, the concentration of DIN in the epilimnion may fall so low that nitrogen becomes limiting to many types of algae. When this occurs, conditions favor the growth of cyanobacteria (bluegreen "algae") because they can convert dissolved nitrogen gas into usable forms of inorganic nitrogen.

Cyanobacteria have a second advantage because they can store extra phosphorus in the spring, when phosphorus is slightly more available, and use it to sustain growth throughout the summer and fall. This is why large blooms of cyanobacteria often develop in late summer or early fall, despite very low concentrations of nutrients in the water column.

Phosphorus is the nutrient that typically limits total algal growth because it is required by all algae, and the concentration of "bioavailable" phosphorus is usually quite low in lakes. Much of the phosphorus that enters lakes is tightly bound to surface of small particles or in organic matter that must be decomposed before the phosphorus is available for algal growth. Total phosphorus measurements, therefore, overestimate the amount of phosphorus available for algal growth. Bioavailable phosphorus includes soluble forms of phosphorus such as orthophosphate, organic phosphorus that can be released by decomposition, and phosphorus that can be released from the surface of particles by microbial enzymes or under low oxygen conditions. The fraction of total phosphorus that is bioavailable varies, but will fall between the orthophosphate and total phosphorus concentrations.

In Lake Samish, total nitrogen and nitrate/nitrite concentrations followed very similar seasonal patterns that included a progressive reduction of nitrate/nitrite during the summer due to algal uptake, and an increase in total nitrogen and nitrate/nitrite during the winter when the water column destratified. Ammonium concentrations were generally very low except in bottom samples during periods of stratification. In aerobic water, ammonium is rapidly converted into nitrite and nitrate by bacteria (or lost through volatilization), but when oxygen concentrations are low, these bacteria are not active, which allows ammonium to accumulate in the isolated hypolimnion.

The Lake Samish orthophosphate and total phosphorus concentrations were usually lower in surface samples at Sites A and B during periods of stratification (Figures 40 and 41). This was most likely caused by algal uptake in the epilimnion and phosphorus release from the sediments into the hypolimnion. Site D is too shallow to stratify so there was little difference between surface and bottom phosphorus concentrations.

3.1.5 Secchi Depth, Turbidity, Coliform Bacteria, and Chlorophyll

Secchi Depth and Turbidity: Secchi depth is an indicator of lake transparency and is defined as the depth at which a black and white disk is no longer visible from the lake surface. The Secchi depth determines the approximate depth of the *photic* zone, where light conditions favor photosynthesis. Turbidity is a measurement of the suspended particles in water, which includes algae as well as inorganic particles and non-living organic matter. When most of the suspended particles in the water column are algae, chlorophyll concentrations are usually good predictors for Secchi depth and turbidity: as algal densities increase, turbidity increases and Secchi depth decreases. When inorganic and non-algal particulates are present, however, only turbidity and Secchi depth are likely to be related.

In Lake Samish, Secchi depths did not appear to follow chlorophyll concentrations very closely, and some of the shallowest Secchi depth readings occurred during winter when algal densities and chlorophyll concentrations were very low (Figure 42, page 65). Similarly, there was no apparent relationship between surface turbidity levels and chlorophyll (Figure 43, page 66). Correlation analysis confirmed that while there was a strong correlation between Secchi depths and turbidity, there was only a minimal correlation between chlorophyll and Secchi depth, and no significant correlation between chlorophyll and turbidity (Figure 44, page 67).[5] This indicates that both algal and non-algal suspended particles are present in Lake Samish, and only direct measures such as chlorophyll or algal density should be used to estimate algal abundance.

Coliform Bacteria Coliform bacteria are a diverse group of bacteria that include species normally found in the intestinal tract and feces of warm blooded animals (*fecal coliforms*). Since fecal coliforms usually don't survive long outside their host, their presence can be used to detect sewage or fecal contamination in water samples. Most types of fecal coliform bacteria are not pathogenic, but if fecal coliforms are present, other potentially harmful pathogens may also be present.

The current surface water standards are based on "designated use" categories, which for Lake Samish is likely to be "Extraordinary Primary Con-

[5] Kendall's τ correlation analysis was used to examine the relationships between chlorophyll, turbidity, and Secchi depth. Correlation test statistics range 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.

tact Recreation." The standard for bacteria is described in Chapter 173–201A of the Washington Administrative Code, Water Quality Standards for Surface Waters of the State of Washington (online version available at http://www.ecy.wa.gov/biblio/wac173201a.html):

> *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.*

The geometric means for all of the Lake Samish sites was $<$2 cfu/100 mL[6], and only one sample exceeded 10 cfu/100 mL (Figure 45, page 68).[7] The IWS samples, however, were collected infrequently and from mid-lake locations, so if there are concerns about swimming beaches or drinking water safety, additional coliform samples should be collected following the sampling protocols described by WAC 173–201A.

Chlorophyll: Chlorophyll concentrations were measured using two techniques: *in vivo* algal fluorescence, which was measured in the field, and chlorophyll biomass, which was measured in the laboratory from water samples collected in the field (Figures 46–77, pages 69–100). Chlorophyll molecules fluoresce when exposed to certain wavelengths of light. This fluorescence can be measured easily and quickly using a field fluorometer attached to a pump that draws water from multiple depths throughout the water column. Measuring chlorophyll biomass is more time consuming and is rarely done at more than a few sites or depths because it requires collecting large volumes of water at each site and depth, followed by processing and analysis in the laboratory.

Although it is easy to measure algal fluorescence in the field, chlorophyll biomass is more widely used for lake monitoring, particularly for assessing lake trophic status. In theory, chlorophyll biomass can be predicted using algal fluorescence. In reality, chlorophyll fluorescence and biomass are related, but not identical. Figures 78 and 79 (pages 101 and 102) illustrate the relationship between fluorescence and *measured* chlorophyll biomass in paired water samples collected at the

[6]cfu = colony-forming units
[7]Site D - 7 meters, July 6, 2008 = 14 cfu/100 mL

same depths as the fluorescence measurements. The linear regression based on all data (Figure 78) was statistically significant, but there were obvious seasonal influences. When the data are separated by season, the summer and winter regressions were greatly improved (the adjusted R^2 was closer to 1.0), but the spring and fall regressions were not statistically significant (Figure 79). The spring and fall results were probably related to changed in algal metabolism. During the spring, algae start to grow rapidly; during the fall, algae begin to die back. Under both conditions, fluorescence and biomass are poorly correlated.

The chlorophyll profiles revealed seasonal patterns and showed the amount of variation related to depth and location in the lake. Algal fluorescence was usually higher in the summer and fall compared to the winter, Sites C and D usually had higher fluorescence values than Sites A and B, and fluorescence was usually higher in samples collected near the surface.

Metalimnetic chlorophyll peaks developed at all sites during the summer, but were especially common at Site A. These peaks represent dense bands of algae that may occupy only a few meters of the water column, and were paired with metalimnetic oxygen peaks (see discussion on page 5). Because the bands may only be a few meters thick, they are best observed using field fluorometry where data can be collected at 1 meter intervals. Water samples collected at 5 meter intervals usually miss the peaks.

Trophic State: One way to evaluate the Lake Samish chlorophyll concentrations is to use Carlson's Trophic State Index (Carlson and Simpson, 1966), which is widely used to classify lakes based on biological productivity. The index may be calculated using chlorophyll, Secchi depth, or total phosphorus concentrations:

$$\mathrm{TSI_{chl}} = 9.81\ (\ln \mathrm{CHL}) + 30.6$$

where CHL = chlorophyll concentration in mg/m^3

Chlorophyll is the most direct measurement of algal productivity, and when available, should be the primary basis for a trophic index (Carlson and Simpson, 1966). This is particularly important in Lake Samish because Secchi depth and phosphorus were poorly correlated with chlorophyll. Typically, unproductive or *oligotrophic* lakes have TSI values lower than 30 while productive or *eutrophic* lakes have TSI values higher than 50. Moderately productive *mesotrophic* lakes lie in the middle with TSIs of 40–50.

Most of the Lake Samish TSI_{chl} values fell within the mesotrophic range of 40–50 (Table 3 and Figures 80–83, pages 21 and 103–106). The summer TSIs (July–Oct) were often higher than winter TSIs, and there was a general gradient of increasing TSI values from Site A → Site B → Site C → Site D (Table 3).

Sites A and B had the lowest TSIs, with summer medians of 38.3 and 41.8, respectively, which would place them in the mesotrophic classification (Table 3). Sites C and D had higher summer TSIs (summer medians = 46.5 and 47.1, respectively), indicating that these sites are near the upper limits of mesotrophic, and occasionally could be classified as eutrophic. Eutrophic lakes commonly experience problems with blooms of cyanobacteria, particularly if the epilimnetic inorganic nitrogen concentrations fall during the summer (see discussion in Section 3.1.4). In Lake Samish, cyanobacteria blooms have been observed regularly in plankton samples collected during summer and fall (R. Matthews, personal observation). Typically, the Lake Samish blooms contain common "nuisance" taxa, including *Gloeotrichia echinulata*, *Microcystis aeruginosa*, *Woronichnia naegelianum*, and a variety of *Anabaena* species.[8]

3.2 Creeks in the Lake Samish Watershed

Four tributaries to Lake Samish and the outlet from Lake Samish were sampled on July 15 and November 10, 2005, July 16 2007, and March 17 2008.[9] Two of the tributaries were unnamed, so they were assigned temporary names as indicated on Figure 1.

Water temperatures were higher and dissolved oxygen concentrations were lower in Friday Creek compared to the other sites (Table 4, page 22). Some of these differences may have been caused by the later sampling date for Friday Creek during the summer of 2005; however, the water temperatures on July 16, 2007 were also higher in Friday Creek compared to the other sites. All of the sites had relatively low alkalinities (<60). Barnes Creek usually had the highest alkalinity

[8] Digital images of common Lake Samish algae are posted online in the IWS digital image library at http://www.ac.wwu.edu/∼iws.

[9] The Friday Creek sample was accidentally omitted from the first sampling trip so we collected a Friday Creek sample on August 9, 2005.

and pH values, which may reflect differences in soils or land use in the drainage area for that creek. Turbidities were generally low (1–2 NTU), with occasional spikes that did not follow any obvious seasonal or site-specific pattern.

The ammonium concentrations were slightly elevated in Friday Creek on most sampling dates (Table 5, page 23), reflecting the export of ammonium from the shallow, productive east arm of Lake Samish. The outlet concentrations were similar to the surface concentrations at Site D (Figure 39), and were much lower than the ammonium concentrations in anaerobic bottom samples at Sites A–C. Mud Creek had an unusually high ammonium concentration on November 2005 and slightly elevated concentration on July 16, 2007. High ammonium concentrations are uncommon in well-oxygenated streams, but because ammonium is soluble, it could have washed into the creek from a nearby source. The most common sources of ammonium in oxygenated surface water include animal waste, fertilizer, or ammonium from upstream wetlands.[10] The fecal coliform counts were fairly low on both dates, so it is unlikely that the ammonium came from animal waste, and more likely that it came from fertilizer or an upstream wetland.

The total nitrogen and nitrate/nitrite concentrations were very high in all tributaries to Lake Samish. The nitrogen may have come from the watershed soils, particularly if there were large numbers of red alder (*Alnus rubra*) upstream from the sampling sites. The roots of red alder host a beneficial fungal community that fixes N_2 nitrogen into nitrate, which is easily absorbed by the host tree, but also easily leached into adjacent streams. The highest nitrate/nitrite concentrations were measured in November 2005 and March 2008, coinciding with short day lengths (less plant uptake) and rainy weather (more leaching from soils). The total nitrogen and nitrate/nitrite concentrations were lower at the lake outlet, particularly in August 2005, when the nitrate/nitrite concentration was only 10.2 μg-N/L. This is consistent with lake data that showed significant nitrate uptake by algae during the summer.

The total phosphorus and orthophosphate concentrations were higher in the tributaries than in the Friday Creek outlet due to algal uptake of phosphorus in Lake Samish. The phosphorus concentrations were high compared to surface samples from Lake Samish (Figures 41–40) and may provide a significant source of phosphorus to the lake. These results indicate that Lake Samish has both external (watershed) phosphorous sources and internal sources from anoxic lake sediments.

[10] Wetlands soils are often anaerobic, and can discharge ammonium and other reduced compounds during periods of high flow.

The fecal coliform data were difficult to interpret because most of the summer 2005 values were above the detection limit of 23 cfu/100 mL, and the flow in Mia Creek was too low to sample in July 2007. Of the samples that could be analyzed, 33% (5/15) were $\geq$100 cfu/100 mL, indicating that there needs to be a more intensive monitoring of fecal coliforms in watershed, particularly since the lake serves as a drinking water source for many of the lakeshore residents.[11] The coliform levels in the lake were usually low ($<$10 cfu/100 mL), but lake coliform samples were off-shore in fairly deep water, and may not reflect conditions at private drinking water intake locations.

4 Summary and Recommendations

These recommendations are essentially the same as those presented previously by Matthews, et al. (2007), but have been updated to include the 2005–2008 monitoring period.

Although the primary goal for this project was to collect baseline water quality data, a second goal was to begin looking as options for protecting water quality in the lake. A full assessment of lake management options is beyond the scope of this project, but several important observations can be made concerning the direction of future lake management efforts.

First, is it important to recognize the features of Lake Samish that will affect management options and factor heavily into the success of any lake management effort. Lake Samish is predominantly a shallow, mesotrophic lake. With the exception of the west arm, which is unusual in itself, the lake favors the growth of aquatic plants, whether they are algae, cyanobacteria, or shoreline vegetation. The mean depth in the east arm is only 9.4 m (Figure 1), and all of the east arm sites had high chlorophyll concentrations at some point during the monitoring project (Figures 46–77). While the lake is shallow enough to support algal growth throughout the water column, it is deep enough to stratify in both arms. Because of it's mesotrophic state, the hypolimnion in both arms became anoxic, releasing phosphorus. The west arm appears to be intermittently meromictic, which resulted in extended periods of anoxia in the hypolimnion (e.g., Figures 10–13) and

[11]The Whatcom County Health Department does not support using surface water for a private domestic water supply.

the release of large amounts of phosphorus from the sediments (Figures 40–41). The release of phosphorus from sediments due to low oxygen concentrations in the hypolimnion is called *internal loading*, and is one of the items that must be considered in the future management of Lake Samish.

A second important feature that affects lake management is land use in the Lake Samish watershed. The tributary data revealed that there is *external loading* of phosphorus from the watershed. The lakeshore is developed, mostly with single-family homes, and the upper watershed is largely devoted to forestry and timber harvesting. A major interstate highway, with heavy truck and vehicle traffic, passes along the eastern side of the lake. Although these land use activities are not necessarily incompatible with recreational use of the lake, they are not particularly desirable in a lake that provides drinking water for lakeshore residents.

Our recommendations for Lake Samish focus on controlling external phosphorus loading, minimizing internal phosphorus loading, and educating watershed residents about drinking water issues and lake stewardship. These recommendations are not intended to serve as a substitute for developing a comprehensive lake management plan.

Recommendations for Maintaining Lake Samish Water Quality

- Develop an environmental education program to help residents of the Lake Samish watershed understand the water quality issues in the lake, and what can be done at the individual level. One example of this is the Watershed Pledge Program developed for the Lake Whatcom watershed (http://www.watershedpledge.org). While it may be difficult to measure the direct success of public education programs in terms of water quality improvement, an educated public is more likely to understand and support watershed and lake management actions.

- Develop strategies for controlling external phosphorus loading. Phosphorus is very difficult to remove after it get into streams or lakes, so where possible, source control remains the best approach. This means either reducing the amount of phosphorus that enters surface runoff (e.g., using phosphorus-free fertilizers) or decreasing the amount of surface runoff that enters the lake (e.g., adding retention/detention basins that facilitate infiltration into the groundwater). The Watershed Pledge Program lists a number of ways to reduce phosphorus in surface runoff near homes. Because of the scale of this task, the Samish Water District should work with an experienced storm water consultant to develop a comprehensive storm water management plan for the watershed.

Lake Samish is already mesotrophic, and in some cases eutrophic, so reducing external phosphorus loading from the watershed will probably not eliminate cyanobacteria blooms. If external loading is reduced, however, the lake should stabilize around its current levels of productivity, and possibly even show some improvement over a long period of time.

- Optionally, after external phosphorus loading has been addressed, develop strategies for reducing internal phosphorus loading. There are many lake management techniques that, given sufficient funding for installation *and maintenance*, can be used to reduce internal loading. The addition of chemicals such as alum will bind with phosphorus, often resulting in years of reduced algal densities. The effect is temporary, and reapplication of the chemical is required on a periodic basis. Hypolimnetic aerators are available that can maintain sufficient oxygen in the hypolimnion to prevent internal phosphorus loading. Aerators are also available that circulate the entire water column, but in most stratified lakes, this is not a desirable approach, and may even increase algal growth. All of these techniques require a significant initial investment, long-term funding for maintenance, and are unlikely to be effective if external loading is not controlled.

- Consider developing a public drinking water supply and distribution system. The algal densities in the lake were very high and probably contribute to the formation of harmful disinfection by-products, particularly in systems that disinfect the water by chlorinated. Although the coliform levels were low in the lake, the results may not reflect conditions at private drinking water intakes. Finally, the lake is subject to potentially hazardous cyanobacteria blooms and exposed to potentially hazardous chemicals from boating activities and the nearby highway. These represent an ongoing risk to individuals drawing domestic drinking water from the lake.

- Conduct an evaluation of on-site sewage disposal in the upper watershed, and its potential influence on water quality in Lake Samish. This evaluation should be included in the assessment of external phosphorus loading into the lake. On-site sewage disposal may be a minor factor in phosphorus loading into the lake because the Lake Samish shoreline is served by a public sewer line, so only portions of the upper watershed are likely to have on-site sewage disposal.

- Although monitoring priority pollutants was beyond the scope of this project, Lake Samish was placed on Washington State's 2004 Water Quality Assessment 303(d) list due to the levels of PCBs and mercury in sports fish collected from the lake. The levels of PCBs were high enough to generate a "Category 5" listing, which will require the Department of Ecology to develop a Total Maximum Daily Load (TMDL) assessment aimed at reducing PCBs in the lake. The mercury levels were lower, resulting in a Category 2 listing that identifies "waters of concern" where there is evidence of a water quality problem but not enough data to require a TMDL.

  High levels of mercury and PCBs have been found in fish tissue from many other lakes in Washington, and throughout North America, so the presence of these pollutants in Lake Samish reflects widespread contamination of freshwater lakes rather than a unique local source. Nevertheless, due to the popularity of sports fishing in Lake Samish, we recommend additional monitoring of priority pollutants in water, sediments, and fish tissue in Lake Samish.

5 References

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Sample Number	Date	Sites	Measured Parameters‡	Chlorophyll Measurements
1	June 15, 2005†	A–D	hl (no pH/cond), wq	profiles (A, B, D only)
2	July 20, 2005†	A–D, creeks	hl (no pH/cond), wq	profiles
3	August 23, 2005†	A–D	hl (no pH/cond), wq	profiles
4	September 20, 2005†	A–D	hl (no pH/cond), wq	profiles (A, B only)
5	October 16, 2005†	A–D	hl (no pH/cond), wq	profiles (A, B only)
6	November 20, 2005†	A–D, creeks	hl (no pH/cond), wq	profiles
7	January 22, 2006†	A–D	hl (no pH/cond), wq	biomass (misc depths)
8	February 26, 2006†	A–D	hl (no pH/cond), wq	profiles
9	Mar 19, 2006†	A–D	hl, wq	profiles
10	April 23, 2006†	A–D	hl, wq	profiles
11	May 21, 2006†	A–D	hl, wq	profiles
12	June 20, 2006†	A–D	hl, wq	profiles
13	July 19, 2006†	A–D	hl, wq	profiles
14	August 24, 2006	A & B	hl, wq (no coliforms)	profiles (A, B only)
15	September 18, 2006	A & B	hl, wq (no coliforms)	biomass (misc depths)
16	October 22, 2006	A & B	hl, wq (no coliforms)	profiles (A, B only)
17	December 18, 2006	A & B	hl, wq (no coliforms)	profiles (A, B only)
18	January 30, 2007	A & B	hl, wq (no coliforms)	profiles (A, B only)
19	February 27, 2007	A & B	hl, wq (no coliforms)	profiles (A, B only)
20	March 29, 2007	A & B	hl, wq (no coliforms)	profiles (A, B only)
21	April 24, 2007	A & B	hl, wq (no coliforms)	no data
22	May 24, 2007	A & B	hl, wq (no coliforms)	profiles (Site B only)
23	June 21, 2007†	A–D	hl, wq	biomass (misc depths)
24	July 16, 2007	creek sampling only		
25	September 13, 2007	A–D	hl, wq (no coliforms)	biomass (misc depths)
26	November 15, 2007	A & B	hl, wq (no coliforms)	biomass (5 m intervals)
27	December 20, 2007†	A–D	hl, wq	biomass (5 m intervals)
28	January 29, 2008	A & B	hl, wq (no coliforms)	biomass (5 m intervals)
29	March 25, 2008†	A–D, creeks	hl, wq	biomass (5 m intervals)
30	April 21, 2008	A & B	hl, wq (no coliforms)	biomass (5 m intervals)
31	May 15, 2008	A & B	hl, wq (no coliforms)	biomass (5 m intervals)
32	June 10, 2008†	A–D	hl, wq	biomass (5 m intervals)
33	July 22, 2008	A & B	hl, wq (no coliforms)	biomass (5 m intervals)

†Contract sampling dates.

‡ Lake measurements included Secchi depth and Hydrolab profiles (hl) for dissolved oxygen, water temperature, pH, and conductivity (cond); water quality samples (wq) were analyzed to measure alkalinity, lab conductivity, total nitrogen, nitrate/nitrite, ammonium, total phosphorus, soluble orthophosphate, turbidity, chlorophyll, and fecal coliforms. Creek measurements included dissolved oxygen and temperature, laboratory pH and cond, all wq analyses except chlorophyll.

Table 1: Summary of Lake Samish sampling dates showing sites that were sampled and parameters that were collected on each date. See specific methods descriptions (beginning on page 1) for details.

Analyte	Abbr.	Method Reference (APHA 1998)	Detection Limit/ Sensitivity
Alkalinity	Alk	SM2320, titration	$\pm$0.5 mg $CaCO_3$/L
Chlorophyll - field	Chl	Turner fluorometer (field meter)	NA
Chlorophyll - lab	Chl	SM10200 H, acetone extraction	$\pm$0.1 mg/m^3
Conductivity - field/lab	Cond	SM2510, lab or field meter	$\pm$0.1 units
Dissolved oxygen - field	DO	SM4500-O G.,membrane electrode (field meter)	$\pm$0.1 mg/L
Dissolved oxygen - lab	DO	SM4500-O C., Winkler, azide	$\pm$0.1 mg/L
Fecal coliforms	FC	SM9221 E , MPN*	$<$1.1 or $<$2
Nitrogen - ammonium	NH_3	SM4500-NH3 H., flow inject, phenate	10 μg NH_3-N/L
Nitrogen - nitrate/nitrite	NO_3	SM4500-NO3 I., flow inject, Cd reduction	10 μg NO_3-N/L
Nitrogen - total	TN	SM4500-NO3 I., flow inject, persulfate digest	10 μg N/L
pH - field/lab	pH	SM4500-H, electometric lab or field meter	$\pm$0.1 units
Phosphorus - orthophosphate	OP	SM4500-P G., flow inject	3 μg PO_4-P/L
Phosphorus - total	TP	SM4500-P G., flow inject, persulfate digest	5 μg P/L
Temperature - field	Temp	SM2550 thermistor (field meter)	$\pm$0.1 C
Turbidity	Turb	SM2130, nephelometric	$\pm$0.2 NTU

*Fecal coliform analyses were provided by Edge Analytical, 805 Orchard Dr., Bellingham, WA.

Table 2: Summary of analytical methods used by the Institute for Watershed Studies in the Lake Samish monitoring project.

All Months and Years

	Min.	Median	Mean	Max.
A	8.0	36.4	36.5	54.5
B	23.8	40.7	39.8	56.4
C	27.1	42.6	42.0	56.3
D	32.4	43.2	42.4	53.8

Summer (July-October)

	Min.	Median	Mean	Max.
A	23.8	38.3	38.8	52.6
B	23.8	41.8	40.9	50.5
C	37.4	46.5	46.1	54.2
D	40.0	47.1	46.7	50.4

Table 3: Summary of TSI_{chl} results for Lake Samish. Results include data collected from June 2005 through July 2008.

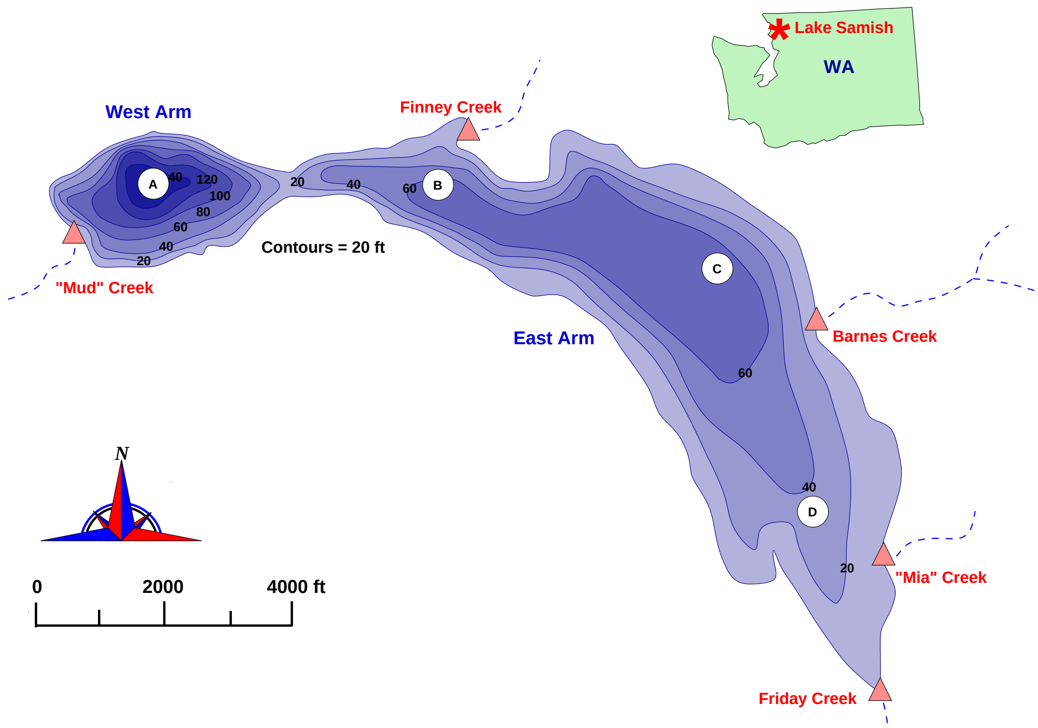
Site	Date	DO (mg/L)	Temp (C)	Alk (mg/L)	Turb (NTU)	pH	Cond (μS)
Barnes Creek	Jul 15, 2005	10.2	12.5	52.0	4.6	7.2	128.7
	Nov 10, 2005	14.7	9.0	37.5	2.7	7.5	103.4
	Jul 16, 2007	10.1	12.9	59.7	1.2	7.3	139.7
	Mar 17, 2008	12.5	6.0	40.0	2.7	7.6	102.6
Finney Creek	Jul 15, 2005	9.7	13.5	28.0	0.8	7.1	149.8
	Nov 10, 2005	14.7	9.2	12.2	3.0	7.2	75.2
	Jul 16, 2007	8.8	16.2	41.4	0.3	7.2	399.0
	Mar 17, 2008	12.7	5.6	16.2	3.9	7.3	92.9
Friday Creek (outlet)	Aug 9, 2005	4.1	20.5	21.3	3.7	6.1	69.4
	Nov 10, 200 5	8.5	10.7	19.7	0.9	7.2	68.4
	Jul 16, 2007	4.8	21.9	19.7	1.4	6.4	66.5
	Mar 17, 2008	12.4	6.4	17.6	1.5	7.3	66.4
Unnamed (Mia Creek)	Jul 15, 2005	9.1	13.4	31.8	2.5	6.7	82.7
	Nov 10, 2005	13.6	9.2	18.0	1.9	7.1	73.9
	Jul 16, 2007	na	na	na	na	na	na
	Mar 17, 2008	10.9	6.5	32.0	11.9	7.0	131.8
Unnamed (Mud Creek)	Jul 15, 2005	8.3	12.9	24.7	0.8	6.3	94.2
	Nov 10, 2005	14.6	8.5	15.9	0.9	7.1	74.8
	Jul 16, 2007	9.1	13.5	19.2	1.1	6.4	83.8
	Mar 17, 2008	12.5	5.9	15.1	1.4	7.1	67.0

Table 4: Dissolved oxygen (DO), temperature (Temp), alkalinity (Alk), turbidity (Turb), pH, and conductivity (Cond) results for Lake Samish watershed creeks.

Site	Date	NH_3	TN	NO_3	TP	OP	FC (cfu/
Site	Date	(μg-N/L)	(μg-N/L)	(μg-N/L)	(μg-P/L)	(μg-P/L)	100 mL)
Barnes	Jul 15, 2005	17.1	1082.7	915.6	46.0	26.9	>23
Creek	Nov 10, 2005	<10	1670.0	1518.2	15.1	9.0	23
	Jul 16, 2007	<10	756.9	678.4	18.0	24.3	240
	Mar 17, 2008	10.0	882.0	767.0	17.1	11.6	4
Finney	Jul 15, 2005	11.7	747.6	622.2	33.1	35.3	>23
Creek	Nov 10, 2005	<10	2061.5	1860.4	15.1	5.7	130
	Jul 16, 2007	24.2	585.9	434.8	9.3	21.4	170
	Mar 17, 2008	<10	1197.0	1089.0	13.2	7.2	52
Friday	Aug 9, 2005	40.6	361.9	10.2	25.9	<3	130
Creek	Nov 10, 2005	28.0	409.8	187.9	9.6	<3	8
(outlet)	Jul 16, 2007	23.0	358.3	88.0	13.8	7.8	80
	Mar 17, 2008	<10	590.0	424.0	5.4	<3	8
Unnamed	Jul 15, 2005	14.5	478.3	293.4	49.8	30.9	>23
(Mia Creek)	Nov 10, 2005	<10	1890.9	1666.2	21.2	10.3	23
	Jul 16, 2007	na	na	na	na	na	na
	Mar 17, 2008	13.2	801.0	534.0	20.5	5.7	104
Unnamed	Jul 15, 2005	<10	582.1	474.3	20.2	15.5	>23
(Mud Creek)	Nov 10, 2005	108.6	2308.4	1901.7	18.6	8.7	13
	Jul 16, 2007	31.7	551.2	464.9	11.7	8.2	23
	Mar 17, 2008	<10	1328.0	1211.0	9.1	7.2	4

*Sample above detection limit of 23 cfu/100 mL

Table 5: Ammonium (NH_3), total nitrogen (TN), nitrate/nitrite (NO_3), total phosphorus (TP), soluble orthophosphate (OP), and fecal coliform (FC) results for Lake Samish watershed creeks.



	Lake Samish Morphology			
	West Arm		East Arm	
Size	130 acre	0.53 km^2	680 acre	2.75 km^2
Maximum depth	140 ft	42.6 m	75 ft	22.9 m
Mean depth	71 ft	21.6 m	31 ft	9.4 m
Lake volume	9230 acre-ft	11.3×10^6 m^3	21,080 acre-ft	26.0×10^6 m^3
Drainage area	3.70 sq mi	9.58 km^2	9.20 sq mi	215.5 km^2
Altitude	273 ft	83.2 m	273 ft	83.2 m
Shoreline length	1.8 mi	2.9 km	6.3 mi	10.1 km

Figure 1: Lake Samish sampling sites, 2005–2008. Figure redrawn from Bortleson, et al. (1976); morphology data from Bortleson, et al. based on survey data collected by the Washington State Dept. of Game in 1956.

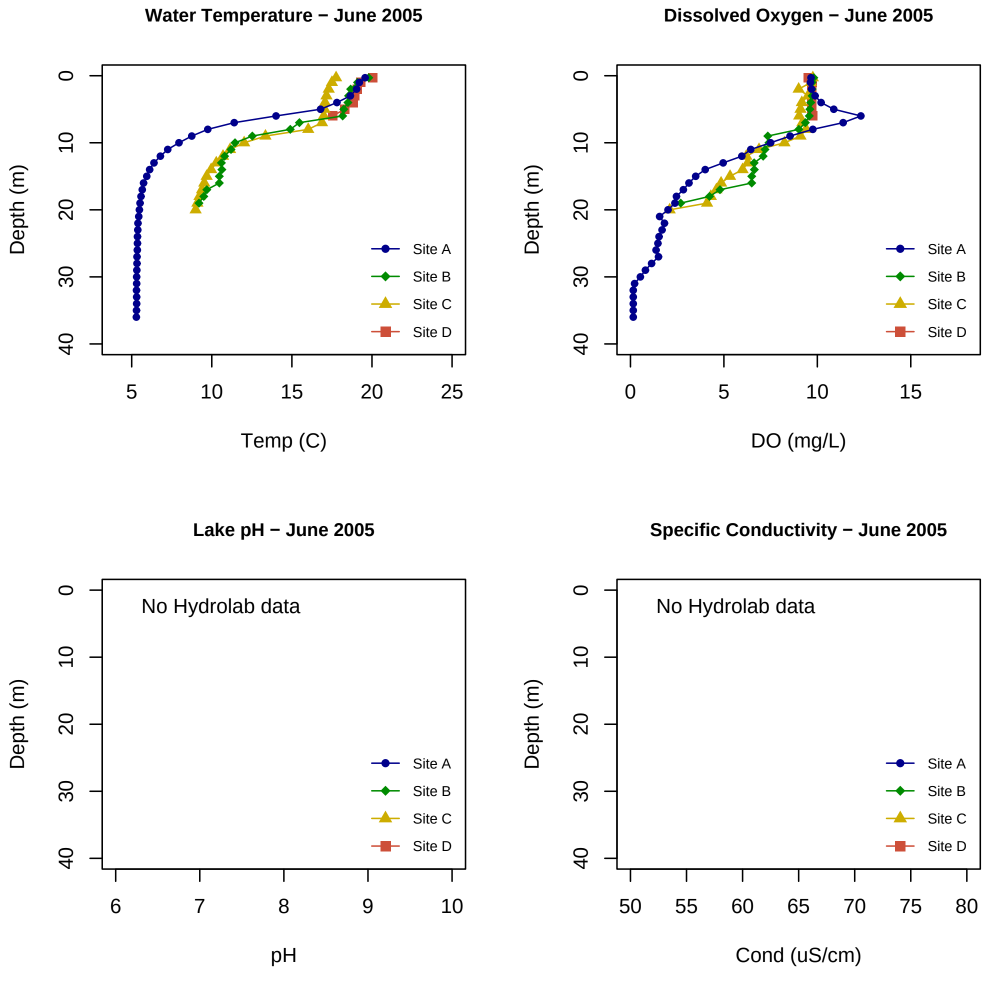


Figure 2: Lake Samish Hydrolab profiles for Sites A–D, June 15, 2005. Field pH and conductivity data were not collected on this date.

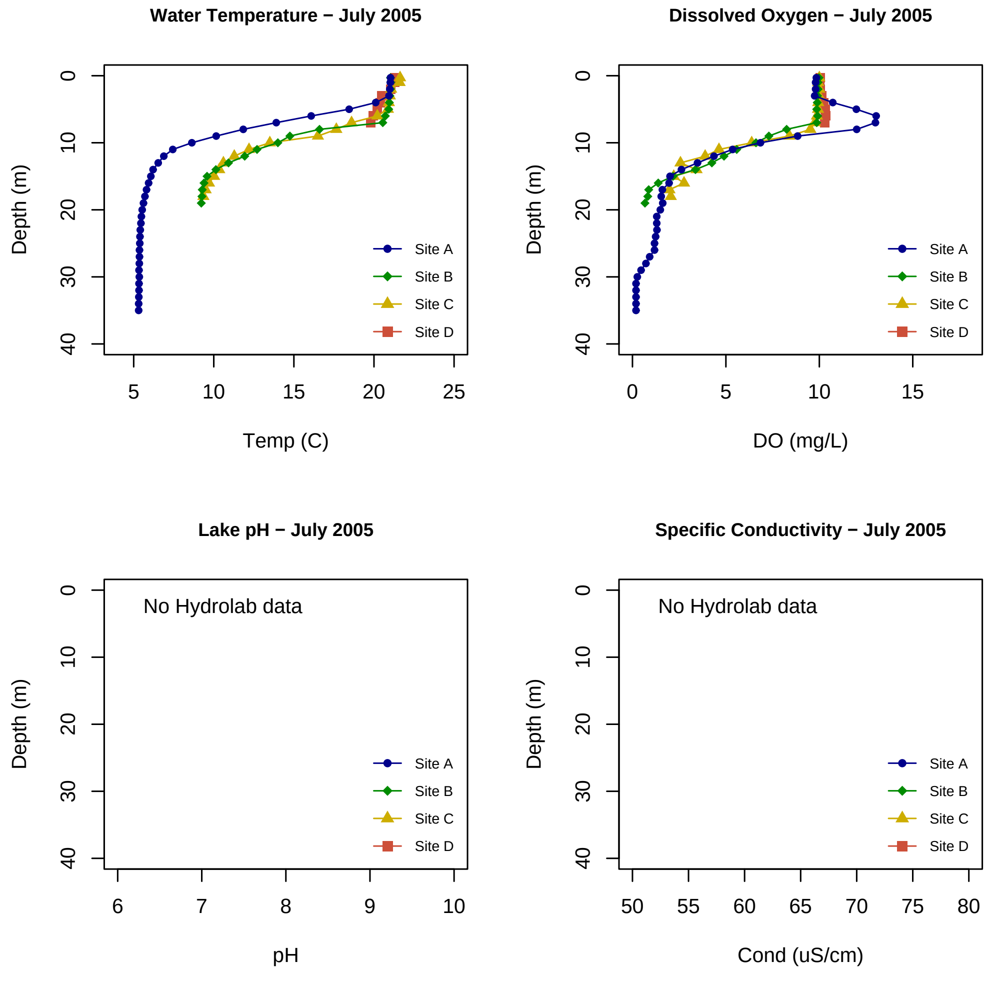


Figure 3: Lake Samish Hydrolab profiles for Sites A–D, July 20, 2005. Field pH and conductivity data were not collected on this date.

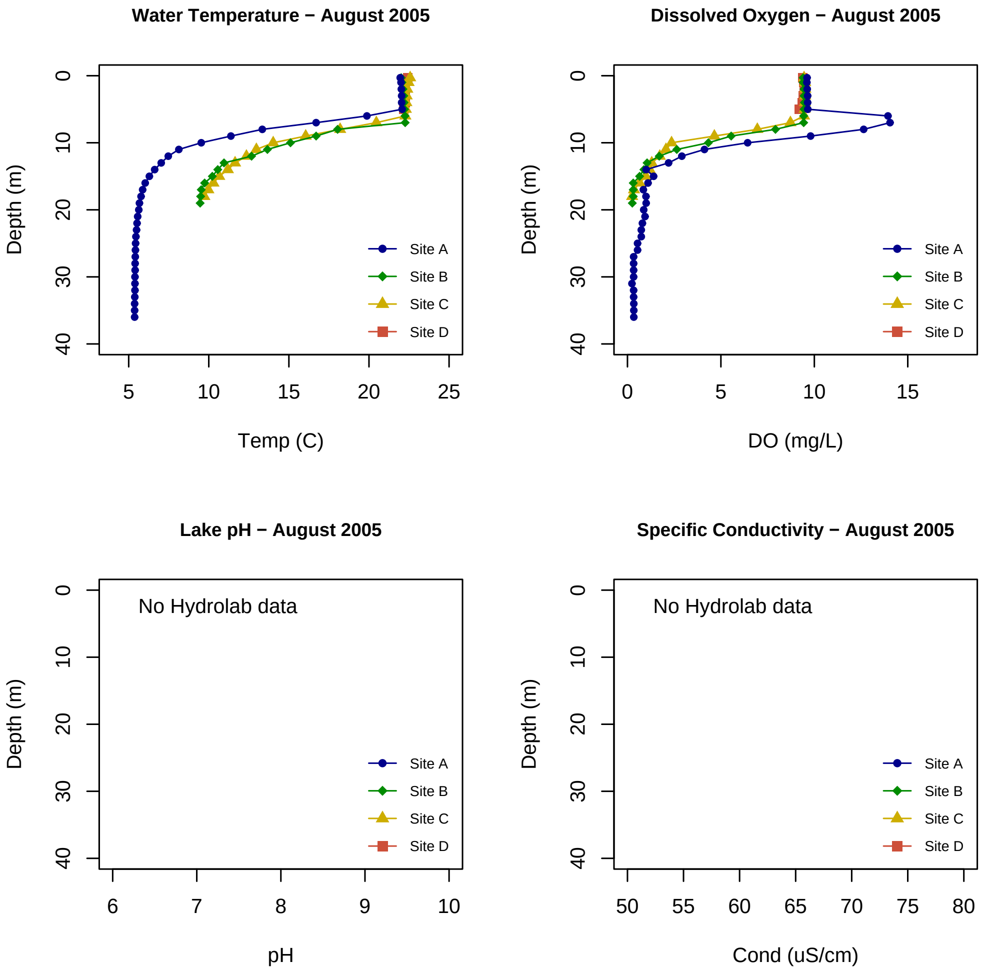


Figure 4: Lake Samish Hydrolab profiles for Sites A–D, August 23, 2005. Field pH and conductivity data were not collected on this date.

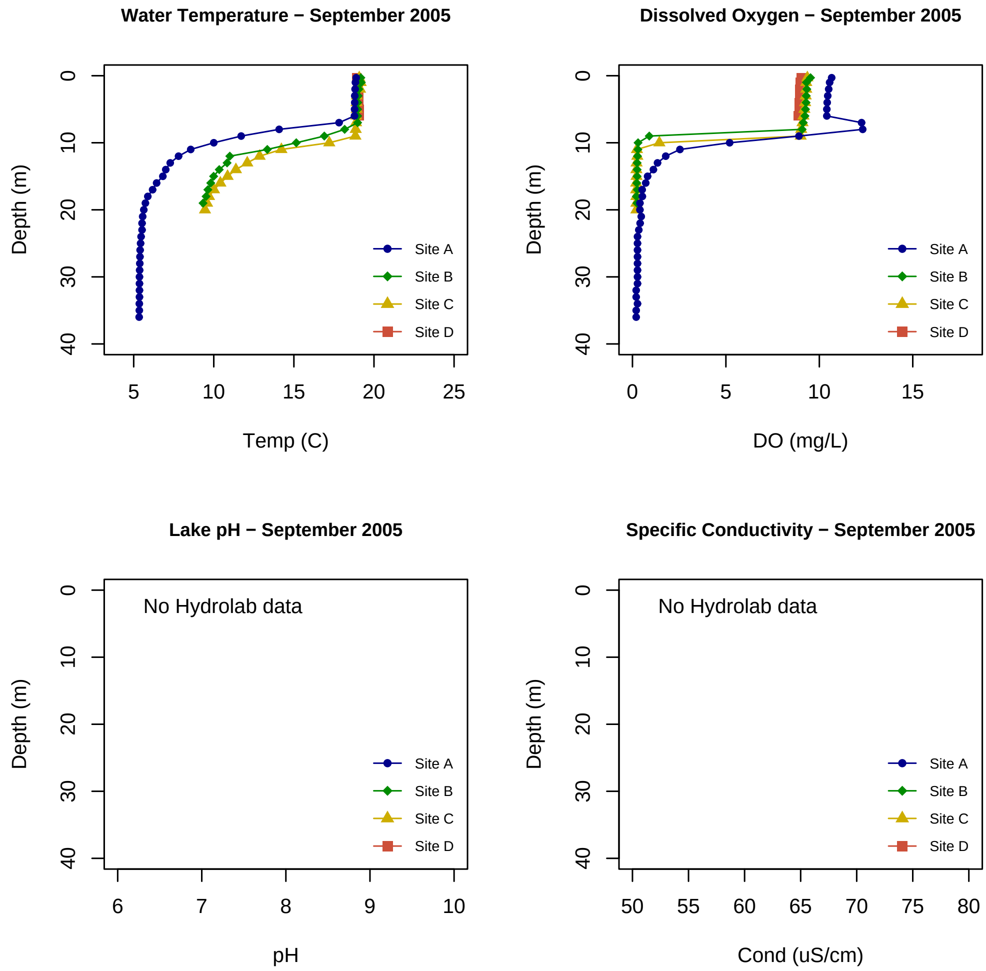


Figure 5: Lake Samish Hydrolab profiles for Sites A–D, September 20, 2005. Field pH and conductivity data were not collected on this date.

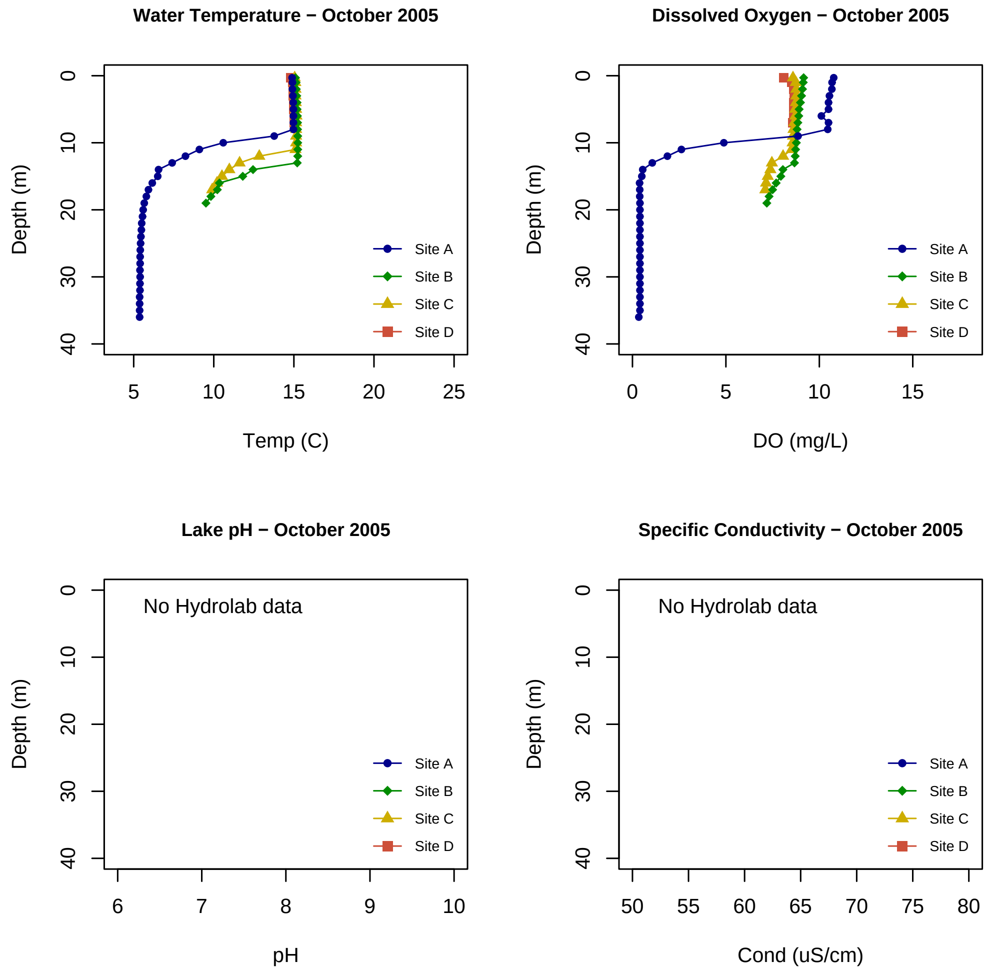


Figure 6: Lake Samish Hydrolab profiles for Sites A–D, October 16, 2005. Field pH and conductivity data were not collected on this date.

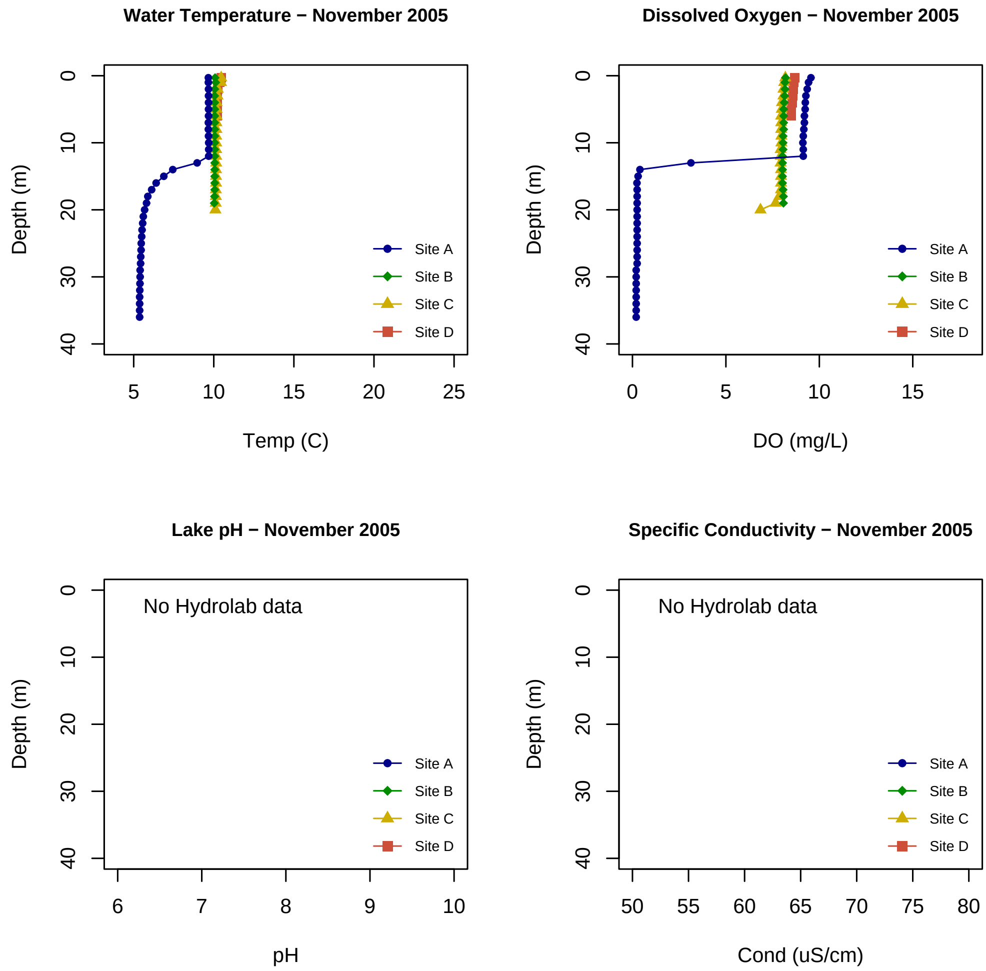


Figure 7: Lake Samish Hydrolab profiles for Sites A–D, November 20, 2005. Field pH and conductivity data were not collected on this date.

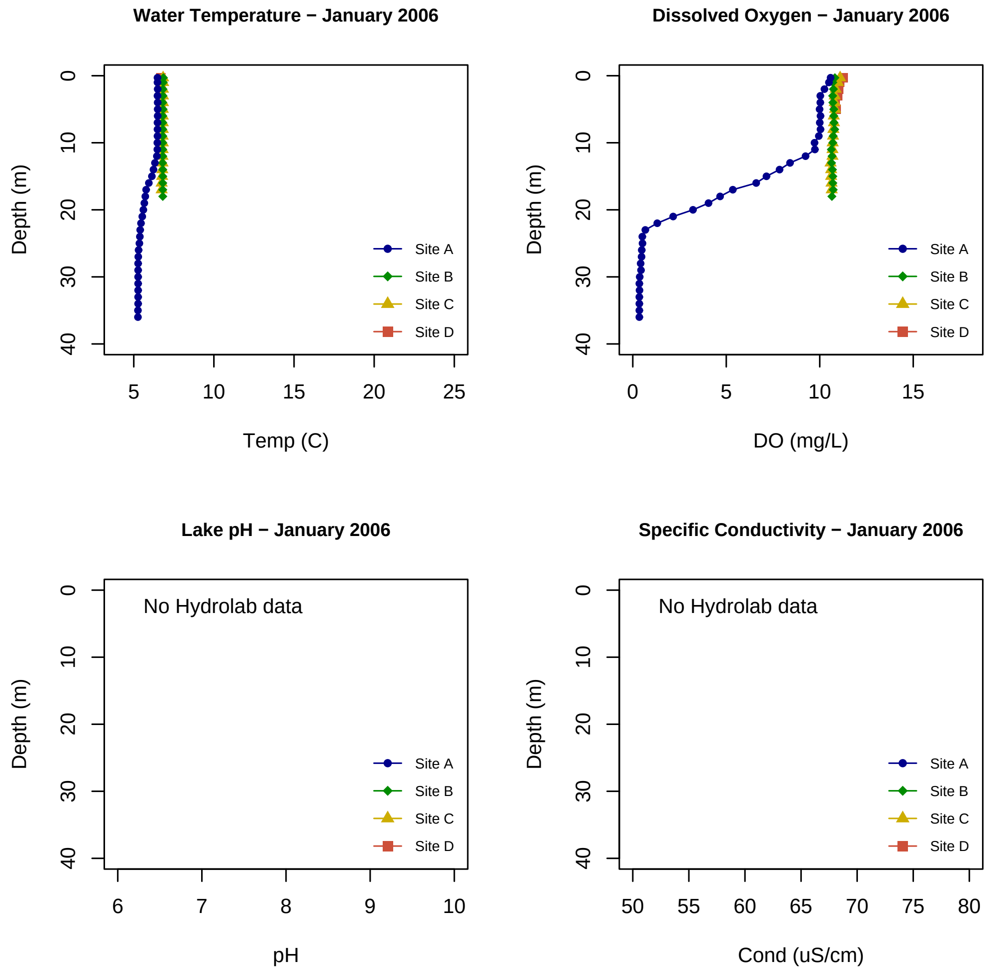


Figure 8: Lake Samish Hydrolab profiles for Sites A–D, January 22, 2006. Field pH and conductivity data were not collected on this date.

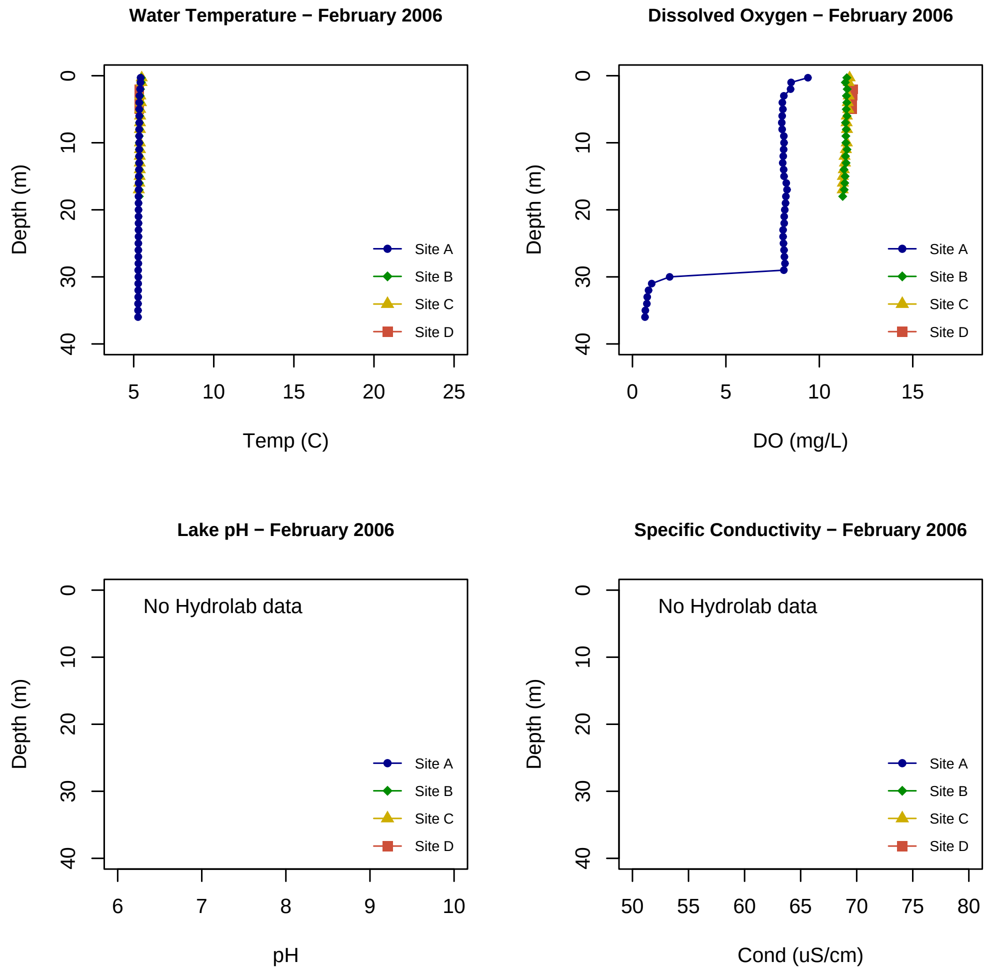


Figure 9: Lake Samish Hydrolab profiles for Sites A–D, February 26, 2006. Field pH and conductivity data were not collected on this date.

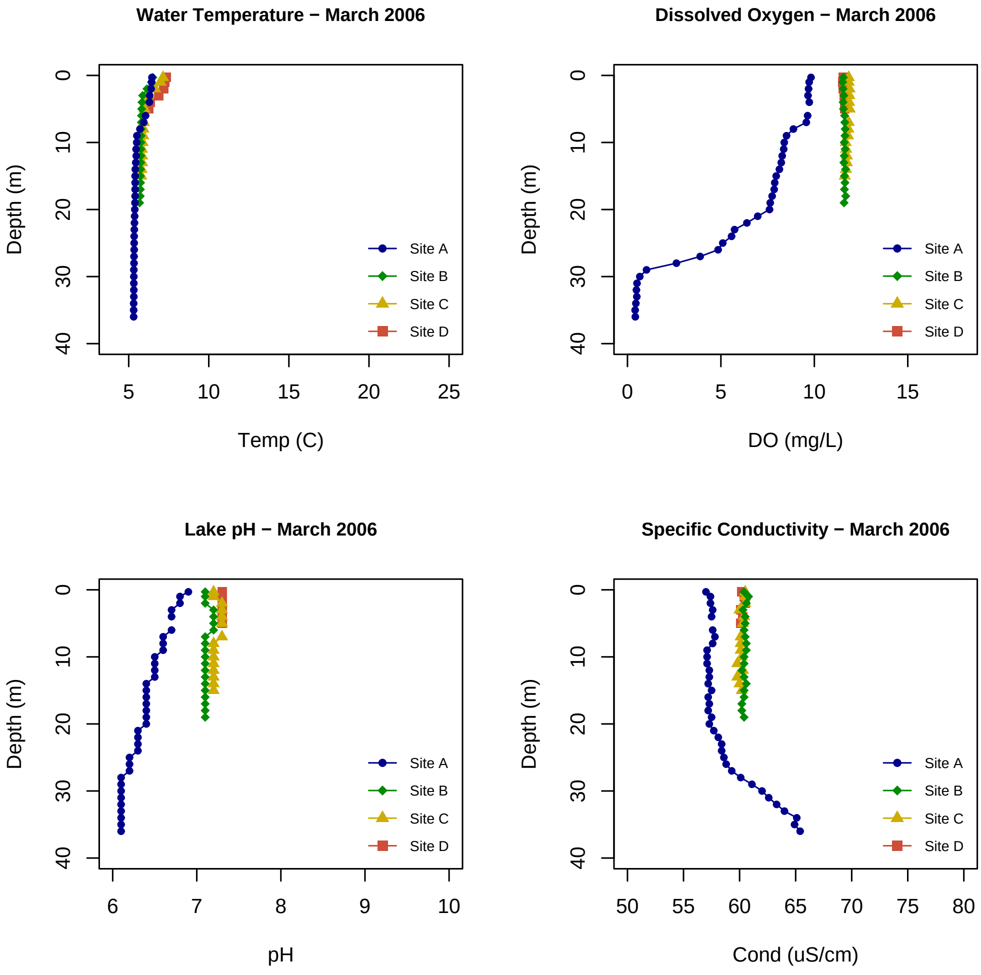


Figure 10: Lake Samish Hydrolab profiles for Sites A–D, March 19, 2006.

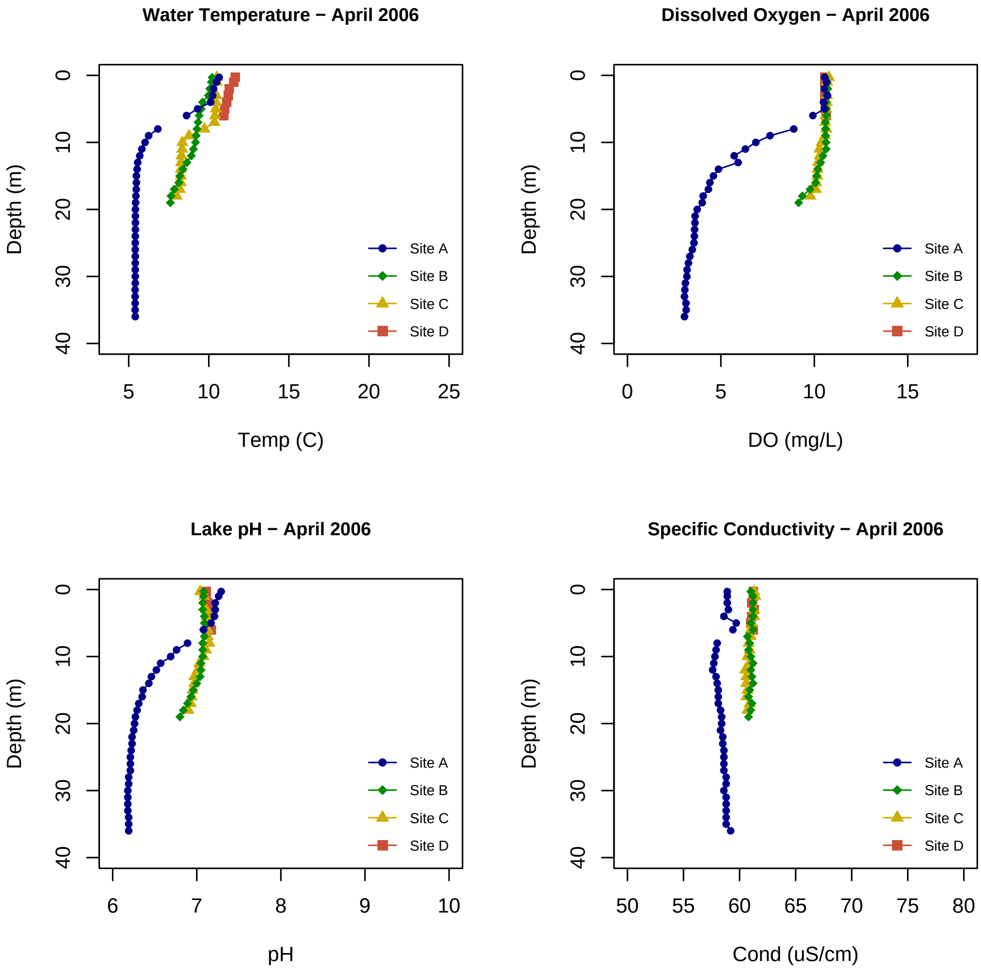


Figure 11: Lake Samish Hydrolab profiles for Sites A–D, April 23, 2006.

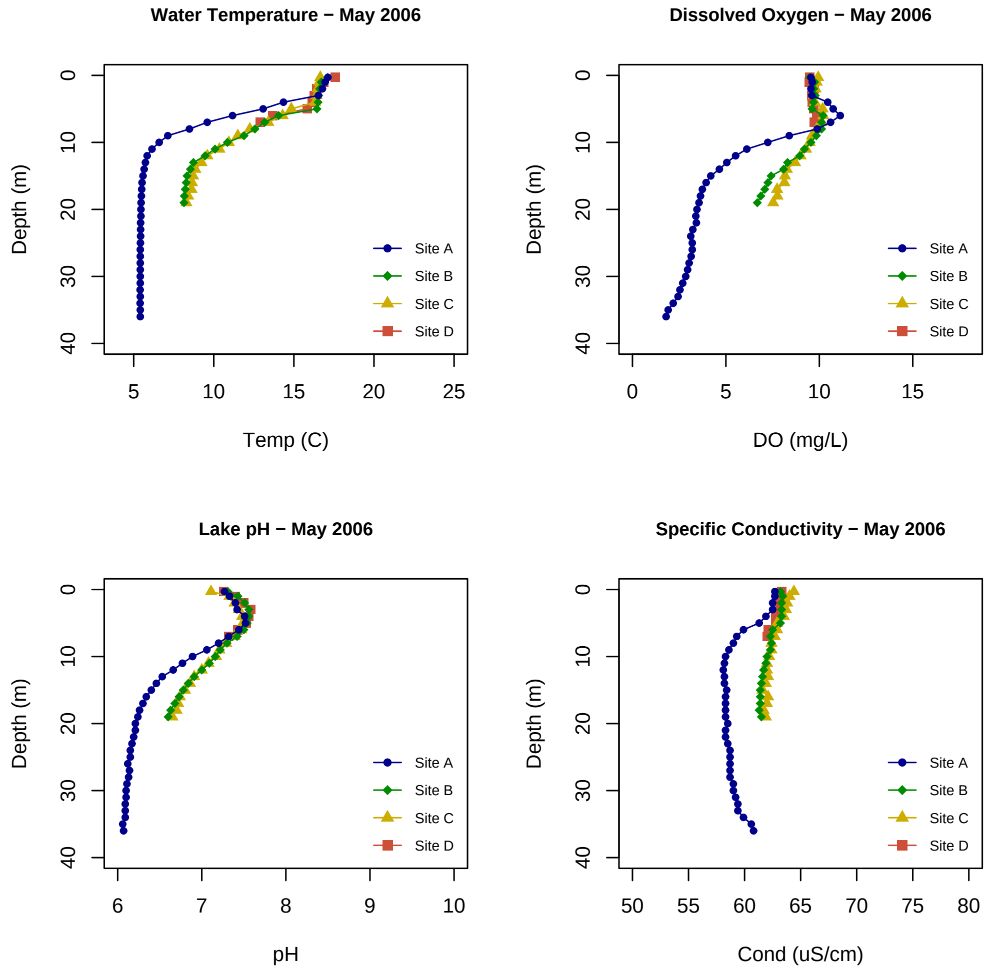


Figure 12: Lake Samish Hydrolab profiles for Sites A–D, May 21, 2006.

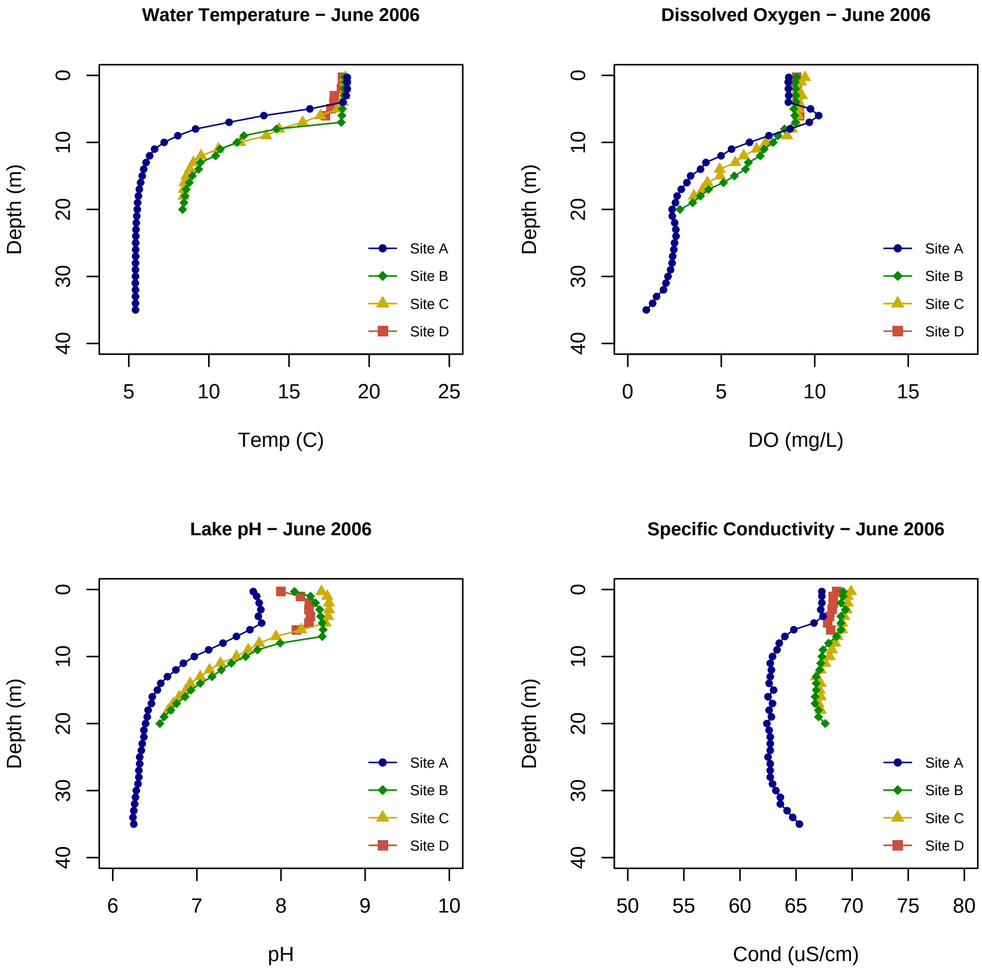


Figure 13: Lake Samish Hydrolab profiles for Sites A–D, June 20, 2006.

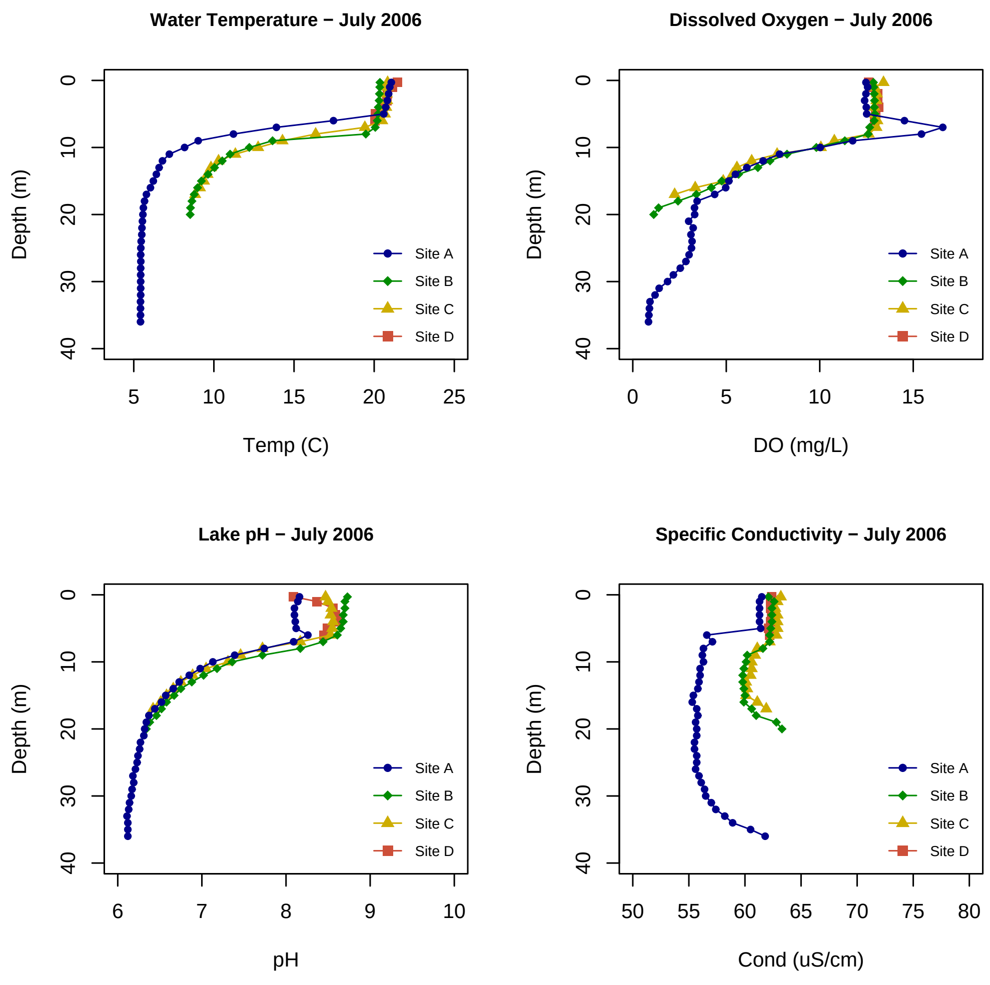


Figure 14: Lake Samish Hydrolab profiles for Sites A–D, July 19, 2006.

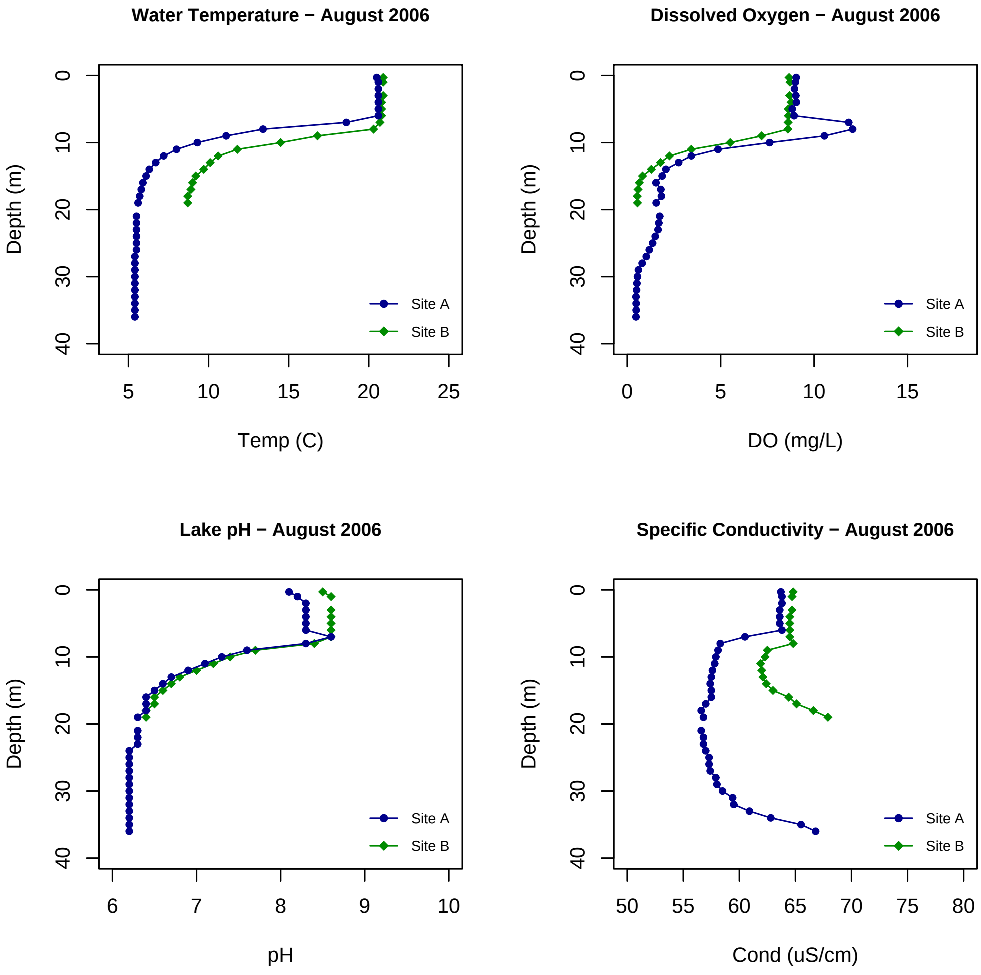


Figure 15: Lake Samish Hydrolab profiles for Sites A and B, August 24, 2006. Sites C and D were not sampled on this date.

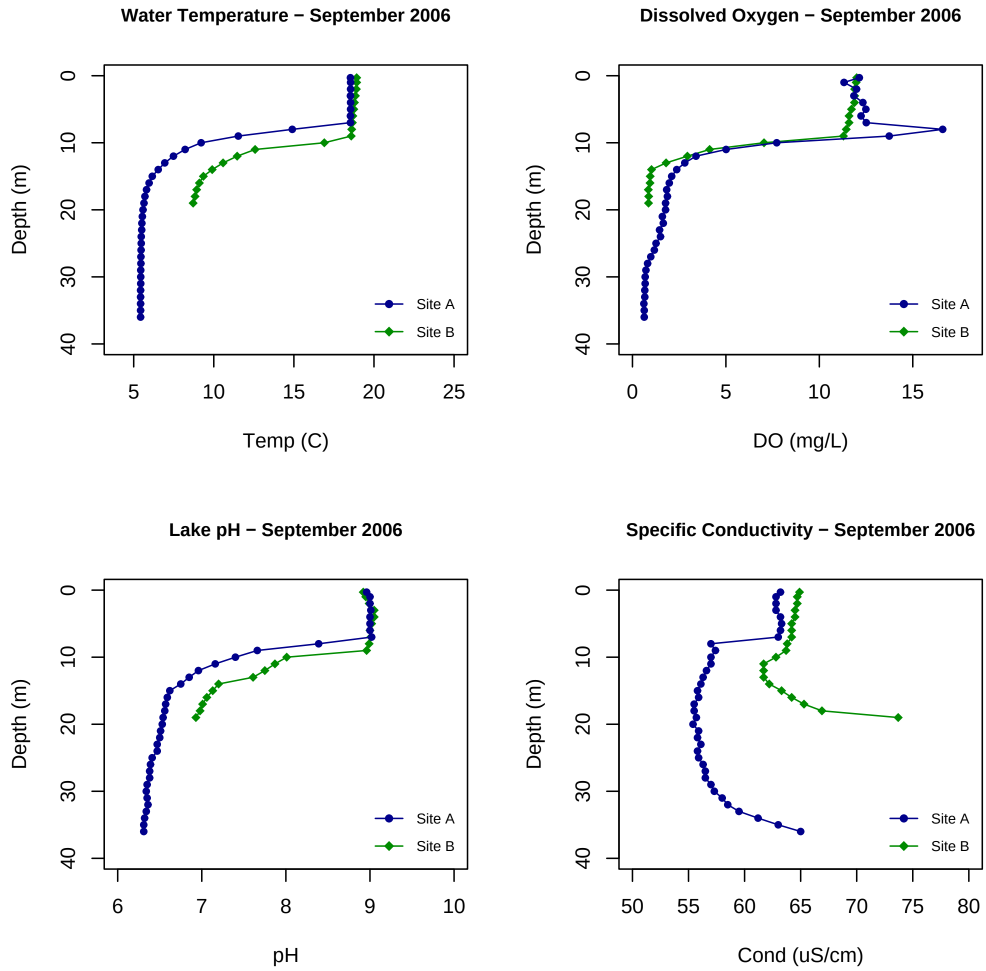


Figure 16: Lake Samish Hydrolab profiles for Sites A and B, September 18, 2006. Sites C and D were not sampled on this date.

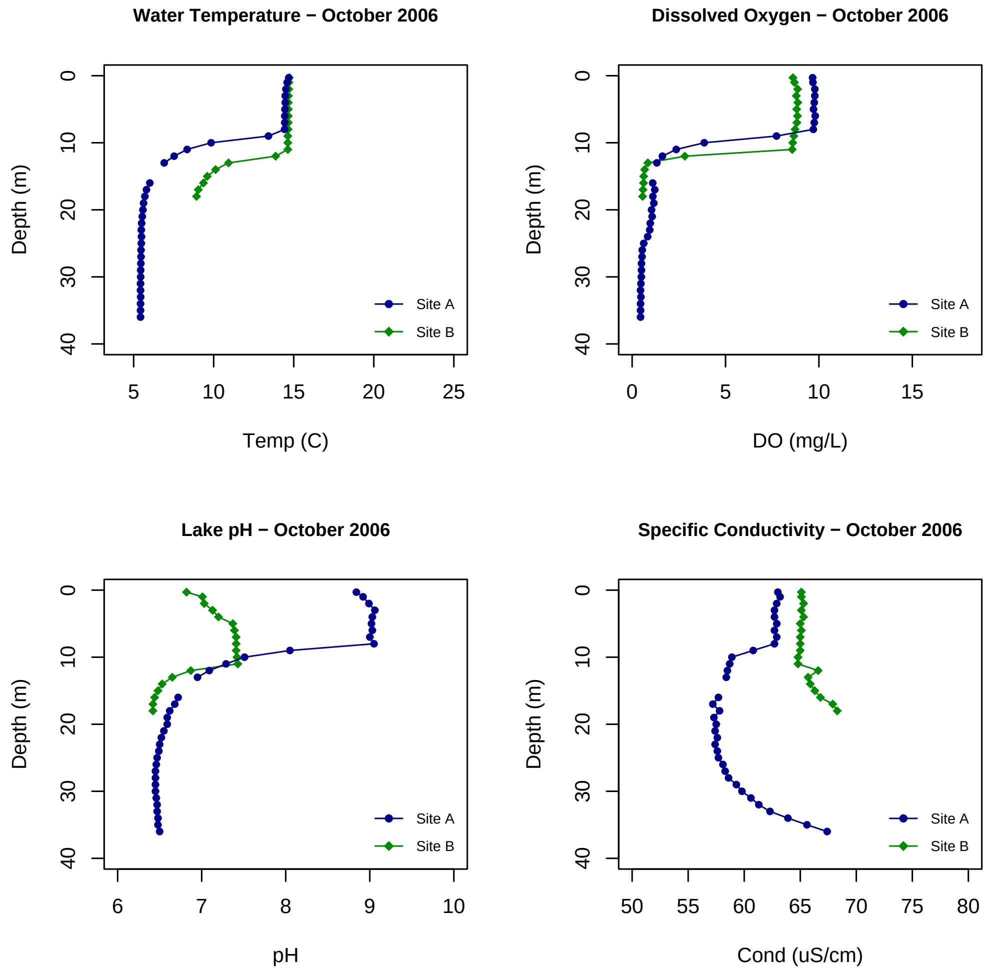


Figure 17: Lake Samish Hydrolab profiles for Sites A and B, October 22, 2006. Sites C and D were not sampled on this date.

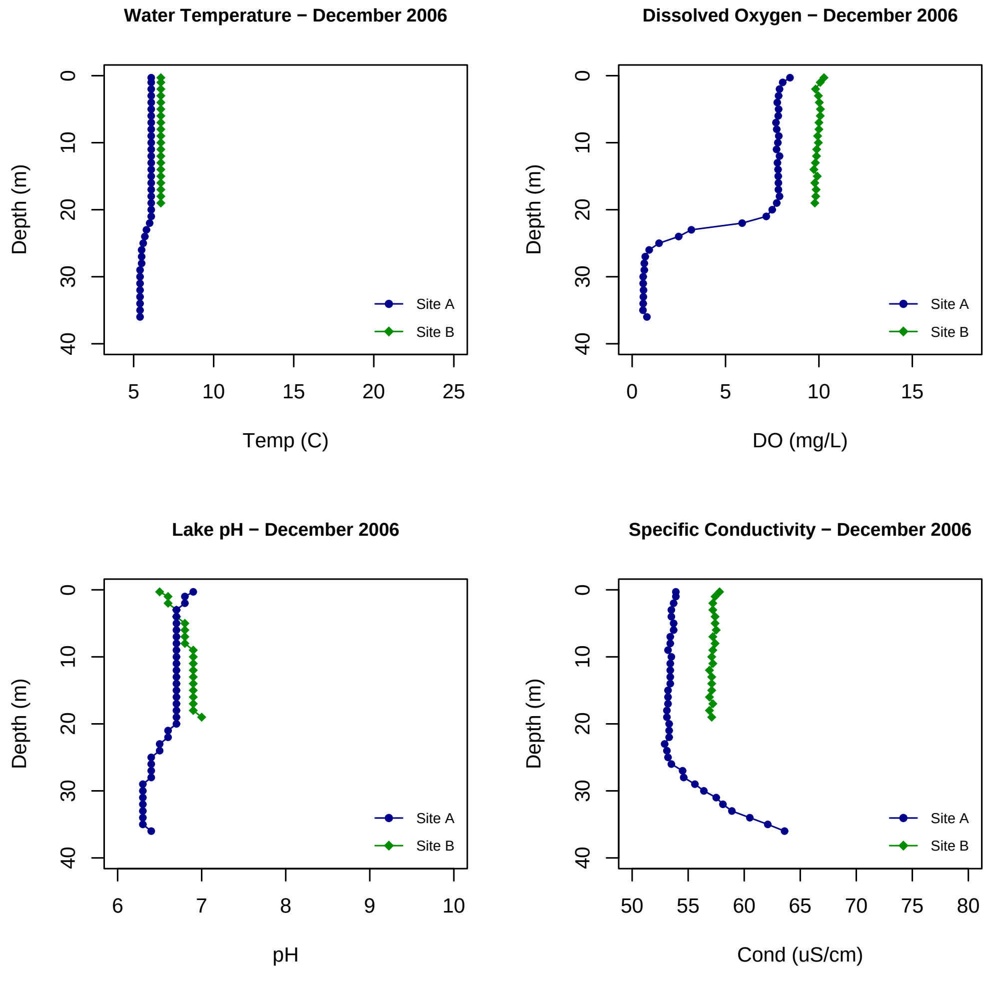


Figure 18: Lake Samish Hydrolab profiles for Sites A and B, December 18, 2006. Sites C and D were not sampled on this date.

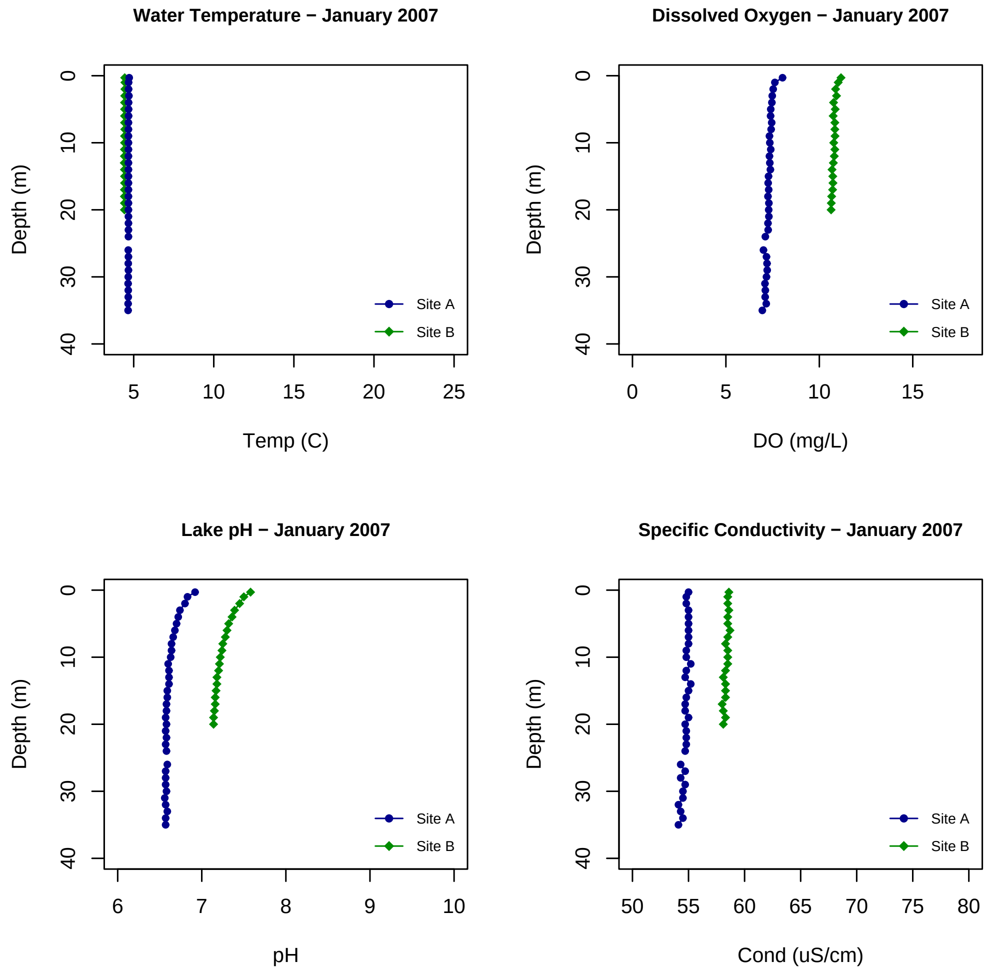


Figure 19: Lake Samish Hydrolab profiles for Sites A and B, January 30, 2007. Sites C and D were not sampled on this date.

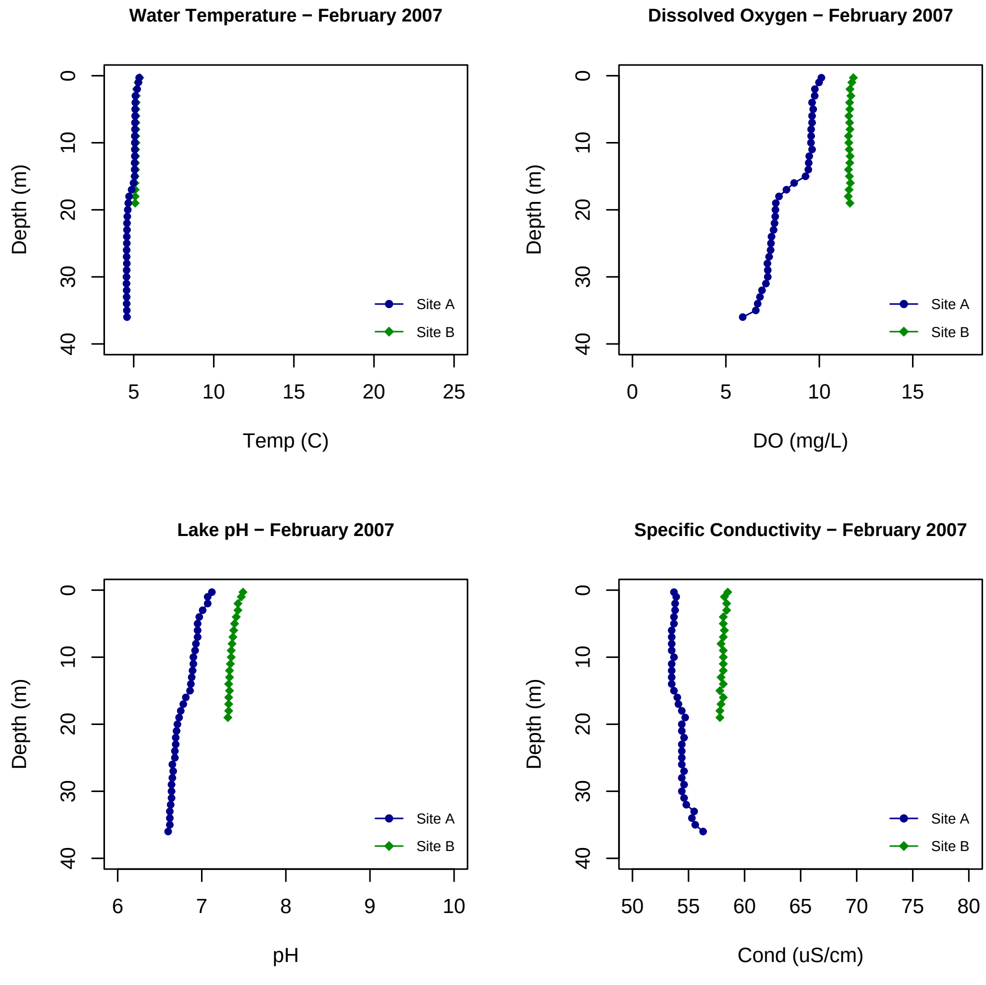


Figure 20: Lake Samish Hydrolab profiles for Sites A and B, February 27, 2007. Sites C and D were not sampled on this date.

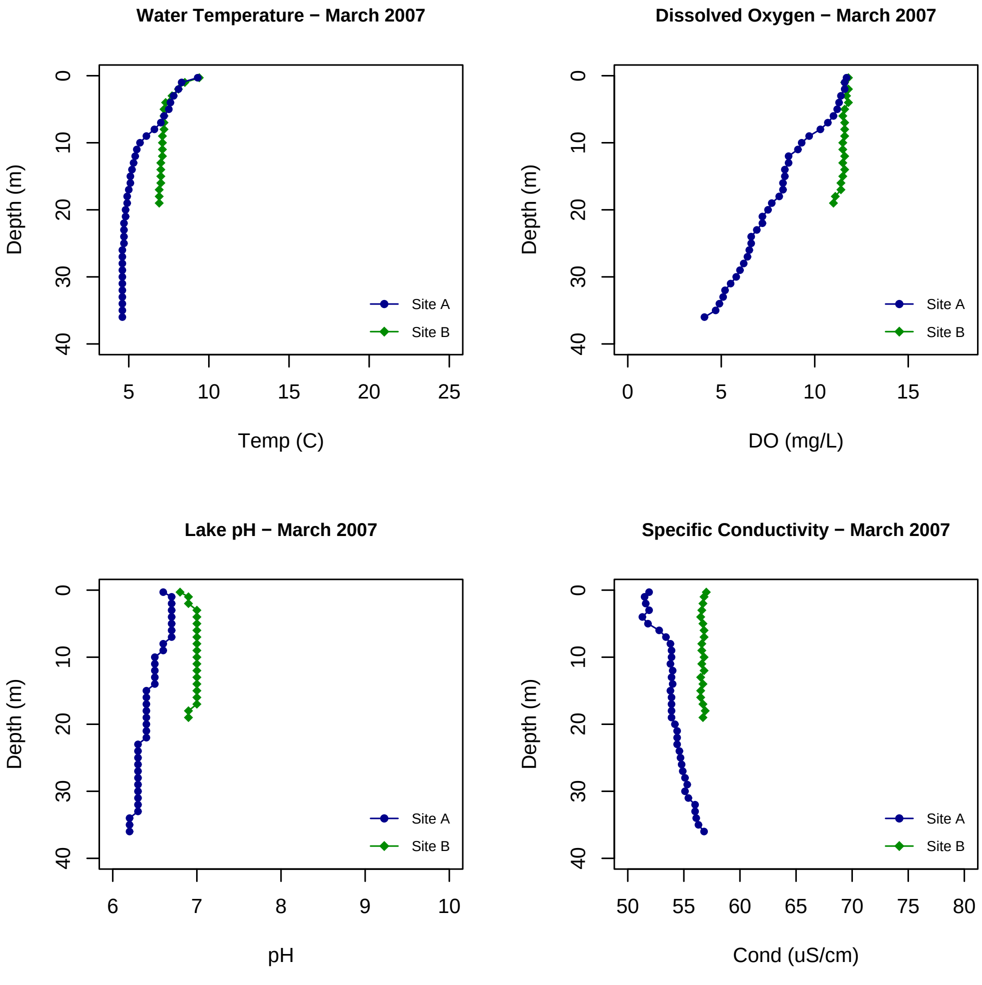


Figure 21: Lake Samish Hydrolab profiles for Sites A and B, March 29, 2007. Sites C and D were not sampled on this date.

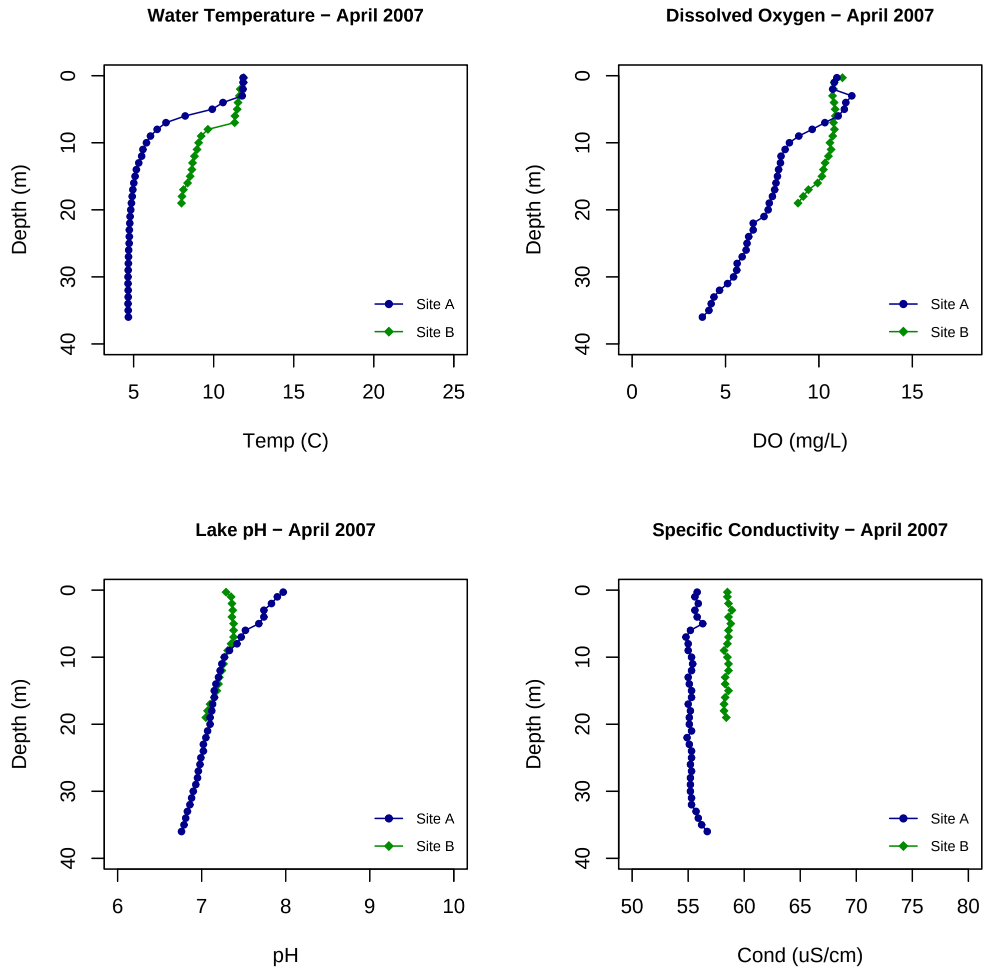


Figure 22: Lake Samish Hydrolab profiles for Sites A and B, April 24, 2007. Sites C and D were not sampled on this date.

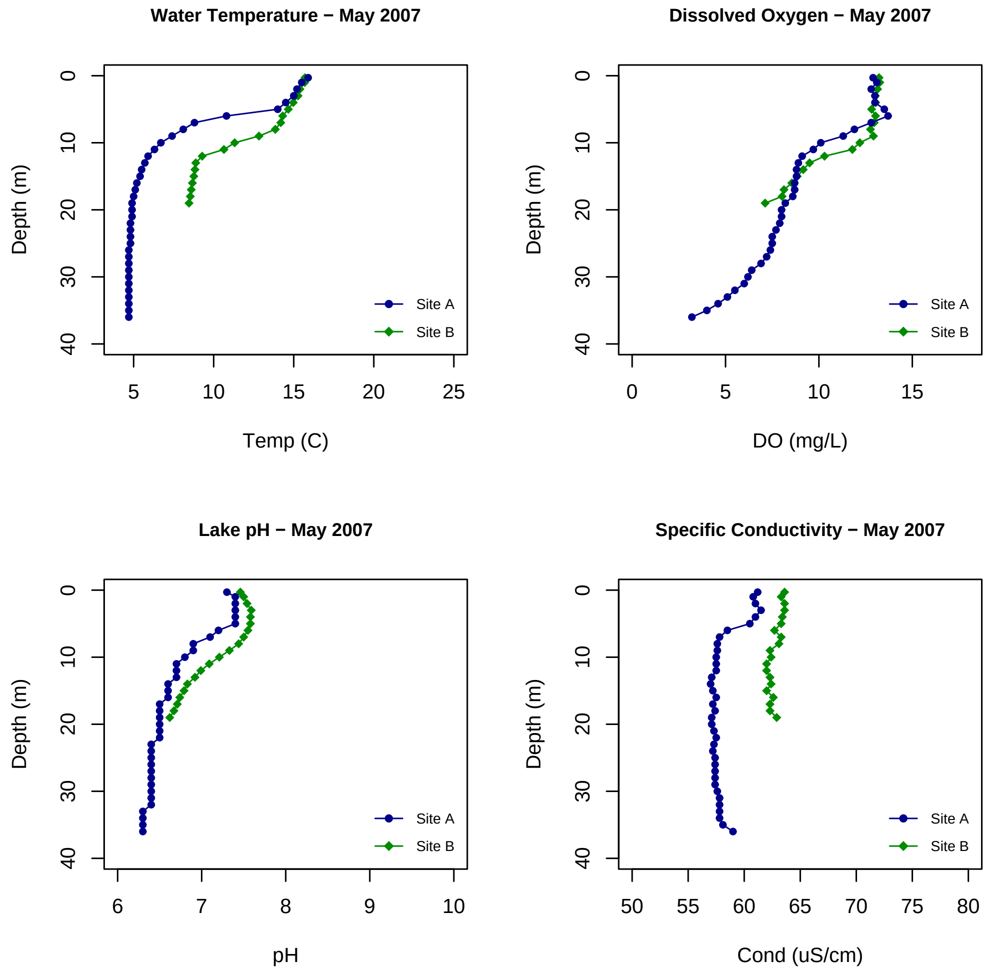


Figure 23: Lake Samish Hydrolab profiles for Sites A and B, May 24, 2007. Sites C and D were not sampled on this date.

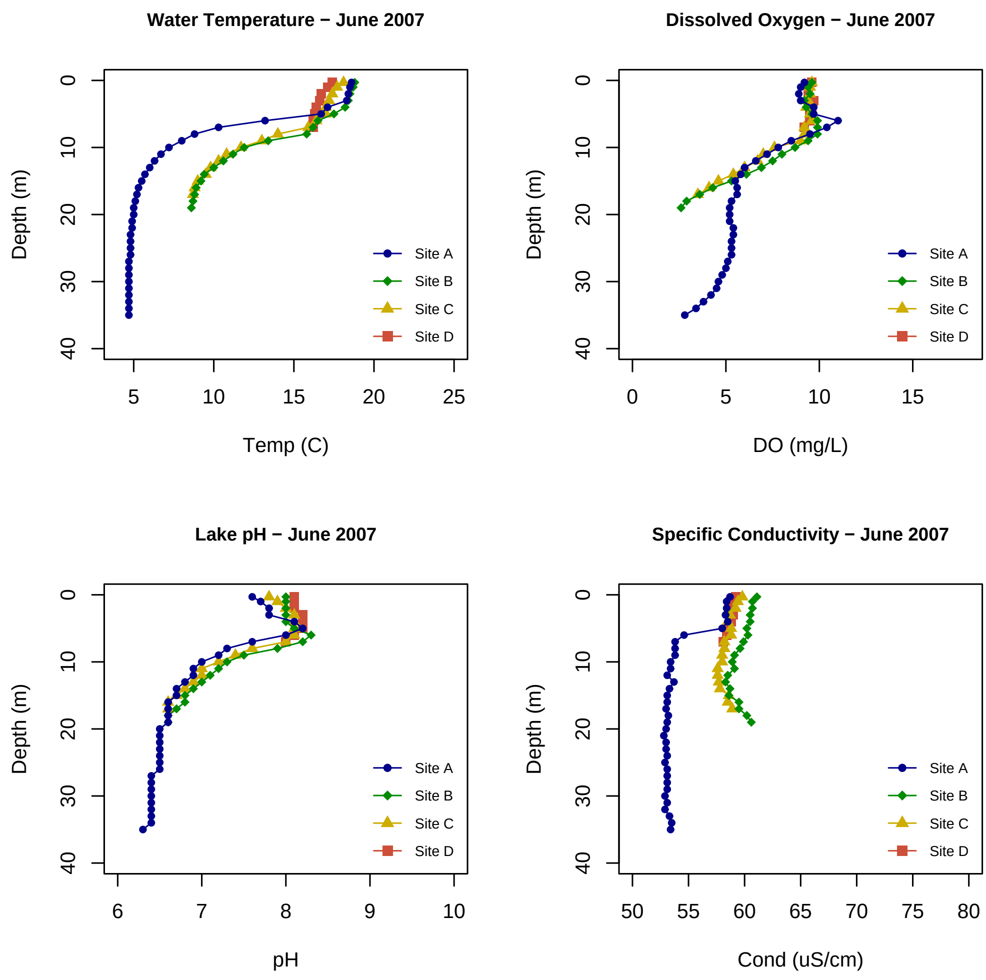


Figure 24: Lake Samish Hydrolab profiles for Sites A–D, June 21, 2007.

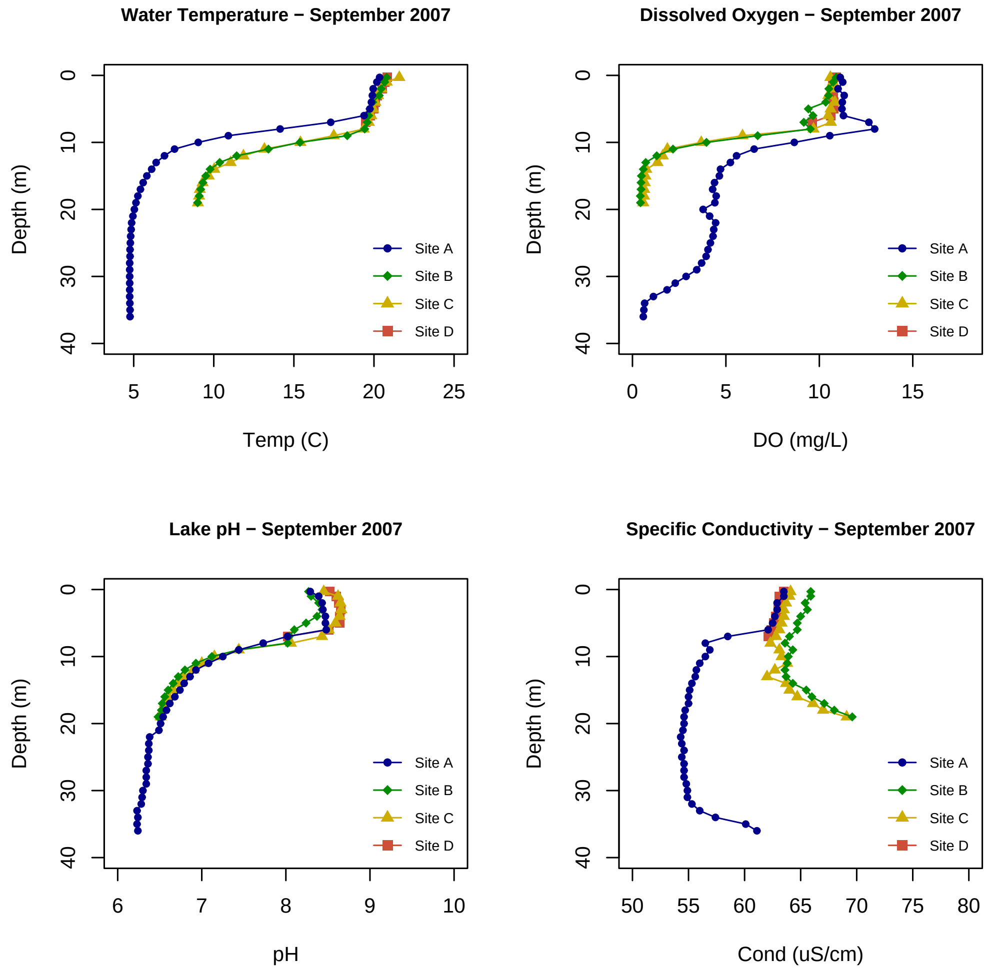


Figure 25: Lake Samish Hydrolab profiles for Sites A–D, September 13, 2007.

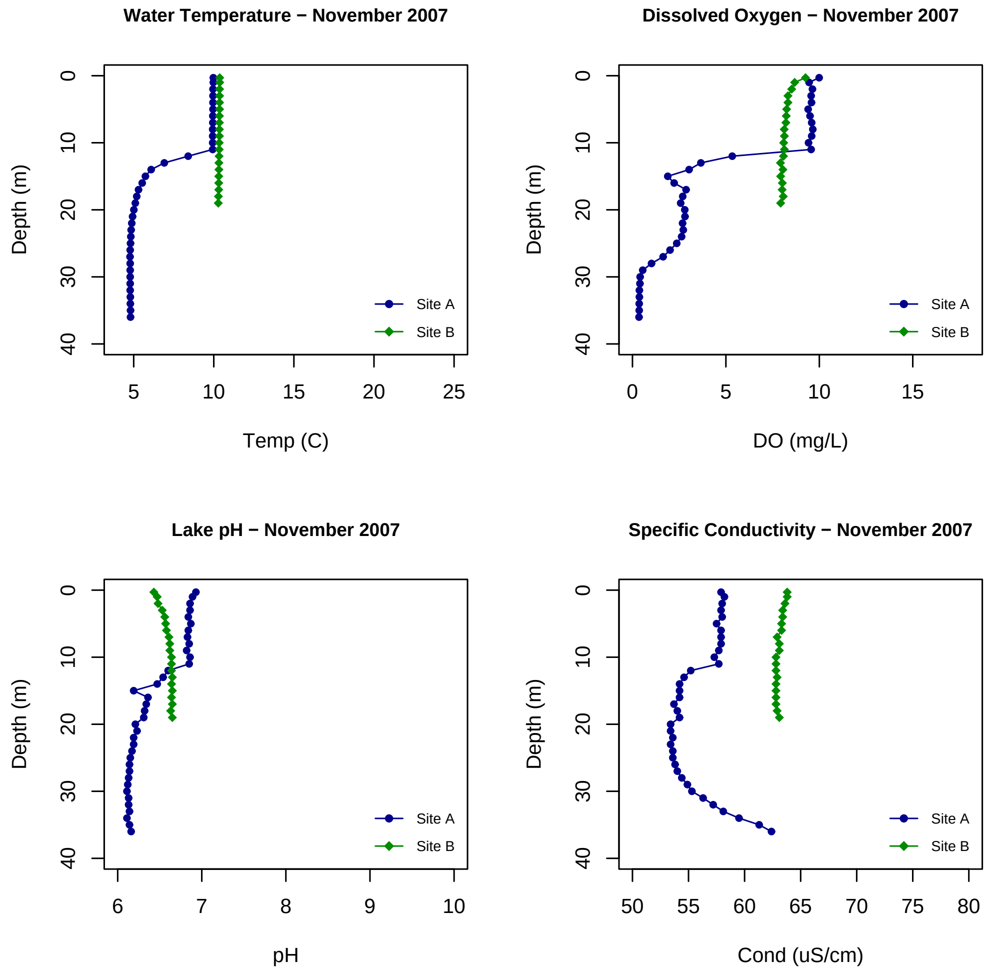


Figure 26: Lake Samish Hydrolab profiles for Sites A and B, November 15, 2007. Sites C and D were not sampled on this date.

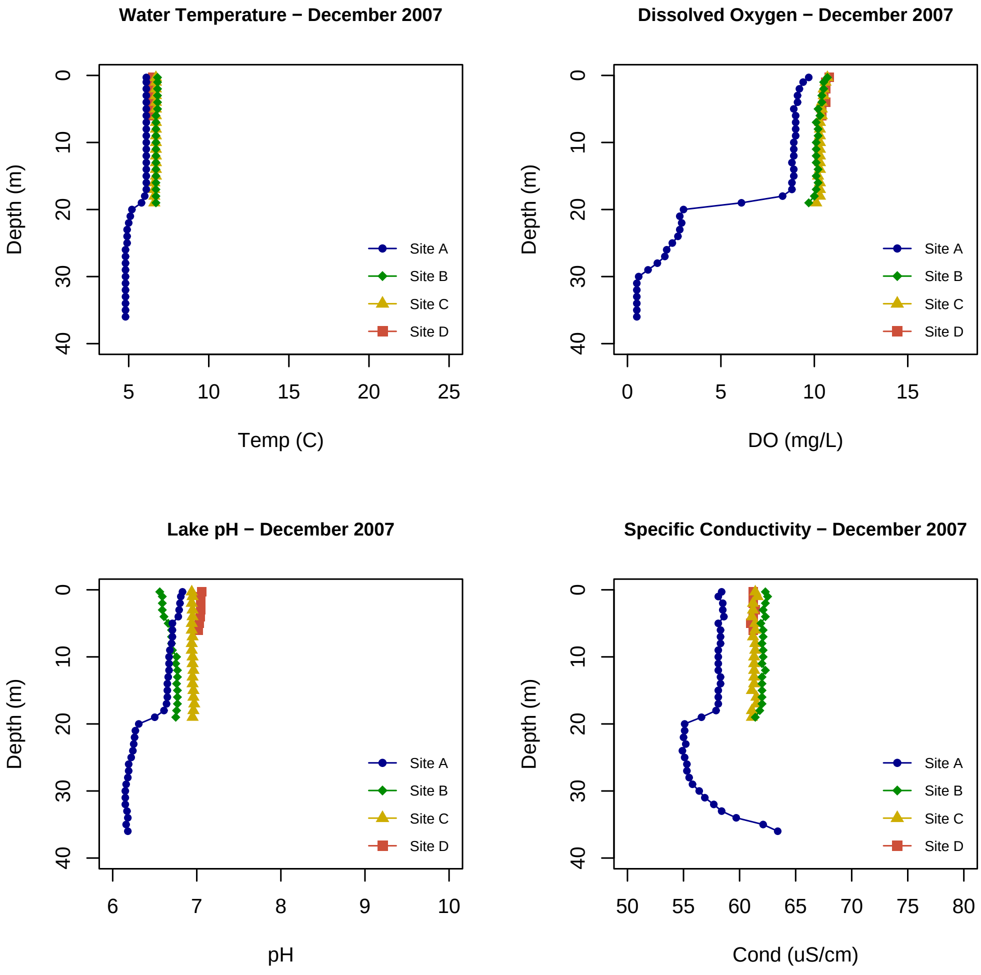


Figure 27: Lake Samish Hydrolab profiles for Sites A–D, December 20, 2007.

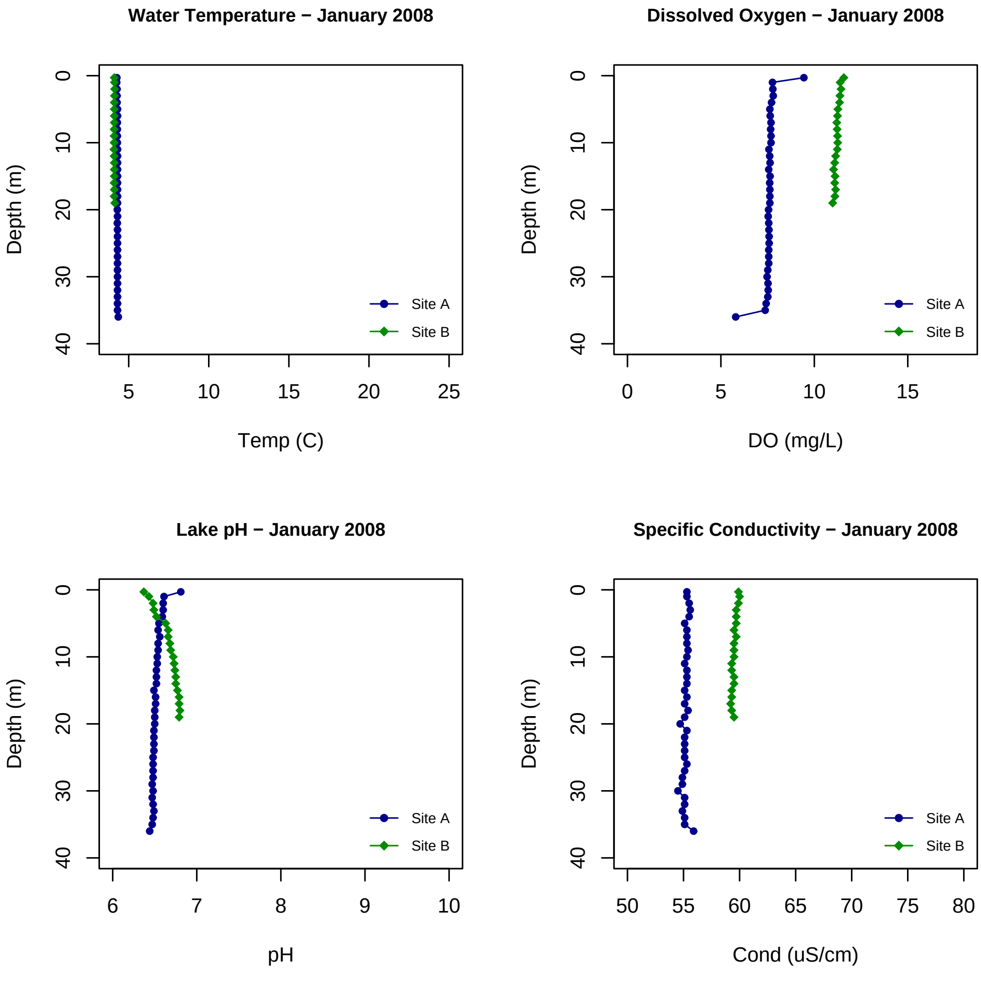


Figure 28: Lake Samish Hydrolab profiles for Sites A and B, January 29, 2008. Sites C and D were not sampled on this date.

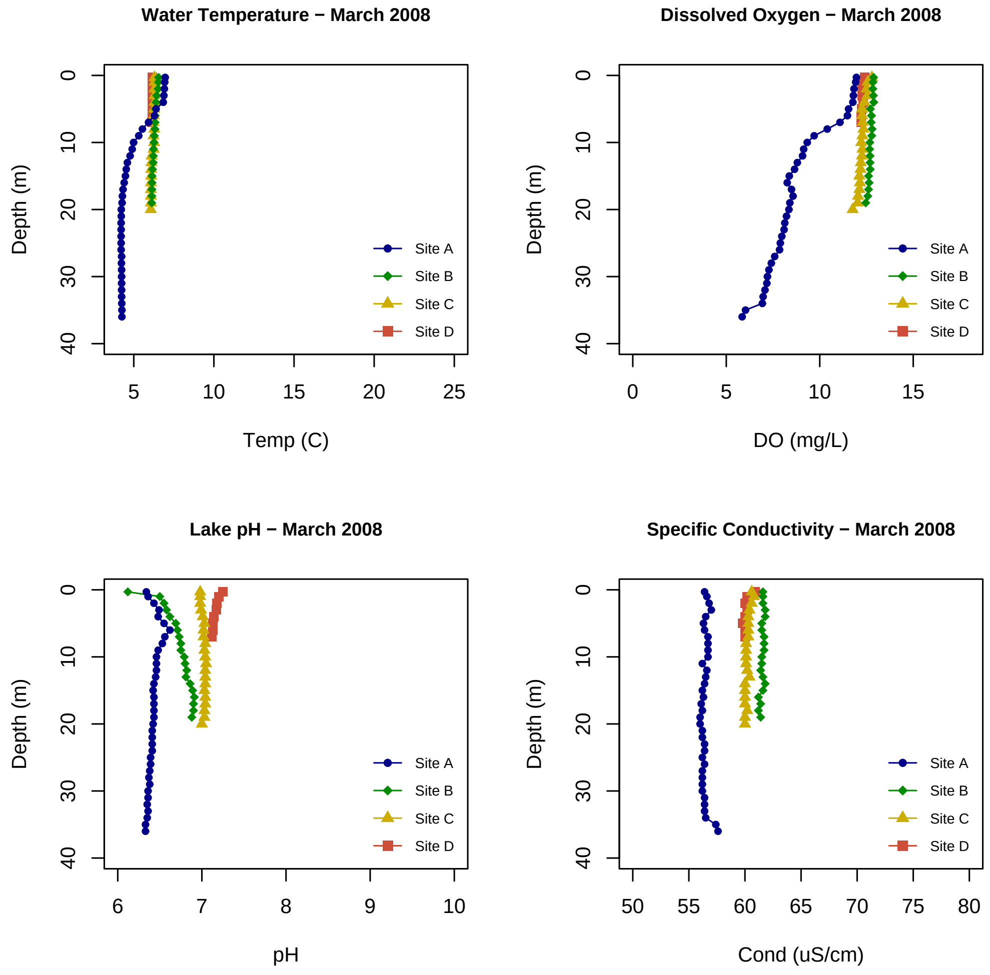


Figure 29: Lake Samish Hydrolab profiles for Sites A–D, March 25, 2008.

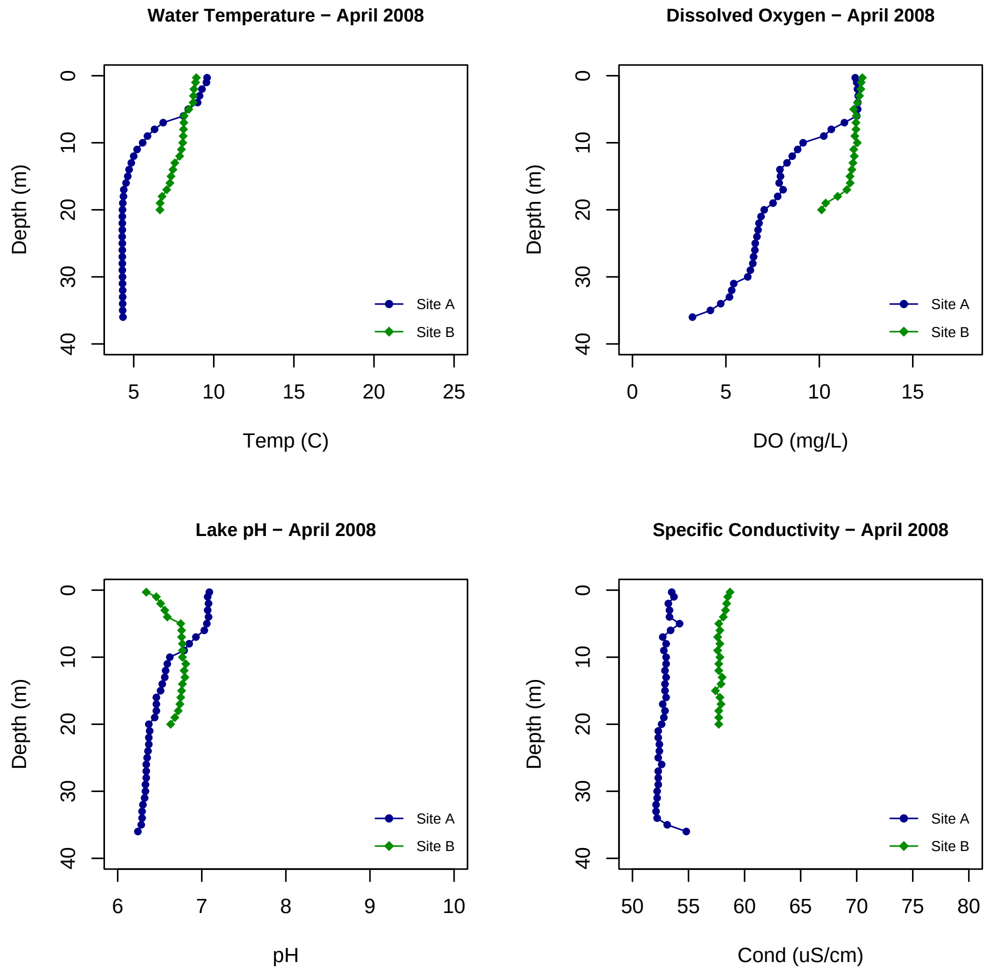


Figure 30: Lake Samish Hydrolab profiles for Sites A and B, April 21, 2008. Sites C and D were not sampled on this date.

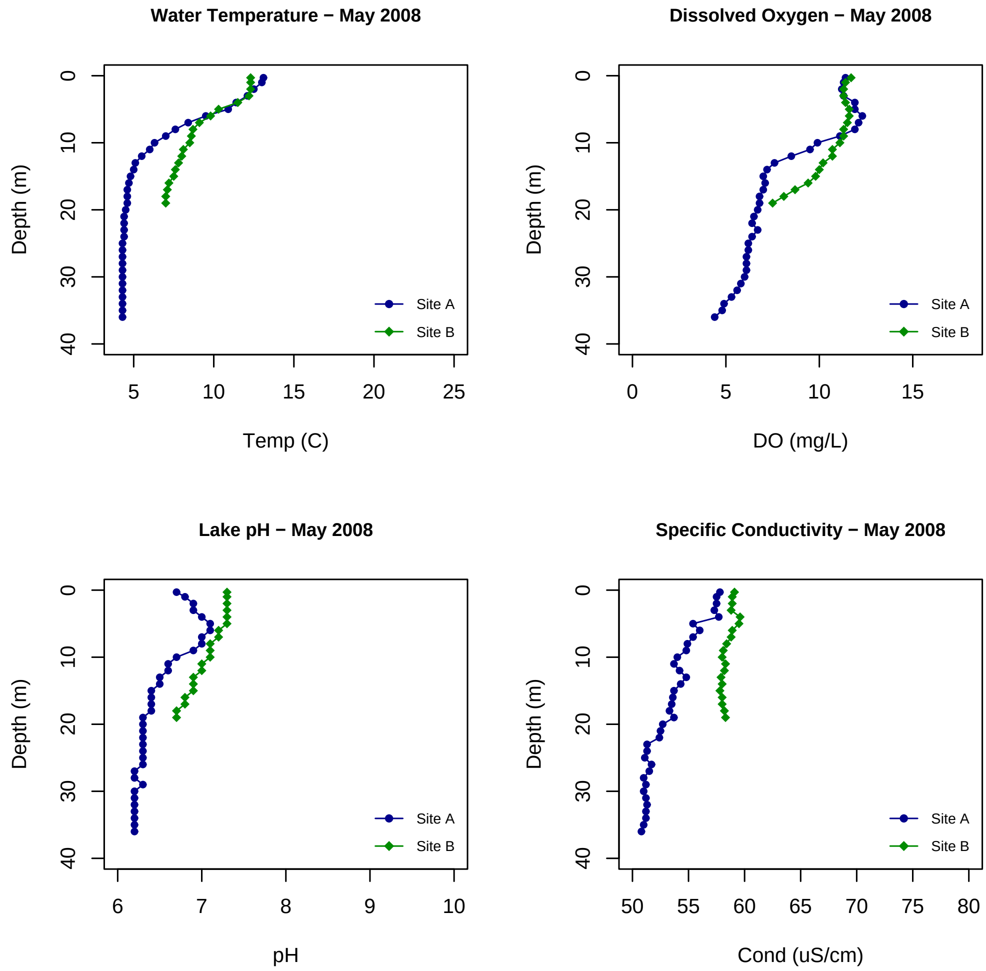


Figure 31: Lake Samish Hydrolab profiles for Sites A and B, May 15, 2008. Sites C and D were not sampled on this date.

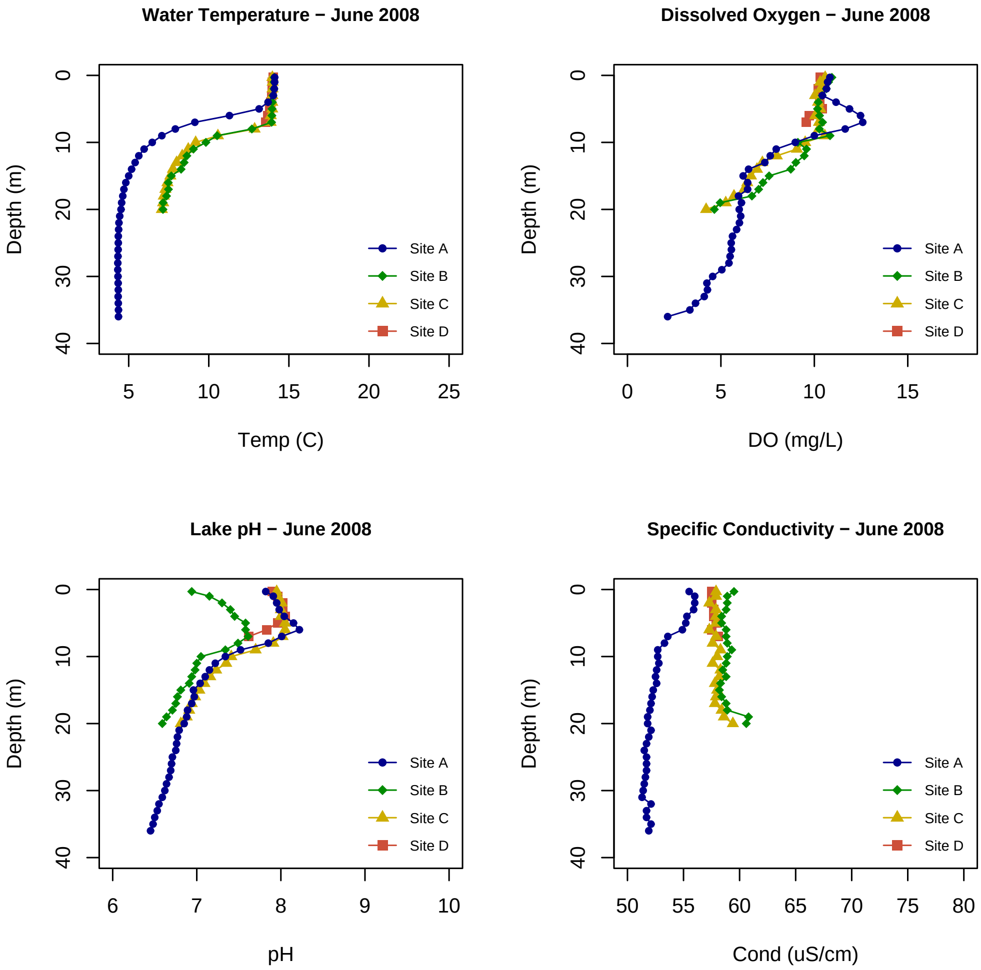


Figure 32: Lake Samish Hydrolab profiles for Sites A–D, June 10, 2008.

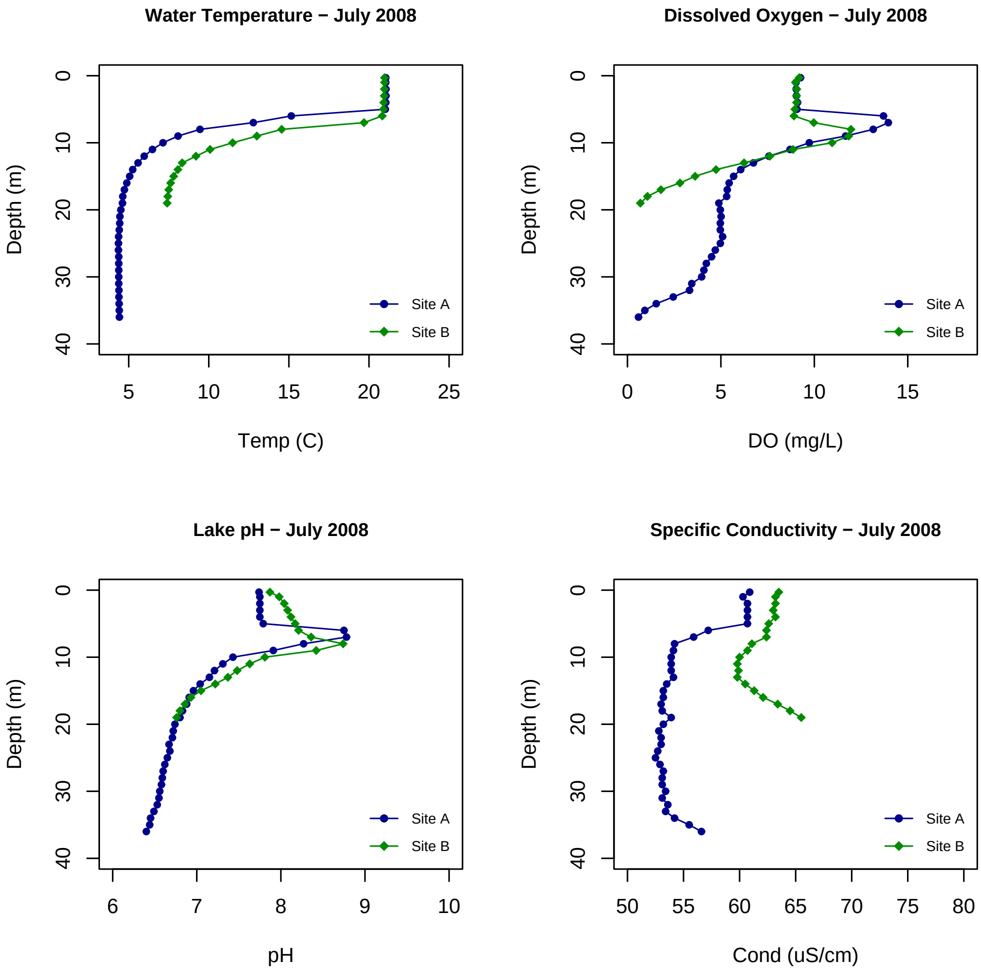


Figure 33: Lake Samish Hydrolab profiles for Sites A and B, July 22, 2008. Sites C and D were not sampled on this date.

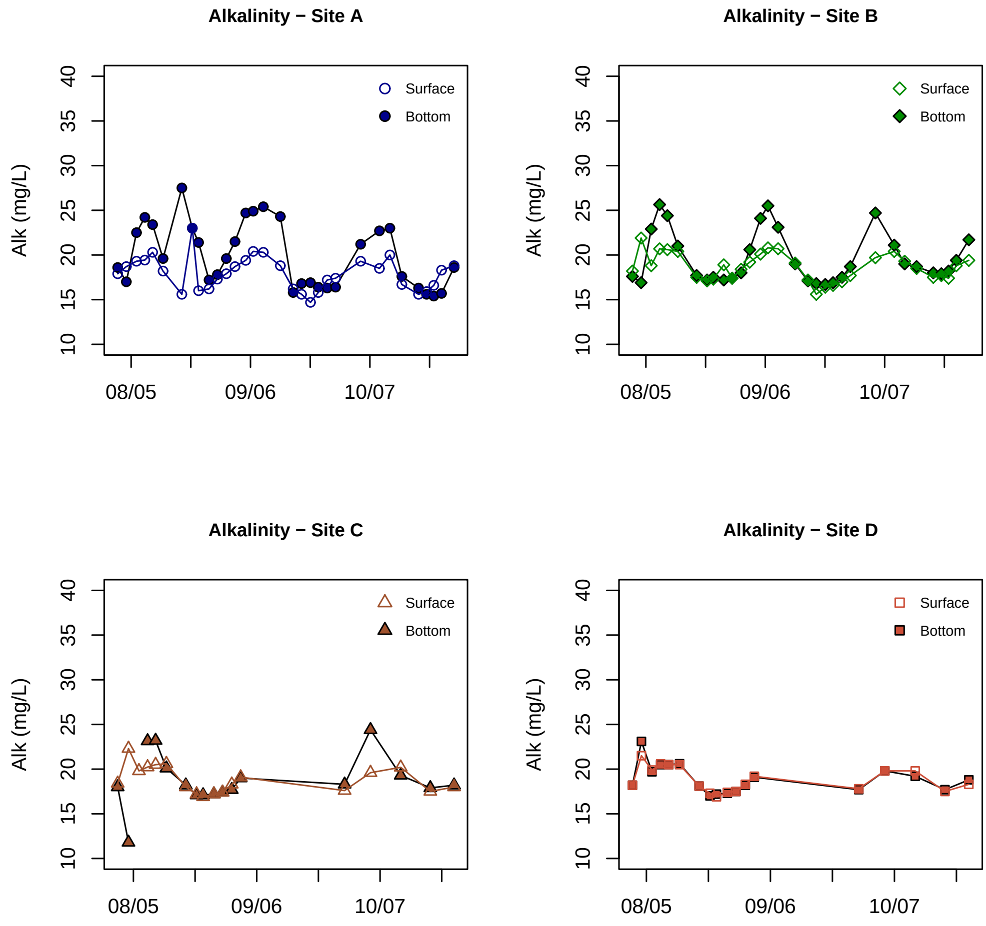


Figure 34: Lake Samish alkalinity data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

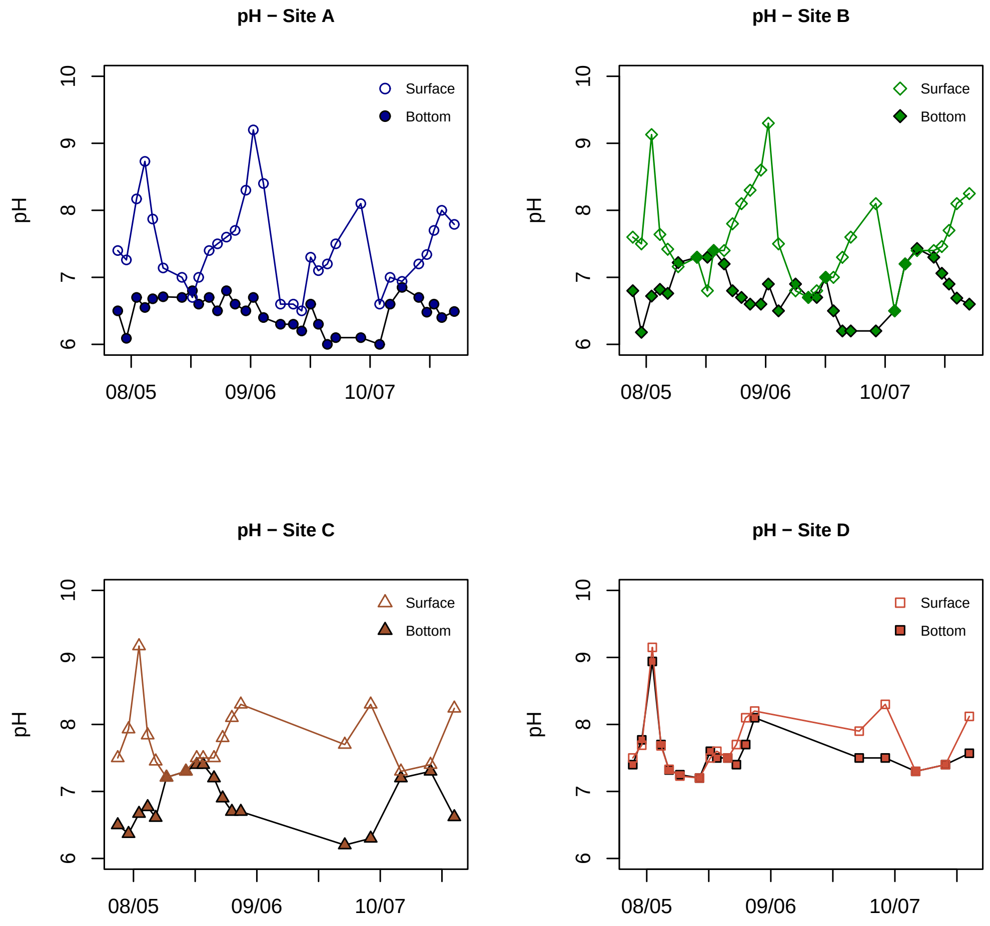


Figure 35: Lake Samish pH data (laboratory analysis), June 2005 through July 2008. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

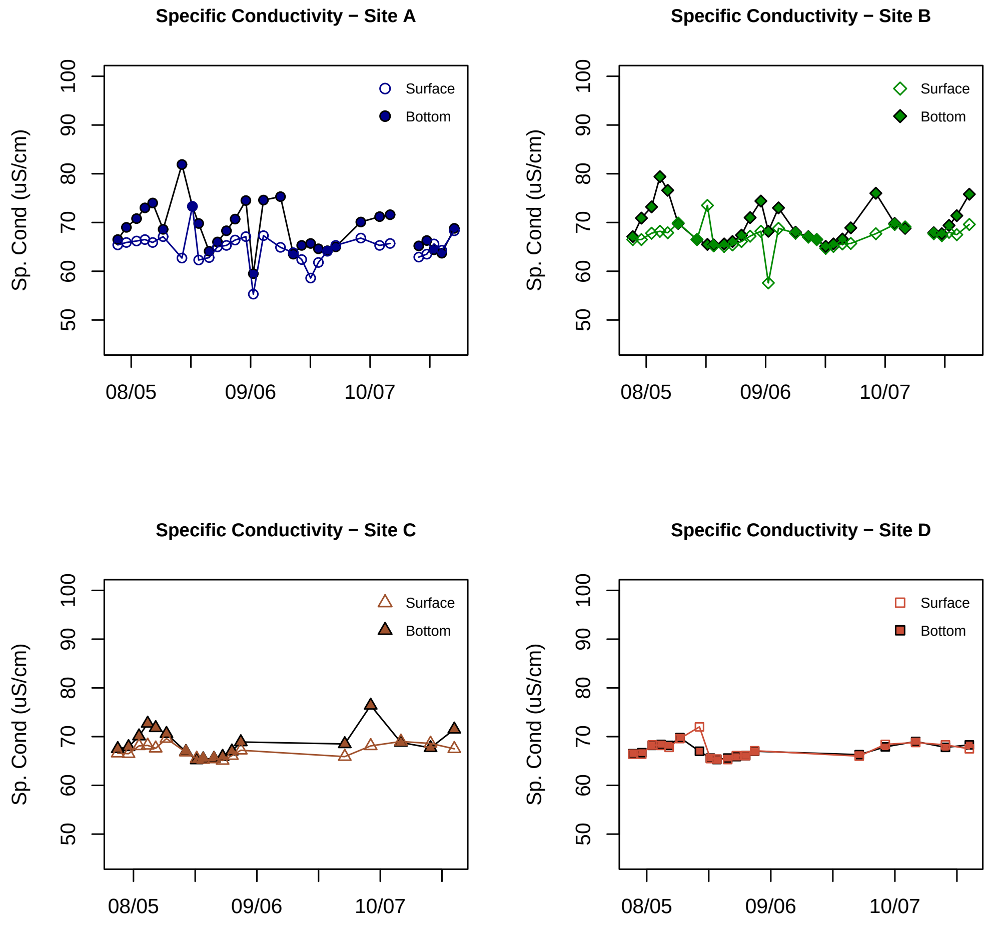


Figure 36: Lake Samish specific conductivity data (laboratory analysis), June 2005 through July 2008. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

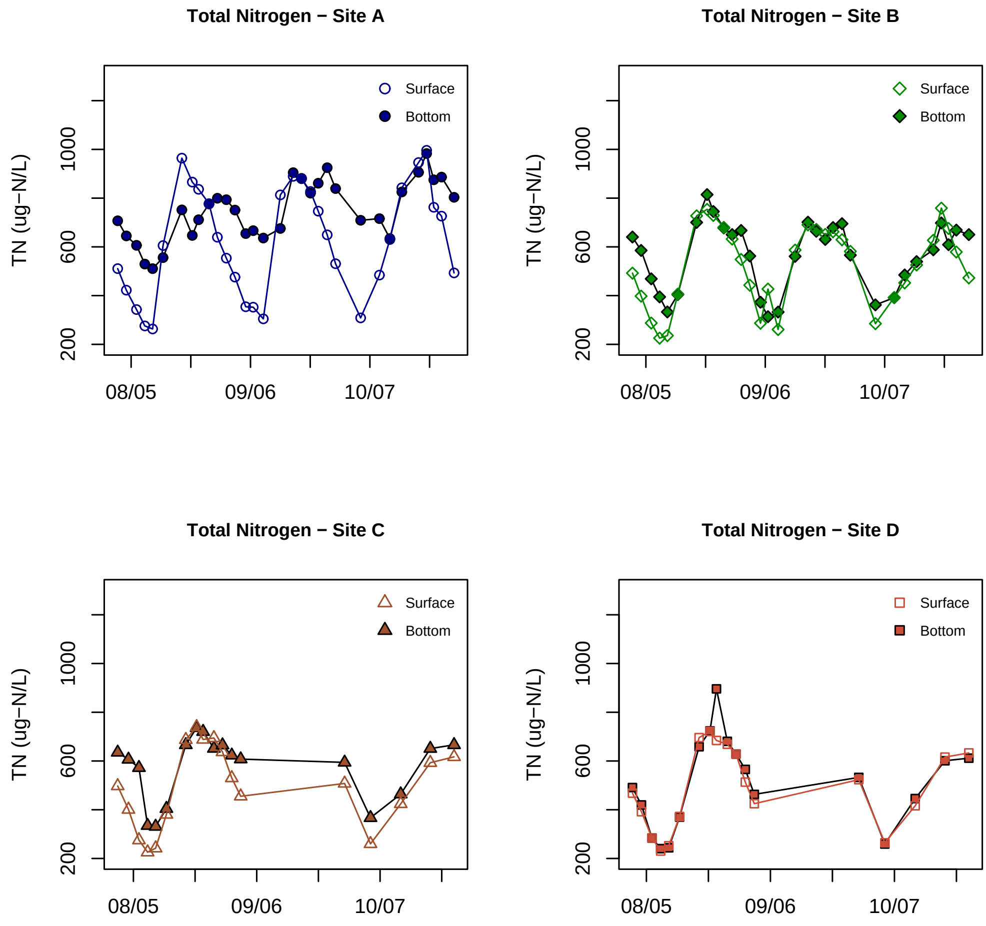


Figure 37: Lake Samish total nitrogen data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

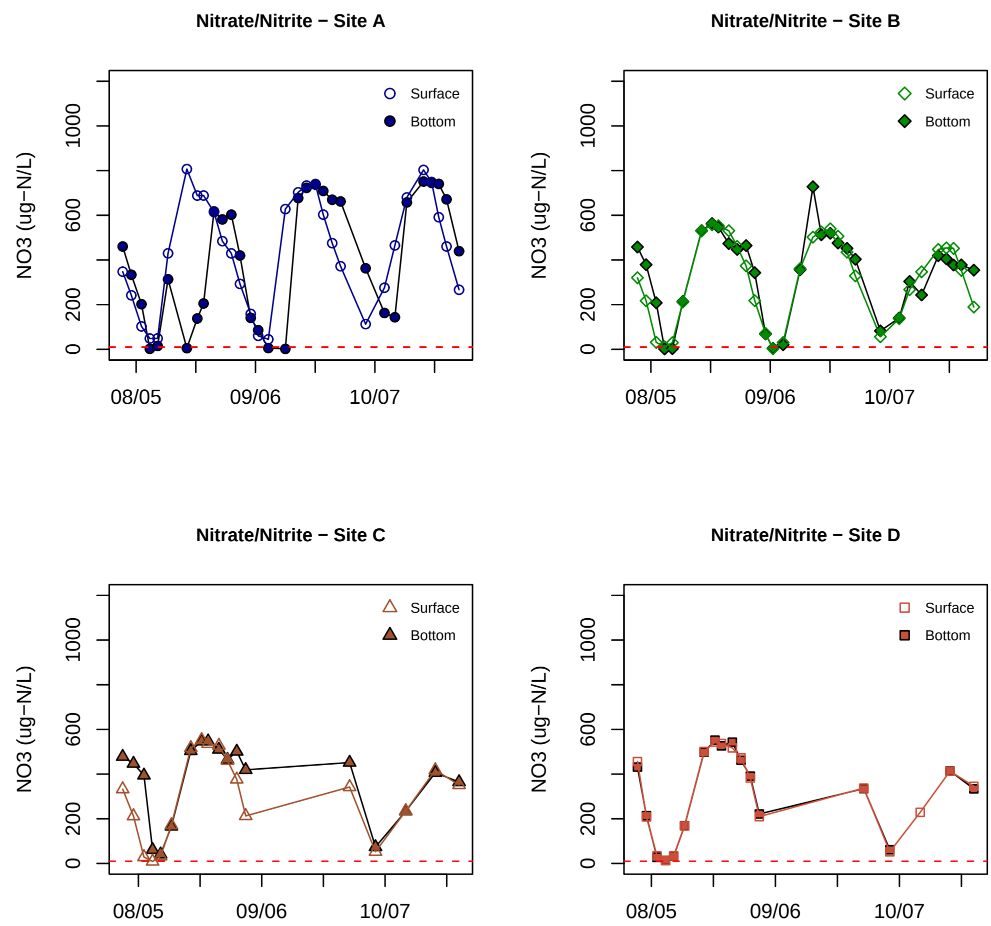


Figure 38: Lake Samish nitrate/nitrite data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

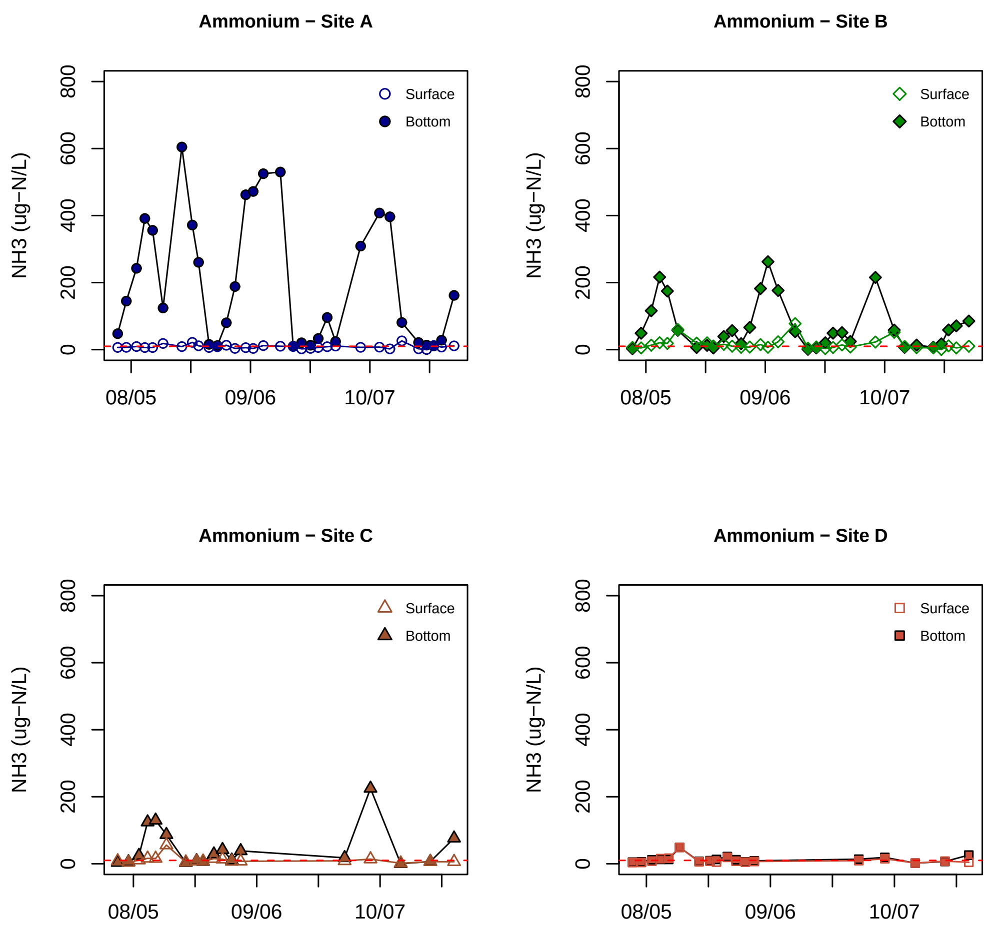


Figure 39: Lake Samish ammonium data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D were not sampled from August 2006 through May 2007. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

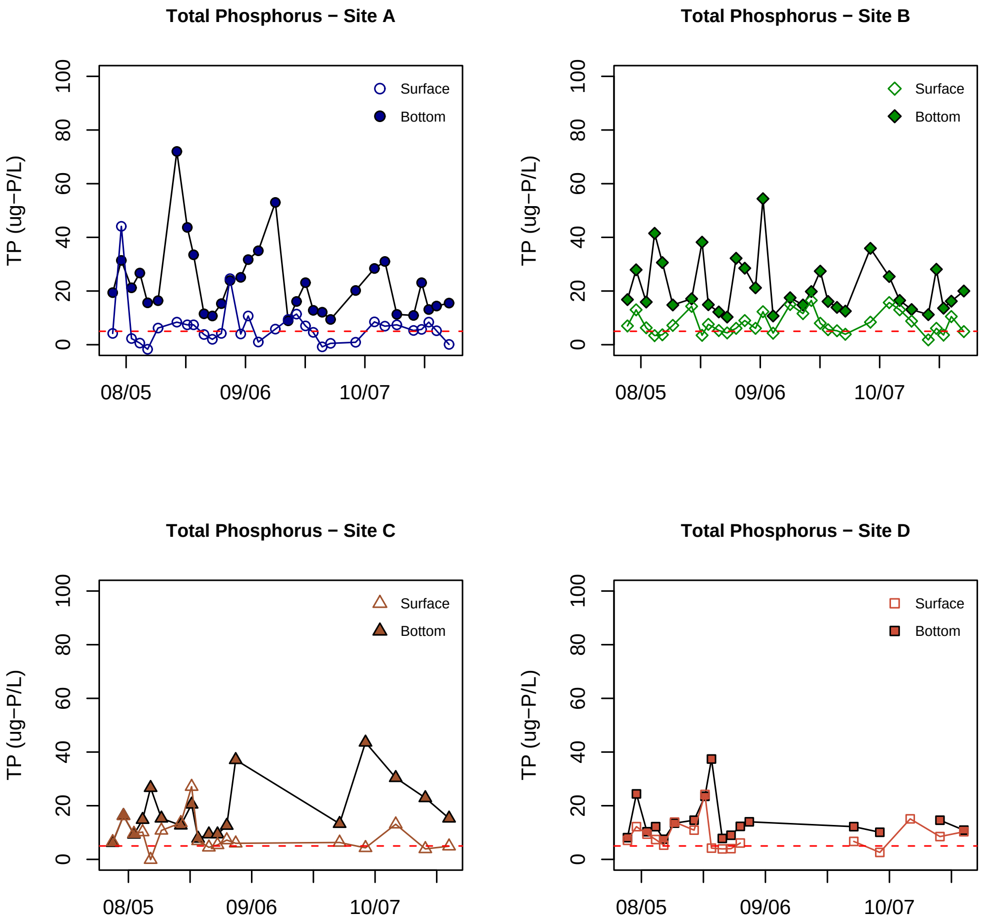


Figure 40: Lake Samish total phosphorus data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

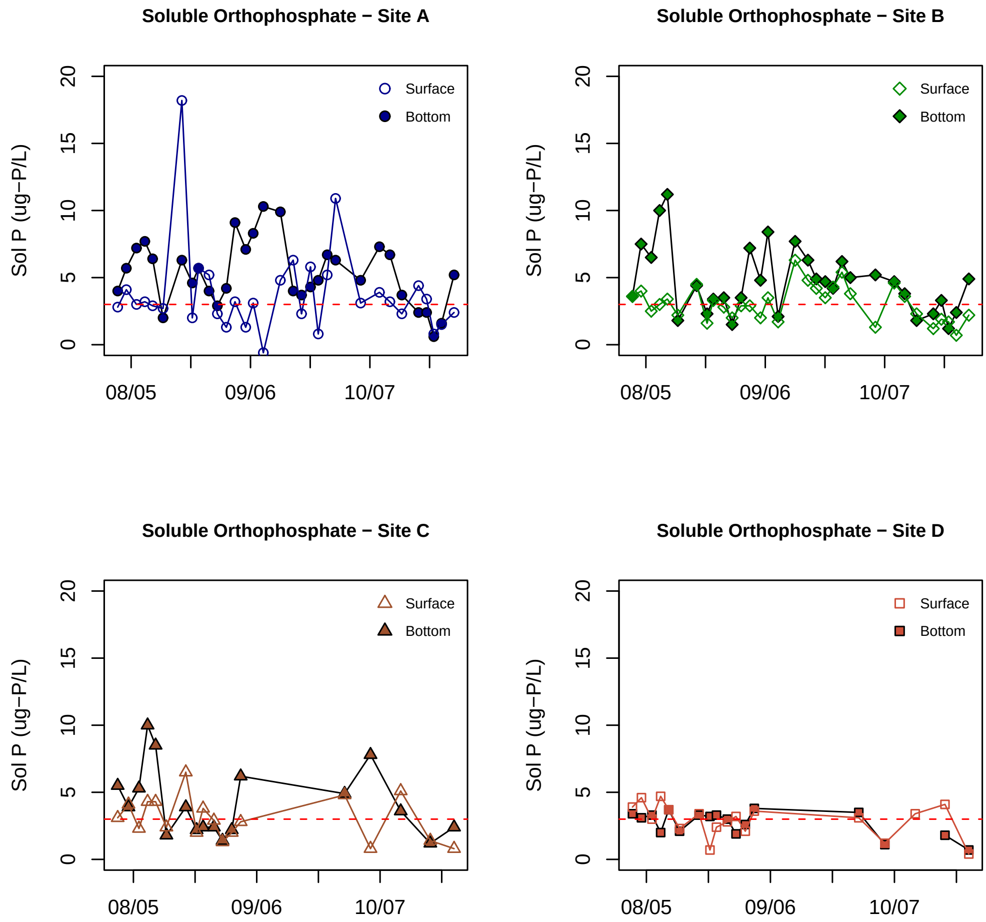


Figure 41: Lake Samish orthophosphate data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

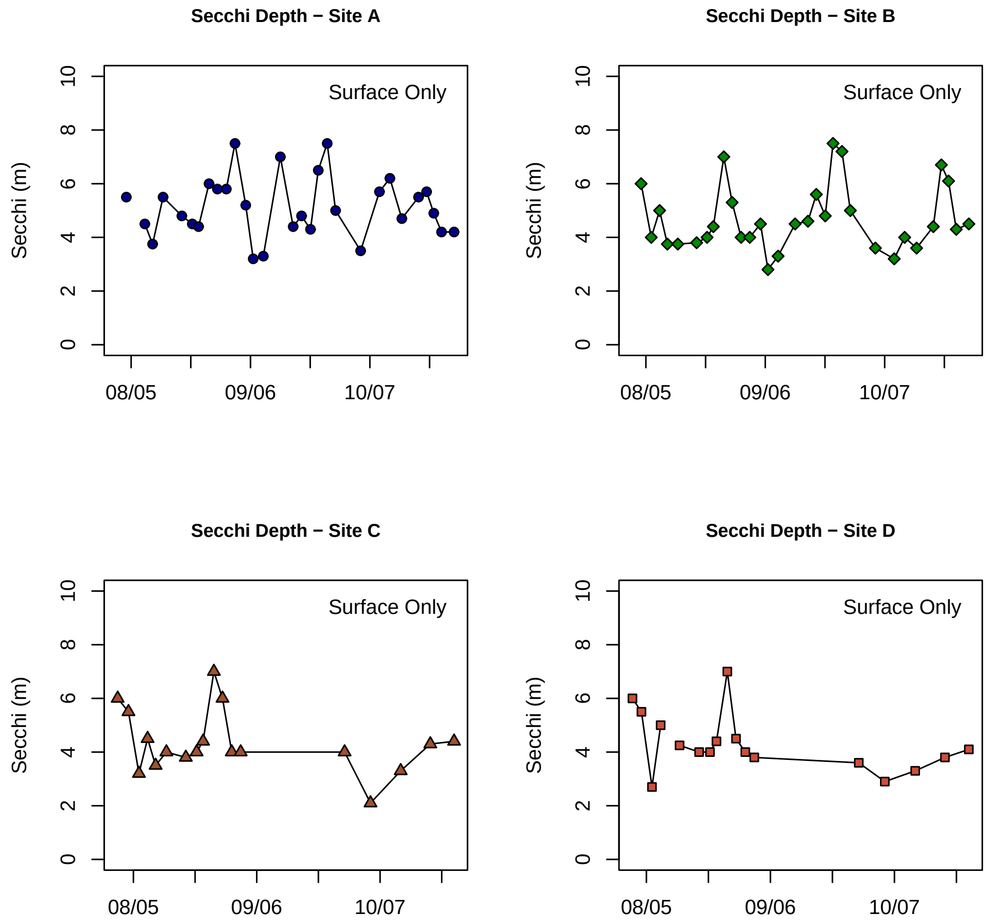


Figure 42: Lake Samish Secchi depth data, June 2005 through July 2008. Samples were collected at the surface for each site; Sites C and D were not sampled from August 2006 through May 2007. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

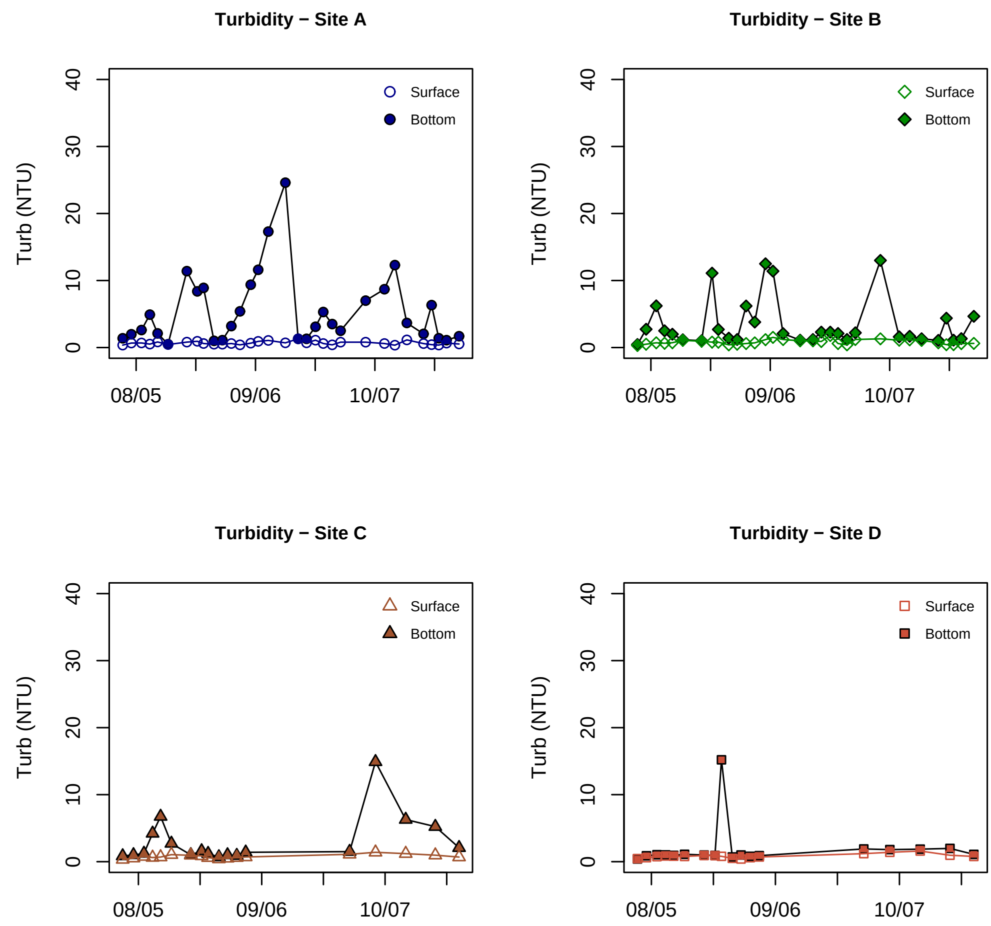


Figure 43: Lake Samish turbidity data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site; Sites C and D on all dates. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

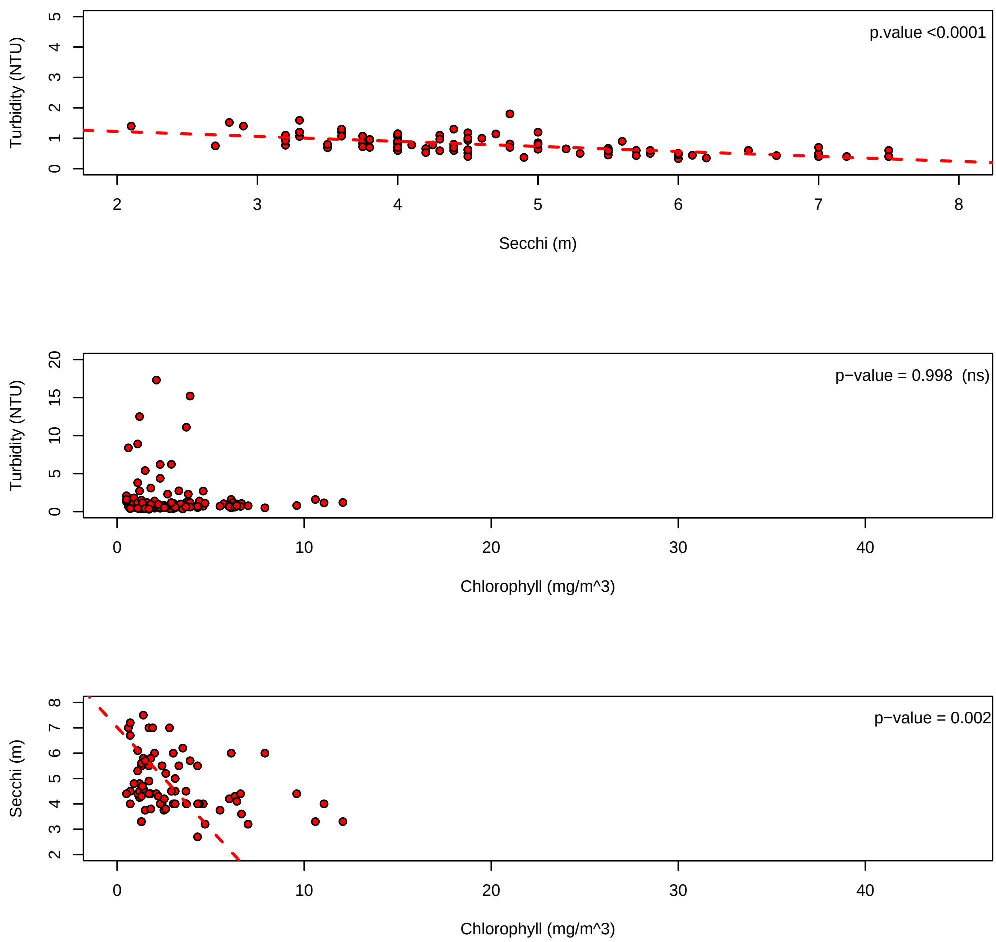


Figure 44: Kendall's τ correlations between turbidity, Secchi depth, and chlorophyll (see page 9 for description of correlation analysis). Diagonal lines are for reference only and do not imply a linear relationship.

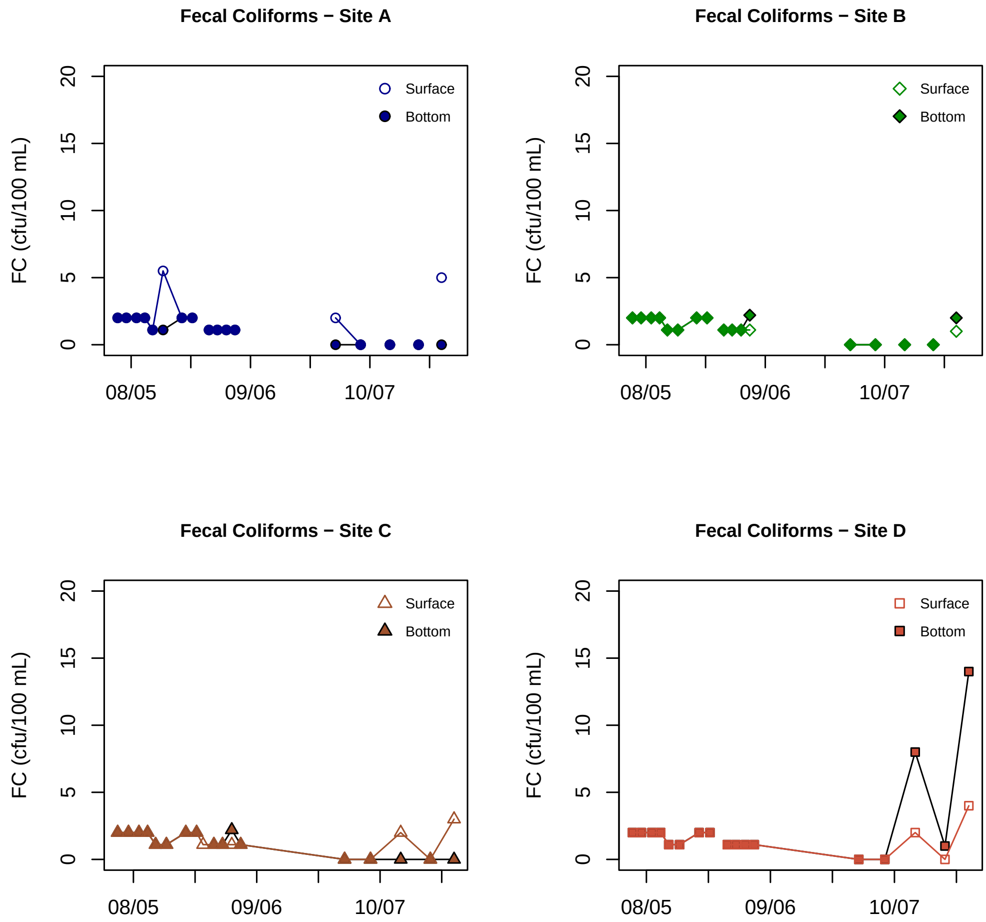


Figure 45: Lake Samish fecal coliform data, June 2005 through July 2008. Samples were collected at the surface and bottom for each site and analyzed by Edge Analytical. Note that lines connecting points do not represent equal time intervals, especially at Sites C and D.

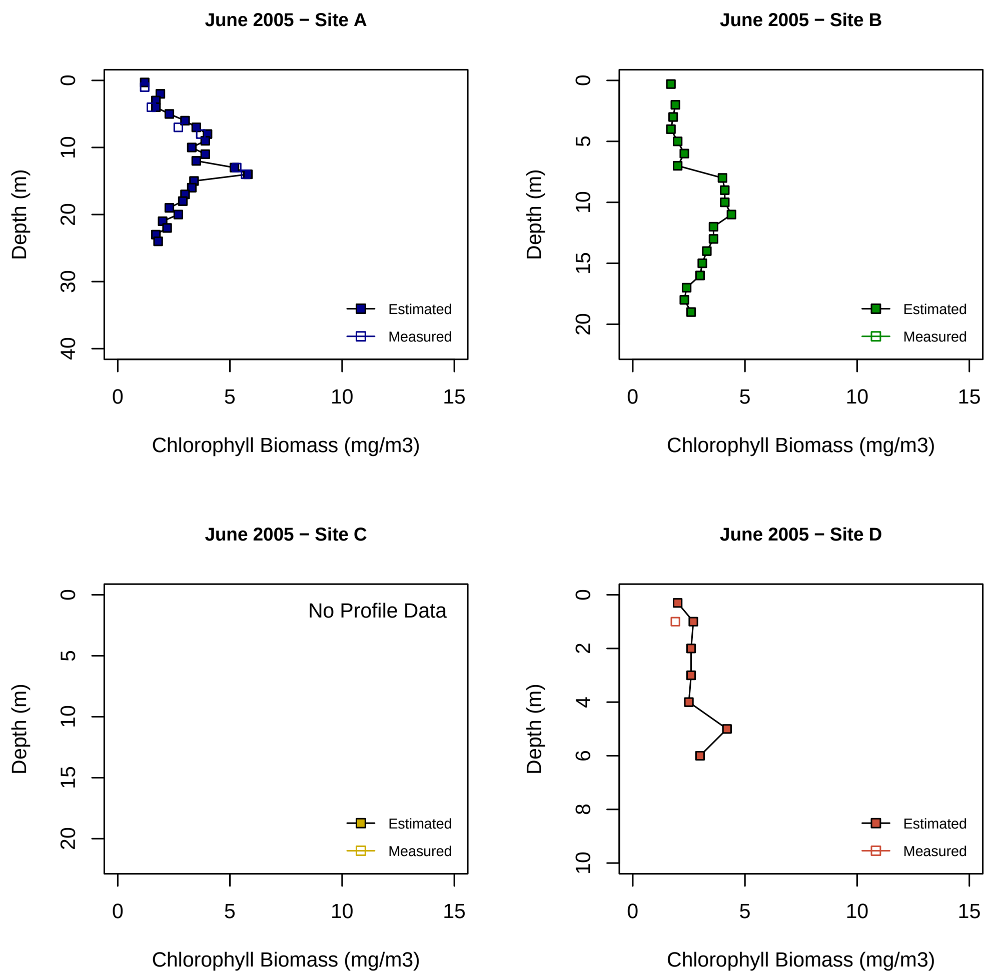


Figure 46: Lake Samish chlorophyll data for Sites A–D, June 15, 2005.

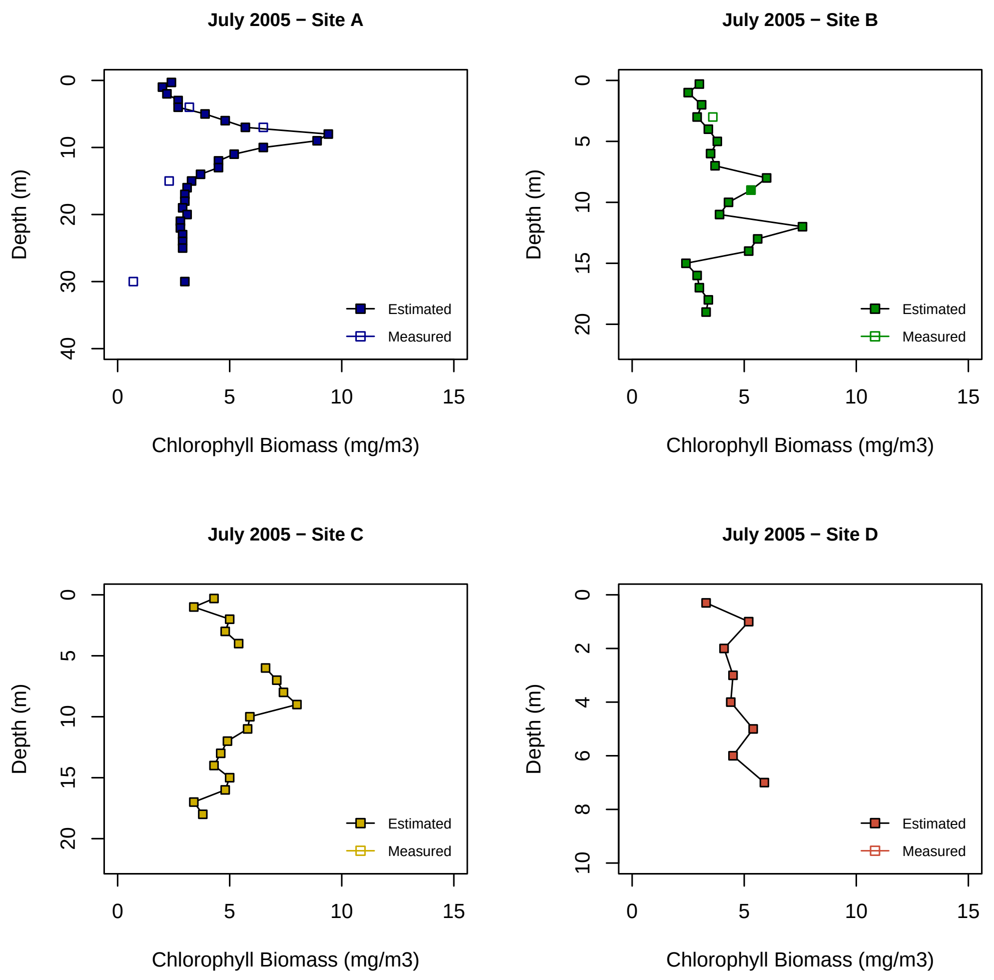


Figure 47: Lake Samish chlorophyll data for Sites A–D, July 20, 2005.

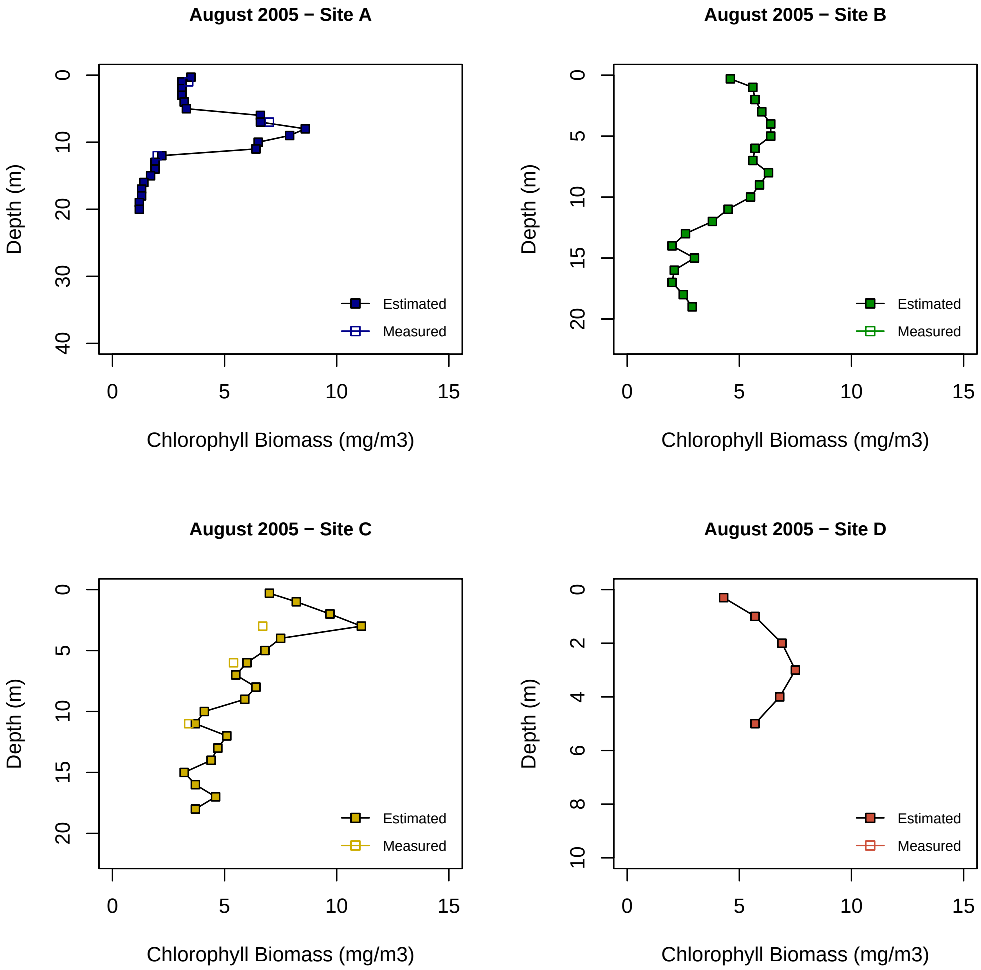


Figure 48: Lake Samish chlorophyll data for Sites A–D, August 23, 2005.

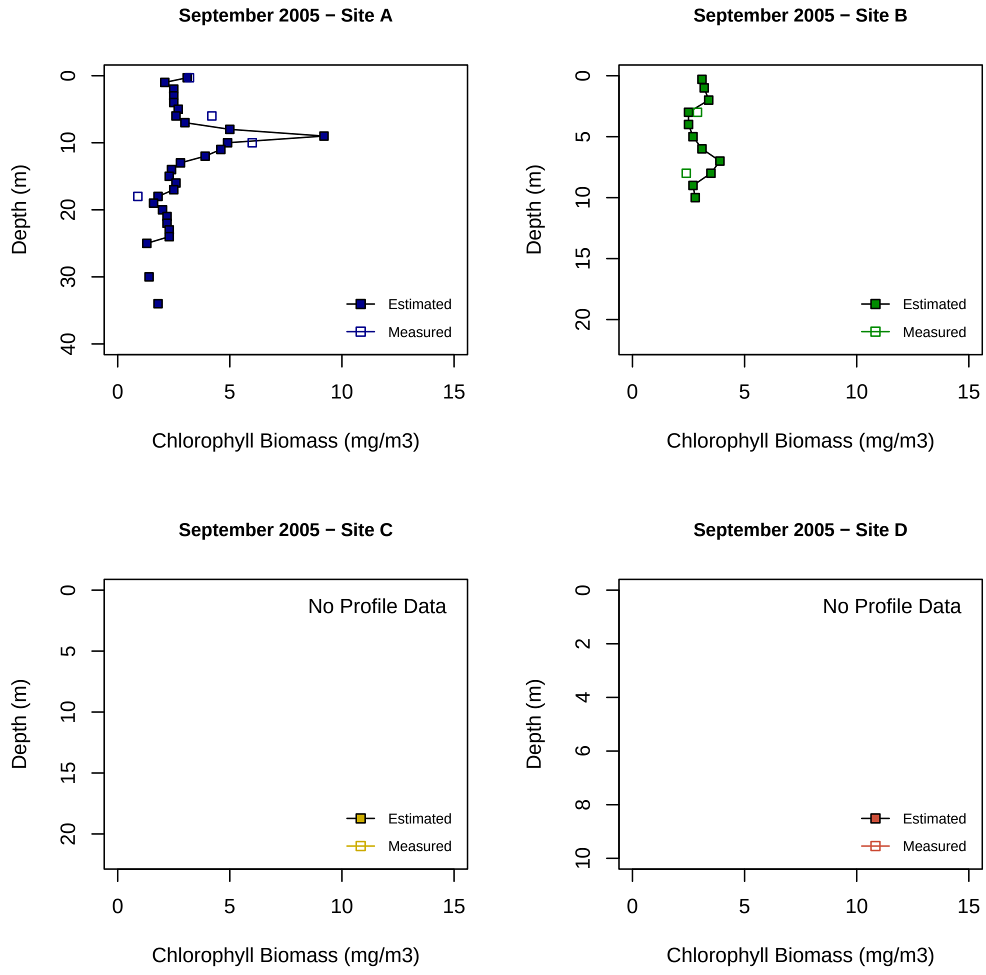


Figure 49: Lake Samish chlorophyll data for Sites A and B, September 20, 2005. Data from Sites C and D have been omitted due to equipment malfunction.

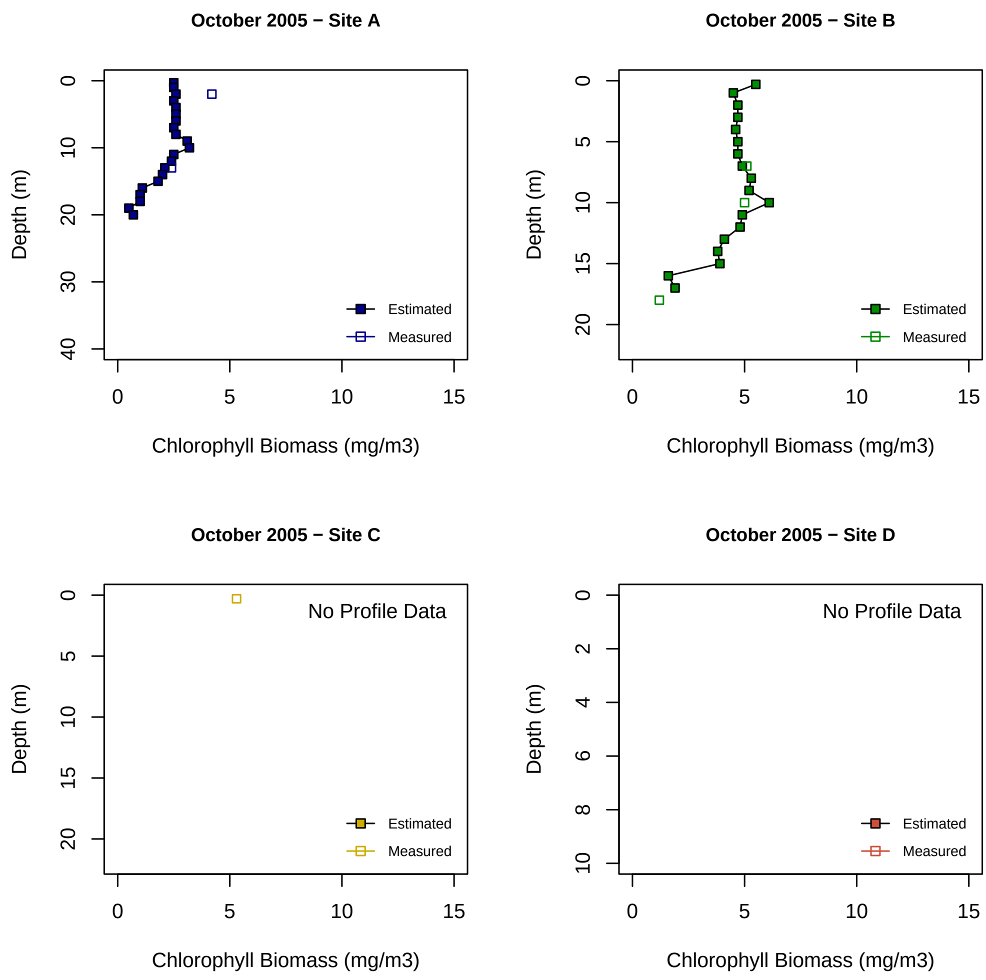


Figure 50: Lake Samish chlorophyll data for Sites A and B, October 16, 2005. Data from Sites C and D have been omitted due to equipment malfunction.

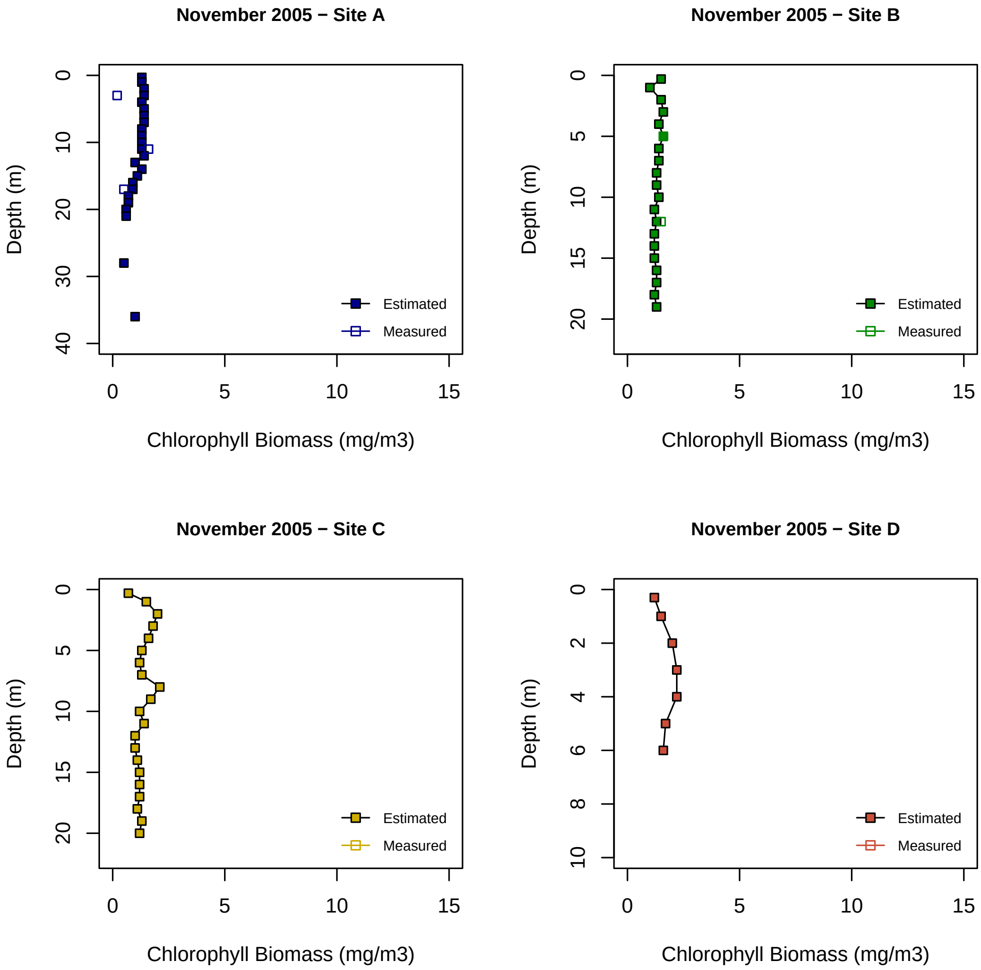


Figure 51: Lake Samish chlorophyll data for Sites A–D, November 20, 2005.

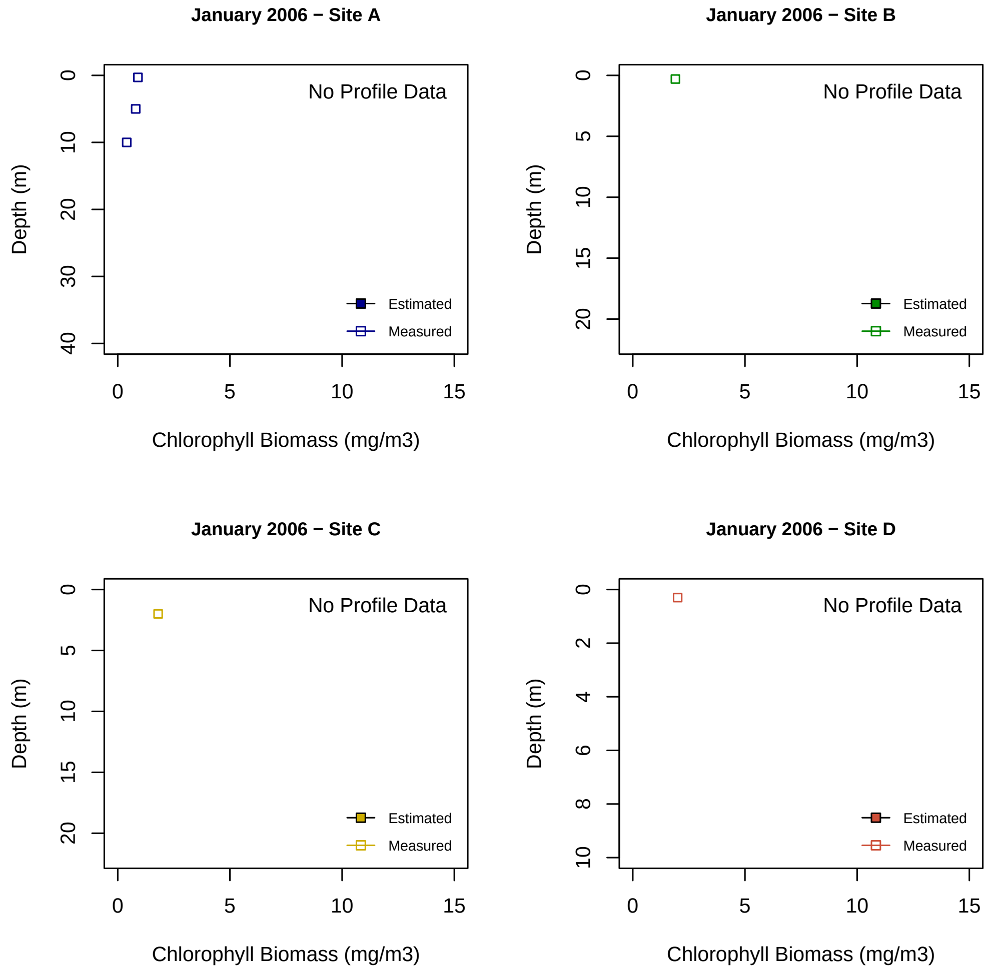


Figure 52: Lake Samish chlorophyll data for Sites A–D, January 22, 2006.

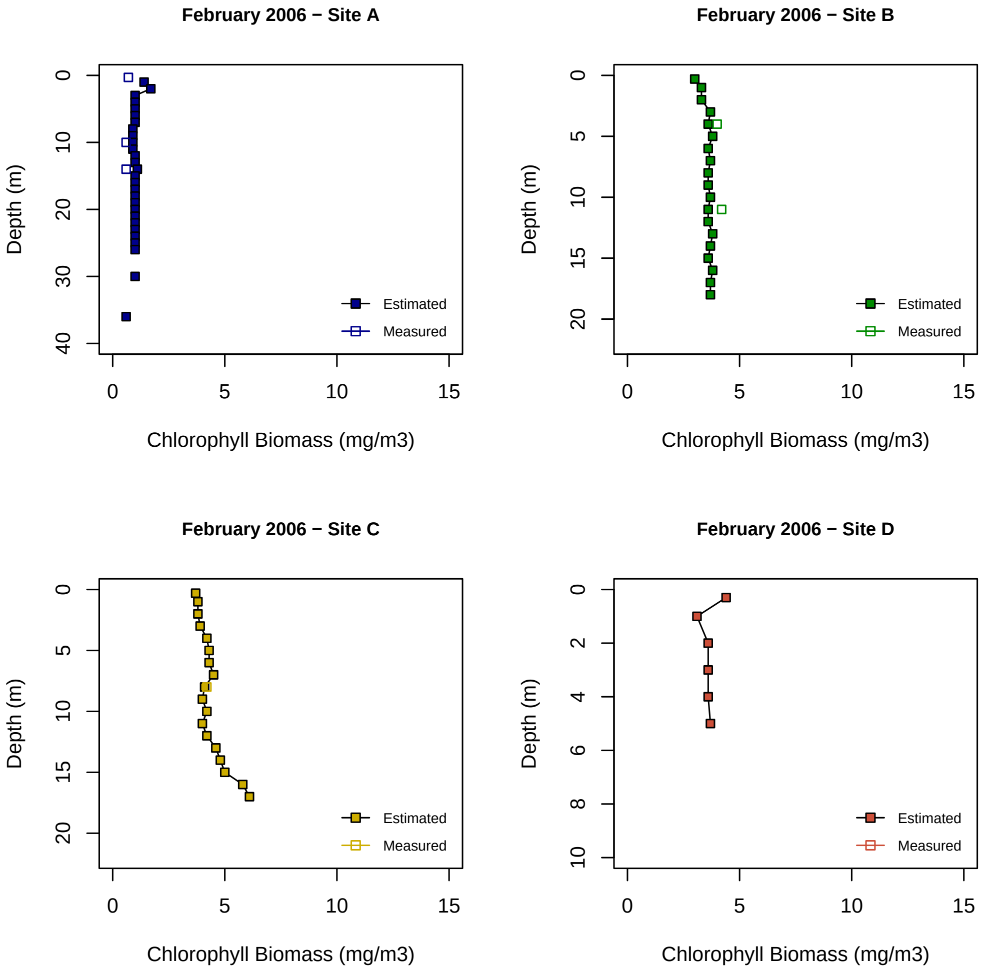


Figure 53: Lake Samish chlorophyll data for Sites A–D, February 26, 2006.

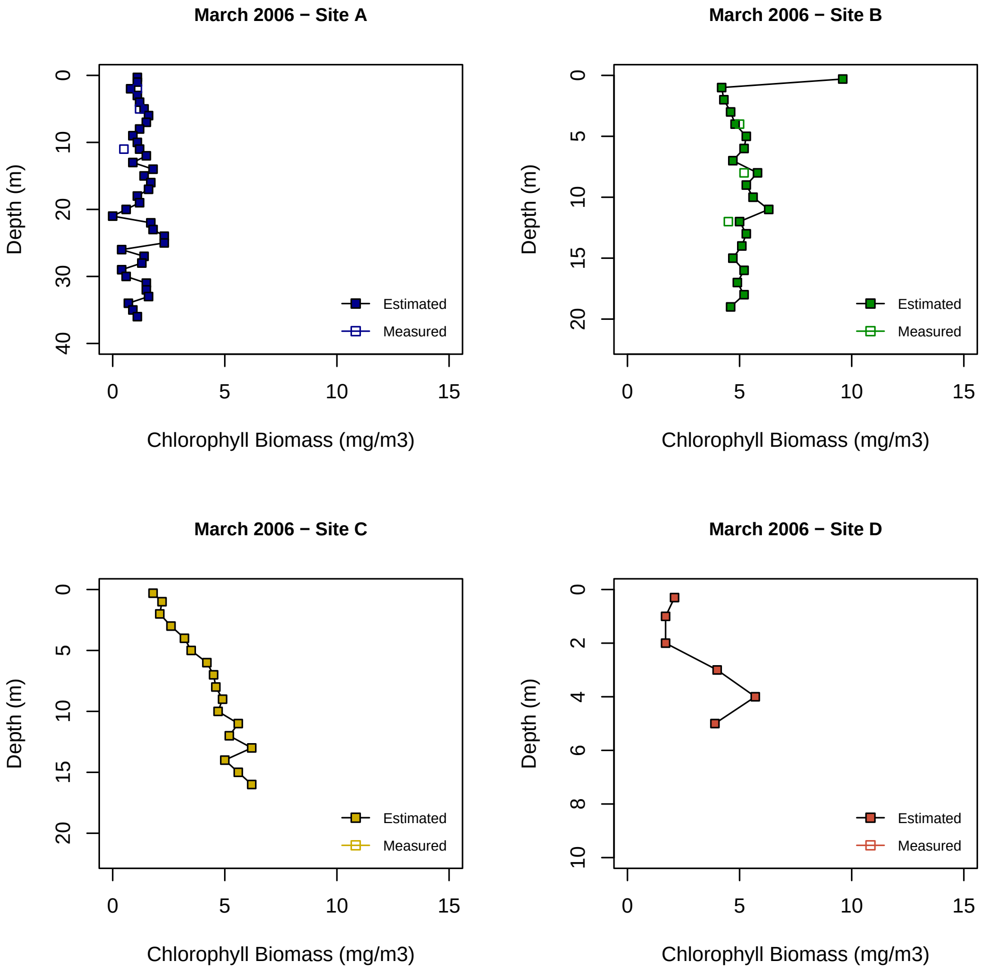


Figure 54: Lake Samish chlorophyll data for Sites A–D, March 19, 2006.

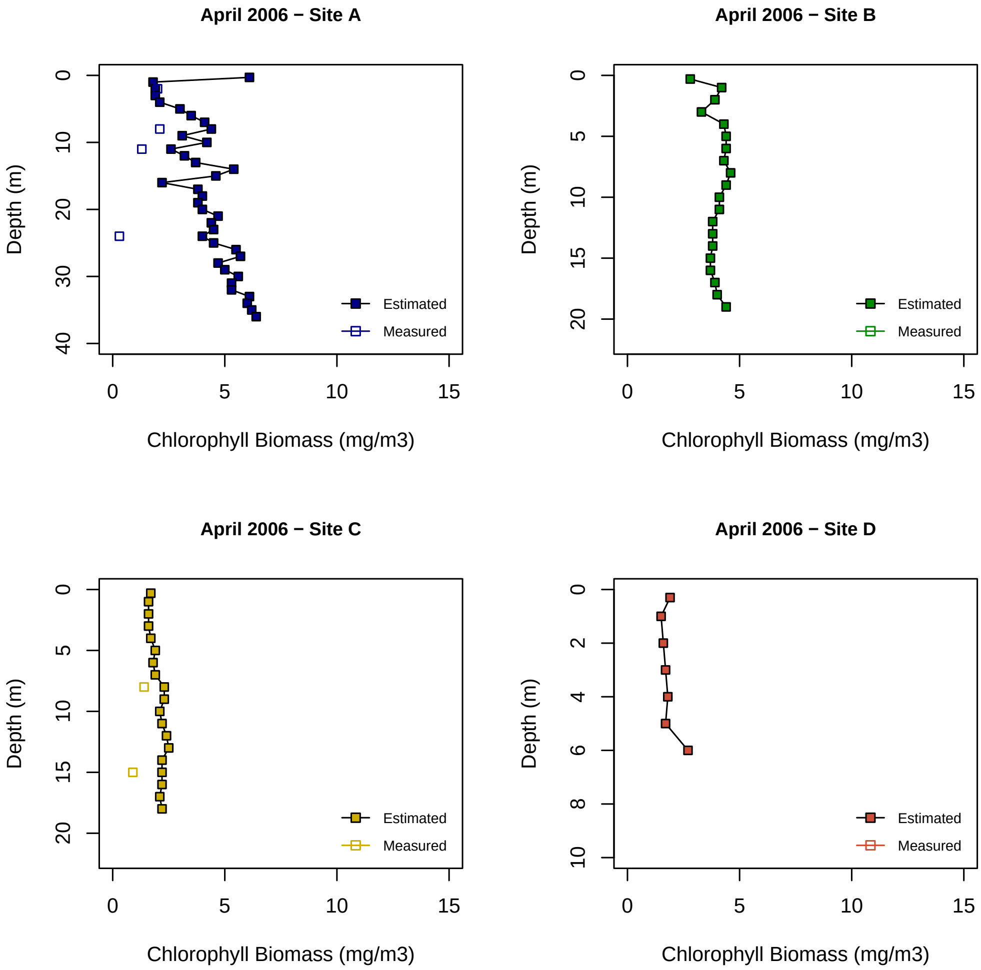


Figure 55: Lake Samish chlorophyll data for Sites A–D, April 23, 2006.

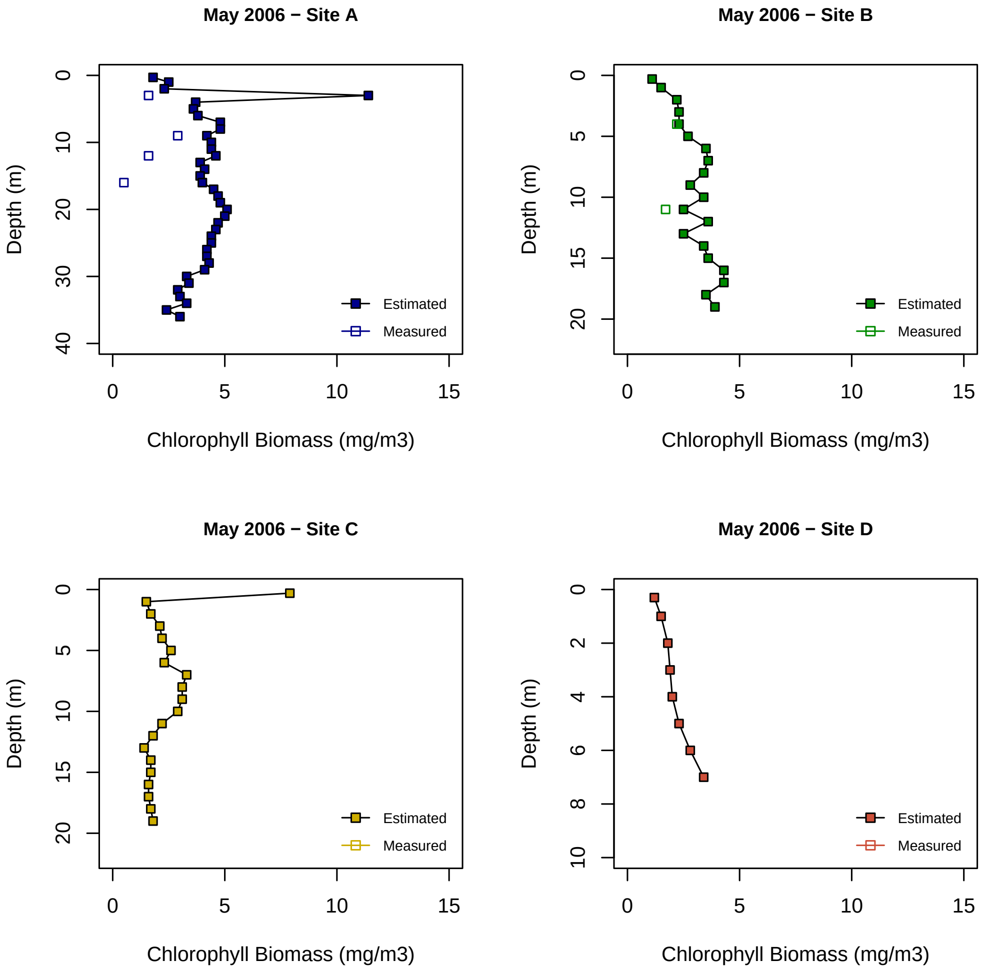


Figure 56: Lake Samish chlorophyll data for Sites A–D, May 21, 2006.

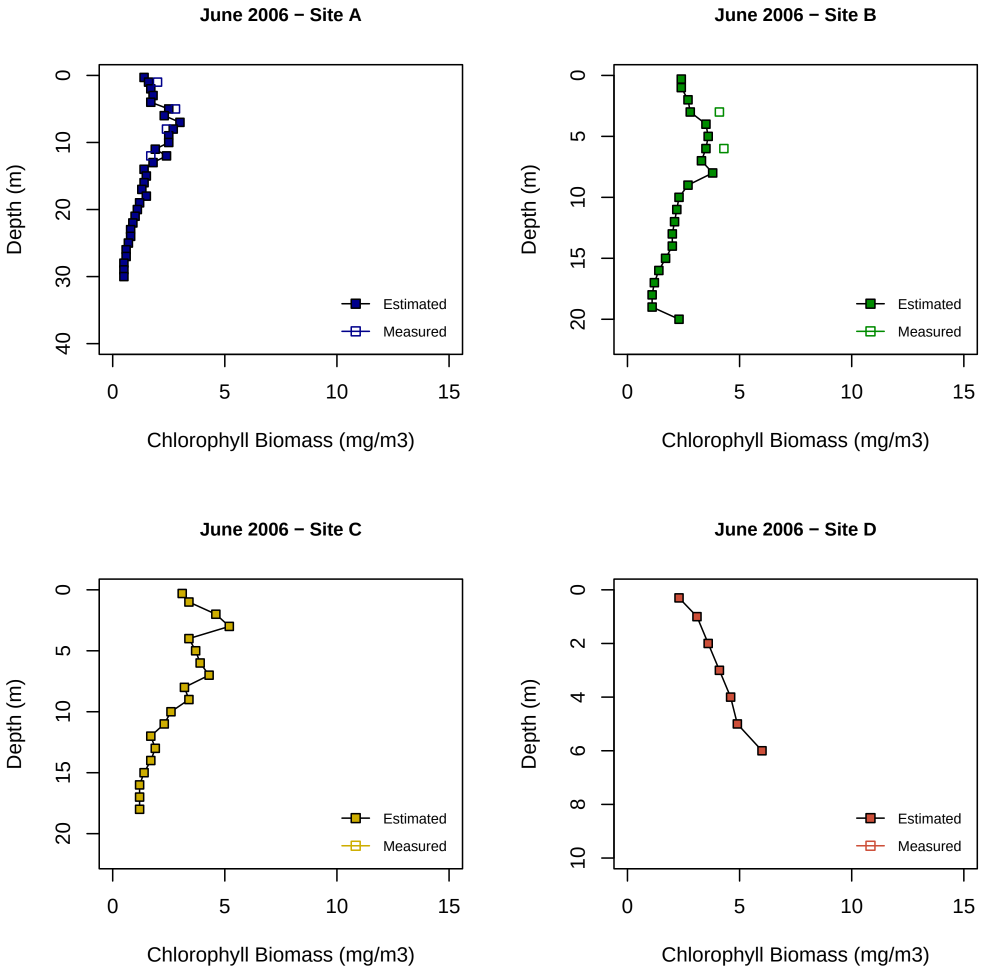


Figure 57: Lake Samish chlorophyll data for Sites A–D, June 20, 2006.

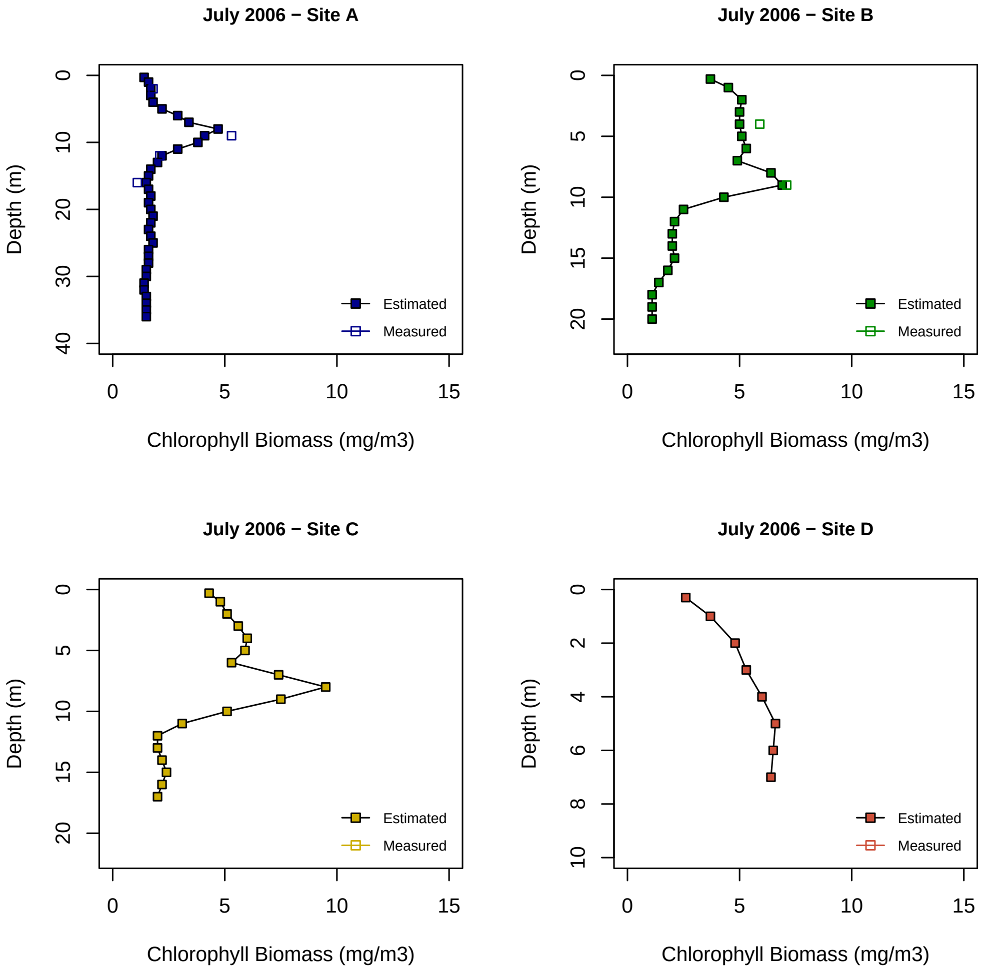


Figure 58: Lake Samish chlorophyll data for Sites A–D, July 19, 2006.

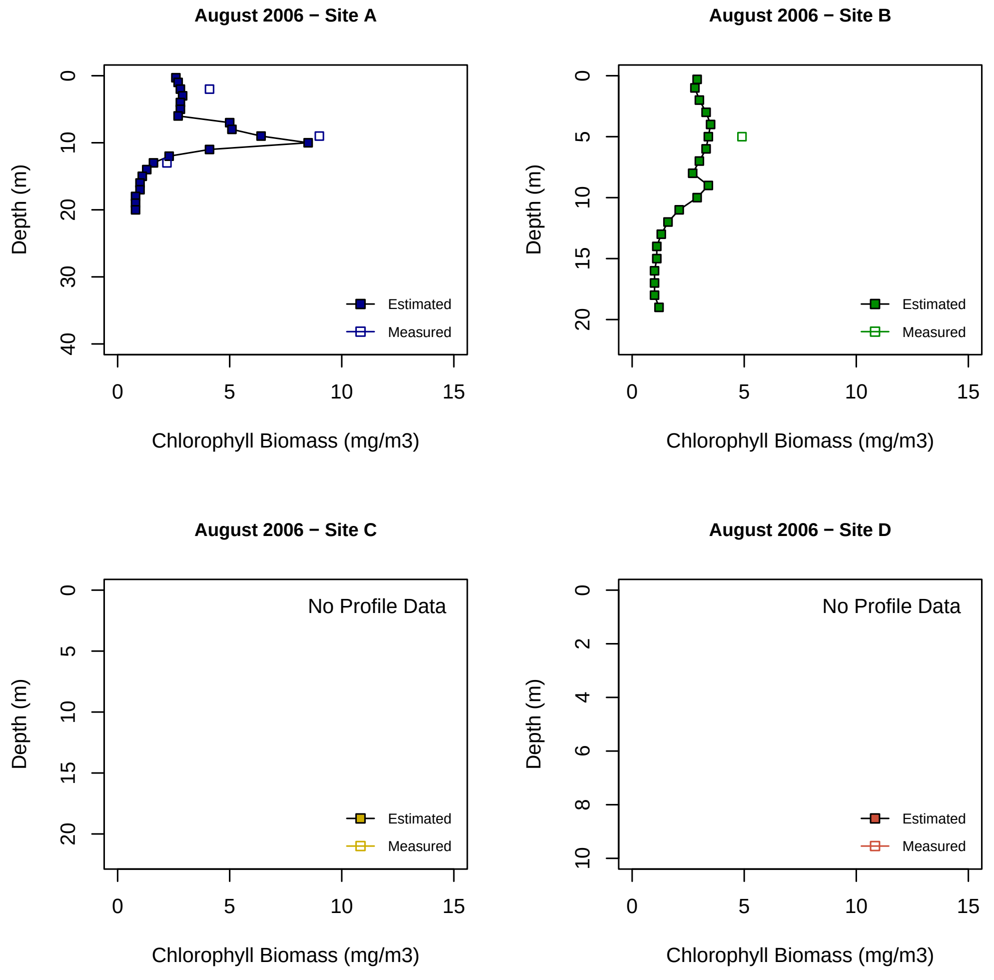


Figure 59: Lake Samish chlorophyll data for Sites A and B, August 24, 2006. Sites C and D were not sampled on this date.

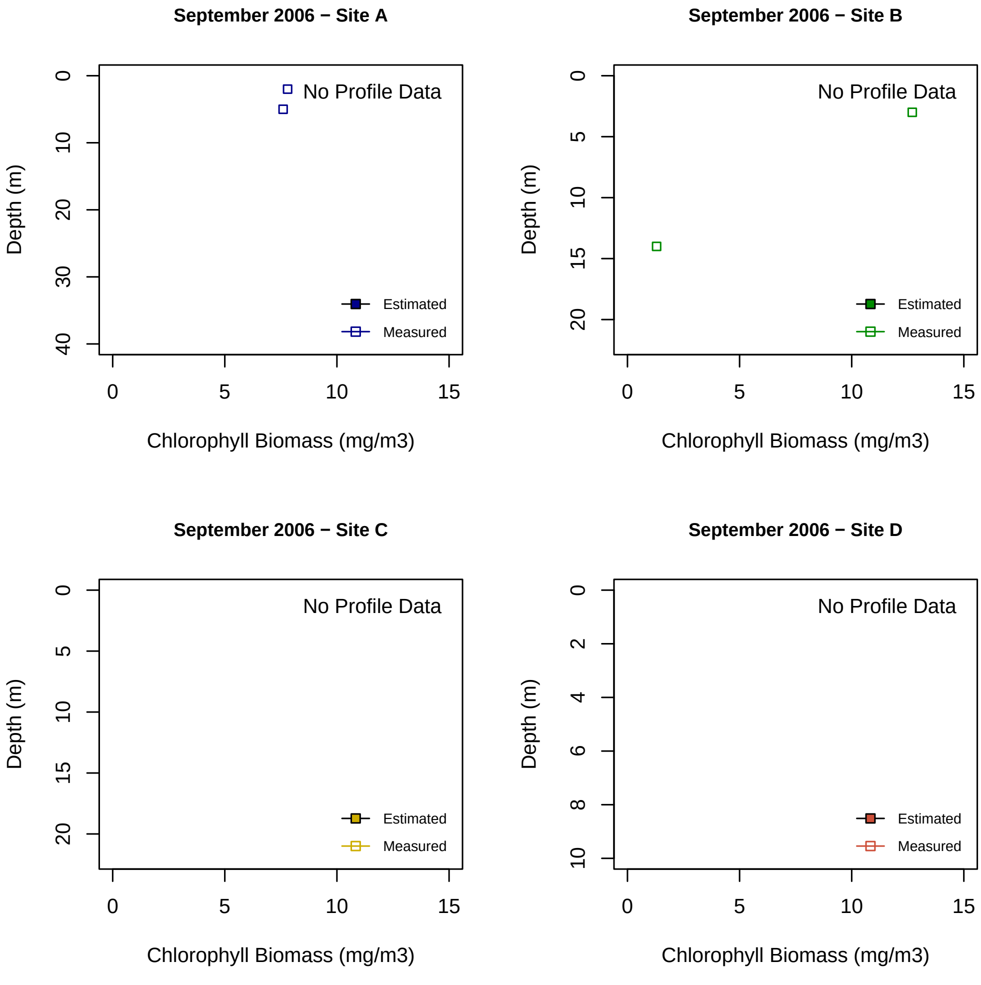


Figure 60: Lake Samish chlorophyll data for Sites A and B, September 18, 2006. Sites C and D were not sampled on this date.

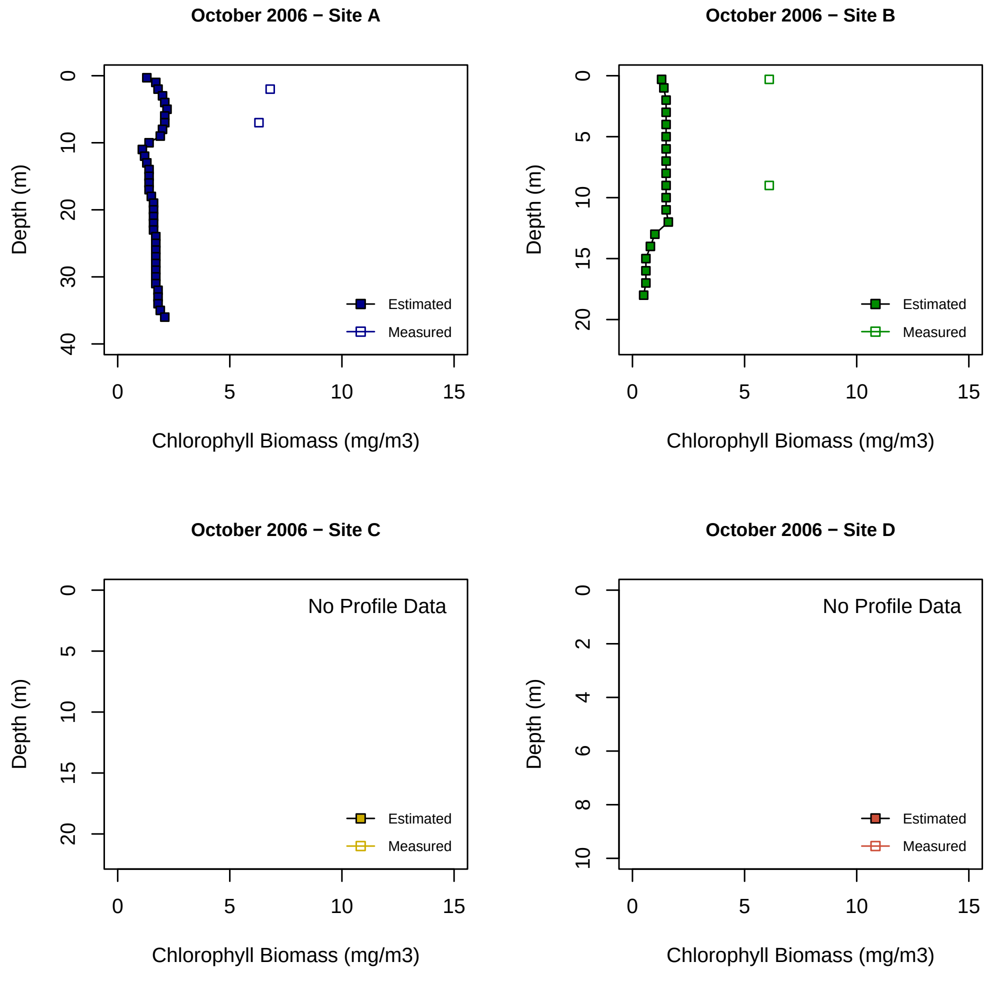


Figure 61: Lake Samish chlorophyll data for Sites A and B, October 22, 2006. Sites C and D were not sampled on this date.

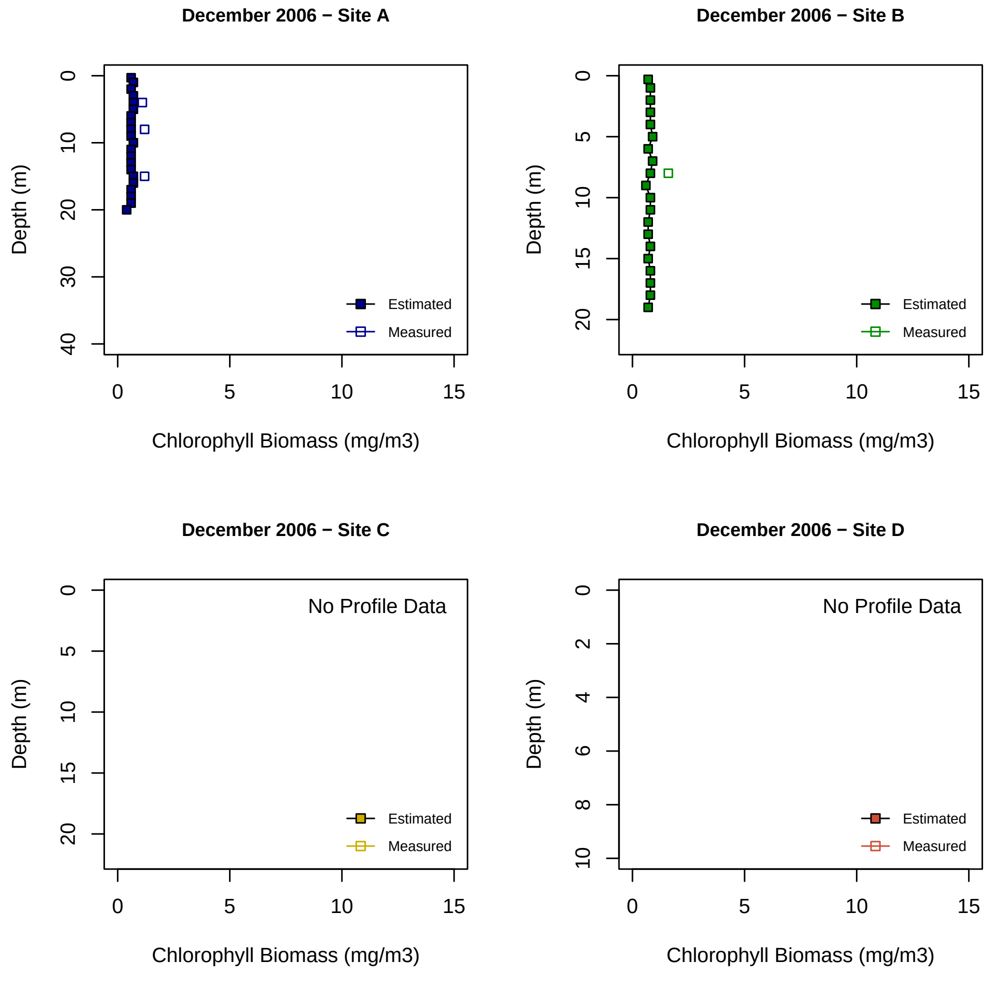


Figure 62: Lake Samish chlorophyll data for Sites A and B, December 18, 2006. Sites C and D were not sampled on this date.

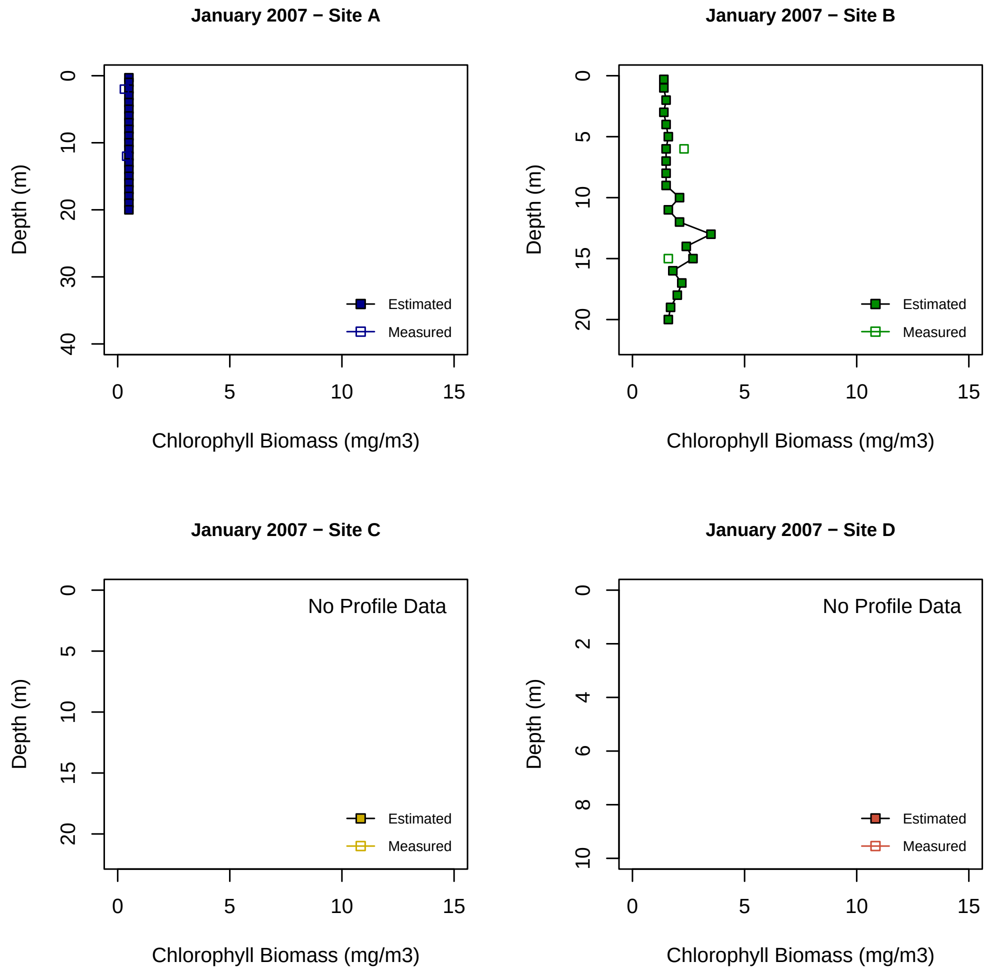


Figure 63: Lake Samish chlorophyll data for Sites A and B, January 30, 2007. Sites C and D were not sampled on this date.

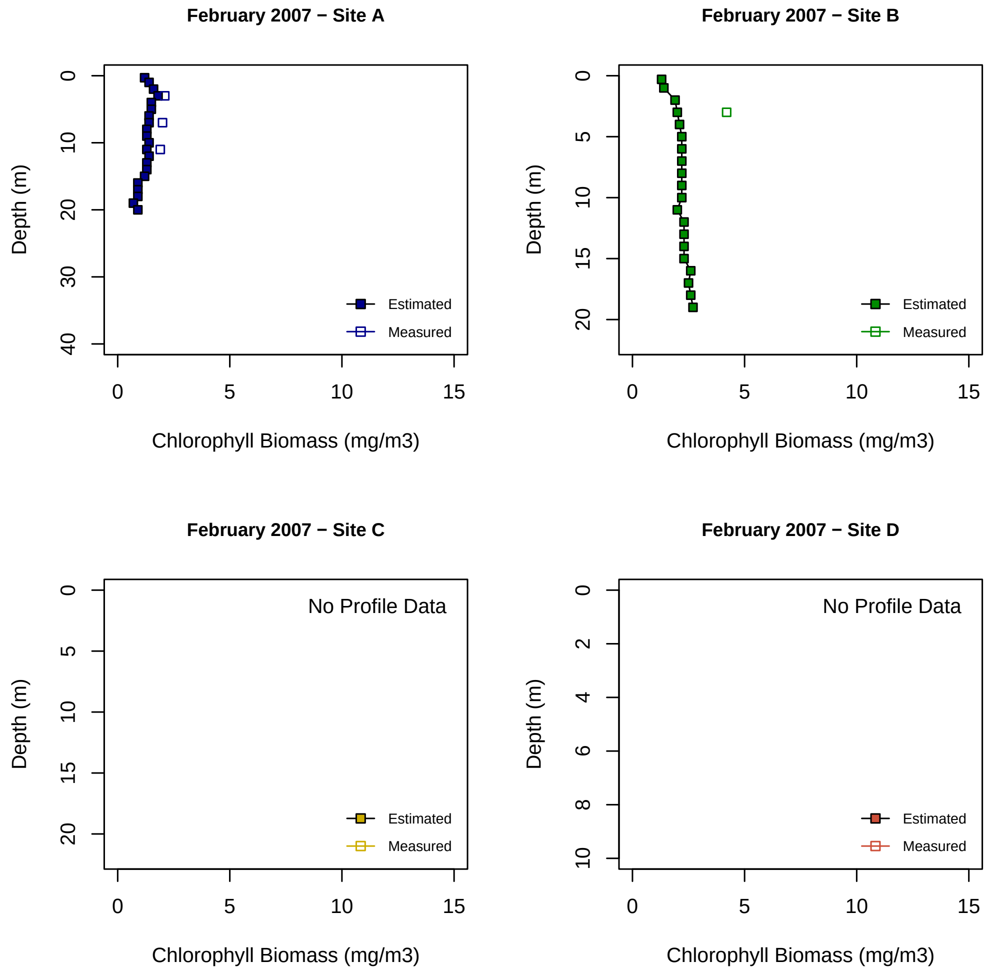


Figure 64: Lake Samish chlorophyll data for Sites A and B, February 27, 2007. Sites C and D were not sampled on this date.

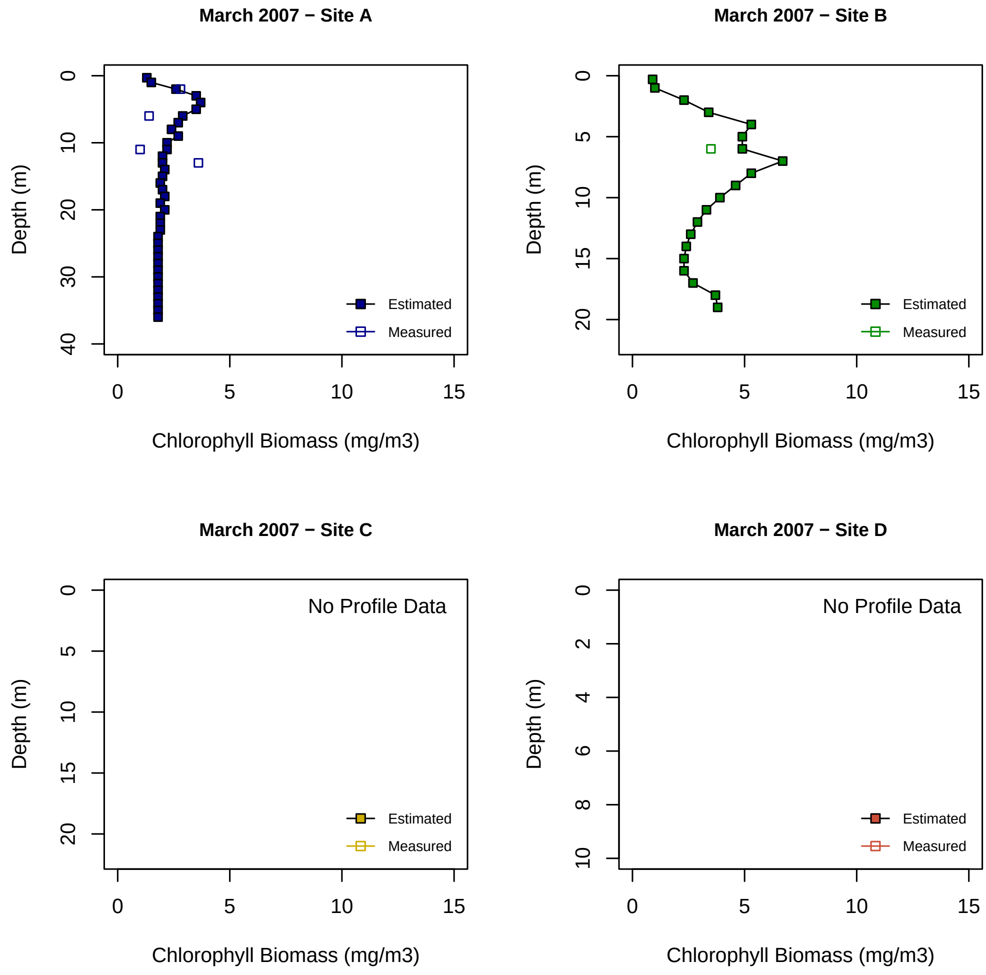


Figure 65: Lake Samish chlorophyll data for Sites A and B, March 29, 2007. Sites C and D were not sampled on this date.

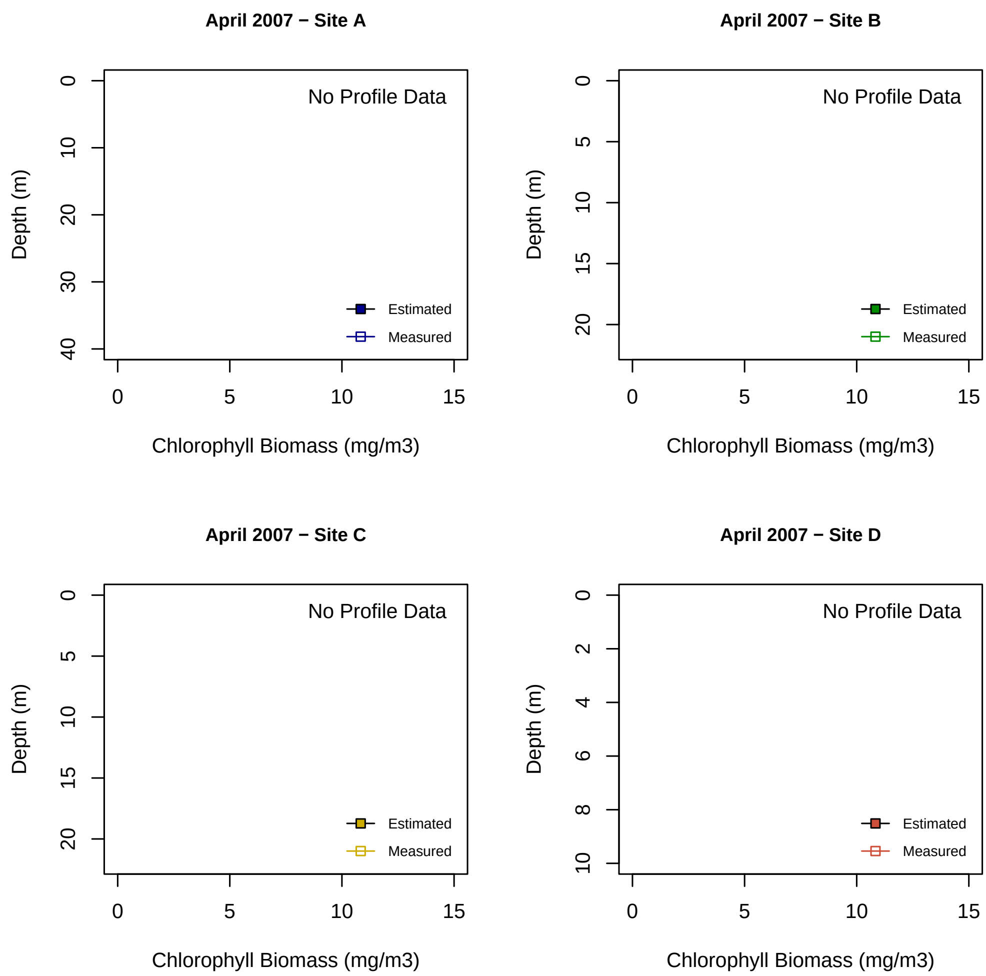


Figure 66: Lake Samish chlorophyll data for April 24, 2007 (no chlorophyll data were collected; the plot is included for information only).

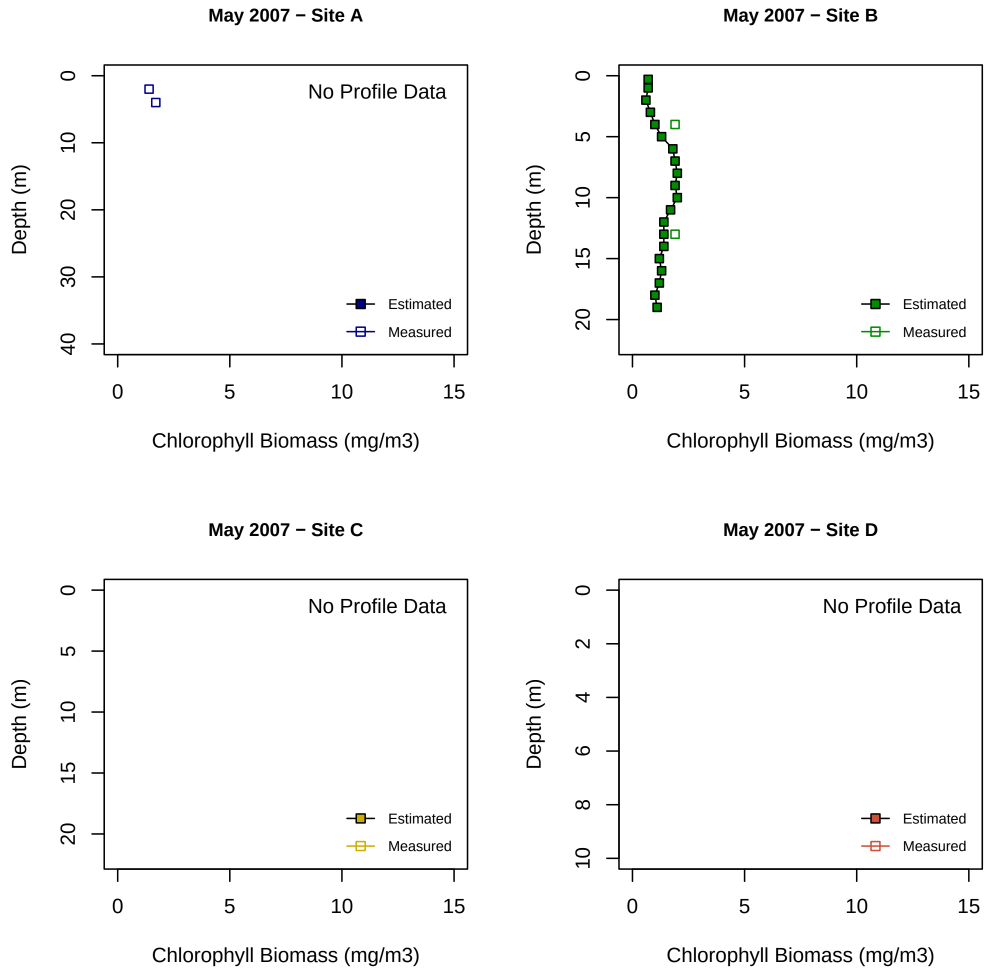


Figure 67: Lake Samish chlorophyll data for Site B, May 24, 2007. Sites C and D were not sampled on this date and only two samples were collected at Site A.

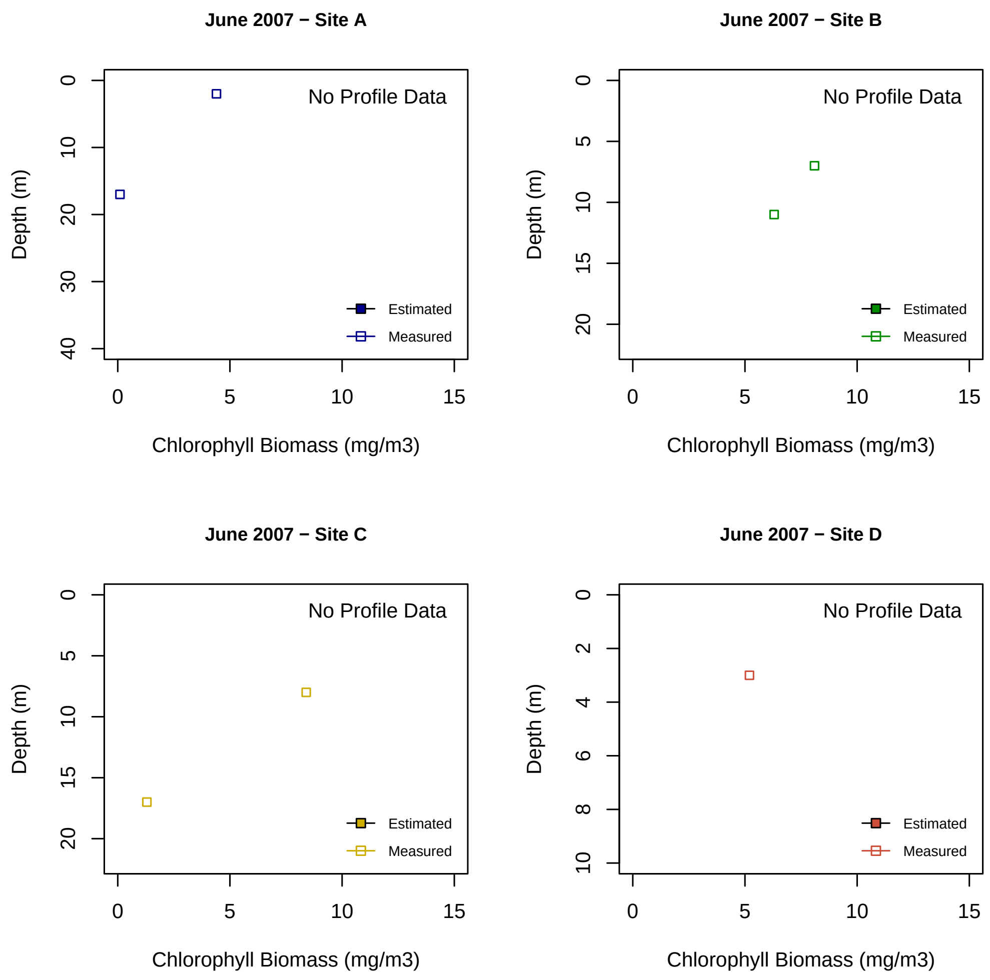


Figure 68: Lake Samish chlorophyll data for Sites A–D, June 21, 2007.

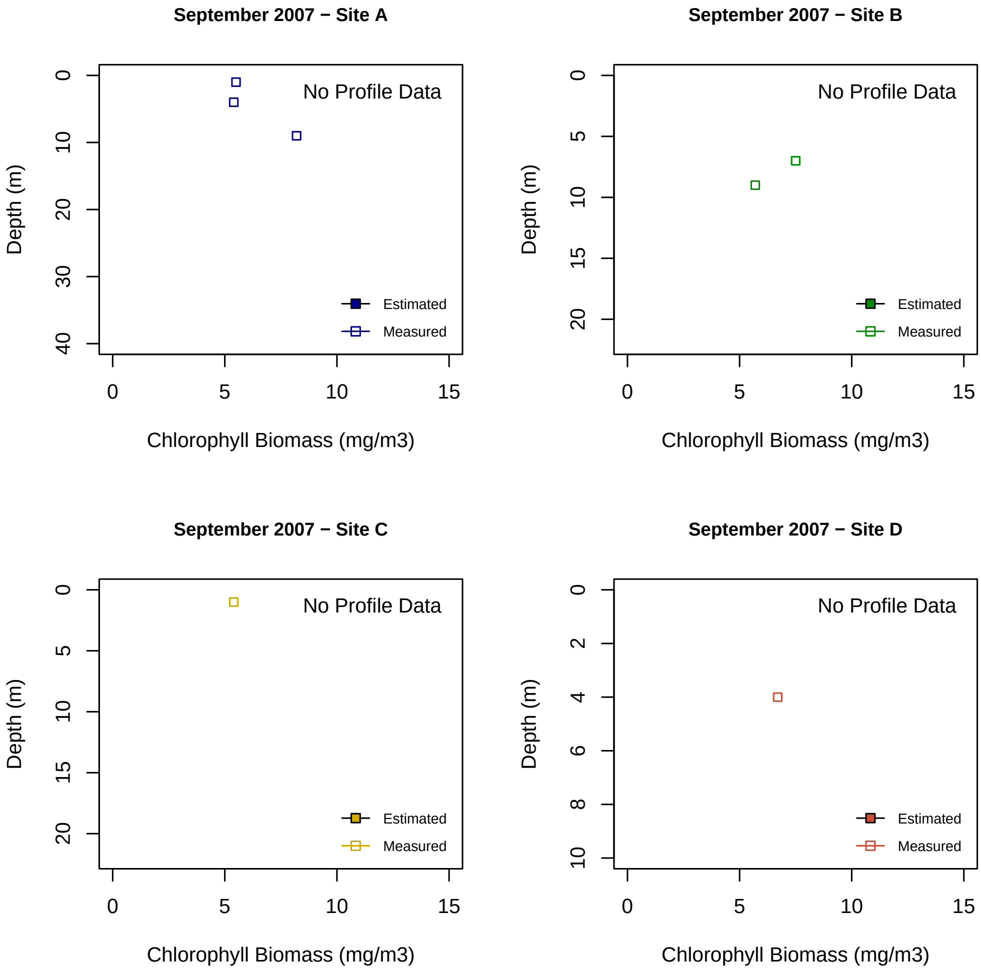


Figure 69: Lake Samish chlorophyll data for Sites A–D, September 13, 2007.

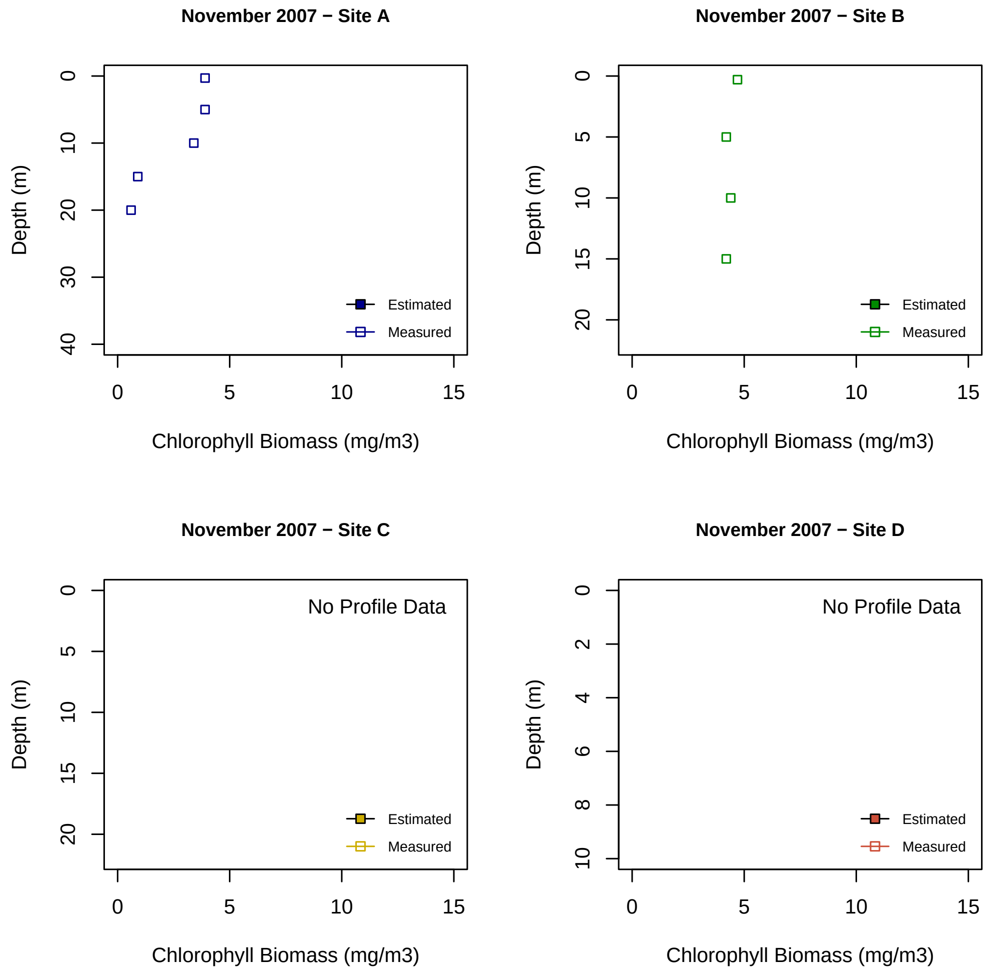


Figure 70: Lake Samish chlorophyll data for Sites A and B, November 15, 2007. Sites A and B were sampled at 5 meter depth intervals; Sites C and D were not sampled on this date.

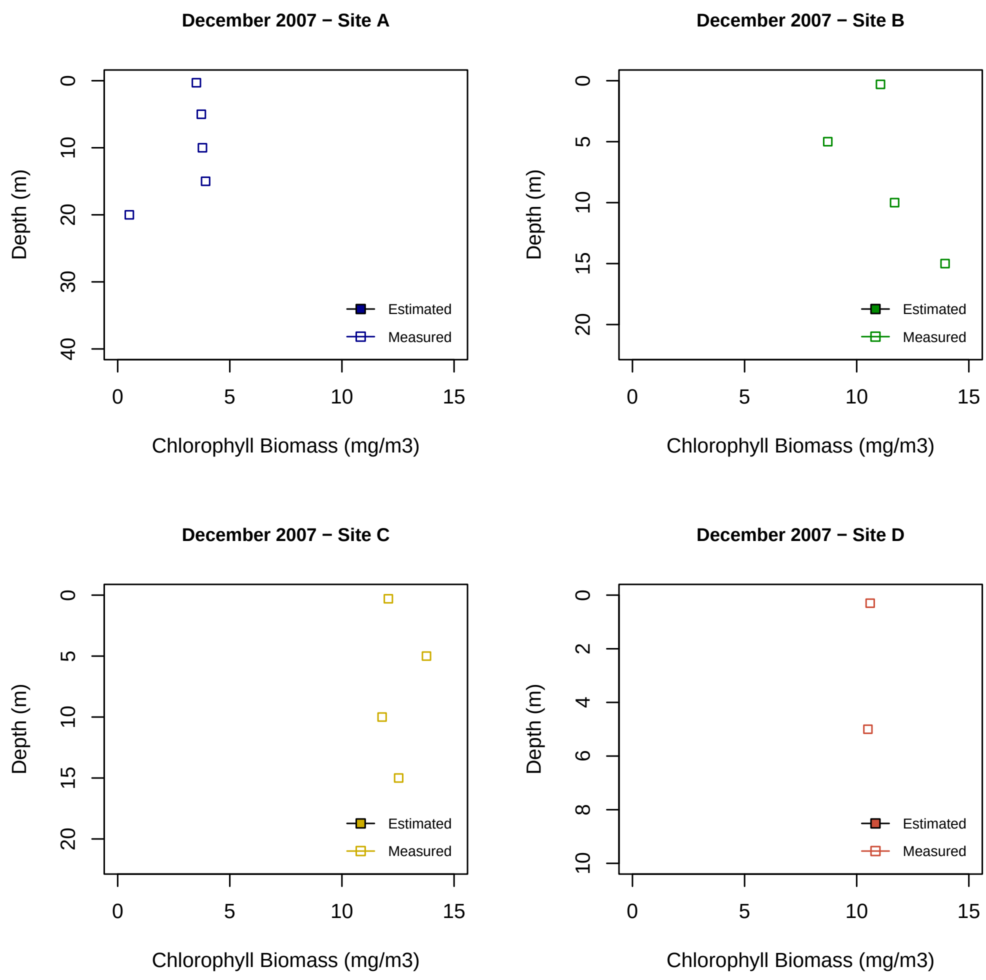


Figure 71: Lake Samish chlorophyll data for Sites A–D, December 20, 2007. All sites were sampled at 5 meter depth intervals.

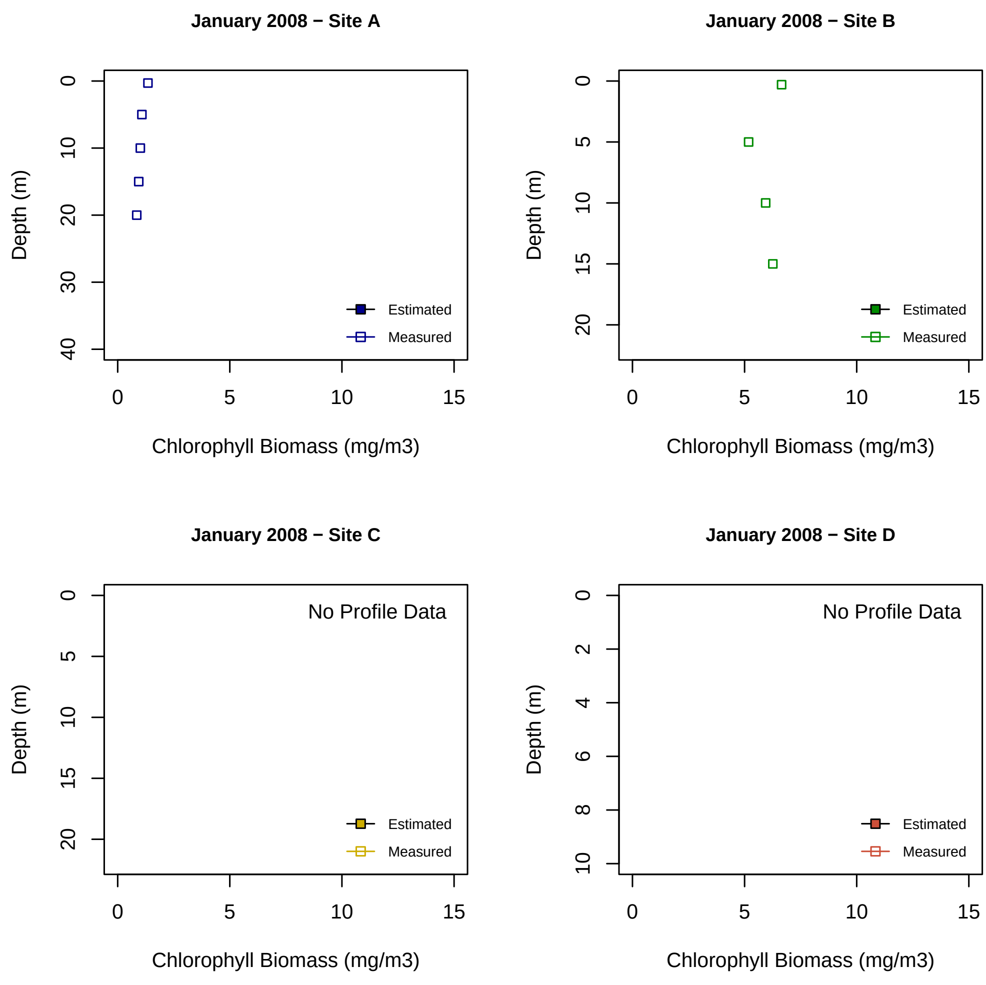


Figure 72: Lake Samish chlorophyll data for Sites A and B, January 29, 2008. Sites A and B were sampled at 5 meter depth intervals; Sites C and D were not sampled on this date.

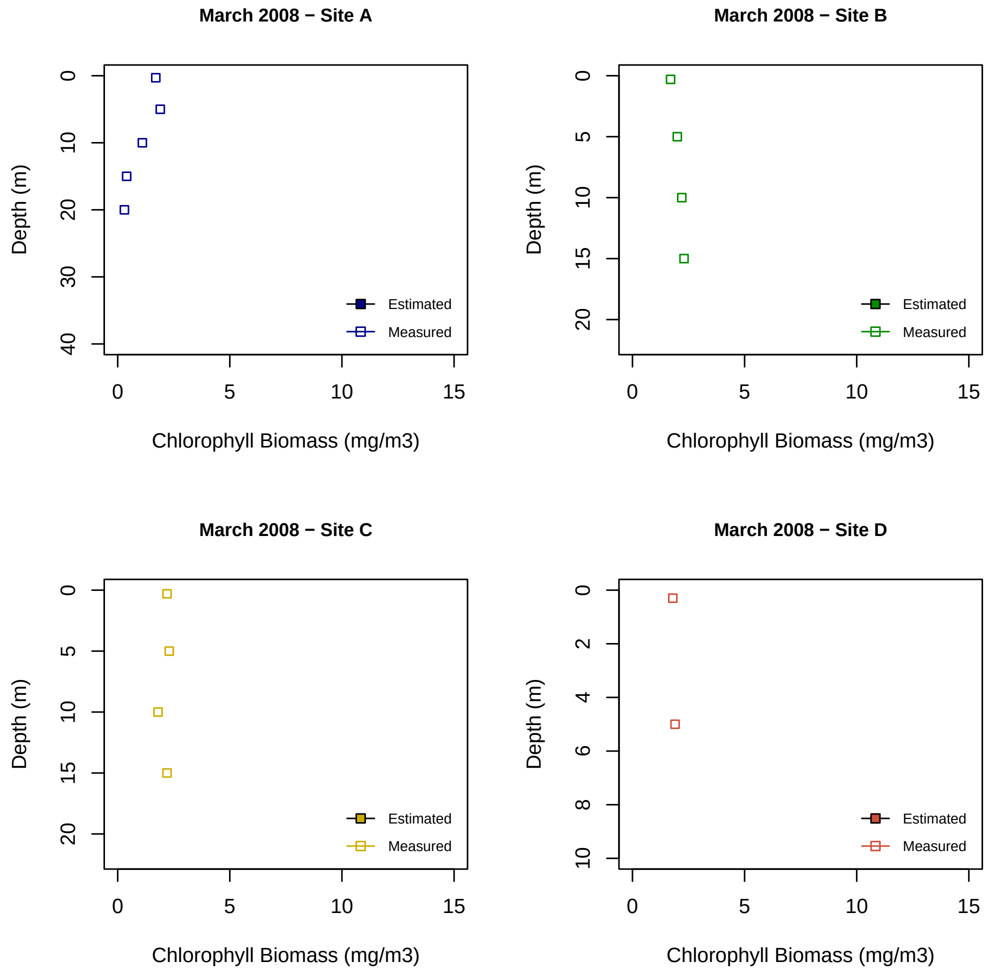


Figure 73: Lake Samish chlorophyll data for Sites A–D, March 25, 2008. All sites were sampled at 5 meter depth intervals.

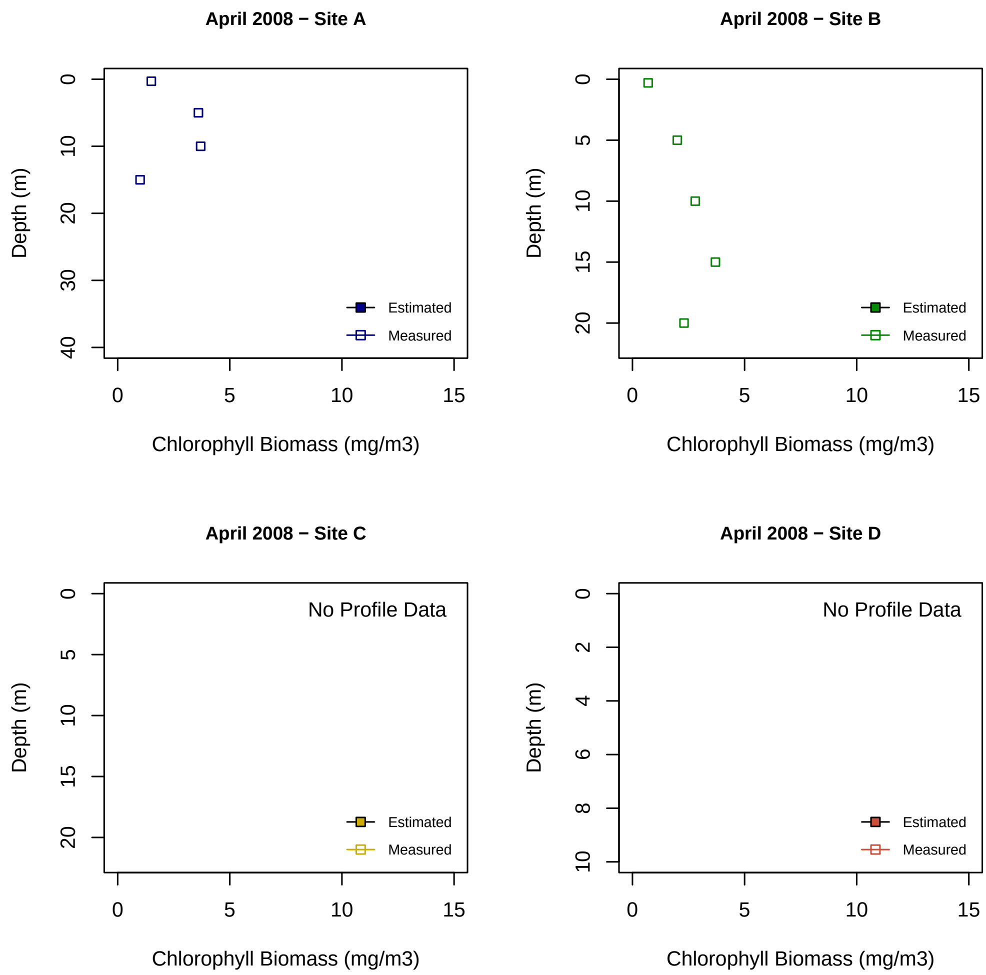


Figure 74: Lake Samish chlorophyll data for Sites A and B, April 21, 2008. Sites A and B were sampled at 5 meter depth intervals; Sites C and D were not sampled on this date.

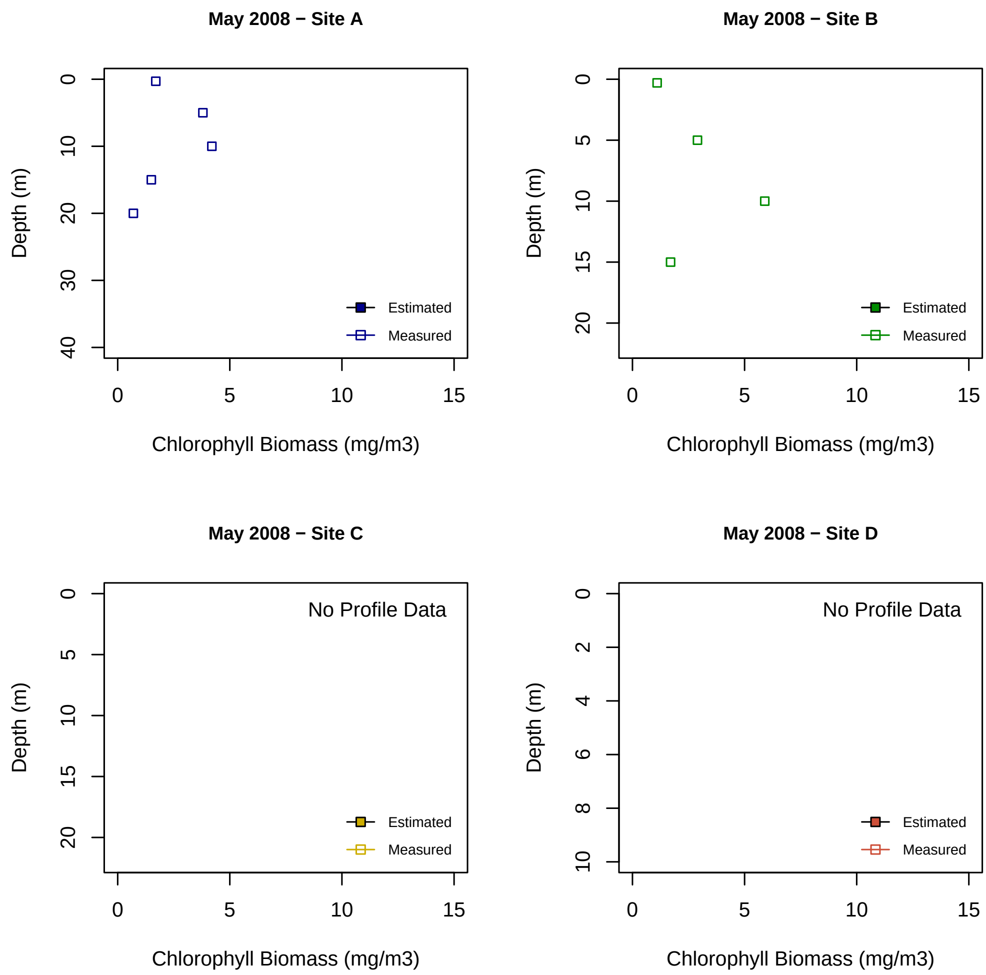


Figure 75: Lake Samish chlorophyll data for Sites A and B, May 15, 2008. Sites A and B were sampled at 5 meter depth intervals; Sites C and D were not sampled on this date.

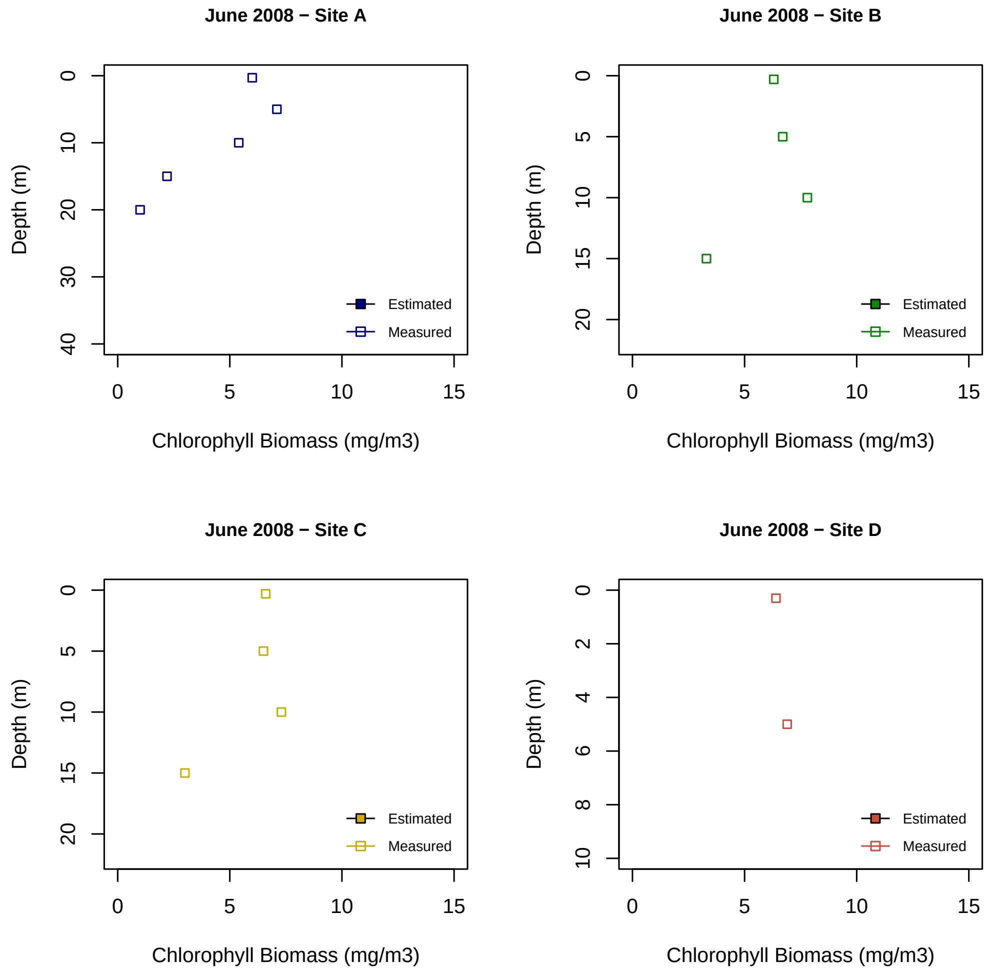


Figure 76: Lake Samish chlorophyll data for Sites A–D, June 10, 2008. All sites were sampled at 5 meter depth intervals.

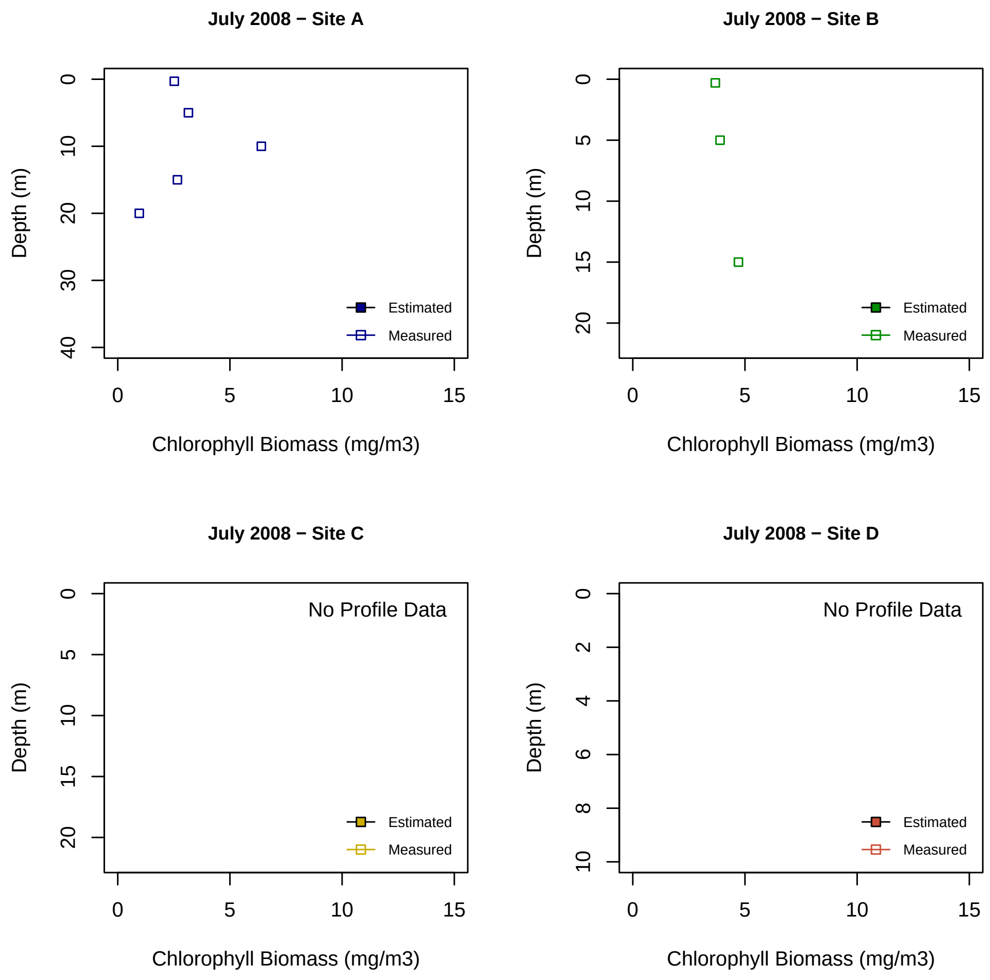


Figure 77: Lake Samish chlorophyll data for Sites A and B, July 22, 2008. Sites A and B were sampled at 5 meter depth intervals; Sites C and D were not sampled on this date.

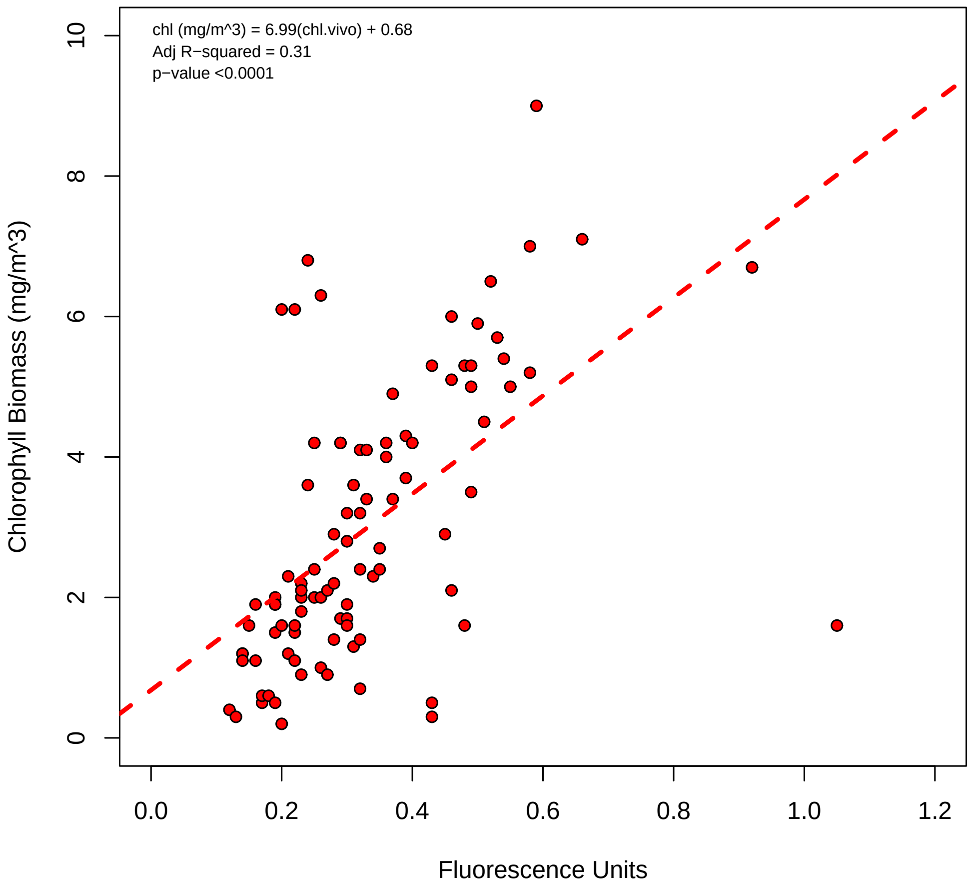


Figure 78: Comparison between chlorophyll fluorescence measured in the field and chlorophyll biomass measured in the laboratory.

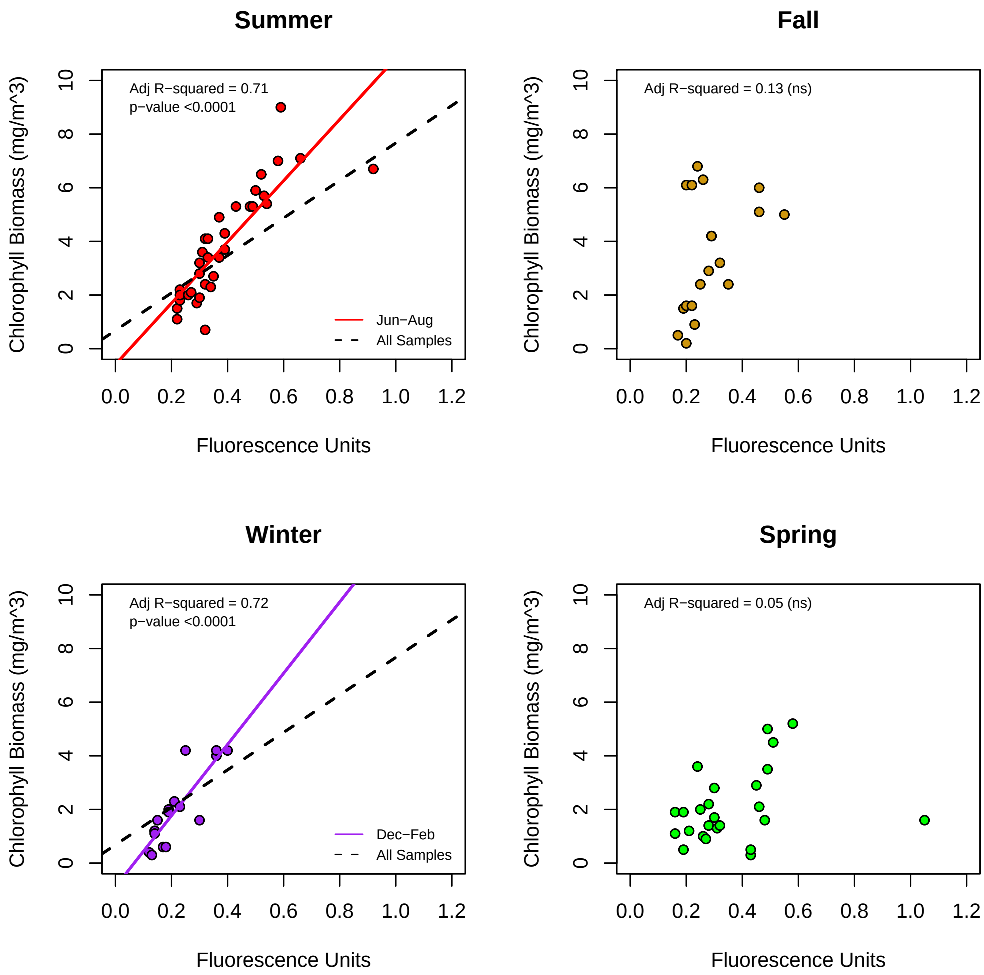


Figure 79: Seasonal comparison between chlorophyll fluorescence measured in the field and chlorophyll biomass measured in the laboratory.

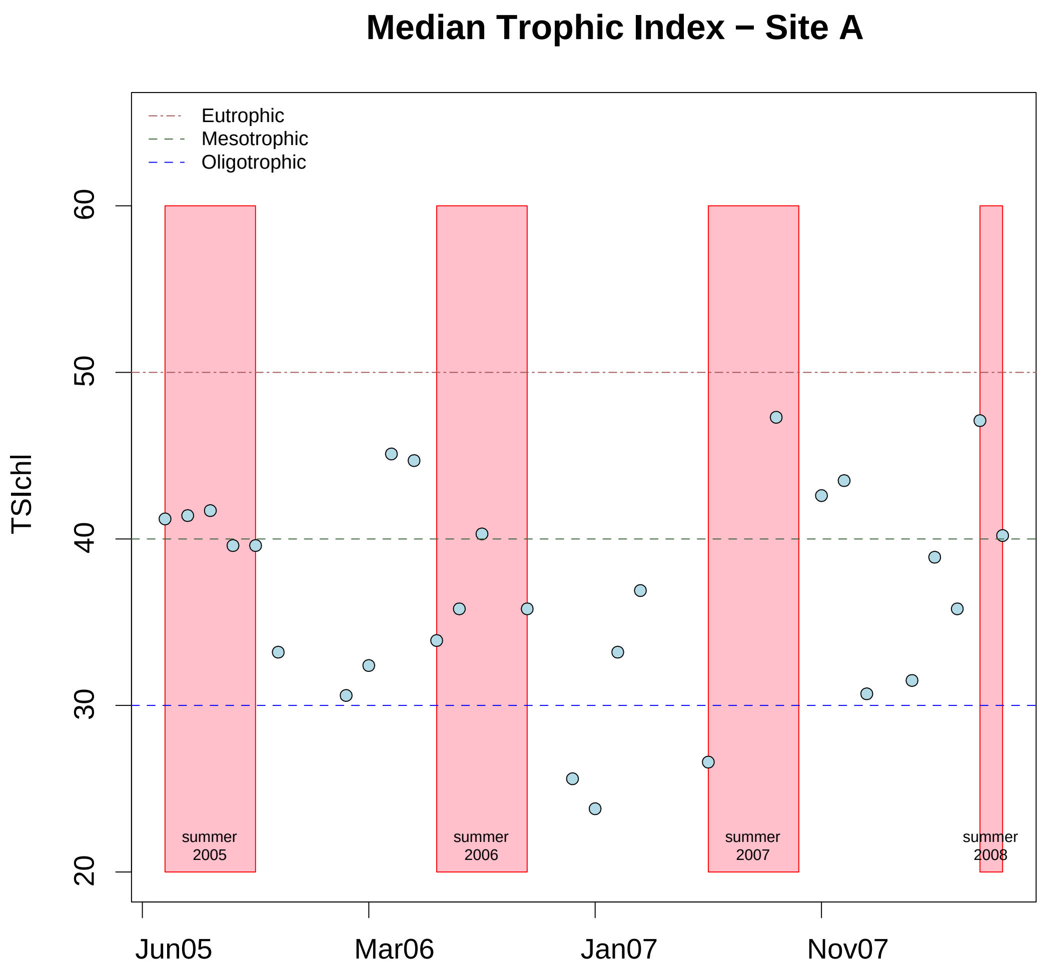


Figure 80: Median Lake Samish TSI_{chl} values at Site A on all sampling dates. Summer samples were collected between June and October. Prior to June 2007, chlorophyll biomass was estimated based on algal fluorescence profiles; chlorophyll biomass was measured directly from June 2007 through July 2008. See page 11 for discussion.

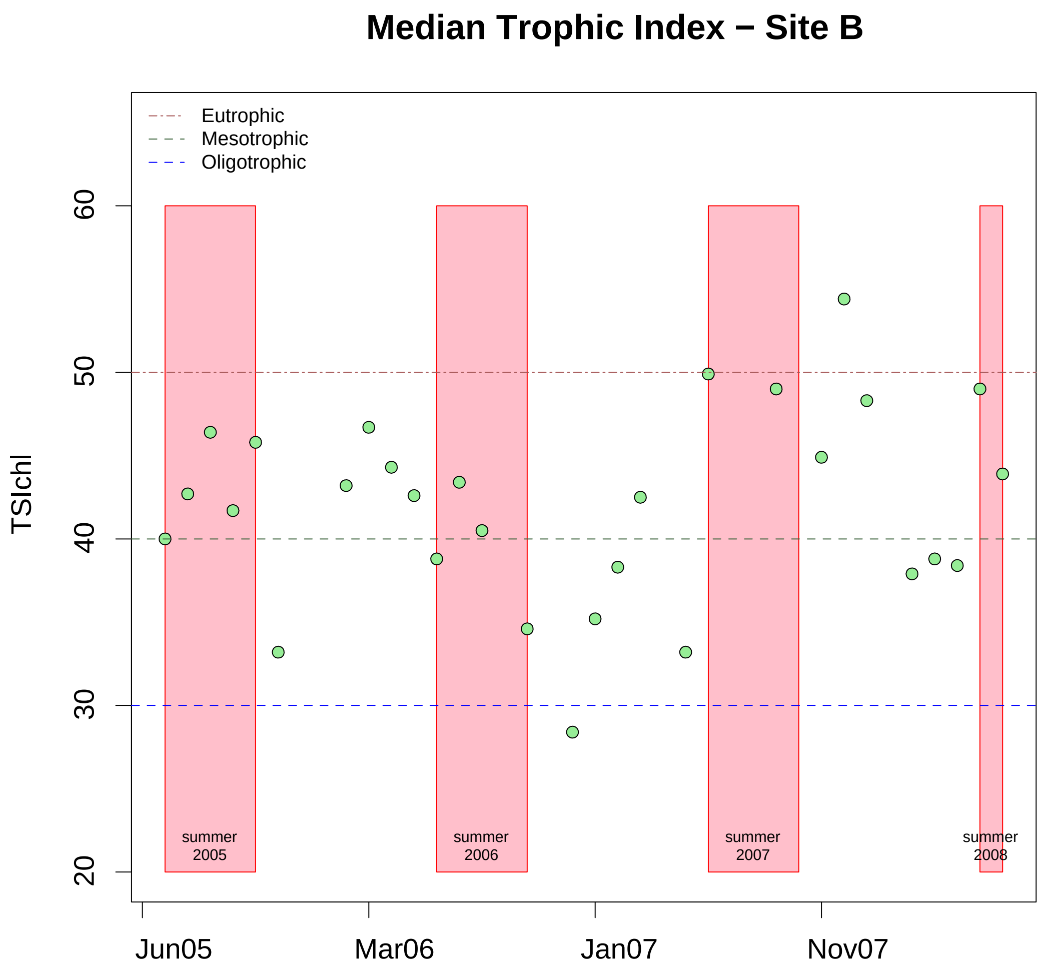


Figure 81: Median Lake Samish TSI_{chl} values at Site B on all sampling dates. Summer samples were collected between June and October. Prior to June 2007, chlorophyll biomass was estimated based on algal fluorescence profiles; chlorophyll biomass was measured directly from June 2007 through July 2008. See page 11 for discussion.

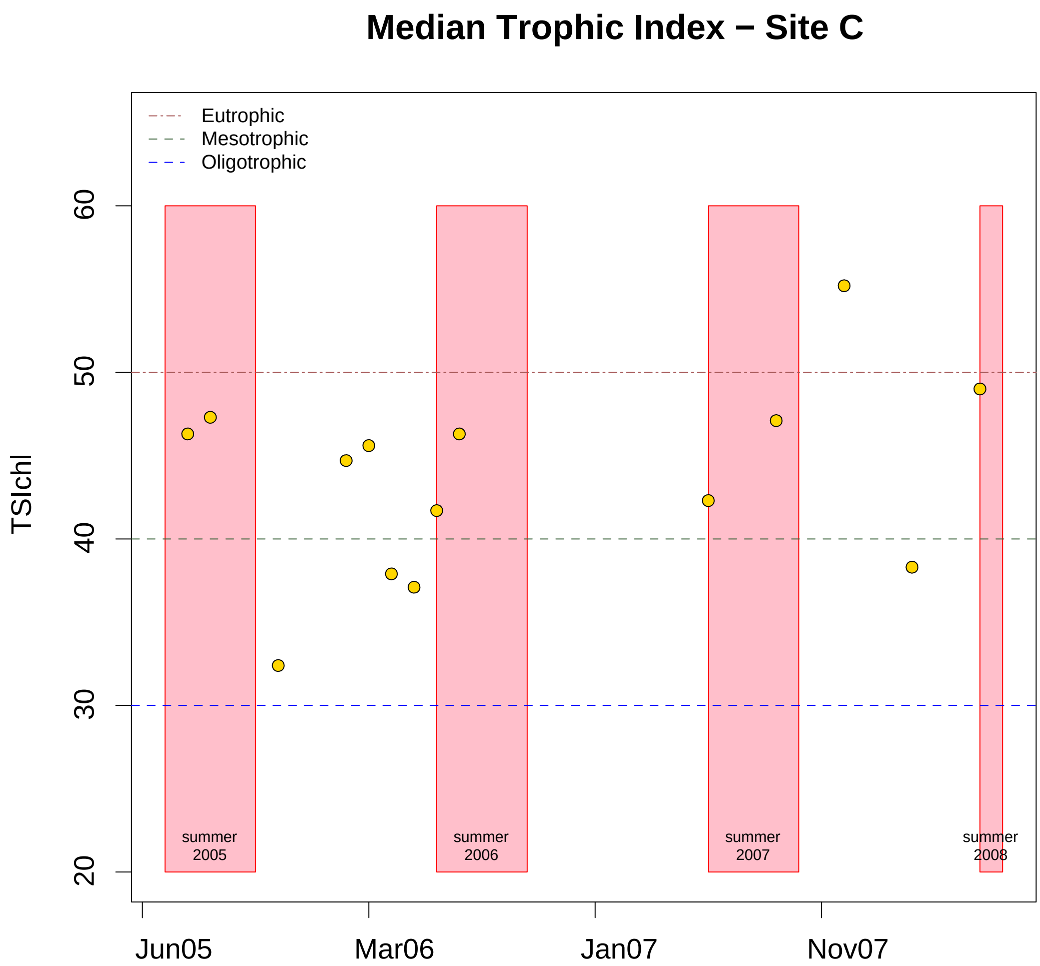


Figure 82: Median Lake Samish TSI_{chl} values at Site C on all sampling dates. Summer samples were collected between June and October. Prior to June 2007, chlorophyll biomass was estimated based on algal fluorescence profiles; chlorophyll biomass was measured directly from June 2007 through July 2008. See page 11 for discussion.

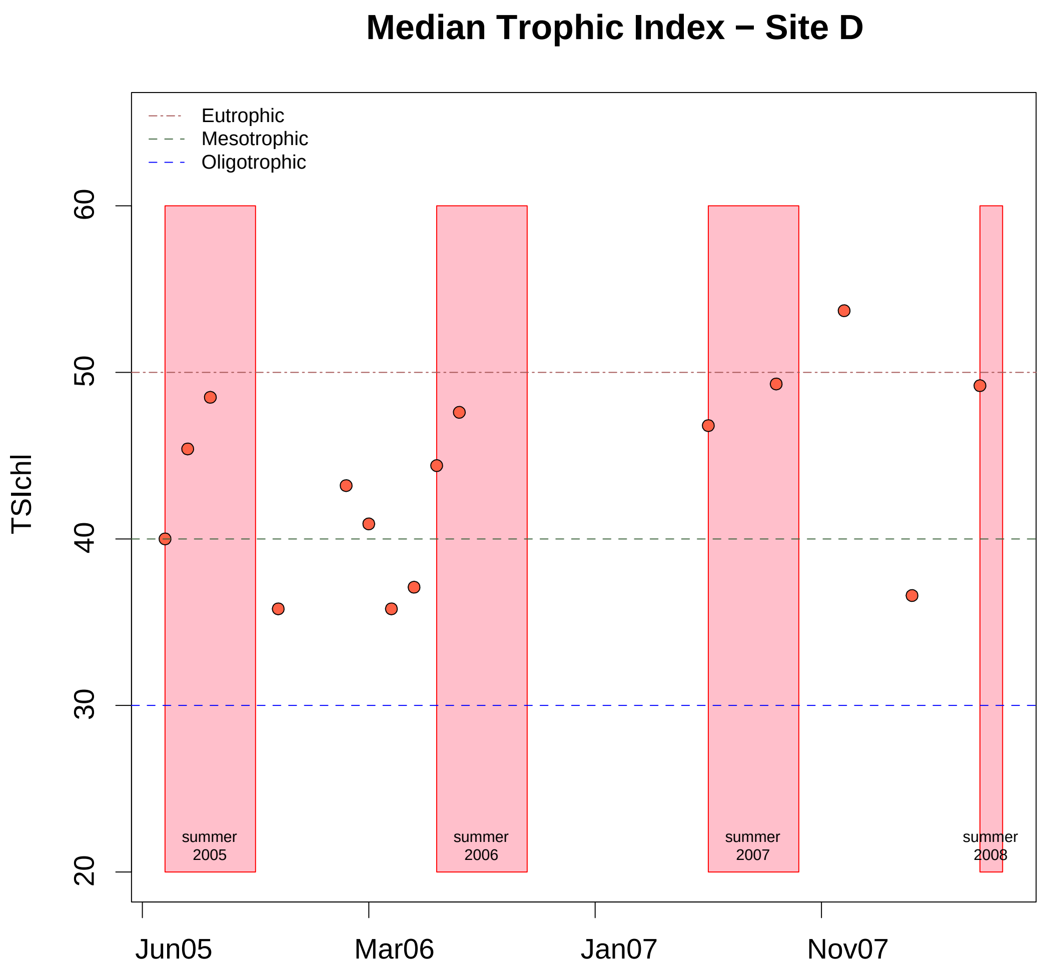


Figure 83: Median Lake Samish TSI_{chl} values at Site D on all sampling dates. Summer samples were collected between June and October. Prior to June 2007, chlorophyll biomass was estimated based on algal fluorescence profiles; chlorophyll biomass was measured directly from June 2007 through July 2008. See page 11 for discussion.

A Lake Samish Monitoring Data

Printed versions of this report include tables of the 2005-2008 lake monitoring data, edited to show detection limits. Online reports do not include copies of the original data, but electronic data files are available from the Institute for Watershed Studies. In addition, the IWS web site (http://www.ac.wwu.edu∼iws) features "dynamic" plots of the Lake Samish water quality data and tables containing the most recent results from the lake.