2009 Blue Lake Water Quality Summary Report

Prepared by:
Whitney Temple
Blue Lake Water Quality Intern
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METRO

Contents

Background

Site Characterization

Blue Lake is a monomictic freshwater lake located in the Lower Columbia Basin 11 miles east of Portland city center in Multnomah County, Oregon. It lies one-half mile south of the Columbia River and one mile west of the Sandy River delta. Twenty-one percent of the 128 acre watershed is privately owned, while the remaining 79% comprises Blue Lake Park, which is owned and managed by Metro. The 65 acre lake has an approximate volume of 710 acre-feet when the water surface elevation is at 14 feet above mean sea level. At this stage, the maximum depth is approximately 7.3 m. (24 ft.) and the average depth is 3.4 m. (10 ft.).

Due to uplift along one or more faults below Blue Lake (Figure 1), its underlying geology is more complex than in southern and western areas of the Portland Basin. The oldest sedimentary layer beneath the lake, the Sandy River Mudstone, has two main layers: a lower clay and silt layer that is largely impervious, and an upper sand and gravel layer known as the Sand and Gravel Aquifer (SGA). The SGA is an abundant source of groundwater, although SGA pumping by the City of Vancouver since 1994 has drawn down SGA levels as much as 20 feet and in some areas, reversed the vertical gradients between the SGA and the adjacent Troutdale Sandstone Aquifer (TSA). The gravelly Blue Lake Aquifer (BLA) directly underlies most of Blue Lake. A ridge comprised of Troutdale Formation sandstone lies along the southern border of the lake. The complexity of the geologic formations in the vicinity of Blue Lake directly impacts local groundwater movement, which is not completely understood.
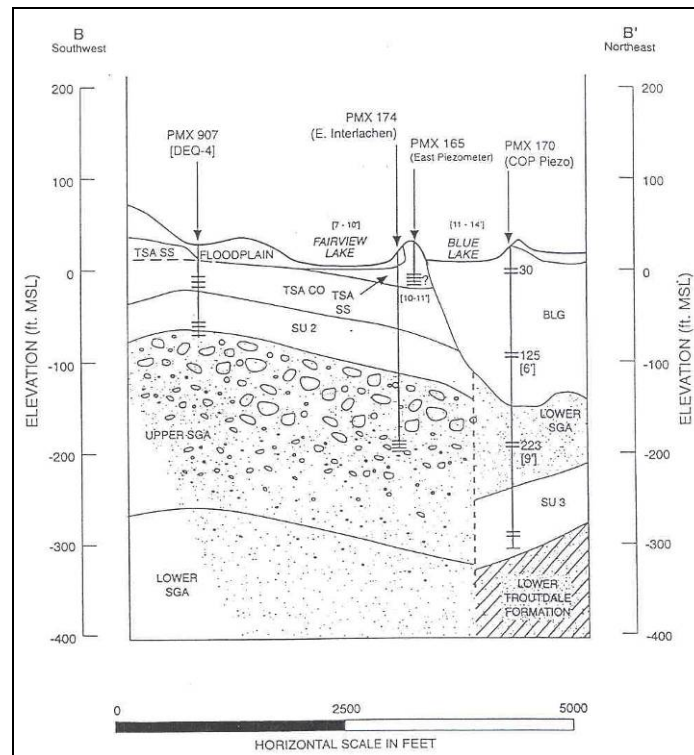

Figure 1: Cross section through Blue Lake and underlying aquifers. *From Woodward Clyde (August, 1994) in Blue Lake Discussion paper (2004)*

The lake lacks any natural surface inflows or outflows. Instead, groundwater inflow, precipitation and overland runoff are the major hydrologic inputs, while groundwater seepage, surface evaporation and controlled releases via a weir on the northeast end of the lake control hydrologic losses. The direction of groundwater flow (into or out of the lake) relates to the stage of the Columbia River; when the river elevation is higher than that of Blue Lake, there is sufficient hydrostatic pressure to drive groundwater flows into the lake, and the opposite occurs when Blue Lake's water elevation exceeds that of the Columbia. Additionally, the City of Portland typically pumps groundwater into the lake each summer in order to maintain a water level sufficient for in-lake recreation and to avoid damage to structures such as docks.   In 2009, approximately 17 million gallons were pumped into the lake on August 20 and 21.

Blue Lake typically stratifies in April or May and turns over in September or early October. When stratified, the thermocline lies about 4-6 meters deep, separating the well-oxygenated epilimnion (top layer) from the hypoxic, higher-nutrient hypolimnion (bottom layer).   Fall turnover releases sediment-bound nutrients into the water column, allowing the lake to support high phytoplankton populations through the fall and winter.

Human Uses

Recreational uses of Blue Lake include motor boating and waterskiing for lakeshore residents, as well as park visitors during the off season, summer paddle boating and canoeing from Blue Lake Park, swimming, and fishing.

Water Quality Concerns

Algae

Oregon Department of Environmental Quality (DEQ) listed Blue Lake on the Clean Water Act Section 303(d) listing for impaired waterbodies in 1998 for supporting excessive algal populations. Cyanobacteria, or blue-green algae, have been particularly problematic due to their tendency to form massive "blooms" and because some species produce neurotoxins and hepatoxins, which can be harmful to aquatic life, humans, and pets. Anecdotal accounts of regular blue-green algae blooms date back to at least 1942, and a lake sediment analysis conducted in 1979 indicated that at that time, the cyanobacterial population in the lake was similar to that in 1900. Copper sulfate was applied generously to the swim area and around the margin of the lake from 1940 through at least the 1970s to control algae. However, its effectiveness may have been less than hoped for due to the high pH and the presence of dissolved organic compounds, both of which could deactivate much of the copper. In 2000, an algicide was applied to the lake in an effort to control blue-green algae and muskgrass (*Chara sp.*), a native plant-like alga.

In 2007, three SolarBee® units (SolarBee, Inc.) were installed to help reduce the instance of nuisance algae blooms.   According to the manufacturer, these long-distance circulators can prevent harmful algal blooms, reduce invasive and nuisance macrophyte stands, and aerate the hypolimnion (bottom layer of water) and sediment to lessen the release of sediment-bound

nutrients. In Blue Lake, the water intake is set at 3 m (10 ft) below the water surface (above the thermocline) for the east and west units and at 4.5 m (15 ft) for the central unit, in order to reduce summertime cyanobacterial blooms, as is illustrated in Figure 2. Mixing is thought to hinder internal buoyancy regulation by cyanobacteria and redistribute oxygen, nutrients, bacteria, and algae throughout the lake, reducing the likelihood of optimal conditions for cyanobacterial blooms.
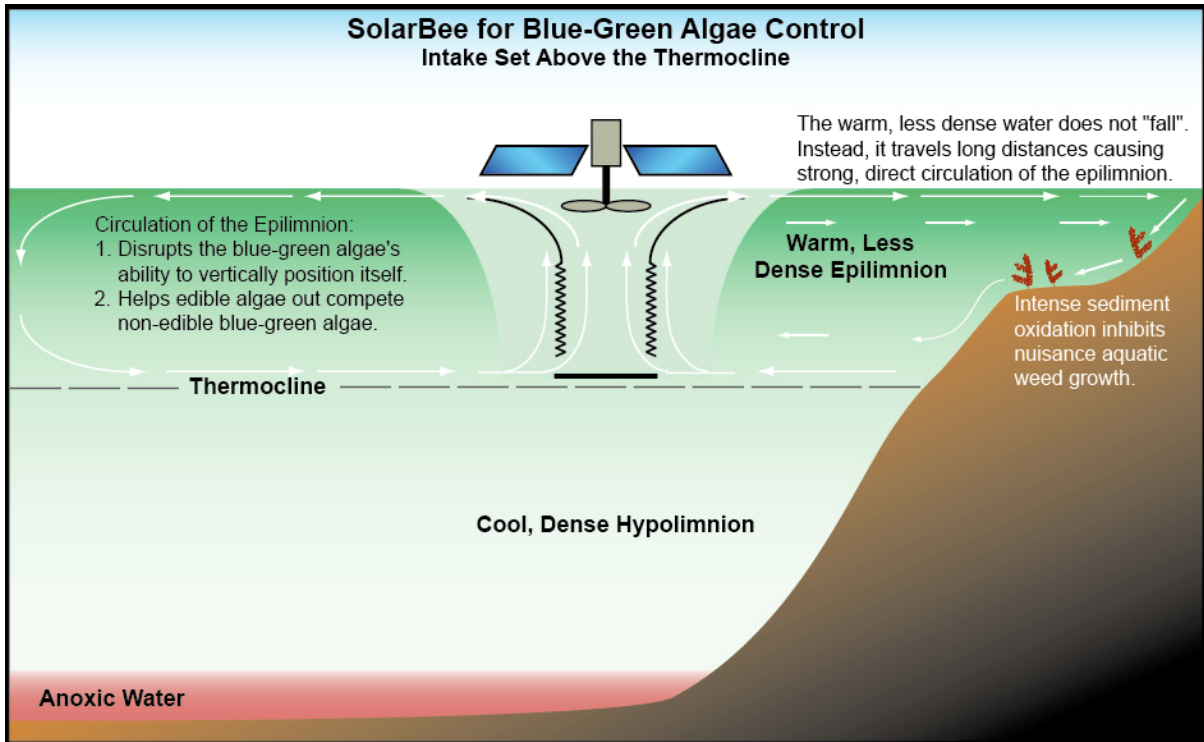

Figure 2: Diagram of SolarBee placement in the water column in Blue Lake. The water intake is set above the thermocline to disrupt cyanobacterial cells' ability to move themselves vertically through the water column, thereby reducing blooms. Additionally, the oxidation of the sediment in the littoral zone is expected to decrease the growth of nuisance aquatic plants. *From SolarBee, Inc. website*

Vegetation

Blue Lake is also on Oregon DEQ's 1998 303(d) listing for supporting abundant aquatic weeds, in order to protect aesthetic quality, boating, and water contact recreation. Currently, three non-native, invasive aquatic plants exist in Blue Lake: curlyleaf pondweed (*Potamogeton crispus*), which peaks in the early summer, fragrant waterlily (*Nymphea odorata*), and Eurasian watermilfoil (*Myriophyllum spicatum*), which peaks in late summer to early fall. Additionally, up to three native plant species and two native plant-like algae are found in the lake. Beak Consultants, Inc. (1979) reported that aquatic macrophytes have interrupted recreational uses of Blue Lake since at least 1936. However, the problematic macrophytes reported prior to the first positive identification of Eurasian watermilfoil (*M. spicatum*) in 1973, American waterweed (*Elodea canadensis*) and sago pondweed (*Stuckenia pectinata*), are both native species. Beak suggested that mechanical harvesting of sago pondweed during the early 1970s likely opened the lake bottom for invasion by formerly isolated Eurasian watermilfoil plants. Additionally,

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because milfoil can root from fragments, continued mechanical harvesting may have aided its spread if all the milfoil fragments were not removed from the lake.

Mechanical harvesting was discontinued after 1975 due to the high operating cost and persistent need for machine repairs. In the winter of 1981-82, Beak Consulting released water from the lake to expose plants to freezing temperatures, with limited success against the milfoil populations and unforeseen damage to retaining walls and docks. Documented chemical methods for macrophyte control include sodium arsenite (1949-1965), standard and Red Band Aquatic Weed oils (aromatic solvents) (1965), Casoron (late 1960s), Cutrine, Aquathol, and Aqua-Kleen (1970s), 2,4-D (1980s), and Fluridone or Diquat (unknown date-2001). The use of aromatic oils and Aqua-Kleen resulted in the death of hundreds of fish and crayfish. As currently installed (with the water intake above the thermocline), the SolarBees are intended to also reduce the growth of aquatic plants in the littoral zone of the lake by one or both of two possible means. One, oxygenating the sediments would convert ammonia, the preferred form of nitrogen, to nitrate, gradually causing a reduction in rooted macrophytes. Alternately, the reduction in nitrogen-fixing cyanobacteria could decrease the amount of ammonia available to macrophytes by reducing the availability of organic nitrogen from decomposing algal biomass, which would be mineralized to ammonia.

pH

Oregon's 303(d) listing for Blue Lake also includes violations for high pH during the summer. The standard is set to protect resident fish and aquatic life. The acceptable range is 6.5-8.5 standard units, which has been exceeded repeatedly, especially at one-half meter depth. Photosynthesis consumes hydrogen ions, or protons, (H^+) through the following equation:

$$106CO_2 + 16\ NO_3^- + H_2PO_4^- + 122\ H_2O + \underline{17H^+} = \text{plant growth} + 138O_2.$$
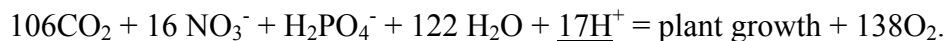
pH reflects the negative log of proton activity (essentially, proton concentration), so decreased proton activity (more photosynthesis) increases pH. Lake turnover in the fall releases ample nutrients to support algal productivity during the fall and winter, but lower light availability and temperature may retard photosynthesis enough to prevent pH violations during these seasons.

Because pH exceedences are presumed to be caused by high levels of photosynthesis, efforts to lower the lake's pH have primarily focused on reducing algal populations, and to a lesser extent, macrophyte populations. However, a major criticism of some previous attempts to control algae and macrophytes is that they have failed to consider natural lake processes and long-term monitoring and adaptation, so most successes in reducing algae and plants, and therefore, pH, have been short-lived.

Monitoring History

Temporary water quality monitoring following pesticide applications has been performed intermittently in order to assess their consequences on lake water chemistry and biota. The first comprehensive water quality assessment of Blue Lake was performed by Beak Consulting, Inc. from 1978-1983 for a Clean Lakes Study. Data from 1983 were used for Oregon DEQ's 1998

303(d) listing of Blue Lake. Rigorous monitoring of chemical parameters occurred in the summers of 2002 and 2003. Fewer water quality variables have been examined since 2006. Since 2007, Metro has hired an intern to collect water chemistry data from May or June to September. In 2009, an expanded field manual was written in order to assure consistency in data collection from year to year. Additionally, historical data from DEQ's online LASAR database and Metro's electronic files were compiled into a single spreadsheet to aid in analyzing water chemistry trends over time. The next section provides a brief analysis of data from 2009 and a comparison to previous years' data.

Water Quality Summary – 2009

Profiling (Metro)

Weekly profiling of the lake occurred from June 4, 2009 through October 23, 2009, except for the weeks of September 16 and October 15. Profiling involved the collection of basic water chemistry data (temperature, pH, dissolved oxygen, and specific conductance) using a Hydrolab Quanta multiprobe sensor at half-meter intervals at Site 2, in the deepest part of the lake (Figure 3). Water clarity, which in Blue Lake is mostly affected by algal populations, was measured using a Secchi disc at this site. The goal of continuous profiling is to understand water chemistry and stratification patterns of the lake, as well as to monitor for indicators of algae blooms such as high pH and low Secchi depth. The only difference in 2009 compared to previous years was that the profiling in previous years occurred at one-half meter and every whole meter rather than at every half meter.


Figure 3: Map of Blue Lake water quality monitoring sites. Site 2 is located at 45.55410° N, -122.45010° W. The Swim Beach is at 45.55487° N, -122.45214° W.

Results

In 2009, Blue Lake's pH frequently exceeded the DEQ 303(d) maximum standard of 8.5 standard units, with 68% of weekly half-meter sample events and 32% of thermocline samples greater than the threshold (Figure 4). At one-half meter, pH increased overall from June to the beginning of August, then declined through September, then rose again in early October, corresponding with a surface algae bloom. At the thermocline, pH fluctuated with no regular pattern, except a peak in late July.
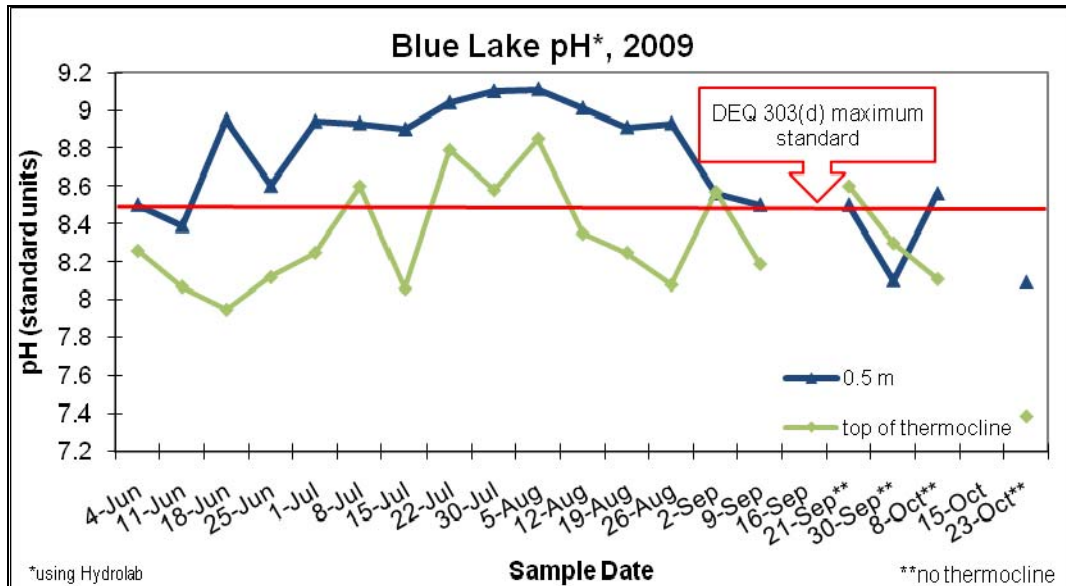
Figure 4: Weekly pH readings at Site 2 in summer 2009 at one-half meter deep and just above the thermocline. Data were collected using a Hydrolab Quanta pH sensor. Measurements taken after fall turnover were collected from 4 meters since no thermocline was present.

Dissolved oxygen at 0.5 meter was stable throughout September, ranging from 8.57 to 11.32 mg/L in 2009 (Figure 5), with an average of 9.27 mg/L. The highest dissolved oxygen levels at 0.5 meters occurred in October during and just following an algal bloom. High dissolved oxygen at this time would be expected because of high algal productivity and because colder water can hold more oxygen. At the top of the thermocline, dissolved oxygen levels were more variable, ranging from 4.52 to 13.04 mg/L and averaging 8.68 mg/L. The peak in dissolved oxygen at the thermocline from July 22 to August 5 corresponds with a similar increase in pH on those dates, most likely reflecting increased algal productivity above the thermocline. The algal total biovolume on August 5 was two to three times higher than the biovolume in the first weeks of July or September, supporting this hypothesis.
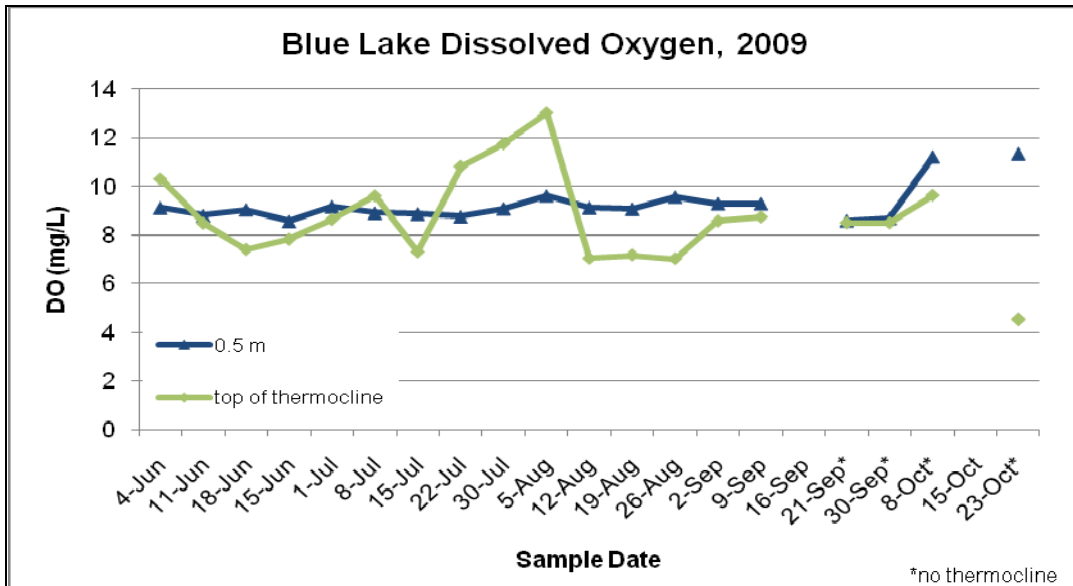
Figure 5: Weekly dissolved oxygen readings at Site 2 in summer 2009 at one-half meter deep and just above the thermocline. Data were collected using a Hydrolab Quanta dissolved oxygen sensor. Measurements taken after fall turnover were collected from 4 meters since no thermocline was present.

Specific conductance increased over the summer at 0.5 meter and above the thermocline (Figure 6), probably due to the the increasing concentration of salts in the lake as the water level decreased by evaporation. Conductivity at the thermocline tended to mimic the pattern of conductivity at 0.5 meter, but the thermocline conductivity tended to be slightly higher while the lake was stratified. As with pH and dissolved oxygen, conductivity spiked from July 22 to August 5 above the thermocline.
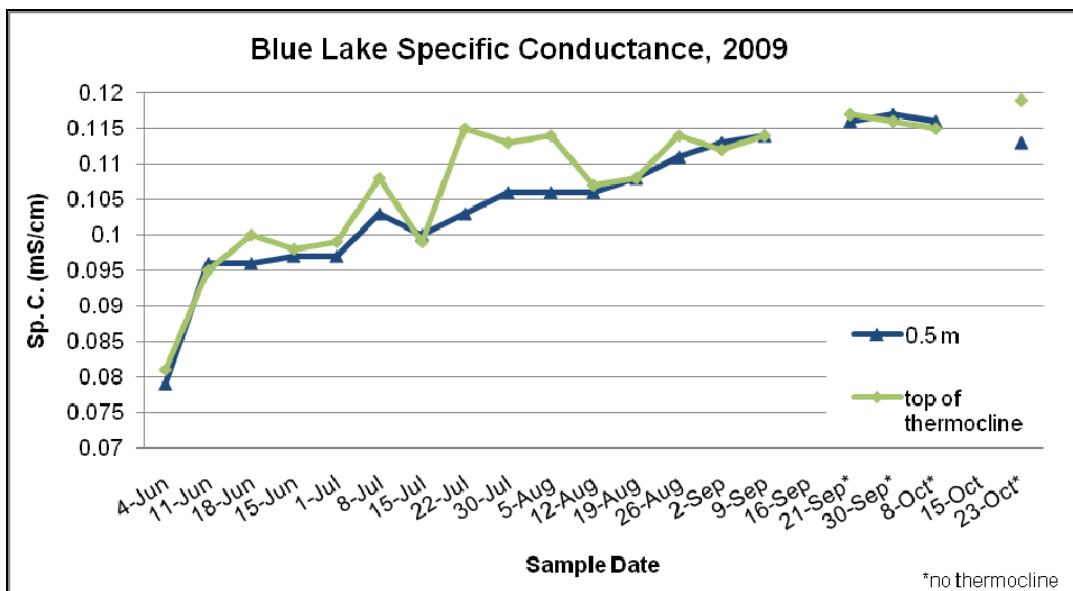

Figure 6: Weekly specific conductance readings at Site 2 in summer 2009 at one-half meter deep and just above the thermocline. Data were collected using Hydrolab Quanta conductivity and temperature sensors. Measurements taken after fall turnover were collected from 4 meters since no thermocline was present.

Secchi depth decreased through the second week of July, then increased until July 22, when Secchi depth was 3.84 m (12.6 ft), the second highest value for the summer (Figure 7). From the end of July through early October, Secchi depth generally decreased, reaching 0.76 m (2.5 ft) on October 8. The Secchi depth increased to 1.07 m (3.5 ft) two weeks later, after the algae bloom had subsided. The spike in water clarity on July 22 is not inconsistent with the high algal productivity above the thermocline, because the Secchi depth was still less than the thermocline depth. The low water clarity in late September is typical of a lake that has turned over, with resuspension of sediments and algal productivity driven by release of sediment-bound nutrients. The lowest Secchi depth (0.76 m or 2.5 ft) occurred in early October during an algae bloom.

Figure 8 shows all Secchi depth data for Site 2 from 2002 to 2009.   Few data points are available for 2002 or 2003, especially during late summer, when Secchi depth typically decreases.   Where data are available, Secchi depth tended to be lower in 2002 and 2003 than in later years.   Data for 2009 follow the generally same pattern as 2007 and 2008, although early summer and early fall depths in 2009 are mostly lower than those for 2007 or 2008.
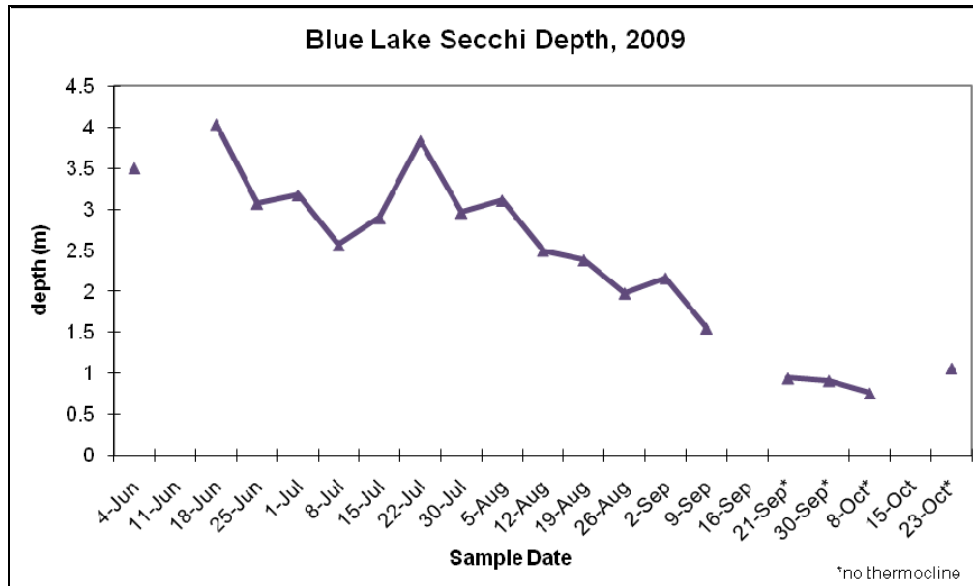

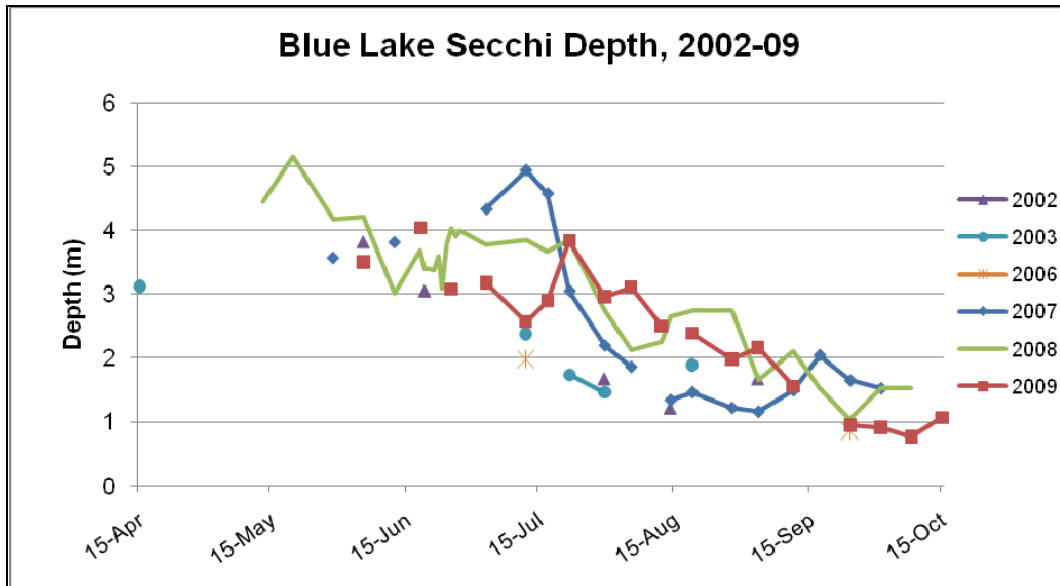**Figure 7: Weekly Secchi depth at Site 2 in 2009.**

Figure 8: Weekly Secchi depth at Site 2, April – October 2002-09.

Nutrients (DEQ)

At Site 2, water samples for nutrient analysis at the DEQ lab were collected on July 1, 2009, and biweekly from July 22 to September 30, 2009 from one-half meter below the water surface and from just above the thermocline. One sample for nutrient analysis was collected from the water surface on October 8, when visible scum was present throughout the lake. Additionally, at one-half meter and above the thermocline, pH was tested using a DEQ-issued pH meter (Beckman model Φ11) and dissolved oxygen was measured by Winkler titration on days when nutrient samples were collected. These methods are considered to be more accurate than measurements taken with the Quanta, but are more time-intensive, so were not used for weekly profiling. For quality assurance, a duplicate sample from one-half meter was analyzed for all parameters during each sampling event. Standard equipment blanks using deionized water were also analyzed in accordance with DEQ's Mode of Operations Manual. Compared to previous years, the duration and frequency of nutrient sampling was scaled back in 2009 at the request of Karen Williams, Oregon DEQ's project manager.

Filters were analyzed for chlorophyll-*a* pigment, an indicator of algal productivity. Pheophytin-*a*, a degradation product of chlorophyll, was also measured and used to correct the chlorophyll-*a* measured value. Filtered samples were analyzed for dissolved orthophosphate, the soluble inorganic fraction of phosphorus, which is the form that is readily available for plants and algae to take up. Phosphorus tends to be the nutrient in least supply relative to the needs of plants and algae in many freshwater lakes, and its oversupply is often linked to their excessive populations. Total Phosphorus quantifies all dissolved and particulate forms of the nutrient and was measured from unfiltered water samples. Total Phosphorus is often used as a proxy for algal productivity.

Nitrogen is the other nutrient that frequently limits primary productivity in freshwater lakes. However, because many cyanobacteria can fix nitrogen from the atmosphere, they may

flourish even when the nitrogen availability in the lake is low. Inorganic nitrogen forms were measured separately from unfiltered samples as nitrate plus nitrite and as ammonia. Organic nitrogen plus ammonia was measured from unfiltered samples as Total Kjehldahl Nitrogen (TKN). Total nitrogen was calculated as nitrates plus TKN. Unfiltered water samples were also analyzed for alkalinity (acid neutralizing capacity), chemical oxygen demand, total organic carbon, total solids, total suspended solids, and sulfate.

The nitrogen-to-phosphorus ratio is an indicator of whether the water is nitrogen or phosphorus limited. It is calculated as total nitrogen (TN) divided by total phosphorus (TP), both in the same mass-concentration units (mg/L). An N:P ratio less than 7 indicates that nitrogen is the limiting nutrient, while a ratio above 10 indicates that phosphorus is the limiting nutrient. A ratio between 7 and 10 indicates the nutrients are co-limiting.

During one sampling event in each August and September, dissolved silica was measured from filtered water samples. Silica comes from the weathering of silicate minerals and is recycled through freshwater lake systems via its incorporation into diatom biomass, descent to the sediment upon diatom death, and subsequent release back into the water column as dissolved silica.

Results

Due to the turnaround time for results from the DEQ lab, most nutrient data for 2009 were unavailable at the time this report was written. All available data from 2002 to 2009 for three major nutrient indicators, Total Phosphorus, Nitrate and Nitrite, and Total Kjeldahl Nitrogen, plus the N:P ratio, are presented below (Figure 9-Figure 12). Because nitrogen and orthophosphate levels in Blue Lake may be below standard DEQ laboratory method reporting limits, many of the data points are considered estimates.

In 2004, Blue Lake was added to DEQ's 303(b) list of pollutants of potential concern for 11 of 29 samples from 6/5/2002 to 8/21/2003 exceeding Total Phosphorus benchmark of 50 µg/L (0.05 mg/L). Most of these samples were from the top of the thermocline, while half-meter samples were at or below the threshold level (Figure 9). Since 2006, however, Total Phosphorus at both the thermocline and 0.5 meter were generally below the benchmark, with three of 27 thermocline samples, and one of 26 half-meter samples above 50 µg/L exceeding it. Both analyzed thermocline samples from July 2009 exceeded the benchmark, while the half-meter samples did not. However, most samples from all years exceeded the threshold of 0.03 mg/L, the level cited by Dunne and Leopold (1978) as sufficient to fuel algal blooms.
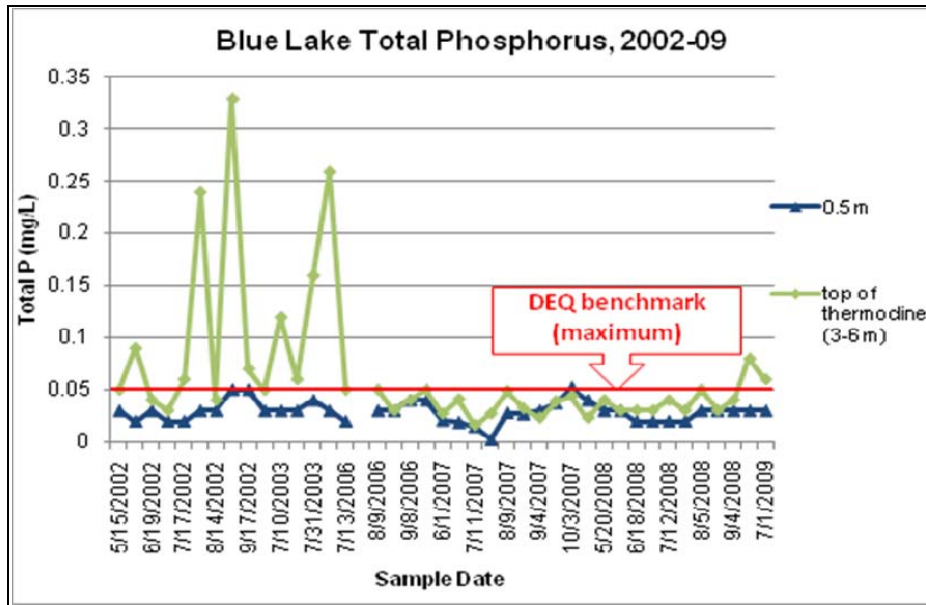
Figure 9: Total phosphorus (mg/L) at Site 2 at one-half meter deep and just above the thermocline, 2002-2009. The maximum DEQ benchmark is 0.05 mg/L.

The level of nitrates in half-meter samples has typically been below 0.005 mg/L (5 μg/L) since 2003 (Figure 10). Above the thermocline, nitrate levels were typically slightly higher than at one-half meter, and most years showed a peak in thermocline nitrates once each summer. In 2002, that peak occurred in September and was ten times higher than typical values, the highest value reported for Blue Lake. In 2003, it occurred in July. Nitrates peaked in August in 2007 and 2008, but at levels much lower than in 2002-03. Only two sample dates from July 2009 are available, and those levels are consistent with 2003-08 half-meter and 2006-08 thermocline values.
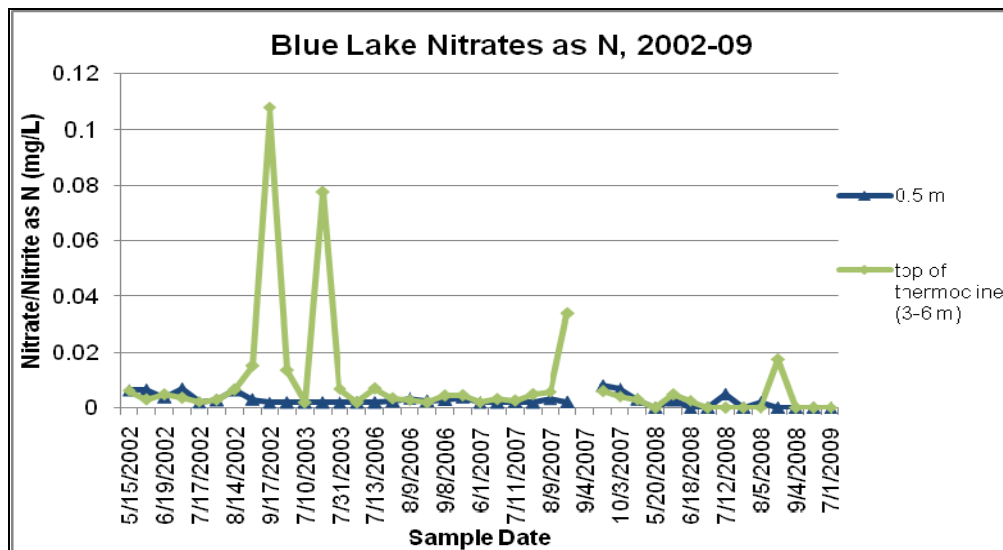

Figure 10: Nitrate and nitrite as nitrogen (mg/L) at Site 2 at one-half meter deep and just above the thermocline, 2002-2009.

Total Kjeldahl Nitrogen (TKN) at one-half meter and the thermocline followed a similar pattern, except for some spikes in thermocline TKN in 2002 and 2006 (Figure 11).   2007-08 data are more consistent, with available July 2009 data being similar to those from July 2008.
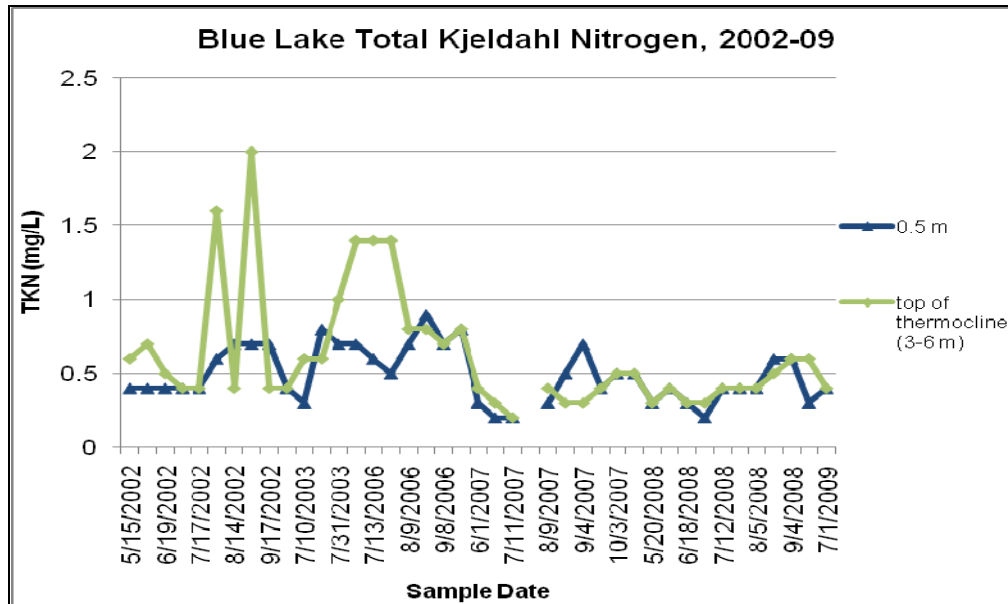

Figure 11: Total Kjeldahl Nitrogen at Site 2 at one-half meter deep and just above the thermocline, 2002-2009.

Summer N:P tends to be higher at 0.5 meters than just above the thermocline (3-6 meters), mainly due to higher levels of total phosphorus at lower depths. The N:P ratios at the two depths tend to follow the same pattern (Figure 12). At the surface, the ratio has consistently been above ten, the lower limit indicating phosphorus limitation. Just above the thermocline at 3-6 meters, the ratio also tends to indicate phosphorus limitation, although it was often in the range of co-limitation of both nitrogen and phosphorus, especially in 2002 and 2003.
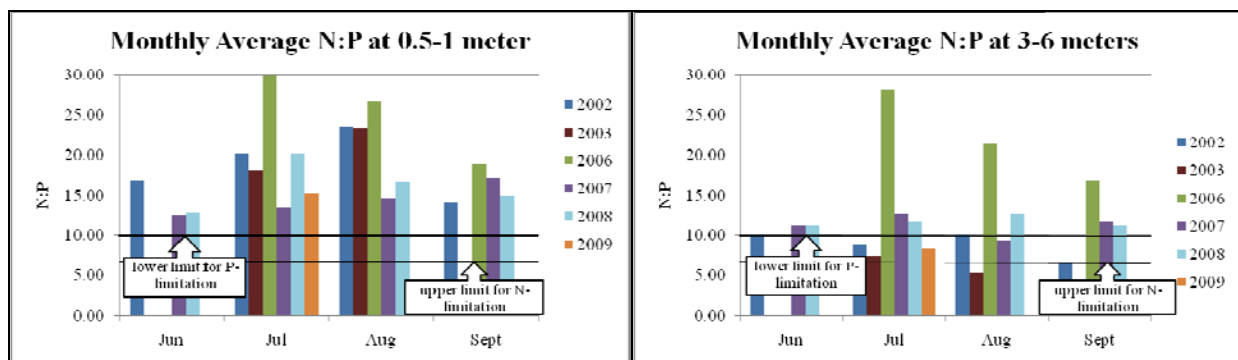

Figure 12: Monthly average ratio of total nitrogen to total phosphorus at 0.5 to 1 meter depths (left) and 3-6 meters (right), 2002-2009. A ratio less than 7 indicates nitrogen limitation, greater than 10 indicates phosphorus limitation, and 7-10 indicates co-limitation of the two nutrients.

Algae

Bi-weekly algal population samples were collected in order to monitor populations throughout the summer and to protect lake users from potentially toxic cyanobacteria, or blue-green algae. In the event that unacceptably high blue-green algae populations were detected, lakeshore residents and park visitors would be notified to avoid contact with or ingestion of the lake water in order to protect their health.

During sampling events when nutrients were sampled for DEQ, an algae sample was collected from Site 2 at one half meter deep and at the top of the thermocline and stored in a dark bottle with Lugol's iodine solution to preserve the algae for subsequent analysis. If an algae bloom was visually detected (based on the presence of scum at the water surface or a Secchi depth of less than 2 meters), then a sample was to be collected just below the surface at the Swim Beach as well. In the case of an obvious algae bloom, an additional sample was to be collected for immediate microcystin and anatoxin analysis so that Oregon Department of Human Services (DHS) could provide lake users with the appropriate health warnings.

Results

Biweekly algae samples for 2009 were collected and a subset was selected for analysis. Samples from Site 2 on July 1, September 2, September 30, and October 8 at one-half meter and on August 5 from above the thermocline were chosen for analysis in order to represent algal populations throughout the summer and at specific times of interest, such as just before the algae bloom or when pH and dissolved oxygen spiked. Grab samples were collected on September 9, when Secchi depth was 1.55 m (5.1 ft), and September 21, when Secchi depth was 0.94 m (3.1 ft) from just below the water surface at Site 2 and the Swim Beach. The September 9 samples were sent for identification and enumeration to Aquatic Analysts. Additionally, a toxins sample was collected on September 10 to be analyzed for microcystin and anatoxin if the previous day's samples had sufficient levels of cyanobacteria. However, that sample was not analyzed because it was kept past its holding time. A second algal toxins sample was collected on September 30, when Secchi depth was 0.91 m (3.0 ft) and algal scum was visible at the water surface. A half-meter algae grab sample was also collected on September 30, and samples from that day were sent for analysis. On October 7, after seasonal sampling had been completed, a lakeshore resident notified Oregon DHS Health Division of an algae bloom in Blue Lake. As a result, algae and toxin samples were collected from an existing monitoring site near a private dock on the south shore of the lake, where algal scum was most abundant, on October 8 and sent for analysis. A DHS public health advisory was posted on October 14 because the algae were a genus that is capable of forming toxins (*Anabaena*). The algal toxin analyses for September 30 and October 8 were both non-detectable for anatoxin-a, and 1.0 µg/L and 11 µg/L for microcystins, respectively.

Samples for 2008 could not be located at the end of the field season and were never analyzed. For 2002-03, 2006-07, and 2009 select algae samples were analyzed for total algal biovolume and proportion of biovolume for each cyanobacterial (blue-green) algae species.

Figure 13 shows the minimum, mean, and maximum total summer algal biovolume in Blue Lake since 2002. The highest biovolume was in 2003, with an average nearly four times higher than that of next highest year (2009). The averages for 2002, 2003 and 2007 were all less than half the 2009 average. 2007 also had the highest maximum biovolume, nearly 400 million μm^3/ml. The second highest maximum biovolume was in 2009, just over 100 million μm^3/ml.

The maxima for 2003 and 2006 were near 5 million μm^3/ml, and the maximum for 2002 was 2.7 million μm^3/ml. Based on these data, there is no clear increasing or decreasing trend in total algal biovolume in recent years.
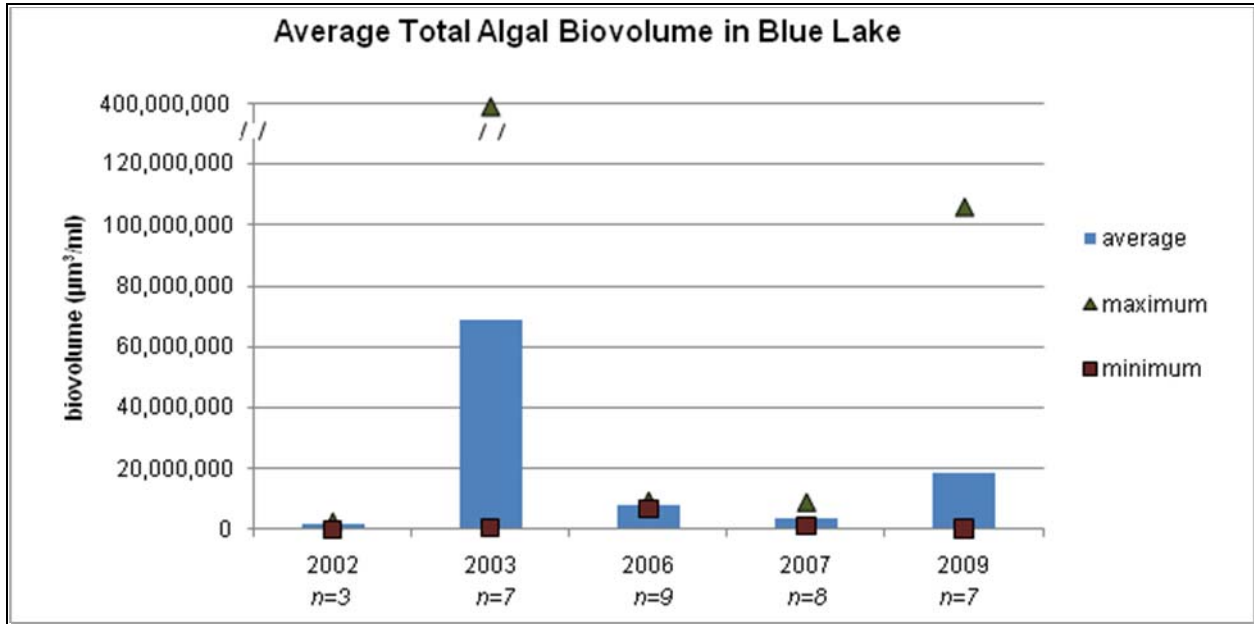

Figure 13: Minimum, average, and maximum summer algal biovolume in Blue Lake for each year. The number of samples for each year is listed at the bottom. Note the break in the y-axis scale for 2003.

Health advisories for toxic algae in waterbodies are issued by Oregon Department of Human Services based on the algal cell density (number of cells per water volume), rather than the algal biovolume. In 2004 and prior, the maximum DHS threshold to lift a health advisory was 15,000 cells/ml of potentially toxigenic cyanobacteria (*Microcystis*, *Anabaena*, and others), or when surface scums containing toxigenic cyanobacteria were present. However, this level was found to be very low risk for recreational users, so the maximum threshold was increased to 100,000 cells/ml of potentially toxigenic cyanobacteria, or 40,000 cells/ml if *Microcystis* or *Planktothrix* are the dominant taxa. Total algal cell density for each sample event in 2002-2009 is shown in Figure 14. Only two events, September 17, 2003 and October 8, 2009, exceeded the thresholds.
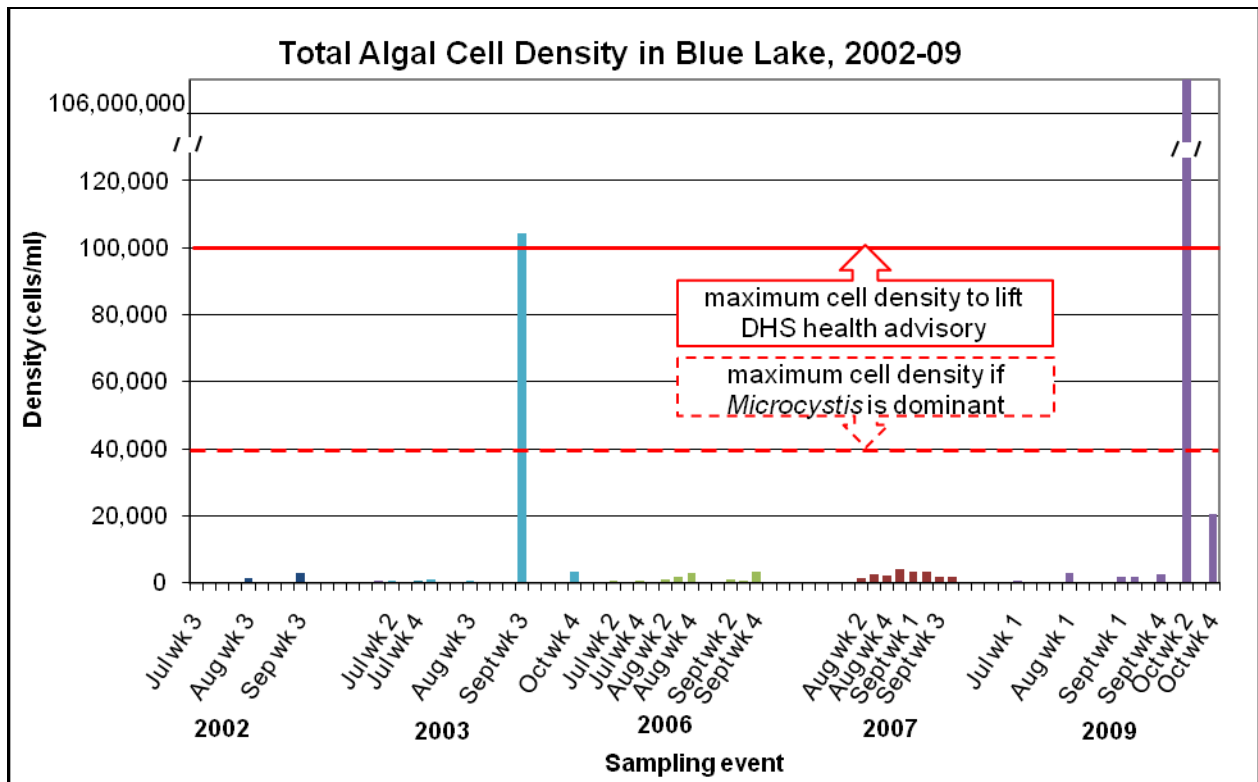
Figure 14: Total phytoplankton cell density (number of cells per milliliter of sample) in Blue Lake, 2002-2009. Where data exist for multiple sites or sample depths on the same date, the highest value is reported here. Note the break in the y-axis scale for the October 2009 sample.

Cyanobacteria (blue-green algae) commonly dominate the algal biomass of nutrient-rich temperate lakes during summer months. This appears to be the case in Blue Lake; among analyzed samples, cyanobacteria comprised most of the total algal biovolume from 2002 to 2009 (Figure 15). The tendency of cyanobacteria to dominate during the summer has to do with their ability to fix nitrogen and thrive in low-nitrogen waters, their ability to regulate their buoyancy to avoid predation or burning, or from decreased grazing pressure by zooplankton due to increased grazing of fish on zooplankton. Blooms are often comprised of filamentous or colonial genera such as *Aphanizomenon, Anabaena* and *Microcystis*, the large size of which also deters some zooplankton grazing. The bloom that occurred during October 2009 was comprised of *Anabaena sp.* and *Microcystis aeruginosa*.
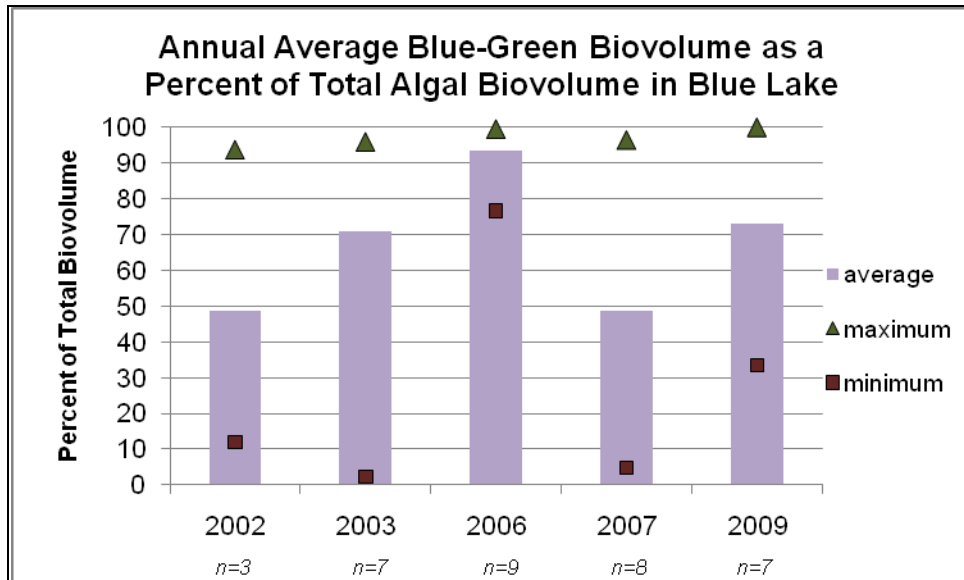
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Figure 15: Average blue-green algae biovolume as a percentage of total algal biovolume in Blue Lake, July – October 2002-2009. The number of samples for each year is listed at the bottom.

Cyanobacterial composition by taxon in Blue Lake varied largely among years (Figure 16). *Anabaena sp.* were by far the most common cyanobacteria in Blue Lake for all years. *Aphanizomenon* and *Microcystis* were also present during some years, but were less common than *Anabaena sp. Anabaena planctonica* was the most common species in 2003, 2006, and 2009, while *Anabaena flos-aquae* dominated in 2007 (see Figure 24 in Appendix A for a composition breakdown by species). No species was dominant in 2002, but the number of samples was low (n=3). The three most dominant species (*Anabaena planctonica, Anabaena flos-aquae,* and *Anabaena circinalis*) are all bloom-formers that can fix nitrogen, regulate their buoyancy, and produce the neurotoxin anatoxin-a and microcystins. *Anabaena* blooms are known to cause odors and unpleasant taste in drinking waters. Another major cyanobacterial species, *Microcystis aeruginosa*, cannot fix nitrogen, is dependent on water-column nitrogen and phosphorus for its growth and is capable of forming both microcystins and anatoxins. *Aphanizomenon flos-aquae* is also a notorious toxic bloom-former.
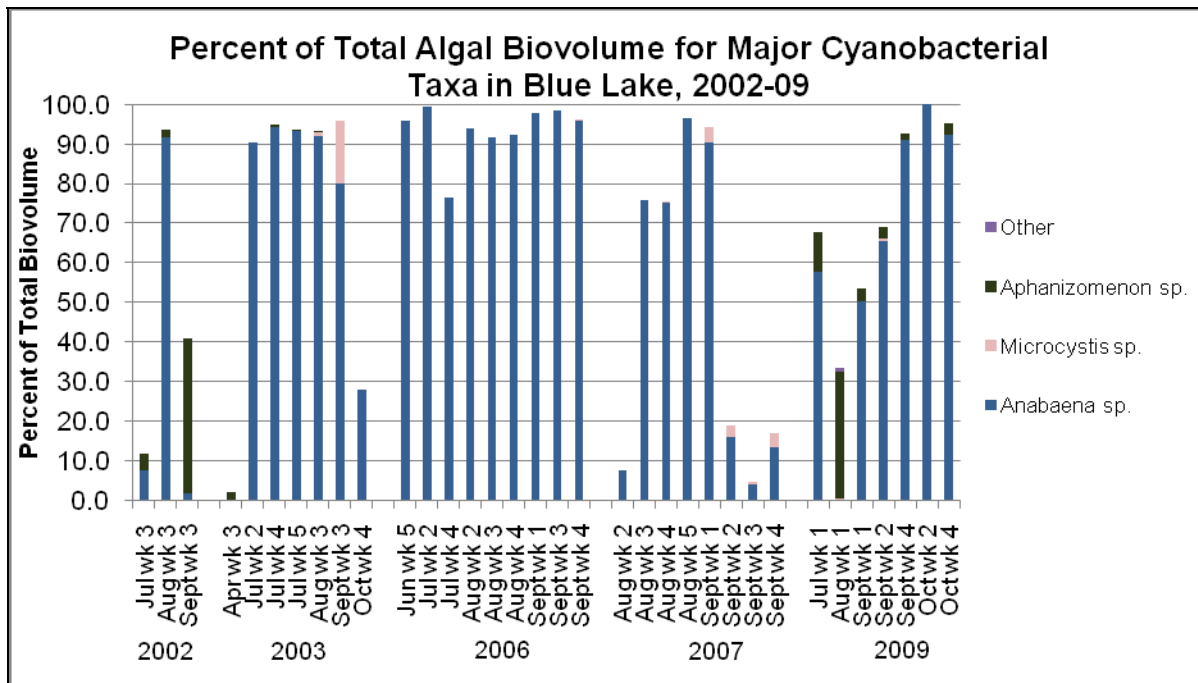
Figure 16: Proportion of major cyanobacterial taxa as a percentage of total algal biovolume in Blue Lake, 2002-2009. Bars that do not reach 100% indicate that other algae besides cyanobacteria were also present in the sample. For more detailed species information, see Figure 24 in Appendix A.

Chlorophyll-*a* is the dominant pigment in phytoplankton and is commonly used as a surrogate for algal biomass because of its ease of measurement. Bi-weekly chlorophyll-*a* data are available for most summer months from 2002-2009, so this may be another useful indicator for algal productivity in Blue Lake, particularly given the low number of algal samples analyzed for some years and the lack of analyzed samples for 2008. At one-half meter depth, the highest chlorophyll-*a* concentrations were mostly in 2006 (Figure 17), which is not consistent with the enumerated algal populations, which were highest in 2003. In July, August, and September (the only months for which there are data), chlorophyll-a concentrations decreased annually from 2006 to 2008 at one-half meter deep. July – September chlorophyll-*a* at the thermocline was also highest in 2006, but unlike the shallower samples, it increased in 2008 and July 2009 relative to the low concentrations in 2007 (Figure 18).
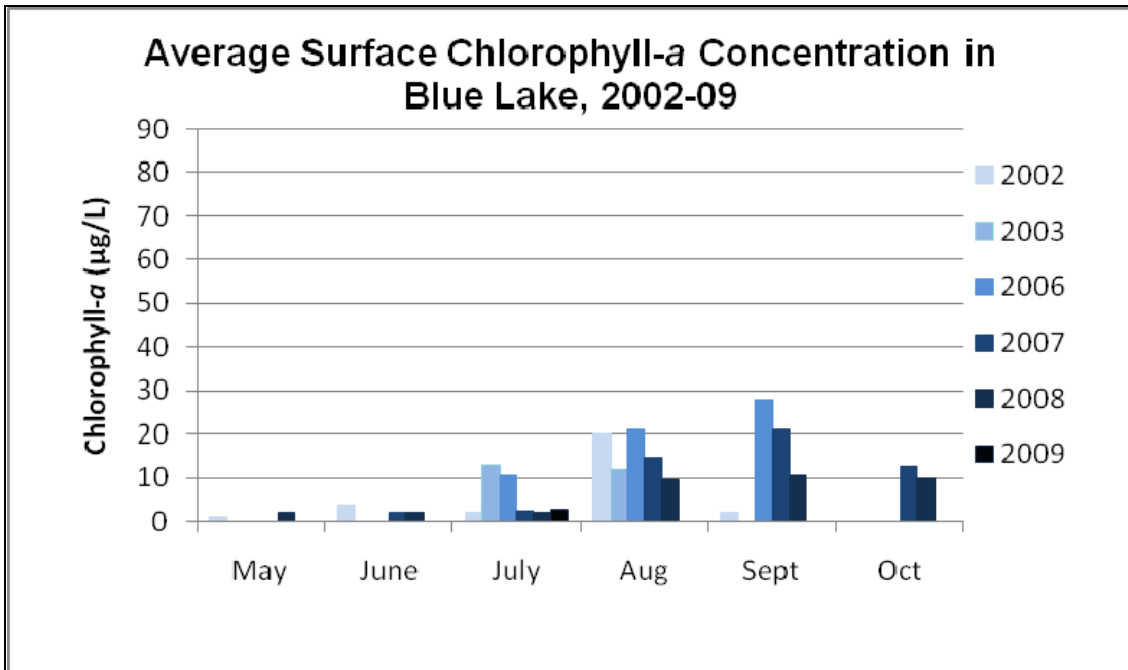
Figure 17: Average chlorophyll-a concentration (ug/L) at Site 2 at one-half to one meter deep, by month, 2002-2009.
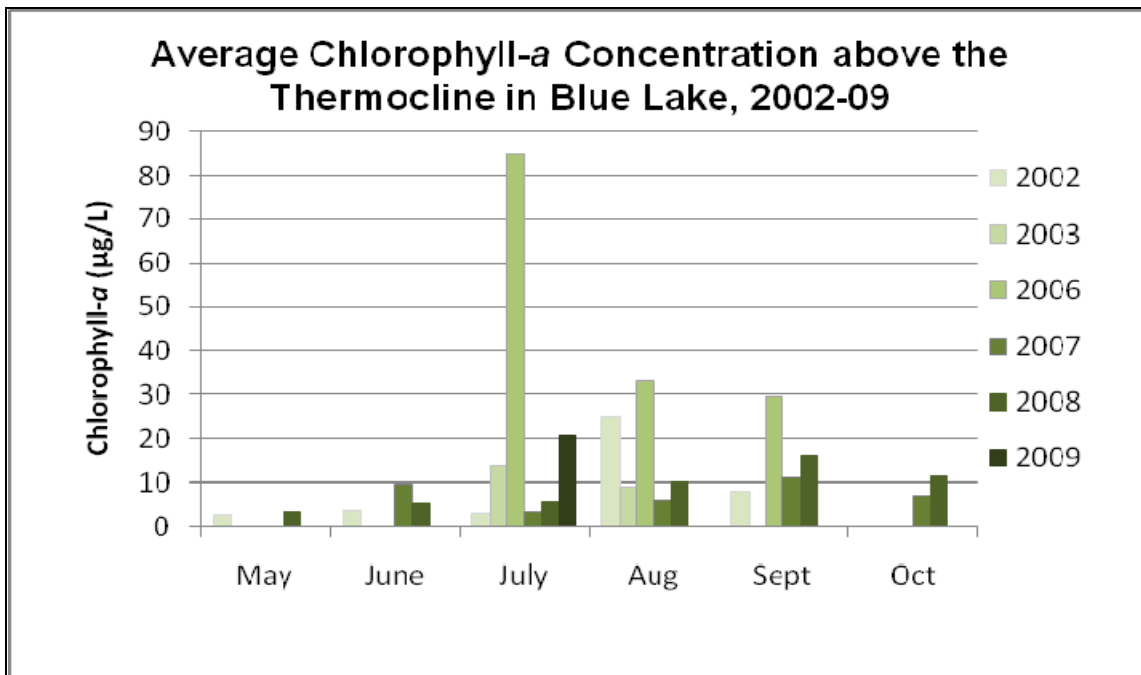

Figure 18: Average chlorophyll-a concentration (ug/L) at Site 2 above thermocline (3-6 meters deep), by month, 2002-2009.

Aquatic vegetation

Two surveys for submersed aquatic plants were conducted during 2009, one on August 4 and 6, and the other on September 10 and 15.   The August survey was conducted later than anticipated due to extreme heat advisories during the preceding week. The survey took place at the same 101 sample points that were surveyed in 2007 and 2008. Emergent vegetation was not sampled or recorded in any of these surveys.   Submersed plants were sampled using a thatching rake mounted to an aluminum pole that was lowered from a boat to the bottom of the lake, rotated 360° once, and lifted from the water. Abundance for each species was determined on a scale of 0-5, with 0 indicating no incidence of that species, 1 being 1-20% coverage of the plant rake by that species, 2 is 21-40%, 3 is 41-60%, 4 is 61-80%, and 5 is 80-100%.

Some pitfalls of this method include differences in abundance determinations among different surveyors and underrepresentation of certain species due to the shape of the rake. Because the tine spacing on the thatching rake is so wide, species that are low to the ground or are minimally branched such as American waterweed (*Elodea canadensis*) may be less susceptible to collection by the rake. To reduce the possibility for differences in abundance determinations among different samplers, a photographic reference for each index category that was used in 2007 was also used in 2009. Additionally, abundance determinations were made cooperatively by two surveyors to improve consistency. Since curlyleaf pondweed (*Potamogeton crispus*) typically senesces by mid-summer, our surveys may not accurately reflect the presence and distribution of this non-native species in 2009.

Every effort was made to replicate the exact methods of previous surveys for consistency in data reporting and analysis. However, this was complicated by inconsistencies in sampling across years. The methods used in 2007 were duplicated because they were sensible and documented in the greatest detail. The abundance scale used in 2003 differed from that in 2007 and 2009. The abundance percentages corresponding to the 0-5 scale used in 2008 were not clearly defined. Care should be taken to ensure that species abundance comparisons made across years are valid based on the indexing system used.

Results

Six aquatic plants and two plant-like macroalgae were found in the August survey. Three of the plants, Eurasian watermilfoil (*Myriophyllum spicatum*), curlyleaf pondweed (*Potamogeton crispus*), and fragrant waterlily (*Nymphea odorata*), are non-native species (Figure 19). All plant and macroalgae species are submersed, except *N. odorata*, which is a floating-leaved plant.   Figure 20 shows the distribution and abundance of all native species in the August survey. The presence of each species is reflected by its p-value, which represents the percentage of sample points at which it was found. Its q-value is defined as one minus p, representing the percentage of instances at which it was absent. The species with the highest p-value in August 2009 was Eurasian watermilfoil (*M. spicatum*), with a value of 0.66, indicating that it was present at 66% of the sites. Common waterweed (*Elodea canadensis*) and muskgrass (*Chara sp.*) both had p-values near 0.2, and all other species had p-values less than 0.1. All p- and q-values are listed in Table 1.
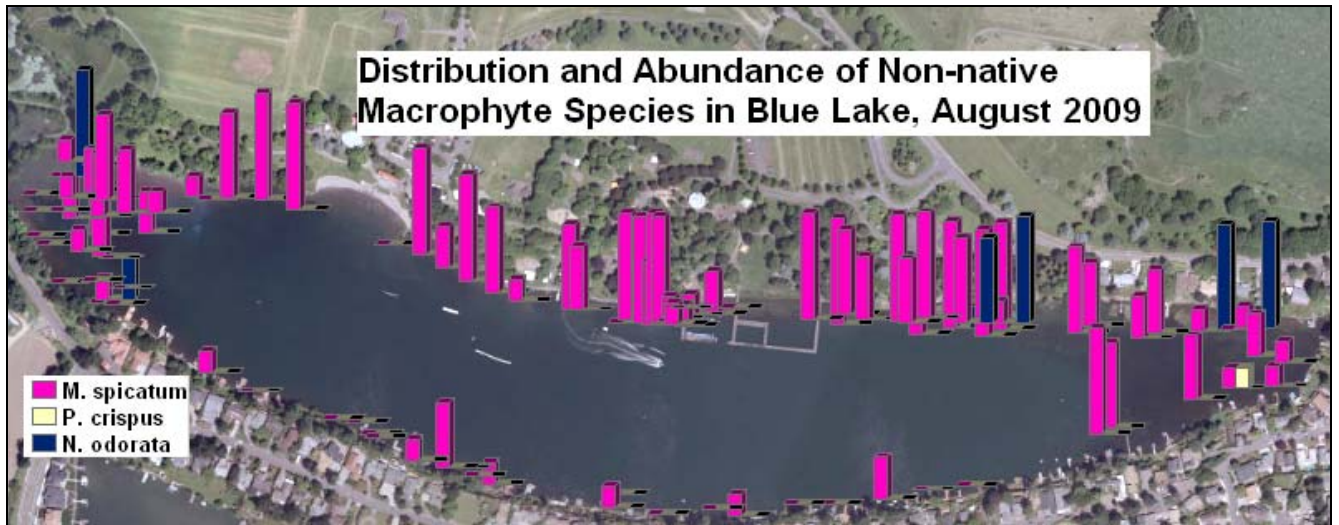
Figure 19: Distribution and abundance of all non-native macrophyte species in Blue Lake on August 4 and 6, 2009.
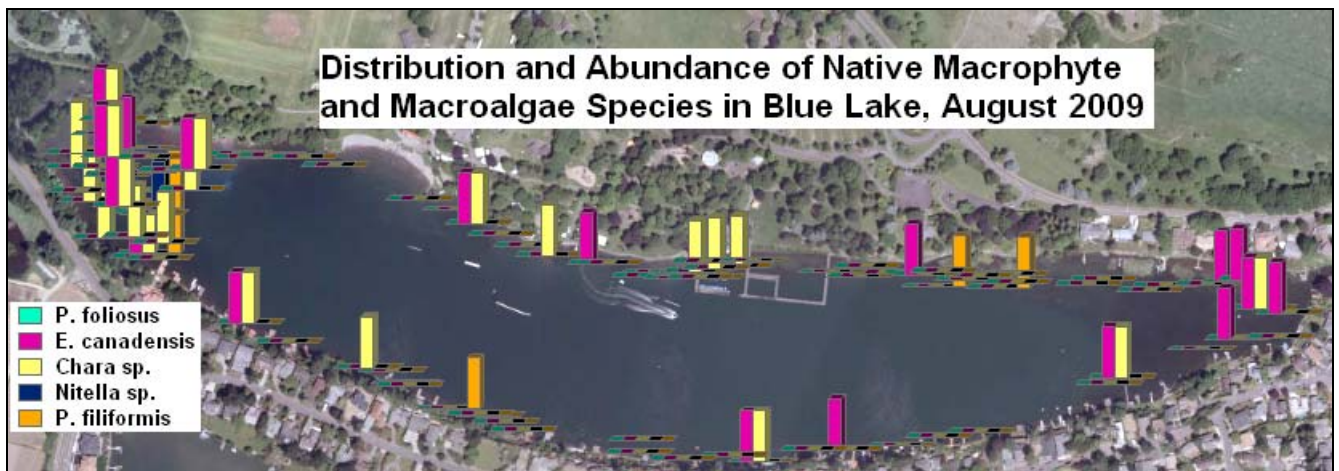

Figure 20: Distribution and abundance of all native macrophyte and macroalgae species in Blue Lake on August 4 and 6, 2009.

	Eurasian Water-milfoil*	Musk-grass	Common Waterweed	Fragrant Waterlily*	Slender-Leaved Pondweed	Leafy Pondweed	Stone-wort	Curlyleaf Pondweed*
	*M. spicatum**	*Chara sp.*	*E. canadensis*	*N. odorata**	*P. filiformis*	*P. foliosus*	*Nitella sp.*	*P. crispus**
Aug 2009 p value	**0.66**	**0.23**	**0.18**	**0.07**	**0.04**	**0.04**	**0.01**	**0.01**
Aug 2009 q value	0.34	0.77	0.82	0.93	0.96	0.96	0.99	0.99
Sept 2009 p value	**0.73**	**0.13**	**0.14**	**0.13**	**0.02**	**0.01**	**0.05**	**0.00**
Sept 2009 q value	0.27	0.87	0.86	0.87	0.98	0.99	0.95	1.00

Table 1: p- and q-values of macrophyte species presence and absence during two sampling events in 2009. *Indicates non-native species.

In the September 2009 survey, Eurasian watermilfoil (*M. spicatum*) was also the most abundant plant, being present at 73% of sites. *E. canadensis, Chara sp.,* and *N. odorata* were the next most common, each being present at 13 or 14% of sites. Stonewort (*Nitella sp.*) was found at 5% of sites, while *P. foliosus* and *P. filiformis* were each found at 1-2% of sites. *P. crispus* was not present in this survey, which would be expected this la
te in the growing season. See Appendix A for maps of the distribution of native and non-native species in September 2009.

Eurasian watermilfoil (*M. spicatum*), the most frequently encountered plant, was found at 73% of sites in September 2009, compared with 71% in September 2007 and 44% in July 2008 (Figure 21). In September 2003, however, it was found in less than one percent of sites. The low presence of *M. spicatum* in July 2008 compared to in 2007 and 2009 may be due to the fact that biomass of this species usually peaks in September, so July samples would be expected to be lower. However, the near absence of *M. spicatum* in September 2003 is surprising based on more recent data (2007-09) as well as historical data (Beak, 1979). Compared to 2007, the presence of all native species increased in 2008-09, except leafy pondweed (*P. foliosus*). Over this time, the presence of two non-native species, fragrant waterlily (*N. odorata*) and curlyleaf pondweed (*P. crispus*) also increased. In September 2003, 2007 and 2009, 69, 23 and 21% of sites had no macrophytes, respectively. Fifteen percent of sites in July 2008 had no macrophytes. The higher incidence of sites with no plants in the sample in 2003 may be due to the larger number of samples collected in 2003 (160) compared to later years (99-101 sites), as well as the later spread of plants, particularly Eurasian watermilfoil, along the northern shore of the lake, first evident in 2007. Figure 22 shows the distribution of macrophyte and macroalgae species in 2003, when it was barely present in the lake.
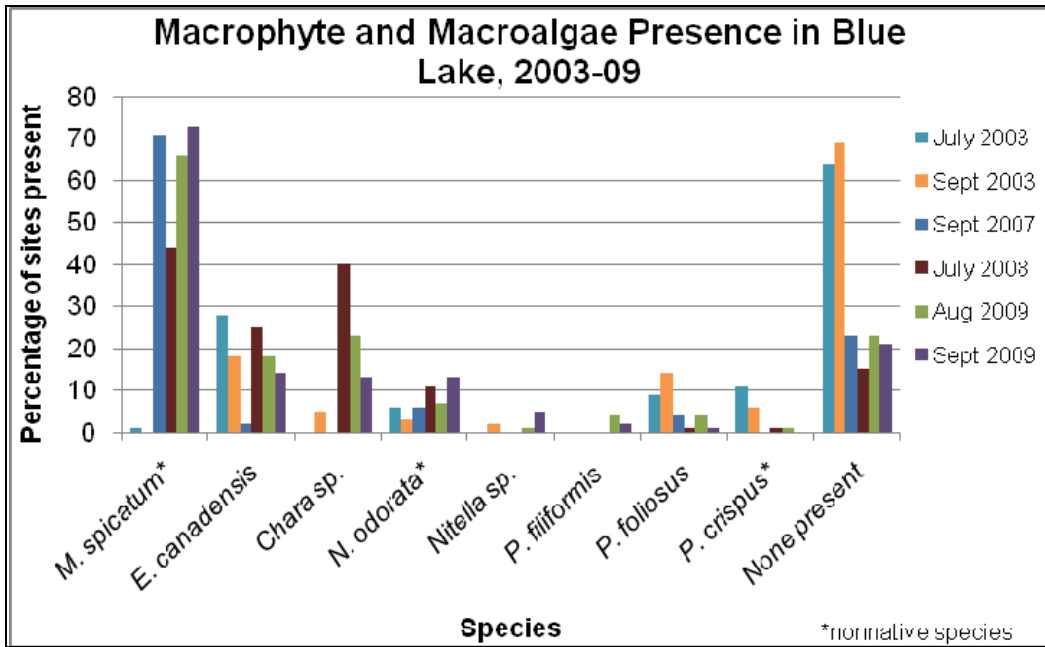
Figure 21: Presence of macrophyte and macroalgae species in Blue Lake from 2003 to 2009. *Indicates non-native species.
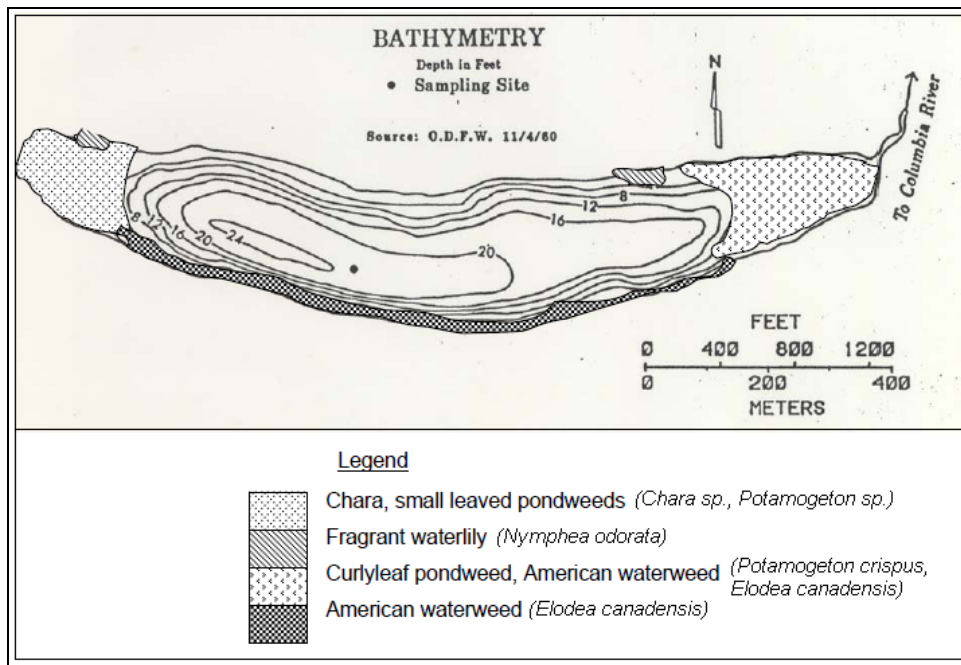

Figure 22: Vegetation distribution in Blue Lake in 2003. *Amended from Pfauth and Sytsma, 2004.*

Maximum species richness increased since 2007, with 4 species found in 2007, 6 in 2008, and 8 in 2009. Richness in 2003 was 5 in July and 6 in September. Average abundance (the total of all abundance 0-5 index scores for a species divided by the number of sample sites) increased for most species in September 2009 compared to September 2007 (abundance data for 2003 and 2008 cannot be reliably compared) (Table 2). The average abundance score increased the most for *E. canadensis*, *Chara sp.*, and *N. odorata*. There was no net change in total

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abundance for *P. crispus*. *Myrioplhyllum spicatum* and *P. foliosus* were the only species that decreased in average abundance compared to in 2007. Changes for *Nitella sp., P. foliosus,* and *P. filiformis* were minimal.

	Eurasian Water-milfoil*	Musk-grass	Common Waterweed	Fragrant Waterlily*	Slender-Leaved Pondweed	Leafy Pondweed	Stone-wort	Curlyleaf Pondweed*
	*M. spicatum**	*Chara sp.*	*E. canadensis*	*N. odorata**	*P. filiformis*	*P. foliosus*	*Nitella sp.*	*P. crispus**
Sept. 2007	2.11	0	0.02	0.22	0	0.04	0	0
Sept. 2009	1.96	0.13	0.19	0.33	.02	0.01	.05	0
Change	**-0.15**	**0.13**	**0.17**	**0.11**	**0.02**	**-0.03**	**0.05**	**0**

Table 2: Average abundance scores for each macrophyte and macroalgae species in September 2007 and 2009. These numbers represent the sum of each abundance index value (0-5) for all sample points for a given species, divided by the number of sample points. The change in average scores between the two years is shown in the bottom row. *Indicates non-native species.

While the recent increases in species richness and average abundance of native species and the decrease in average abundance of a problematic non-native species (*M. spicatum*) since 2007 seem encouraging, they are based on only a few years' data and should not be regarded as solid trends until more data are available. Differences among years may be due to annual variation in plant communities as a result of natural variations in water chemistry and physical conditions, differences among surveyors, or from using sampling points rather than an exhaustive survey. For example, Eurasian watermilfoil (*M. spicatum*) was only found at one of 160 sampling sites in July 2003 and not at all in September 2003, even though it was by far the most abundant macrophyte in previous surveys (from the late 1970s) and in all years since 2003.

Species richness is positively affected by alkalinity and pH and negatively affected by water level variations and turbidity. Light is also an important factor in macrophyte and macroalgae distribution; macrophytes can typically survive to depths where light is at least 21% of incident (surface) photosynthetically available radiation (PAR) and macroalgae, at least 10% of PAR. Nutrient concentrations in the water column are unlikely to be controlling factors in the abundance of macrophytes, especially compared to phytoplankton, because most macrophytes have much lower nitrogen and phosphorus requirements per unit of fixed carbon (biomass). Also, most macrophytes take up nitrogen and phosphorus mostly from the sediments rather than the water column. Last, they are slow-growing (relative to phytoplankton), so their growth is less likely to be affected by short term variations in nutrient availability.

Conclusions

Effect of Solarbees

In 2007, before the installation of the SolarBees, a framework with which to assess the effectiveness of the SolarBee units was developed. It was determined that a statistically significant difference (using alpha = 0.1) in the direction of improving water quality in any of three parameters (pH, Secchi depth, and blue-green algal cell counts) from data collected at the same time of year under similar weather conditions would be indicative of the SolarBees' success. This approach uses the assumption that changes in those parameters before and after 2007 are caused by the SolarBees. Table 3 shows a comparison of July to October average pH (total, at one-half to one meter deep, and just above the thermocline), Secchi depth, and blue-green algal cell densities for pre-SolarBee years (2002-03, and 2006) and post-SolarBee years (2007-09).

For the pH comparison, biweekly monitoring data from DEQ collected at Site 2 in July through October were used, because those are the months of greatest concern and due to the completeness of the dataset for those months. Data from two depths, near the surface (0.5-1 m) and just above the thermocline (3-6 m), were included in the analysis.   Where more frequent data existed (during the annual wakeboard tournaments, when water quality was measured daily for one week, for example), data were excluded so as not to bias the analysis. A comparison of pH using the combined set of datapoints from both depths was first analyzed to detect whether or not a significant difference existed in pH before and after the installation of the SolarBee units. Then, in order to elucidate where the changes were occurring, data were analyzed separately for each of the two depths. For the Secchi depth comparison, all weekly Secchi depth data from Site 2 were used. For the algal comparison, blue-green algal cell density values (cells/ml) from July to October were compiled from existing reports from Aquatic Analysts. Since 2006, Aquatic Analysts provided blue-green cell density values in their reports. For 2002 and 2003, however, those values were back-calculated by dividing the total biovolume for each cyanobacterial species by the biovolume of a single cell of that species using cell biovolume values provided by Aquatic Analysts (see Table 7 in Appendix B: Additional Tables). For all years, where data were available at multiple sites or depths for the same date, the sample with the highest total biovolume was used in the analysis. Pre- and post-SolarBee data were compared using a t-test with alpha = 0.1.

pH, when data for the two depths were combined, increased significantly after the installation of the SolarBees (*t=3.31, p=0.07*) (Table 3). This, however, is in the direction of worsening water quality. When separated by depth, pH did not change significantly near the epilimnion surface, but increased significantly just above the thermocline (*t=5.54, p=0.03*). For the combined pH comparison, the number of sampling points is much higher in July for earlier years and is higher in October for later years (Table 4).

Secchi depth also increased significantly after the installation of the SolarBees (*t=2.88, p=0.09*). Based on the Secchi depth, the SolarBees would be considered successful according to the pre-determined indicators. However, it should be noted that the pre-SolarBee average Secchi depth may be under-represented due to the bulk of sampling events taking place early in the summer when algal productivity, the main reducer of Secchi depth in Blue Lake, tends to be low (Table 5). Also, the total number of pre-2007 Secchi depth data points is low. Moreover,

another parameter (pH) changed significantly in the direction of worsening water quality. No mention was made in 2007 as to whether or not the determination of SolarBee success based on one parameter would be overturned by the occurrence of a statistically significant change in the direction of worsening water quality for another parameter.

Average blue-green algal cell density (cells/ml) did not differ significantly before and after the SolarBee installation (*t=0.55, p=0.46*).   As an exploratory analysis, total algal biovolume before and after SolarBee installation was compared using a t-test, and it was found that the average total algal biovolume for all species did not differ between the two time periods (*t=0.35, p=0.56*).   The average blue-green algal biovolume as a percentage of total biovolume also did not change significantly after the SolarBee installation (*t=2.5, p=0.12*).

	pH combined		pH @ 0.5-1 m		pH @ 3-6 m		Secchi depth (ft)		Blue-green algal cell density (#/ml)	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
July – October mean	8.07 ± 0.75	8.31 ± 0.51	8.75 ± 0.52	8.54 ± 0.47	7.76 ± 0.62	8.09 ± 0.46	5.83 ± 1.88	7.77 ± 3.49	589,575 ± 2326294	138,557 ± 394594
number of samples	51	49	16	23	35	24	10	43	16	15
t statistic	3.31		1.87		5.01		2.88		0.55	
p value	0.07*		0.18		0.03*		0.09*		0.46	

Table 3: Comparison of pH, Secchi depth, and blue-green algal cell density before (pre) and after (post) Solar Bee installation in Blue Lake (May 2007). "Pre" includes data from 2002, 2003, and 2006. "Post" includes data from 2007, 2008, and 2009. Only data from July-October were used in this analysis. Plus or minus values represent standard deviation. *Indicates significant difference using α = 0.1.

	July	August	September	October	TOTAL
Pre-SolarBee (2002-03, 2006)	24	12	12	3	**51**
Post-SolarBee (2007-09)	13	12	14	10	**49**

Table 4: Number of datapoints per month used for the combined pH comparison.

	July	August	September	October	TOTAL
Pre-SolarBee (2002-03, 2006)	5	3	1	0	**9**
Post-SolarBee (2007-09)	15	12	11	5	**43**

Table 5: Number of datapoints per month used for the Secchi depth comparison.

	July	August	September	October	TOTAL
Pre-SolarBee (2002-03, 2006)	5	5	5	1	**16**
Post-SolarBee (2007-09)	1	5	7	2	**15**

Table 6: Number of datapoints per month used for the blue-green algal cell density comparison. The post-SolarBee values include data from 2007 and 2009 only, because 2008 samples were not processed.

Improvements

Secchi depth increased significantly after the installation of the SolarBees in 2007. Average monthly chlorophyll-*a* values from 2007 and 2008 tended to be lower than the high values in 2006. Anecdotal accounts from lakeshore residents and park staff indicate that the algal productivity has decreased in recent years, although the limited number of analyzed samples complicates validation of these accounts.

Continuing problems

High pH continued to be problematic in Blue Lake in 2009, with 16 of 19 weekly measurements at one-half meter and six of 19 measurements just above the thermocline at or above the DEQ benchmark of 8.5 standard units. Additionally, pH at the bottom of the epilimnion (just above the thermocline) has increased on average since the installation of the SolarBees in 2007.

Eurasian watermilfoil (*Myriophyllum spicatum*), the most abundant macrophyte in the lake and a non-native invasive species, has spread throughout the lake since 2003, when it was only found at one site, to being found at 77% of sites in September 2009. The abundance of this species, especially along east, west, and north shores of the lake was sufficient in 2009 to cause frequent entanglement of boat motors when moving through those areas.

Based on the available algae biovolume data, there has been no significant change in total algal biovolume or the proportion of it comprised by cyanobacterial species after the installation of the SolarBees. While a toxic blue-green algae bloom did occur in 2009, it was late enough that it occurred after the peak season for water-contact recreation. However, it had by far the highest algal cell density for all years present, exceeding the DHS health advisory threshold by 1000-fold. Because the algal productivity in the lake is limited by phosphorus, the release of sediment-bound phosphorus to the water column during fall turnover, in concert with warm temperatures and ample sunlight after turnover may have fueled the October bloom. Continued mixing of the water column by the SolarBees may have aided its intensity.

Summary

The observed changes in water chemistry, algal productivity, and macrophyte abundance and distribution are likely related. One hypothesis is that the SolarBees succeeded in reducing algal productivity, resulting in increased water clarity (measured by Secchi depth). This increase in water clarity and light penetration may have increased the growth of submersed plants, and allowed for the spread of macrophytes, especially *M. spicatum*, across the north, east, and west shores of the lake. As a result, photosynthesis by the abundant macrophytes may have caused the observed increases in pH. However, there is no clear evidence that any changes that occurred were verifiably caused by the SolarBees. Notes from a former Metro scientist indicate that in the past, Blue Lake has shifted between algal and macrophyte dominance every few years.

An alternate hypothesis is that altered food web dynamics may cause changes in a lake's algae populations, which could then drive the observed changes in water clarity and macrophyte populations. Trout have been stocked in Blue Lake by Oregon Department of Fish and Wildlife for recreational fishing since at least 2003. Since 2006, 4500 trout were added per year. In 2005, 1500 were stocked, while none were stocked in 2004. 2003 stocking records could not be

found. Therefore, the increasing trend of stocking more fish could have induced greater grazing pressure on the zooplankton by the trout, which would in turn reduce zooplankton grazing on phytoplankton, allowing for increases in the phytoplankton populations. However, this hypothesis does not seem to fit the recent changes seen in Blue Lake, as no clear increase in phytoplankton populations occurred over this time as would be expected.

Recommendations

Several factors may constrain future efforts to improve water quality at Blue Lake.   First, natural (pre-development) conditions of the lake appear to be eutrophic (high nutrient). Sediment core analyses taken in the 1970s indicated that the cyanobacteria populations in the lake in 1900 were similar to those in the '70s. External nutrient loading appears to be a less important determinant of Blue Lake's productivity than it might be for other lakes of its size and latitude, because of its small drainage basin area relative to the area of the lake. Also, the lack of hydrologic inflows or outflows such as streams into or out of the lake means that precipitation, evaporation, and groundwater flow control lake recharge. Therefore, the flushing of nutrients from the lake is relatively slow, and they are instead recycled within the sediments, biota, and water column. According to the nutrient budget calculated by Beak (1979), 98% of the phosphorus in the lake came from the sediments. The next highest inputs estimated by Beak are rooted aquatic plants (1.2%) and precipitation (0.6%). Surface runoff from fertilizers only accounted for 0.004% of the total phosphorus budget in their study, so reducing fertilizer and other anthropogenic phosphorus inputs is unlikely to have a demonstrable effect on algal populations.

The lake has historically had sufficient nutrients to support abundant algae and macrophytes. Additionally, incoming groundwater from the Blue Lake Aquifer is high in both nitrogen and phosphorus. Moreover, the physical characteristics of the lake (soft sediments, shallow depth, gentle slope, high light availability, and warm temperature) are suitable for macrophyte growth. These factors may be even more important than nutrient levels in determining abundance and distribution of aquatic macrophytes and macroalgae in Blue Lake. Because nutrients tend to be consistently abundant, light, temperature, and water turbulence may also be more important factors in algal distribution.

Therefore, reducing the anthropogenic nutrient load does not appear to be a viable option to reduce nuisance algae and macrophyte levels in Blue Lake. Instead, the approach that has been taken of epilimnion circulation using the SolarBee units appears to be a reasonable one, at least for algae control.   However, lasting shifts in algal or macrophyte populations may take several years to occur and more years of data would be necessary to detect such changes. While anecdotal accounts from park staff and residents indicate that algae populations have decreased and water clarity has increased since the installation of the three SolarBee units in 1997, they also indicate that macrophyte problems have been worse since then.   The data analyzed in this report seem to support these statements.

This double-bind highlights the ecological theory of alternate stable states in small, shallow lakes: a shallow eutrophic lake can support high levels of algae, but if the algae populations are lowered, increased water clarity and high levels of available nutrients allow for profuse growth of aquatic plants. Alternately, the removal of aquatic plants may lead to increased sediment re-suspension and nutrient diffusion into the water column, which may increase algae populations and turbidity. With that in mind, future management activities

should be developed with the ultimate goals of interested parties (Oregon DEQ, Metro, and Interlachen Homeowner's Association), as well as natural lake aging processes taken into account.

Future management plans should also take into account the development of the Blue Lake Golf Learning Area, to be located at the East Wetland, across Blue Lake Road from Blue Lake Park. Changes such as circulating groundwater through the lake or irrigating the golf course using lake water would impact Blue Lake's water quality. Likewise, the addition of fill materials to the East Wetland area and subsequent compression of the underlying soils could change the movement of groundwater into and out of Blue Lake. Such a change could also impact the lake's water chemistry.

If algal control is the primary goal, continued use of the SolarBee units only until fall turnover and continued monitoring are recommended in order to have a solid base of data that would represent long-term changes rather than short-term annual variations. For macrophyte control, control methods in target areas (around boat docks), such as harvesting, bottom barriers, or small-scale herbicide applications may be effective. However, the preservation of some macrophyte cover is important for fish habitat and controlling sediment re-suspension. Management of Blue Lake may involve a trade-off between having abundant macrophytes, abundant algae, or some level of both, but it cannot be expected to be a clear lake with low productivity. Acceptable outcomes in terms of lake productivity should be examined among interested parties, so that long-term management goals and plans can be determined. The existing dataset and ongoing monitoring will be helpful in assessing changes in the lake chemistry and primary productivity over time and evaluating the effectiveness of management activities. Continued collaboration among all three interested parties in development of future management activities will be important.

References:

Beak, 1979. Environmental Investigations and Recommended Modifications for Blue Lake, Multnomah County, Oregon. Beak Consultants Incorporated, Project D2416.

Dunne and Leopold, 1978. Water in Environmental Planning. W.H. Freeman and Company, New York.

Eilers, J., 2009. An Assessment of Circulation Technology Applied to Blue Lake, Oregon (Draft).

Kalff, J., 2002. Limnology. Prentice Hall, New Jersey. 592 p.

Oregon Department of Human Services, 2009. Public Health Advisory Guidance for Toxigenic Cyanobacteria in Recreational Waters. Version 1.2.

Pfauth M. and M.D. Sytsma, 2004. Integrated Aquatic Vegetation Management Plan. Portland State University Center for Lakes and Reservoirs.

Williams, K. 2003. Draft Blue Lake Discussion Paper. Oregon Department of Environmental Quality.

Appendix A: Additional Figures
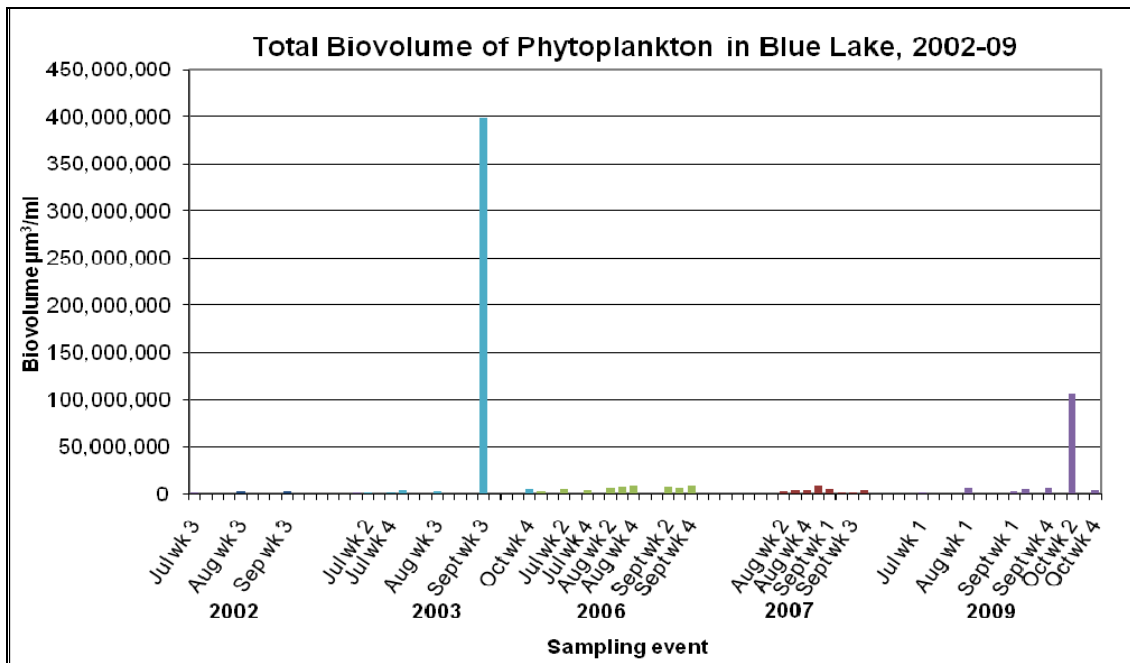
Figure 23: Total phytoplankton biovolume (all species) for each sampling event, by month, week, and year.
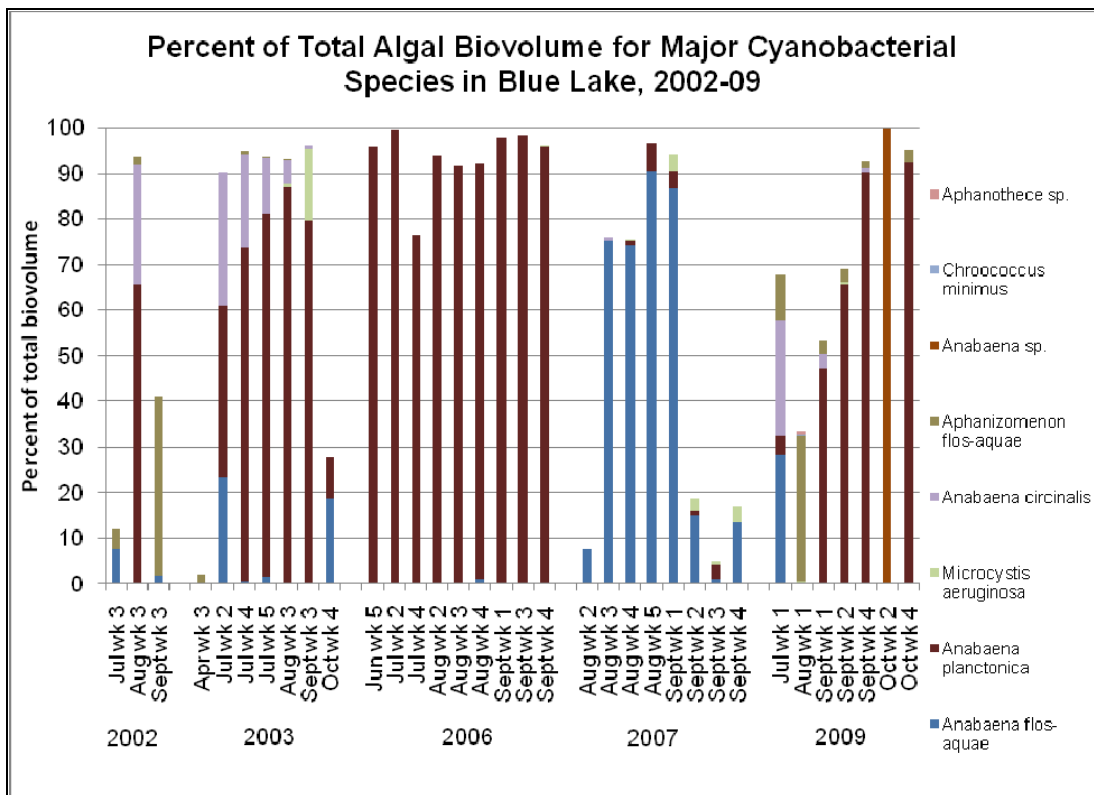

Figure 24: Proportion of total algal biovolume for major cyanobacterial species in Blue Lake, 2002-2009.

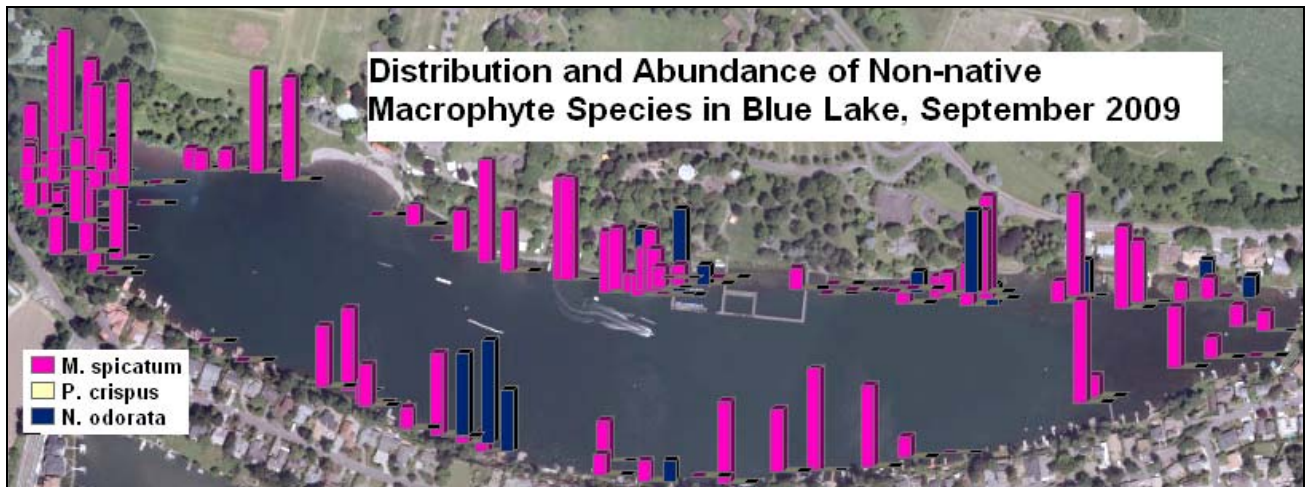**Figure 25: Map of distribution and abundance of native macrophyte and macroalgae species in Blue Lake in September 2009.**

Figure 26: Map of distribution and abundance of non-native macrophyte species in Blue Lake in September 2009.
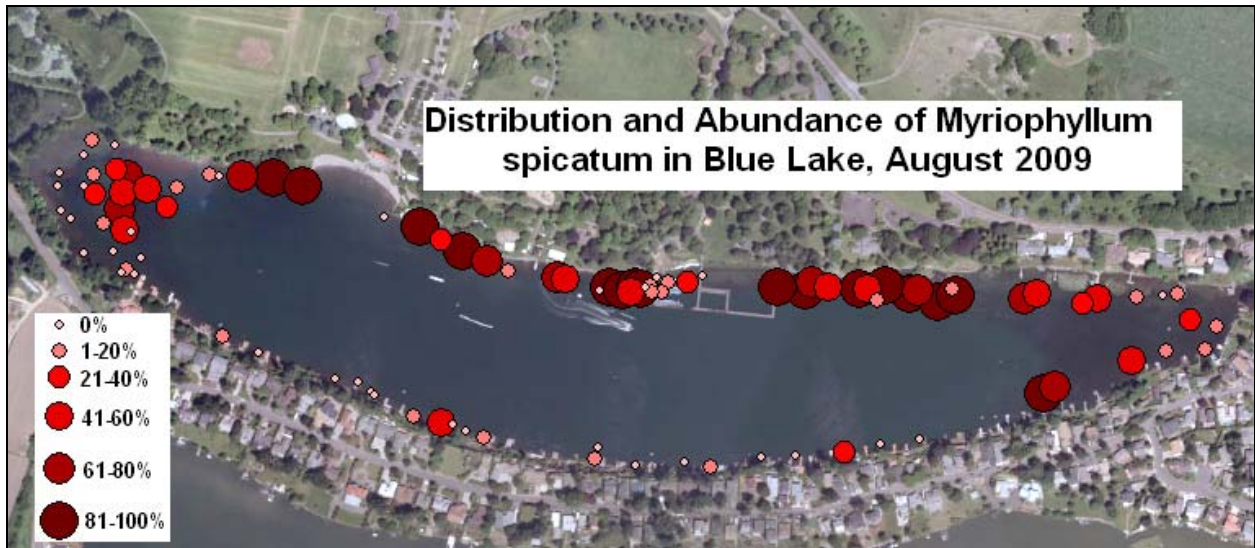
Figure 27: Map of distribution and abundance of *Myriophyllum spicatum* in Blue Lake, August 2009. Percentages indicate the percent cover of the plant rake by a given species.
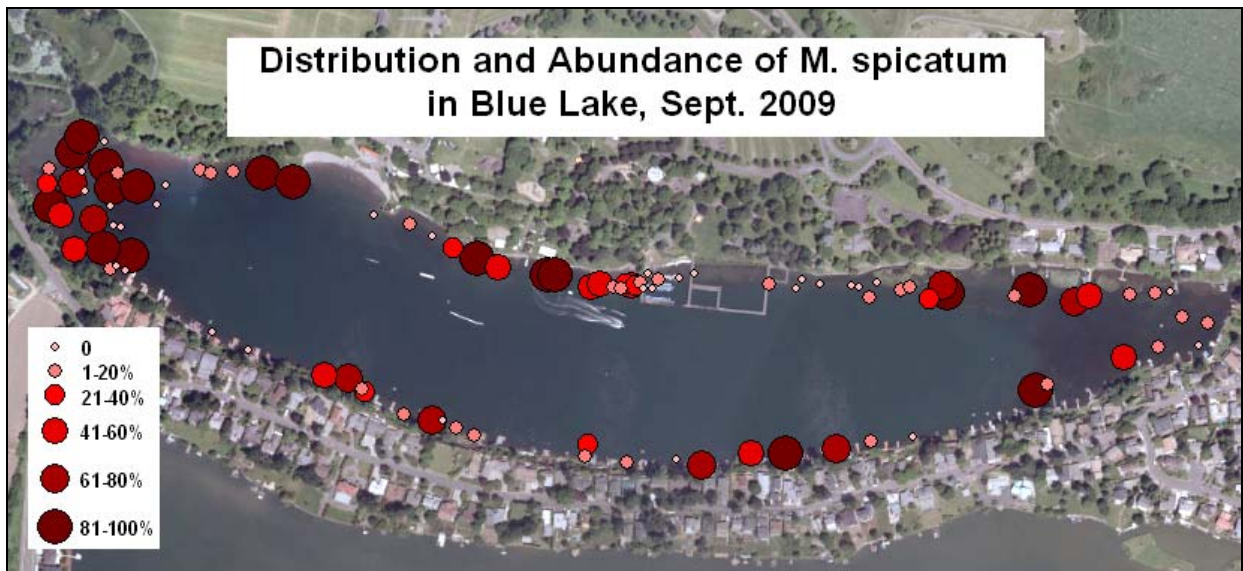

Figure 28: Map of distribution and abundance of *Myriophyllum spicatum* in Blue Lake, September 2009. Percentages indicate the percent cover of the plant rake by a given species.

Appendix B: Additional Tables

Species	Biovolume per cell (µm^3)
Anabaena circinalis	71
Anabaena flos-aquae	67
Anabaena planctonica	183
Aphanizomenon flos-aquae	63
Aphanothece sp.	3
Chroococcus minimus	14

Table 7: Individual cell biovolume data provided by Aquatic Analysts. These data were used to back-calculate blue-green algal cell density values for 2002 and 2003 for the SolarBee comparison.