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Lake Samish Monitoring Project 2006 Final Report

Robin A. Matthews
Western Washington University, robin.matthews@wwu.edu

Joan Vandersypen
Western Washington University, joan.vandersypen@wwu.edu

Kara Hitchko
Western Washington

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Lake Samish Monitoring Project
2006 Final Report

Dr. Robin Matthews
Ms. Joan Vandersypen
Ms. Kara Hitchko

Institute for Watershed Studies
Huxley College of Environmental Studies
Western Washington University [*]

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1 Introduction

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 monthly water quality data from the lake and twice-annual data 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 monthly from June 2005 through June 2006 at 4 sites in Lake Samish (Figure 1). 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. 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[1], ammonium), turbidity, and alkalinity. Separate surface and bottom water samples were collected to mea-

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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.

sure 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.

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.

Although not part of the monitoring contract, plankton samples were collected at each site to identify major phytoplankton taxa in the lake. The samples were collected by passing the fluorometer discharge water through a 50 μm plankton net. The samples were split into preserved (Lugol's iodine) and unpreserved subsamples and examined to identify dominant taxa. Photographs of dominant taxa have been included in Appendix B.

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.

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 unstratified throughout the year (Figures 2–13).

Lake stratification occurs as 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.[2] The surface water eventually stratifies into 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.

As the lake surface cools in fall or winter, the density difference between the epilimnion and hypolimnion decreases. Eventually, the surface and bottom water densities are sufficiently similar that wind-generated internal waves[3] 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 2005/2006 data, the east arm of Lake Samish appears to stratify from about April or May through October at locations where the water column is at least 12–15 meters deep. In shallower areas (Site D), the water is too shallow to maintain a stable stratification.

The west arm (Site A) presented a more complex picture. Similar to Sites B–C in the east arm, Site A was stratified during the summers of 2005 and 2006. By the end of November, however, the east arm sites had mixed but Site A was still stratified (Figure 7). There was still a slight thermal gradient at Site A in January 2006 (Figure 8). By February, the water temperature was nearly uniform from surface to bottom (Figure 9). Normally, under these conditions, the entire

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

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

water column should mix and dissolved chemicals should be nearly uniform at all depths. The January and February dissolved oxygen profiles indicated that water circulation at Site A was minimal, and low oxygen conditions persisted in the hypolimnion throughout the winter. By April, increasing solar radiation caused the lake surface to heat, rebuilding the lake's thermal stratification for the summer (Figure 11). This unusual pattern is called *intermittent meromixis*, and in the case of the west arm, is probably due to the relative isolation and protection of that portion of the lake from prevailing winds, coupled with a small surface area and a deep, steep-sided basin (Hakala, 2004). The uniform water temperatures during February should have resulted in little, if any, density difference between the surface and bottom waters. The oxygen gradient was probably maintained because bacterial decomposition removed oxygen faster that it could be restored by the lake's slow water circulation rate.

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 2–13). Epilimnetic oxygen concentrations were high during periods of stratification, and oxygen concentrations were high throughout the water column following lake turnover. Only Site A, which did not appear to destratify, 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.

As mentioned previously, the February dissolved oxygen data from Site A (Figure 9) revealed that this portion of the lake did not completely destratify during the winter of 2006. It is not clear whether this is a common occurrence in Lake Samish. The only other seasonal water quality data available for Lake Samish were collected during the summer of 1993 and spring through fall of 1994 by C. McNair (1995) as part of her M.S. thesis.[4] Although McNair sampled the west arm of Lake Samish, she confined her sampling to the upper 20 meters, and did not collect dissolved oxygen profiles during the period when the site might have been unstratified. Lakes that are intermittently meromictic due to morphology often have sheltered, deep basins, with small surface areas, and often have constricted outlets (Hakala, 2004). These conditions all apply to the west arm of Lake Samish, so it is quite likely that the lake will destratify under the right combination of wind direction, wind speed, and water temperature. Resolving this question would require a detailed analysis of sediment cores or long term lake monitoring.

In addition to 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. 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.

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[4] There have been several student projects that involved collecting water quality data from Lake Samish, but none meet the quality control requirements for inclusion in this report.

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 14–16). Alkalinity concentrations were fairly low ($<$30 mg/L) throughout the sampling period (Figure 14). 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 than the bottom (Figure 15). 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 Lake Samish pH data showed the influence of photosynthesis and bacterial decomposition. During summer stratification, the epilimnetic 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 is particularly well-illustrated in Figure 13, where the pH profiles decreased sharply in the hypolimnion, and were highest at 5–10 meters, corresponding with peak epilimnetic chlorophyll densities. Similar patterns were apparent in the laboratory data (Figure 14). When the water column was stratified, the surface pH was higher than the bottom (Sites A–C).

The conductivity patterns in lakes are complicated. The dissolved ions that affect conductivity are derived from many compounds, not just the compounds affecting pH and alkalinity. 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 tributary data (Table 3), the conductivity of water entering the lake was about 60–100 μS/cm during November 2005 (high flow) and about 100–150 μS/cm during July 2005 (low flow). The lake's conductivities were about 60–80 μS/cm , which was similar to the November tributary concentrations. The slightly elevated surface conductivities measured in January (Site D) and February (Sites A and B) may have been caused by dissolved compounds in storm runoff

Lake Samish conductivities were also influenced by lake stratification, which, coupled with low oxygen conditions at Sites A–C, caused dissolved ions to leak into the hypolimnion from the sediments. As a result, Sites A–C had higher conductivities in bottom samples during the period of stratification. For Site A, this included nearly all of the sampling dates. For Sites B–C, stratification ended by November; Site D remained unstratified on all dates.

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 17–21). 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 + 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 of 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 considerably, 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. This is because total nitrogen concentrations, which include both organic and inorganic forms of nitrogen, are usually dominated by nitrate. There was a progressive reduction of nitrate/nitrite and total nitrogen throughout the summer of 2005, lasting until turnover. The nitrogen depletion was more pronounced in the surface samples at Sites A–C because algal growth was higher in the epilimnion and also because these sites were stratified. Site D, which remained unstratified, showed little difference between surface and bottom nitrogen concentrations. During the winter the nitrogen concentrations increased to their seasonal maximum at Sites B–D, only to begin a second decline during the summer of 2006. Site A remained stratified all winter, so although the surface samples gained nitrogen during the winter, the bottom samples did not.

Only the bottom samples at the stratified sites contained significant amounts of ammonium because ammonium is not stable in oxygenated water. The bottom samples from Site A had very high ammonium concentrations during most of the sampling period, including January–March, 2006, when Sites B–C were no longer stratified. The Site A ammonium concentrations dropped abruptly in April and May 2006, concurrent with an increase in nitrate/nitrite and total nitrogen. It is not clear what caused these changes, but the intermittent meromixis at this site may have been a factor.

The Lake Samish orthophosphate and total phosphorus concentrations were lower in most of the surface samples at the stratified sites (Figures 20 and 21). This was most likely caused by algal uptake in the epilimnion, along with phosphorus released from the sediments into the hypolimnion. In addition, the bottom samples might include phosphorus associated with dead algae and other organic matter that settled to the lower portion of the water column.

The orthophosphate data at Sites B–C showed typical patterns associated with phosphorus release from sediments (Figure 21). As mentioned earlier, much of the phosphorus entering lakes is bound to the surface of small particles. Under oxygenated conditions, phosphorus will remain attached to the particle surface, but when oxygen concentrations fall below $\sim$2 mg/L, physical and chemical changes occur that release phosphorus in soluble (bioavailable) forms. In Lake Samish, when the oxygen concentrations at the bottom of the lake were high, orthophosphate concentrations were low, and surface and bottom concentrations were similar. After stratification, it took several months for the oxygen levels at the bottom of the lake to drop, so only the June–September 2005 data showed hypolimnetic release of orthophosphate. Site A also appeared to have phosphorus released from the sediments between June and October 2005, but the 2006 data were difficult to interpret and may reflect the effects of meromixis. The orthophosphate concentrations differences at Site D were probably not significant because the values were very close to the minimum detection limit (dl = 3 μg PO_4-P/L).

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 22). The turbidity levels were low in the surface samples ($\leq$ 1.1 NTU), and more variable in the bottom samples (0.4–15.2 NTU), but there were no obvious seasonal patterns related to algal density (Figure 23). Correlation analysis[5] confirmed that while turbidity and Secchi depth were strongly correlated, chlorophyll was only weakly correlated with turbidity and not significantly correlated with Secchi depth (Figure 24).

Chlorophyll: Chlorophyll concentrations were measured using two techniques: algal *in situ* 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. The resulting fluorescence profile reveals variations in algal densities from the surface to the bottom of the lake. Measuring chlorophyll biomass is more time consuming and is rarely done at more than a few sites or depths.

Chlorophyll fluorescence and biomass are related, but not identical, and many factors influence their relationship. Chlorophyll biomass is more widely used for lake monitoring, so we collected paired fluorescence and biomass data to determine whether there was a linear relationship between biomass based on fluorescence (Figure 25). The linear model was highly significant, with only a small bias in early spring (April-May) when chlorophyll biomass was consistently low relative to fluorescence. Based on these results, we could estimate chlorophyll biomass with a high degree of confidence.

The chlorophyll concentrations in Lake Samish followed seasonal patterns. The highest concentrations were measured from August through October and the lowest concentrations were measured from November through February (Figures 26–28). In addition, there were obvious differences between sites. The highest chlorophyll concentrations were measured at Sites C and D, both of which are located in the east arm and are all relatively shallow.

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[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. Pearson's r correlation analysis can also be used, but this test assumes that the correlations will be monotonic and linear, which was not true for most of the data.

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 concentrations, Secchi depth, or total phosphorus concentrations:

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

where:

CHL = chlorophyll concentration in μg/L
SD = Secchi depth in meters, and
TP = total phosphorus in μg-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, where 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 29 and Table 2). The TSIs were higher during late summer and early fall (July through October), which corresponded to peak chlorophyll and algal densities in the lake (Figure 30). Sites A and B had the lowest summer TSIs, with medians of 40.0 and 45.2, respectively. Sites C and D had median summer TSIs of 60.3 and 63.6, respectively, which placed these sites in the eutrophic category. Lakes in this category 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. Appendix B includes photographs of the major phytoplankton taxa found in Lake Samish.

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 colonies/100 mL and none of the counts exceeded 10 cfu/100 mL[6], 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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[6] 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 18), 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.[7] 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 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 outlet due to algal uptake of phosphorus in Lake Samish. The phosphorus concentrations were fairly high compared to surface samples from Lake Samish (Figures 21–20) 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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[7] 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.[8] 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 26–28). 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 appeared to be intermittently meromictic, which resulted in prolonged anoxia in the hypolimnion (Figures 10–13 and 14–16) and high levels of phosphorus release from the sediments (Figures 20–21). 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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[8] 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 Daily Maximum 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

APHA. 1998. Standard Methods for the Examination of Water and Wastewater, 20th Edition. American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, DC.

Carlson, R E. and J. Simpson. 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society. 96 pp.

DeLuna, E. 2004. Microbial patterns in the metalimnion of Lake Whatcom, Washington. M. S. thesis, Huxley College of Environmental Studies, Western Washington University, Bellingham, WA.

Bortleson, G. C., N. P. Dion, J. B. McConnell, and L. M. Nelson. 1976. Reconnaissance Data on Lakes in Washington, Volume 1, Clallam, Island, Jefferson, San Juan, Skagit, and Whatcom Counties. Water-Supply Bull. 43(1), Washington State Department of Ecology, Tacoma, WA.

Hakala, A. 2004. Meromixis as a part of lake evolution – observations and a revised classification of true meromictic lakes in Finland. Boreal Environment Research 9: 37–53.

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

McNair, C. 1995. Dynamic Deep Chlorophyll Maxima and their Association with Environmental Gradients: A Multivariate Analysis. M. S. Thesis, Western Washington University, Bellingham, WA.

Wetzel, R. G. 1983. Limnology, Second Edition. Saunders College Publishing, New York, NY.

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 μg/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 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	±0.1 units
Phosphorus - orthophosphate	OP	SM4500-P G., flow inject	3 μg PO_4-P/L
Phosphorus - total	TN	SM4500-P G., flow inject, persulfate digest	5 μg 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.

Annual - June 2005 through June 2006				
	Min.	Median	Mean	Max.
Site A	20.6	38.6	38.0	54.5
Site B	31.1	43.2	42.5	62.4
Site C	26.5	44.5	45.9	67.0
Site D	32.3	43.3	45.9	67.4

Summer - July through October 2005				
	Min.	Median	Mean	Max.
Site A	24.7	40.0	40.5	52.6
Site B	35.3	45.2	45.2	62.4
Site C	42.1	60.3	55.8	67.0
Site D	42.3	63.6	56.5	67.4

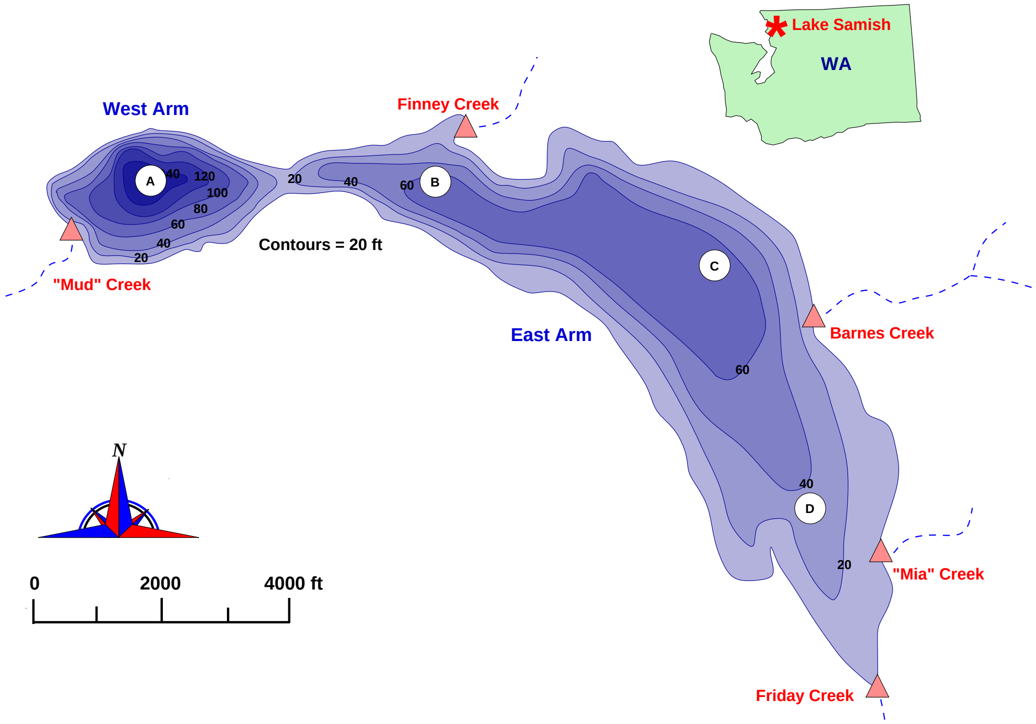
Table 2: Carlson’s Trophic State Index - TSI(CHL) results for Lake Samish.

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	$0.53\ \text{km}^2$	680 acre	$2.75\ \text{km}^2$
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	$11.3 \times 10^6\ \text{m}^3$	21,080 acre-ft	$26.0 \times 10^6\ \text{m}^3$
Drainage area	3.70 sq mi	$9.58\ \text{km}^2$	9.20 sq mi	$215.5\ \text{km}^2$
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.

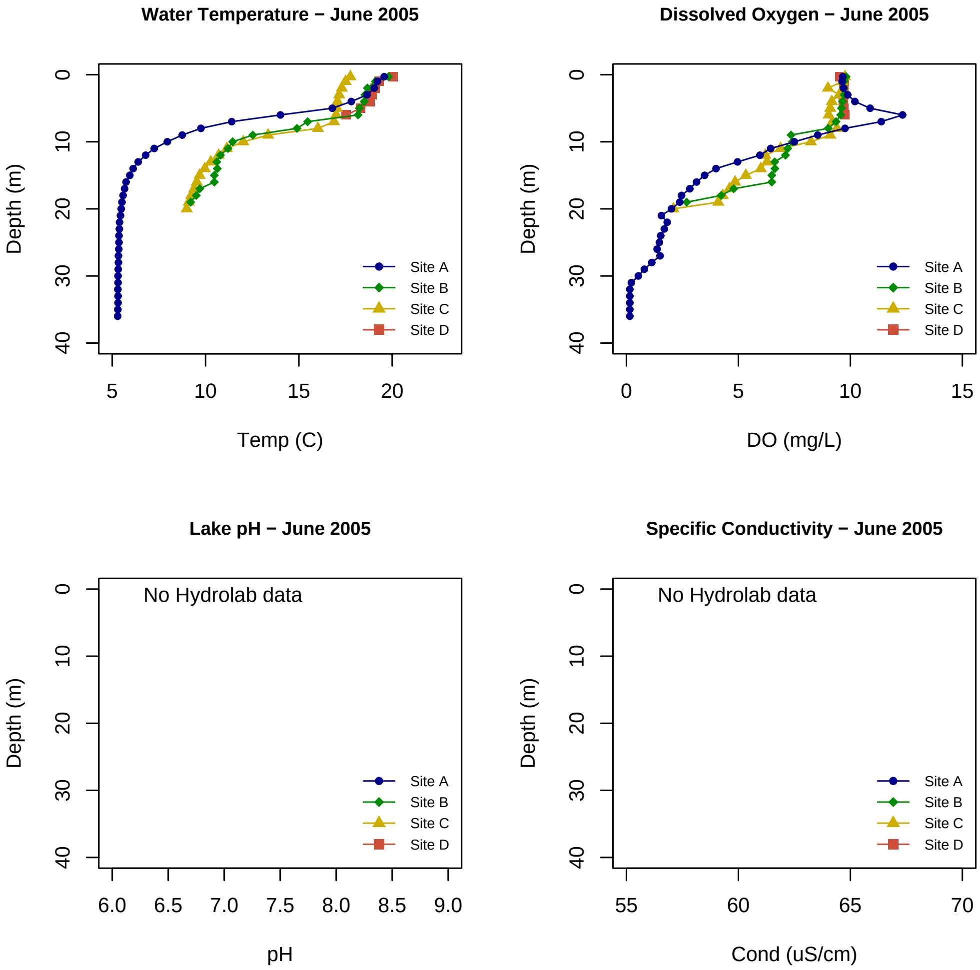


Figure 2: Lake Samish Hydrolab profiles for Sites A–D, June 21, 2005.

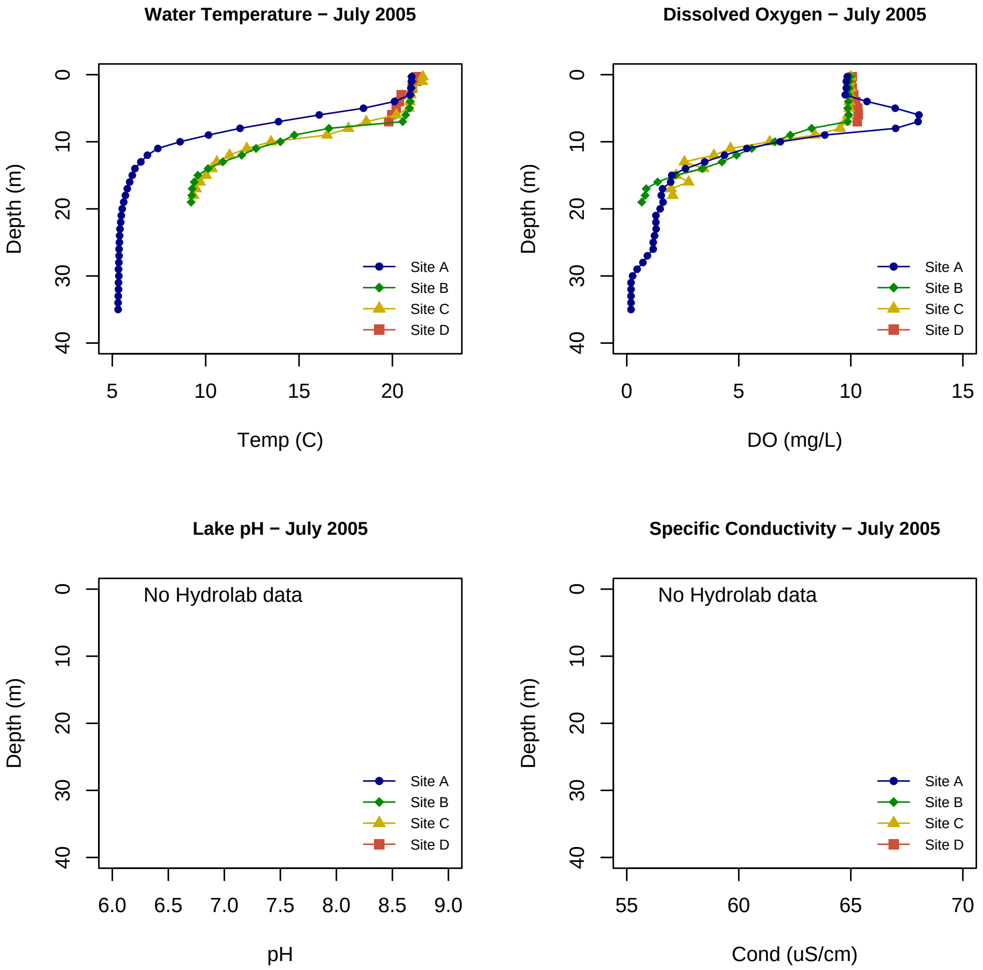


Figure 3: Lake Samish Hydrolab profiles for Sites A–D, July 20, 2005.

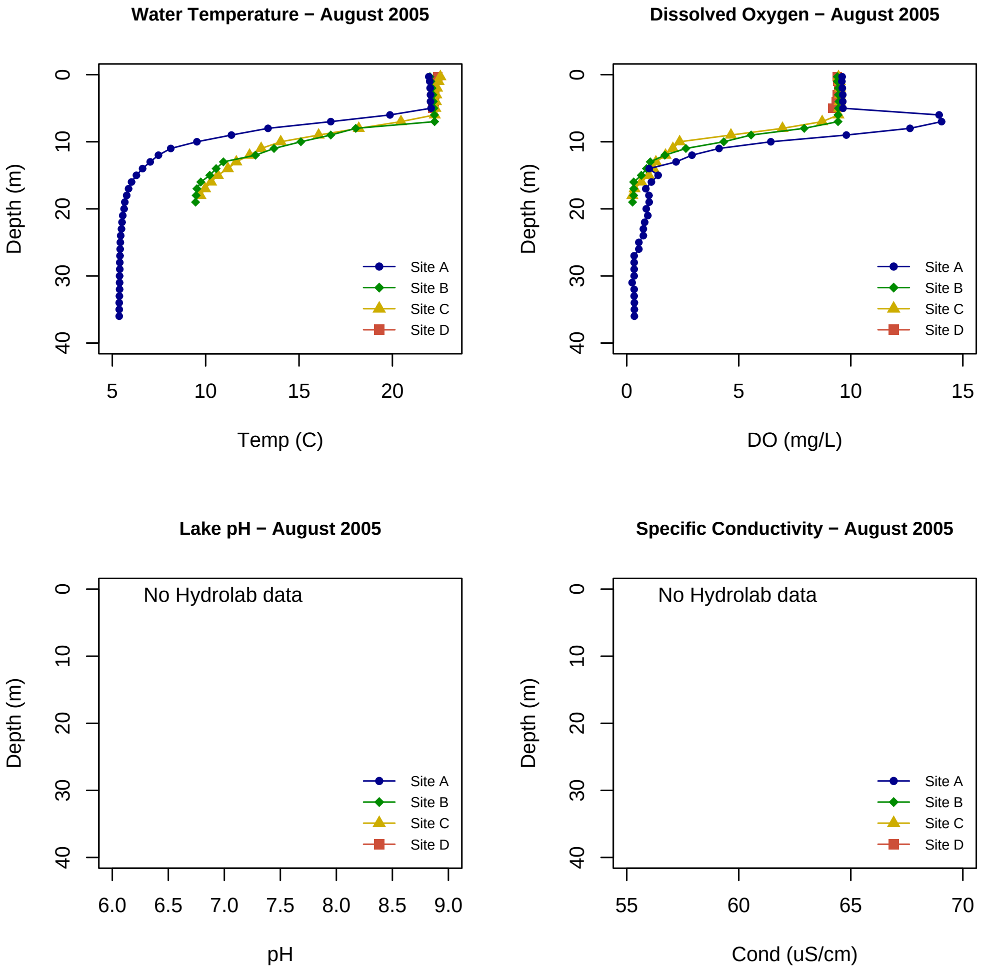


Figure 4: Lake Samish Hydrolab profiles for Sites A–D, August 23, 2005.

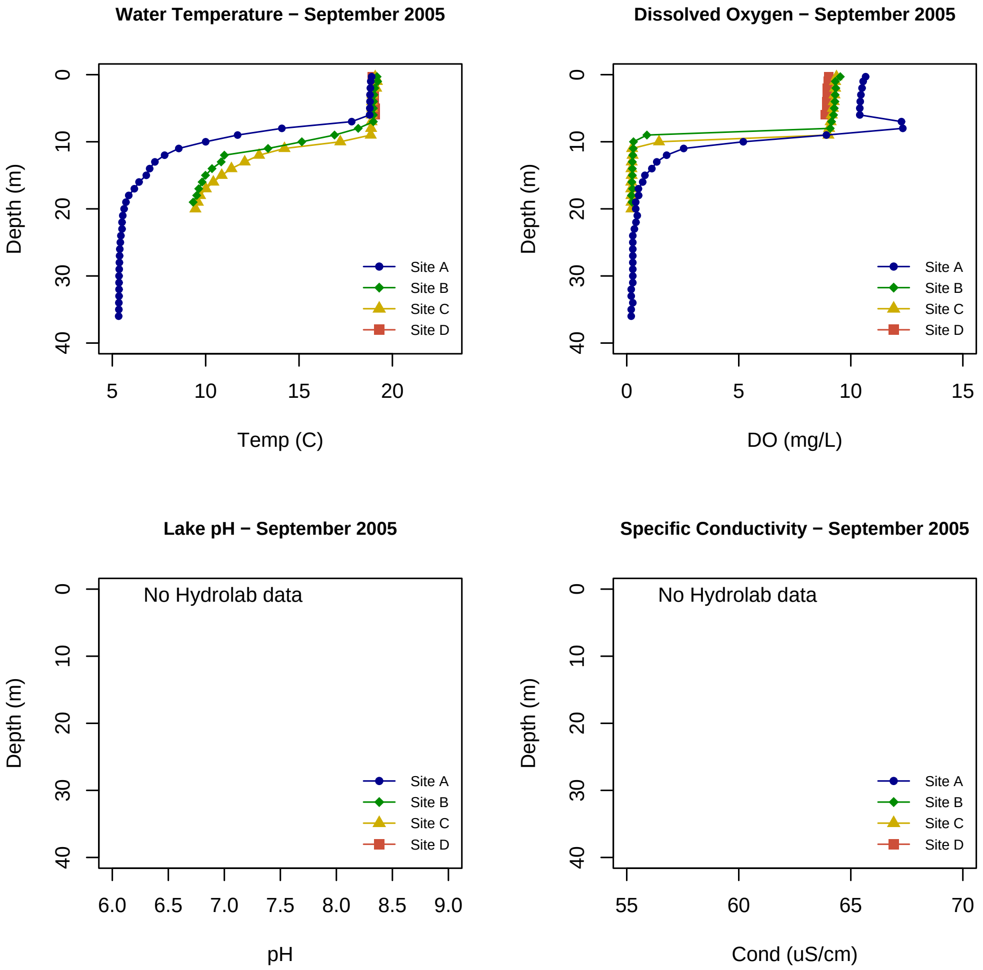


Figure 5: Lake Samish Hydrolab profiles for Sites A–D, September 20, 2005.

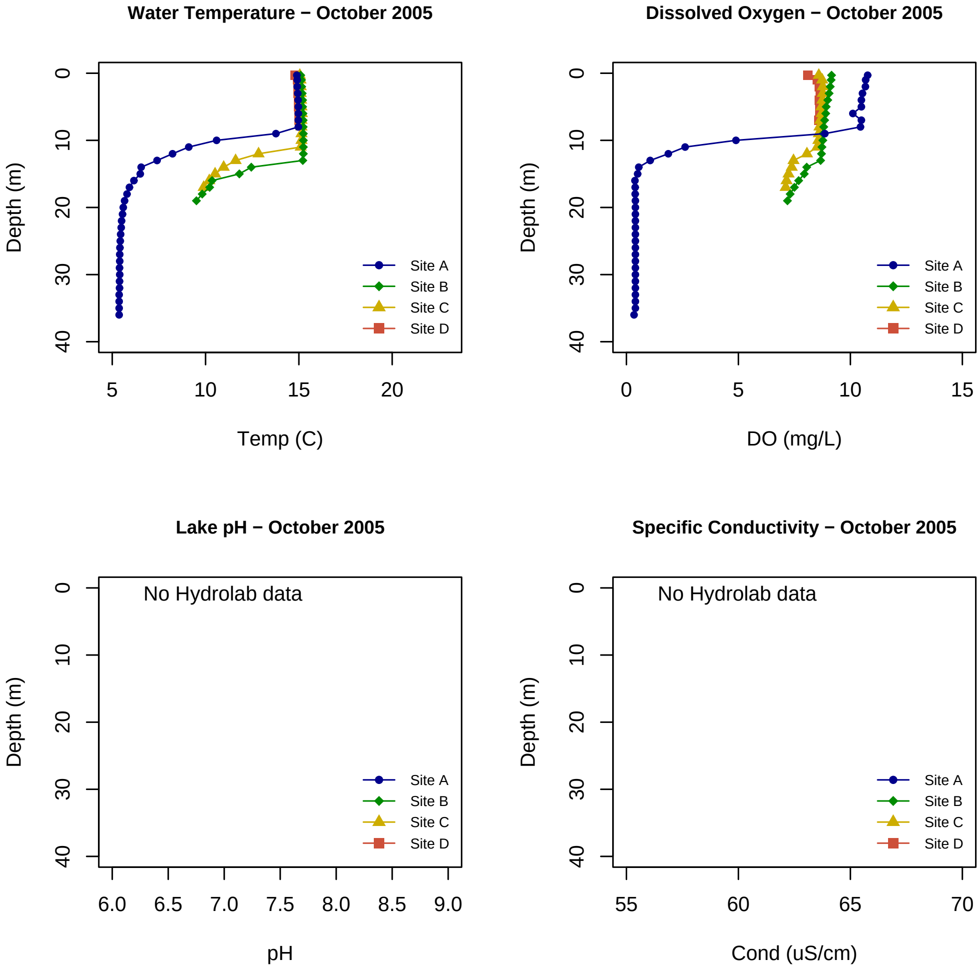


Figure 6: Lake Samish Hydrolab profiles for Sites A–D, October 16, 2005.

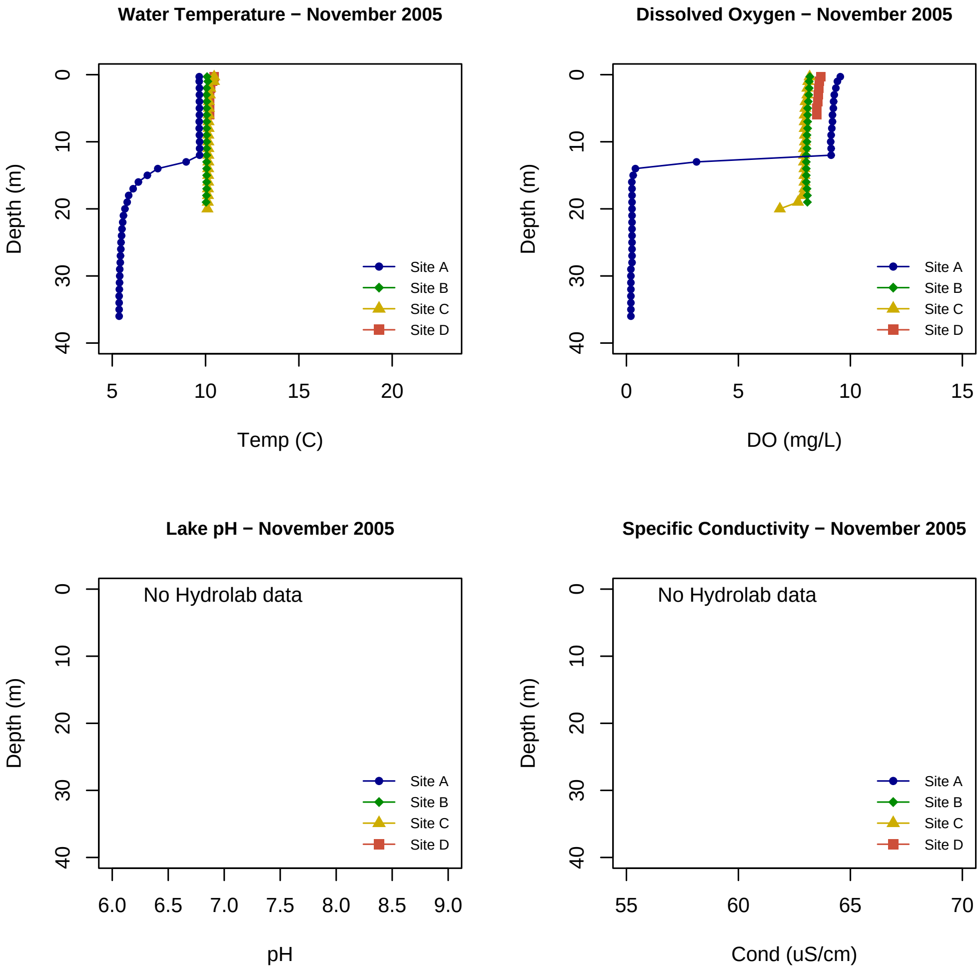


Figure 7: Lake Samish Hydrolab profiles for Sites A–D, November 20, 2005.

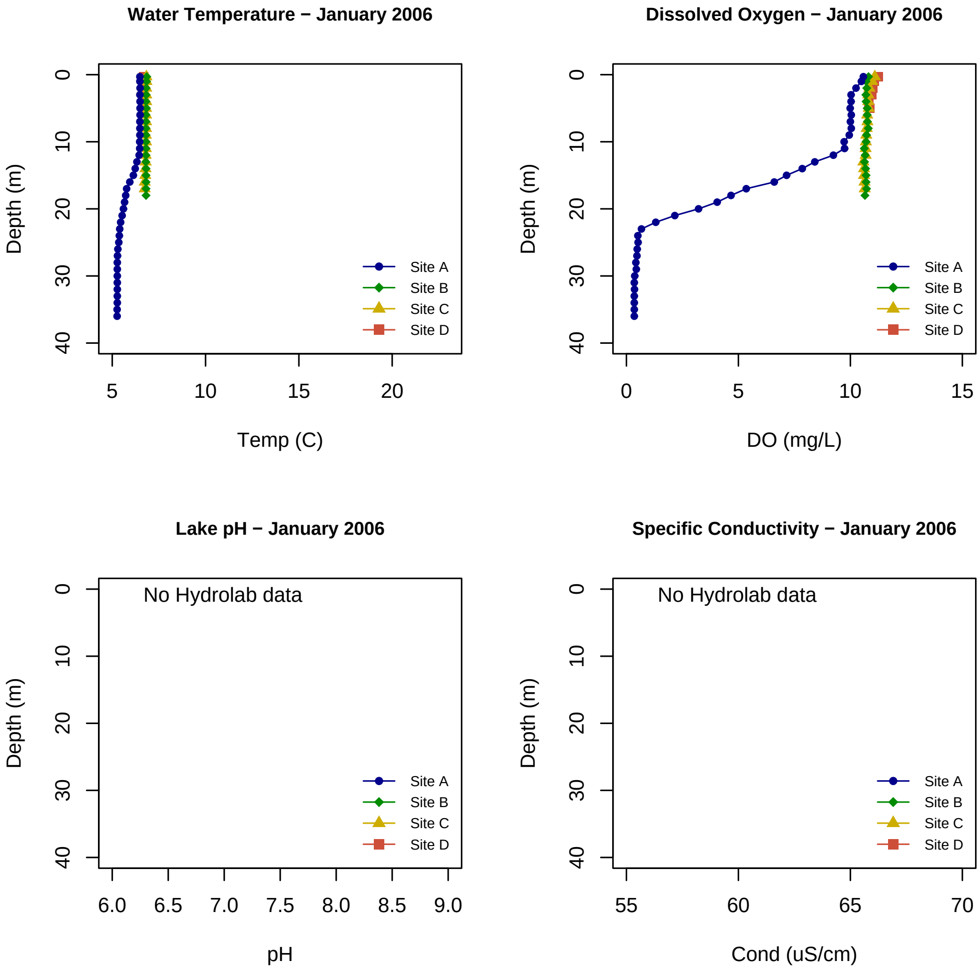


Figure 8: Lake Samish Hydrolab profiles for Sites A–D, January 22, 2006.

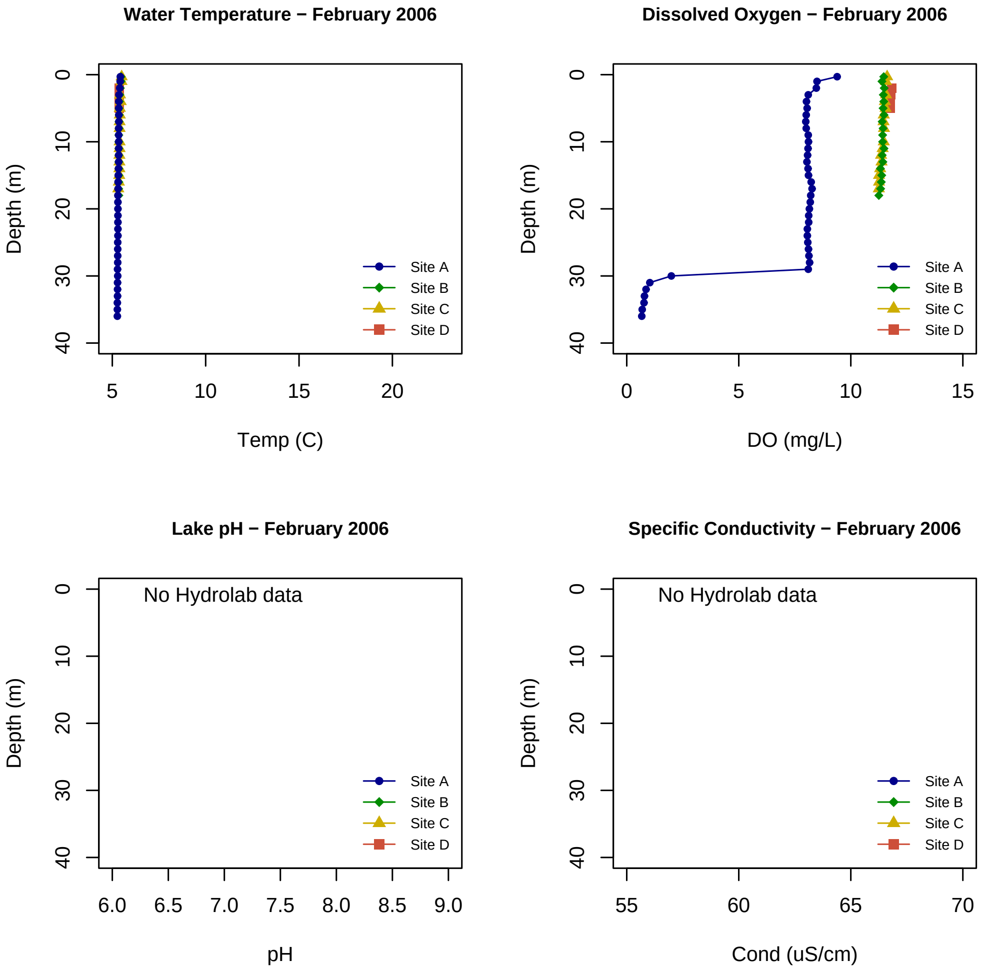


Figure 9: Lake Samish Hydrolab profiles for Sites A–D, February 26, 2006.

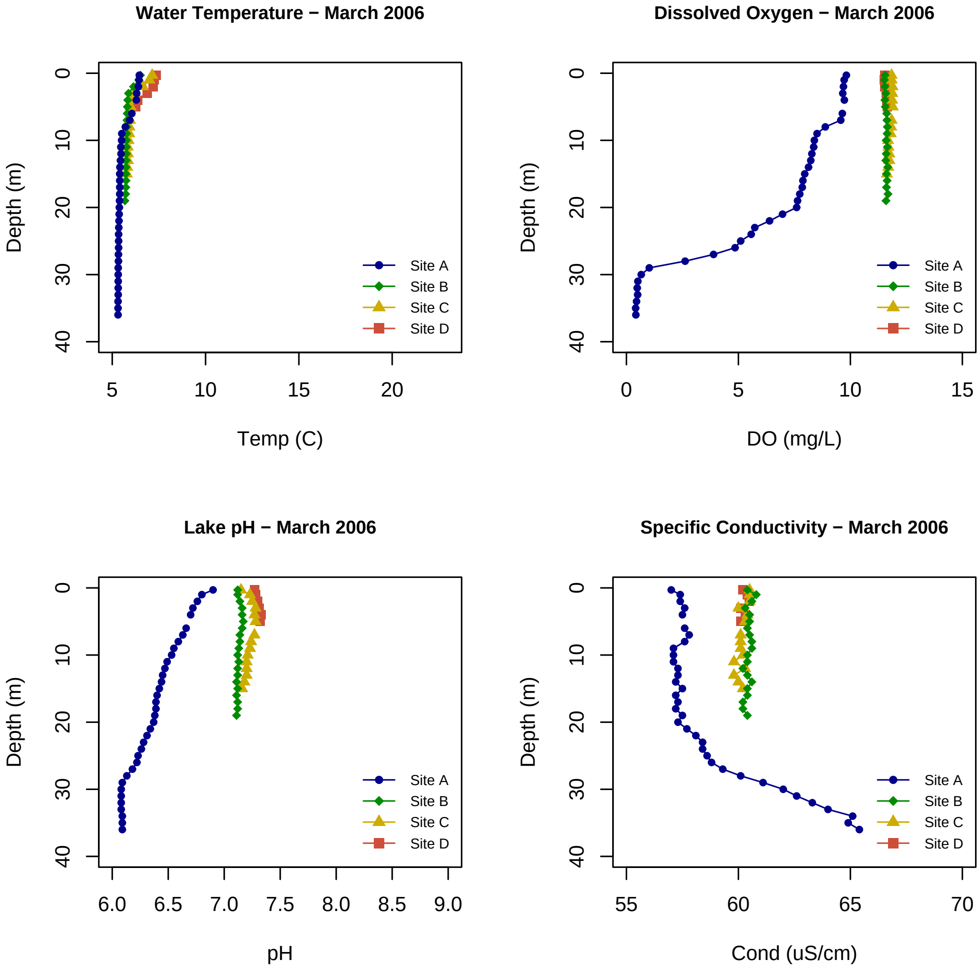


Figure 10: Lake Samish Hydrolab profiles for Sites A–D, March 19, 2006.

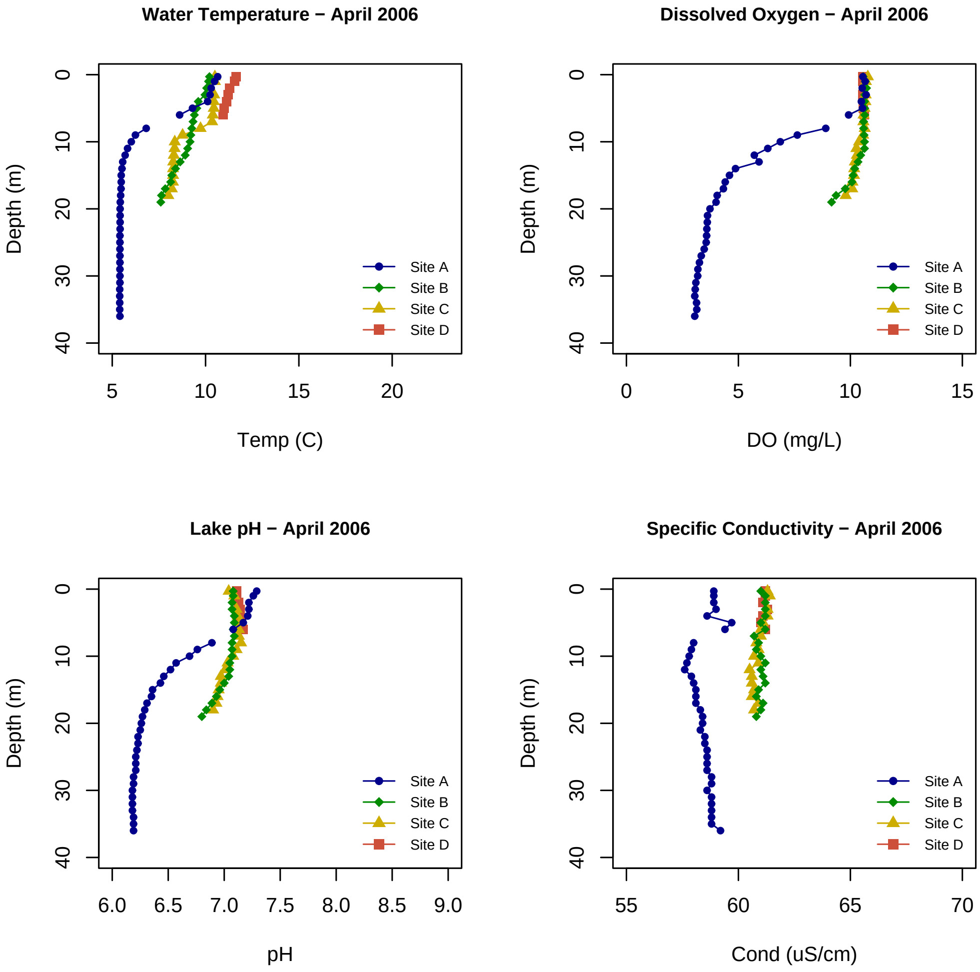


Figure 11: Lake Samish Hydrolab profiles for Sites A–D, April 23, 2006.

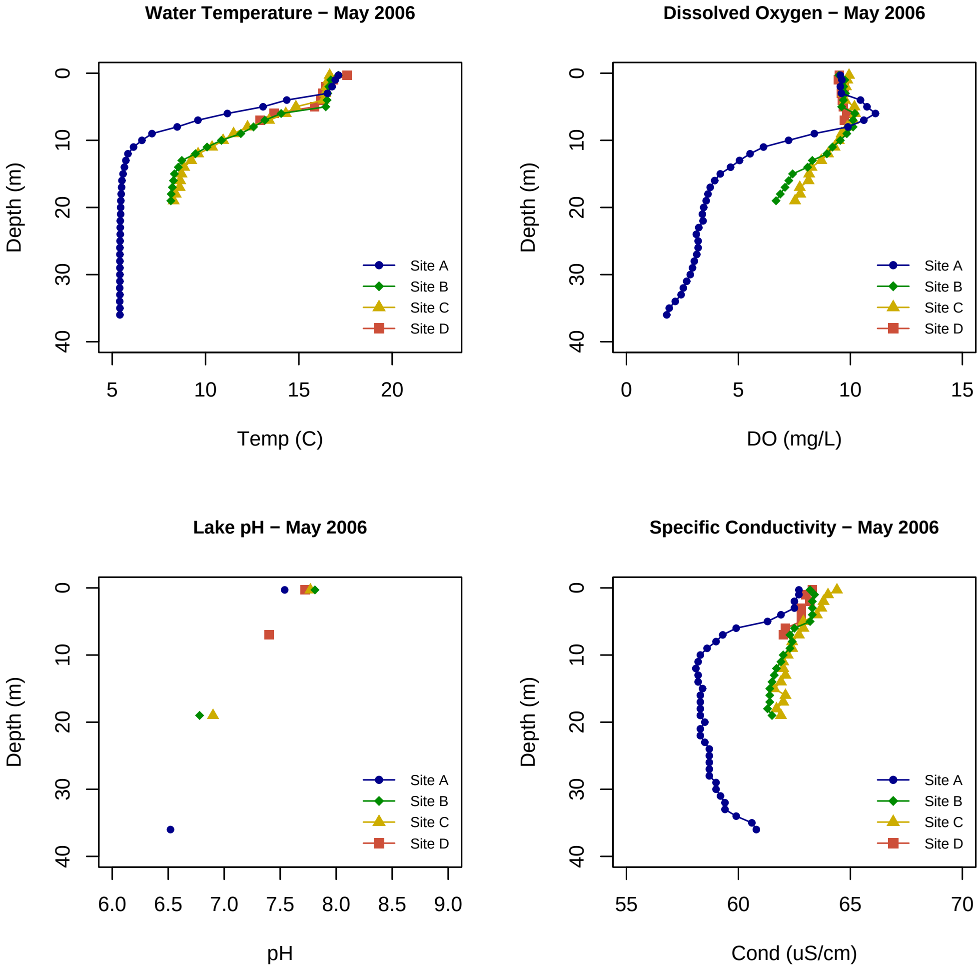


Figure 12: Lake Samish Hydrolab profiles for Sites A–D, May 21, 2006.

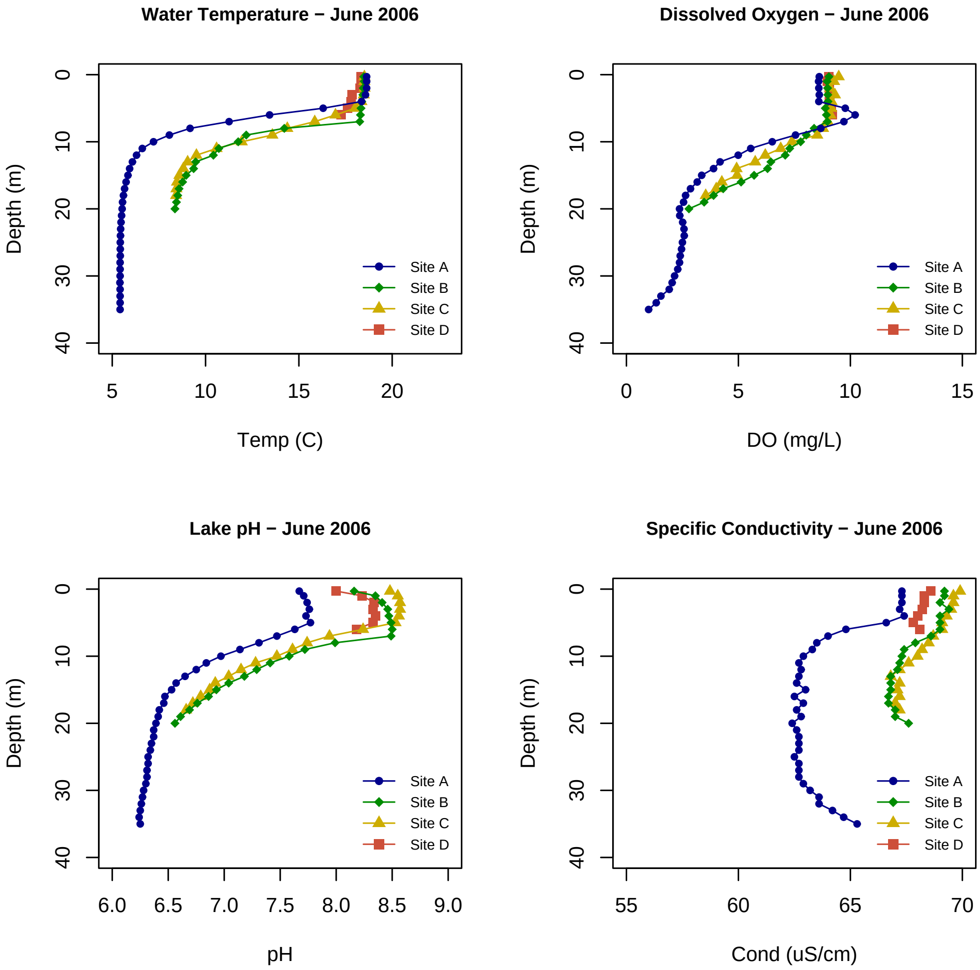


Figure 13: Lake Samish Hydrolab profiles for Sites A–D, June 20, 2006.

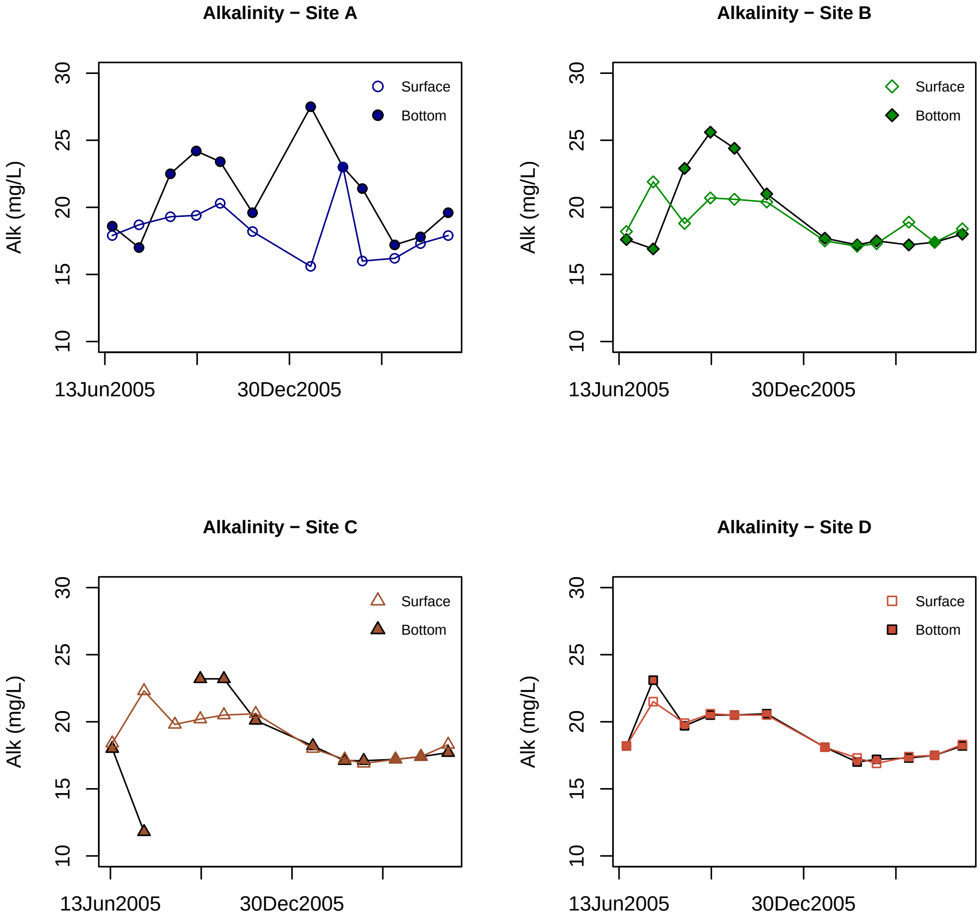


Figure 14: Lake Samish alkalinity data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site.

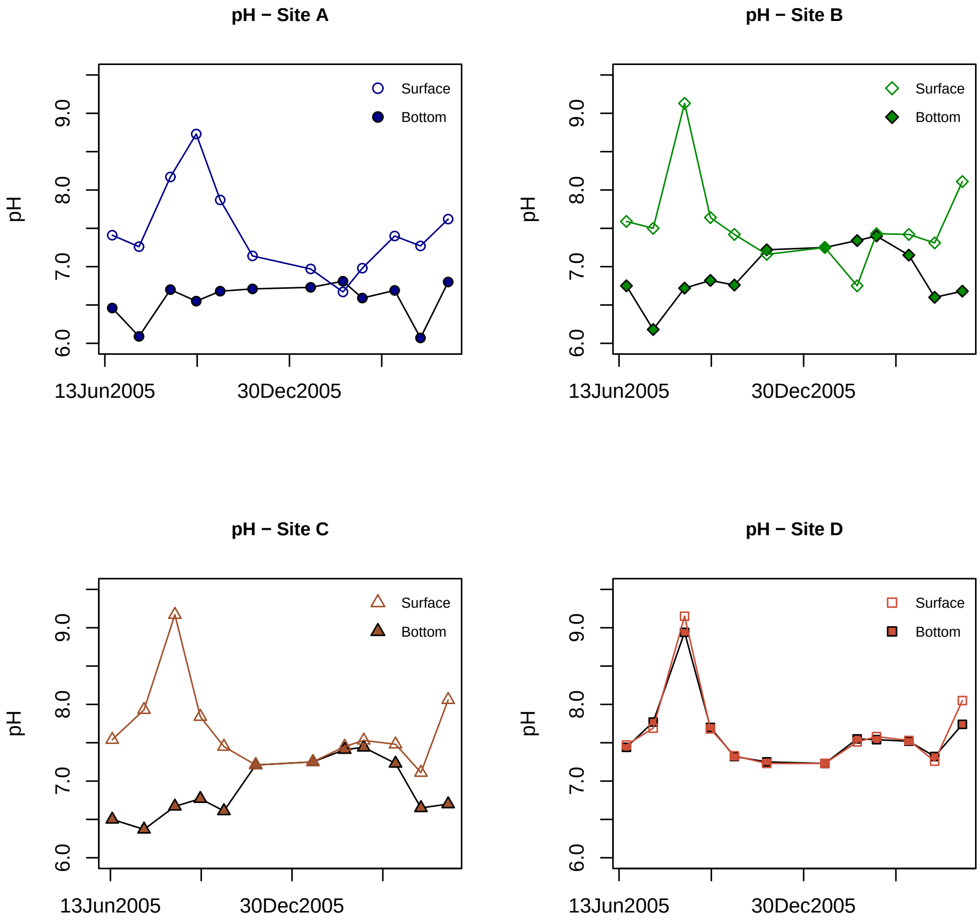


Figure 15: Lake Samish pH data (laboratory analysis), June 2005 through June 2006. Samples were collected at the surface and bottom for each site.

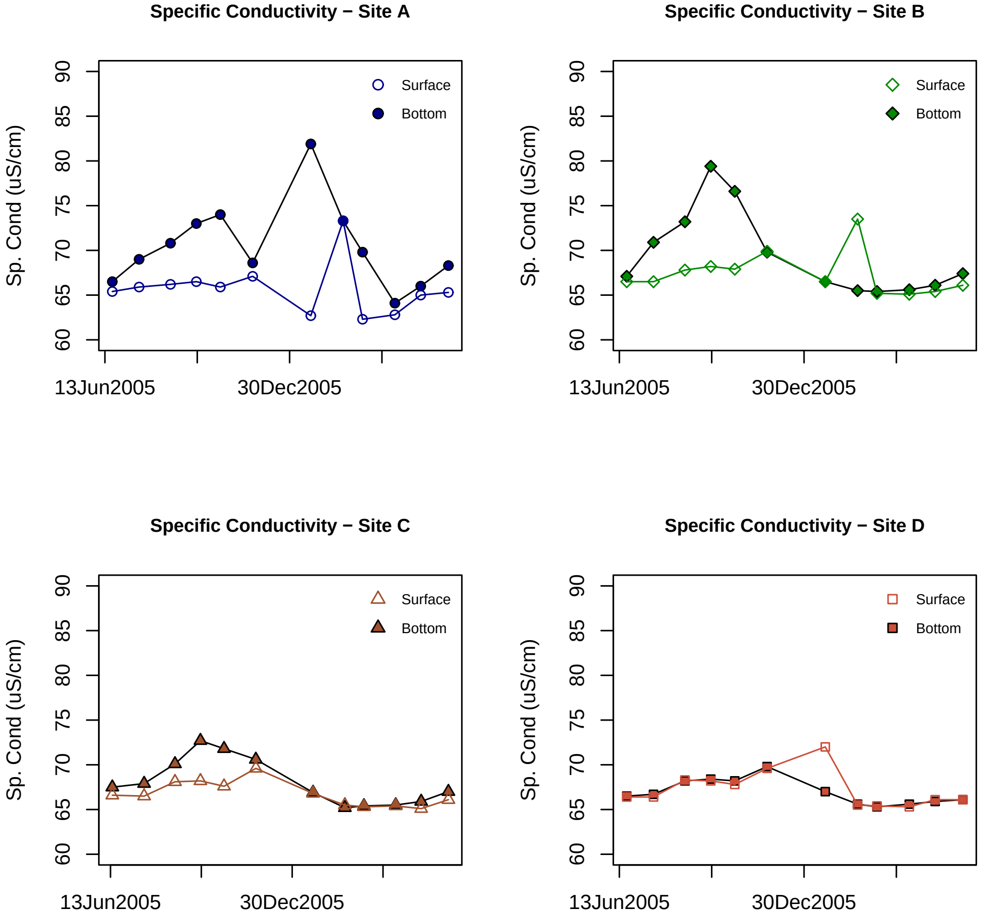
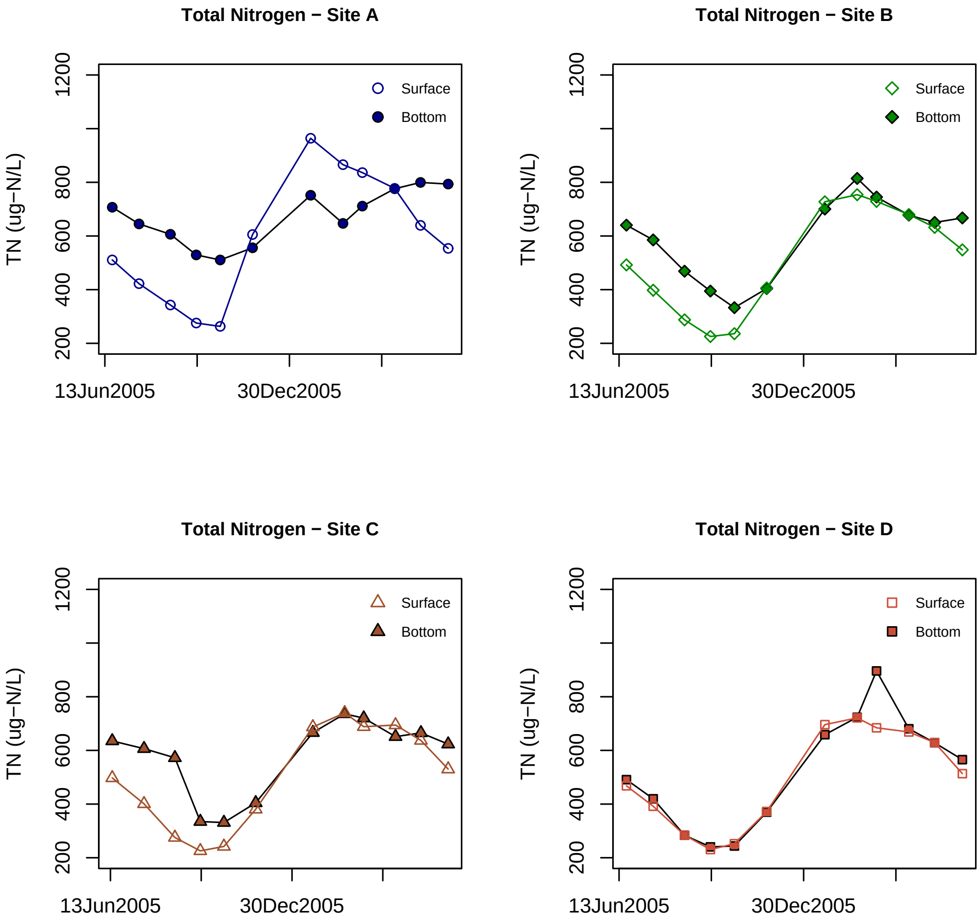


Figure 16: Lake Samish specific conductivity data (laboratory analysis), June 2005 through June 2006. Samples were collected at the surface and bottom for each site.


Total Nitrogen − Site A

Total Nitrogen − Site B

Total Nitrogen − Site C

Total Nitrogen − Site D

Figure 17: Lake Samish total nitrogen data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site.

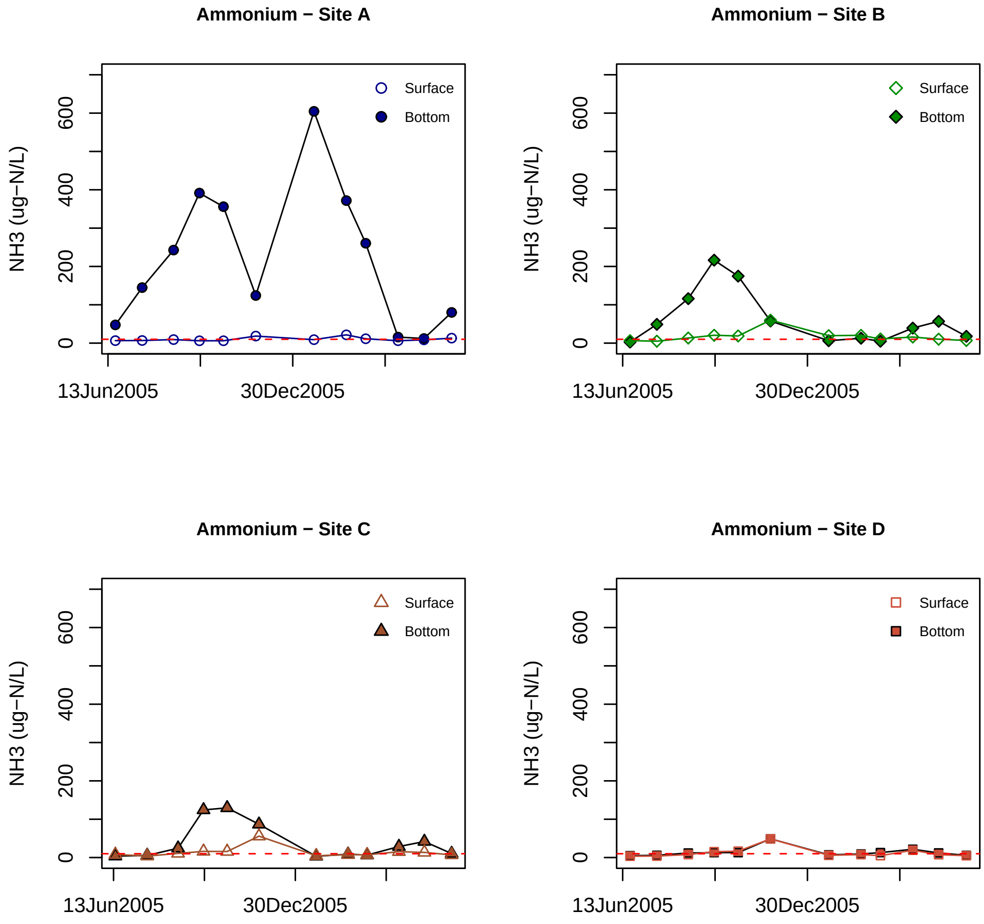
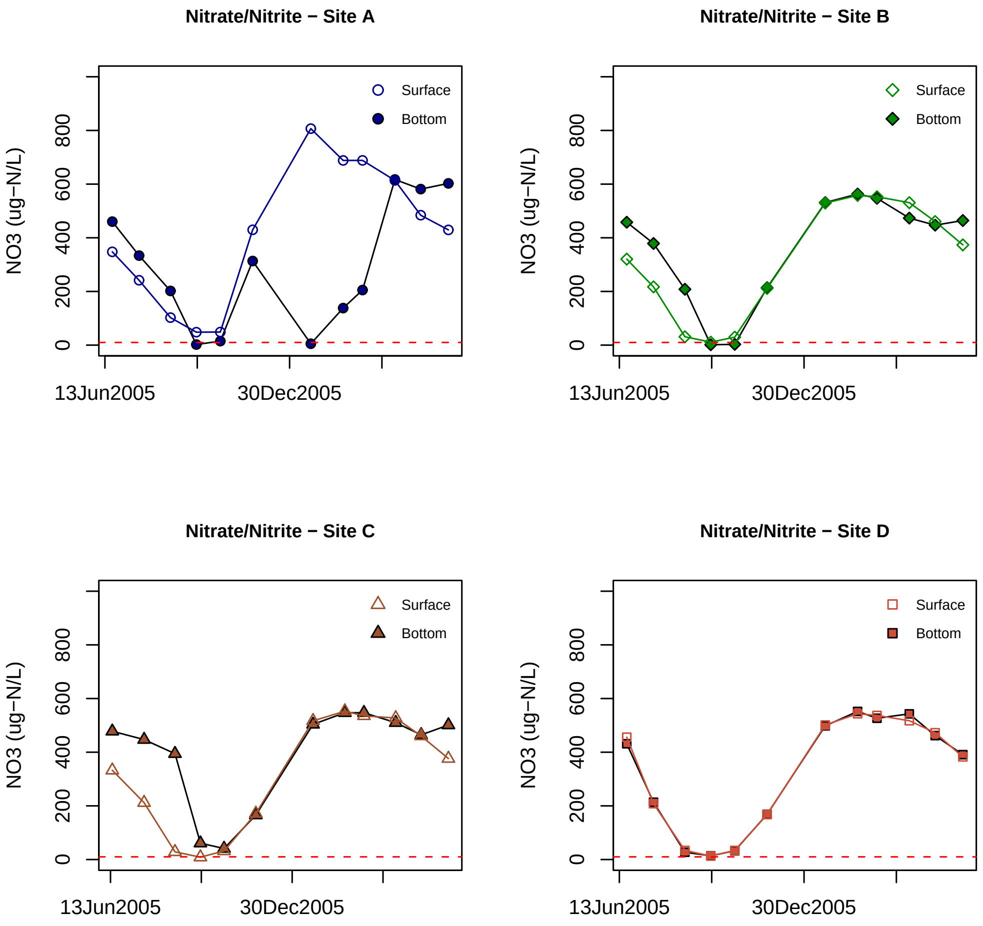


Figure 18: Lake Samish ammonium data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit.


Nitrate/Nitrite − Site A

Nitrate/Nitrite − Site B

Nitrate/Nitrite − Site C

Nitrate/Nitrite − Site D

Figure 19: Lake Samish nitrate/nitrite data, June 2005 through June 2006. 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.

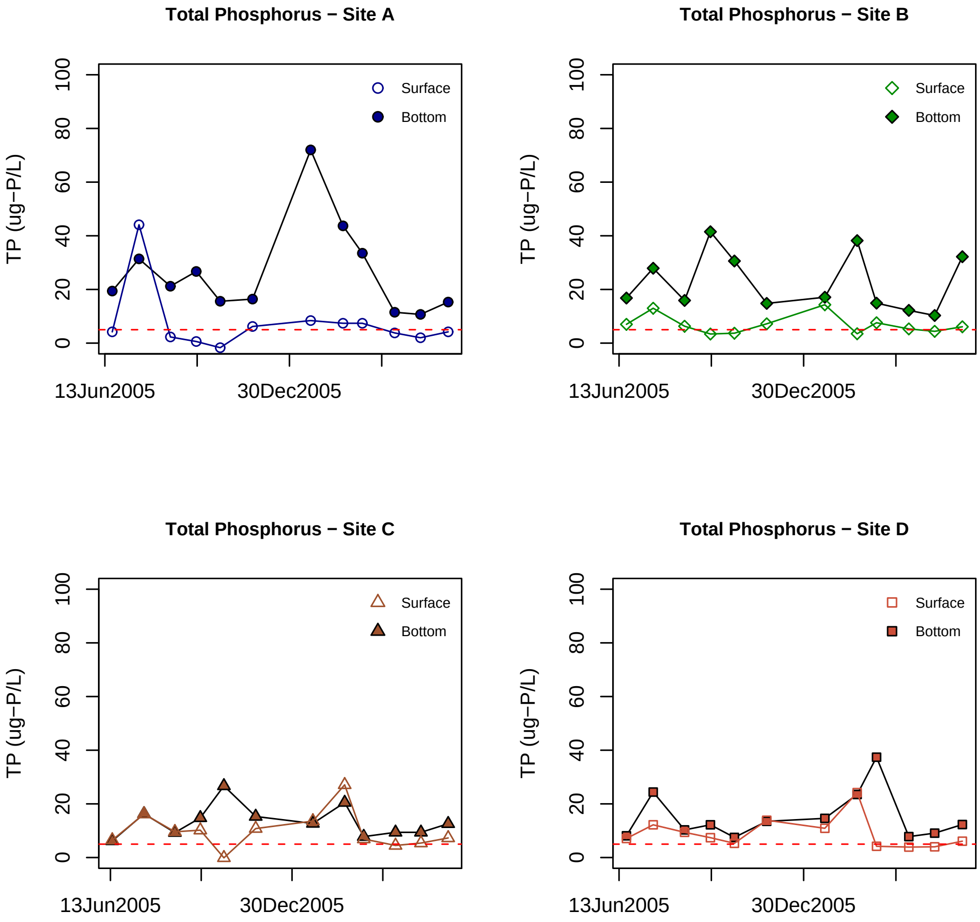


Figure 20: Lake Samish total phosphorus data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit.

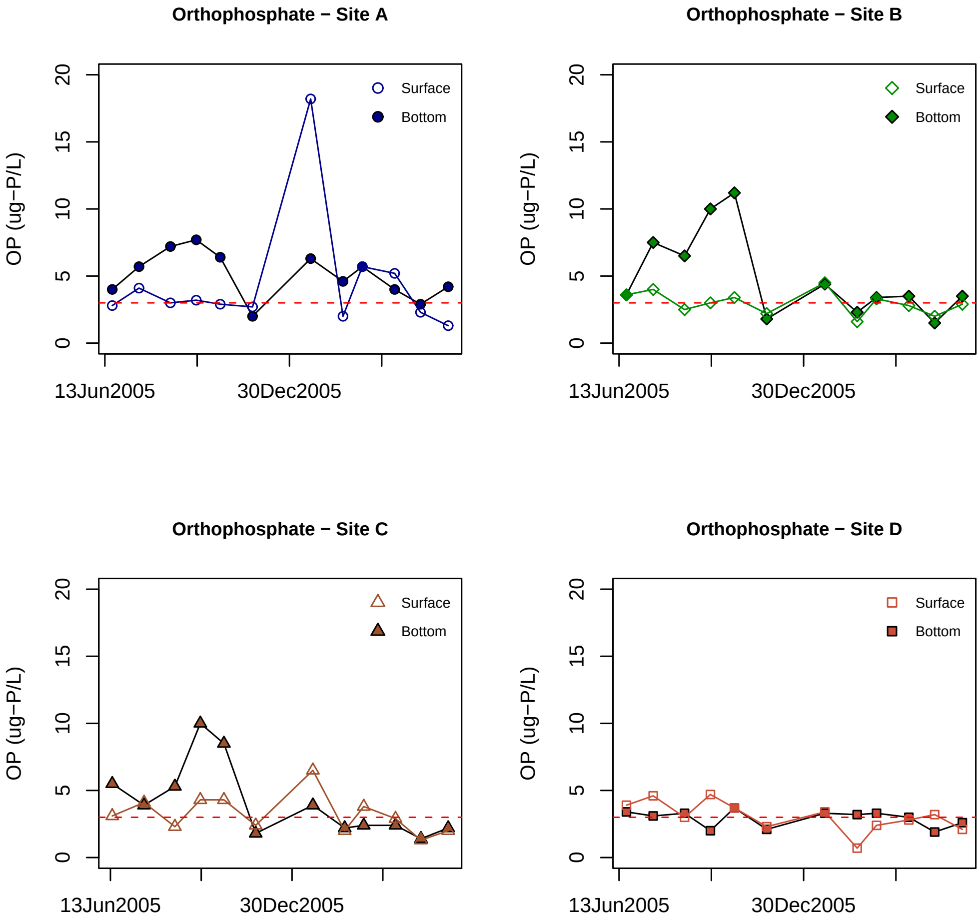


Figure 21: Lake Samish orthophosphate data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site. Data were not censored, and some values were below detection. Horizontal dashed reference line shows detection limit.

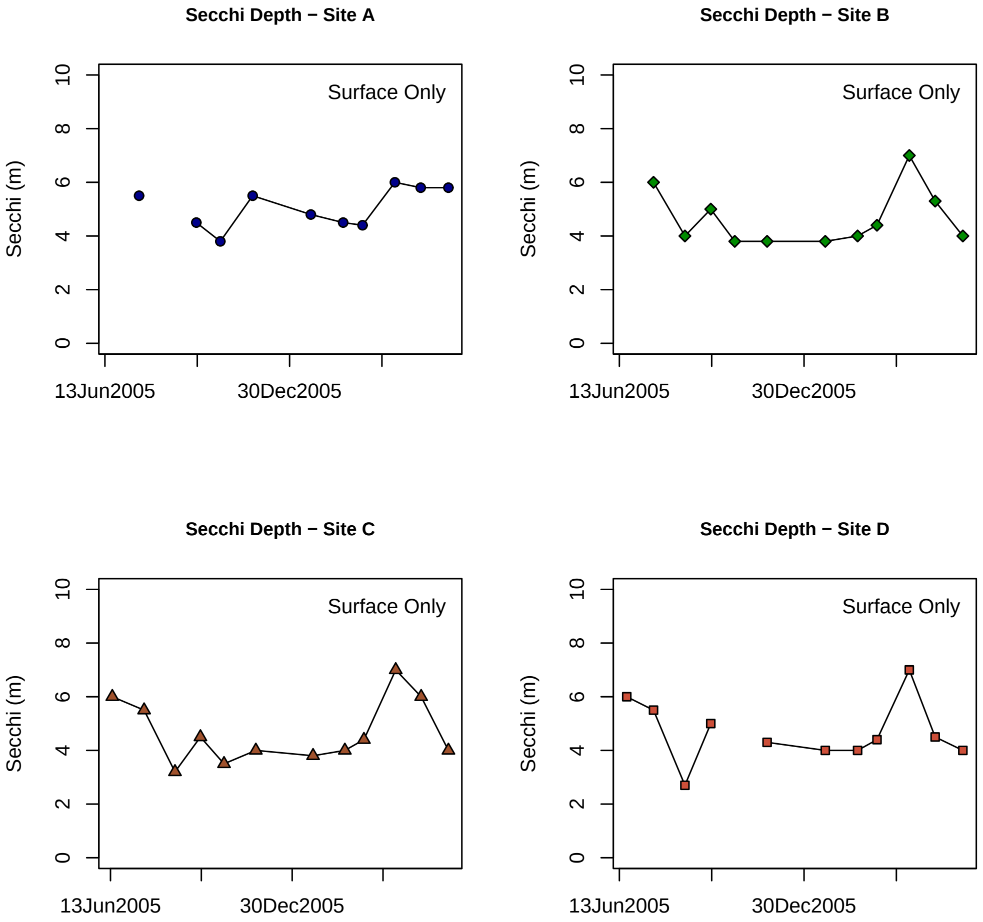


Figure 22: Lake Samish Secchi depth data, June 2005 through June 2006. Samples were collected at the surface for each site.

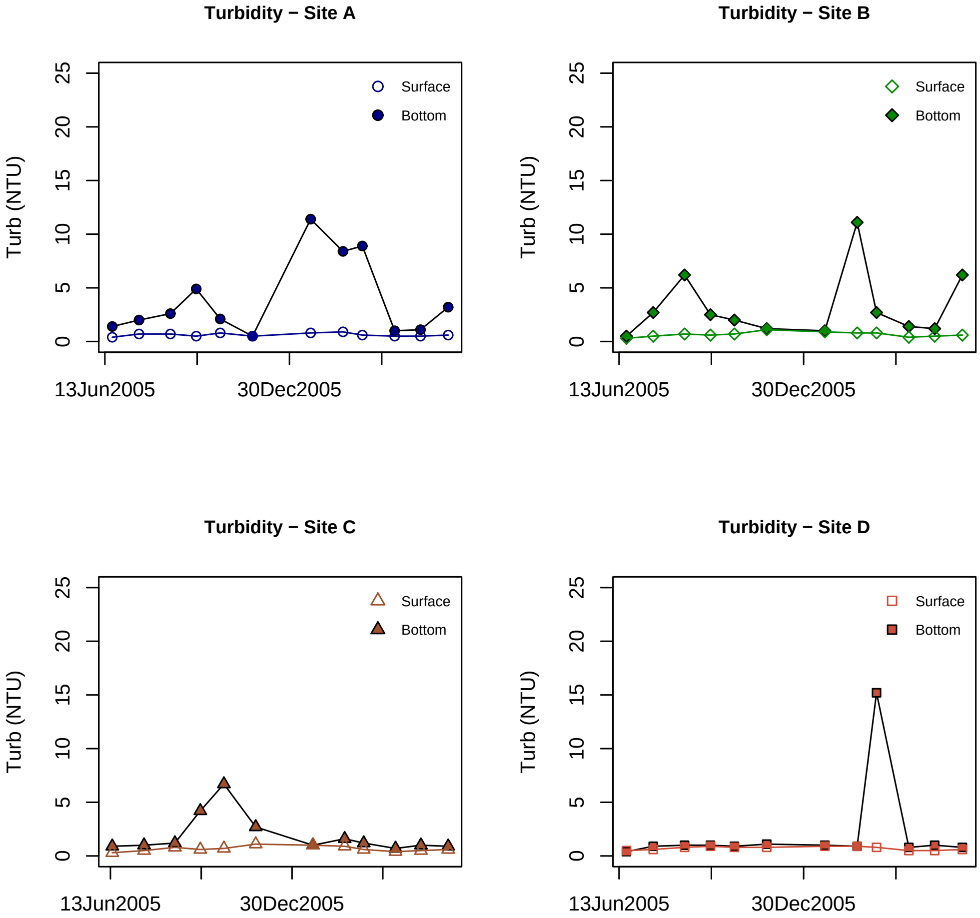


Figure 23: Lake Samish turbidity data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site.

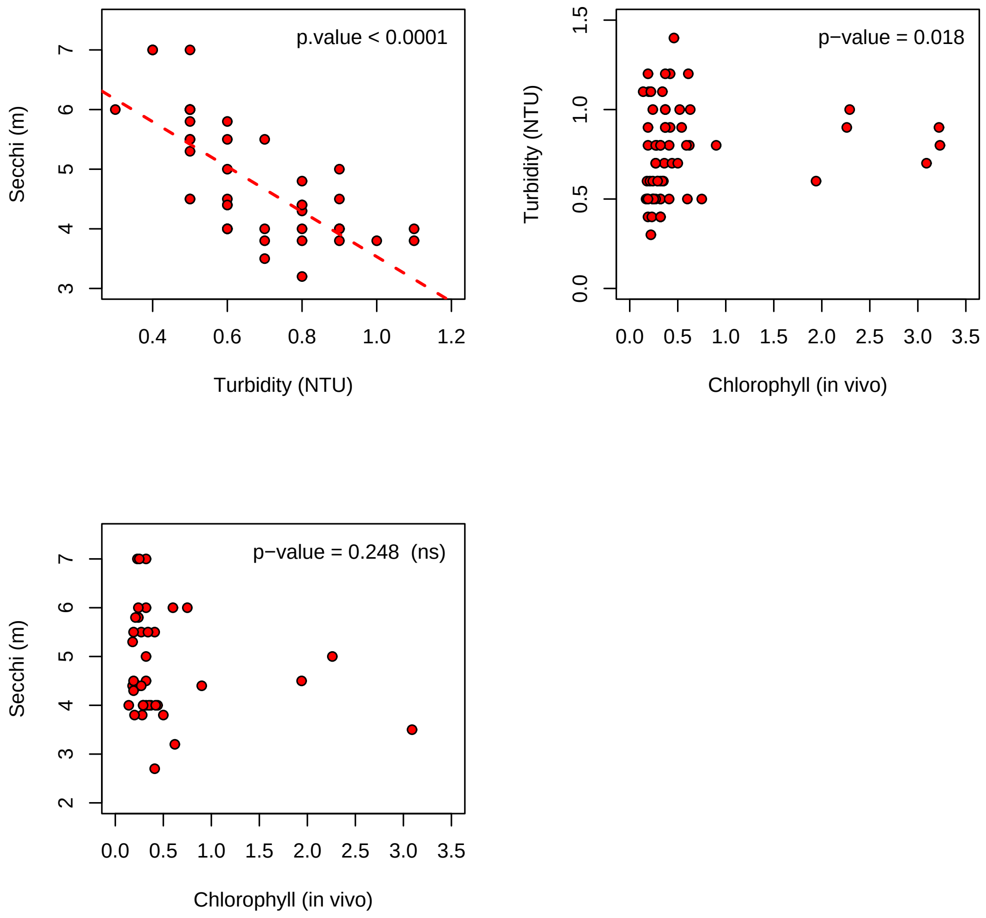


Figure 24: Kendall's τ correlations between turbidity, Secchi depth, chlorophyll, and orthophosphate. See page 5 for a description of correlation analysis. Diagonal line on turbidity vs. Secchi figure is for reference only and does not imply a linear relationship.

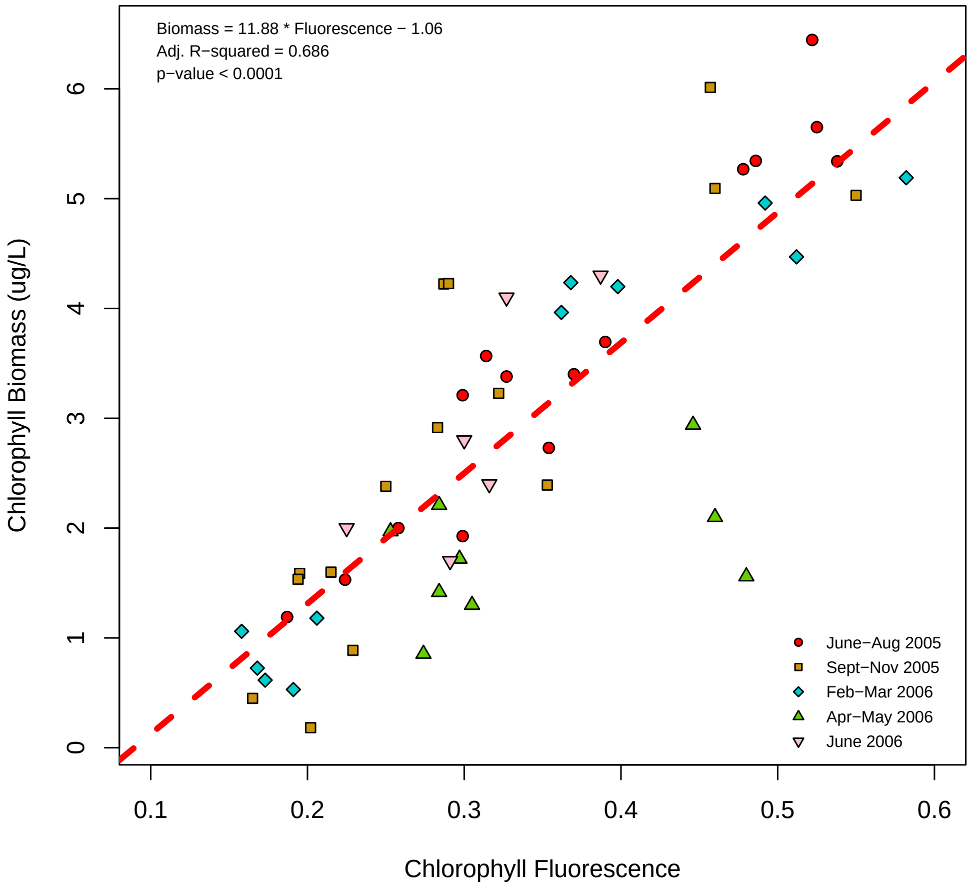


Figure 25: Comparison between chlorophyll fluorescence measured in the field and chlorophyll biomass measured in the laboratory.

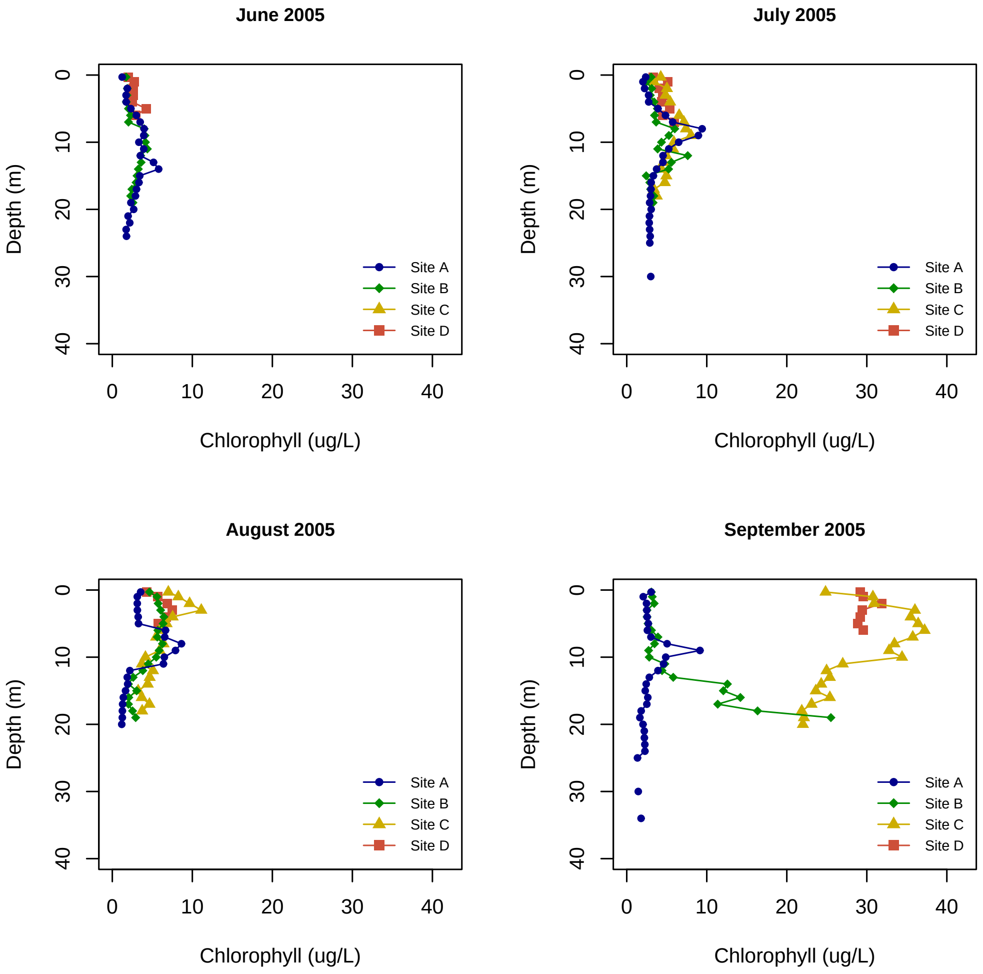


Figure 26: Lake Samish chlorophyll profiles, June through September 2005. Chlorophyll biomass was estimated based on fluorescence regression model.

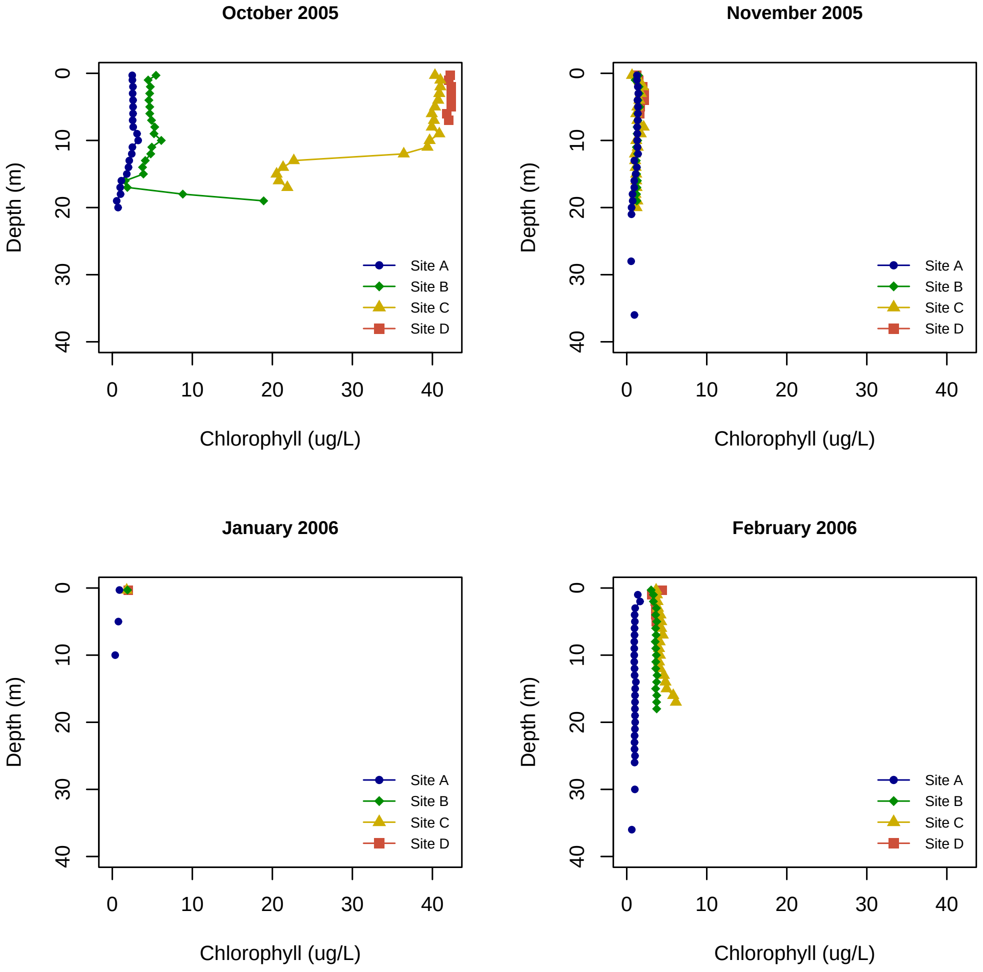


Figure 27: Lake Samish chlorophyll profiles, October through November 2005 and January through February 2006. Chlorophyll biomass was estimated based on fluorescence regression model.

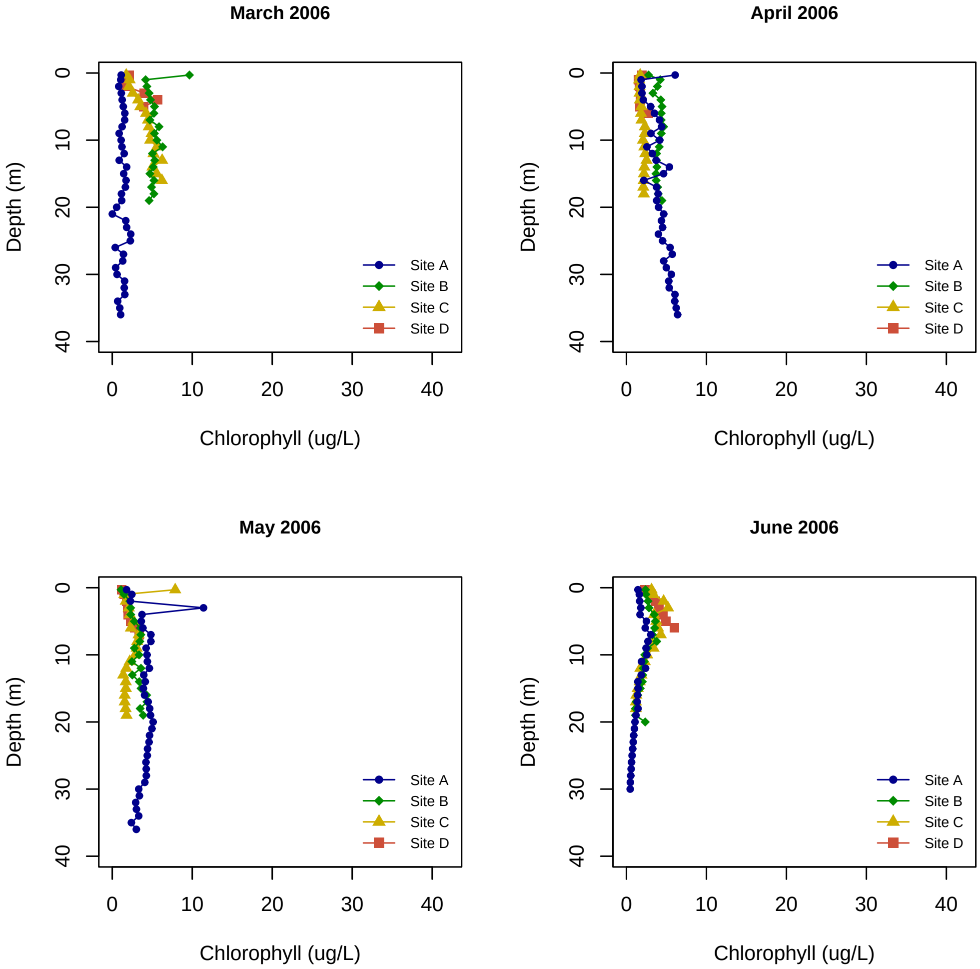


Figure 28: Lake Samish chlorophyll profiles, March through June 2006. Chlorophyll biomass was estimated based on fluorescence regression model.

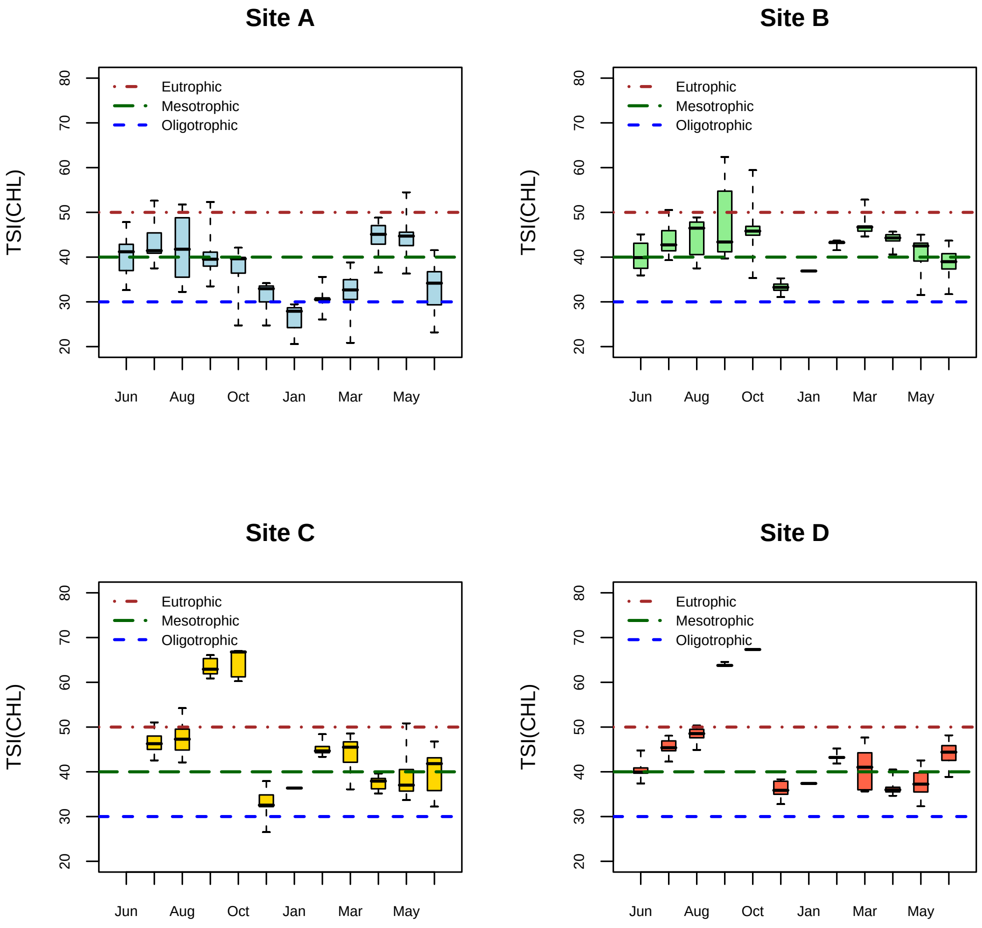


Figure 29: Boxplots showing Lake Samish monthly TSI(CHL) values. Chlorophyll biomass was estimated based on fluorescence regression model. Boxplots show median and upper/lower quartiles; whiskers show maximum/minimum values. See page 11 for further discussion.

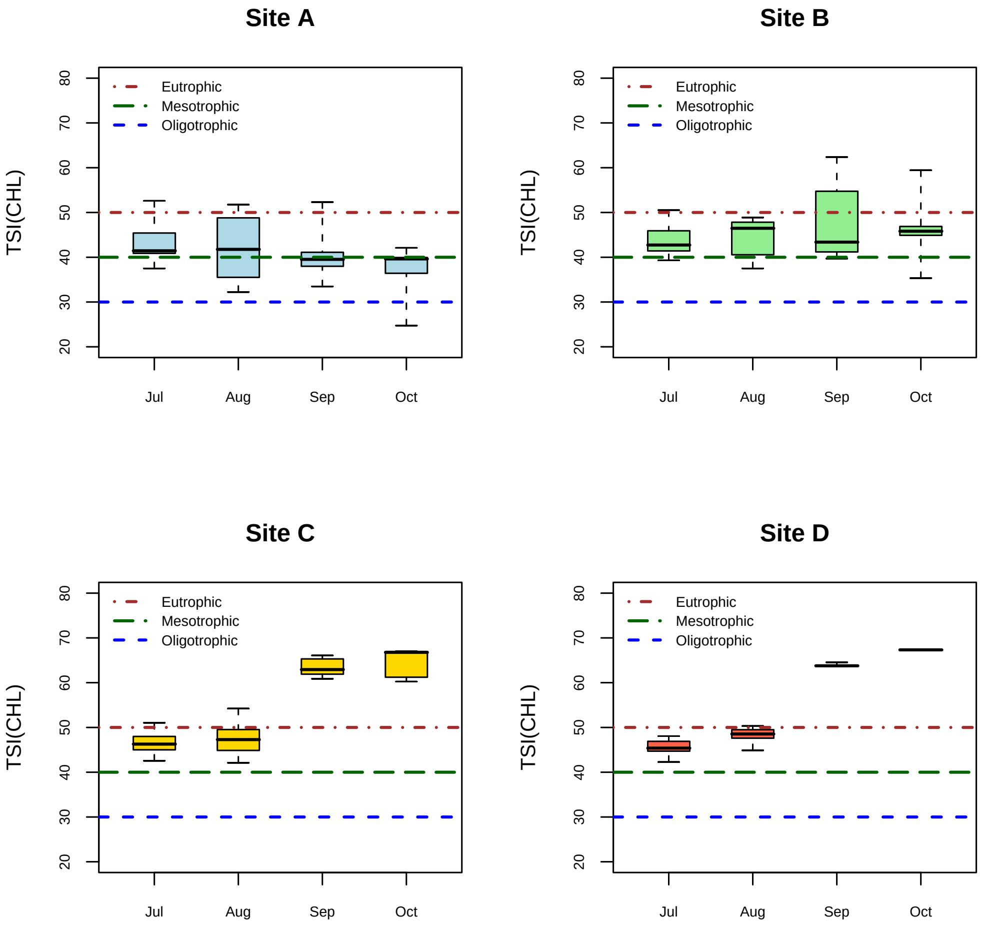


Figure 30: Boxplots showing Lake Samish summer TSI(CHL) values (July through October 2005). Chlorophyll biomass was estimated based on fluorescence regression model. Boxplots show median and upper/lower quartiles; whiskers show maximum/minimum values. See page 11 for further discussion.

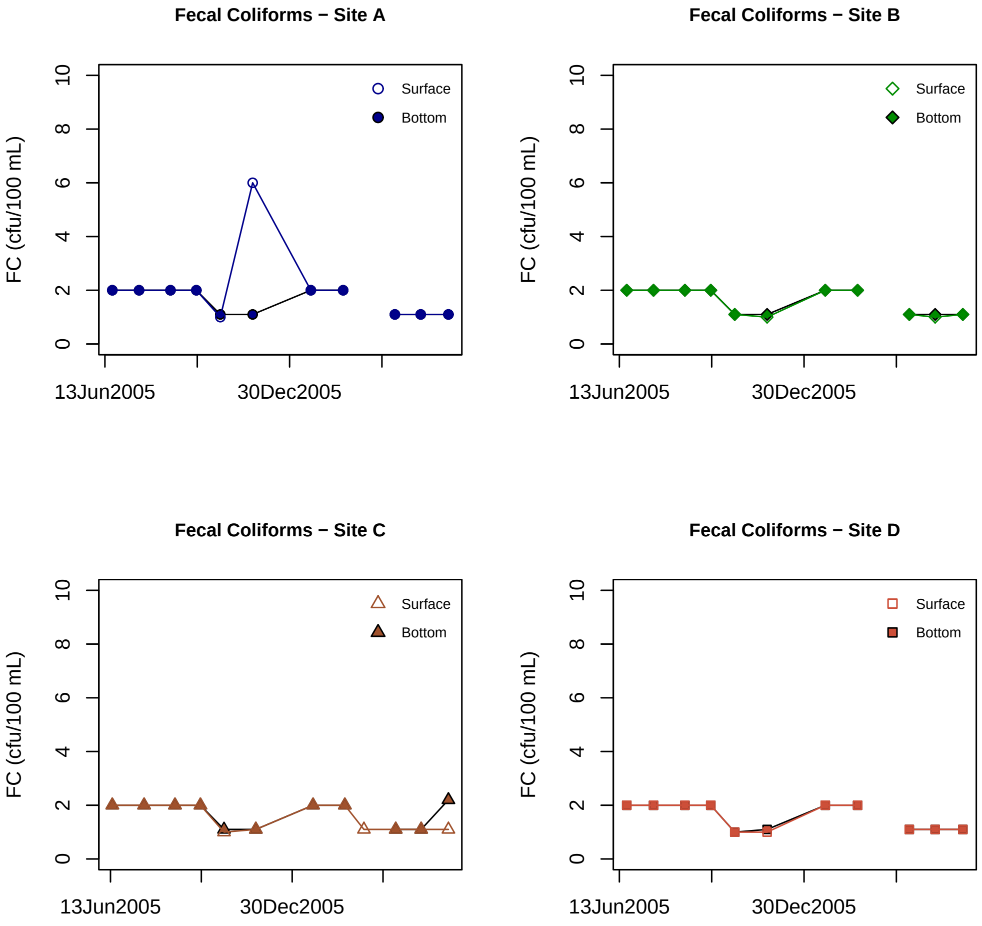


Figure 31: Lake Samish fecal coliform data, June 2005 through June 2006. Samples were collected at the surface and bottom for each site and analyzed by Edge Analytical.

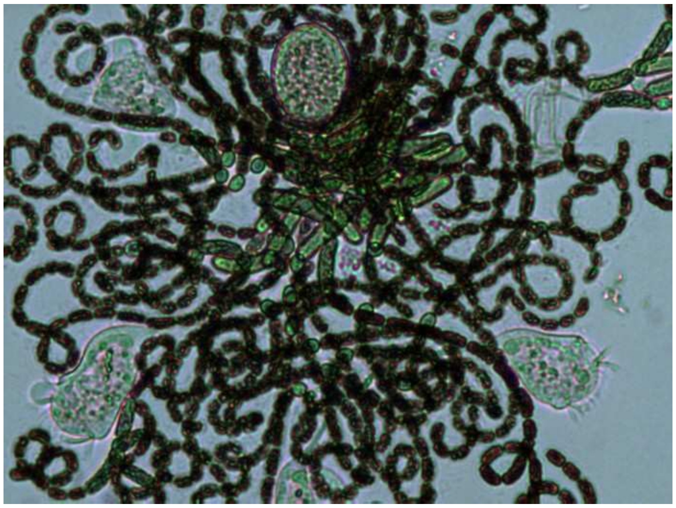
A Water Quality Data

Copies of the original data, including quality control results and coliform reports from Edge Analytical, are included in the printed copies of the report. Online reports do not include copies of the original data, but electronic data files are available from the Institute for Watershed Studies.

B Lake Samish Phytoplankton Images

The images in this appendix were photographed using a Nikon Eclipse 80i compound microscope equipped with a QImaging MicroPublisher 3.3 RTV image capture system. All taxonomic identifications were provided by Dr. Robin Matthews using standard taxonomic source materials. Due to the complex nature of algal identification, all taxonomic names should be considered provisional. High resolution TIF images are available for the algae included in this appendix, as well as additional images collected from Lake Samish during 2005 and 2006. For information, contact the Institute for Watershed Studies.

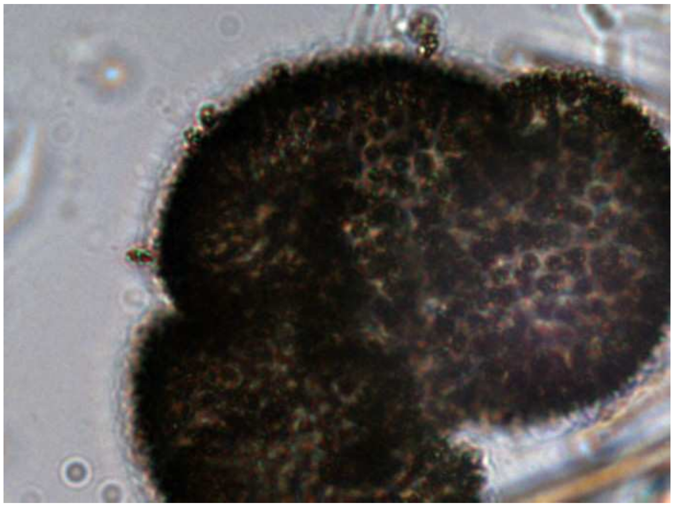
Anabaena circinalis (100x)



Anabaena flos−aquae (100x)

Figure 32: Lake Samish phytoplankton images: cyanobacteria (bluegreen algae).

Woronichinia naegleliana (200x)



Gloeotrichia echinulata (40x)

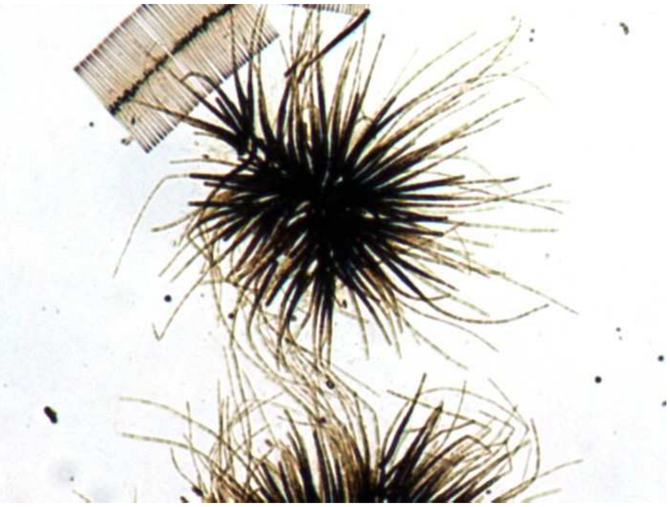
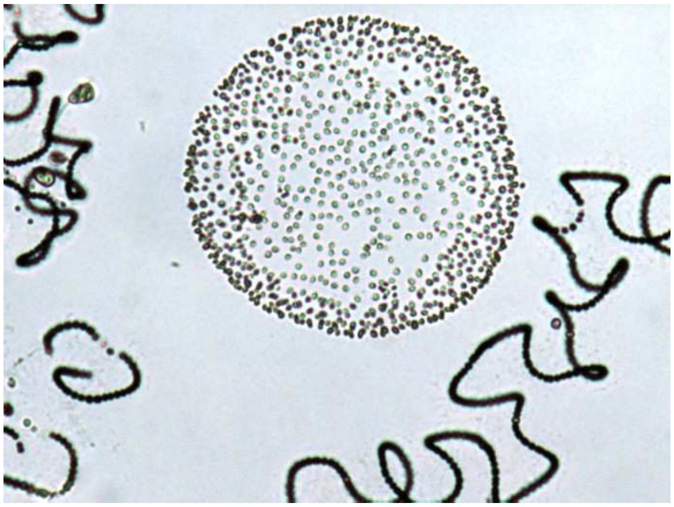


Figure 33: Lake Samish phytoplankton images: cyanobacteria (bluegreen algae).

Microcystis smithii (100x) − formerly Aphanocapsa pulchra



Microcystis aeruginosa (40x) − with other bluegreens

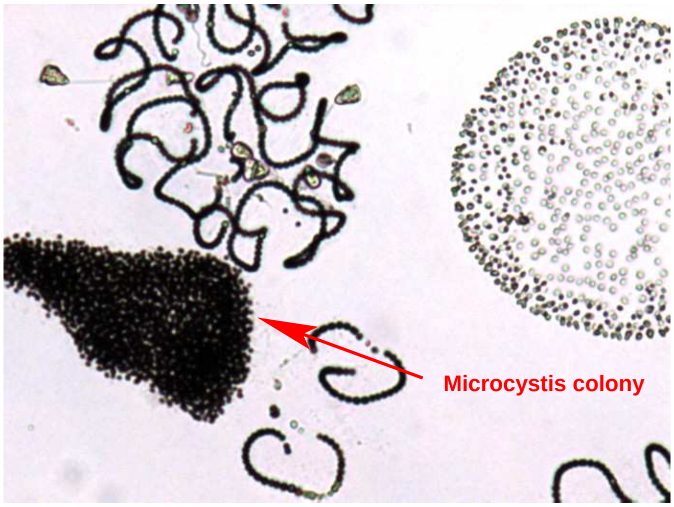
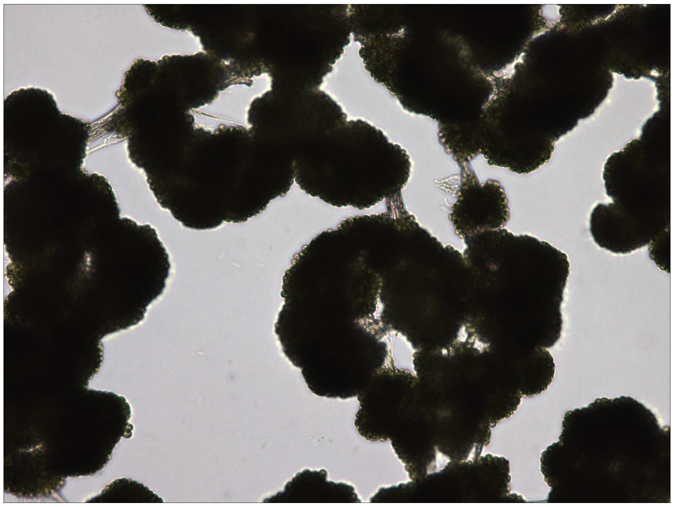


Figure 34: Lake Samish phytoplankton images: cyanobacteria (bluegreen algae).

Botryococcus braunii (100x)



Pandorina morum (600x)

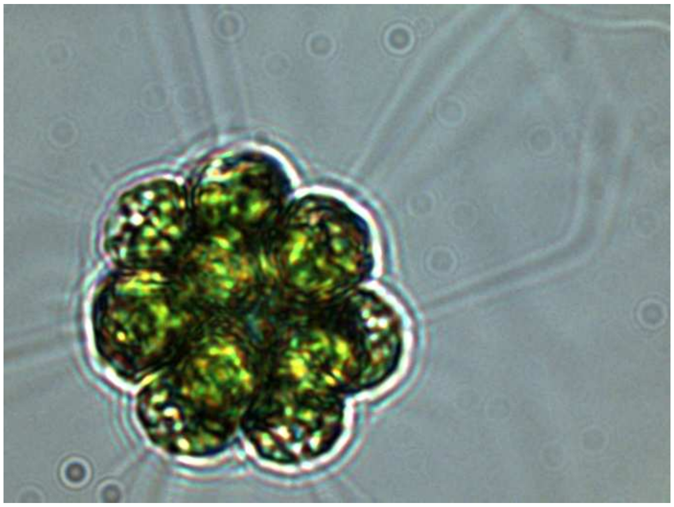
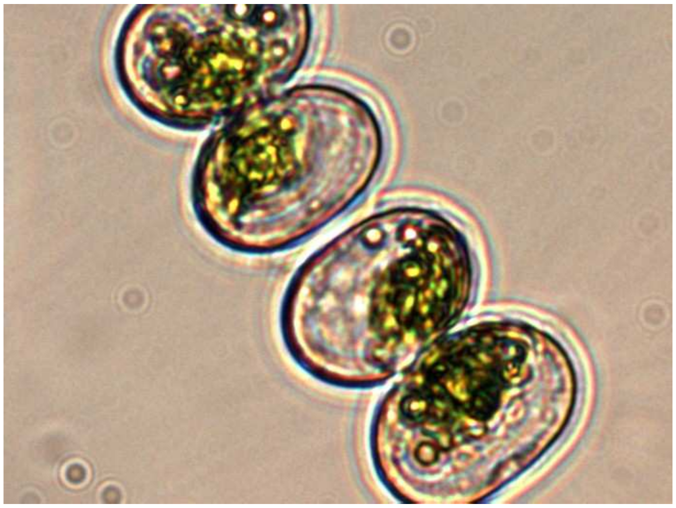


Figure 35: Lake Samish phytoplankton images: colonial green algae.

Cosmarium (400x)



Staurastrum (400x)

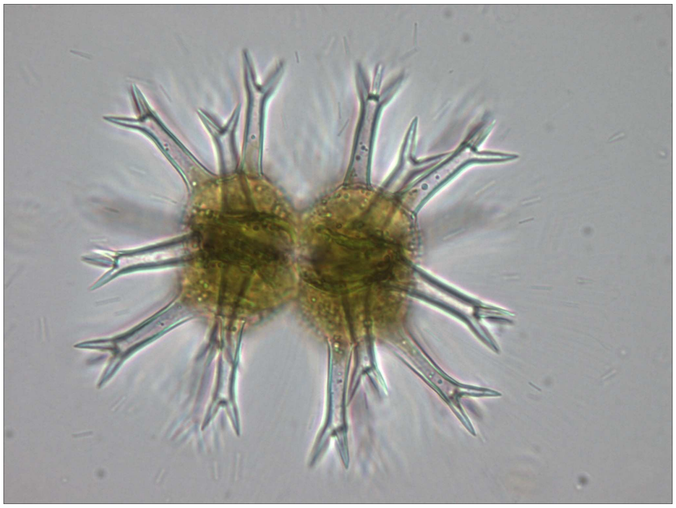
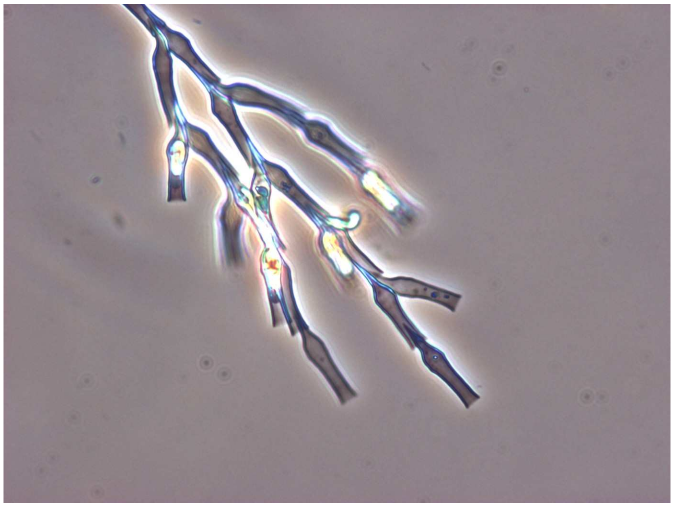


Figure 36: Lake Samish phytoplankton images: desmids (green algae).

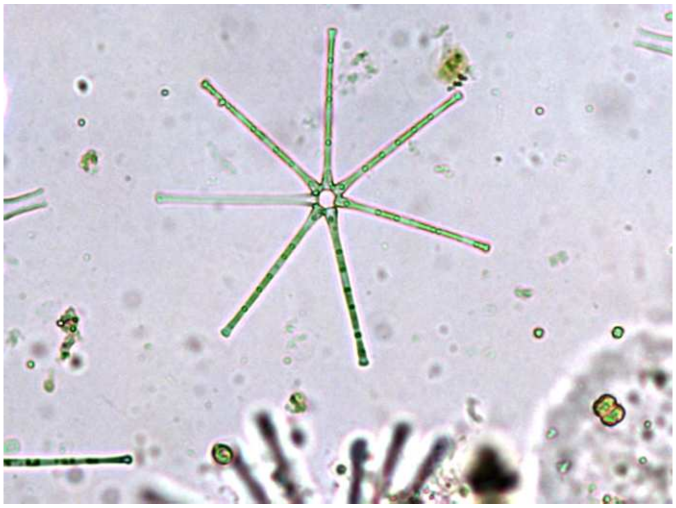
Dinobryon (200x) − phase contrast



Mallomonas (400x)

Figure 37: Lake Samish phytoplankton images: chrysophytes and diatoms.

Asterionella formosa (100x)



Centric diatom with Melosira filaments (200x)

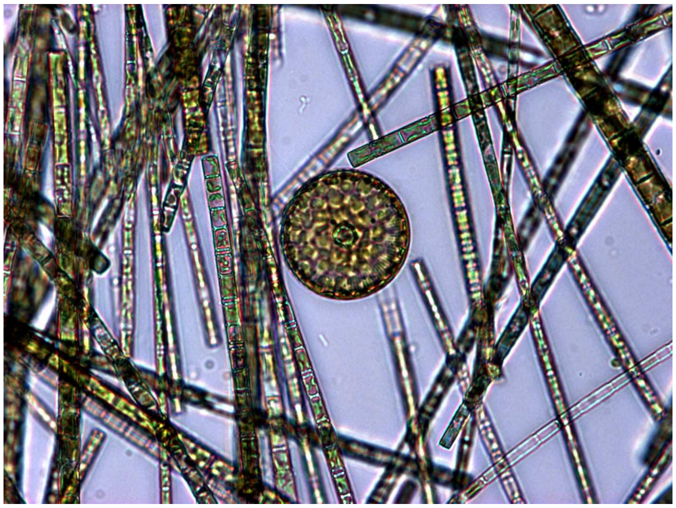
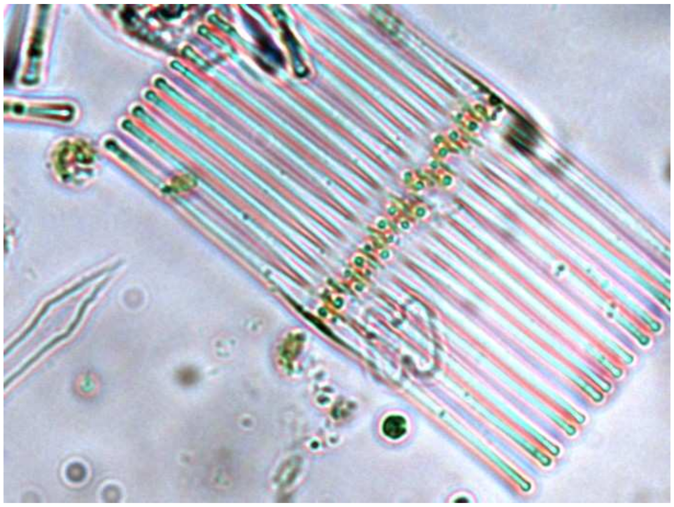


Figure 38: Lake Samish phytoplankton images: chrysophytes and diatoms.

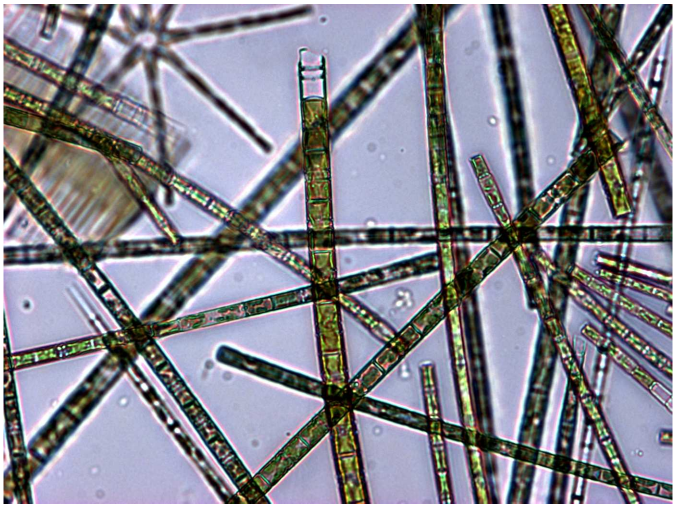
Fragillaria (200x)



Synedra cluster (100x)

Figure 39: Lake Samish phytoplankton images: chrysophytes and diatoms.

Melosira (200x) − several species



Melosira (200x) − several species

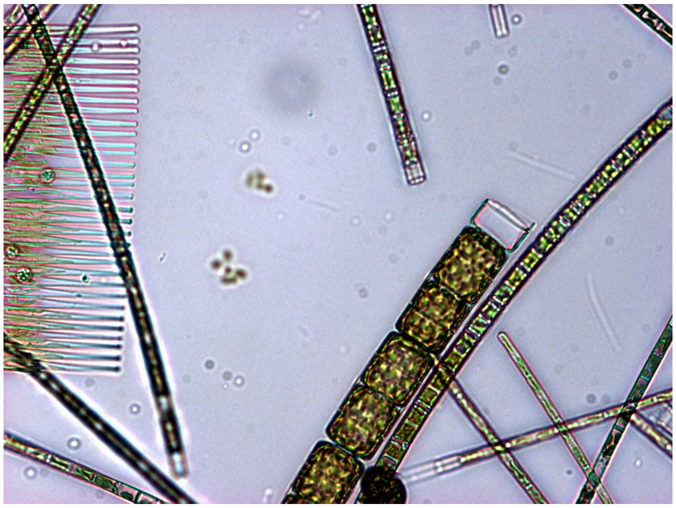


Figure 40: Lake Samish phytoplankton images: chrysophytes and diatoms.

Ceratium hirundinella (40x)

Gymnodinium (400x)

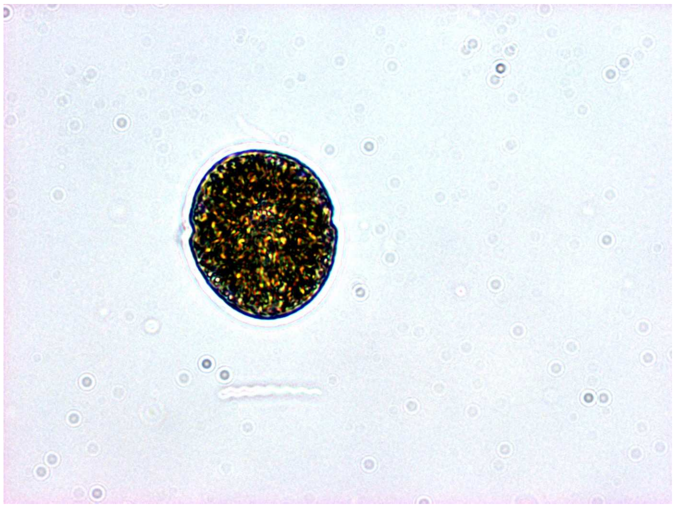


Figure 41: Lake Samish phytoplankton images: dinoflagellates.