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# Lake Samish Water Monitoring Project 2007 Final Report

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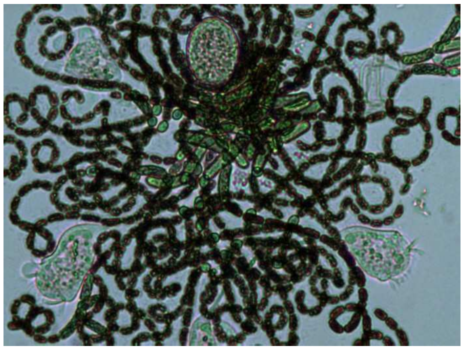
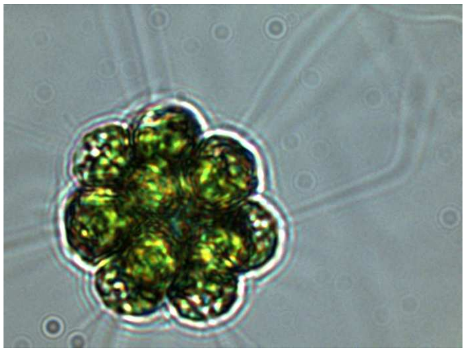
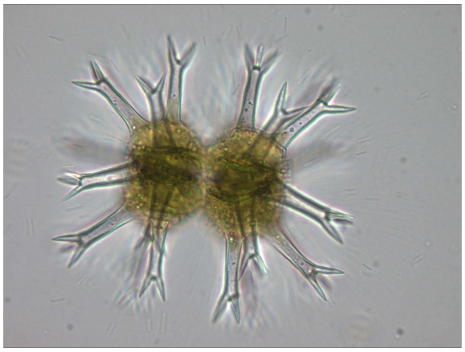
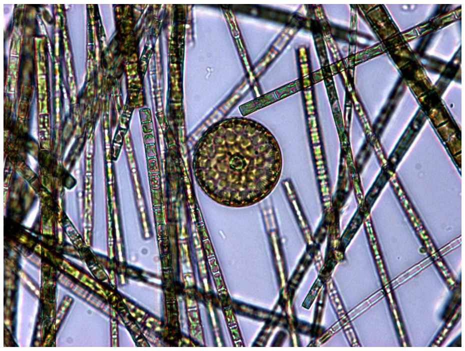

# Lake Samish Water Monitoring Project
# 2007 Final Report

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# 1 Introduction

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

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 approximately monthly[1] from June 2005 through June 2007 at representative sites in Lake Samish (Figure 1). Samples were collected at four sites (Sites A–D) from June 2005 through July 2006 and at 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 has been reduced to quarterly.

Temperature and dissolved oxygen measurements were collected at 1 meter depth intervals from the surface to the bottom at each site using a Hydrolab field meter.

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[1] The original project included 12 months of water quality monitoring. The scope of work was extended through a no-cost amendment to allow additional sampling at a reduced level of effort.

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

Surface and bottom water samples were collected at each lake site and transported to the laboratory to measure pH, conductivity, phosphorus (total phosphorus and orthophosphate), nitrogen (total nitrogen, nitrate/nitrite[2], ammonium), turbidity, and alkalinity. Separate surface and bottom water samples were collected to measure fecal coliform counts; the coliform samples were delivered on ice to the Samish Water District.

Chlorophyll fluorescence was measured in the field at 1 meter depth intervals from the surface to the bottom at each site using a field fluorometer. On each sampling date, water samples were collected at six randomly selected depths to measure chlorophyll biomass. Due to equipment failure, field fluorometer data are not available after March 2007.

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

## 2.2 Stream Sampling

Water samples were collected In July and November 2005 from 4 tributaries flowing into Lake Samish and from the lake outlet at Friday Creek (Figure 1). Temperature and dissolved oxygen was measured using a YSI field meter. Water samples were collected at each stream site and transported to the laboratory to measure pH, conductivity, phosphorus (total phosphorus and 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 1. All data for the Lake Samish monitoring project have been included in Appendix A.

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[2] 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.

# 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 2–24).

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.

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 2005–2007 data, the east arm of Lake Samish begins to stratify in April at locations where the water column is at least 12–15 meters deep (Sites B and C). 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 appears to develop temperature stratification by April (Figures 11 and 22), and remains stratified throughout the summer and early fall. Destratification is less predictable

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

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

at Site A. In January and February 2006, despite nearly uniform surface to bottom water temperatures, the water column at Site A did not appear to mix completely, and oxygen levels were near zero at the bottom of the lake (see Figures 8–9). The following winter, the water column was completely mixed in January (Figure 19), but not in February (Figure 20).

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.

### 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 2–24). 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 by-products 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 *metalimnion*). This metalimnetic oxygen peak was present at Site A throughout the summer in 2005 and 2006, and appeared to be developing during the summer of 2007. 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, et al., 2006). 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 measure *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 10–13 and 25–27). Alkalinity concentrations were fairly low ($<$30 mg/L) throughout the sampling period (Figure 25). This means that Lake Samish is not well buffered against pH changes. When the water column in Lake Samish was stratified, the surface alkalinities were often slightly lower than at the bottom and surface pH levels were often higher (Figure 26). 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.

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 60–100 $\mu$S/cm, which was similar to the lake's surface conductivities ($\sim$60–80 $\mu$S/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 28–32). 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. Nitrogen rarely limits algal growth, but 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 can 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 somewhere 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 31 and 32). 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, 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 33). Similarly, there was no apparent relationship between surface turbidity levels and chlorophyll (Figure 34). Correlation analysis confirmed that while there was a correlation between Secchi depths and turbidity, there were no significant correlations between chlorophyll and Secchi depth or turbidity (Figure 35).[5] This

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[5] Kendall's $\tau$ 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 $\pm1$, the stronger the correlation. The significance is measured using the p-value; significant correlations have p-values $<0.05$.

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.

**Chlorophyll:** Chlorophyll concentrations were measured using two techniques: *in situ* algal fluorescence, which was measured in the field, and chlorophyll biomass, which was measured in the laboratory from water samples collected in the field. 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.

The Lake Samish fluorescence profiles (Figures 36–40) 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.

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. To test this relationship we collected paired fluorescence and biomass data, then looked for a linear relationship between biomass and fluorescence. The linear model was highly significant, despite a small seasonal bias in samples collected during the spring (Figures 41–42), so we were able to estimate chlorophyll biomass from the fluorescence readings.

The estimated chlorophyll concentrations were plotted for each site to show seasonal and site-specific patterns (Figure 43). The most obvious pattern is that the chlorophyll concentrations were considerably higher during 2005, especially at Sites C and D, which masks most of the other chlorophyll patterns. In general, chlorophyll levels were lower at Site A, showed the greatest variation at Sites C and D, and were lower in the winter at all sites.

**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:

$$\begin{aligned} \mathrm{TSI(CHL)} &= 9.81\ (\ln \mathrm{CHL}) + 30.6 \\ \mathrm{TSI(SD)} &= 60 - 14.41\ (\ln \mathrm{SD}) \\ \mathrm{TSI(TP)} &= 14.42\ (\ln \mathrm{TP}) + 4.15 \end{aligned}$$

CHL = chlorophyll concentration in $\mu$g/L
SD = Secchi depth in meters, and
TP = total phosphorus in $\mu$g-P/L

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 (Figure 44 and Table 2). The summer 2005 TSIs (July–Oct. 2005) were higher than the summer 2006 TSIs, matching the higher chlorophyll and algal densities in the lake (Figure 45). Sites A and B had the lowest TSIs, with most values between 35–45, indicating that these sites are currently mesotrophic. Sites C and D had higher summer TSIs (approx. 45–65), indicating that these sites are at 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 were observed regularly in plankton samples collected during the summer and fall of 2005 (R. Matthews, personal observation). The blooms contained common "nuisance" taxa, including *Gloeotrichia echinulata*, *Microcystis aeruginosa*, *Woronichnia naegelianum*, and a variety of *Anabaena* species.[6]

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

### 3.1.6 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 found in a sample, 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 Contact 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 organisms 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[7], and none of the counts exceeded 10 cfu/100 mL, so the Lake Samish samples passed both parts of the surface water standard for coliforms.

## 3.2 Creeks in the Lake Samish Watershed

Four tributaries to Lake Samish and the outlet from Lake Samish were sampled during the summer and fall of 2005. Two of the tributaries were unnamed, so they were assigned temporary names as indicated on Figure 1. All of the tributaries were sampled in July and November; the outlet at Friday Creek was sampled in August and November.

Water temperatures were higher and dissolved oxygen concentrations were lower in Friday Creek compared to the Lake Samish tributaries (Table 3). Some of these

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[7] cfu = colony-forming units

differences may have been caused by the later summer sampling date for Friday Creek; however, these types of lake influences are commonly observed in outlet creeks. Barnes Creek usually had the highest alkalinity, conductivity, pH, and turbidity values, which may reflect differences in soils or land use in the drainage area for that creek.

The ammonium concentrations were slightly elevated in Friday Creek, 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 30), and were much lower than the ammonium concentrations in anaerobic bottom samples at Sites A–C. Mud Creek had an unusually high ammonium concentration in November 2005. 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.[8] The fecal coliform count was low (13 cfu/100 mL), 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. 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 concentrations were measured in November, when leaching would be highest, and plant uptake lowest. The total nitrogen and nitrate/nitrite concentrations were lower at the lake outlet, particularly in August, when the nitrate/nitrite concentration was only 10.2 $\mu$g-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 outlet due to algal uptake of phosphorus in Lake Samish. The phosphorus concentrations were fairly high compared to surface samples from Lake Samish (Figures 32–31) and probably 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.

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[8] 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 values were above the detection limit of 23 cfu/100 mL. The November results were reasonably low at all sites except Finney Creek. The two high counts from Friday Creek (August) and Finney Creek (November) are sufficient to warrant 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.[9] The coliform levels in the lake were consistently 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

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 36–40). 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 (Figures 10–13 and 25–27) and the release of large amounts of phosphorus from the sediments (Figures 31–32). 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.

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

A second important feature that affects lake management is land use in the Lake Samish watershed. The tributary data revealed that there is significant *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.

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

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

Table 1: Summary of analytical methods used by the Institute for Watershed Studies in the Lake Samish monitoring project.

| | Min. | Med. | Mean | Max. | N |
|---|---|---|---|---|---|
| Site A | | | | | |
| All data (June 2005–March 2007) | 20.6 | 36.3 | 36.4 | 54.5 | 512 |
| Summer 2005 (July–October) | 24.7 | 40.0 | 40.5 | 52.6 | 97 |
| Summer 2006 (July–October) | 23.4 | 35.8 | 36.7 | 51.6 | 95 |
| Site B | | | | | |
| All data (June 2005–March 2007) | 24.2 | 41.0 | 40.2 | 62.4 | 361 |
| Summer 2005 (July–October) | 34.3 | 45.2 | 45.2 | 62.4 | 80 |
| Summer 2006 (July–October) | 24.2 | 35.0 | 37.1 | 49.6 | 60 |
| Site C | | | | | |
| All data (July 2005–July 2006) | 26.5 | 44.6 | 45.8 | 67.0 | 209 |
| Summer 2005 (July–October) | 42.1 | 60.3 | 55.8 | 67.0 | 76 |
| Summer 2006 (July only) | 37.6 | 46.2 | 44.4 | 52.6 | 18 |
| Site D | | | | | |
| All data (June 2005–July 2006) | 32.3 | 43.8 | 46.0 | 67.4 | 86 |
| Summer 2005 (July–October) | 42.3 | 63.6 | 56.5 | 67.4 | 29 |
| Summer 2006 (July only) | 39.9 | 47.5 | 46.4 | 49.1 | 8 |

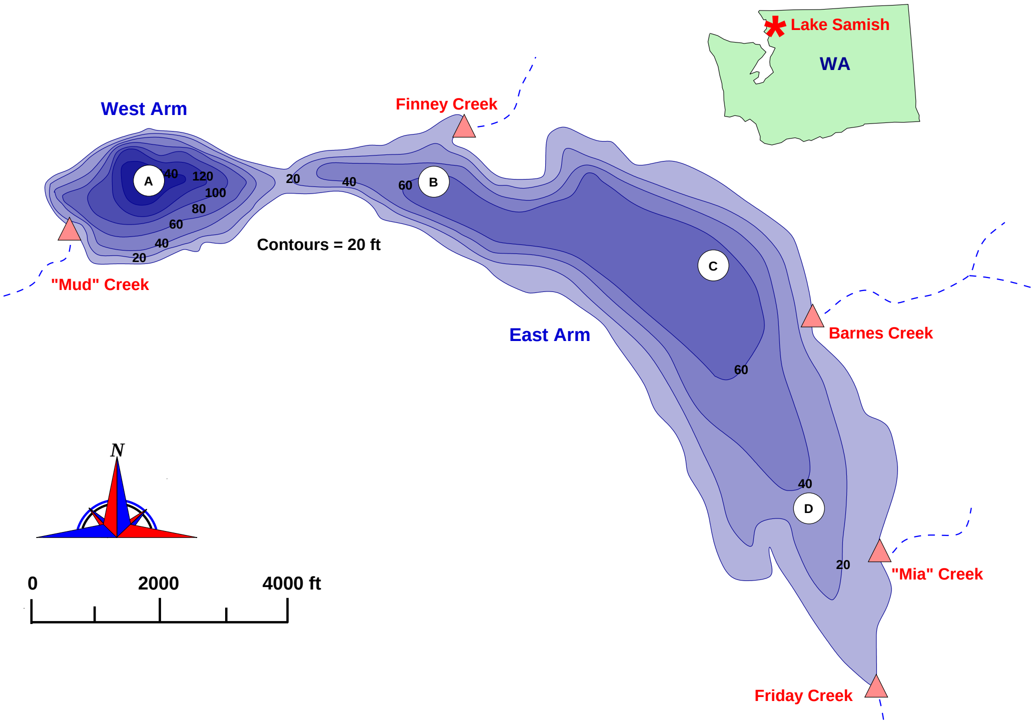
Table 2: Carlson’s Trophic State Index - TSI(CHL) results for Lake Samish.

| Site | Month | Day | Year | DO | Temp | Alk | Turb | pH | Cond |
|---|---|---|---|---|---|---|---|---|---|
| Unnamed (Mud Creek) | July | 15 | 2005 | 8.26 | 12.9 | 24.7 | 0.76 | 6.29 | 94.2 |
| | Nov | 10 | 2005 | 14.61 | 8.5 | 15.9 | 0.88 | 7.05 | 74.8 |
| Finney Creek | July | 15 | 2005 | 9.66 | 13.5 | 28.0 | 0.77 | 7.05 | 149.8 |
| | Nov | 10 | 2005 | 14.65 | 9.2 | 12.2 | 3.00 | 7.23 | 75.2 |
| Unnamed (Mia Creek) | July | 15 | 2005 | 9.06 | 13.4 | 31.8 | 2.51 | 6.72 | 82.7 |
| | Nov | 10 | 2005 | 13.63 | 9.2 | 18.0 | 1.91 | 7.13 | 73.9 |
| Barnes Creek | July | 15 | 2005 | 10.15 | 12.5 | 52.0 | 4.58 | 7.22 | 128.7 |
| | Nov | 10 | 2005 | 14.71 | 9.0 | 37.5 | 2.67 | 7.49 | 103.4 |
| Friday Creek (outlet) | Aug | 9 | 2005 | 4.05 | 20.5 | 21.3 | 3.73 | 6.11 | 69.4 |
| | Nov | 10 | 2005 | 8.47 | 10.7 | 19.7 | 0.86 | 7.21 | 68.4 |

| Site | Month | Day | Year | $NH_3$ | TN | $NO_3$ | TP | OP | FC |
|---|---|---|---|---|---|---|---|---|---|
| Unnamed (Mud Creek) | July | 15 | 2005 | <10 | 582.1 | 474.3 | 20.2 | 15.5 | >23* |
| | Nov | 10 | 2005 | 108.6 | 2308.4 | 1901.7 | 18.6 | 8.6 | 13 |
| Finney Creek | July | 15 | 2005 | 11.7 | 747.6 | 622.2 | 33.1 | 35.3 | >23* |
| | Nov | 10 | 2005 | <10 | 2061.5 | 1860.4 | 15.1 | 5.7 | 130 |
| Unnamed (Mia Creek) | July | 15 | 2005 | 14.5 | 478.3 | 293.4 | 49.8 | 30.9 | >23* |
| | Nov | 10 | 2005 | <10 | 1890.9 | 1666.2 | 21.2 | 10.2 | 23 |
| Barnes Creek | July | 15 | 2005 | 17.1 | 1082.7 | 915.6 | 46.0 | 26.9 | >23* |
| | Nov | 10 | 2005 | <10 | 1670.0 | 1518.2 | 15.1 | 9.0 | 23 |
| Friday Creek (outlet) | Aug | 9 | 2005 | 40.6 | 361.9 | 10.2 | 25.9 | <3 | 130 |
| | Nov | 10 | 2005 | 28.0 | 409.8 | 187.9 | 9.6 | <3 | 8 |

*Sample above detection limit of 23 cfu/100 mL

Table 3: Water quality data for creeks in the Lake Samish watershed. All sites were sampled in July and November, 2005 except Friday Creek, which was sampled in August and November, 2005.



| | 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$\times$10$^6$ m$^3$ | 21,080 acre-ft | 26.0$\times$10$^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, 2005–2006. 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.

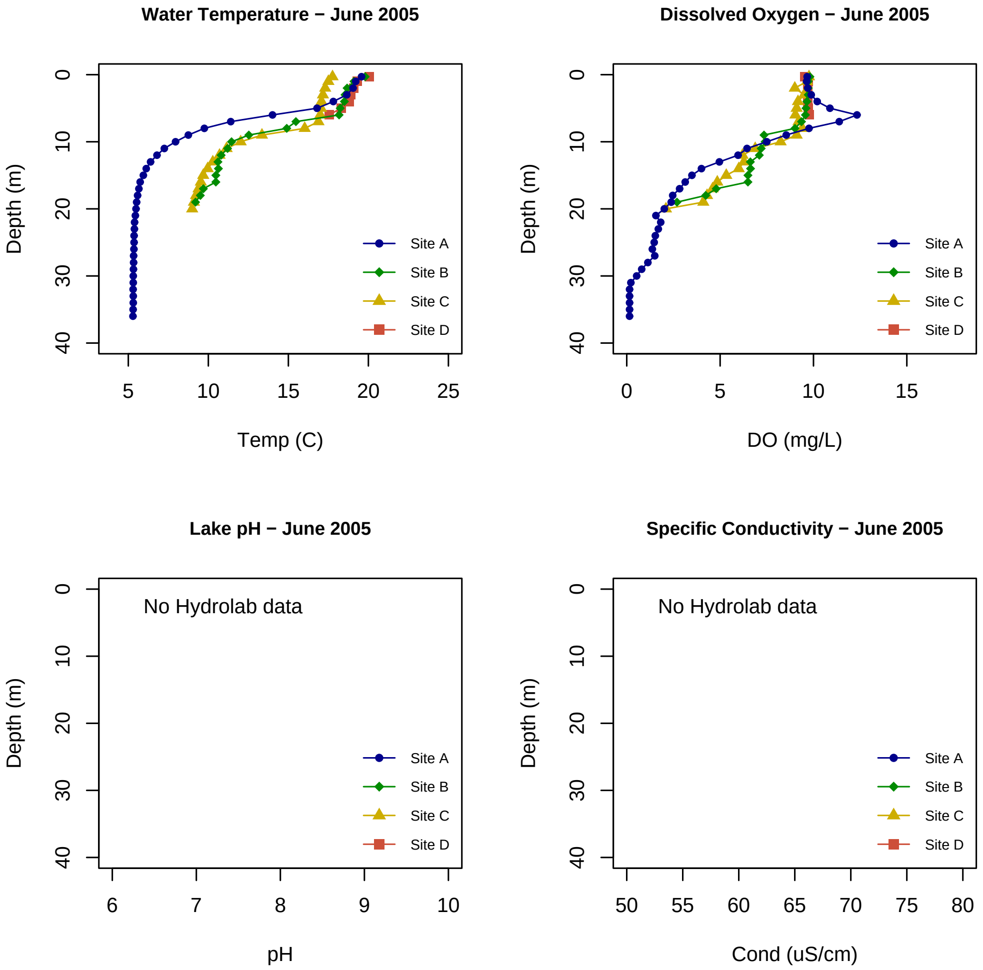


Figure 2: Lake Samish Hydrolab profiles for Sites A–D, June 21, 2005.

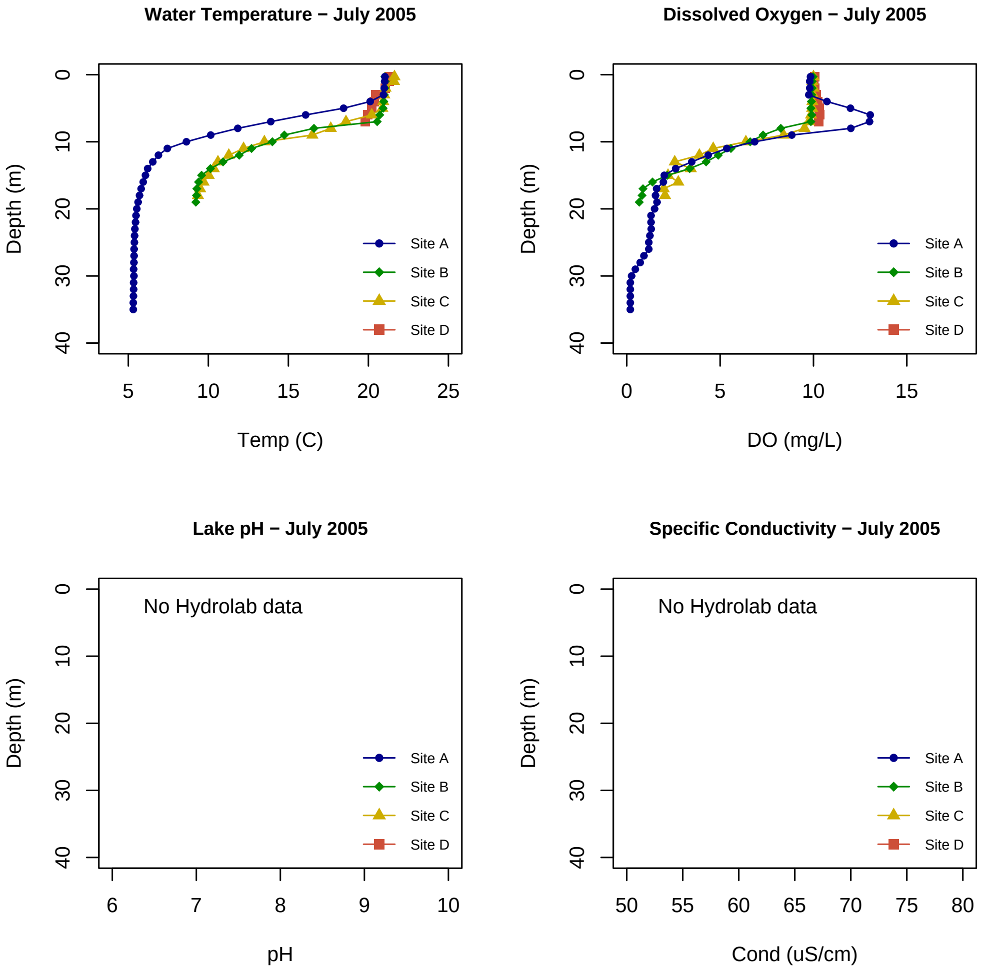
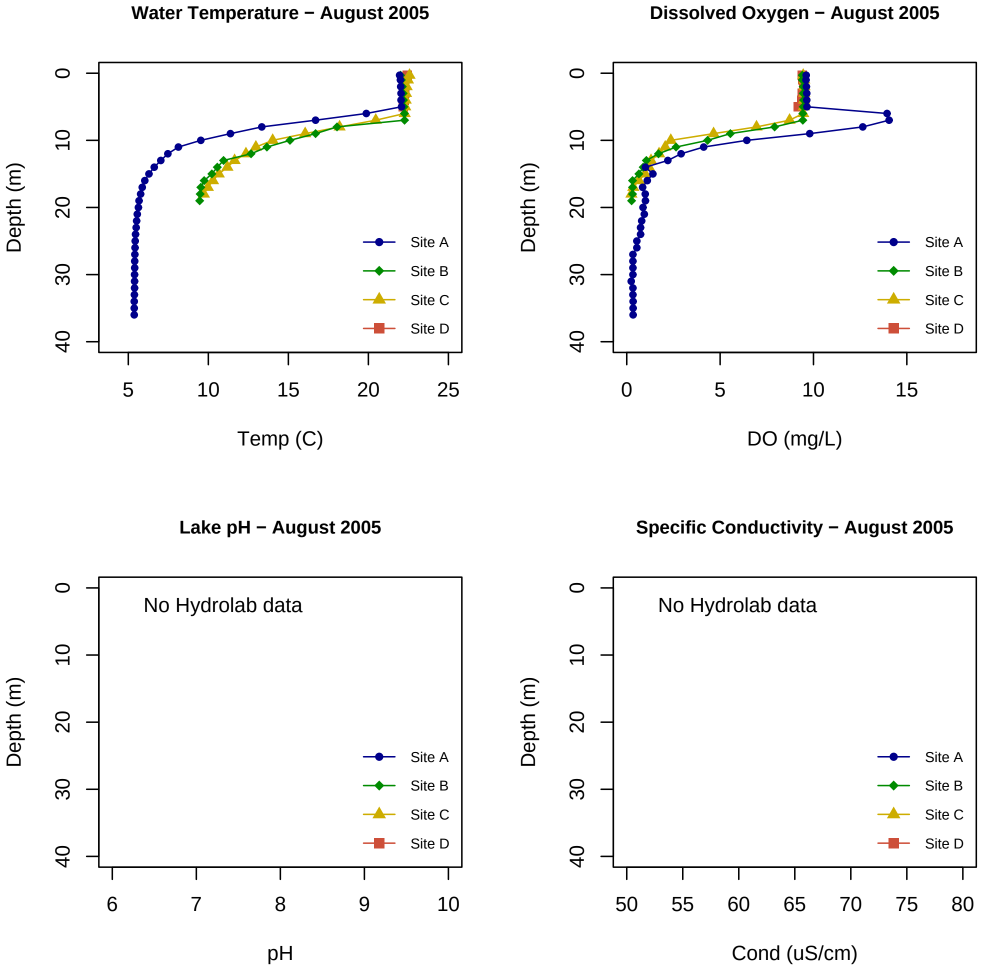


Figure 3: Lake Samish Hydrolab profiles for Sites A–D, July 20, 2005.


Water Temperature − August 2005

Dissolved Oxygen − August 2005

Lake pH − August 2005

Specific Conductivity − August 2005

Figure 4: Lake Samish Hydrolab profiles for Sites A–D, August 23, 2005.

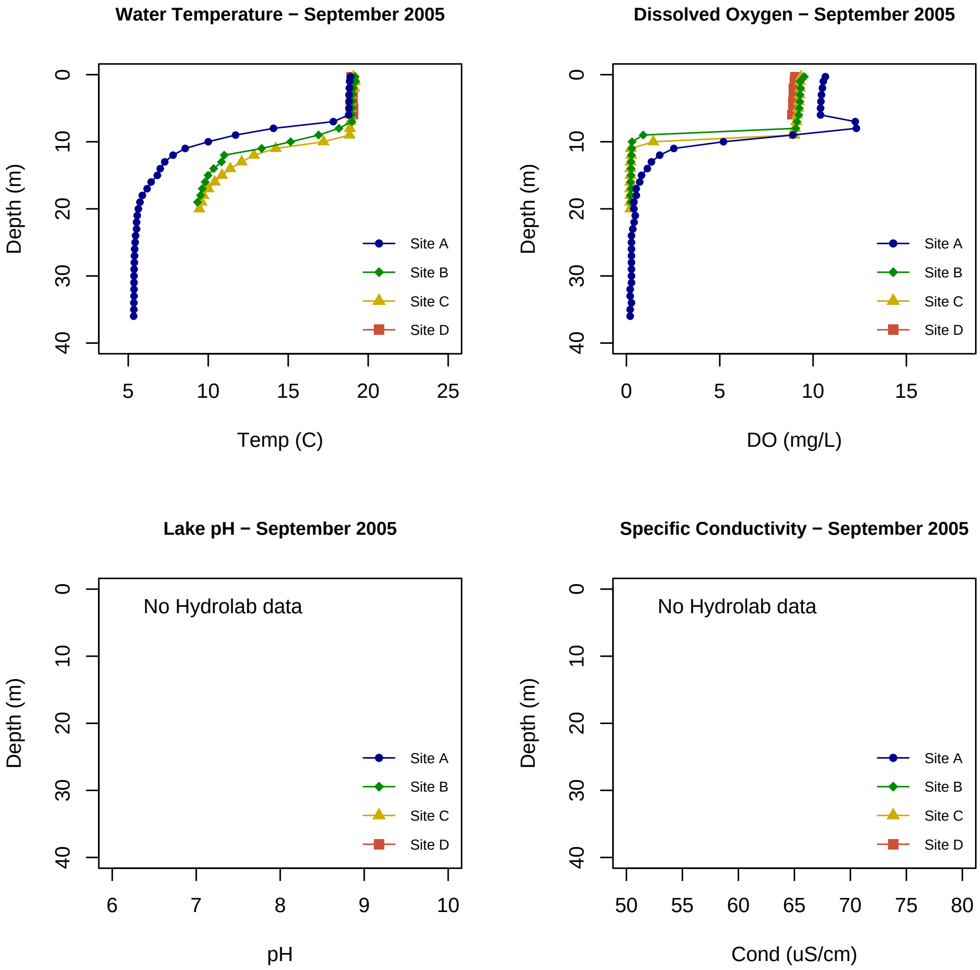
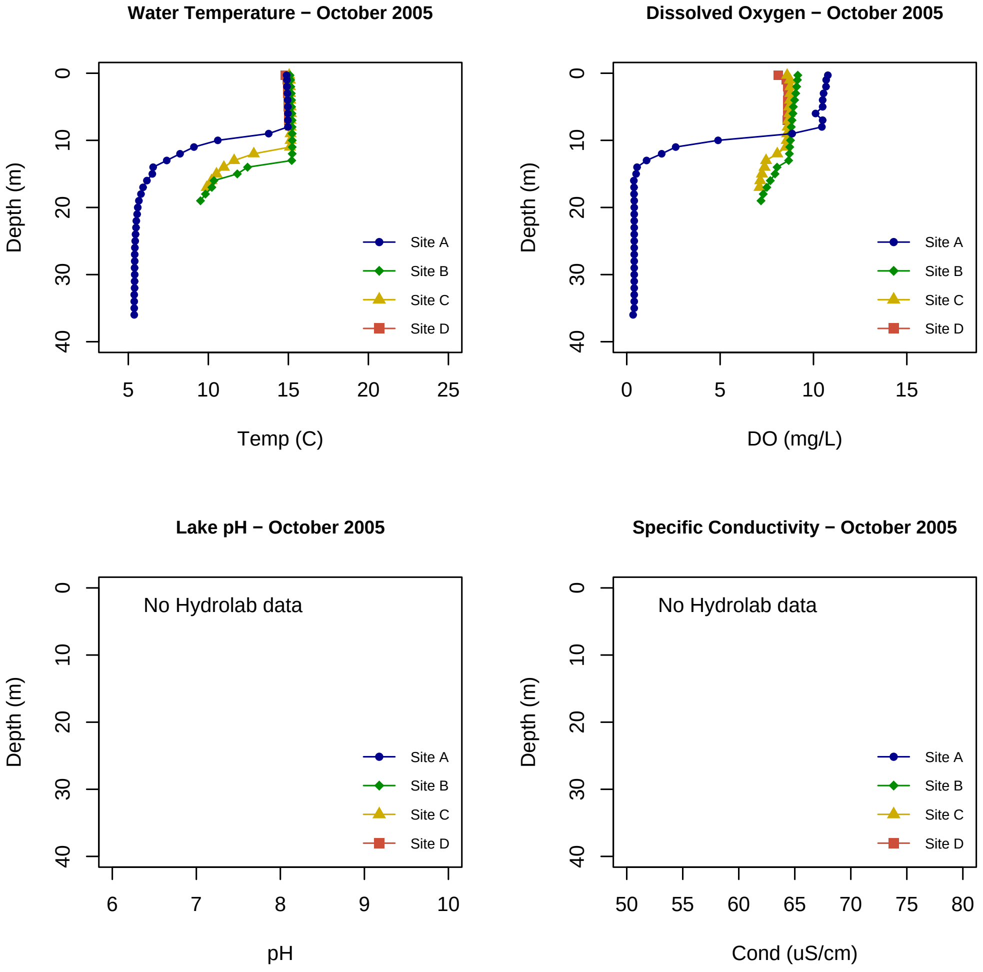


Figure 5: Lake Samish Hydrolab profiles for Sites A–D, September 20, 2005.



Water Temperature − October 2005

Dissolved Oxygen − October 2005

Lake pH − October 2005

Specific Conductivity − October 2005

Figure 6: Lake Samish Hydrolab profiles for Sites A–D, October 16, 2005.

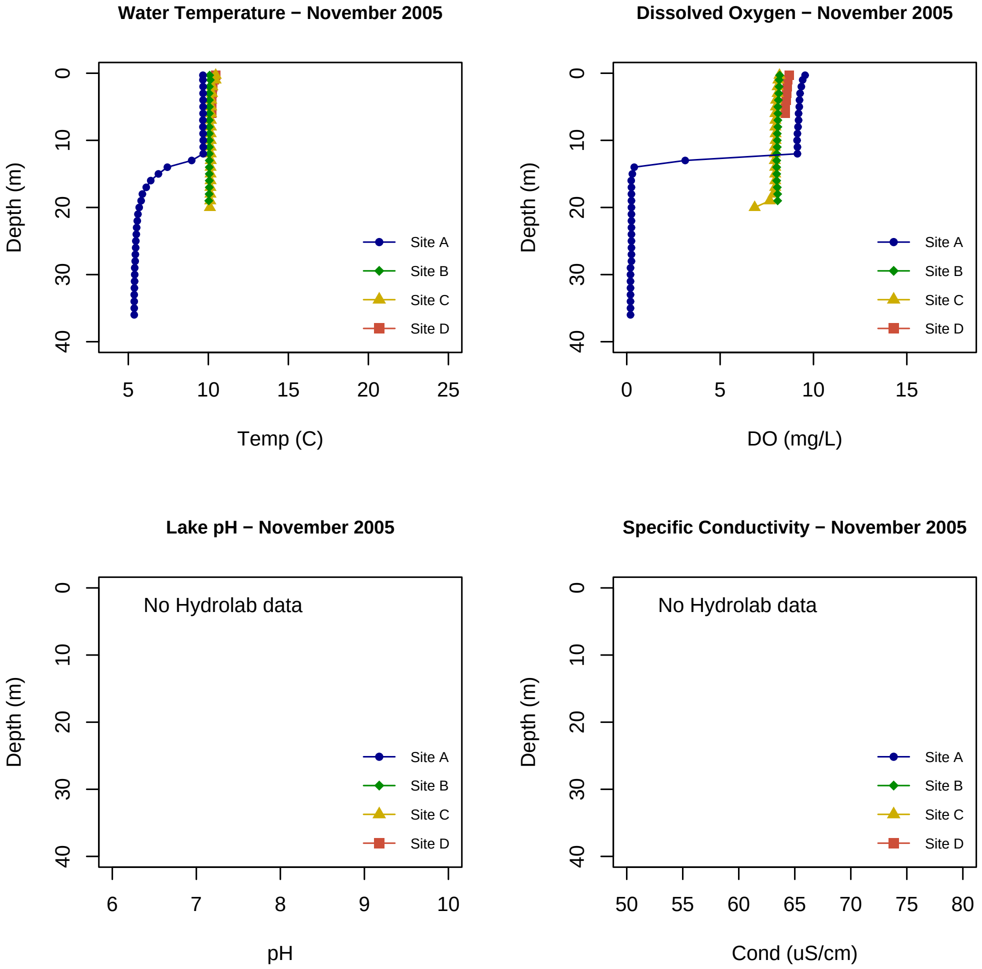
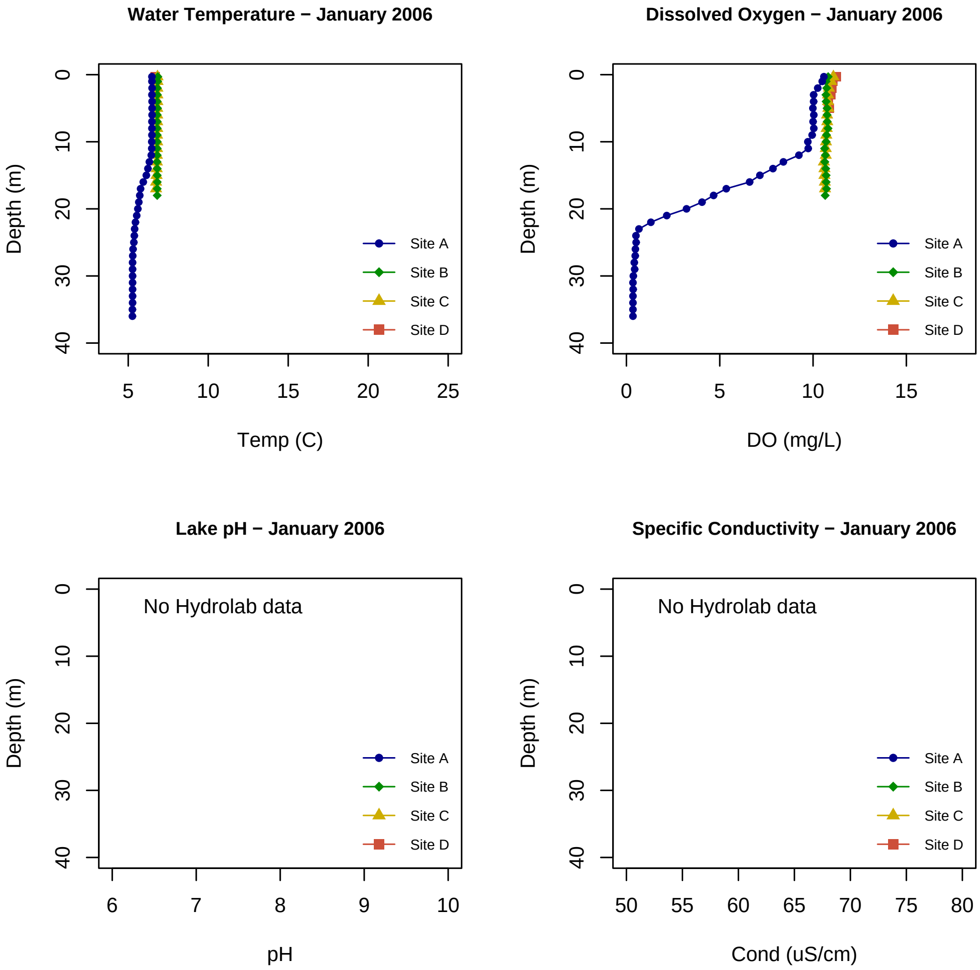


Figure 7: Lake Samish Hydrolab profiles for Sites A–D, November 20, 2005.


Water Temperature − January 2006

Dissolved Oxygen − January 2006

Lake pH − January 2006

Specific Conductivity − January 2006

Figure 8: Lake Samish Hydrolab profiles for Sites A–D, January 22, 2006.

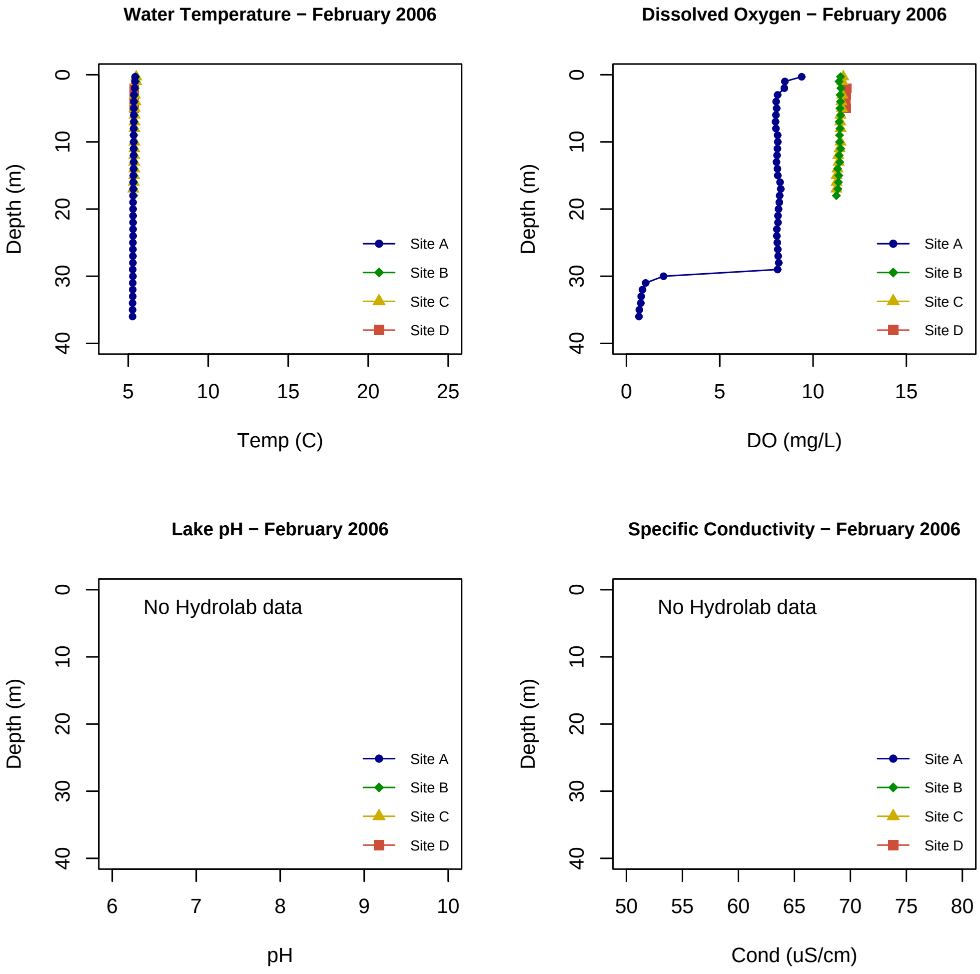


Figure 9: Lake Samish Hydrolab profiles for Sites A–D, February 26, 2006.

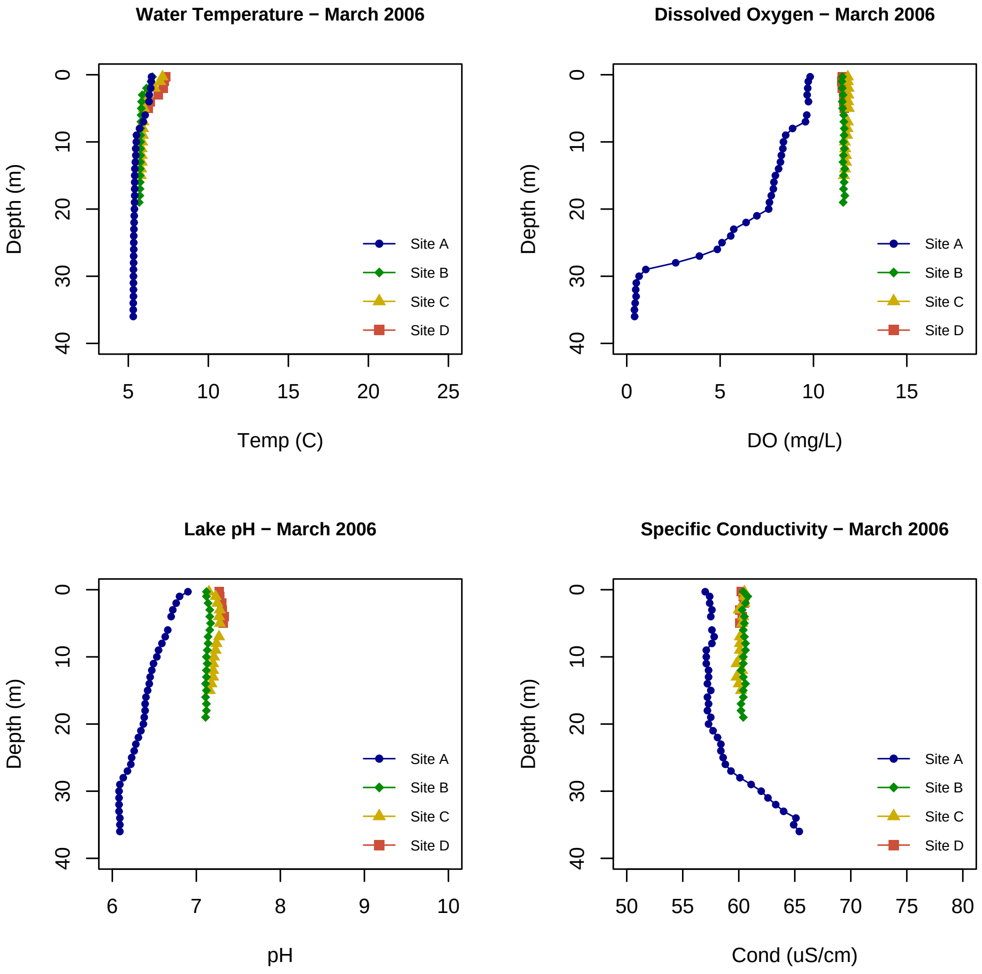
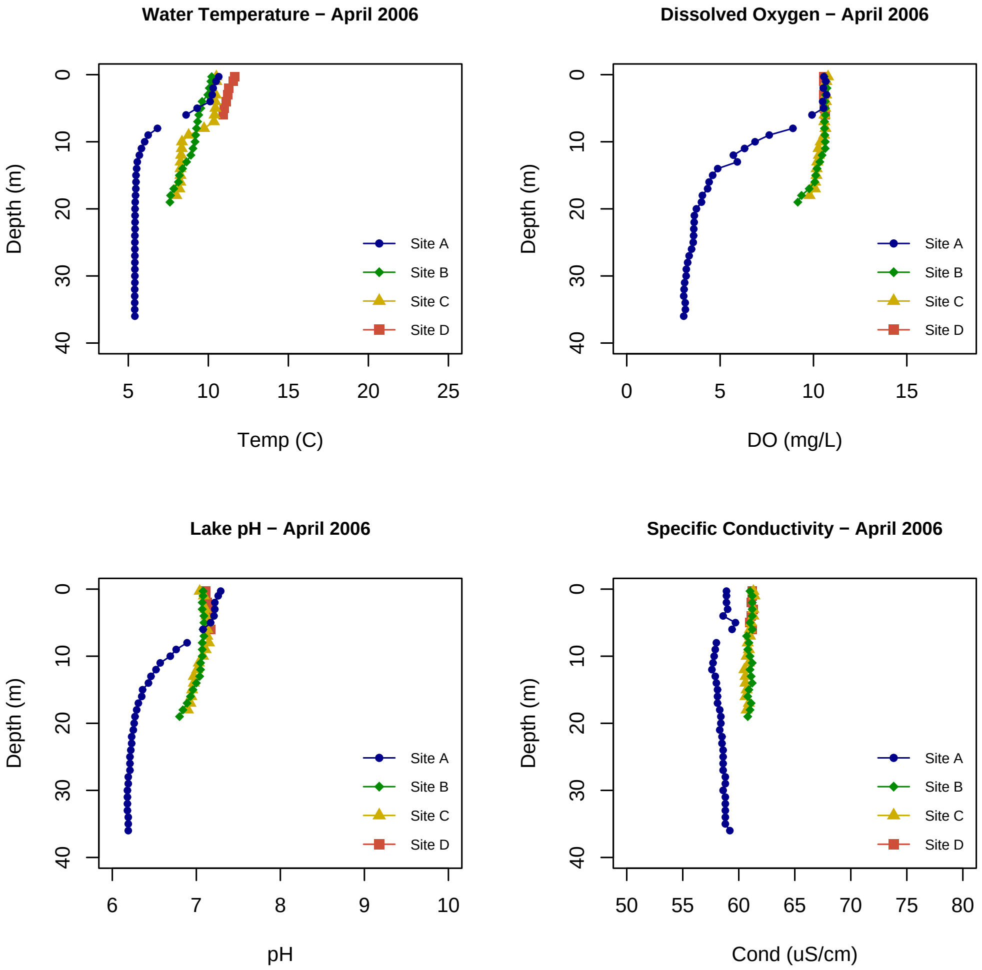


Figure 10: Lake Samish Hydrolab profiles for Sites A–D, March 19, 2006.


Water Temperature − April 2006

Dissolved Oxygen − April 2006

Lake pH − April 2006

Specific Conductivity − April 2006

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

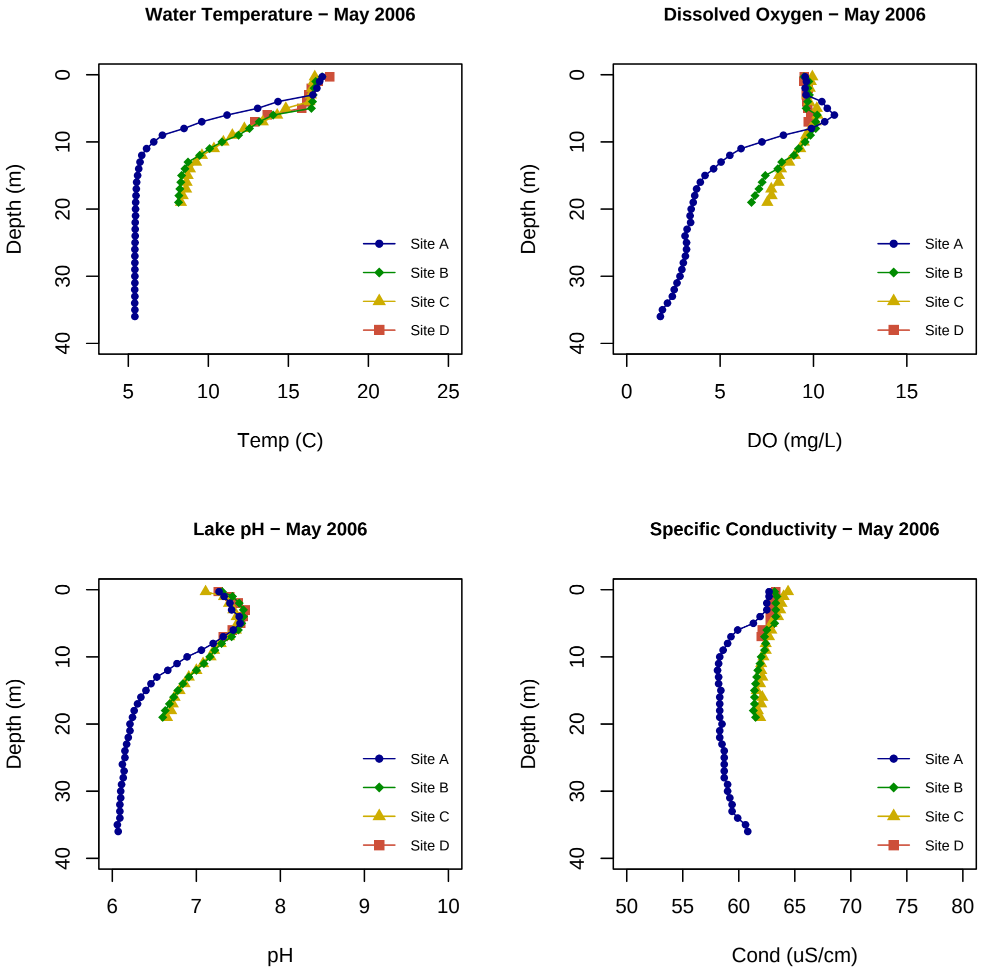


Figure 12: Lake Samish Hydrolab profiles for Sites A–D, May 21, 2006.

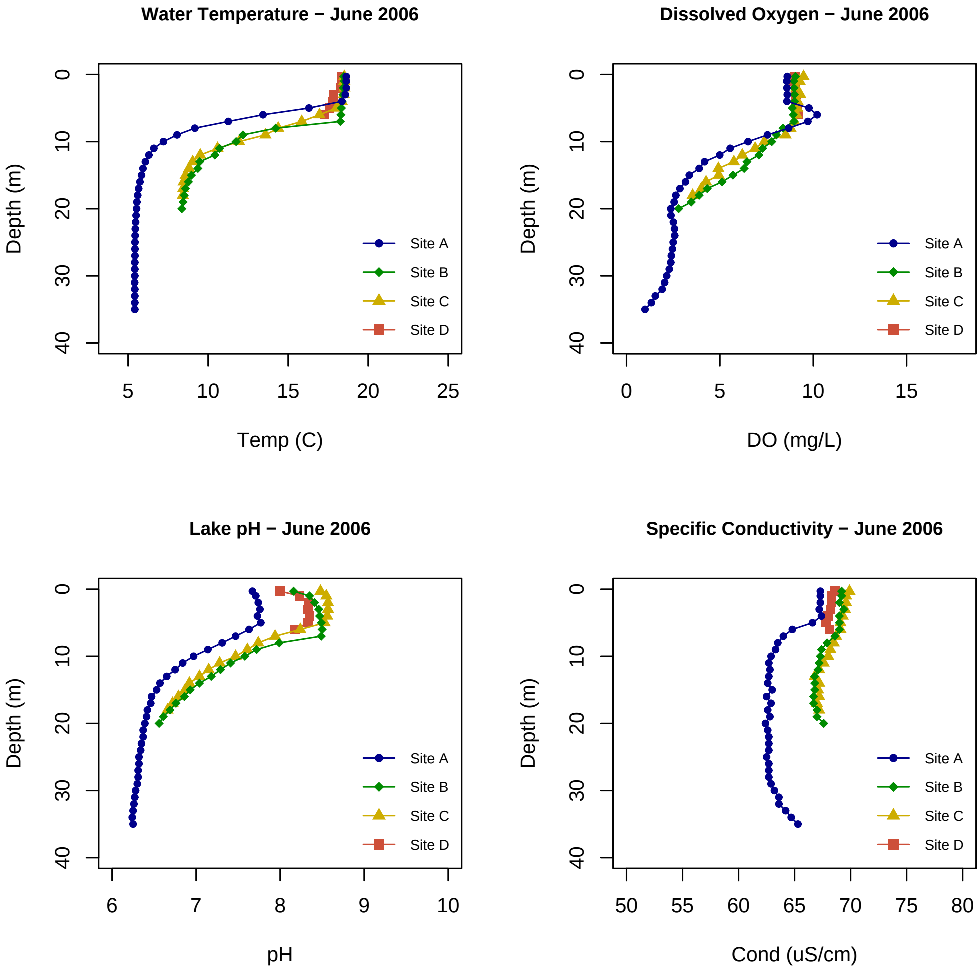


Figure 13: Lake Samish Hydrolab profiles for Sites A–D, June 20, 2006.

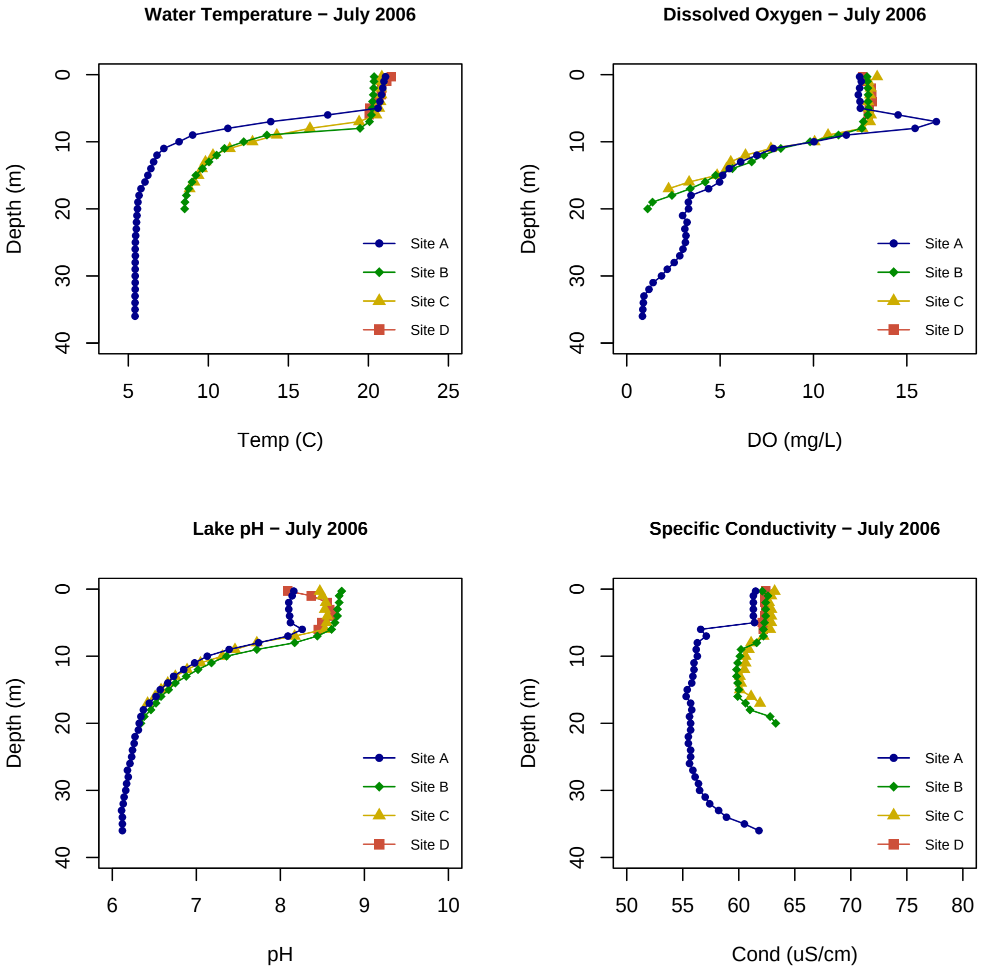


Figure 14: Lake Samish Hydrolab profiles for Sites A–D, July 19, 2006.

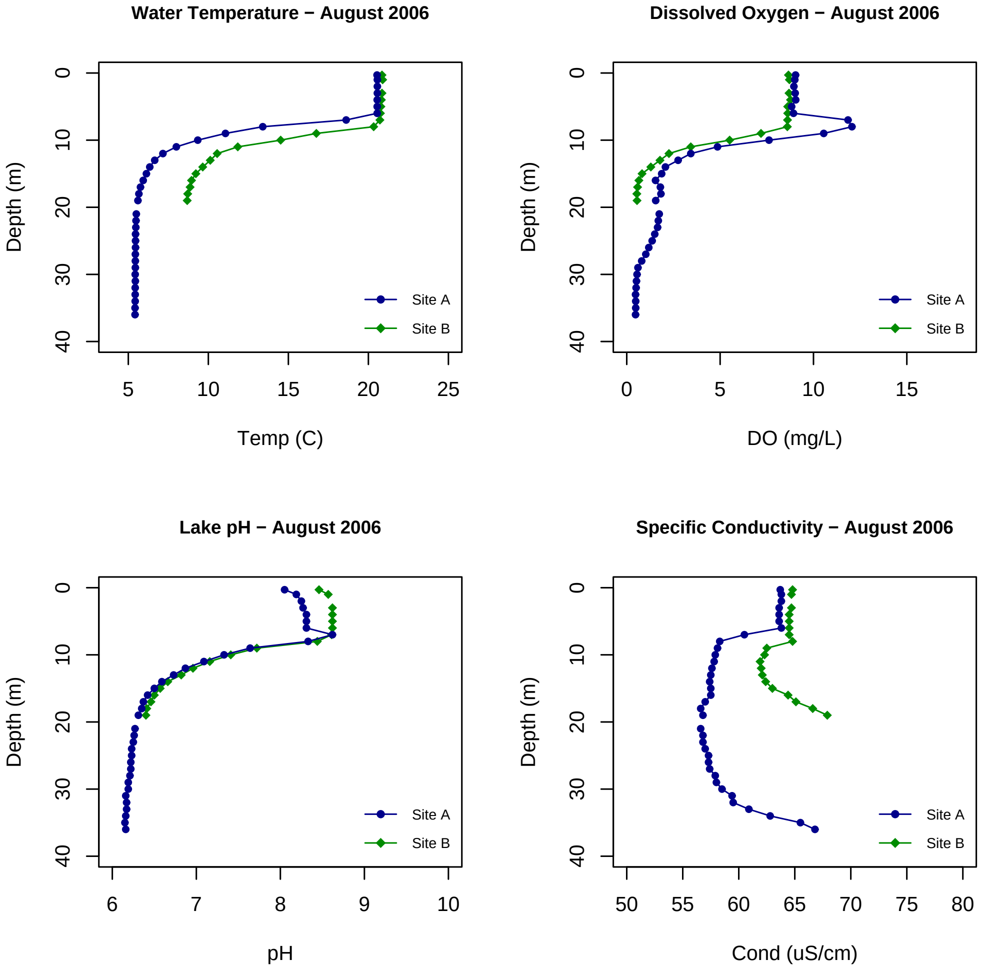
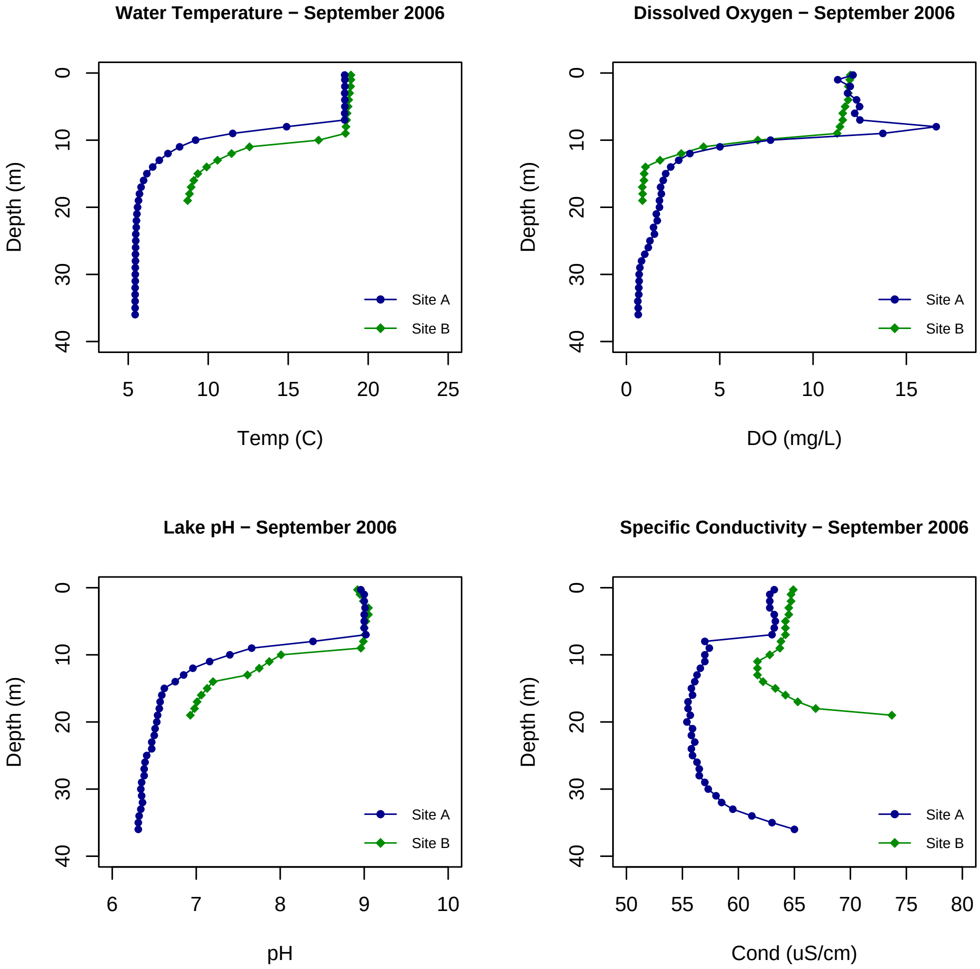


Figure 15: Lake Samish Hydrolab profiles for Sites A and B, August 24, 2006. Sites C and D were not sampled on this date.

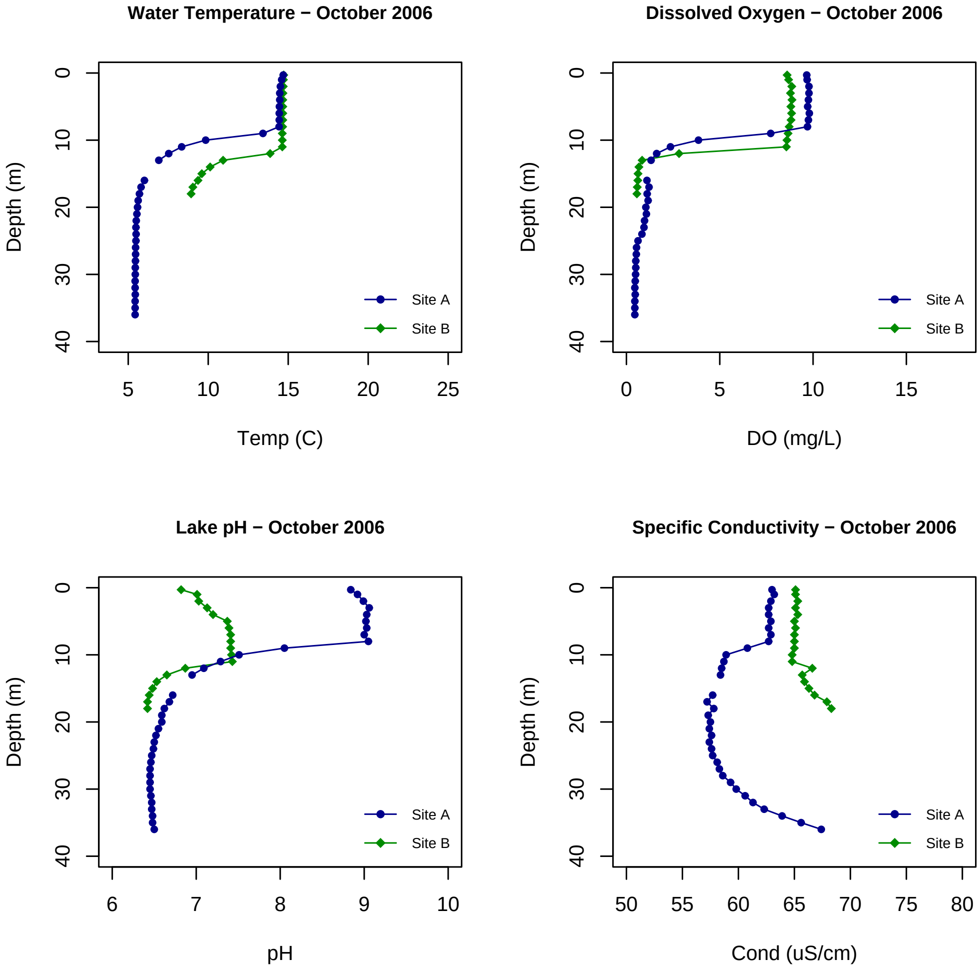

Water Temperature − September 2006

Dissolved Oxygen − September 2006

Lake pH − September 2006

Specific Conductivity − September 2006

Figure 16: Lake Samish Hydrolab profiles for Sites A and B, September 19, 2006. Sites C and D were not sampled on this date.

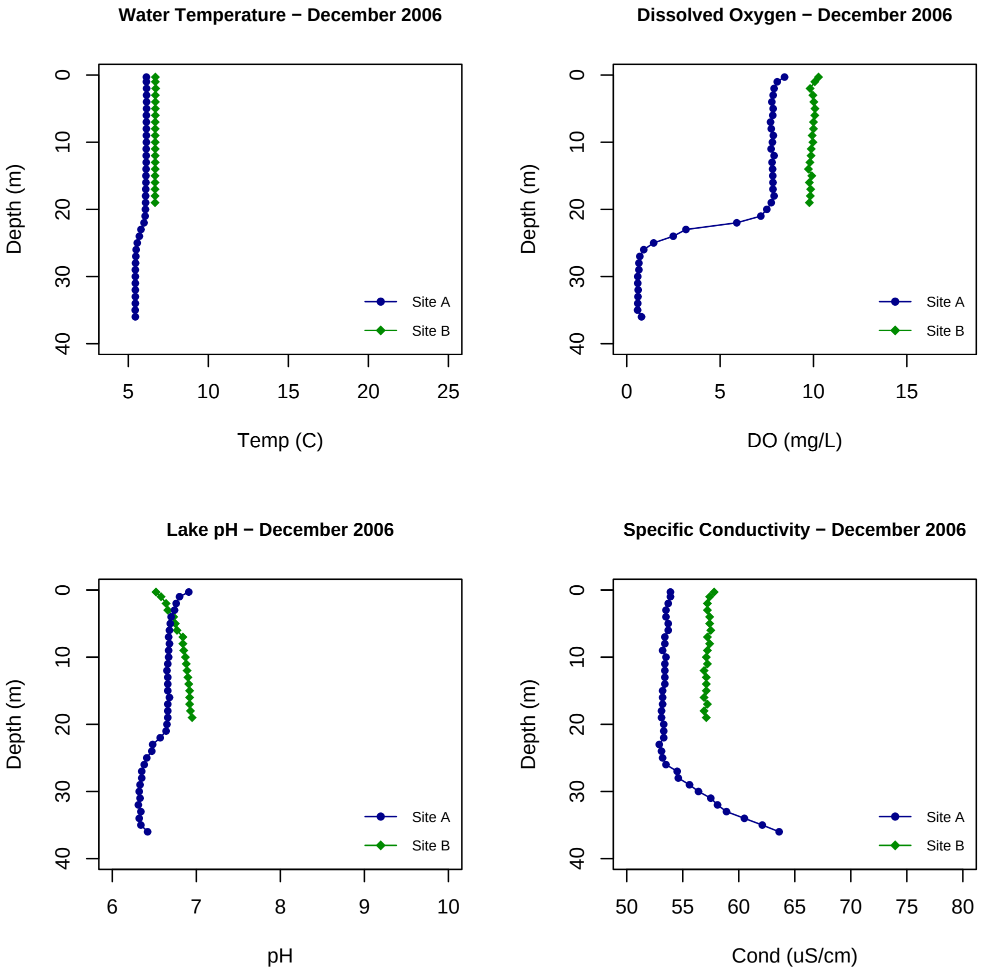

Water Temperature − October 2006

Dissolved Oxygen − October 2006

Lake pH − October 2006

Specific Conductivity − October 2006

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


Water Temperature − December 2006

Dissolved Oxygen − December 2006

Lake pH − December 2006

Specific Conductivity − December 2006

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

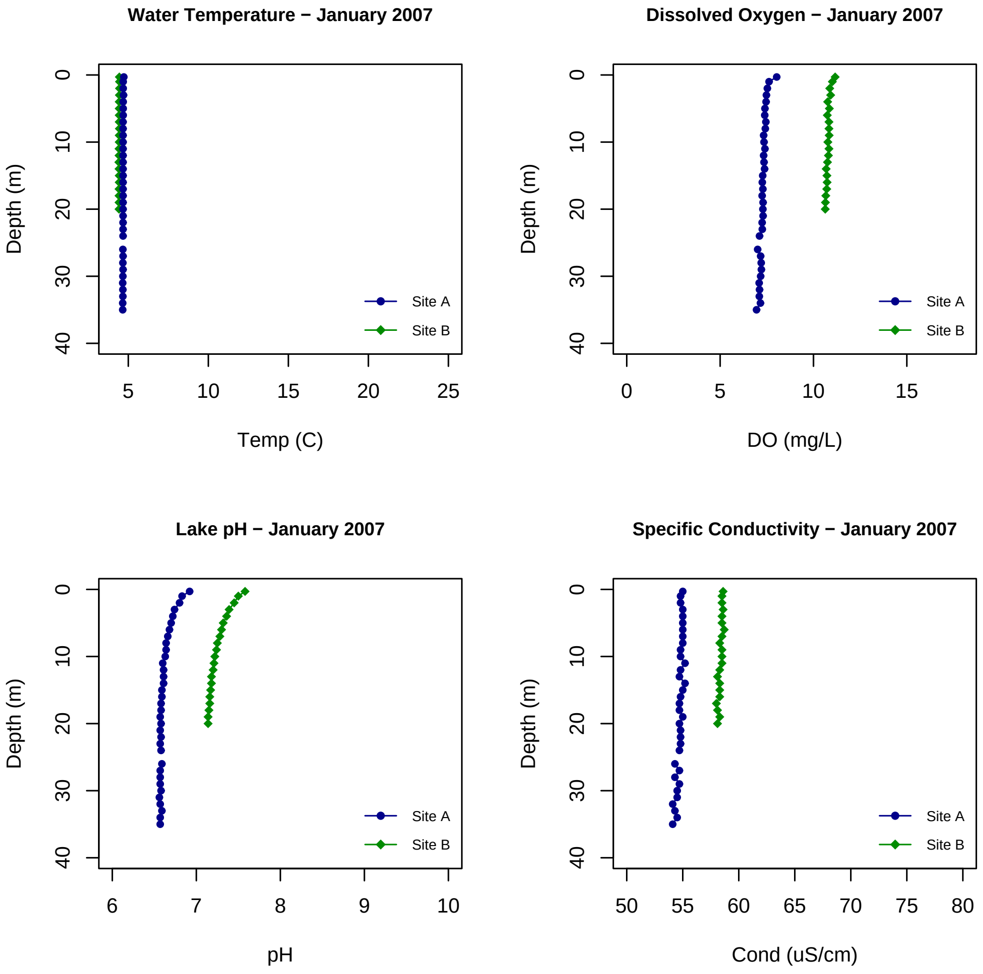
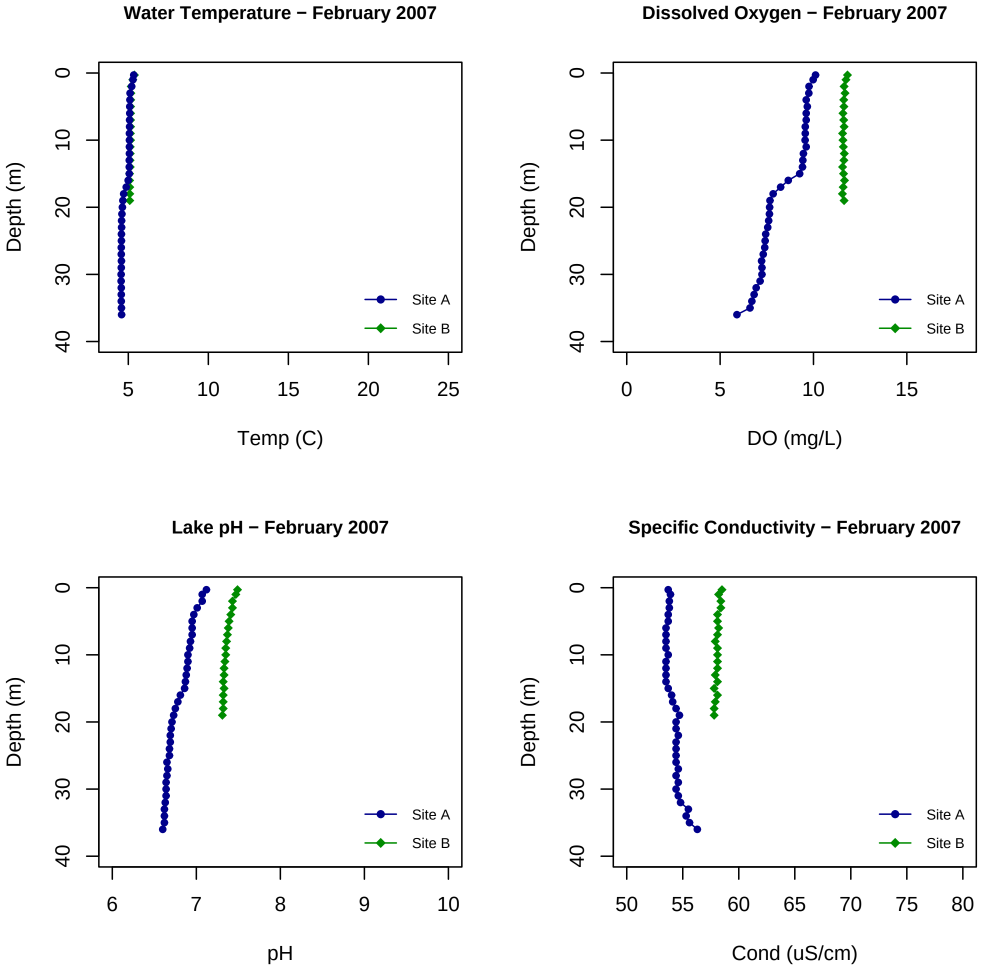


Figure 19: Lake Samish Hydrolab profiles for Sites A and B, January 30, 2007. Sites C and D were not sampled on this date.


Water Temperature − February 2007

Dissolved Oxygen − February 2007

Lake pH − February 2007

Specific Conductivity − February 2007

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

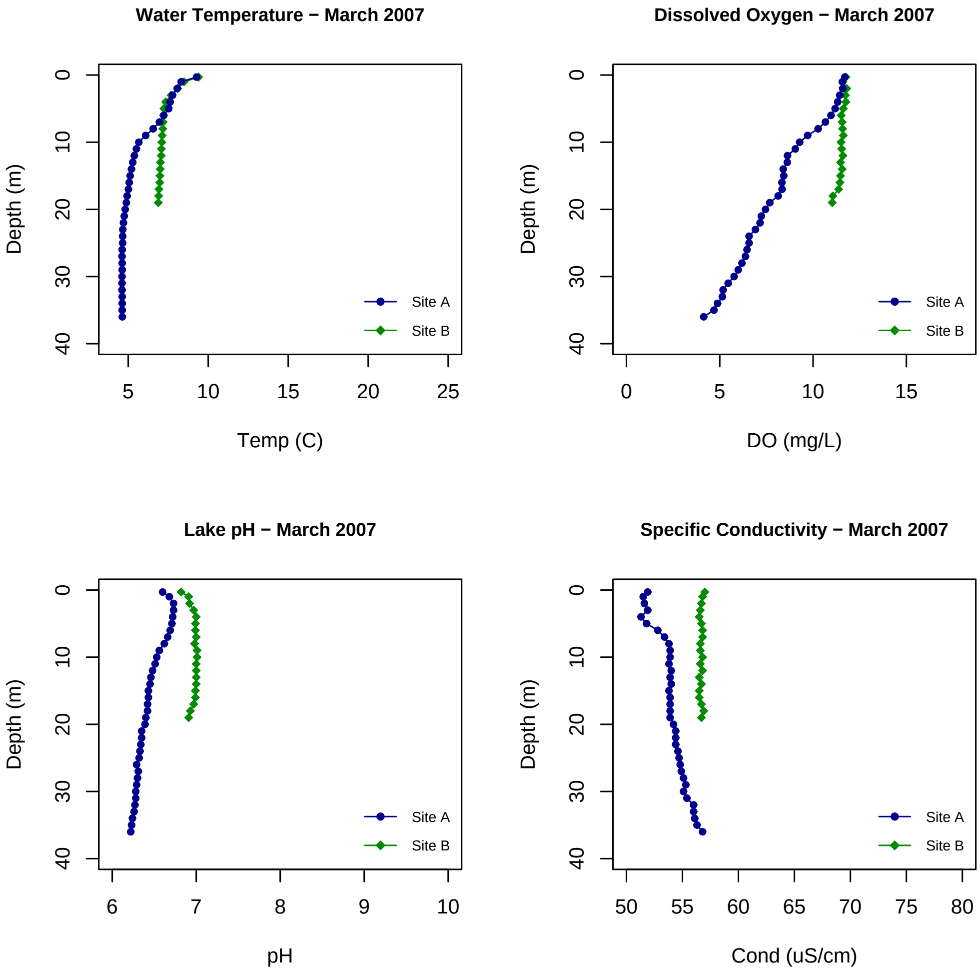


Figure 21: Lake Samish Hydrolab profiles for Sites A and B, March 29, 2007. Sites C and D were not sampled on this date.

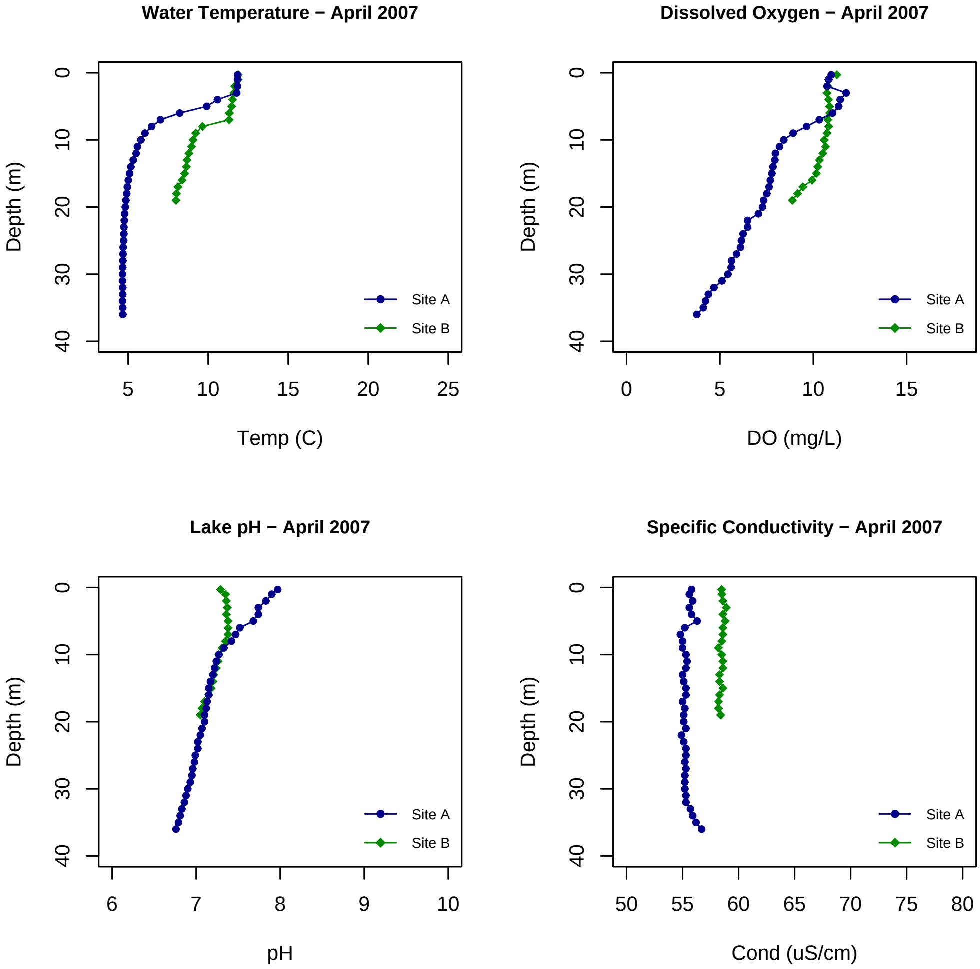


Figure 22: Lake Samish Hydrolab profiles for Sites A and B, April 24, 2007. Sites C and D were not sampled on this date.

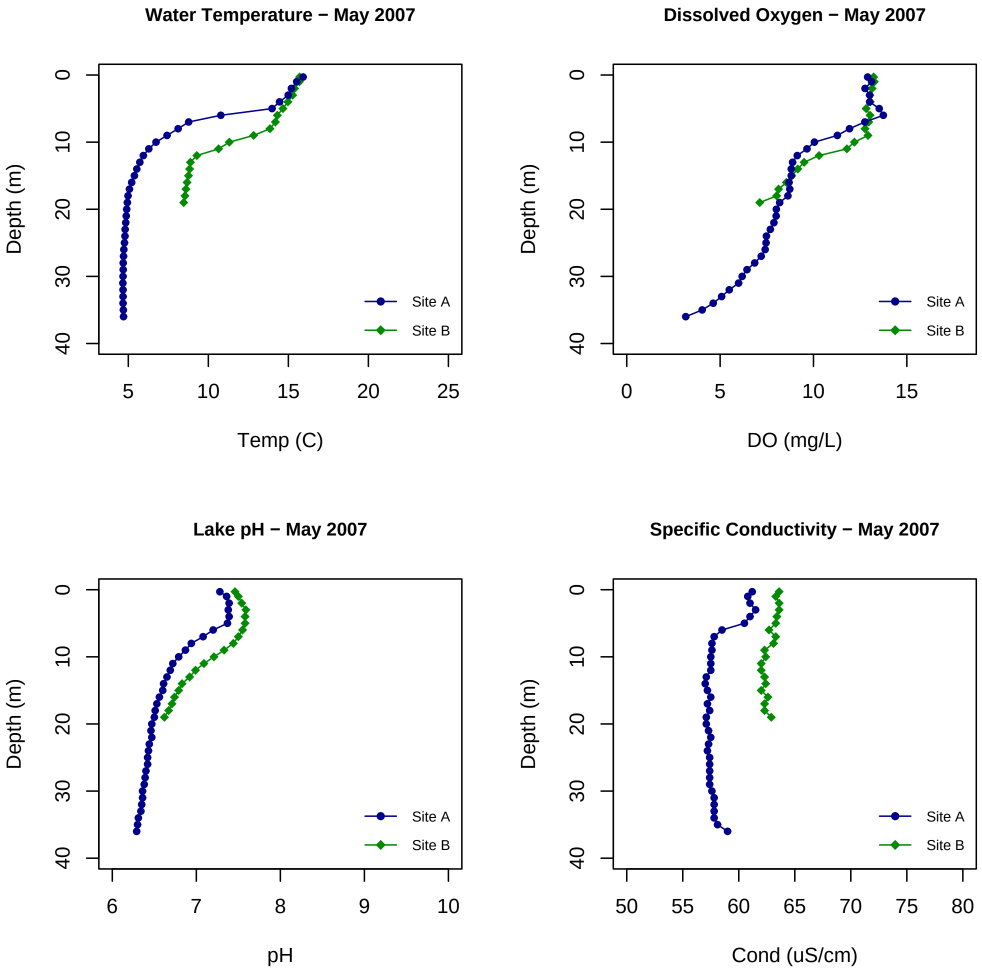


Figure 23: Lake Samish Hydrolab profiles for Sites A and B, May 24, 2007. Sites C and D were not sampled on this date.

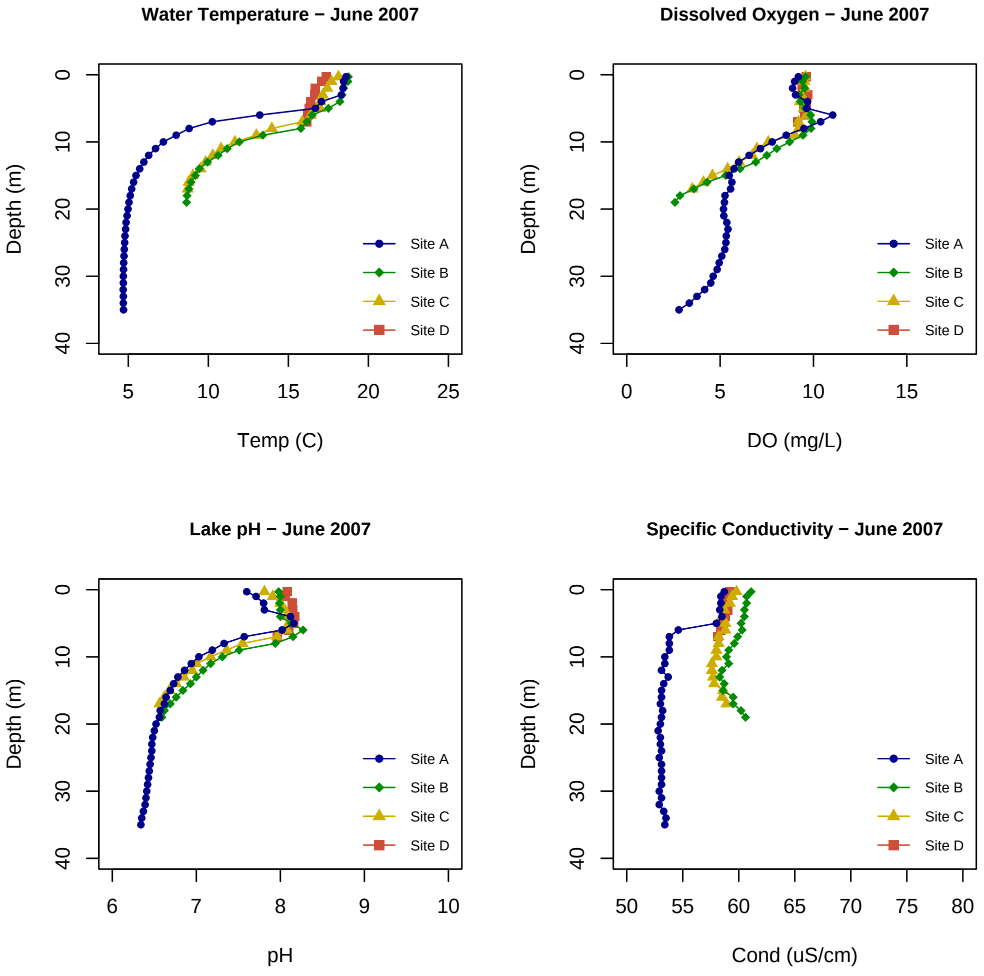


Figure 24: Lake Samish Hydrolab profiles for Sites A–D, June 21, 2007.

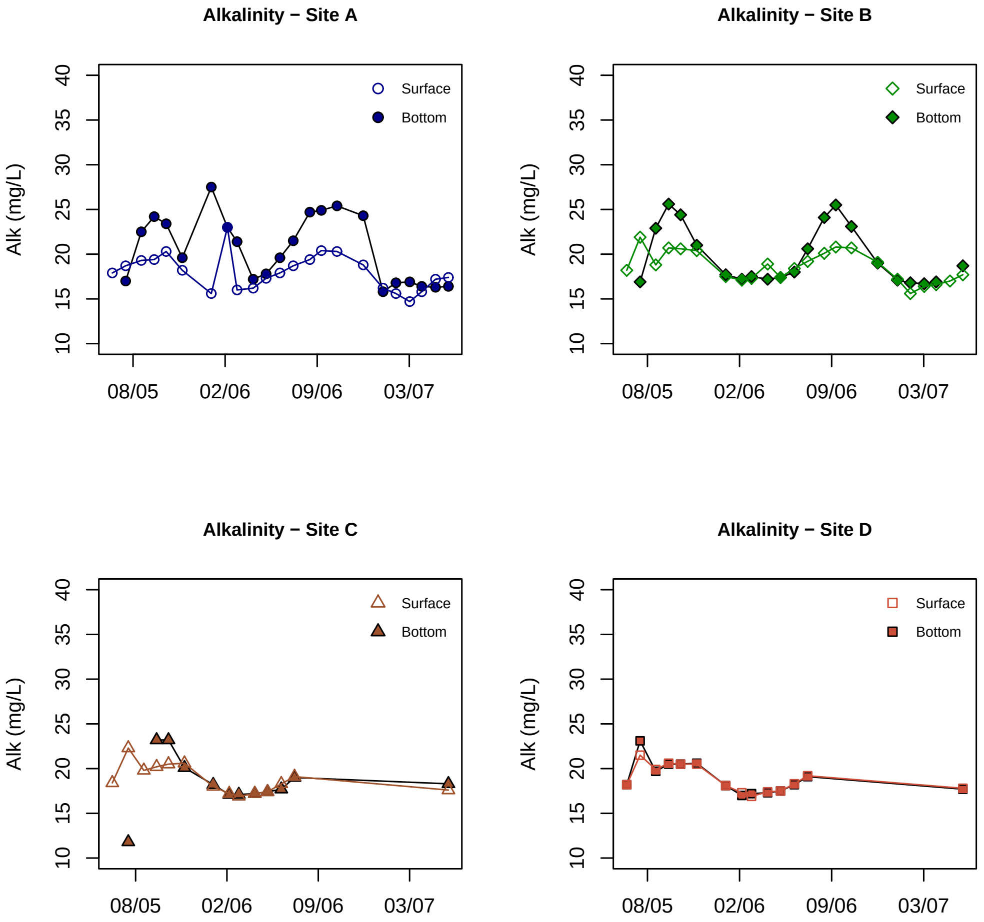


Figure 25: Lake Samish alkalinity data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled from August 2006 through May 2007.

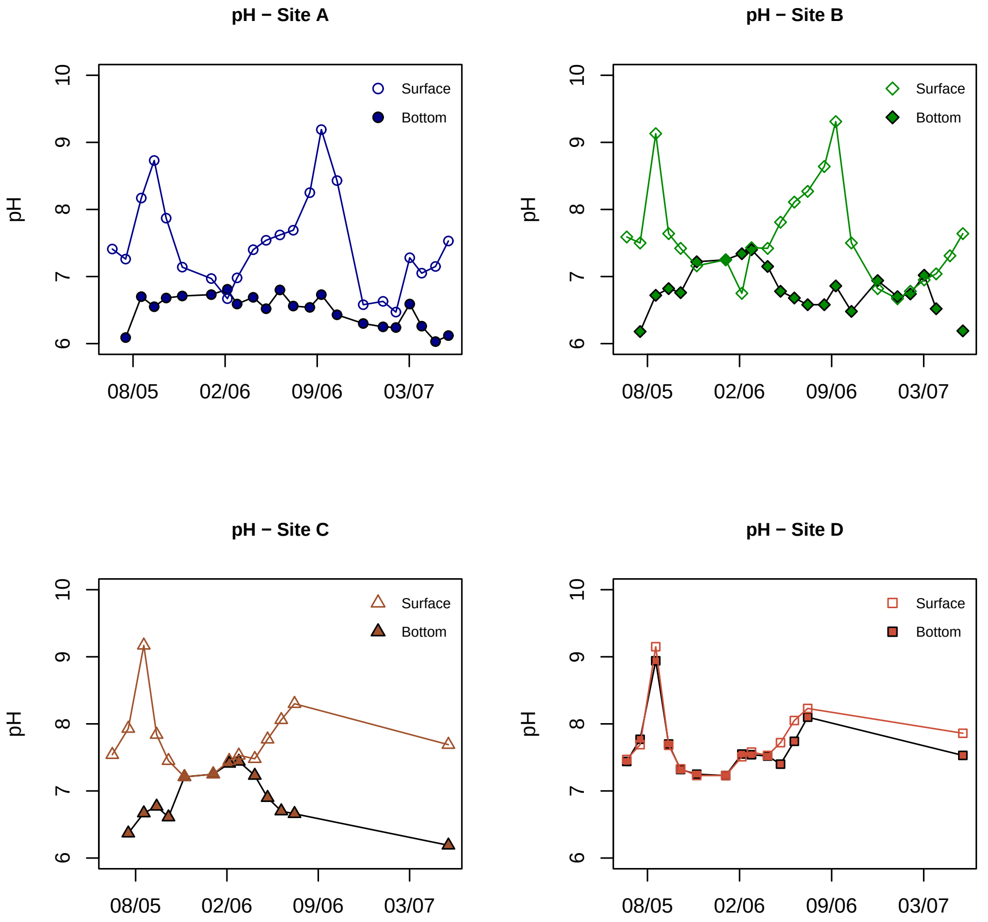


Figure 26: Lake Samish pH data (laboratory analysis), June 2005 through June 2007. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled from August 2006 through May 2007.

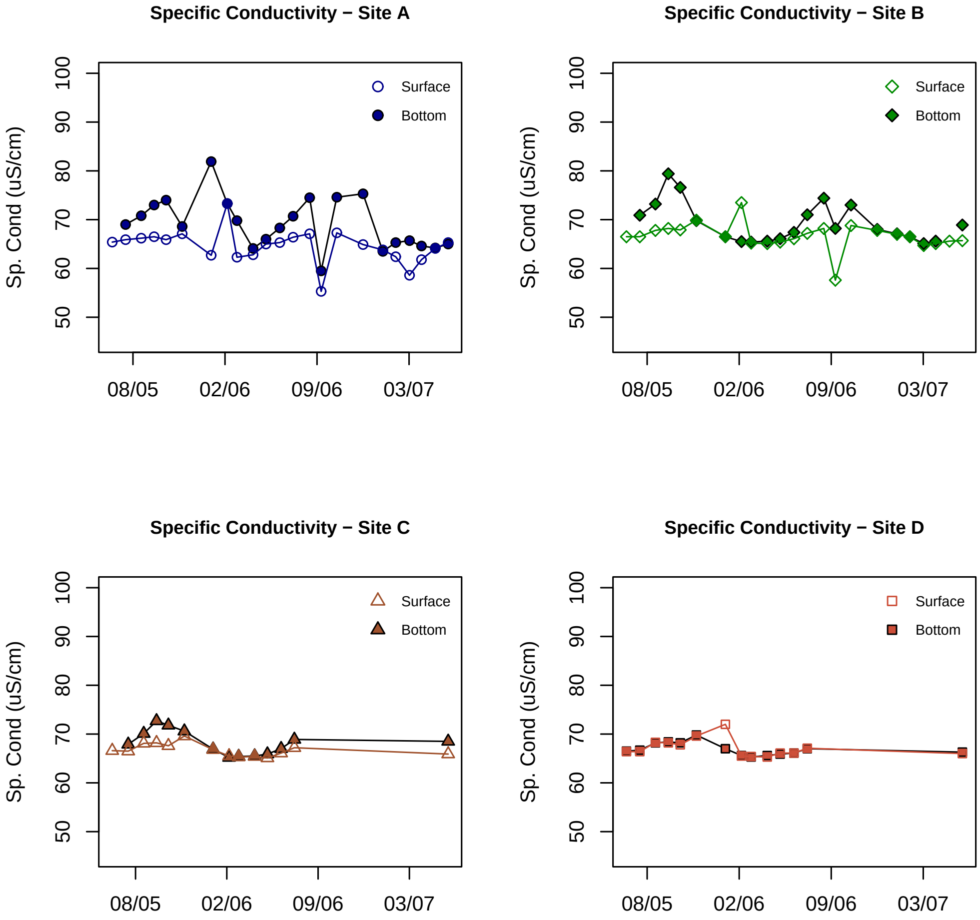


Figure 27: Lake Samish specific conductivity data (laboratory analysis), June 2005 through June 2007. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled from August 2006 through May 2007.

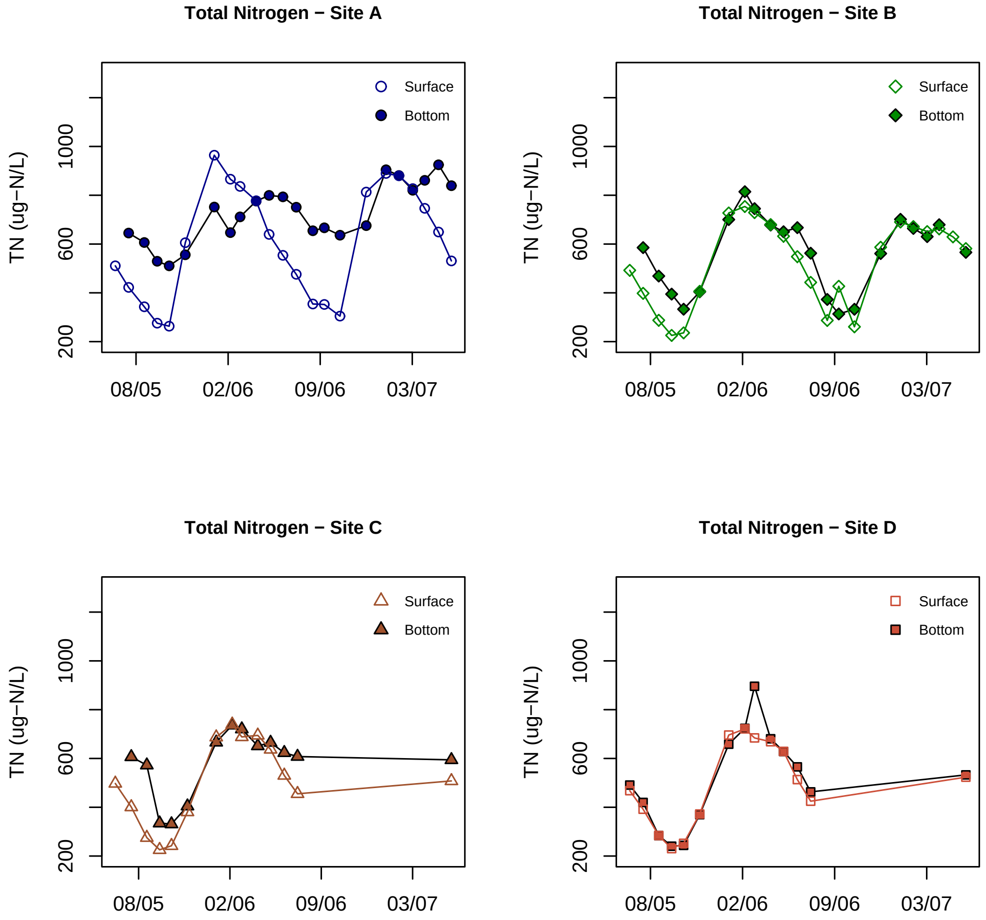


Figure 28: Lake Samish total nitrogen data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled from August 2006 through May 2007.

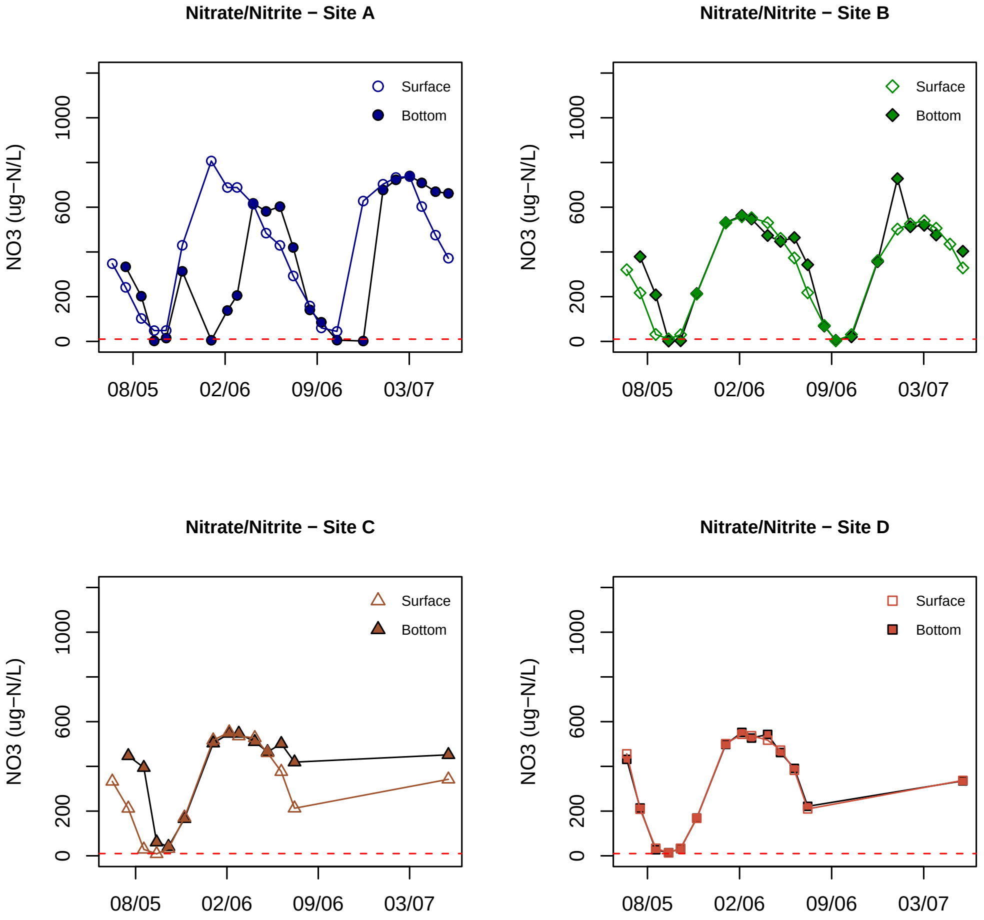


Figure 29: Lake Samish nitrate/nitrite data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D were not sampled from August 2006 through May 2007.

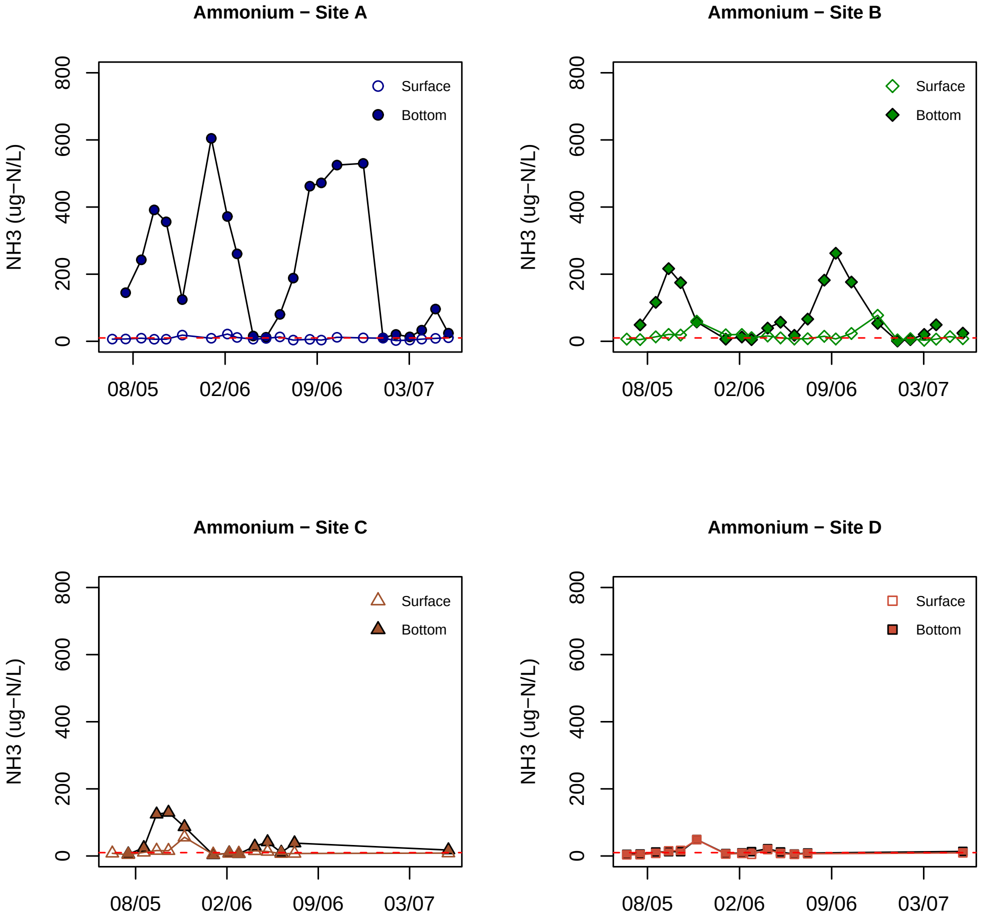


Figure 30: Lake Samish ammonium data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D were not sampled from August 2006 through May 2007.

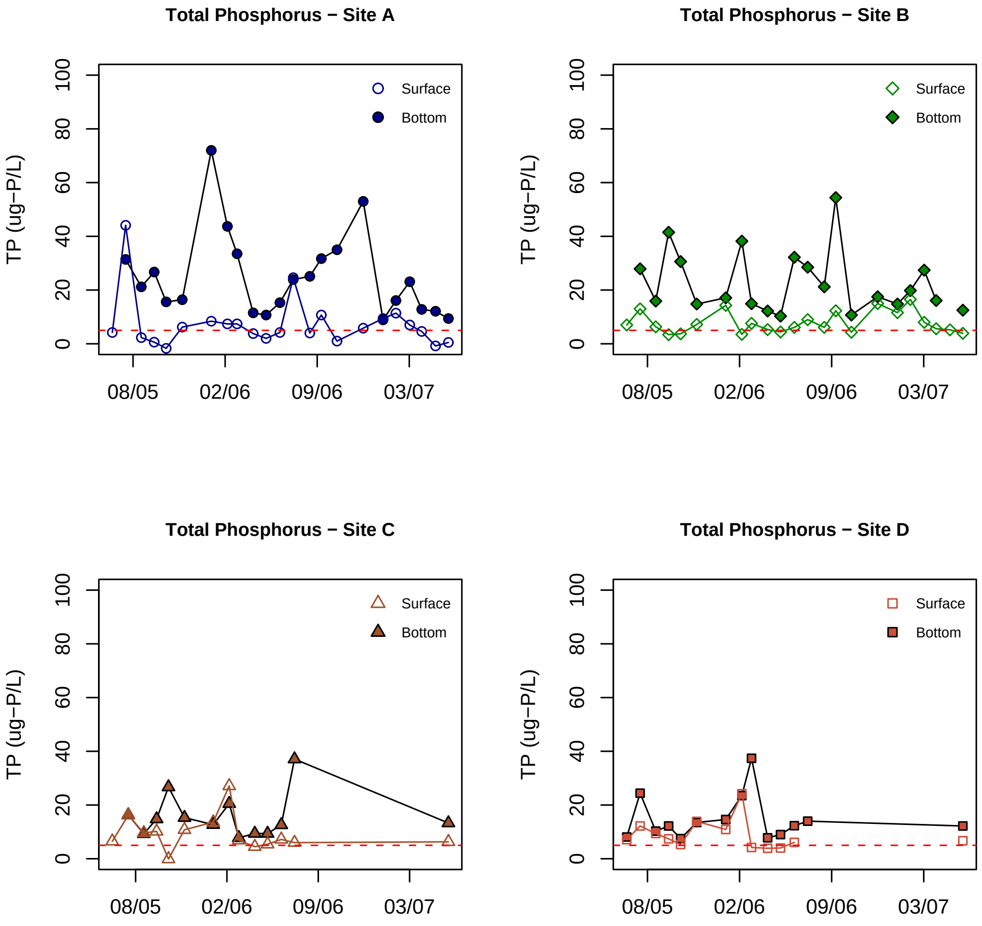


Figure 31: Lake Samish total phosphorus data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D were not sampled from August 2006 through May 2007.

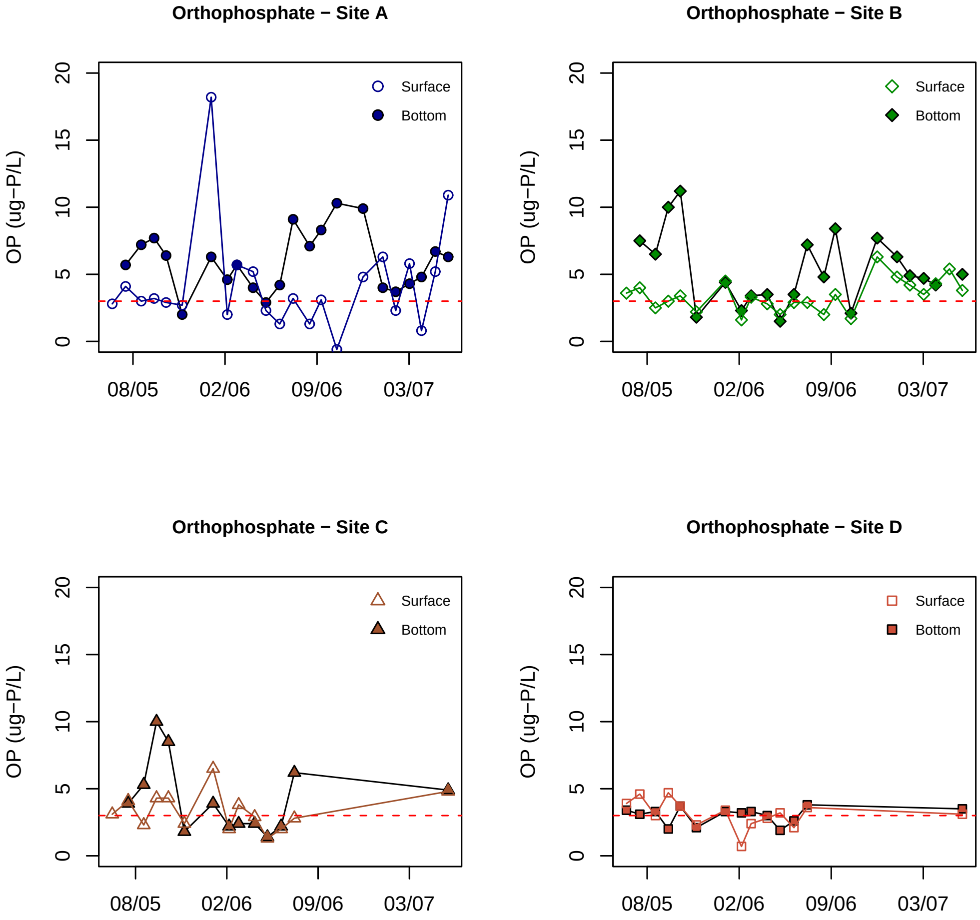
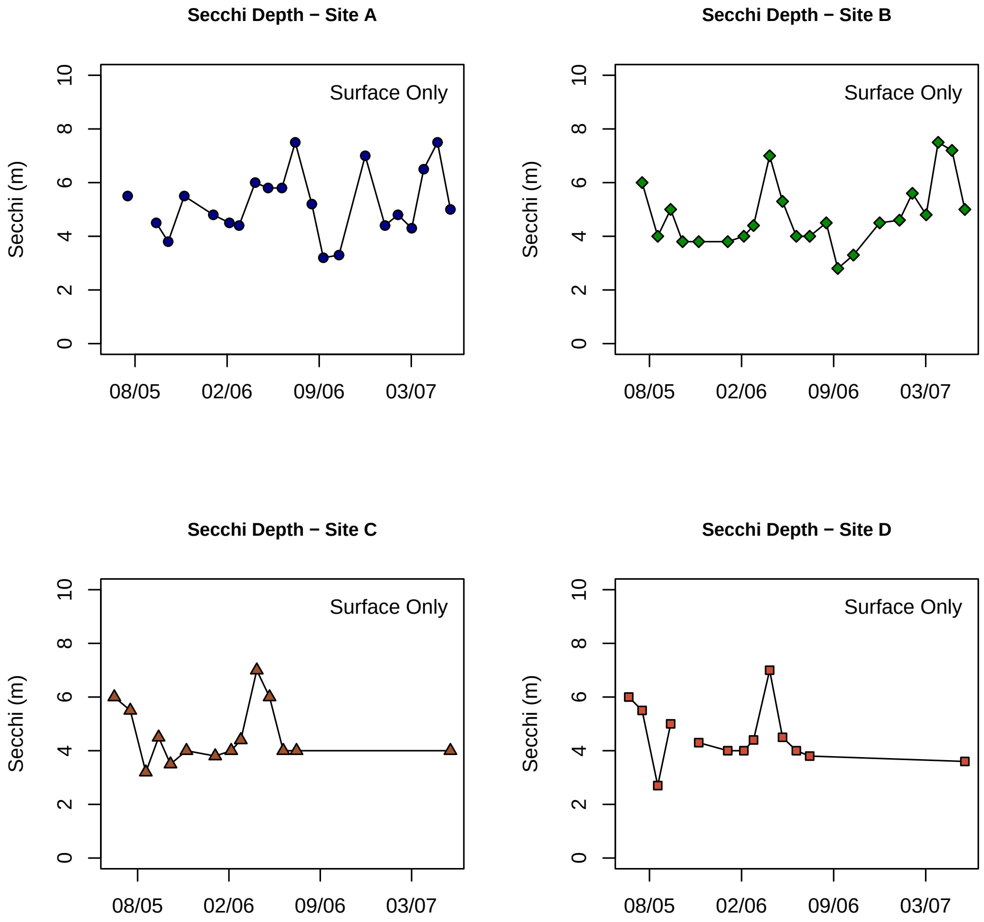


Figure 32: Lake Samish orthophosphate data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit; Sites C and D were not sampled from August 2006 through May 2007.



Secchi Depth − Site A

Secchi Depth − Site B

Secchi Depth − Site C

Secchi Depth − Site D

Figure 33: Lake Samish Secchi depth data, June 2005 through June 2007. Samples were collected at the surface for each site; Sites C and D were not sampled from August 2006 through May 2007.

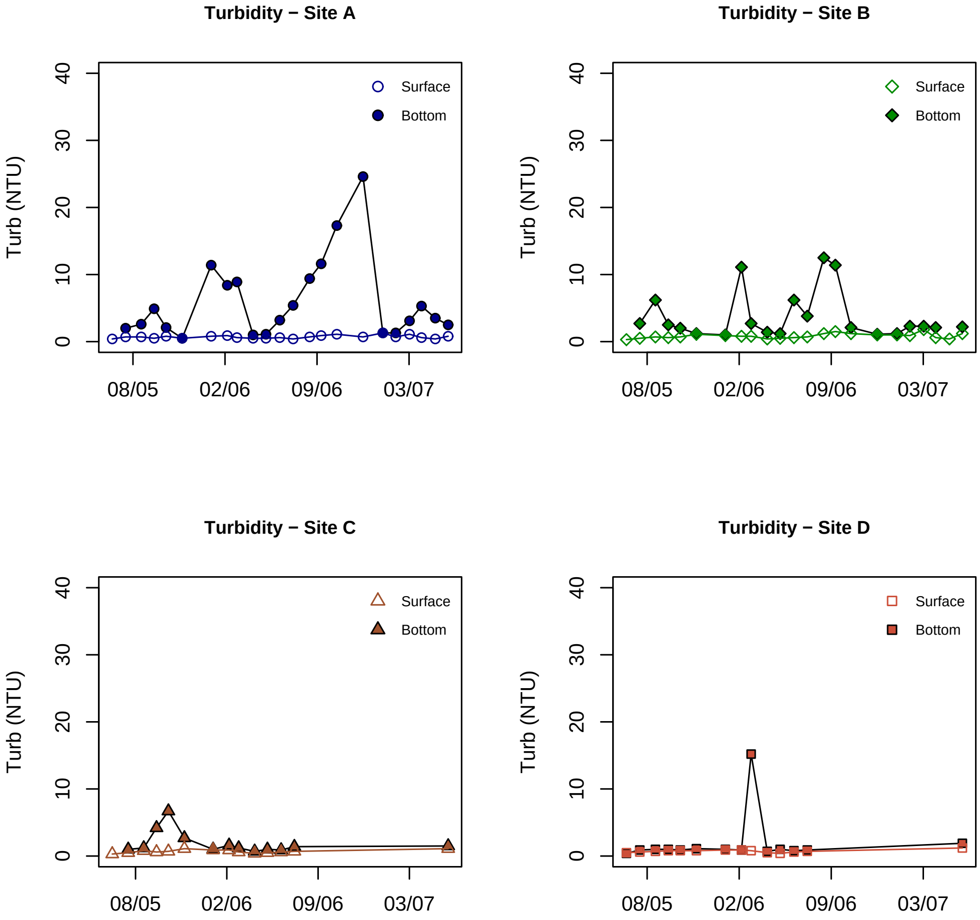


Figure 34: Lake Samish turbidity data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site; Sites C and D were not sampled from August 2006 through May 2007.

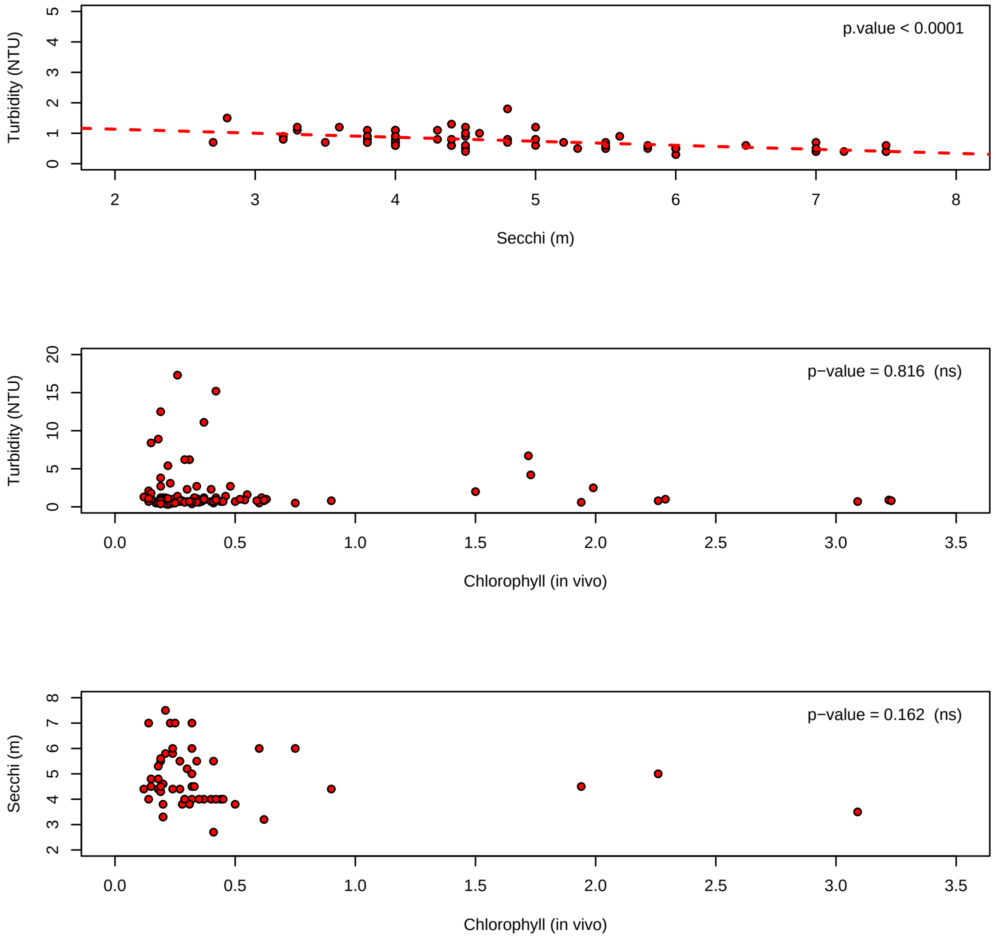


Figure 35: Kendall's $\tau$ correlations between turbidity, Secchi depth, chlorophyll, and orthophosphate. See page 5 for a description of correlation analysis. Diagonal line on turbidity vs. Secchi figure is for reference only and does not imply a linear relationship.

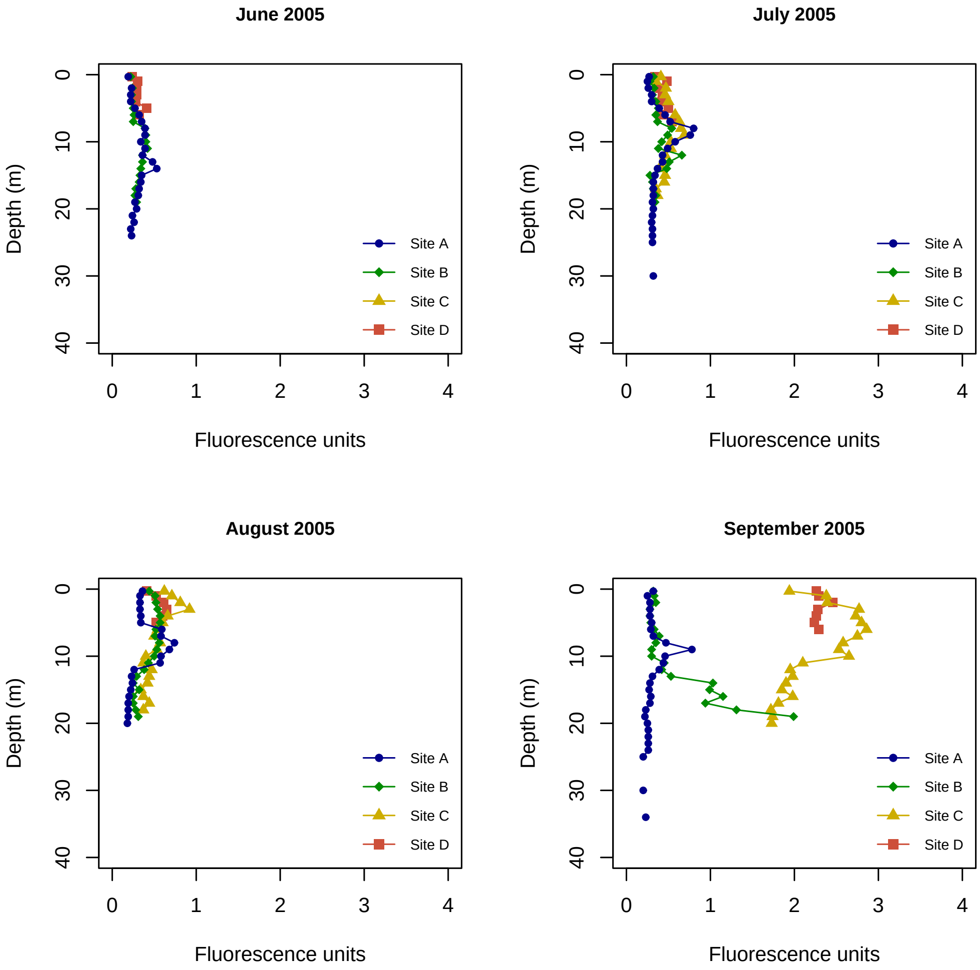


Figure 36: Lake Samish algal fluorescence profiles, June through September 2005.

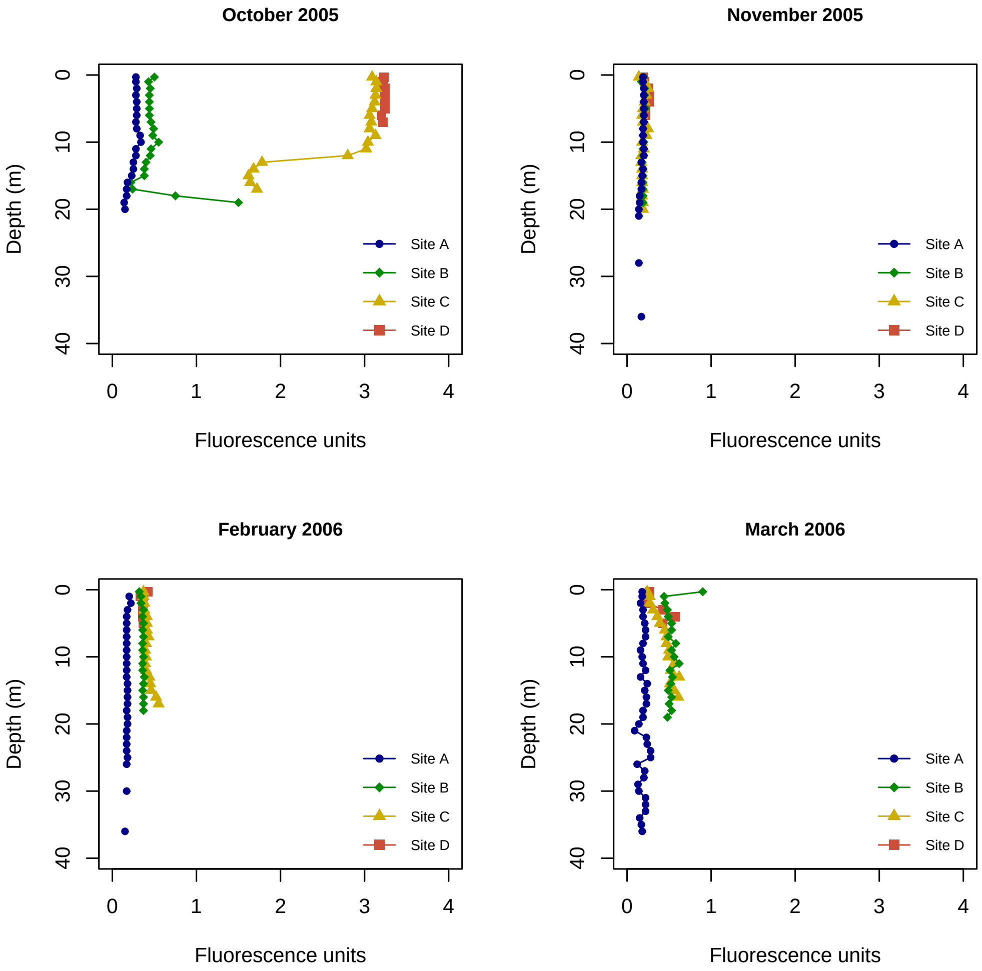


Figure 37: Lake Samish algal fluorescence profiles, October 2005 through March 2006. December 2005 and January 2006 data are not available.

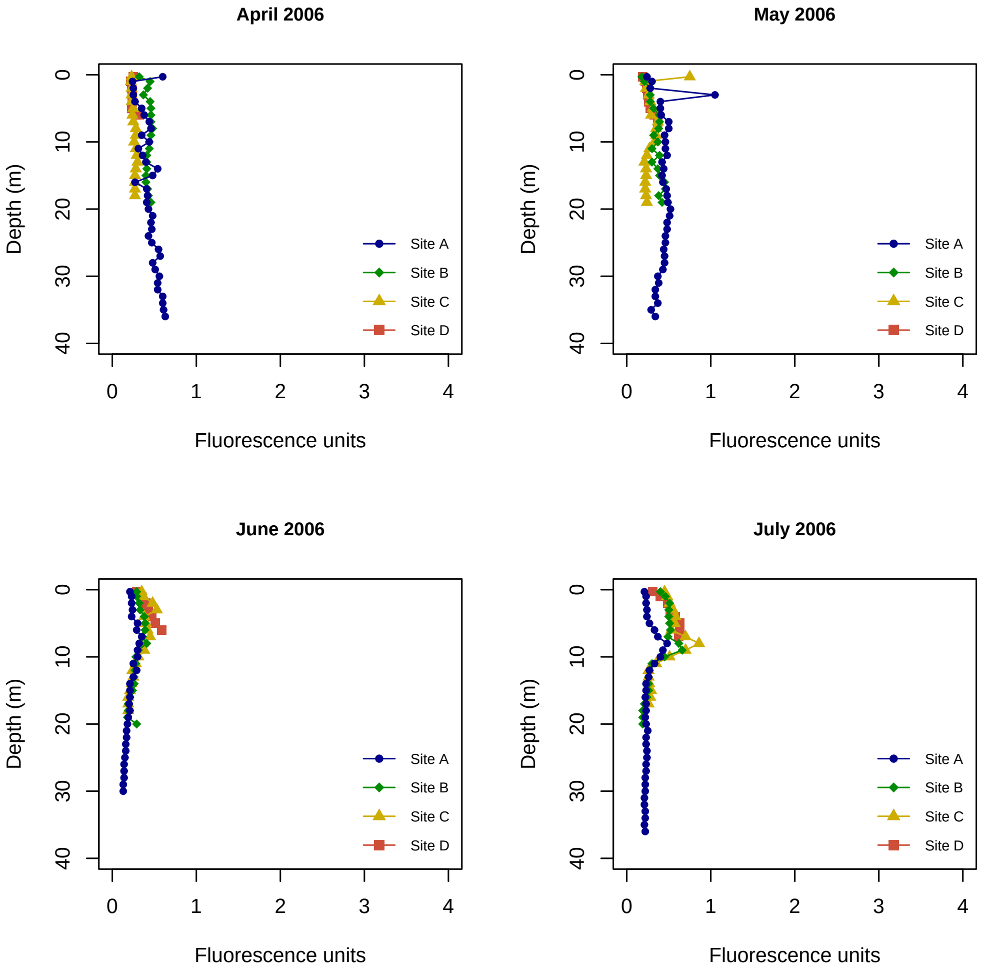


Figure 38: Lake Samish algal fluorescence profiles, April through July 2006.

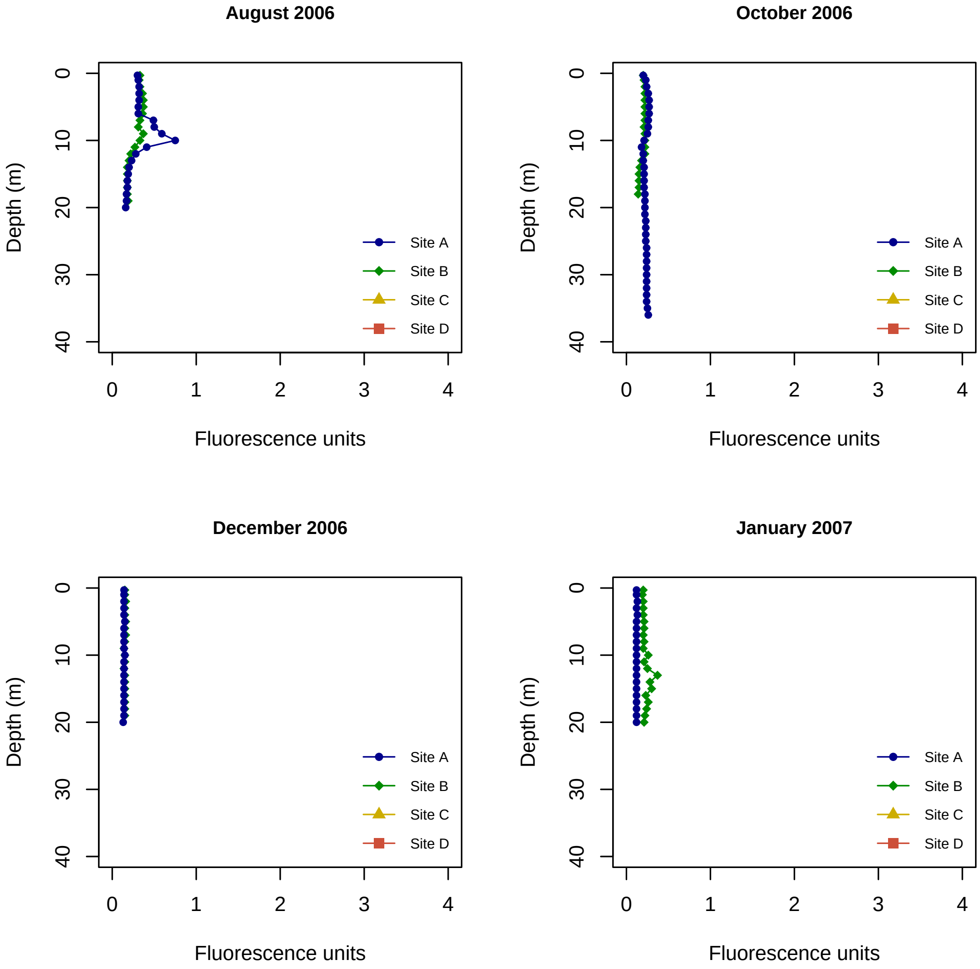


Figure 39: Lake Samish algal fluorescence profiles, August 2006 through January 2007. September and November 2006 data are not available. Sites C and D were not sampled on this date.

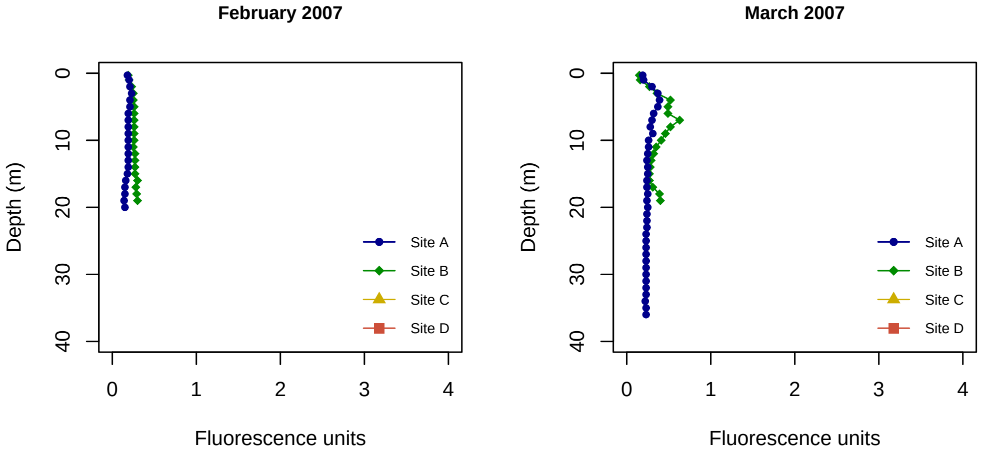


Figure 40: Lake Samish algal fluorescence profiles, February through March 2007. April, May and June 2007 data are not available. Sites C and D were not sampled on this date.

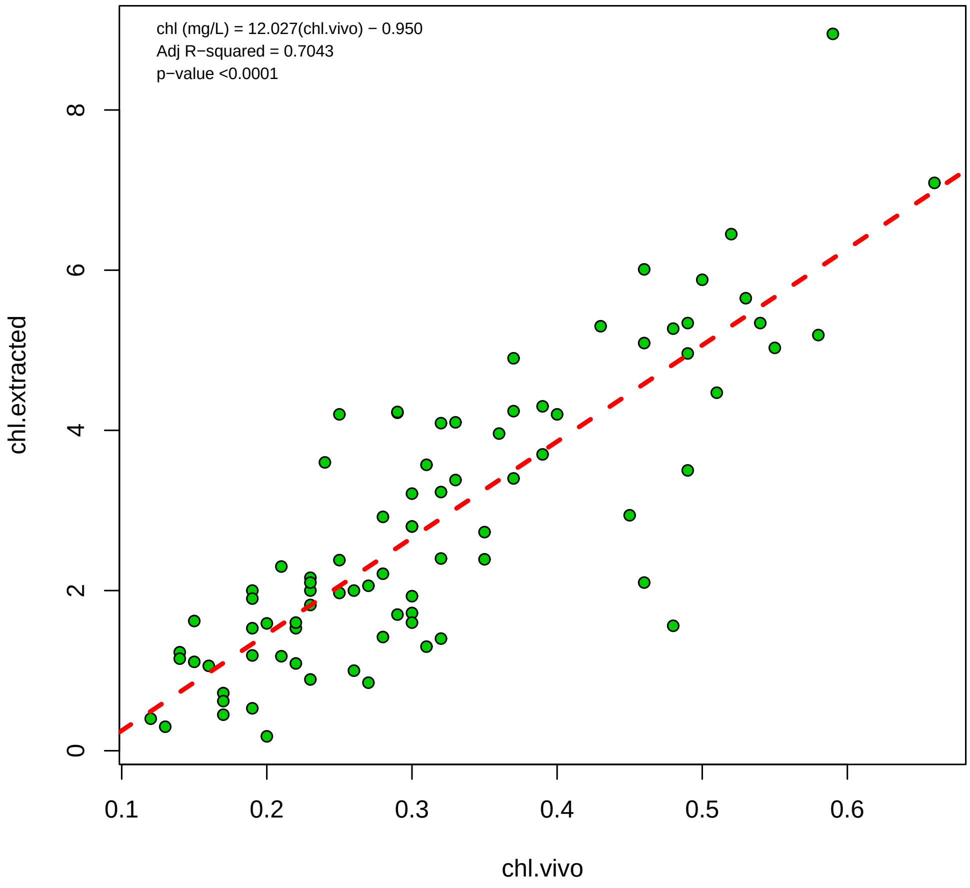


Figure 41: Comparison between chlorophyll fluorescence measured in the field and chlorophyll biomass measured in the laboratory.

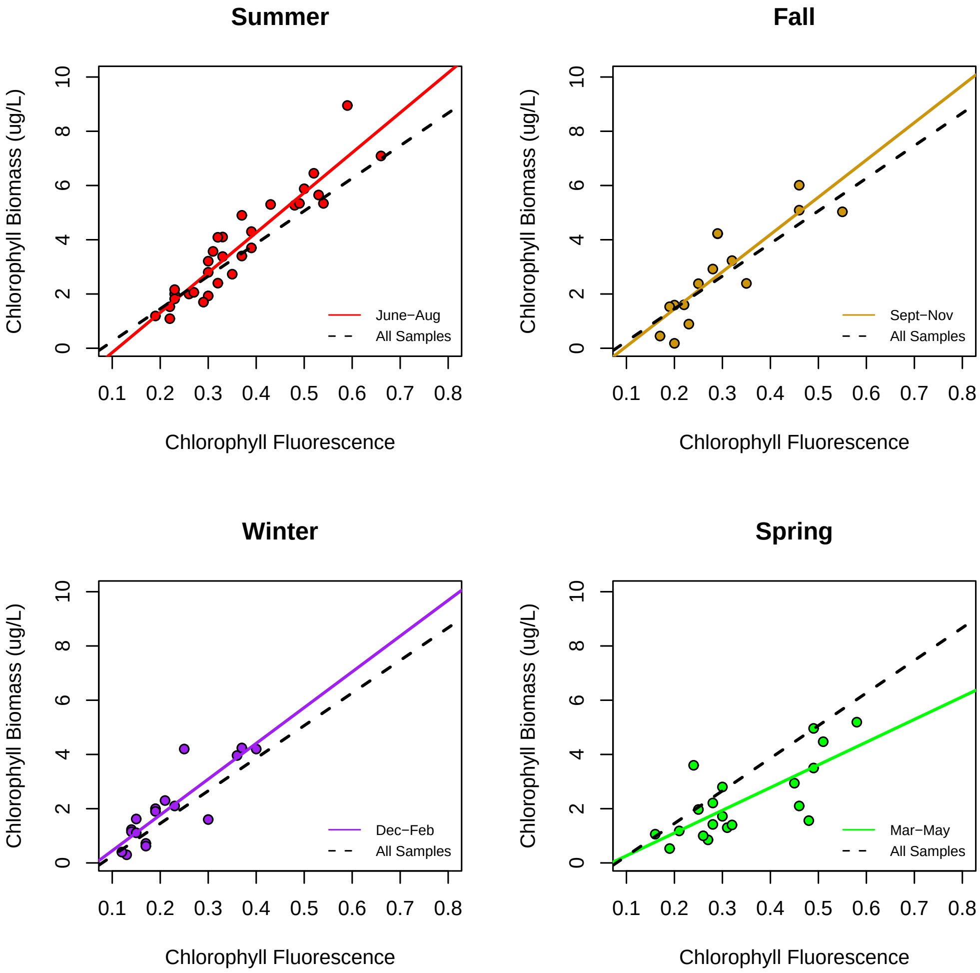


Figure 42: Seasonal comparison between chlorophyll fluorescence measured in the field and chlorophyll biomass measured in the laboratory.

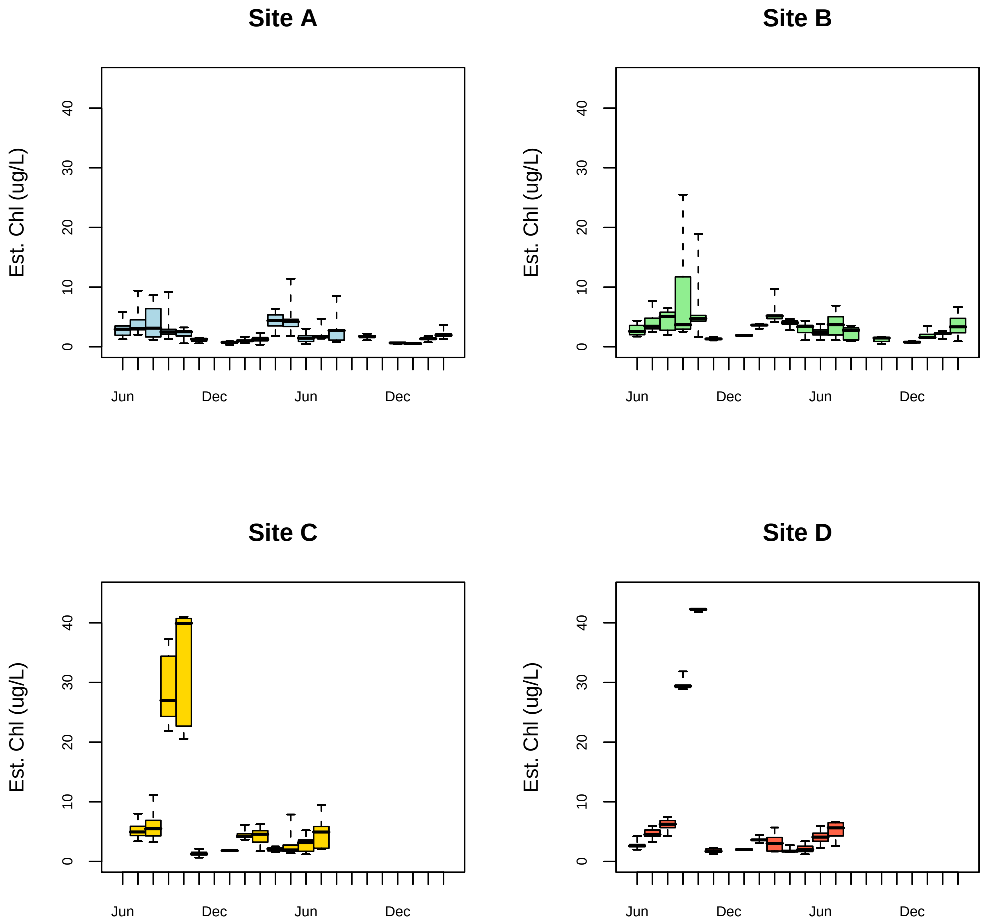


Figure 43: Boxplots showing Lake Samish estimated chlorophyll concentrations based on fluorescence regression model.

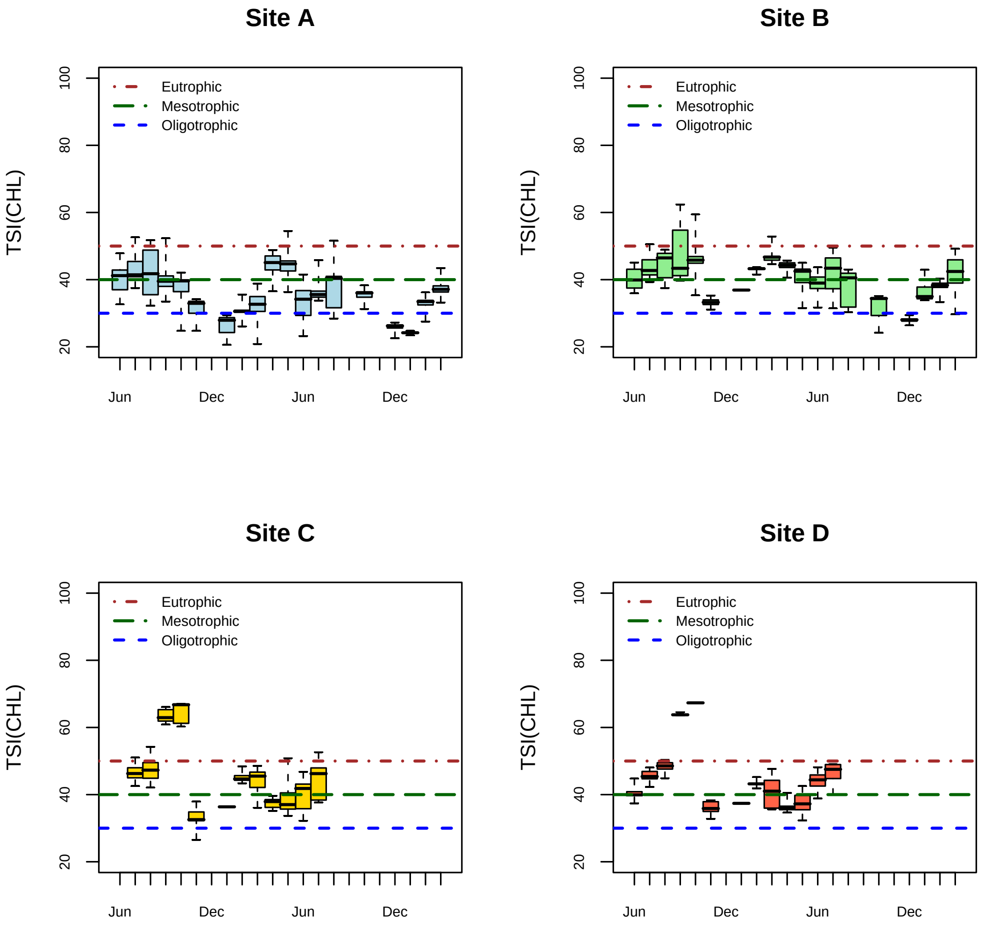


Figure 44: Boxplots showing Lake Samish monthly TSI(CHL) values. Chlorophyll biomass was estimated based on fluorescence regression model. Boxplots show median and upper/lower quartiles; whiskers show maximum/minimum values. See page 9 for discussion.

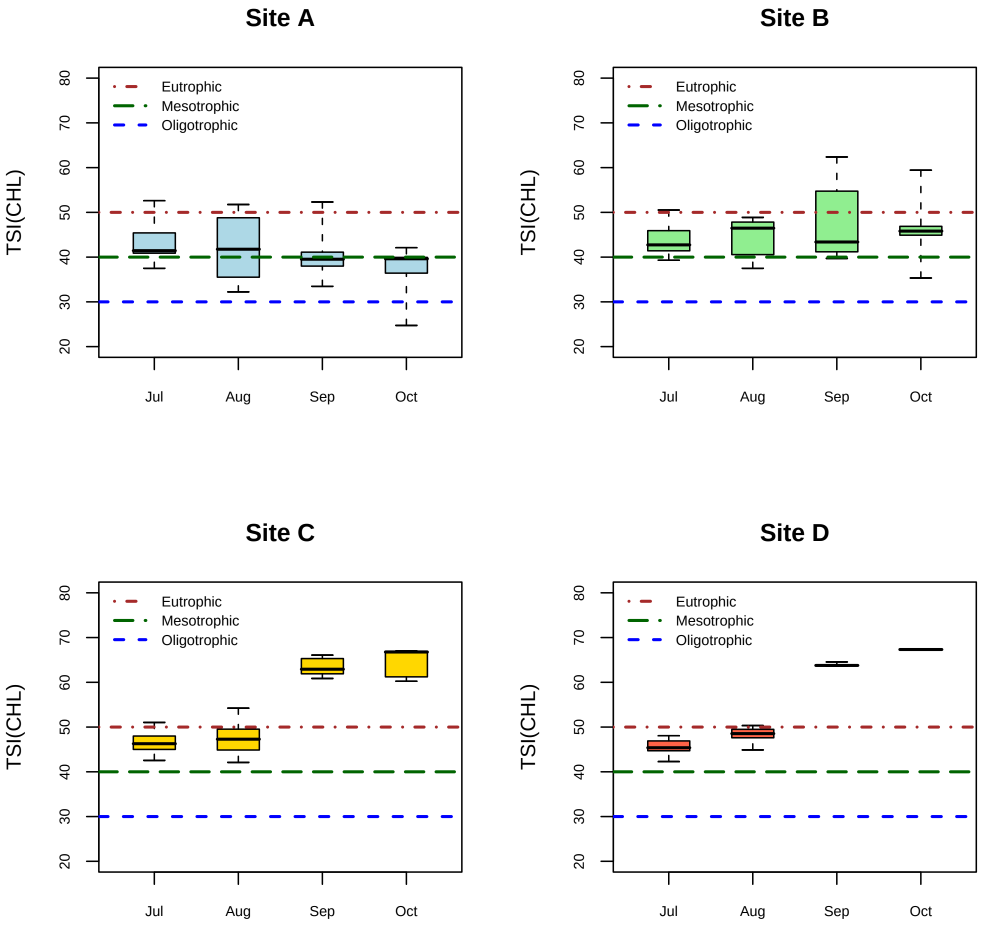


Figure 45: Boxplots showing Lake Samish summer TSI(CHL) values (July through October 2005). Chlorophyll biomass was estimated based on fluorescence regression model. Boxplots show median and upper/lower quartiles; whiskers show maximum/minimum values. See page 9 for discussion.

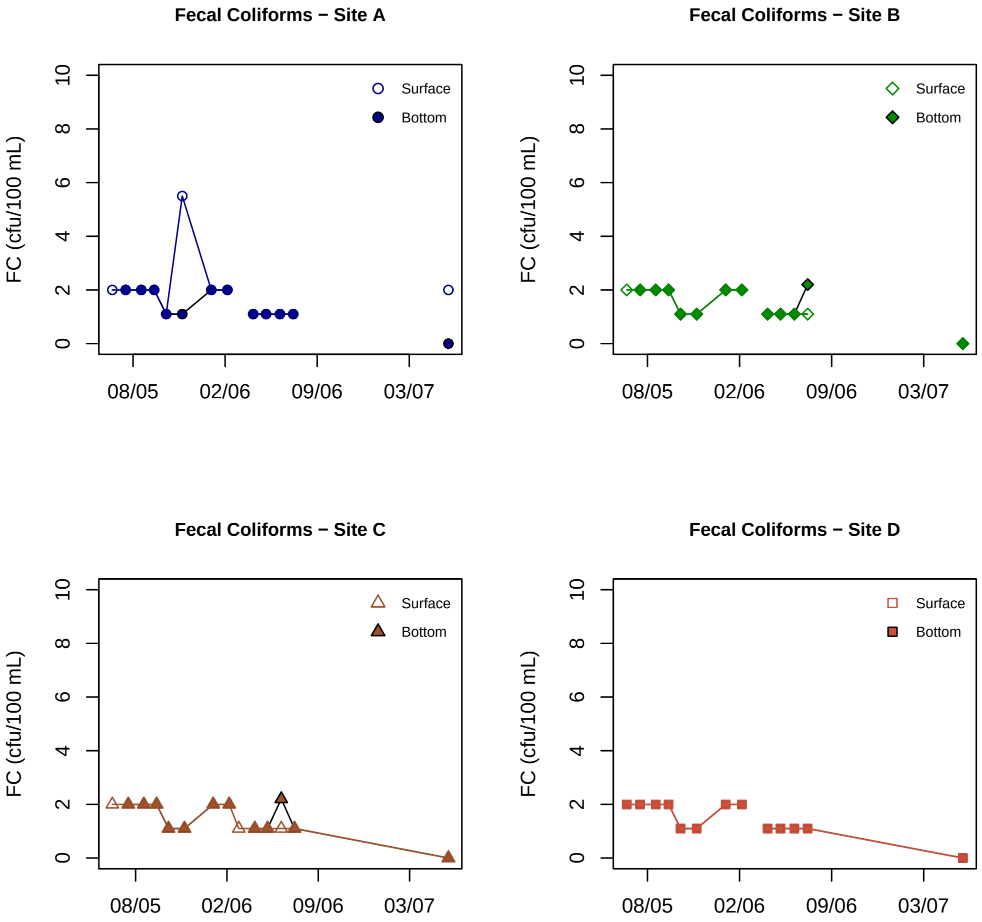


Figure 46: Lake Samish fecal coliform data, June 2005 through June 2007. Samples were collected at the surface and bottom for each site and analyzed by Edge Analytical.

# A Water Quality Data

Printed versions of this report include tables of the 2005-2007 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.