An Assessment of Circulation Technology Applied to Blue Lake, Oregon

Joseph Eilers*
SolarBee, Inc.
Bend, OR

March 23, 2009

* Northwest Regional Manager for SolarBee, Inc. & Prof. Hydrologist, MaxDepth Aquatics, Inc.

ABSTRACT

Blue Lake is a small (24.7 ha), shallow (Z_{max} = 7.3 m) located 8 km east of Portland, Oregon. The lake is bordered by 81 private residences on the south shore and by Blue Lake Park, operated by Portland Metro, on the north shore. The lake has a 70-year record of chemical applications and various interventions used in attempts to control excessive submerged macrophyte growth and cyanobacterial blooms. Three SolarBee circulators were installed in Blue Lake in May 2007 with the specific objective of minimizing summertime cyanobacterial blooms. Water quality sampling and macrophyte surveys were conducted by staff from Portland Metro in 2007 and 2008, supplemented by multi-parameter sonde measurements collected by SolarBee staff. Water quality in both 2007 and 2008 was improved compared to data collected from 2002, 2003 and 2006. Secchi disk transparency for the June-September period increased from pre-treatment median values of 5.95-7.5 m and from 11.9-13.0 m during the circulation treatment. pH decreased from medians of 8.8-8.9 during pre-treatment years to 8.1-8.2 in 2007-2008. Chlorophyll *a* median summer values ranged from 2.8 in 2002 to 15.1 µg/L in 2003 and 27.5 µg/L in 2004. Chlorophyll *a* declined to a median concentration of 6.8 µg/L in 2007 and to 2.2 µg/L in 2008. Total phosphorus concentrations declined from median concentrations of 40 µg/L in 2003 and 2006 to 26 µg/L in 2007 and 25 µg/L in 2008. Median summer total Kjeldahl nitrogen ranged from 525 µg/L to 800 µg/L prior to treatment and from 325-350 µg/L during treatment. The macrophyte, *Myriophyllum spicatum* (Eurasian water milfoil), was present at 38 percent fewer sites in 2008 compared to 2007 and it was abundant at 86 percent fewer sites in 2008 compared to 2007. A native species of macrophyte, *Elodea canadensis* (Canadian waterweed) was present at only 2 sites in 2007 compared to 25 sites in 2008. The native macroalgae, *Chara* (muskweed), was not present in 2007, but was found at 40 percent of the sites sampled in 2008. Blue Lake, which had been posted in previous years warning against recreational contact with cyanobacteria, was open to the public for recreation throughout 2008. All objective measures of performance including decreased cyanobacteria, improved measures of water quality, and reduction in invasive macrophytes, demonstrated that circulation technology, when applied properly, can yield dramatic improvements in lake condition.

INTRODUCTION

Management of shallow lakes, particularly those in urban environments, presents numerous challenges because of high recreational demand and increased likelihood of problems associated with extensive macrophyte growth and nuisance algal populations. Blue Lake, located 8 km east of Portland, Oregon, is typical of many shallow, urban lakes (Figure 1). It has a surface area of 24.7 ha (61 ac), a maximum depth of 7.3 m (24 ft), and mean depth of 3.5 m (11 ft) [Figure 2]. The entire southern shore and eastern end of the lake are lined with 81 private residences and the northern shore is bounded by Blue Lake Park, a public facility managed by Portland Metro.

Figure 1. Blue Lake shown north of Fairview Lake on a satellite image captured on July 12, 2008. Blue Lake Park is shown to the north of Blue Lake.

Blue Lake has no surface inlets and has an intermittent outlet on the east end that discharges to the Columbia River. Natural inflow to Blue Lake is from groundwater discharge and precipitation on the lake surface. Annual precipitation for the area averages 94.2 cm (37.07 in) [PDX 1970-2000]. The stage for Blue Lake declines during the summer, but in recent years groundwater has been pumped into the west end of the lake from a well field operated by the Portland Water Bureau.

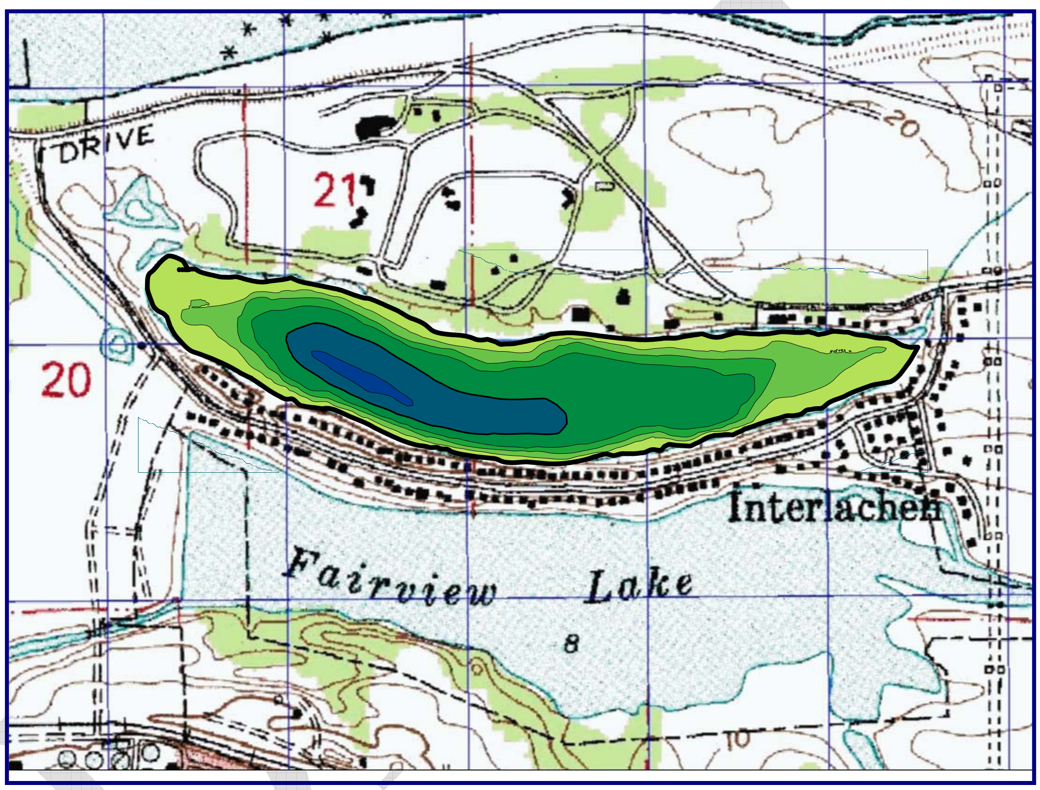


Figure 2. Morphometry of Blue Lake illustrating the location of the deepest portion on the west end of the lake.

Blue Lake has been operated as a recreational resource for Portland and surrounding areas for over 70 years. Management interventions used to address various issues have been summarized by Eilers & St. Amand (2004). These actions have included repeated chemical treatments with copper sulfate, sodium arsenite, 2,4-D, and several chlorinated hydrocarbons. Other treatments have included rotenone to remove "rough" fish, aquatic weed harvesting, lake drawdown, lake flushing, and supplemental inflows derived from groundwater pumping. A management plan prepared for Portland Metro and the Interlachen Association recommended continued use of herbicides and other measures to control aquatic macrophytes (Pfauth & Sytsma 2004).

The lakeshore residents decided to pursue a new strategy, one that avoided the use of chemicals and appeared to be sustainable. The residents entered into a non-binding agreement with SolarBee, Inc. (www.solarbee.com) to try circulation technology in Blue Lake for the sole purpose of attempting to control the excessive populations of cyanobacteria that had negatively impacted the lake in recent years. SolarBee, Inc. agreed to provide three circulators to operate in Blue Lake free of charge for 2007 upon the condition that the residents and cooperating management agencies would purchase the units if they were successful in controlling the cyanobacteria. Because of mixed result and complicating conditions in 2007, which are described later, that agreement was extended through 2008. The purpose of this report is to present the results of water quality and macrophyte sampling in 2007 an 2008 and to compare those results with data from previous years.

METHODS

Three SolarBee circulators (model SB10000HW) were installed in Blue Lake on May 4, 2007 at the locations shown in Figure 3. Each unit was secured with one anchor line attached to one of three floats. This allowed each circulator to move freely in a radius of about 30 m (100 ft). The intake tubes on the two end units were set to a depth of 3 m (10 ft) and the central unit was set to 4.5 m (15 ft). The circulators have a maximum pumping rate of 54,500 m^3/day (10,000 gallons per minute; 44.3 ac-ft/d), but the average daily rate is about 46,325 m^3/day (8,500 gpm; 37.7 ac-ft/d). Under isothermal conditions, this pumping rate would result in completely mixing the lake every 6.2 days [700 ac-ft / (37.7 ac-ft/d X 3 units)]. The SolarBee circulators were operated continuously through 2007. To avoid perceived problems associated with the circulators dispersing sediments entrained in the water column caused by wakeboard boats during a competition in July 2007, the units were shut down immediately preceding the wakeboard competition in June 2008 and were re-started several days following the event.

Figure 3. Location of SolarBee circulators shown in yellow and SolarBee monitoring sites shown in magenta. The DEQ/Portland Metro primary monitoring site was close to the SolarBee monitoring site between the west and center circulators.

Water quality profiles (temperature, conductivity, pH, and dissolved oxygen) were collected by SolarBee staff periodically using a YSI multi-parameter sonde (model 600QS) and measuring every 0.3 m (1 ft) interval in the water column. Profiles were also collected by staff with Portland Metro using a Hydrolab Quanta at intervals of every meter. Water samples were collected by Portland Metro staff at depths of 0.5 m and immediately above what they judged to be the onset of the thermocline. Water samples were preserved and transported to the Department of Environmental Quality laboratory in Portland for analysis.

Analytical methods are described at www.deq.state.or.us/lab/. Phytoplankton samples collected by Portland Metro were preserved with Lugol's solution and shipped to Aquatic Analysts for analysis of community composition and algal biovolume. One hundred algal units were counted and identified to genus or species if possible. Portland Metro staff sampled the abundance and distribution of aquatic macrophytes by selecting 100 random sites in July, 2007 and re-sampling in the vicinity of 99 of those sites in July, 2008. Each site was sampled by lowering a rake, rotating it to collect plants, and raising it to the surface. Plants were identified and ranked in terms of abundance using an ordinal scale from 0 to 5, where 0 = "not present", 1 = < 1 % coverage, 2 = 1–25 %, 3 = 26–50 %, 4 = 51–75 %, and 5 = 76–100 %. Secchi disk transparency was measured with a standard 20 cm black/white disk by staff from both SolarBee and Portland Metro. Additional data were extracted from a study of Blue Lake conducted in 2003 by Pfauth and Sytsma (2004). All water quality data derived from the various sampling efforts were standardized to use results from surface samples (0.5 to 1.0 m) depths and data collected over the deepest area on the west-central portion of the lake.

The data were analyzed by plotting time series of like data examining for outliers and inconsistencies. This identified cases of different units, but no other problems in the data were detected.

RESULTS

1. 2007 & 2008 (Treatment)

a. **Water Temperature:** Maximum water temperature in 2007 reached 27.3 ºC in July 2007 (Figure 4) , but was relatively warmer for a longer period in 2008 (Figure 5). Blue Lake does not exhibit a classic thermocline observed in deeper lakes, but instead shows a gradual decline of several degrees Celsius from surface to the bottom during the summer. The lake was isothermal during most of the period from fall through spring.

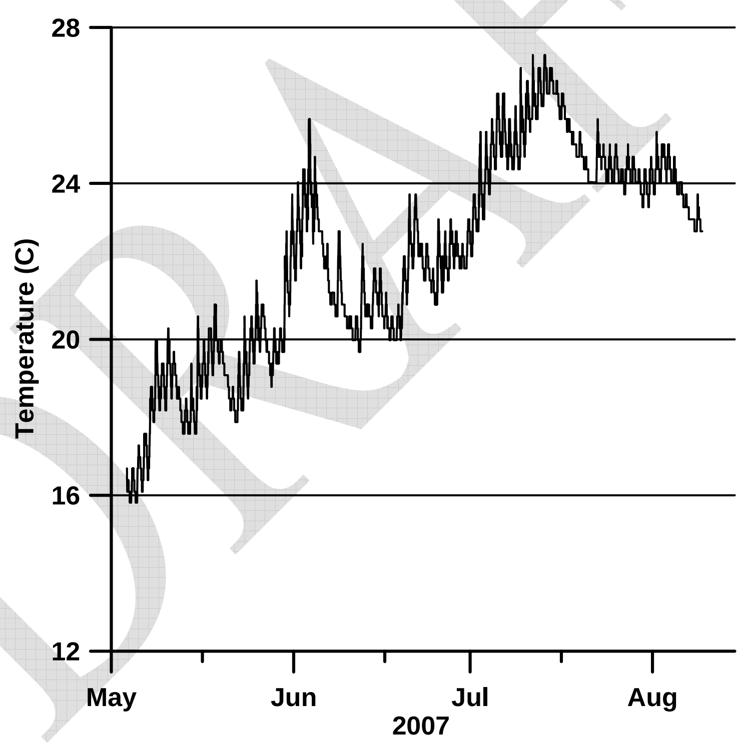


Figure 4. Temperature of surface water (0.3 m) measured in the center of Blue Lake during 2007.

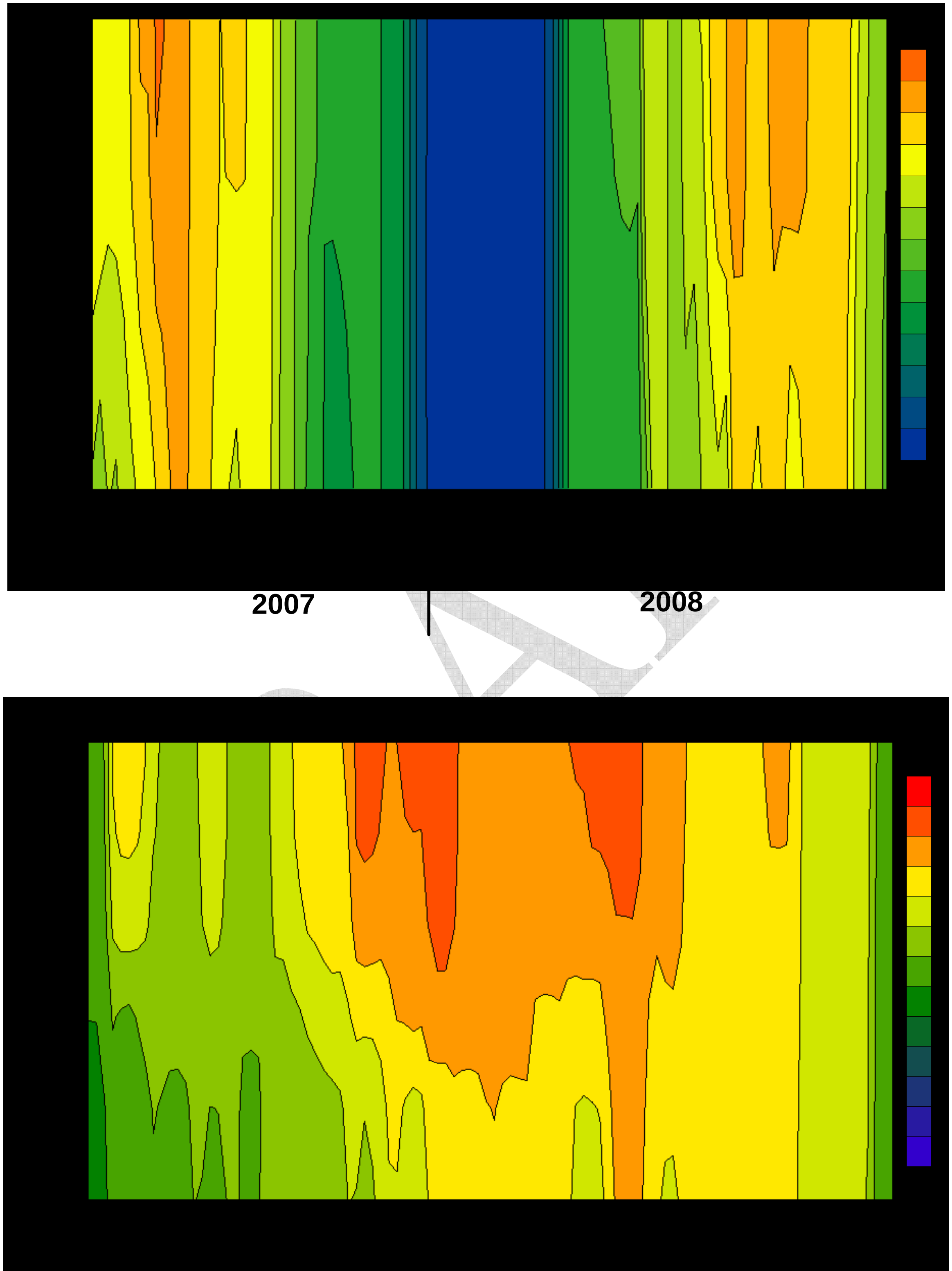


Figure 5. Lake temperatures based on profiles collected by Portland Metro staff in 2008.

b. <u>Transparency</u>: Lake transparency can be affected by inorganic turbidity, such as observed in adjacent Fairview Lake or by light scattering associated with phytoplankton cells. In the past, high algal densities have greatly reduced transparency in Blue Lake. Lake transparency was greatest in July 2007, but declined abruptly in late July, immediately following a 3-day wakeboard contest (Figure 6). The decline in transparency was associated with a bloom of *Anabaena* that extended throughout the remainder of the summer. Transparency in 2008 showed a pattern similar to that observed in 2007 in that the greatest transparency was observed in early summer and declined until fall. However, the transparency in 2008 remained greater than that observed in 2007 (Figure 7). Daily measurements of transparency before, during, and after the wakeboard event of 2008 indicated a decline in transparency during the event and a recovery in transparency three days following the event (Figure 8).

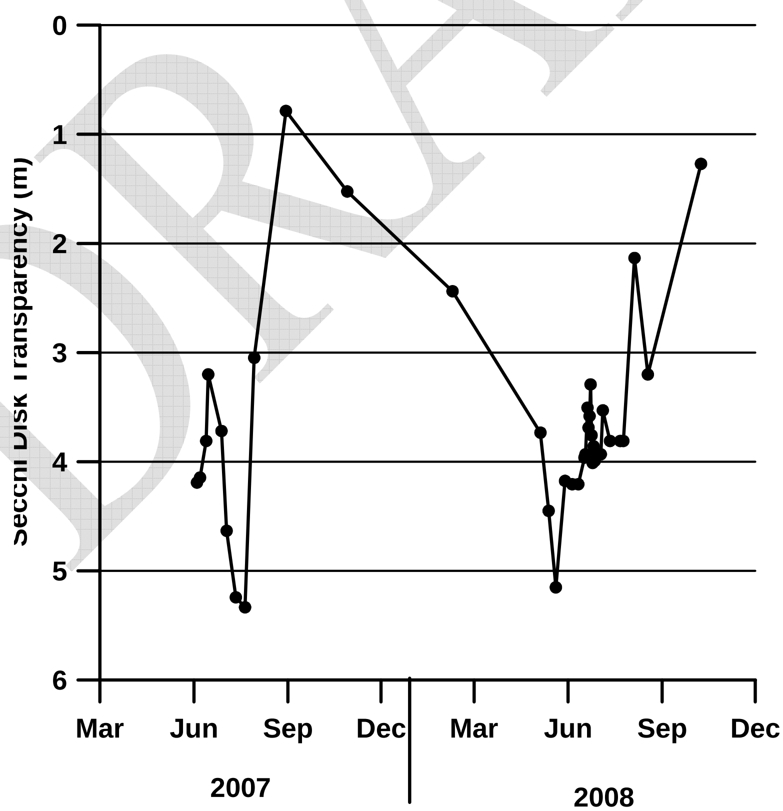


Figure 6. Secchi disk transparency in Blue Lake during 2007 and 2008.

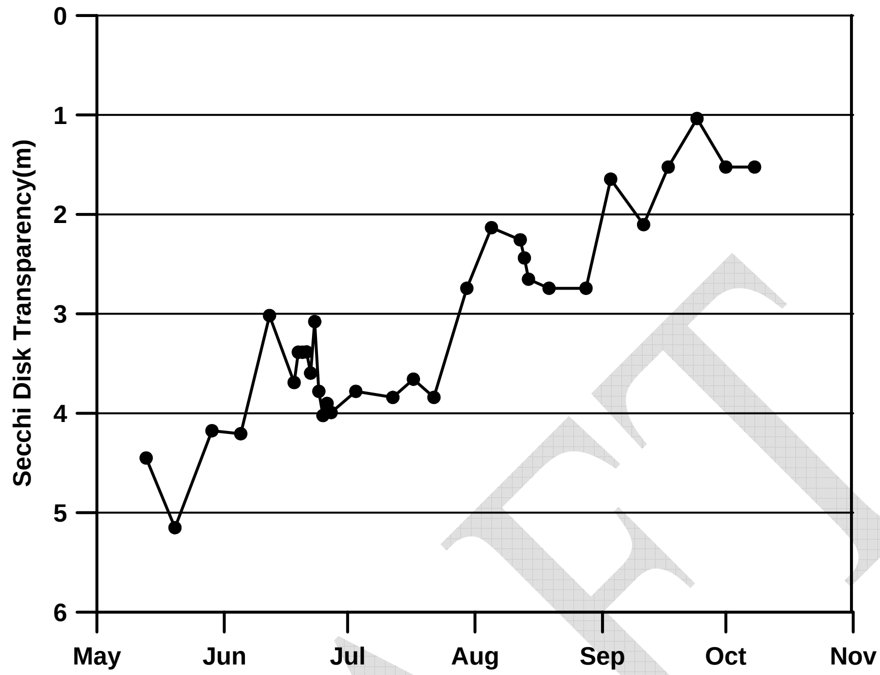


Figure 7. Secchi disk transparency for 2008 shown on an expanded time scale.

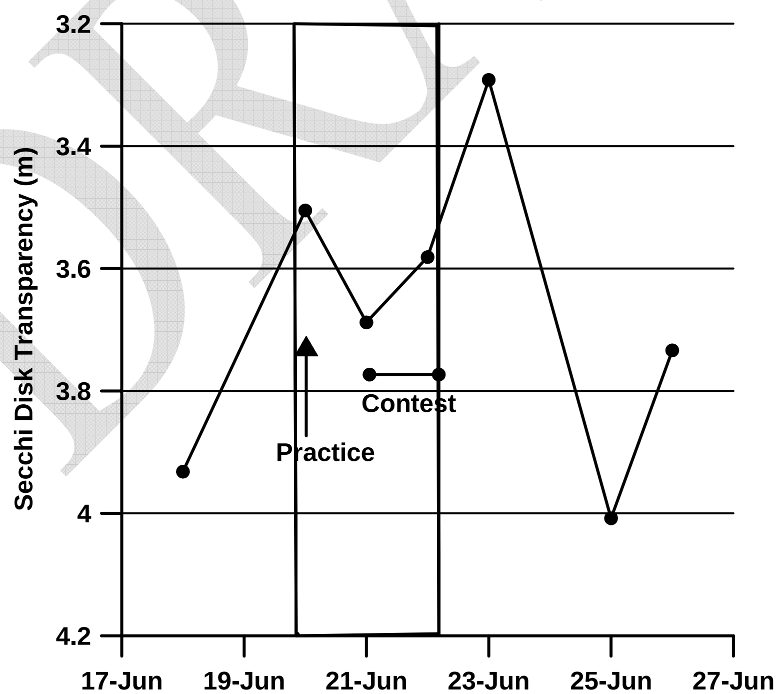


Figure 8. Secchi disk transparency observed during the period around the wakeboard contest of 2008.

c. **pH:** pH is one indicator of primary production, whereby high rates of photosynthesis draw dissolved carbon dioxide from the water causing pH to increase. Overall, pH values appeared to be slightly greater in 2007 compared to 2008 (Figure 9). Median summertime pH in 2007 was 8.1, compared to 8.05 in 2008. The water quality standard for pH is 8.5 for water bodies in western Oregon. Surface pH in Blue Lake reached a peak in July 2008 and generally remained relatively high through September (Figure 10).

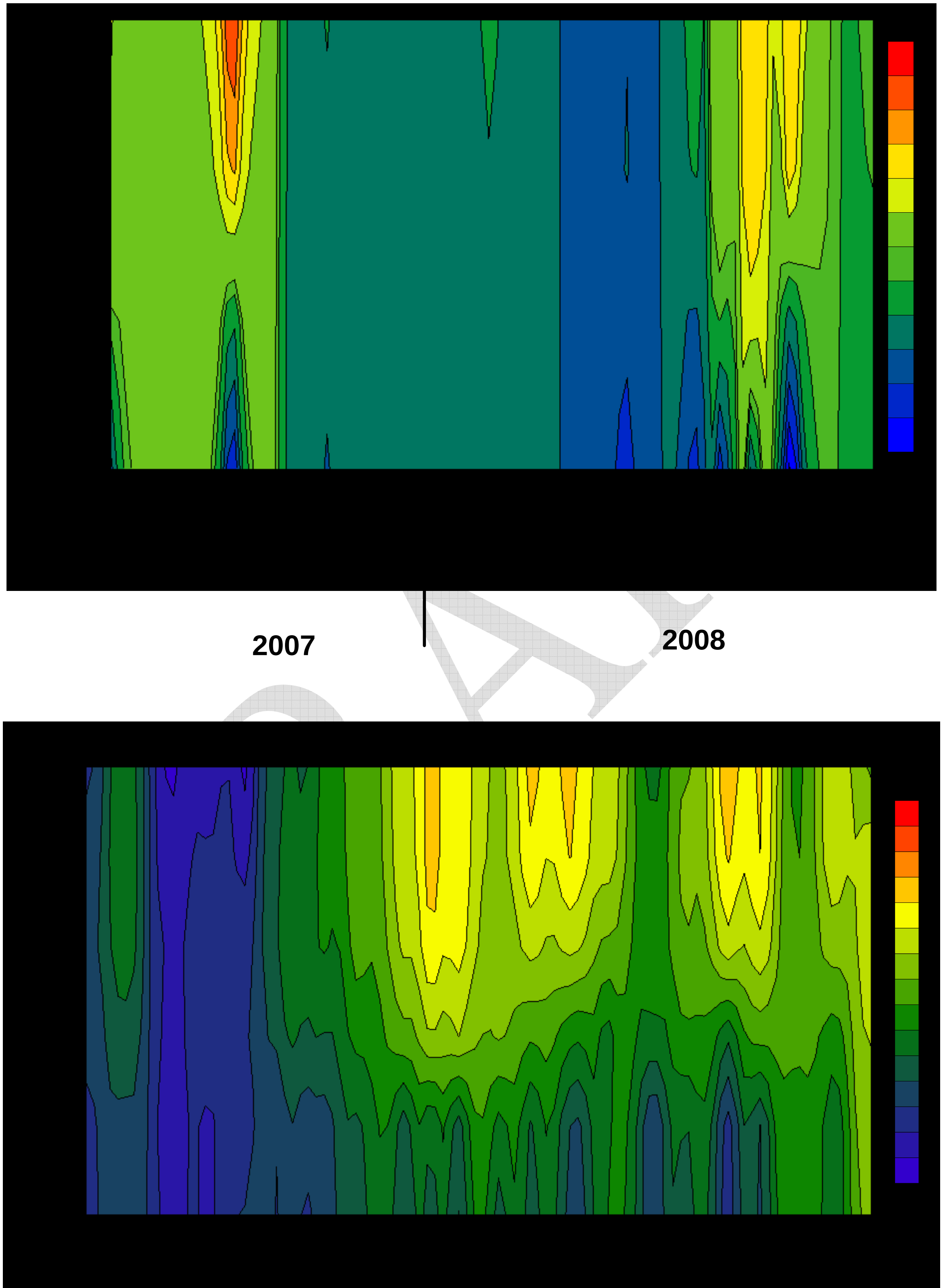


Figure 9. Lake pH based on profiles for 2007 and 2008 from data collected by SolarBee staff (top) and profiles collected by Portland Metro staff in 2008 (bottom).

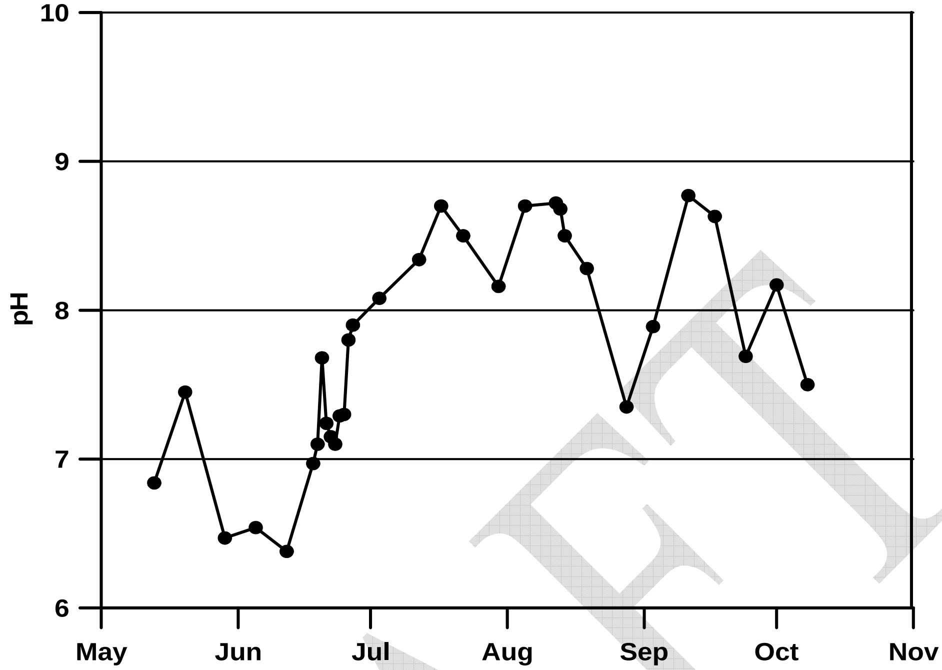
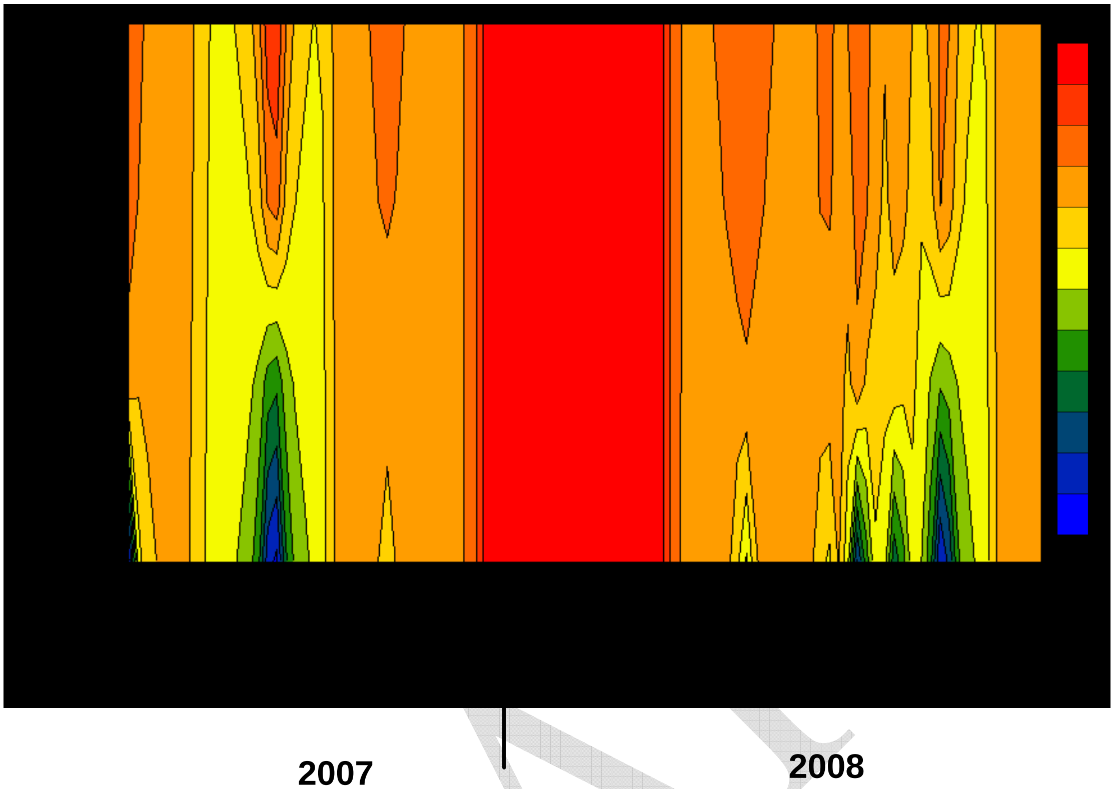


Figure 10. Surface water (0.5 m) pH values for 2008 in Blue Lake.

d. <u>Dissolved Oxygen</u>: Dissolved oxygen (DO) concentrations from values expected on the basis of water temperature and atmospheric pressure can be caused by high rates of photosynthesis as rates of DO production exceed rates of equilibration with the atmosphere. Where decomposition rates are high (respiration), DO concentrations can decline to zero. Concentrations of DO in the surface waters of Blue Lake in 2007 and 2008 did not deviate dramatically from values expected based on equilibrium with the atmosphere (Figure 11). Concentrations of DO in the bottom waters exhibited deficits typically associated with sediment decomposition. However, DO concentrations remained above 0.5 mg/L throughout 2007 and 2008, thus averting anoxic conditions. Surface (0.5 m) concentrations of dissolved oxygen showed no pattern in 2008 (Figure 12).



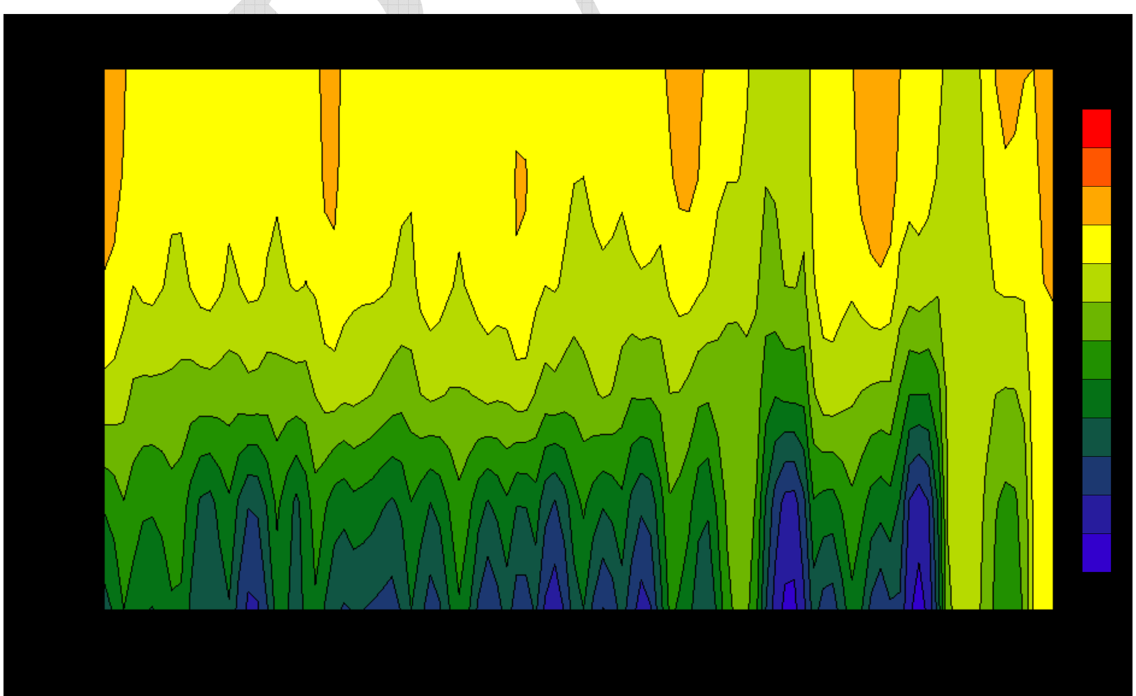


Figure 11. Lake dissolved oxygen concentrations based on profiles for 2007 and 2008 from data collected by SolarBee staff (top) and profiles collected by Portland Metro staff in 2008 (bottom).

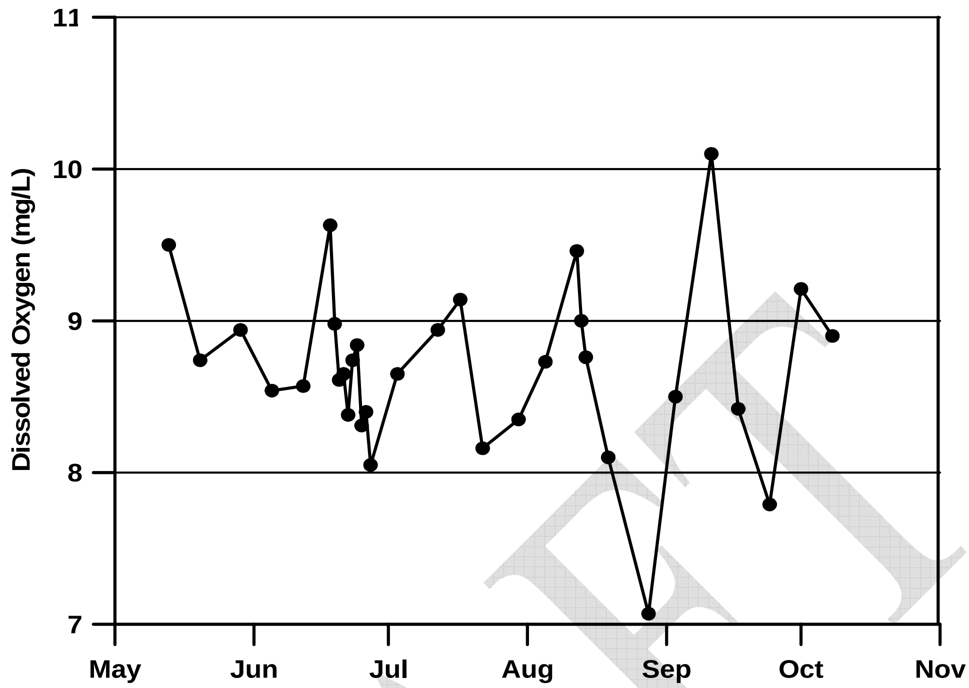


Figure 12. Dissolved oxygen concentrations measured in the surface waters (0.5 m) of Blue Lake during 2008.

f. <u>Specific Conductance</u>: Conductivity is a measure of the total dissolved ions present in the water. Elevated conductivity values arise from evapoconcentration, inflow of water with high dissolved constituents, or low concentrations of dissolved oxygen which can result in release of additional ions into solution. Conductivity values in the surface waters of Blue Lake increased during the summer, most likely as a consequence of evapoconcentration and secondarily as a result of groundwater pumping into the lake (Figure 13). Elevated values of conductivity in the bottom waters were likely caused by oxygen depletion, thus leading to changes in redox conditions in the water overlying the sediment. Surface conductivity values showed some variation in June 2008 with some precipitation, and then increased throughout much of the summer (Figure 18).

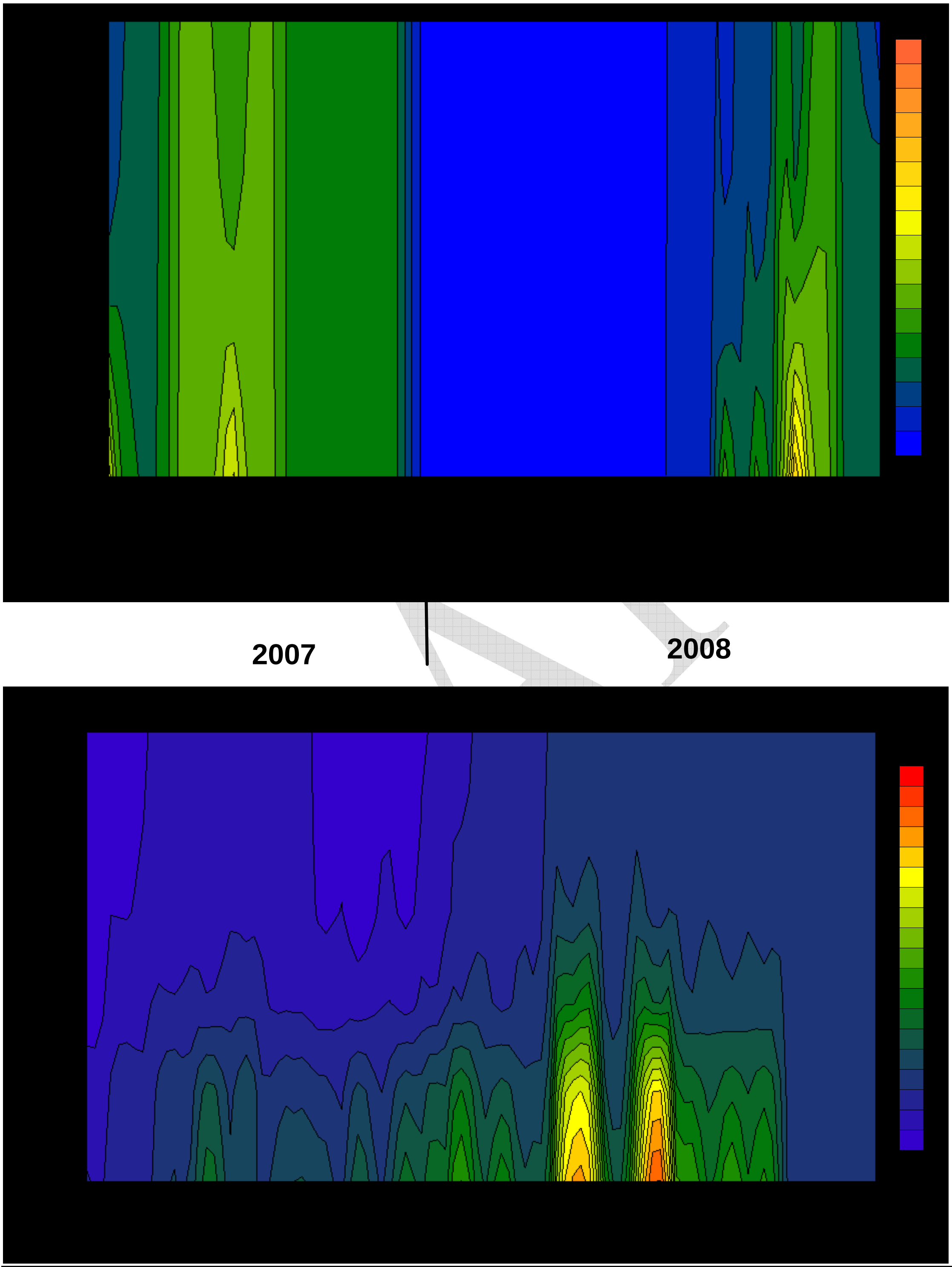


Figure 13. Lake conductivity based on profiles for 2007 and 2008 from data collected by SolarBee staff (top) and profiles collected by Portland Metro staff in 2008 (bottom).

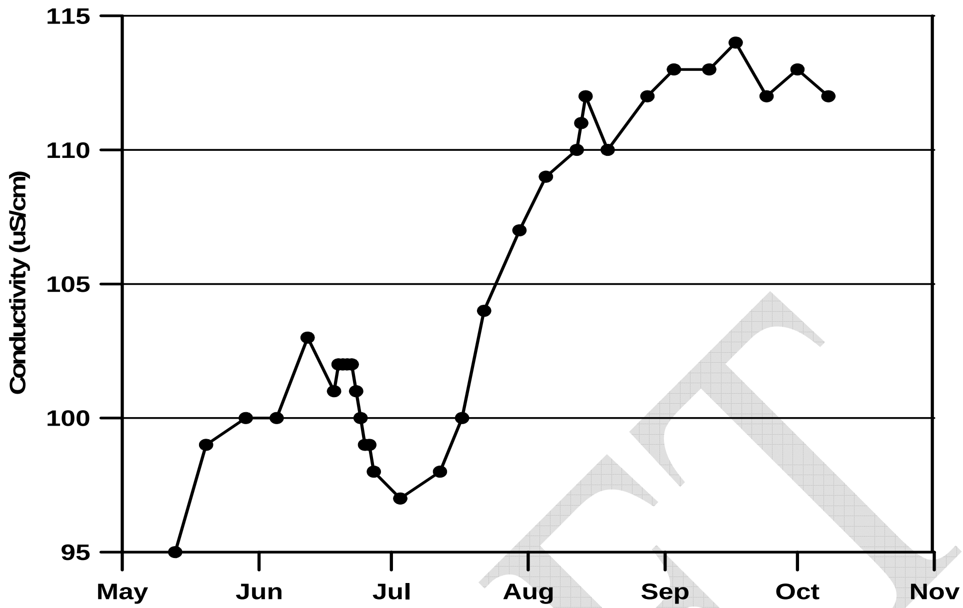


Figure 14. Surface water conductivity measured in Blue Lake in 2008.

f. <u>Phosphorus</u>: Phosphorus is typically the limiting nutrient in temperate lakes controlling the abundance of phytoplankton biomass (Schindler et al. 2008). Median total phosphorus concentrations in the surface waters of Blue Lake were 26 µg/L in 2007 and 25 µg/L in 2008. Total phosphorus concentrations in the samples collected from deeper in the water column were typically greater than those measured in the surface waters. There is no standard for total phosphorus concentrations in Oregon lakes, although lakes with values greater than 20 µg/L can support high densities of phytoplankton. Dissolved phosphorus concentrations (PO_4) ranged between 1 µg/L to 10 µg/L in the surface waters of Blue Lake in 2007 and 2008.

f. <u>Nitrogen</u>: Nitrogen is often measured as reduced N (as total Kjeldahl nitrogen [TKN]) and inorganic components of nitrate + nitrite and ammonia. Nitrite concentrations in surface waters are usually negligible and the oxidized inorganic nitrogen is usually just referred to as nitrate. Concentrations of nitrate and ammonia were almost always below the detection limits reported by the laboratory for these samples from Blue Lake. It is likely that there were ecologically meaningful concentrations of nitrate and ammonia present in the lake, but more sensitive analytical techniques are required to achieve the needed level of performance. The median concentrations of TKN for the surface waters of Blue Lake were 350 µg/L in 2007 and 325 µg/L in 2008.

g. Other Analytes: Additional parameters were analyzed by the DEQ laboratory, but are not presented here. These results are available online from DEQ at www.deq.state.or.us/lab/lasar.htm.

h. Aquatic Macrophytes: Species of aquatic macrophytes report in 2007 and/or 2008 included *Myriophyllum spicatum* (Eurasian watermilfoil), *Elodea canadensis* (Canadian waterweed), *Nymphaea odorata* (Water lily), *Potamogeton foliosus.* (Leafy pondweed), *Potamogeton crispus* (Curly-leafed pondweed), and *Chara* (muskgrass)[Figure 15]. The pondweeds (*P. foliosus* and *P. crispus*) were found at only one or two sites in 2007 and 2008. Three of the remaining taxa exhibited dramatic changes between 2007 and 2008. Milfoil (*M. spicatum*) declined dramatically from 2007 to 2008 in both extent and abundance (Figure 16). Milfoil, a shallow-rooted invasive species, exhibited a profound decrease at the west end of the lake, although it appeared to increase slightly on the east end of the lake. The proportion of sites where milfoil was present decreased by 38 percent from 2007 to 2008 and the proportion of sites where it was classified as abundant (classes 4 & 5) declined from 28 to 4 percent of total sites (Figure 17). The three remaining taxa increased in distribution and abundance. *E. canadensis*, a native taxon, increased from present at only 2 percent of sites in 2007 to present at 25 percent of sites in 2008 (Figure 18). Water lilies (*Nymphaea odorata*) showed a slight increase in abundance between 2007 and 2008. Members of this genus are deeply rooted and comparatively slow growing (Figure 19). *Chara*, a native macroalgae, showed the most startling change. It was not found at any of the 100 sites surveyed in 2007, but was present at 40 percent of the sites in 2008 (Figure 20).

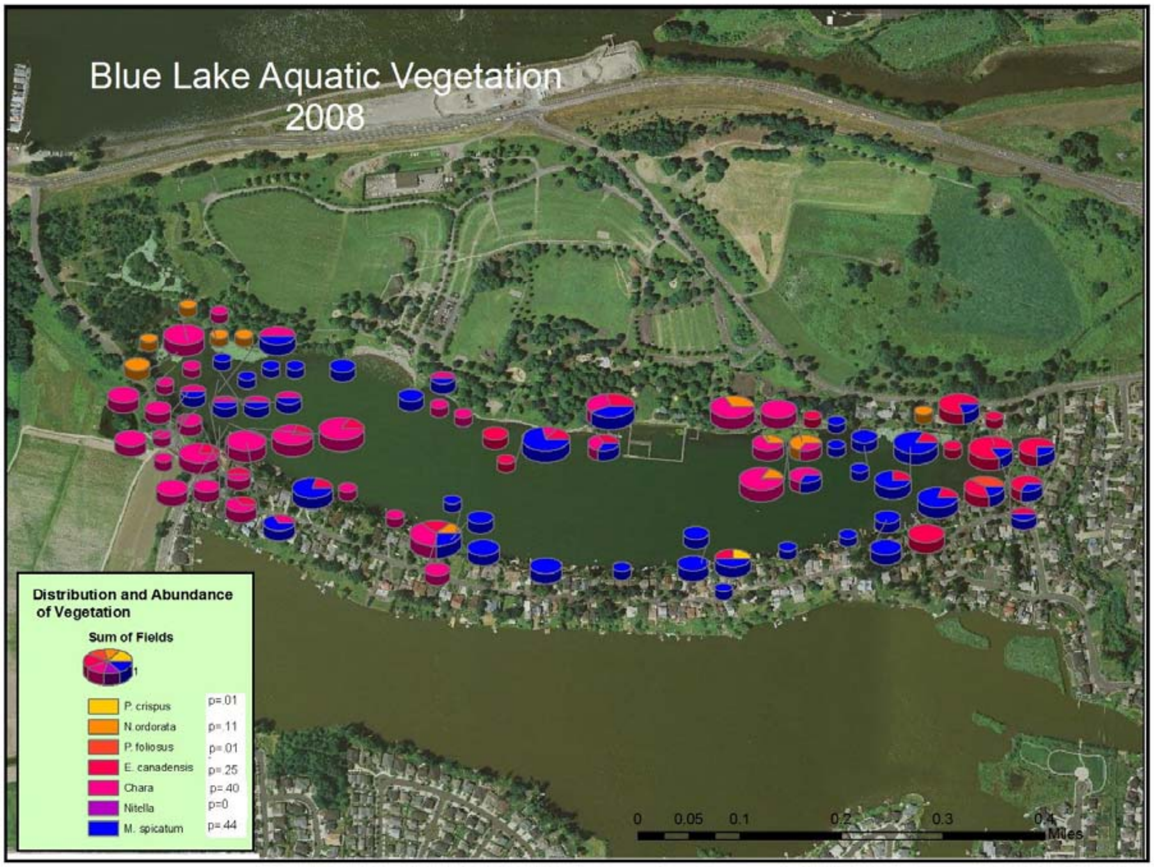
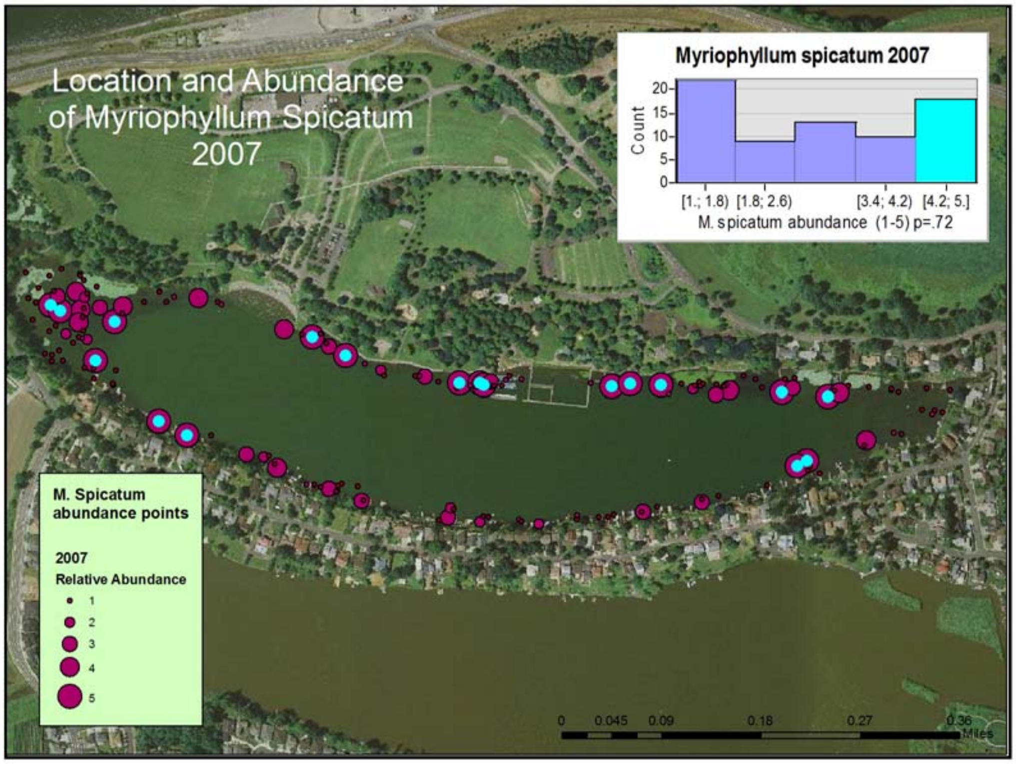


Figure 15. Distribution of aquatic macrophytes in Blue Lake measured in 2008. The size of the cylinders is proportional to the ordinal ranking of abundance of macrophytes. The colors represent different taxa show in the legend.



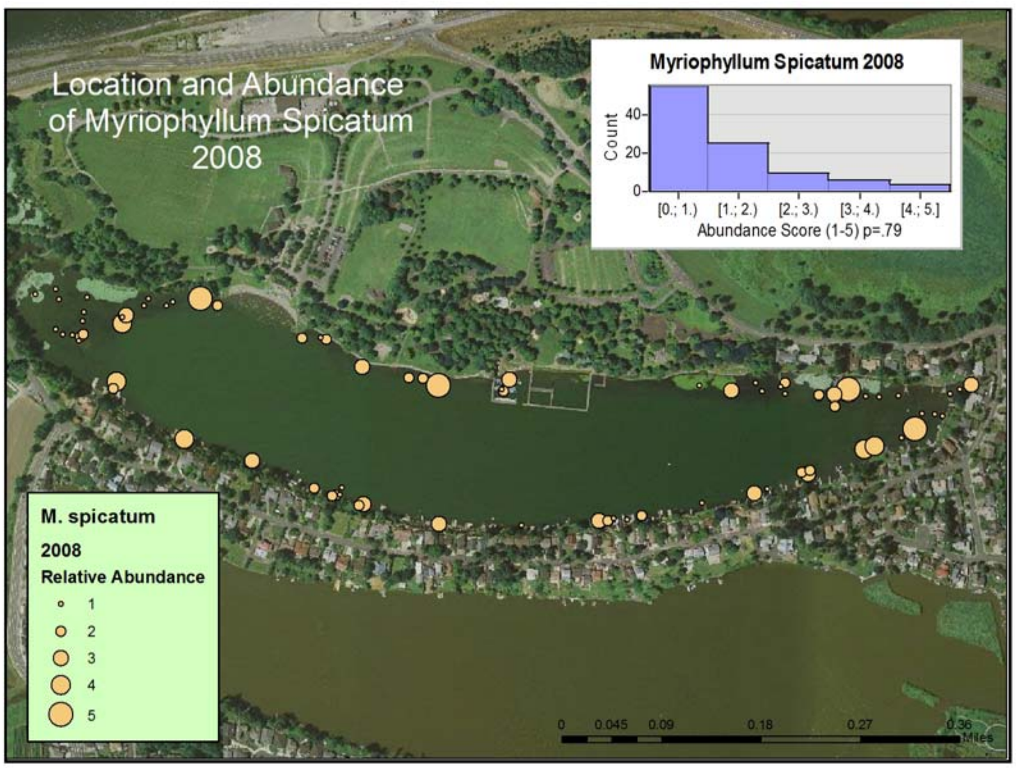


Figure 16. Distribution and abundance of *Myriophyllum spicatum* (milfoil) in Blue Lake for 2007 (top) and 2008 (bottom).

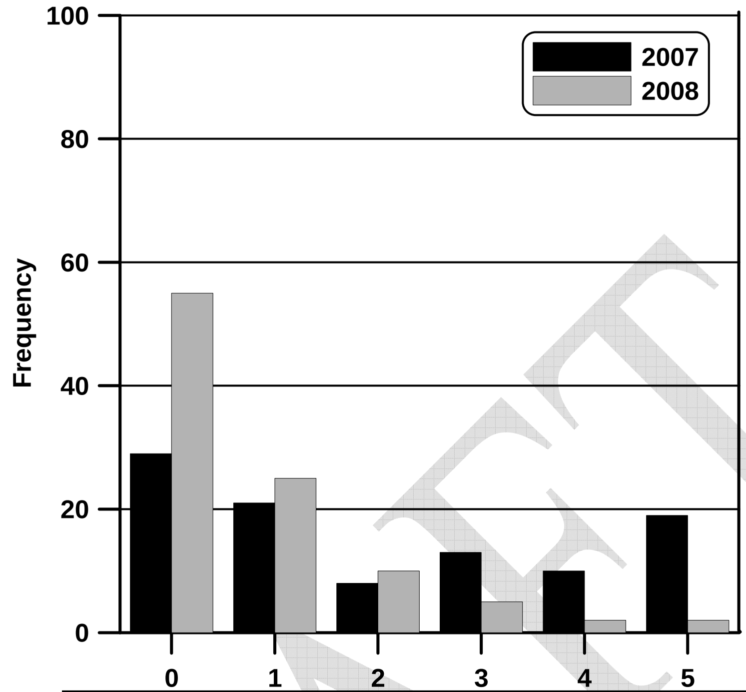


Figure 17. Changes in frequency and abundance of *M. spicatum* in Blue Lake between 2007 and 2008.

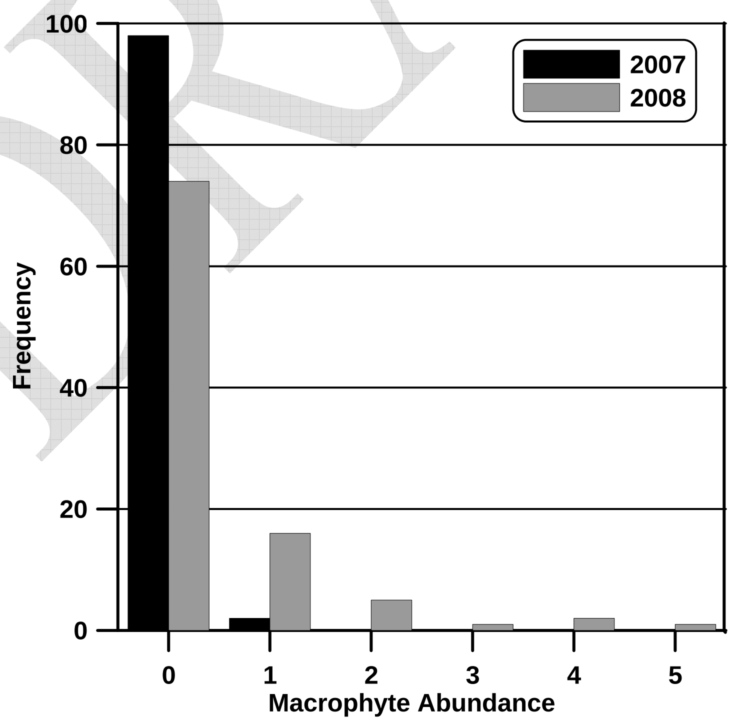


Figure 18. Changes in frequency and abundance of *E. canadensis* in Blue Lake between 2007 and 2008.

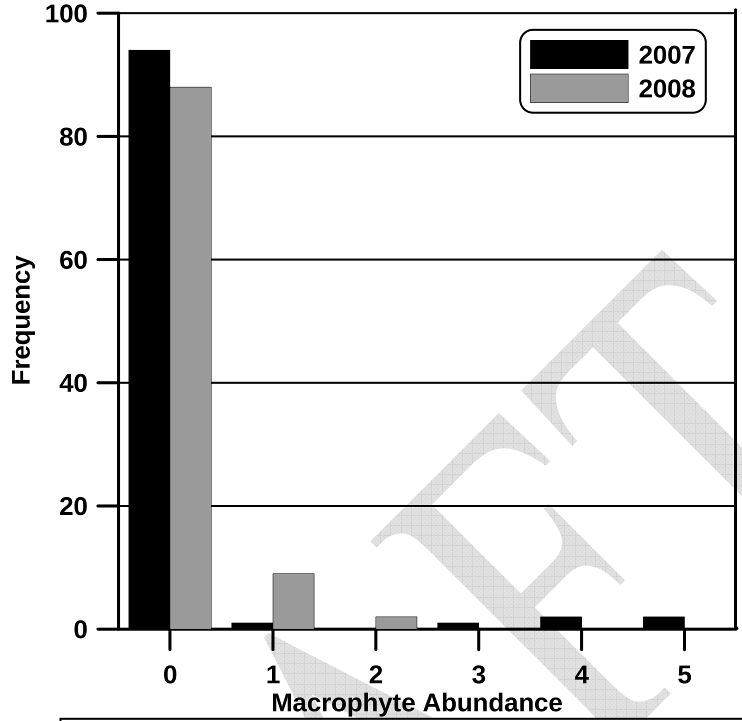


Figure 19. Changes in frequency and abundance of *Nymphaea* in Blue Lake between 2007 and 2008.

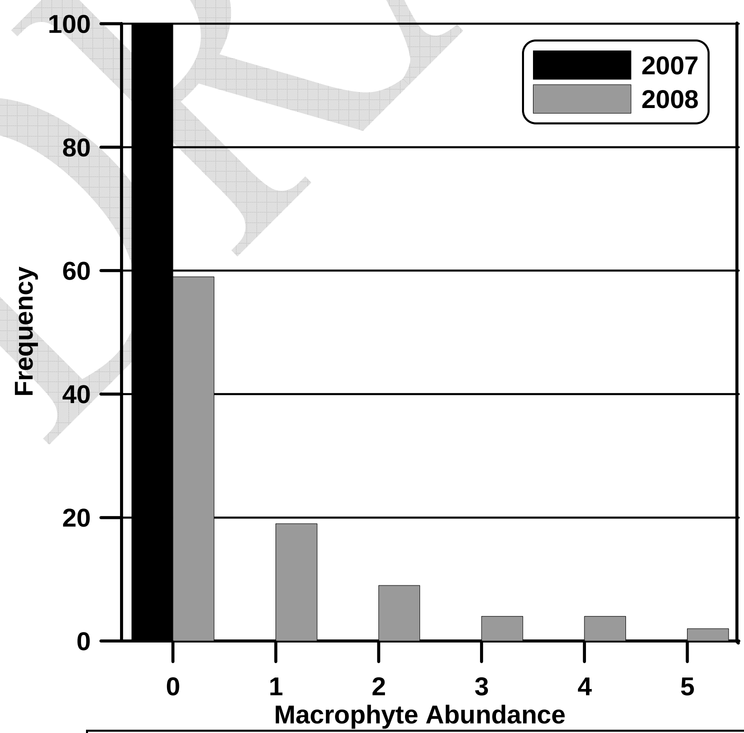


Figure 20. Changes in frequency and abundance of *Chara* in Blue Lake between 2007 and 2008.

i. Phytoplankton: Phytoplankton data are available for selected pre-treatment samples and samples collected in 2007. Only four phytoplankton samples were collected in 2008 because the lake transparency was typically greater than their criterion for collection (Secchi disk transparency < 2 m). Those samples are no longer available for analysis. The available data show that there were notable blooms in Blue Lake recorded in 2002, 2003 and 2007 (Figure 21). Blooms were present from 2004-2006 as documented by photographs from area residents (Figure 22), although no phytoplankton data are available to quantify the intensity or composition of the blooms. Only in 2008, can we assume that the absence of phytoplankton data reflects the absence of cyanobacterial blooms because visual triggers to collect samples by staff with Portland Metro and document the conditions were apparently not met.

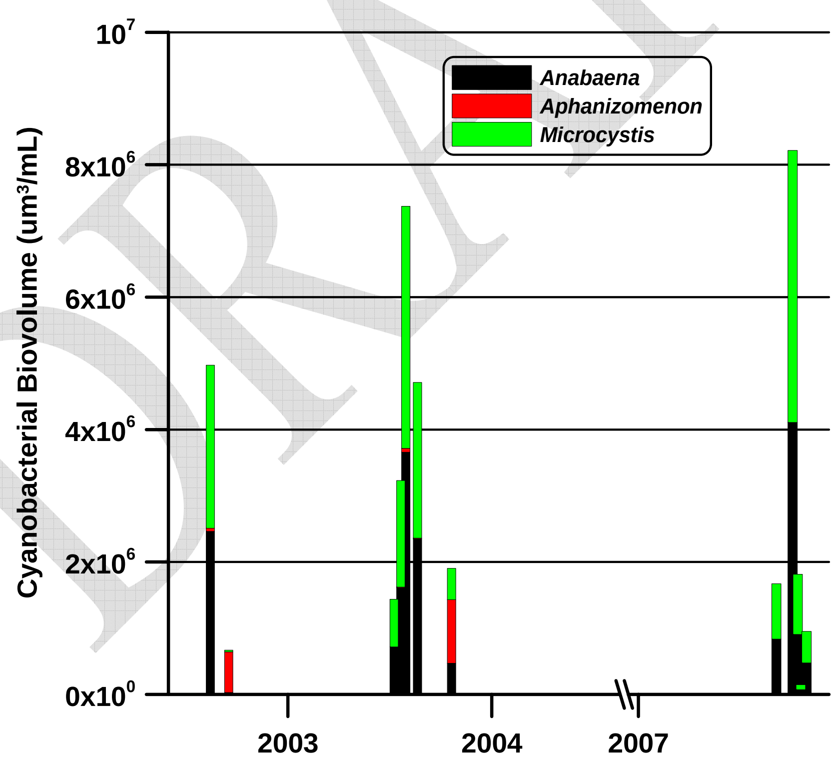


Figure 21. Biovolume of cyanobacteria genera measured in 2002, 2003, 2007 from Site 2 (lake centroid).

Figure 22. Photographs of east end of Blue Lake in August 2004 and 2006.

j. <u>Chlorophyll *a*</u>: Chlorophyll *a* is often used as a surrogate for phytoplankton biomass. This assumption is subject to some criticism (Schindler et al. 208), but nevertheless is presented here, in part, because the Oregon DEQ often uses a criterion of 10 to 15 µg/L chlorophyll as a non-enforcement guideline for lake water quality assessments. Median chlorophyll *a* concentrations for 2007 and 2008 were 6.8 µg/L and 2.2 µg/L, respectively. Chlorophyll concentrations were low through July 2008, but increased markedly in August and September (Figure 23).

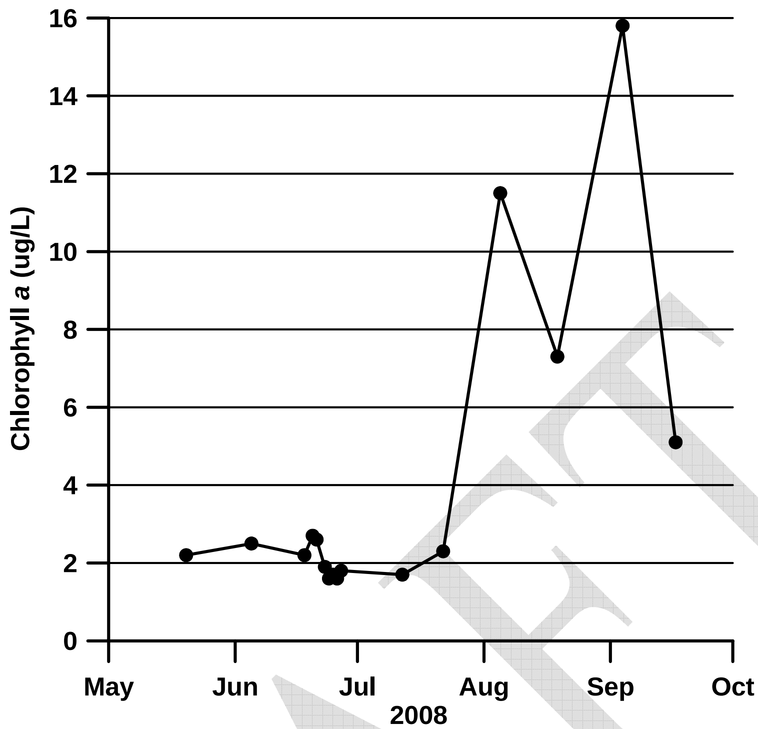


Figure 23. Chlorophyll *a* concentrations measured in the surface waters (0.5 m) of Blue Lake in 2008.

2. Comparison with Pre-Treatment Data

a. <u>Temperature</u>: Detailed water temperature data are not available for Blue Lake prior to 2007. However, air temperature for the PDX [Portland International Airport] climate station located about10 km west of Blue Lake likely provides a reasonable surrogate for surface water temperature trends in Blue Lake. The data indicate that 2003 was a warm summer, comparable to conditions observed in 2008 where median daily mean air temperatures for the period June-September were 17.78 ºC (64.0 °F) in both 2003 and 2008 (Figure 24). Summer temperatures in the intervening years were noticeably cooler, with median daily mean air temperatures ranging from 13.89 to 14.28 ºC (57.0 to 57.7 °F) for 2004-2007.

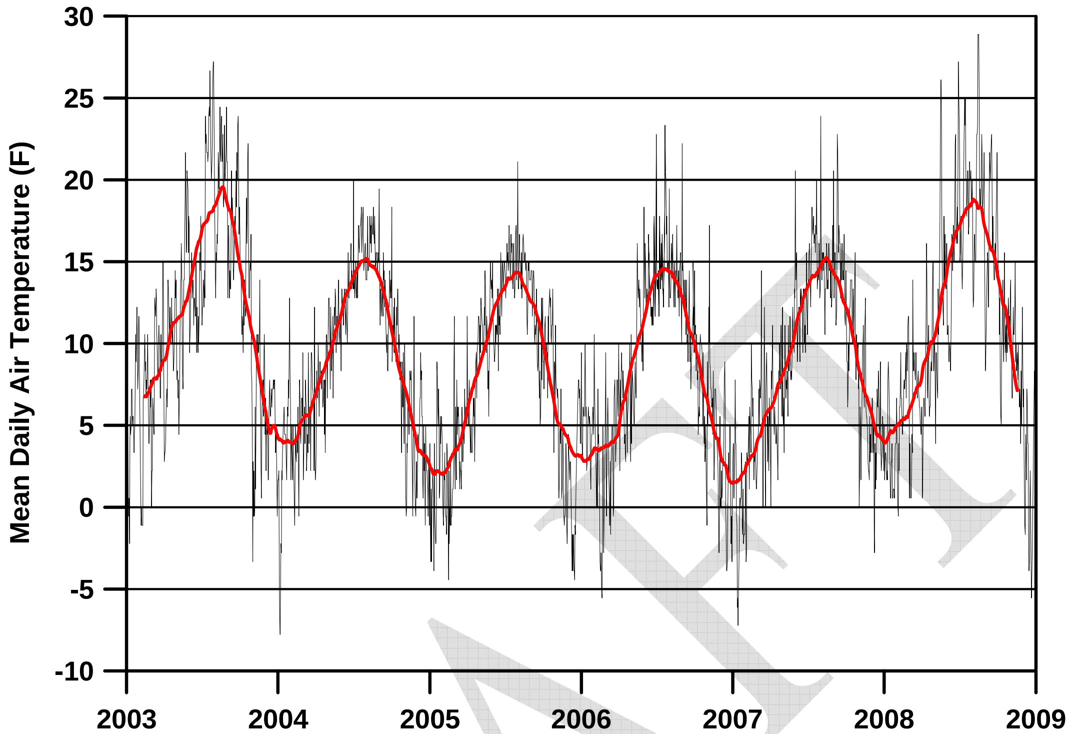


Figure 24. Mean daily air temperature measured at PDX from 2003 through 2008 (black). The red line represents the running average of the daily values.

b. <u>Secchi Disk Transparency</u>: Secchi disk transparency increased from summertime (June-Sept) medians of 2.3-1.8 m in 2002-2003 to 4.0 m in 2007 and 3.6 m in 2008 (Figure 25). The number of observations in the pre-treatment period is somewhat sparse; however, both ANOVA (parametric) and Kruskal-Wallis (non-parametric) results show the differences between periods to be highly significant (Table 1). The 2007 and 2008 transparency data show a pronounced decline in the August and September, however, there are insufficient data to determine if this pattern also occurred prior to treatment. The available data suggest that the pre-treatment pattern, if any, was different because the three lowest transparency values measured prior to treatment occurred in July.

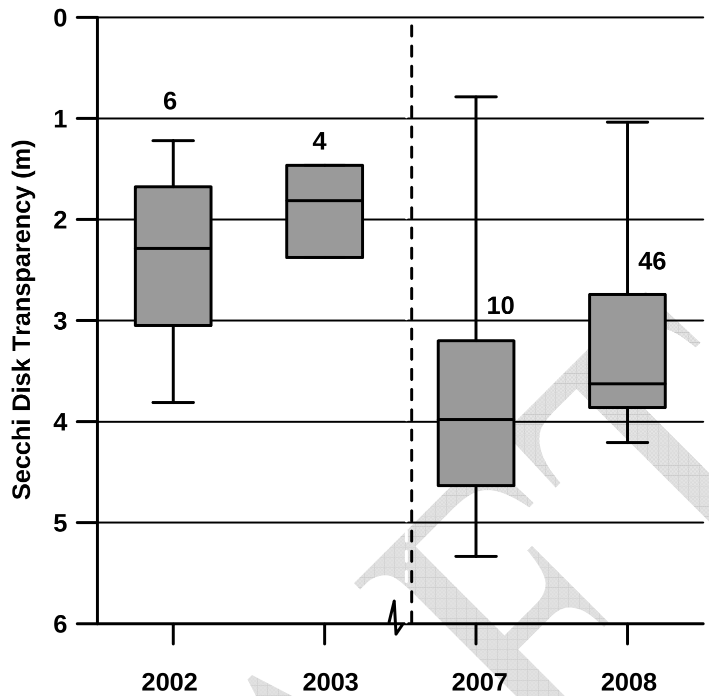


Figure 25. Boxplots of Secchi disk transparency measured in pre-treatment and treatment periods in Blue Lake. The numbers above each boxplot indicate the observations for each year (June-Sept).

Table 1. Statistical comparisons among years for water quality parameters measured in Blue Lake from 2002 to 2008.

Parameter	2002			2003			2006			2007			2008			F[a]	P[b]
	N	CT[c]	SE/R[d]	N	CT	SE/R	N	CT	SE/R	N	CT	SE/R	N	CT	SE/R		
Secchi (m)	6	2.39	0.36	4	1.87	0.44	-	-	-	10	3.81	0.28	46	3.32	0.13	6.58	0.0006
		2.29	17.9		1.81	9.5		-	-		3.98	44.9		3.63	35.1	5.71	0.0016
Chlorophyll (ug/L)	4	7.0	6.9	4	17.8	6.9	7	36.3	5.2	7	8.3	5.2	18	4.8	3.2	7.16	0.0003
		2.8	15.9		11.1	30.3		27.5	34.3		6.8	22.1		2.2	13.4	9.21	0.0000
pH	4	8.82	0.32	4	8.86	0.32	7	8.79	0.24	7	8.12	0.24	46	7.96	0.09	5.05	0.0014
		8.78	53.0		8.92	57.3		8.84	51.6		8.12	29.4		8.05	29.1	5.78	0.0005
TP (ug/L)	8	30.1	2.6	4	41.9	3.6	5	41.0	3.3	8	26.7	2.6	19	24.9	1.7	8.22	0.0001
		27.5	22.1		32.5	38.3		40.0	37.3		26.4	19.9		25.0	16.6	6.63	0.0004
PO_4 (ug/L)	4	4.6	0.89	4	6.0	0.87	_	_	_	6	8.0	0.72	19	3.4	0.41	10.7	0.0001
		4.8	17.8		5.5	22.4		_	_		8.0	28.4		3.0	12.1	8.05	0.0005
TKN (ug/L)	8	544	61	4	708	86	5	840	77	7	354	65	19	355	40	10.9	0.0000
		525	28.5		650	35.6		800	36.3		350	16.4		325	14.7	9.77	0.0000

[a] F value testing the differences among mean values between years using a one-way ANOVA for the top row and a parametric ANOVA applied to the ranks in the second row.
[b] P values for the level of significance between the mean values in the top row and the level of significance of the differences of the ranks in the second row.
[c] Measures of central tendency, where the value in the top row is the mean and the value in the second row is the median.
[d] SE represents the stand error of the mean in the first row and R represents the rank computed using the Kruskal-Wallis one-way nonparametric AOV by year.

c. <u>pH</u>: pH values declined considerably between 2002-2006 and 2007-2008 (Figure 26). Median pH values in the pre-treatment period ranged from 8.8-8.9, whereas median pH values in 2007 and 2008 were 8.1 and 8.0, respectively. Although some pH values in 2007 and 2008 still exceeded 8.5, the decline from over 8.8 prior to treatment to about 8.0 during treatment is highly significant ($P < 0.05$).

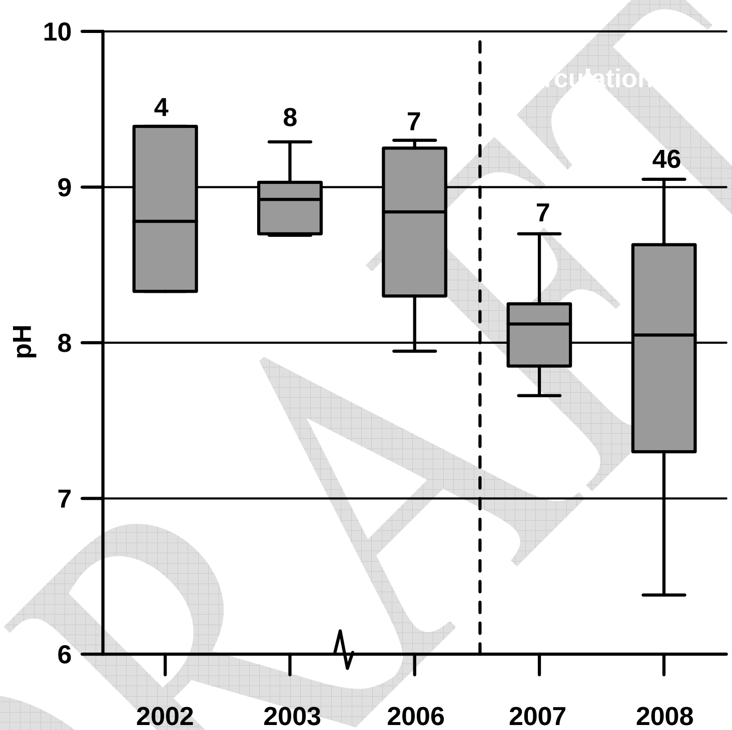


Figure 26. Boxplots of pH measured in pre-treatment and treatment periods in Blue Lake. The numbers above each boxplot indicate the observations for each year (June-Sept).

d. <u>Dissolved Oxygen</u>: The available data show a significant decline in the concentrations of dissolved oxygen in the surface water of Blue Lake between pre- and post-treatment (Figure 27). Maximum DO concentrations declined from 10.9 mg/L in 2002 to 9.0 mg/ in 2007 and 9.4 mg/L in 2008.

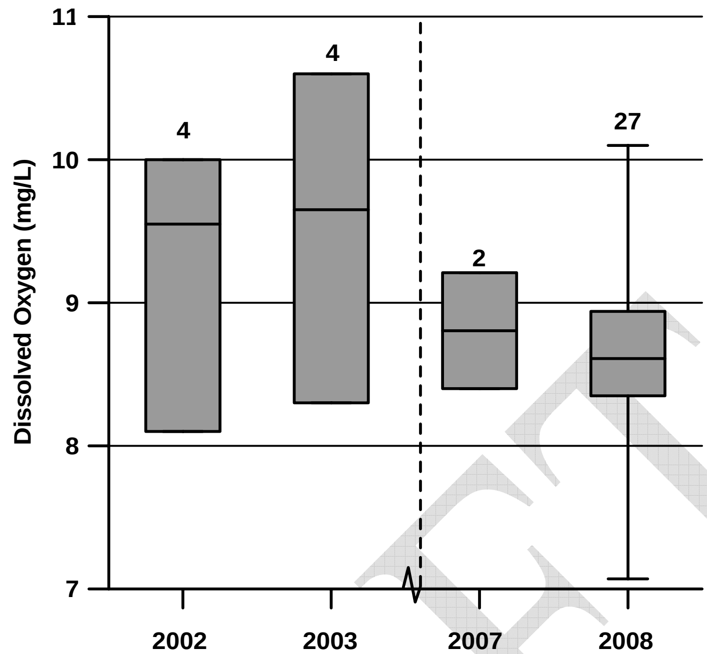


Figure 27. Dissolved oxygen concentrations in the surface waters of Blue Lake measured from 2002-2008.

e. Phosphorus: Concentrations of total phosphorus declined from median values of 28 in 2002 to 32 µg/L in 2003 and 40 µg/L in 2006 before treatment to 26 µg/L in 2007 and 25 µg/L in 2008 (Figure 28). This represents a decline of about 36 percent between the 2003 and 2006 years. However, the differences between 2002 and 2003 individually were not significantly lower than those in 2007 and 2008. Concentrations of dissolved phosphorus showed little change between pre-treatment and treatment periods (Figure 29). Median concentrations of dissolved phosphorus was 4.8 µg/L in 2002 and 5.5 µg/L in 2003, then increased to 8.0 µg/L in 2007, and declined to the lowest concentrations of 3.0 µg/L in 2008.

f. Nitrogen: Concentrations of TKN declined from median values of 525 µg/L in 2003, 650 µg/L in 2003 and 800 µg/L in 2006 prior to treatment to 350 µg/L in 2007 and 325 µg/L in 2008 (Figure 30). This represents a decline of about 55 percent in TKN and is highly significant (Table 1).

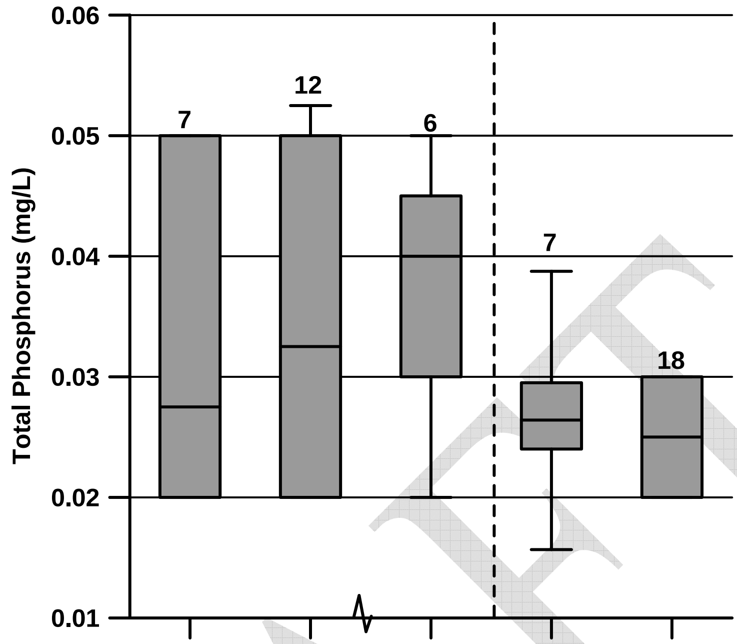


Figure 28. Boxplot of total phosphorus measured in pre-treatment and treatment periods in Blue Lake.

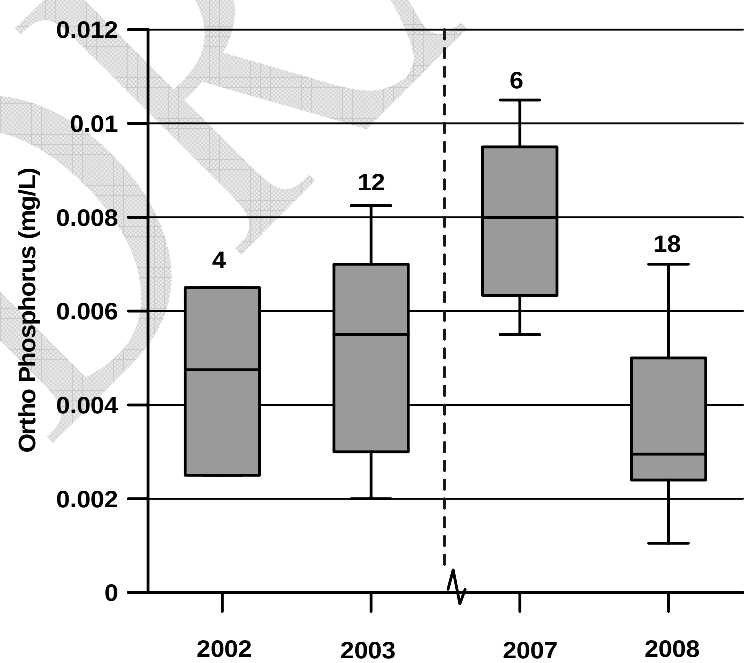


Figure 29. Boxplot of ortho phosphorus measured in pre-treatment and treatment periods in Blue Lake.

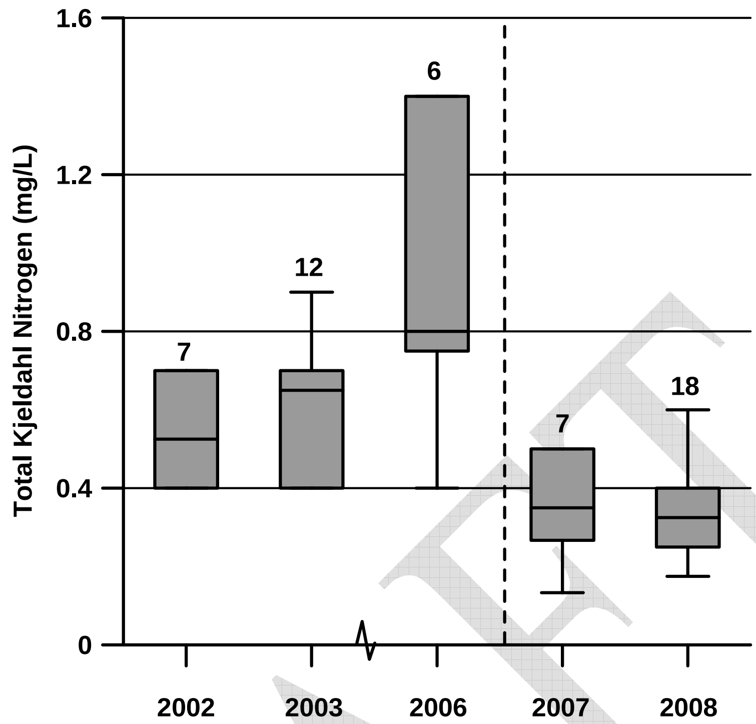


Figure 30. Boxplots of total Kjeldahl nitrogen measured in pre-treatment and treatment periods in Blue Lake. The numbers above each boxplot indicate the observations for each year (June-Sept).

g. <u>Chlorophyll *a*</u>: Median chlorophyll concentrations were as low as 2.8 µg/L in 2002, but increased to median values of 15.1 µg/L in 2003 and 27.5 µg/L in 2006. The maximum chlorophyll concentration prior to treatment was 100 µg/L measured in July 2006 compared to maximum values of 17 µg/L in 2007 and 18 µg/L in 2008 (Figure 31). Median chlorophyll values were 6.8 µg/L in 2007 and 2.2 µg/L in 2008, which are both significantly less than those measured in 2003 and 2006, but not those in 2002. The decline in chlorophyll between pre-treatment and treatment periods, excluding data from 2002, is highly significant (Table 1).

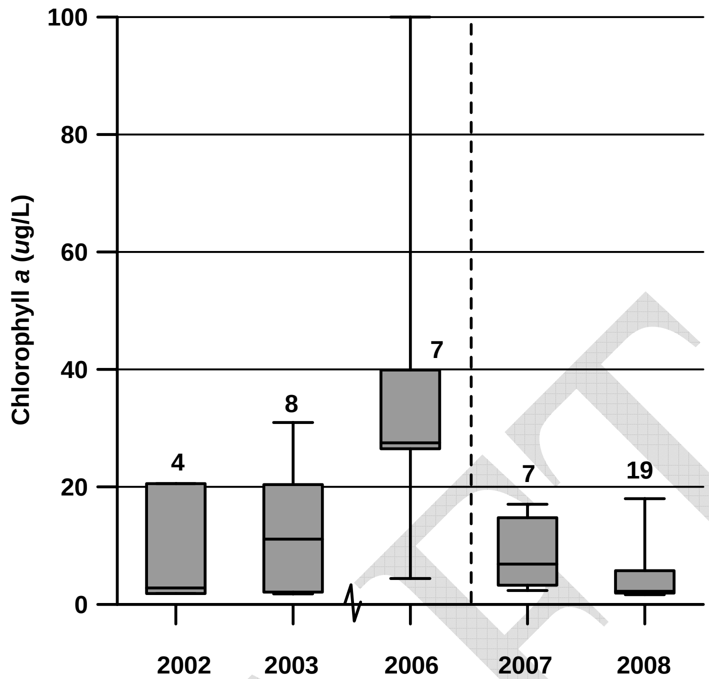


Figure 31. Boxplots of chlorophyll *a* measured in pre-treatment and treatment periods in Blue Lake. The numbers above each boxplot indicate the observations for each year (June-Sept).

h. Other: No quantitative data regarding macrophytes are available for the period immediately preceding the circulation treatment. The last macrophyte survey conducted in 2003 showed that the lake was dominated by *P. crispus*, *P. folius*, and *E. canadensis* (Pfauth and Sytsma 2004). Interestingly, there was only one site with *M. spicatum* present in 2003 and *Chara* was moderately abundant, whereas *Chara* was absent and *M. spicatum* was dominant in 2007.

DISCUSSION

Prior to treatment with circulation in 2007, Blue Lake had experienced repeated episodes of cyanobacteria (largely *Anabaena*) blooms that had caused the lake to be posted with warnings for recreational for recreational contact. In September 2003, a shoreline sample contained almost 8 million cells/mL of *Microcystis aeruginosa,* even though it represented only 16 percent of the biovolume; 80 percent of the biovolume was *Anabaena.* In July 2006, an intense cyanobacteria bloom resulted in a mid-lake sample of chlorophyll *a* concentrations of 100 µg/L. A paleolimnological analysis of the lake in 2004 showed that the lake was becoming more eutrophic and the forecast was for increased problems associated with cyanobacteria (Eilers & St. Amand 2004). The treatment of the lake with circulation appeared to have interrupted this trend.

The macrophyte populations exhibited major changes from 2007 to 2008. *M. spicatum* declined substantially in extent and density, whereas both *E. canadensis* and *Chara* expanded coverage greatly. The most recent macrophyte survey in Blue Lake prior to treatment with circulation was conducted by Pfauth and Sytsma (2004) in 2003. The July 24 survey of 160 sites showed that total macrophyte coverage was lower in 2003 compared to 2007 and 2008. In 2003, the dominant taxon was *E. canadensis*, with *P. crispus* and *P. foliosus* as subdominants. *M. spicatum* was present at only one site (0.6 %) in 2003 compared to being present at 73 percent of the sites in 2007 and 55 percent in 2008. *P. crispus* and *P. foliosus* were virtually absent from Blue Lake in 2007 and 2008, despite both being present at 10 percent of the sites in 2003. *Chara*, which was not present in 2007, was noted as a moderately abundant taxon in 2003. It appears that small population of *M. spicatum* present in 2003 expanded rapidly until 2007 when the circulation treatment was initiated. It is unclear why the other two invasive species, *P. crispus* and *P. foliosus*, declined between 2003 and 2007 instead of increasing concomitantly with *M. spicatum* although they may have been out-competed by *M. spicatum*. An additional complicating factor in assessing the apparent changes in macrophytes is that circulation was initiated in May 2007, three months before the survey of July 2007.

The observed changes in Blue Lake in 2007 and 2008 may have been affected by potentially confounding factors. In July 2007, a wakeboard event was held while the circulators were operating. During the three-day event, the circulators moved a volume of water equivalent to one-half of the lake volume and presumably redistributed the sediment that was disturbed by the powerful wakeboard boats. The flocculent surficial sediments would have been highly enriched in nutrients and *Anabaena* akinetes (cf. Eilers & St. Amand 2004). Thus, the sediment disturbance caused by the wakeboard contest was likely exacerbated by the effective circulation achieved by the SolarBees. By shutting down the circulators prior to and during the wakeboard event in 2008, the sediment that was distributed was allowed to settle before re-starting the machines.

Blue Lake loses considerable amounts of water in the summer caused by evaporation which occurs at time when groundwater inputs are low (Figure 32). The decline in lake stage has been offset in recent years by pumping groundwater into the lake (Figure 33). The groundwater is enriched in phosphorus and the supplemental pumping provides a significant boost to the phosphorus loading of the lake at a time when phytoplankton populations can most effectively use this new source of phosphorus. Median phosphorus (as P) concentrations from the five Portland production wells in this area ranged from 100 to 180 μg/L and median nitrate (as N) concentrations ranged from < 0.01 to 1.05 mg/L (unpublished data, Portland Water Bureau). Given this challenge, it is even more impressive the degree to which water quality conditions were improved in Blue Lake during the circulation treatment.

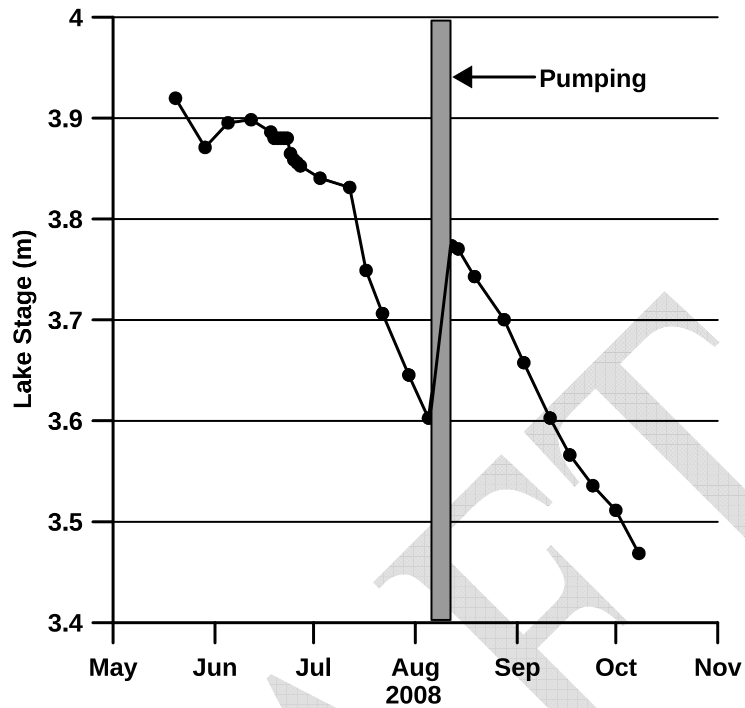


Figure 32. Stage of Blue Lake (arbitrary datum) measured in 2008.

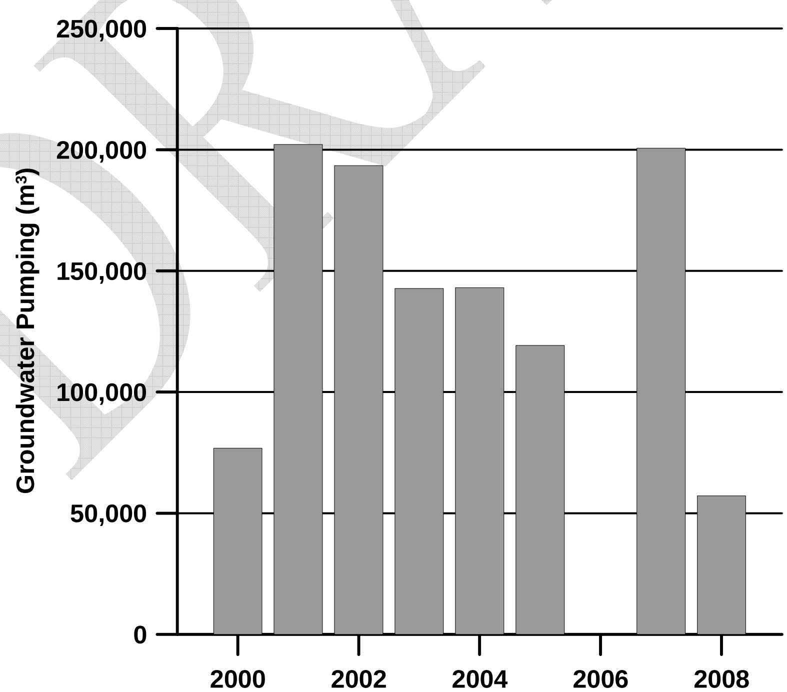


Figure 33. Groundwater pumping into Blue Lake from the Portland well field (data courtesy of the Portland Water Bureau).

Most shallow lakes enter a quasi-stable state of being either macrophyte-dominated or phytoplankton-dominated (Scheffer 2004). In the macrophyte-dominated state, submerged, emergent, or floating macrophytes grow to such as extent that phytoplankton have insufficient light, lack access to adequate nutrients, or are repulsed by chemicals produced by the macrophytes. In the phytoplankton-dominated state, excessive growth of phytoplankton early in the growth season out-compete macrophytes for light. Consequently, efforts to control macrophytes or phytoplankton in shallow lakes often result in switching the lake state from macrophyte-dominated to phytoplankton-dominated systems or vice versa, a situation referred to as "alternative stable states". Blue Lake appeared to be moving towards a system that was becoming increasingly dominated by cyanobacteria as indicated by the increasing rates of *Anabaena* deposition in the sediments (Figure 34). The treatment response in 2008 appears to be a major reversal of the trend to 2004.

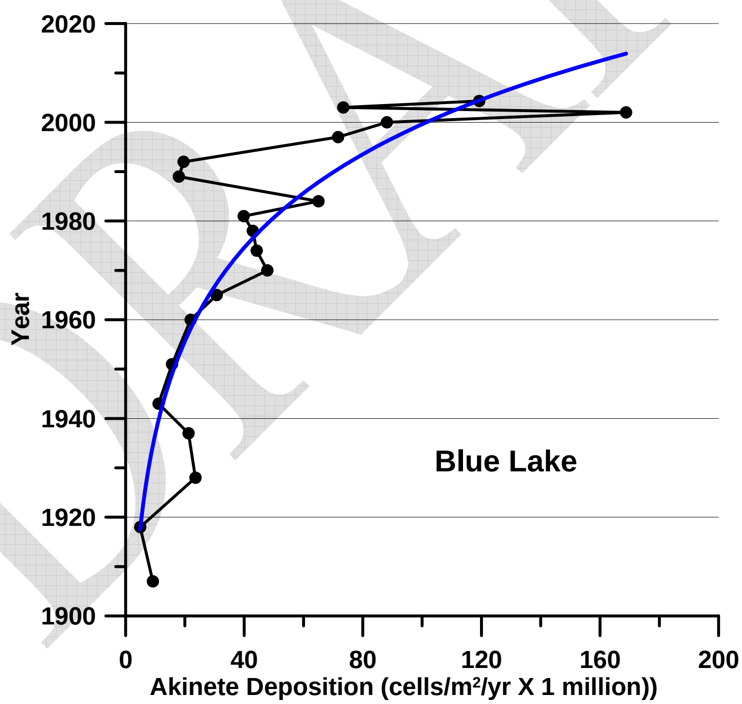


Figure 34. Deposition rate of *Anabaena* akinetes (resting cells). The blue line represents the polynomial fit to the observed data [from Eilers & St. Amand 2004] .

Reducing both cyanobacteria and invasive macrophytes simultaneously by applying a single non-chemical treatment is unprecedented. This raises obvious questions regarding how circulation technology achieves these results. Circulation in sufficient amounts can physically disrupt the physical habitat of cyanobacteria and counter advantages associated with buoyancy control. However, only the area immediately surrounding a SolarBee has sufficient velocity to promote the required level of disturbance. Other hypotheses offered to explain the efficacy of circulation in controlling cyanobacteria include increased exposure to UV damage, increased grazing from zooplankton, and disruption of quiescent conditions. Others have raise the possibility that circulation promotes cyanophage infection of cyanobacteria (Knud-Hansen & Eilers, In Prep). By pumping water from depth, presumably with higher densities of cyanophage (c.f., Frederickson et al. 2003), it increases the probability for contact between cyanophage and its host cyanobacteria. A recent review of virus-cyanobacteria interactions is presented by Middleboe et al (2008). However, the cyanophage hypothesis remains one of a number of hypotheses that have been raised to explain cyanobacteria responses to circulation.

Regardless of the mechanism for control of cyanobacteria, it is unlikely that the same mechanism would promote control of invasive macrophytes. There are two reasonable hypotheses to explain control of shallow-rooted macrophytes with circulation. First, control of cyanobacteria would have the effect of reducing N-fixation and would decrease the deposition of decaying cyanobacteria in the shallows. Decomposition of the cyanobacteria provides an excellent source of ammonia through mineralization of organic nitrogen. By shutting off this source of nitrogen, shallow-rooted macrophytes could become N-limited. Alternatively, circulation promotes oxidation of surficial sediments by continually drawing oxygenated waters over the sediment. Oxidation of sediments causes conversion of ammonia, the preferred source of nitrogen for many macrophytes, to nitrate (Barko and Smart 1981;__ 1986; Smith and Barko 1990). As a result, shallow-rooted macrophytes are gradually extirpated. These two hypotheses to explain the effects of circulation on macrophytes are not mutually exclusive.

Regardless of the mechanisms involved, the results of the circulation trial in Blue Lake have unequivocally shown a major reduction of cyanobacteria and dramatic improvements in other attributes of water quality, defined as increased transparency, decreased pH, less extreme dissolved oxygen concentrations, reduced chlorophyll, lower phosphorus and nitrogen concentrations, and reduced extent and abundance of the invasive macrophyte, *M. spicatum*.

LITERATURE CITED

Barko, J.W. and R.M. Smart. 1981. Sediment-based nutrition of submersed macrophytes. *Aquatic Botany.* 10:339-352.

Barko, J.W. and R.M. Smart. 1986. Sediment-related mechanisms of growth limitation in submersed macrophytes. *Ecology.* 67:1328-1340.

Eilers, J.M. and A. St. Amand. 2004. Recent Paleolimnology of Blue Lake, OR. Report to the Oregon Department of Environmental Quality. MaxDepth Aquatics, Inc., Bend, Oregon. 33 pp.

Frederickson, C.M., S.M. Short, and C.A. Suttle. 2003. The physical environment affects cyanophage communities in British Columbia inlets. *Microbial Ecology*. 46:348-357.

Geiger, N.S. 1983. Blue Lake Clean Lakes Program. Phase I Diagnostic /Feasibility Study. Final Report. Beak Consultants, Inc., Portland, Oregon.

Knud-Hansen, C. and J.M. Eilers. In Prep. Empirical evidence for sustainable cyanobacteria bloom control through mechanically-induced circulation.

Middleboe, M.S., and S. Jaquet, and Weinbauer. 2008. Viruses in freshwater ecosystems: an introduction to the exploration of viruses in new aquatic habitats. *Freshwater Biology*. 53:1069-1075.

Pfauth, M. and M. Sytsma. 2004. Integrated aquatic vegetation management plan for Blue Lake, Fairview, Oregon. Portland, Oregon. Portland State University. 93 pp.

Scheffer, Marten. 2004. Ecology of Shallow Lakes. Kluwer Academic Press. Boston. 357 pp.

Schindler, D.W, R.E. Hecky, D.L. Findlay, M.P. Stainton, B.R. Parker, M.F. Patterson, K.G. Beaty, M. Lyngh, and S.E.M. Kasian. 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen inputs: Results of a 37-year whole-ecosystem experiment. *Proc. Nat. Acad. Sci.* 105:11254-11258.

Smith, C.S. and J.W. Barko. 1990. Ecology of Eurasian watermilfoil. *J. Aquatic Plant Mangement.* 55-64.

ACKNOWLEDGEMENTS

I wish to thank representatives of Portland Metro, Dawn Tavis, Elaine Stewart and Teri Dresler, the Oregon Department of Environmental Quality and Karen Font Williams, and the Portland Water Bureau for providing data used in this assessment. I thank Joe Horton, Blue Lake Homeowners Association, for collecting some of the Secchi disk and temperature data used here.