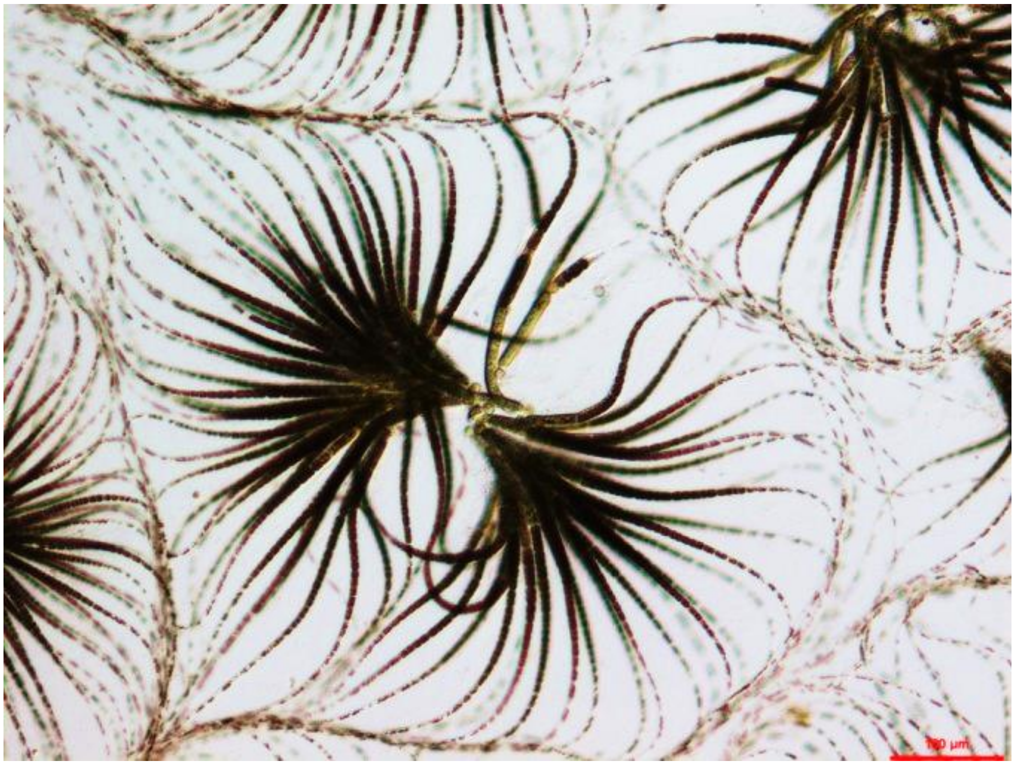
DATA ANALYSIS REPORT

GREEN LAKE PHYTOPLANKTON STUDY



Prepared for
Seattle Parks and Recreation

Prepared by
Herrera Environmental Consultants, Inc.

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DATA ANALYSIS REPORT

GREEN LAKE PHYTOPLANKTON STUDY

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This report was prepared by Rob Zisette with funds provided by Seattle Parks and Recreation. The author appreciates the opportunity to compile and evaluate the vast amount of data collected by many researchers on this fascinating and important lake. He also appreciates the valuable review comments provided by Kevin Stoops (formerly with Seattle Parks and Recreation), Kathleen Conner (project manager with Seattle Parks and Recreation), Sally Abella (King County Water and Land Resources Division), Harry Gibbons (Tetra Tech), concerned citizens (Gayle Garman, Richard Fleming, Karen Schurr, and Garet Munger), and fellow Herrera scientists (Joy Michaud and John Lenth).

Executive Summary

Green Lake is a shallow eutrophic lake located just north of downtown Seattle (Figure 1). Green Lake is surrounded by Green Lake Park that is owned and managed by Seattle Parks and Recreation. This urban lake is classified as eutrophic (rich in nutrients and algae) because it has produced excessive amounts phytoplankton (free-floating algae), primarily due to the concentrations of phosphorus that promote growth of these algae. The phytoplankton group of particular concern is cyanobacteria; a group commonly referred to as blue-green algae that are actually photosynthetic bacteria.

Green Lake is an important recreational and aesthetic resource for city residents. Although the lake is heavily used, enjoyment of it has been diminished due to poor water quality. Intense blooms of cyanobacteria have plagued the lake since at least 1916 (KCM 1995). Various techniques have been used to reduce the amount of cyanobacteria by reducing phosphorus concentrations (Herrera 2003, 2005). The most significant recent efforts to improve water quality and reduce cyanobacteria have been lake-wide applications of aluminum sulfate (alum) in 1991 and 2004.

Although water quality goals have been met since the 2004 alum treatment, those goals are based on average lake conditions. During recent years (2012-2014), toxic cyanobacteria scums have occurred in isolated areas of the lake. High concentrations of microcystin detected in scum samples have resulted in closure of the lake to direct contact recreational use (swimming) for substantial periods. Microcystin is a cyanotoxin produced by some cyanobacteria but no other algae. In response to this, Green Lake stakeholders have modified cyanobacteria monitoring, public notification, and lake closure procedures.

The purpose of the Green Lake Phytoplankton Study is to:

- Document effects of the 1991 and 2004 alum treatments on the amount and type of phytoplankton in the lake
- Evaluate nutrient and phytoplankton relationships and trends using data collected since 1959
- Evaluate algae scum accumulation patterns using observation data collected for the lake over the past 2 years
- Evaluate cyanotoxin data from algae scum samples and beach water samples collected at the lake since 2007
- Document cyanobacteria monitoring protocols, public notification, and lake closure procedures currently used by Green Lake stakeholders
- Provide Seattle Parks and Recreation with recommendations on the next steps for controlling phytoplankton and addressing additional lake needs

Conclusions drawn from this study include:

- Both alum treatments effectively reduced the total amount of phytoplankton (as chlorophyll) during the summer in Green Lake. The reduction was greater and lasted longer following the 2004 alum treatment than the 1991 alum treatment because of the threefold higher dose of alum applied in 2004.

- Alum dramatically reduced the amount of cyanobacteria (as biovolume) in Green Lake for at least 10 years following the 2004 alum treatment, but did not appear to affect the amount of cyanobacteria in the first 3 years following the 1991 alum treatment.

- Total phytoplankton (algae) and cyanobacteria (blue-green algae) abundance in Green Lake is primarily controlled by phosphorus. Statistical analysis of the data clearly showed that total phytoplankton and cyanobacteria biomass are most correlated with the concentration of total phosphorus in the lake. While nutrient ratios suggest that algae may occasionally be controlled by nitrogen, recent increases in the concentration of nitrogen have increased the importance of total phosphorus as the primary nutrient limiting the growth of algae in Green Lake.

- The 2004 alum treatment effectively met water quality goals for total phosphorus and Secchi depth by reducing total phosphorus concentrations and phytoplankton growth in Green Lake for 10 years, achieving its design goal.

- Total phosphorus and toxic cyanobacteria concentrations substantially increased in both of the past two years (2013 and 2014). Toxic cyanobacteria caused lake closures over 2- to 3-month periods and substantial impacts to recreational uses of Green Lake in both years, but no closures occurred in the first 9 years following the 2004 alum treatment. Prior to the 2004 alum treatment, the lake was closed to primary contact recreation for a 1- to 5-month period in the late summer/fall of 1999, 2002, and 2003.

- Goals specific to prevention of cyanobacteria blooms and lake closures have not been established for Green Lake. Current water quality goals are based on average summer values that were established in 1991 before cyanotoxins were monitored or a concern. These goals do not adequately protect public health or prevent recreational impacts from toxic cyanobacteria.

- Microcystin has been the only cyanotoxin of concern in Green Lake. All lake closures were based the microcystin concentration in algae scum samples that exceeded the state guideline of 6 µg/L. Anatoxin-a is the only other cyanotoxin that has been measured in Green Lake and it has never exceeded the state guideline of 1 µg/L.

- Microcystin concentrations in algae scum samples increased in 2012 and again in 2014. The highest microcystin concentration of 25,000 µg/L observed in scum on September 11, 2014, is thought to be the highest ever recorded in Washington State.

- Microcystin was much lower in samples collected outside the algae scum and the state guideline was only exceeded on one occasion in outside scum samples (6.7 µg/L on

September 11, 2014). Consumption of algae scum is a much higher public health threat to Green Lake users and their dogs than consumption of waters outside algae scum. Risks associated with microcystin consumption are much higher for children and dogs than adult users because of their greater risk for consumption of scum and lower tolerance to microcystin due to low body mass.

- Microcystin concentrations measured weekly at the swimming beaches since 2007 did not exceed the state guideline until 2014 when the guideline was exceeded on three occasions from late August to early October, and those concentrations varied greatly on the same date at the two beaches located on opposite shores of the lake. The dramatic increase in microcystin at the swimming beaches in 2014, along with the steady increase in phosphorus and chlorophyll over the past 3 years, suggests that concentrations may further increase and result in more extensive beach closures in 2015 if cyanobacteria are not controlled.

- Anabaena and Microcystis were the dominant phytoplankton species and primary producers of microcystin in algae scum samples collected from shore locations at Green Lake. Algae scum did not contain toxic concentrations of microcystin except when Microcystis or Anabaena were observed in the scum sample. Although more scum samples were dominated by Anabaena (18) than Microcystis (4), the median microcystin was higher for Microcystis than Anabaena for all categories of relative abundance. Quantitative analysis of phytoplankton in scum samples would be necessary to determine if Microcystis actually produces more microcystin than Anabaena in Green Lake.

- Daily algae scum ratings recorded by a volunteer at 30 shore stations over the past 2 years were typically higher in the summer than winter months (November through April). The amount of scum was often higher during periods of low wind speed regardless of the prevailing wind direction, but varied greatly and was unpredictable on a daily basis.

- The highest scum accumulation was typically observed at sheltered locations in the northwest area of lake (Duck Island Beach) during the winter and northeast area of the lake during the summer (vicinity of East Beach). Signage warning avoidance of algae scums by Green Lake users is particularly important in the vicinity of East Beach, Duck Island Beach, and Densmore Inlet due to the high frequency of scum observations and common access to the lake in these areas.

- Although the scum rating data greatly enhanced the understanding of algae scum patterns in Green Lake, algae scum ratings have not been consistent enough to determine when to close specific areas of the lake to primary contact recreation due to the highly variable wind conditions and scum accumulation, and unknown species composition of the scum.

Based on the study findings, the following is recommended:

- Treat Green Lake with alum as soon as possible to control cyanobacteria and prevent lake closures anticipated to recur in the summer of 2015. The alum treatment should be designed to cost effectively reduce water column phosphorus and inactivate any sediment phosphorus that has been deposited in the lake from external loading over the past 10 years.

- Prepare an Algae Control Plan for the alum treatment that includes the following tasks and provides the associated information:
  - Reassess and develop new water quality goals to better align with protection of public and pet health, and prevention of lake closures from toxic cyanobacteria.
  - Collect and analyze sediment cores for phosphorus fractions and other parameters of interest. Sediment analysis results should be used to evaluate recent changes in phosphorus loading, and to evaluate alternative alum treatment designs to effectively intercept internal and external phosphorus loadings.
  - Update the lake phosphorus budget to account for potential changes in internal and external phosphorus loadings.
  - Evaluate alternatives and recommend a preferred alternative for controlling toxic cyanobacteria. The control alternatives evaluation should focus on variations in alum treatment dose, timing, application technique, and application strategy. An alternative to long-term treatment strategy of 2004 should include smaller, periodic treatments to prevent pulses of phosphorus in the water column and the associated blooms of toxic cyanobacteria. The control alternatives evaluation should include qualitative analysis of internal control methods that have been previously evaluated for Green Lake (dilution, aeration, circulation, treatment, and dredging), and those that have been developed since the previous evaluation (scum removal by vactoring, treatment with Phoslock®, and circulation by SolarBee®). Recommendations should be made for reducing external phosphorus loading where appropriate and feasible.
  - Prepare a lake water quality monitoring plan to evaluate short-term and long-term effects of the proposed alum treatment.
  - Prepare a public education and outreach plan to identify stakeholders, and describe methods for informing and obtaining feedback from stakeholders on the Algae Control Plan.
- Implement the Algae Control Plan to include the following tasks and provide the associated information:
  - Prepare the application and obtain an Aquatic Plant and Algae Management General Permit for an alum treatment.
  - Prepare contractor specifications for an alum treatment.
  - Procure a contractor to perform the alum treatment in 2015 or 2016 depending on the available funding and schedule.

- Prepare and distribute signs and other education materials.
- Provide technical oversight and water quality monitoring of the alum treatment.

If funding is available, preparation of the Algae Control Plan should be expedited in anticipation of performing an alum treatment by early summer 2015 to mitigate impacts from a cyanobacteria bloom anticipated to occur in the late summer of 2015. It is anticipated that it would require approximately 3 months to prepare the plan from January through March 2015, and a maximum of 3 months to obtain a permit and secure a contractor via public bidding from April through June 2015. Treatment during a cyanobacteria bloom in the late summer or fall of 2015 is not preferred due to additional alum and potential water quality impacts of performing a treatment during a cyanobacteria bloom when an excessive amount of algae scum is present on the lake surface. Alternatively, an alum treatment should be successfully performed in the spring of 2016 to control phosphorus and subsequent cyanobacteria blooms. At this time, funding is only available for design and permitting in 2015, and for treatment in 2016.

Upon completion of the Algae Control Plan and treatment of the lake with alum in 2015 or 2016, Seattle Parks and Recreation should consider future study and preparation of a Lake Management Plan to address additional needs for Green Lake:

- Eurasian watermilfoil management
- Shoreline vegetation management
- Fisheries management
- Stormwater management
- Outlet control
- Sediment and fish contamination
- Public education

1. INTRODUCTION

Green Lake is a shallow eutrophic lake located just north of downtown Seattle (Figure 1). Green Lake is surrounded by Green Lake Park that is owned and managed by Seattle Parks and Recreation. This urban lake is classified as eutrophic (rich in nutrients and algae) because it has produced excessive amounts phytoplankton (free-floating algae), primarily due to the concentrations of phosphorus that promote growth of these algae. The phytoplankton group of particular concern is cyanobacteria; a group commonly referred to as blue-green algae that are actually photosynthetic bacteria.

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2. BACKGROUND

Cyanobacteria blooms in Green Lake are supported by physical and chemical processes within the lake, as well as drainage into the lake from the surrounding urban watershed that supplies nutrients. Previous studies have shown that most of the primary limiting nutrient, phosphorus, can be attributed to internal processes within the lake, with sediments on the lake bottom identified as the primary source. The movement of certain cyanobacteria from the sediments to the overlying water has been identified as a significant source of internal phosphorus loading (Barbiero 1991; Barbiero and Welch 1992). However, other processes common to shallow lakes (e.g., macrophyte decay and benthic fish activity) are also important (Welch and Cooke 1995).

Green Lake is listed by the Washington Department of Ecology (Ecology) as an impaired water body due to concentrations of total phosphorus and fecal coliform bacteria in the lake water, and due to organic chemical contamination in fish tissue (Ecology 2014a). The regulatory action required to address these impairments is the establishment of a total maximum daily load (TMDL) for Green Lake. However, a TMDL has not been established for Green Lake and the lake is not included on Ecology's list of funded water quality improvement projects for water resource inventory area (WRIA) 8 (Ecology 2014b). In addition to phosphorus, Green Lake is also identified on Ecology's 303(d) list of impaired waters because of the presence of fecal coliform bacteria in the water and organic chemical contamination of fish tissue (Ecology 2014a).

Seattle Parks and Recreation, with funding assistance from Ecology and the US Environmental Protection Agency (US EPA), implemented a lake restoration program in 1991 for Green Lake based on a Phase I diagnostic feasibility study of the lake conducted in 1981 (URS 1983), a water quality improvement plan prepared in 1987 (URS 1987), and subsequent restoration alternative evaluations (URS 1990a, 1990b, 1990c). Goals established for the lake restoration program included reducing the mean total phosphorus concentration in the summer to less than 30 micrograms per liter (µg/L) and maintaining average water transparency (Secchi depth) in the summer to greater than 2.5 meters (8.2 feet).

The cornerstone of the lake restoration program was the application of aluminum sulfate (alum) to inactivate sediment phosphorus, thereby reducing internal phosphorus loading and phosphorus availability to cyanobacteria. Alum treatment was selected because internal sources accounted for 88 percent of the phosphorus input to the lake from July through September 1981, and sediments likely were the principal source (KCM 1995; Bostridge 1982). Sediment phosphorus release occurs by various mechanisms, but primarily by the solubilization of iron-bound phosphorus under anoxic (no oxygen) conditions. Sediment phosphorus release typically occurs during the summer in the hypolimnion of a stratified lake (in deep waters below thermocline, which is the depth where the temperature change is greater than 1°C per meter). Green Lake has been shown to become weakly stratified on several occasions during the summer in the small, deep area of the lake, but not in the main body of the lake due to wind mixing (KCM 1995). Although Green Lake is only weakly stratified, dissolved oxygen concentrations occasionally become depleted in the bottom waters above the sediment during the summer in the deep area of the lake and less frequently in the main body of the lake due to a high sediment oxygen demand (KCM 1995).

Green Lake was treated with alum and the buffering agent sodium aluminate in October 1991. For 3 years after the alum treatment, phosphorus concentrations in the lake were meeting the target of less than 30 µg/L (KCM 1995). Other management efforts included; stormwater controls, dilution of the lake with City drinking water, waterfowl management, and public education (KCM 1995). The restoration project completion report concluded that an alum treatment would be necessary every 5 to 8 years to control phosphorus levels in the lake and to prevent summer algal blooms (KCM 1995). In addition, the report recommended that the lake restoration goal for average summer phosphorus concentration be revised to less than 25 µg/L; a recommendation that was accepted by the stakeholders.

As predicted, the 1991 alum treatment improved water quality for a few years (KCM 1995). However, Green Lake suffered from cyanobacteria blooms on several occasions in subsequent summers. Blooms of cyanobacteria resulted in potentially toxic levels of microcystin (produced by cyanobacteria) and prompted closure of the lake to all contact recreation in 1999 (8 years after the 1991 treatment), 2002, and 2003. Increased phosphorus loading likely contributed to these cyanobacteria blooms that may have originated from both internal and external sources (e.g., erosion from the Green Lake path construction in 1996, excretion from grass carp planted in 2001, and leaching from the large wood chip pile in Lower Woodland Park until it was removed in 2005).

In 2003, a study was conducted to determine the optimum approach for again treating Green Lake with alum (Herrera 2003). That study included a water quality and fisheries data compilation, alum literature review and dose calculation, alum dose testing, alum treatment technical specifications, permit requirements, and an estimate of treatment cost.

As of July 2002, treatment of a lake with alum required the issuance of a permit from Ecology for coverage under the state's National Pollutant Discharge Elimination System (NPDES) Waste Discharge General Permit for Aquatic Nuisance Plant and Algae Control. In order to obtain the NPDES permit for an alum application, an Integrated Phosphorus Management Plan (IPMP) was prepared (Herrera 2003) and Ecology issued an NPDES permit to Seattle Parks and Recreation in December 2003. Permit requirements changed in 2012 when Ecology developed the Aquatic Plant and Algae Management General Permit to be used for alum treatments instead of the NPDES permit. As part of this new permit and instead of an IPMP, alum treatments of 5 acres or more now require a discharge management plan (DMP) and State Environmental Policy Act (SEPA) addendum (Ecology 2014c).

Green Lake was treated with alum (aluminum sulfate) and a buffering agent (sodium aluminate) in March and April 2004 according to the Ecology-approved IPMP and contractor specifications. Treatment observations and water quality monitoring results collected during the Green Lake 2004 alum treatment were presented in the treatment monitoring report (Herrera 2004). Water quality monitoring results collected in the summer of 2004 following the treatment were presented in the Year 1 (2004) post-treatment monitoring of Green Lake (Herrera 2005). This report included additional special studies about lake sediments to assess the long-term effects of the 2004 alum treatment on the water quality of Green Lake. Lake sediment monitoring was conducted to determine effects of the alum treatment on reducing the available phosphorus in lake sediments. The effects of carp on the internal loading of phosphorus in Green Lake were also modeled and evaluated. Seattle Parks and Recreation prepared a post-treatment monitoring summary report that included annual reports for 10 years (2004-2013) following the 2004 alum treatment (Seattle Parks 2014).

3. Data Sources and Analysis Methods

The number of water quality and phytoplankton data values used in this report are presented in Table 1. Locations of established lake and shore monitoring stations are shown in Figure 2. Data were compiled for shallow water samples collected at depths from 1 to 6 meters in the months of May through October, representing summer months of all years for which there were data. Data for deep water samples (below 6 meters depth) or other months were not compiled or used for this study. Sources of historical water quality and phytoplankton data compiled for this study include:

- **Rehabilitation study in 1959 (Sylvester and Anderson 1960):** 12 sampling events with median values of temperature and nutrients from two depths (surface and 2.7 meters) at six stations, Secchi depth at the center station, and chlorophyll *a* and phytoplankton composition(but not biovolume) from depth-integrated sample at the center station. (This data set was collected following a large sewage spill into the lake, and was therefore used for historical perspective and not recommendations of future actions.)

- **Restoration diagnostic feasibility study in 1981 (URS 1983; Bolstridge 1982):** 12 sampling events with mean values of water quality parameters and phytoplankton composition (but not species biovolume) from four depths (0-5 meters) at the Index station.

- **Cyanobacteria research in 1989 and 1990 (Barbiero 1991):** 14 to 17 sampling events per year with mean values of temperature from 4 meters at six stations, Secchi depth at six stations, phosphorus (but not chlorophyll or nitrogen) from three depths (0 to 4 m) at three stations and four depths (0 to 6 m) at three stations, and cyanobacteria species biovolume from vertical net tows at six random stations.

- **Phase IIC restoration project in 1992 - 1994 (KCM 1995):** 6 to 12 sampling events per year with mean values of temperature from seven depths (0-6 meters), Secchi depth, nutrients (but no total nitrogen in 1993) from four depths (0-6 m), and chlorophyll *a* and phytoplankton species biovolume from depth-integrated sample at the Index station.

- **Lake monitoring by Seattle Parks in 1995 and 2004– 2013 (Herrera 2003; Seattle Parks 2014):** 6 to 12 sampling events per year mean values of temperature from seven depths (0 to 6 meters) and Secchi depth at the Index station, and chlorophyll *a* and phosphorus from depth-integrated composite sample (0 to 4 m) at Composite A and B stations. (Data were also compiled 1996 and 1999 – 2002, but were not used because there were only 1 to 4 sampling events per year).

- **Secchi depth monitoring by Friends of Green Lake in 2003 (FOGL 2004):** 11 sampling events with only Secchi depth at the northeast pier. (This data set was not used because no other parameters were monitored in 2003).

- **Lake monitoring by Friends of Green Lake and King County in 2005 – 2014 (King County 2014a):** 12 sampling events per year with temperature, Secchi depth, nutrients (dissolved nutrients on only two sampling events per year), and chlorophyll *a* from 1 meter depth at the Index station. (Data were not compiled for additional samples collected at 3 and 7 meters depth on two sampling events per year.)

- **Phytoplankton composition data from Friends of Green Lake in 2008 (FOGL 2009):** 10 sampling events for phytoplankton species biovolume from 1 meter depth at the Index station.

- **Algae scum rating data from Friends of Green Lake in 2012 – 2014 (Munger 2014):** Daily scum ratings from 31 shore stations.

- **Cyanotoxin and qualitative phytoplankton data from the Washington State Toxic Algae Database and King County in 2007 - 2014 (Ecology 2014d; King County 2014b, 2014c):** Occasional grab samples at various shore locations for cyanotoxins (microcystin and anatoxin-a) and phytoplankton species presence, and semi-monthly grab samples at the west beach station and occasional grab samples at the east beach station for cyanotoxins only.

Phytoplankton samples collected from Green Lake in the summer of 2013 were analyzed specifically for this study. A total of 12 samples were collected by trained FOGL members at a depth of 1 meter from May 6 through October 21, 2013, as part of routine monitoring for the King County Lake Stewardship Program (which has been contracted through Seattle Public Utilities since 2005). King County had preserved and stored the samples for potential enumeration of phytoplankton species. King County shipped the archived samples to WATER Environmental Services, Inc. (WATER) for phytoplankton analysis. WATER analyzed 11 of the samples for phytoplankton species cell counts and biovolume according to the method previously used by WATER for phytoplankton analyses conducted for Green Lake in 1992, 1993, 1994, and 2008. The sample collected on October 21, 2013, was lost. In addition, the sample analyzed for August 26, 2013, was collected from a depth of 3 meters instead of 1 meter because King County had spilled a portion of the 1 meter sample.

3.1. Lake Monitoring Data

For this study, Herrera compiled historical water quality and phytoplankton data collected for Green Lake in the following study periods and associated years:

- **Pre 1991 Alum Treatment:** 1959, 1981, 1989, and 1990

- **Post 1991 Alum Treatment:** 1992 through 1995

- **Post 2004 Alum Treatment:** 2004 through 2014

Data were tabulated for each sample date for the months of May through October of each year. Water quality parameters included: water temperature, Secchi depth, chlorophyll *a*, total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate+nitrite nitrogen, and ammonia nitrogen. Total and dissolved nitrogen to phosphorus ratios were calculated for each sample date when data were available.

Summary tables were prepared presenting the number of water quality and phytoplankton parameter values used in the analysis, and the resulting summer mean values from May through October. Summer means were also computed separately for water quality samples collected by King County and Seattle Parks during the post-2004 alum treatment period. Although King County collected samples from the Index station and Seattle Parks collected samples from the Composite A and B stations, King County showed that water quality was very similar across the lake by comparing results for samples collected at the Index and Composite A station in 2005-2008 (which is why King County stopped collecting samples at the Composite A station in 2009). In addition, samples were collected by both sources on a regular schedule from May through October, with the exception that Seattle Parks did not collect samples in October. King County and Seattle Parks used the same analytical methods and achieved similar detection limits. The two data sets were combined for the water quality data analysis because the summer means from the King County and Seattle Parks data sets are very similar for the water quality parameters measured by both sources (see Section 4 - Lake Data Analysis).

Phytoplankton parameters included percent composition of total cell biovolume for the following major phytoplankton groups:

- Cyanaophyta (cyanobacteria/blue-green algae)
- Chlorophyta (green algae)
- Chrysophyta (primarily diatoms and some other genera including *Dinobryon*)
- Others (primarily flagellated Dinophytes and Cryptophytes)

Cell biovolume concentration data were compiled for each phytoplankton species and summed for the following groups:

- Total Phytoplankton (all phytoplankton species)
- Total Cyanobacteria (all cyanobacteria species)
- Microcystis (*M. aeruginosa and M. wesenbergii*)
- Anabaena (*A. circinalis, A. spiroides, A, flos-aquae, A. lemmermannii, A. planktonica,* and unknown *Anabaena* species)
- Aphanizomenon (*A. flos aquae*)
- Gloeotrichia (*G. echinulate*)
- Woronichinia (*Coelosphaerium naegelianum,* renamed as *Woronichinia,* and unknown *Woronichinia* species)
- Other Cyanobacteria (*Anacystis*, *Aphanocapsa*, *Aphanothece*, *Anathece*, *Chroococcus* sp., *Gomphosphaeria lacustris*, *Oscillatoria* sp., Oscillatoriaceae, Oscillatoriales - Pseudanabaenaceae, and Nostocales)

These groups of species were selected because of their following characteristics (US EPA 2012 and other sources):

- **Microcystis** – frequently observed in Green Lake, common and typically a high producer of the cyanotoxin microcystin in other lakes, unable to form heterocysts for nitrogen fixation, unable to form akinetes (resting spores), and able to vertically migrate using gas vesicles (but has not been shown to translocate large amounts of sediment phosphorus in Green Lake or other lakes)
- **Anabaena** – most frequently observed in Green Lake in recent years, common and typically a moderate producer of cyanotoxins microcystin and anatoxin-a in other lakes, able to form heterocysts for nitrogen fixation, able to form akinetes (resting spores), and able to vertically migrate using gas vesicles (which may translocate large amounts of sediment phosphorus, but this was not observed historically in Green Lake due to low abundance)
- **Aphanizomenon** – frequently observed in Green Lake, common and typically a low producer of cyanotoxins microcystin and anatoxin-a in other lakes, able to form heterocysts for nitrogen fixation, able to form akinetes (resting spores), and able to vertically migrate using gas vesicles (which has been shown historically to translocate large amounts of sediment phosphorus in Green Lake)
- **Gloeotrichia -** frequently observed in Green Lake, uncommon but possible producer of microcystin in other lakes, able to form heterocysts for nitrogen fixation, able to form akinetes (resting spores), and able to vertically migrate using gas vesicles (which has been shown historically to translocate large amounts of sediment phosphorus in Green Lake)
- **Woronichinia** – frequently observed in Green Lake, uncommon but possible producer of cyanotoxins in other lakes, unable to form heterocysts for nitrogen fixation, unable to form resting akinetes (spores, and able to vertically migrate using gas vesicles (but has not been shown to translocate large amounts of sediment phosphorus in Green Lake or other lakes)
- **Other Cyanobacteria** – occasionally observed in Green Lake, uncommon producer of cyanotoxins in other lakes (with the exception of *Oscillatoria* which is a common producer of anatoxin-a), typically unable to form heterocysts for nitrogen fixation, typically unable to form akinetes (resting spores), and typically able to vertically migrate using gas vesicles (but have not been shown to translocate large amounts of sediment phosphorus in Green Lake or other lakes)

The following summary figures were prepared:

- Water quality by year in box and whisker plots for water temperature, Secchi depth, chlorophyll *a*, total phosphorus, total nitrogen, total N:P ratio, and dissolved N:P ratio
- Water quality by month for all study years within each of the three study periods in box and whisker plots for water temperature, Secchi depth, chlorophyll *a*, total phosphorus, total nitrogen, total N:P ratio, and dissolved N:P ratio

- Phytoplankton group biovolume composition by year in stacked bar graphs of for Cyanophyta, Chlorophyta, Chrysophyta, and Others
- Phytoplankton group biovolume composition by month for all study years within each of three study periods in stacked bar graphs for Cyanophyta, Chlorophyta, Chrysophyta, and Others
- Cyanobacteria group biovolume by year in stacked bar graphs for Microcystis, Anabaena, Aphanizomenon, Gloeotrichia, Woronichinia, and Other Cyanobacteria
- Cyanobacteria group biovolume by month for all study years within the post-1991 and post-2004 alum treatment periods in stacked bar graphs of for Microcystis, Anabaena, Aphanizomenon, Gloeotrichia, Woronichinia, and Other Cyanobacteria

Temporal trends in water quality were evaluated for the post-2004 alum treatment period using a seasonal Mann Kendall trend test. The statistical significance of trends in the data were evaluated based on an alpha (α) level of 0.05. Temporal trends for water quality in other study periods or any phytoplankton data were not evaluated statistically due to insufficient data. Rather, differences in water quality between study periods and years were evaluated from the box and whisker plots, where a non-overlapping interquartile range (25th to 75th percentile) was generally considered to be significantly different.

Relationships among water quality and phytoplankton data were explored Kendall tau rank correlation analysis; statistical significance was again evaluated base on an alpha (α) level of 0.05. Kendall tau rank correlation analysis is a non-parametric test that is used to identity relationships between two variables. Significant relationships were identified using this analysis for each of the three study periods and for all periods combined.

Principal Component Analysis (PCA) was also used to explore relationships among water quality and phytoplankton data for the post-1991 and 2004 alum treatment periods. PCA was not used for the pre-1991 alum treatment period due to incomplete data for all variables. PCA is based on orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The number of principal components is less than or equal to the number of original variables. This transformation is defined in such a way that the first principal component has the largest possible variance (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to (i.e., uncorrelated with) the preceding components. PCA was performed using log-transformed and standardized data because it requires the data to exhibit a normal distribution and be on a common scale. In addition, zero values for some phytoplankton parameters were changed to very low values because zero cannot be log-transformed and PCA requires a complete data set. A value of 0.01 percent was used for zero values of phytoplankton group composition and a value of 0.00001 mm^3/L was used for zero values of cyanobacteria species biovolume.

3.2. Algae Scum Monitoring Data

Algae scum rating data were collected at 31 shore stations (see Figure 2) on a daily basis from February 2, 2013, through October 15, 2014 (Munger 2014). Rating data were recorded between 9:00 am and 11:00 am on most dates at all sites with some exceptions. Data for one site (site 17) were deleted because the site became obscured by water lilies and ratings were not recorded at this site for most the study period. Algae scum ratings range from 0 to 8 as follows:

- **0** = No scum visible
- **1** = Scum present in scattered small clumps on surface or thin scum, not immediately detected visually
- **2** = Scum present in scattered patches or in thin windrow along shoreline
- **3** = Scum present in a band about 10 inches wide and 6 feet along shoreline
- **4** = Scum present in band more than 12 inches wide and 6 feet along shoreline
- **5** = Scum more than 3 feet wide along shoreline
- **6** = Scum more than 5 feet wide and with “soupy” appearance
- **7** = Scum more than 6 feet wide and with "thick soupy" appearance
- **8** = Scum more than 6 feet wide and with "very thick soupy" appearance

Based on the location, each station was designated in the database by a shore identification (N, E, S, or W shore of the lake), shore aspect angle (angle in degrees of the direction towards shore which is perpendicular to the shoreline), and shore aspect identification (N, NE, E, SE, S, SW, or W based on the shore aspect angle). Mean scum ratings were calculated for each site and group of sites for each date and the following four seasonal periods: Winter 2013 (2/2/13 – 4/30/13), Summer 2013 (5/1/13 – 10/31/13), Winter 2014 (11/1/13 – 4/30/14), and Summer 2014 (5/1/14 – 10/15/14). The frequency of each rating was calculated for each site within each of these periods.

Wind direction, wind speed, and solar radiation data were compiled for the first 12 hours (midnight to noon) of each scum observation date. These climate data were based on observations in 1-minute intervals at the following weather station: University of Washington Atmospheric Sciences Rooftop. Mean values were calculated for wind speed and solar radiation. Median values were calculated for wind direction to avoid errors with averaging northerly degrees, and categorized into six directions (N, NE, E, SE, S, SW, W, or NW). Although the wind data used in the analysis represents the best available prevailing wind speed and direction for the period of interest, Green Lake likely exhibits different wind conditions than the University of Washington due to topographic and lake effects on wind. Specific microclimates for Green Lake likely resulted in different wind directions and speeds at the various shore locations on many occasions, particularly during periods of low wind.

Daily mean scum and climate data were plotted chronologically for the entire study period. Maps were prepared showing pie charts of average scum rating frequencies at each shore station for each of the four seasonal periods. Stacked bar charts showing the frequency of four wind speed classes in each of the six wind direction categories were included on each map. The wind speed categories were based on the quartiles of all wind speed data (< 25th percentile, 25-50th percentile, 50-75th percentile, and > 75th percentile).

3.3. Cyanotoxin Monitoring Data

Cyanotoxin and phytoplankton data for Green Lake were downloaded from the Washington State Toxic Algae Database for the period from January 1, 2011, to October 21, 2014 (Ecology 2014d). Surface grab samples were collected within algae scum or outside algae scum at various shore locations, primarily by King County staff and occasionally by FOGL members. Many of the sampled scums were located within a small area that was not characteristic of the remaining shoreline, and some sampled scums were only present at the sample location for a short period of time.

The King County Laboratory analyzed the samples for the cyanotoxins microcystin (which included microcystin LR and other microcystin compounds) and anatoxin-a. One-half the detection limit was used for results reported as less than the method detection limit (MDL), which was either 0.05 or 0.16 μg/L for microcystin and either 0.01 or 0.019 μg/L for anatoxin-a. Each sample value was designated as “in scum” or “not in scum” based on information recorded on sample collection forms and provided by King County (2014c).

Most of the samples were also analyzed for relative phytoplankton abundance where each species observed in a sample was designated as either dominant, subdominant, or present. Each phytoplankton species was assigned to the following groups: Microcystis, Anabaena, Aphanizomenon, Gloeotrichia, Woronichinia, Other Cyanobacteria, and Other Phytoplankton. The microcystin concentration for each sample was then assigned to the corresponding abundance designation for each phytoplankton group.

Cyanotoxin data were obtained from King County for routine weekly samples collected at the West Beach and East Beach from June 5, 2007, to October 13, 2014 (King County 2014b). Surface grab samples were typically collected on a weekly basis from May through October for each year at the West Beach and for 2014 only at the East Beach.

Microcystin concentration data were plotted chronologically for the algae scum samples where “in scum” and “not in scum” samples were plotted separately. Microcystin concentration data were plotted chronologically for the swimming beach samples where West Beach and East Beach samples were plotted separately. Finally, microcystin concentration data were presented in box and whisker plots for each abundance category (dominant, subdominant, or present) within each phytoplankton group.

4. LAKE DATA ANALYSIS

Data analysis results are presented and discussed separately for water quality and phytoplankton. Relationships between water quality and phytoplankton are then presented and discussed.

The number of water quality and phytoplankton parameter values are presented in Table 1. Summer mean values from May through October are presented in Table 2.

As noted in Section 3.1 – Lake Monitoring Data, summer means were computed separately for water quality samples collected by King County and Seattle Parks during the post-2004 alum treatment period. As shown in Table 2, summer means from the King County and Seattle Parks data sets are very similar for the water quality parameters measured by both sources. Therefore, the two data sets were combined for the water quality data analysis.

4.1. Water Quality Data

Water quality data are presented as box plots in Figures 3 through 9 showing annual and monthly trends among the three study periods. Figure 10 presents results of the seasonal trend analysis of water quality data for the post-2004 alum treatment period. Results are summarized separately for each water quality parameter.

4.1.1. Temperature

Water temperature exhibited a wide range during each summer that was similar among all years (see Figure 3). The summer mean temperature was very similar among years, ranging from 17.9 to 20.5 degrees Celsius (°C) and exceeding the Washington State Surface Water Quality Standard of 16°C (based on a 7-day average maximum in lakes; WAC 173-201A) in each study year. Monthly mean temperatures for each study period typically increased from approximately 16°C in May to 22°C in July and August, and decreased to 14°C in October. The highest maximum temperatures were observed in July 1959 (25°C) and August 2009 (26°C).

4.1.2. Secchi Depth

Secchi depth is a measure of water transparency, which is affected by the amount and size of algae and other particles in the water, and is used to determine the trophic state of lakes along with chlorophyll and total phosphorus. The Secchi depth goal for Green Lake is for the summer mean to exceed 2.5 meters (m) (Herrera 2003), compared to a common threshold of less than 1.9 m for eutrophic lakes. This goal was established in 1991 and is compared to all study years in Figure 4.

The Secchi depth goal was met in every study year except 1959 and 2003 when the summer mean Secchi depth was 2.0 m and 1.9 m, respectively (see Figure 4). (Note: Secchi depth data for 2003 are not shown in Figure 4 because only Secchi depth was measured in 2003 and those results were not analyzed for this study.) With the exception of 1959, the summer minimum and mean Secchi depths were similar among the pre-1991 and post-1991 alum treatment years, and were typically greater (higher transparency) in the post-2004 alum treatment years. Secchi depth exhibited a greater range after the 2004 alum treatment.

Monthly mean Secchi depth decreased from a maximum of approximately 4 m in May to a minimum of approximately 2 m in October in the pre-1991 and post-1991 alum treatment years, but only decreased from a maximum of 4 m in May to a minimum of 3 m in September in the post-2004 alum treatment years. This observation suggests that phytoplankton growth did not increase as much over the summery months following the 2004 alum treatment as compared to summers before this treatment.

4.1.3. Chlorophyll

Chlorophyll *a* is a convenient and common measure of phytoplankton biomass. However, it is present in highly varied amounts among phytoplankton species and growth stages, and often does not relate well to cell biovolume or water transparency. Chlorophyll is used to determine trophic state of lakes, and a common threshold for eutrophic lakes is a summer mean chlorophyll *a* concentration of greater than 7 micrograms per liter (μg/L) (USEPA 2010). A chlorophyll goal has not been established for Green Lake.

Chlorophyll was much higher in the pre-1991 alum treatment years than the post-1991 alum treatment period, and was lowest in the post-2004 alum treatment period (see Figure 5). Summer mean chlorophyll before the 1991 alum treatment ranged from 27 to 29 μg/L. This greatly exceeded the eutrophic threshold of 7 μg/L, and was approaching the hypereutrophic threshold of greater than 30 μg/L. Summer mean concentrations ranged from 5 to 12 μg/L following the 1991 alum treatment. Summer mean concentrations ranged from 2 to 6 μg/L since the 2004 alum treatment, never exceeding the eutrophic threshold. Summer mean chlorophyll initially decreased slightly from 4 μg/L in 2004 to a low of 2 μg/L in 2008, and then increased to a high of 6 μg/L by 2014. (If October data had been included in the analysis the average would have been 7 μg/L.) Chlorophyll exhibited a significant increasing trend since the 2004 alum treatment ($p=0.01$, see Figure 10).

Monthly mean chlorophyll significantly increased from May to October during the pre-1991 alum treatment period, but did not exhibit a strong seasonal pattern during the post-1991 or post-2004 treatment periods (see Figure 5). The variance in chlorophyll was much lower following the 1991 alum treatment and even lower following the 2004 alum treatment.

4.1.4. Total Phosphorus

Total phosphorus is also used to determine the trophic state of lakes because phosphorus is typically the most limiting nutrient for freshwater phytoplankton and relates well with chlorophyll and Secchi depth. The total phosphorus goal for Green Lake is for the summer mean to be less than 25 μg/L (Herrera 2003), which is a commonly used threshold for eutrophic lakes. This goal was established in 1991 and is compared to all study years in Figure 6.

Total phosphorus was much higher in the pre-1991 than the post-1991 alum treatment years, and was lowest in the post-2004 alum treatment years (see Figure 6). Summer mean total phosphorus greatly exceeded the current goal and eutrophic threshold of 25 µg/L in 1959, and decreased to near the goal in 1989 and 1990. The high value observed in 1959 was likely due to a very large sewage spill that occurred in 1959. Although the goal was generally met in all years following both alum treatments, total phosphorus was much lower and exhibited less variation following the 2004 alum treatment. However, summer mean total phosphorus increased the past 2 years to a high of 19 µg/L in 2014 (which did not change when October data were included in the mean after the data were analyzed for this report). Total phosphorus exhibited a significant increasing trend during the post-2004 alum treatment period (p=0.04, see Figure 10).

Monthly mean total phosphorus significantly increased from May to October during the pre-1991 alum treatment period and, unlike chlorophyll, also during the post-1991 alum treatment. Similar to chlorophyll, total phosphorus did not exhibit a strong seasonal pattern during the post-2004 treatment period (see Figure 6). The seasonal variance in total phosphorus was much lower following the 1991 and 2004 alum treatments.

4.1.5. Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) is a measure of dissolved phosphorus that is immediately available for phytoplankton uptake. SRP is not presented in box plots, but summer mean SRP is presented for each year in Table 2. Summer mean SRP was high at 19 µg/L in 1959, similar among other pre-1991 treatment years (3 to 4 µg/L) and the post-1991 alum treatment years (2 to 4 µg/L), and at or near the detection limit in post-2004 treatment years (1 to 2 µg/L). SRP was typically 5 to 15 percent of total phosphorus in all years except 1959 (27 percent).

4.1.6. Total Nitrogen

Total nitrogen is the sum of organic nitrogen and dissolved inorganic nitrogen, which is comprised of nitrate+nitrite and ammonia nitrogen. Total nitrogen can be the most limiting nutrient for freshwater phytoplankton when total phosphorus is high, which can occur in hypereutrophic lakes that have excessively high nutrients from inputs of human or animal waste. There is no total nitrogen goal for Green Lake and some have suggested a total nitrogen threshold of 180 µg/L for eutrophic lakes (Welch 1992).

Total nitrogen was much higher in the pre-1991 than the post-1991 alum treatment years, and was lowest immediately following the 2004 alum treatment (summer mean values ranged from 445 to 721 µg/L for the pre-1991 treatment period, 286 to 344 µg/L for the post-alum treatment period, and 210 to 387 µg/L for the post-2004 treatment period) (see Figure 7). However, total nitrogen has increased each year since 2010, and exhibited a significant increasing trend during the post-2004 alum treatment period when the summer mean value increased from and 210 µg/L in 2005 to 387 µg/L in 2014 (p=0.01, see Figure 10).

Monthly mean total nitrogen exhibited different patterns among the three study periods, increasing during the summer of the pre-1991 alum treatment years with the exception of an unusually high value in May, peaking in August during the post-1991 treatment years, and not exhibiting a pattern during the post-2004 treatment years (see Figure 7). Similar to total phosphorus, the seasonal variance in total nitrogen was much lower following the 1991 and 2004 alum treatments.

4.1.7. Nitrate Nitrogen

Nitrate+nitrite nitrogen is a measure of two dissolved inorganic forms of nitrogen that are readily used by phytoplankton and microbes in lakes, but this parameter generally represents just nitrate nitrogen in surface waters when oxygen is present. Nitrate nitrogen is not presented in box plots, but summer mean values are presented in Table 2. Summer mean nitrate nitrogen was high in 1959 (107 µg/L) but unusually low in 1981 (12 µg/L), moderate during the post-1991 alum treatment years (15-27 µg/L), and was not detected during the post-2004 treatment years when detection limits ranged from 5 to 20 µg/L.

4.1.8. Ammonia Nitrogen

Ammonia nitrogen is another form of dissolved inorganic nitrogen readily used by phytoplankton and other microbes in lakes. Ammonia nitrogen is not presented in box plots, but summer mean values are presented in Table 2. Summer mean ammonia nitrogen was high in 1959 (224 µg/L), moderate in 1981 (22 µg/L), moderate to high in the post-1991 alum treatment years (22 to 101 µg/L), and typically detected at low concentrations in the post-2004 treatment years (5 to 13 µg/L) except for a recent increase to 22 µg/L in 2014. The increase in 2014 was based on only two samples that contained less than 9 µg/L in May and 39 µg/L in August 2014, and the source of ammonia in August 2014 is unknown but may have been from phytoplankton decomposition.

4.1.9. Total Nitrogen to Phosphorus Ratio

The total nitrogen to total phosphorus ratio by weight (total N:P) is often used to evaluate which of the two nutrients limit phytoplankton growth. Traditionally, a total N:P ratio of 7 is used to assess nutrient limitation; where ratios greater than 7 indicate phosphorus limitation and ratios less than 7 indicate nitrogen limitation (Welch 1992). As noted below, other ratios have been proposed based on nutrient addition experiments and observations, and with consideration of nutrient concentrations over different time scales (Sterner 2008).

It is generally accepted that phosphorus is the primary limiting nutrient in lakes and nitrogen is the primary limiting nutrient in marine waters. A recent review of nutrient limitation literature concluded that while phosphorus appears to control phytoplankton growth in oligotrophic lakes over the long term (years), most lakes appear to be limited over the short term (months) by both phosphorus and nitrogen (co-limitation), and possibly by other resources such as iron (Sterner 2008). One study concluded that nutrient limitation depends on both nutrient concentrations and their ratio (Guildford and Hecky 2000). Based on nutrient relationships observed in 221 lakes, they found that phosphorus-deficient growth occurred consistently at total N:P ratios greater than 22, and nitrogen-deficient growth occurred consistently at total N:P ratios less than 9. These limits are included in the total N:P box plot (Figure 8) for reference, with co-limitation assumed to occur between these limits.

Based on these limits, the summer mean total N:P ratios observed in Green Lake indicate that phytoplankton are typically limited by both nitrogen and phosphorus over the long term, with the exception of possible nitrogen limitation in 1959 and phosphorus limitation in some of the post-2004 alum treatment years (see Figure 8). The summer mean total N:P ratio was lower during the pre-1991 alum treatment period (8 to 14) than the post-1991 alum treatment period (15 to 20) and the post-2004 alum treatment period (13 to 26) due to the reduced total phosphorus by the alum treatments. This ratio generally increased during the post-2004 alum treatment period to a maximum of 26 in 2012, but decreased over the past 2 years when chlorophyll increased (see Figures 5 and 8).

The recent decrease in total N:P ratio was because total phosphorus increased proportionately more than total nitrogen between 2012 and 2014 (see Figures 6 and 7). Assuming nitrogen fixation rates and the N:P ratio of external inputs have not recently changed, this observation suggests that internal phosphorus loadings may have recently increased from the release of soluble phosphorus in sediments deposited in the lake since the 2004 alum treatment (but not from release of phosphorus bound to aluminum by the treatment). Relationships between nutrients and phytoplankton are evaluated in Section 4.3. Overall, the total N:P ratio did not exhibit a significant increasing trend during the post-2004 alum treatment period ($p=0.30$; see Figure 10).

The monthly mean total N:P ratio typically fluctuated within the nitrogen/phosphorus co-limitation range of 9 to 22 for all study periods, and no consistent seasonal trends were apparent (see Figure 8).

4.1.10. Dissolved Nitrogen to Phosphorus Ratio

Short term changes in dissolved nutrients and dissolved N:P ratios may affect phytoplankton composition in lakes due to species differences in nutrient requirements. For example, many cyanobacteria can fix nitrogen by converting atmospheric nitrogen (N_2) to ammonium (NH_4^+) when dissolved nitrogen is in short supply, while other phytoplankton can only use dissolved nitrogen.

The summer mean dissolved N:P ratio was lower during the pre-1991 alum treatment period (ratio range of 11 to 12) than the post-1991 alum treatment period (ratio range of 17 to 38), and was lowest during the post-2004 alum treatment period (ratio range of 5-8) with the exception of one high value for 2014 (ratio of 35) (see Figure 9). Considering these ratios and the amount of dissolved nutrients, phytoplankton were likely limited by both nutrients in the pre-1991 alum treatment period (moderate to high dissolved nitrogen and phosphorus) and in the post-2004 alum treatment period (low dissolved nitrogen and phosphorus), but were limited by only phosphorus in the post-1991 alum treatment period (moderate to high dissolved nitrogen and low dissolved phosphorus). The unusually high dissolved N:P ratio in 2014 was due to an unusually high concentration of ammonia nitrogen for that period from phytoplankton decomposition or unknown sources as noted above. There was no significant seasonal trend in dissolved N:P ratio during the post-2004 alum treatment period ($p=0.89$; see Figure 10).

Monthly mean total N:P typically did not exhibit a seasonal pattern for any period (see Figure 9).

4.2. Phytoplankton Data

Phytoplankton data are presented as stacked bar charts in Figures 11 and 12 showing annual and monthly trends among the three study periods. Percent composition of phytoplankton groups and biovolume of cyanobacteria species are presented and discussed separately.

4.2.1. Group Composition

Phytoplankton group composition was very similar in the two pre-1991 alum treatment years with data (1959 and 1981) (see Figure 11), which is quite remarkable and may be a coincidence considering the length of time between those observations. Before the alum treatments, Green Lake phytoplankton were dominated by cyanobacteria (70 to 72 percent Cyanophyta) and included much lesser amounts of diatoms (15 to 17 percent Chrysophyta), green algae (9 to 10 percent Chlorophyta), and others (3 to 4 percent Other Groups).

Phytoplankton composition substantially changed in each of the 3 years following the 1991 alum treatment. Cyanobacteria continued to dominate the year following the 1991 alum treatment, but steadily declined from 70 percent in 1992 to 31 percent in 1994 when there was a similar percentage of diatoms (35 percent Chrysophyta) and lower amounts of other groups (12 percent Chlorophyta and 21 percent Other Groups). This large amount of change in phytoplankton composition was not observed for water quality parameters, suggesting that other factors may have affected the gradual decline in cyanobacteria abundance over the initial three years following the October 1991 alum treatment. One such factor may have been a delayed response of cyanobacteria to the reduced phosphorus supply after to an initial germination of resting spores in early 1992. Gloeotrichia reached its maximum biomass and comprised 99 percent of the total biovolume in June 1992, but disappeared by July 1992 and was rarely present in 1993. Another factor may have been changes in grazing pressure by large zooplankton (cladocerans consisting of water fleas in the order Cladocera), but the higher cladoceran biomass observed in 1994 than 1992 (KCM 1995) was likely in response to rather than a cause of the reduced cyanobacteria abundance in 1994 because cyanobacteria are not a preferred food by cladocerans.

Cyanobacteria abundance in Green Lake was at its lowest in the post-2004 alum treatment period, when Cyanophyta represented only 13 percent in 2008 and 8 percent in 2013 (see Figure 11). Diatoms were clearly dominant in 2008 (63 percent Chrysophyta), while both diatoms and green algae dominated phytoplankton in 2013 (38 percent Chrysophyta and 43 percent Chlorophyta). Differences in summer mean phytoplankton composition following the two alum treatments appear related to the higher alum dose and resulting lower total phosphorus for the 2004 alum treatment because cyanobacteria dominance and total phosphorus were much lower following this treatment than the 1991 alum treatment, and total nitrogen and total N:P ratio were similar among the four post-alum treatment years with phytoplankton and nutrient data.

Monthly mean phytoplankton composition varied greatly among the study years and did not follow the seasonal succession pattern expected for temperature and light conditions, which typically transitions from diatoms in the spring (low temperature and high light), to green algae in the summer (high temperature and high light), and to cyanobacteria in the fall (high temperature and low light) (Welch 1992). For example, cyanobacteria were most abundant (highest percent composition) in the following months of each year: June 1959, October 1981, August 1992, June 1993, July 1994, July 2008, and August 2013 (see Figure 11). One interesting pattern is that diatoms were most abundant in May or June of the pre-1991 alum treatment years, but were most abundant in September or October of post-1991 and 2004 alum treatment years. These observations suggest that phytoplankton composition in Green

Lake are affected more by the varied phosphorus conditions than the more consistent temperature and light conditions. Differences in zooplankton grazing pressure may have also accounted for some of the inter-annual differences in seasonal succession patterns.

4.2.2. Cyanobacteria Biovolume

The summer mean total cyanobacteria biovolume varied greatly within and between the three study periods, ranging from a low of 0.04 mm^3/L in 2008 to a high of 5.8 mm^3/L in 1992 (see Figure 12). The range of summer mean total cyanobacteria biovolume was similar in the pre-1991 and post-1991 treatment periods (1.7 to 4.6 mm^3/L and 1.2 to 5.8 mm^3/L, respectively), but much lower in the post-2004 treatment period (0.04 to 2.4 mm^3/L). These results clearly show that the 1991 alum treatment had a negligible effect on cyanobacteria biovolume while the 2004 alum treatment resulted in a significant reduction in cyanobacteria biovolume for at least nine years.

Different phytoplankton sampling techniques were used for each of the three study periods, which may have affected cyanobacteria biovolume results. Phytoplankton samples were collected using a plankton net in 1989 and 1990 for the pre-1991 alum treatment years, as water-column composite samples from two stations (Composite A and B) for the 3 years in the post-1991 alum treatment period, and as grab samples at a 1 meter depth from one station (Index) for the 2 years in the post-2004 alum treatment period. Grab samples collected at the Index station in post-2004 alum treatment period are assumed to represent lake-wide conditions based on the well mixed conditions and equivalent chlorophyll concentrations measured by King County at the Index and Composite A stations during that period. Although a plankton net collection efficiency of 0.49 was applied to the 1989 and 1990 samples (KCM 1995), comparisons to theses pre-1991 study years should be made with caution due to potentially variable net efficiencies caused by differences in net tow speed and clogging.

Cyanobacteria biovolume data represent phytoplankton suspended in the water column throughout the lake body, which may have differed from that accumulated in shoreline scum or present on the sediment surface. For example, high concentrations of Gloeotrichia were observed in algae scum samples in October 2008 when none was observed in the water column samples (FOGL 2009). This observation suggests that Gloeotrichia may have migrated rapidly from the sediment surface to the water surface in October 2008, and represents how quickly phytoplankton composition can change in the lake and species can be missed when only one sample is collected every two weeks.

Gloeotrichia was responsible for the very high biovolume observed in 1989 and 1992, and the moderate biovolume observed in 1994, while it contributed to the moderate biovolume in 1991 but was not present in 1993. Gloeotrichia was not present in 2008 or 2013 following the 2004 alum treatment when chlorophyll and total phosphorus were low. The timing of Gloeotrichia blooms varied among the years, reaching maximum biovolume in August of 1989 and 1990, June of 1992, and July of 1994.

Aphanizomenon was moderately abundant in each year of the pre- and post-1991 alum treatment periods, and was rarely present in the post-2004 alum treatment period. Aphanizomenon bloomed in the late summer of the pre-1991 alum treatment period, but was commonly present in low amounts throughout the post-1991 alum treatment period.

Anabaena was rarely present in the pre-1991 alum treatment period, but was relatively abundant in the post-1991 and 2004 alum treatment periods.

Microcystis was rarely observed in the phytoplankton samples with the exception that it dominated cyanobacteria biovolume in September 1990 and September 2013.

Woronichinia represented a very small portion of cyanobacteria biovolume except for August of 1993 and 1994, and obtaining dominance and its highest biovolume in August 2013.

Other cyanobacteria were most prevalent in the post-2004 alum treatment period, but did not dominate cyanobacteria with the exception of Anacystis and Chroococcus in October 2008, and again in May to June 2013.

4.3. Correlation Analysis Results

Correlation of water quality and phytoplankton parameters was analyzed using Kendal tau rank correlation analysis because it can be used to evaluate non-linear relationships that are apparent in the data. Kendall tau correlation coefficients (τ) can range from -1 to +1. Negative coefficients indicate there is a negative relationship between the two values (i.e., as one variable increases, the other decreases). Positive values indicate there is a positive relationship (i.e., as one variable increases, so does the other). Coefficients at or near 0 indicate there is no strong relationship between the variables.

Table 3 presents the Kendall tau correlation coefficients (τ) for each of the three study periods (Pre, Post1, and Post2) and for all periods combined (All). Significant correlations (α=0.05) are summarized separately for key parameters. The Kendall tau correlation coefficient (τ) is included in parentheses in the discussions below.

4.3.1. Secchi Depth

Among the water quality parameters for all periods, Secchi depth was most correlated to chlorophyll (-0.49) and total phosphorus (-0.34). Negative correlations were significant for all three study periods and were most significant for the pre-1991 alum treatment period (-0.61 for chlorophyll and -0.62 for total phosphorus). These results suggest that water transparency in Green Lake was primarily affected by total phosphorus because of its positive effect on phytoplankton biomass as chlorophyll. The strong relationship among the three trophic state parameters supports their use for lake goals, and agrees with the basic limnological principal that lake water clarity is most affected directly by phytoplankton biomass and indirectly by phosphorus.

Secchi depth was less negatively correlated with total nitrogen (-0.18) and nitrate nitrogen (-0.23) using all data, but these parameters were not correlated for the post-2004 alum treatment period. Interestingly, Secchi depth was positively correlated with total N:P ratio for the post-2004 alum treatment period only, which means water transparency increased when the total N:P ratio increased in recent years. This relationship may be related to effects of N:P ratio on phytoplankton composition rather than biomass as noted below, where higher N:P ratios favor the growth of diatoms and greens that have less effect on water transparency than nitrogen-fixing cyanobacteria.

Secchi depth was significantly correlated to all phytoplankton parameters except Microcystis and Gloeotrichia biovolume. The only parameters significantly correlated for all three periods were total phytoplankton biovolume (-0.37 to -0.52) and total cyanobacteria biovolume (-0.31 to -0.46), and these negative correlations were strongest for the pre-1991 alum treatment period. Using all data, relatively strong negative correlations were also observed for Cyanophyta percent (-0.33), Aphanizomenon biovolume (-0.40), and Anabaena biovolume (-0.34).

4.3.2. Chlorophyll

Chlorophyll correlated with all water quality parameters except temperature. Among all periods, chlorophyll was most correlated to Secchi depth (-0.49) and total phosphorus (-0.43), followed by total nitrogen (-0.36). The total N:P ratio was positively correlated only for the post-1991 alum treatment period (0.32), but was weakly negatively correlated using all data (-0.19). These results suggest that phytoplankton biomass as chlorophyll in Green Lake was directly affected by total phosphorus and total nitrogen, but not by their ratio.

Chlorophyll was significantly correlated to all phytoplankton parameters except Microcystis and Other Cyanobacteria biovolume. Using all data, the strongest correlations were observed for total phytoplankton biovolume (0.59), Aphanizomenon biovolume (0.57), and total cyanobacteria biovolume (0.50).

4.3.3. Total Phytoplankton Biovolume

Total phytoplankton biovolume correlated with all water quality parameters except temperature and dissolved nutrients. Among all periods, total phytoplankton biovolume was most correlated to chlorophyll (0.59), total phosphorus (0.48), total nitrogen (0.46), and Secchi depth (-0.46). The total N:P ratio was weakly negatively correlated only for all periods combined (-0.21), as for chlorophyll, but not for either of the three periods. These results suggest that phytoplankton biovolume in Green Lake was directly affected by total phosphorus and total nitrogen, but not by their ratio.

As for chlorophyll, total phytoplankton biovolume was significantly correlated to all phytoplankton parameters except Microcystis and Other Cyanobacteria biovolume. Using all data, the strongest correlation was observed for total cyanobacteria biovolume (0.54) compared to cyanobacteria species (0.21 to 0.36) or other groups (-0.19 to -0.30).

4.3.4. Phytoplankton Group Composition

Phytoplankton group composition correlated with water quality parameters to a lesser extent than did total phytoplankton biovolume. Among all periods, percent Cyanophyta significantly correlated primarily with chlorophyll (0.39), total phosphorus (0.37), Secchi depth (-0.33), and total N:P ratio (-0.31), and least with total nitrogen (0.19). Percent Chlorophyta did not correlate with total phosphorus or total nitrogen, but weakly correlated opposite from percent Cyanophyta with chlorophyll (-0.22), Secchi depth (0.22), and total N:P ratio (0.22). Correlation results for percent Chrysophyta and Other Groups were similar to percent Chlorophyta, except there was a significant negative correlation with total phosphorus (-0.36) and total nitrogen (-0.17) for Chrysophyta, and a significant correlation with total phosphorus (-0.29) for Other Groups.

These results suggest that phytoplankton group composition is significantly affected by the total nutrient concentration and resulting amount of phytoplankton. Increased total phosphorus generally increased percent Cyanophyta and decreased percentages of other phytoplankton groups, suggesting that phosphorus control is the key to cyanobacteria control.

4.3.5. Total Cyanobacteria Biovolume

Water quality correlation results for total cyanobacteria biovolume among all periods were similar to those for percent Cyanophyta except that total cyanobacteria biovolume also correlated with soluble reactive phosphorus (0.29) and not with total N:P ratio. However, significant correlation with soluble reactive phosphorus only occurred for the pre-1991 treatment period (0.28) when soluble reactive phosphorus concentrations were high. Total cyanobacteria biovolume significantly correlated most with total phosphorus (0.50) and chlorophyll (0.50), and less with total nitrogen (0.23) and Secchi depth (-0.28).

4.3.6. Cyanobacteria Species Biovolume

Microcystis biovolume did not correlate with any water quality parameters due to a lack of Microcystis in most phytoplankton samples. Among all periods, Anabaena biovolume correlated with chlorophyll (0.37) and Secchi depth (0.34), but not with any other water quality parameters. Aphanizomenon biovolume was highly correlated with chlorophyll (0.57), total phosphorus (0.44), and Secchi depth (-0.40). Aphanizomenon was only correlated with total nitrogen for the post-2004 alum treatment period (0.40), and was the only cyanobacteria species to correlate (negatively) with total N:P ratio among all periods (-0.27). Gloeotrichia biovolume only correlated with total phosphorus (0.31) and chlorophyll (0.20). Woronichinia biovolume primarily correlated with total nitrogen (0.33) and chlorophyll (0.29), and less with Secchi depth (-0.22) and total phosphorus (0.17). Other cyanobacteria biovolume only correlated with Secchi depth (-0.26) among all periods. Thus, Aphanizomenon biovolume exhibited the strongest relationship with chlorophyll and total phosphorus among all cyanobacteria species.

4.4. Principal Component Analysis Results

Principal component analysis identified a total of 10 components that explained 94 percent of the variance in all 18 tested parameters, which included 6 water quality parameters and 12 phytoplankton parameters (Table 4). Component 1 (PC1) explained 34 percent of the variance, component 2 explained 14 percent of the variance, and the remaining 8 components progressively explained less variance (each decreasing from 11 to 2 percent).

Figure 22 graphically presents the principal component results for the first two principal components (PC1 versus PC2), which when combined explained 48 percent of the variance in the water quality and phytoplankton data. The lower plot shows a projection of the sampling events (grouped by month and year) on the factor plane whereas the upper plot shows a projection of the 18 tested parameters on the factor plane.

Results from the principal components analysis generally show PC1 primarily reflects different chemical and biological conditions in the lake after each alum treatment because nutrient and algae concentrations were much lower after the 2004 alum treatment than after the 1991 alum treatment. This is evident in the lower plot by the grouping of sampling events from years after 2004 alum treatment (2008 and 2013) on the left (negative) side of the axis for PC1, and sampling events from years after the 1991 alum treatment (1992 and 1994) on the right (positive) side. The closer association between years and periods than months also indicates that variance in the data is much more associated with annual than monthly or seasonal changes in the parameters tested.

Examining the upper plot indicates this relationship between treatment periods is primarily driven by parameters on the right due to higher values after the 1991 alum treatment and parameters on the left due to higher values after the 2004 alum treatment. Parameters associated on the right include total phosphorus, phytoplankton biomass (as total biovolume and chlorophyll), and cyanobacteria biovolume (total and all species except the other, nontoxic species group). Parameters on the left include total nitrogen, total N:P ratio, percentage of non-toxic phytoplankton groups (Chlorophyta, Chrysophyta, and Others), and Secchi depth. Vertical separation of these parameters by PC2 along the y axis indicates that total phosphorus is closely associated with cyanobacteria (percent Cyanophyta) and total nitrogen is closely associated with green algae (percent Chlorophyta).

The principal component analysis results generally reflect many of the same relationships that were identified through the correlation analysis where amounts of potentially toxic species of cyanobacteria were more closely related to total phosphorus than total nitrogen or total N:P ratio after the two alum treatments of Green Lake.

5. ALGAE SCUM DATA ANALYSIS

The algae scum rating for each of the 30 stations were averaged to obtain one mean scum rating for the lake on each observation date. The mean daily algae scum rating for the lake is presented chronologically with solar radiation from February 2013 through October 2014 in Figure 13. Mean scum ratings were highly variable, but exhibited the following temporal pattern:

- Decreasing from February to May 2013 when solar radiation was increasing
- Increasing from July through October 2013 when solar radiation was decreasing
- Decreasing from November 2013 to January 2014 when solar radiation was near zero from midnight to noon
- Low with occasional moderate values from January to August 2014 when solar radiation was increasing
- Increasing from August through October 2014 when solar radiation was decreasing

Thus, an inverse relationship was generally observed between changes in algae scum accumulation and the amount of daylight.

Daily wind speed and direction were even more variable over time than algae scum or solar radiation, and did not exhibit an apparent temporal pattern during the scum observation period (Figure 14).

Mean daily algae scum ratings did not correlate well with wind speed, but did exhibit a general decrease with increasing wind speed in all directions (Figure 15).

Maps of algae scum rating frequency and wind speed/direction are presented separately in Figures 16 through 19 for the following winter and summer periods:

- **Winter 2013** (February through April 2013)
- **Summer 2013** (May through October 2013)
- **Winter 2014** (November 2013 through April 2014)
- **Summer 2014** (June through October 2014)

These scum and wind frequency maps show the following patterns:

- The winter periods exhibited less frequent scums and lower scum ratings than the summer periods.
- Winter 2013 and Winter 2014 periods (Figures 16 and 17) exhibited similar wind patterns where winds were most frequently coming from the northeast, east,

southeast, and south directions. Low to moderate wind speeds were most common in the northeast and east directions, and high wind speeds were most common in the southeast and south directions.

- The frequency and predominant locations of scum were similar between the winter periods, but the scum ratings were higher for Winter 2014 (frequently greater than 3) than Winter 2013 (did not exceed 3). The percentage of stations exhibiting a moderate to high scum rating (greater than or equal to a rating of 3 for a 10-inch wide band) on at least one occasion was 73 percent for Winter 2013 versus 100 percent for Winter 2014. The percentage of stations exhibiting a high scum rating (greater than or equal to a rating of 5 for a 3-foot wide band) on at least one occasion was 0 percent for Winter 2013 versus 23 percent for Winter 2014.

- Winter 2014 scum ratings greater than 3 (10-inch wide band of scum) were most frequently observed in relatively sheltered areas at the following sites (in decreasing order):

  - Sites 20 and 21 (Duck Island Beach in northwest area)

  - Sites 25 and 26 (Densmore Inlet in north area)

  - Site 3 (south of East Beach in northeast area)

- Summer 2013 and Summer 2014 periods exhibited similar wind patterns where winds were most frequently coming from the west, southwest, south, and northeast directions. Low to moderate wind speeds were most common in all of these directions except high wind speeds were most common in the south direction.

- The frequency and predominant locations of scum were similar between the summer periods, but the scum ratings were higher for Summer 2014 than Summer 2013 at some locations. The percentage of stations exhibiting a moderate to high scum rating (greater than or equal to a rating of 3 for a 10-inch wide band) on at least one occasion was 97 percent for Summer 2013 and Summer 2014. The percentage of stations exhibiting a high scum rating (greater than or equal to a rating of 5 for a 3-foot wide band) on at least one occasion was 37 percent for Summer 2013 versus 40 percent for Summer 2014. However, a very high scum rating (greater than or equal to 6 feet wide with thick or very thick soupy appearance) was observed at 2 stations (7 percent) in Summer 2014, but not at any stations in Summer 2013.

- Summer 2014 scum ratings greater than 3 (10-inch wide band of scum) were most frequently observed in relatively sheltered areas at the following sites (in decreasing order):

  - Site 3 and 4 (south of East Beach and at Hearthstone Outlet in northeast area)

  - Site 1 (Fishing Pier in northeast area)

  - Sites 20 and 21 (Duck Island Beach in northwest area)

- The sheltered areas showing higher algae scum accumulation also accumulated decaying fragments of Eurasian watermilfoil, which may have increased scum accumulation by providing additional protection from wave disturbance of the algae scum.

In summary, algae scum ratings were typically higher in the summer than winter months (November through April). The amount of scum was often higher during periods of low wind speed regardless of the prevailing wind direction, but varied greatly and was unpredictable on a daily basis. The highest scum accumulation was typically observed at sheltered locations in the northwest area of lake (Duck Island Beach) during the winter and northeast area of the lake during the summer (vicinity of East Beach). Signage warning avoidance of algae scums by Green Lake users is particularly important in the vicinity of East Beach, Duck Island Beach, and Densmore Inlet due to the high frequency of scum observations and common access to the lake in these areas. Although the rating data greatly enhanced the understanding of algae scum patterns in Green Lake, algae scum ratings have not been consistent enough to determine when to close specific areas of the lake to primary contact recreation due to the highly variable wind conditions and scum accumulation, and unknown species composition of the scum.

6. Cyanotoxin Data Analysis

Data for concentrations of cyanotoxins (microcystin and anatoxin-a) and the relative dominance of phytoplankton species in Green Lake were compiled for 2007-2014 from King County and the Washington Department of Ecology's Washington State Toxic Algae Database (King County 2014; Ecology 2014). Microcystin is a hepatotoxin (liver toxin) where oral consumption can lead to chronic toxicity (liver injury, kidney damage, or tumor promotion) or acute toxicity (severe liver damage followed by shock, heart failure, and death) depending on the dose. Anatoxin-a is a neurotoxin (nerve toxin) where oral consumption can cause loss of coordination, involuntary muscle contractions (twitching), convulsions, or death by respiratory paralysis. Cyanotoxin concentrations in swimming beach and algae scum samples are compared to Washington State recreational guidelines for microcystin (6 µg/L) and anatoxin-a (1 µg/L) (WDOH 2008). These samples were not analyzed for other known cyanotoxins, which include saxitoxins, cylindrospermopsins, aplysiatoxins, and lyngbyatoxin-a. Anabaena and Aphanizomenon are commonly present in Green Lake and known producers of saxitoxins, while species known to produce the other known cyanotoxins have not been observed in Green Lake.

Anatoxin-a data are not graphically presented because this cyanotoxin was never detected at the swimming beaches (65 samples collected from May 2010 to October 2014) and it was rarely detected and only at low levels in algae scum samples (detected at 0.1 µg/L in 2 of 27 samples collected from October 2011 to September 2014). The state guideline of 1 µg/L was never exceeded in any of the beach or algae scum samples. Although Anabaena is a known producer of anatoxin-a and was commonly present in Green Lake during this time period, these results indicate that neither Anabaena nor other cyanobacteria species are significant producers of anatoxin-a in Green Lake.

Microcystin data are presented and described separately for swimming beaches and algae scum samples, followed by the dominant cyanobacteria observed in algae scum samples. Microcystin includes microcystin LR and other microcystin compounds, but is described as a single compound for ease of discussion.

6.1. Beach Microcystin

Microcystin concentrations in swimming beach samples are presented chronologically in Figure 20. Microcystin concentrations have generally increased at the swimming beaches in recent years. Microcystin was rarely detected and never exceeded 0.1 µg/L at the West Beach in 2007 through 2010. Microcystin was frequently detected but never exceeded 1 µg/L at the West Beach in 2011 through 2013. Microcystin increased at the West Beach and was observed at similar concentrations at the East Beach in 2014. The state recreational guideline of 6 µg/L was exceeded on three occasions in 2014:

- 18.6 µg/L at West Beach (versus 0.4 µg/L at East Beach) on August 25, 2014
- 8.0 µg/L at West Beach (versus 2.4 µg/L at East Beach) on September 2, 2014

- 68.6 µg/L at East Beach (versus 0.5 µg/L at West Beach) on October 6, 2014

Although cyanobacteria bloom conditions were observed by King County during collection of these samples (King County 2014), these results show how cyanobacteria accumulation and microcystin concentration can vary greatly on opposite shores of the lake at the same time. The dramatic increase in microcystin at the swimming beaches in 2014 (see Figure 20) suggests that concentrations may further increase and result in more extensive beach closures in 2015, if cyanobacteria are not controlled.

6.2. Scum Microcystin

Microcystin concentrations in algae scum samples have been used since 1999 to close Green Lake to primary contact recreation. Lake recreation closure and opening dates have not been recorded by local or state agencies. Based on press releases and other communication records, lake closures due to scum microcystin concentrations are estimated to have occurred in the following years:

- **1999** – begin on August 20, 1999, and end in October 1999
- **2002** – begin on August 5, 2002, and end on January 16, 2003
- **2003** – begin in August 2003, and end in September 2003
- **2012** – begin on October 2, 2012, and end November 28, 2012
- **2013 -** begin on September 12, 2013, and end on December 9, 2013
- **2014** – begin on August 25, 2014, and end December 19, 2014

Microcystin concentrations in algae scum samples collected from 2011 through 2014 at various shore locations in Green Lake are presented chronologically in Figure 20. Samples were collected inside and outside of algae scum on several occasions and are shown separately in this figure. Microcystin was much higher and typically exceeded the state guideline of 6 µg/L inside the scum, but never exceeded the guideline outside the scum with one exception (6.7 µg/L on September 11, 2014). Microcystin increased from 2011 to 2012, and was highest in 2014 in both the inside and outside scum samples. The highest microcystin concentration of 25,000 µg/L observed in scum on September 11, 2014, is thought to be the highest ever recorded in Washington State (King County 2014).

These results clearly show that microcystin increased with the increased amount of scum in 2014, and that consumption of algae scum is a much higher public health threat to Green Lake users and their dogs than consumption of waters outside algae scum. Risks associated with microcystin consumption are much higher for children and dogs than adult users because of their greater risk for consumption of scum and lower tolerance to microcystin due to low body mass.

6.3. Scum Cyanobacteria Dominance

In addition to cyanotoxin analysis, 38 of the algae scum samples collected from inside and outside scum in Green Lake were also analyzed for phytoplankton species dominance.

Microscopic examination of the scum samples was used to classify all phytoplankton genera observed in the sample as either dominant, subdominant, or present. For this study, phytoplankton observed in the samples were categorized as either Microcystis, Anabaena, Aphanizomenon, Gloeotrichia, Woronichinia, Other Cyanobacteria, and Other Phytoplankton. Microcystin concentrations for dominant, subdominant, and present categories of each group are presented as box plots in Figure 21. Summary statistics for Microcystis and Anabaena are presented in Table 5.

Microcystin was highest when either Microcystis or Anabaena were dominant or subdominant in the 38 scum samples analyzed for phytoplankton. Although more scum samples were dominated by Anabaena (18) than Microcystis (4), the median microcystin was higher for Microcystis than Anabaena for all categories of relative abundance (see Figure 21 and Table 5). These results suggests that microcystin production may have been higher for Microcystis than Anabaena, but that Anabaena was a more common source of microcystin in Green Lake. However, quantitative analysis of scum samples would be necessary to determine species differences in microcystin production.

Microcystis was not observed in 11 scum samples that exhibited a median microcystin of 0.2 µg/L and a maximum microcystin of 78 µg/L (see Table 5). Neither Microcystis or Anabaena were observed in four scum samples that exhibited a median microcystin of 0.1 µg/L and a maximum microcystin of only 0.2 µg/L. These results also suggest that algae scum does not contain toxic concentrations of microcystin above the recreational guideline of 6 µg/L unless Microcystis or Anabaena are observed in the scum sample.

Anabaena was dominant and Microcystis was subdominant in the scum sample analyzed for phytoplankton with the highest microcystin concentration (23,800 µg/L). It is likely that there were large amounts of both microcystin producers in this sample, but the relative proportion of microcystin originating for them is not known.

Aphanizomenon was dominant in only one sample (7.1 µg/L microcystin), and was subdominant in two samples (0.1 and 73 µg/L microcystin). Gloeotrichia was dominant in three samples (9.1 and 34 µg/L microcystin) and was not subdominant in a sample. Woronichinia was not dominant in a sample and was subdominant in one sample (64 µg/L microcystin). No other cyanobacteria were dominant or subdominant in a scum sample. Other phytoplankton were dominant in 11 samples (0.02 to 78 µg/L microcystin) and subdominant in eight samples (0.1 to 295 µg/L microcystin). Thus, microcystin was lower when Microcystis or Anabaena were not the dominant phytoplankton in the scum sample. These results also suggest that either Microcystis or Anabaena were the primary microcystin producers in all scum samples because other cyanobacteria were rarely dominant and are not typically known as high microcystin producers in other lakes. Furthermore, the occurrence of several scum samples dominated by other phytoplankton and containing moderate microcystin concentrations suggests that relatively small amounts of Microcystis or Anabaena in a scum sample may result in algae scum with microcystin exceeding the state recreational guideline.

In summary, qualitative analysis of phytoplankton in the algae scum samples indicates that Microcystis and Anabaena were the primary microcystin producers in Green Lake in recent years. Algae scum did not contain toxic concentrations of microcystin above the recreational guideline of 6 µg/L unless Microcystis or Anabaena were observed in the scum sample. Although more scum samples were dominated by Anabaena (18) than Microcystis (4), the median microcystin concentration was higher for Microcystis than Anabaena for all categories of relative abundance. Quantitative analysis of phytoplankton and microcystin in scum samples would be necessary to determine if Microcystis actually produces more microcystin than Anabaena in Green Lake.

7. CYANOBACTERIA MONITORING AND LAKE CLOSURE PROTOCOLS

Multiple organizations are involved with cyanobacteria monitoring and lake closure decisions for Green Lake, including:

- **Friends of Green Lake and other volunteers**– monitor and sample algae scum (currently conducted by Garet Munger)
- **King County Environmental Lab** – analyze samples for cyanotoxins and phytoplankton abundance
- **King County Department of Natural Resources and Parks Science Section** – sample algae scum and beach cyanotoxins, coordinate cyanotoxin and phytoplankton analyses, post beach cyanotoxin results on the King County website, submit scum cyanotoxin and phytoplankton results to the Washington State Toxic Algae Program database, evaluate cyanotoxin results, and advise Seattle-King County Public Health
- **Seattle-King County Public Health** – make decisions on lake closure and signage
- **Seattle Parks and Recreation** – post closure on website, post/remove signs at lake, and issue press releases about a closure
- **Washington State Department of Health** – provide technical input on signage and closure as needed
- **Washington State Department of Ecology** – provide funding for cyanotoxin testing and manage cyanotoxin and phytoplankton data in Washington State Toxic Algae Program database

Many individuals are involved in these activities within each organization, and various contact persons have changed over time. Currently, the primary contact person for monitoring and recommendations is Sally Abella at King County Department of Natural Resources and Parks Science Section (sally.abella@kingcounty.gov), (206) 447-4605). A decision making flow chart prepared in March 2013 is presented in Figure 23.

Cyanobacteria monitoring of Green Lake has been very effective since February 2013 when Garet Munger began daily monitoring of algae scum at 31 shore sites (see Figure 2). He immediately reports significant observations and shares photographs with Sally Abella, they coordinate algae scum sampling at problem areas for cyanotoxin testing, and Sally Abella promptly evaluates the results and recommends appropriate actions to protect public and pet health.

The Washington State Department of Health developed three toxic algae advisory signs for use at lakes throughout the state (Figure 24). One type of advisory sign is to be posted at a lake. The following signs are used for increasing public health and pet risk from exposure to cyanotoxins:

- **CAUTION – TOXIC ALGAE MAY BE PRESENT, Lake may be unsafe for people and pets**. This Level 1 sign is intended for use when toxic cyanobacteria have been observed in the lake, but cyanotoxins have not been tested or observed at levels exceeding state recreational guidelines.
- **WARNING – TOXIC ALGAE PRESENT, Lake unsafe for people and pets**. This Level 2 sign is intended for use when cyanotoxin levels in algae scum samples exceed state recreational guidelines, but high cyanotoxin levels (e.g., greater than 2,000 µg/L) are not observed throughout the lake.
- **DANGER – LAKE CLOSED due to toxic algae – KEEP OUT OF LAKE**. This Level 3 sign is intended for use when dense cyanobacteria and high concentrations of cyanotoxins (e.g., greater than 2,000 µg/L) are present throughout the lake, or if there have been multiple reports of animal deaths and/or human illnesses.

Both the CAUTION and WARNING signs have been posted at Green Lake, but not the DANGER sign. The Washington State Department of Health also developed one toxic algae education sign that focuses on risks to dogs and has been used at Green Lake (see upper right sign in Figure 24). An additional education sign was recently developed specifically for use at Green Lake that is intended to limit activities of humans and pets to areas free of algae scum (see lower right sign in Figure 24). Recent problems with toxic algae signs at Green Lake include:

- Concurrent posting of CAUTION and WARNING signs
- Signs removed or thrown in the lake by citizens
- Delays in the posting or removal of signs
- Confusion by lake users on who is at risk, which activities should be avoided, and where activities are safe
- Apathy or ignorance of lake users about risks to adults, children, and pets

Various stakeholders are currently addressing these and other issues to improve public advisories and education at Green Lake. Based on King County recommendations, Seattle Parks will evaluate potential modifications to the sign style/locations and posting protocols in 2015 depending on plans for algae control, which may include an alum treatment before toxic conditions occur again in 2015.

8. STUDY CONCLUSIONS

The Green Lake Phytoplankton Study has clearly shown that:

- Both alum treatments effectively reduced the total amount of phytoplankton (as chlorophyll) during the summer in Green Lake. The reduction was greater and lasted longer following the 2004 alum treatment than the 1991 alum treatment because of the threefold higher dose of alum applied in 2004.
- Alum dramatically reduced the amount (as biovolume) and percentage of cyanobacteria in Green Lake for at least 10 years following the 2004 alum treatment, but did not appear to affect the amount of cyanobacteria in the first 3 years following the 1991 alum treatment.
- Total phytoplankton (algae) and cyanobacteria (blue-green algae) abundance in Green Lake is primarily controlled by phosphorus. Statistical analysis of the data clearly showed that total phytoplankton and cyanobacteria biomass are most correlated with the concentration of total phosphorus in the lake. While nutrient ratios suggest that algae may occasionally be controlled by nitrogen, recent increases in the concentration of nitrogen have increased the importance of total phosphorus as the primary nutrient limiting the growth of algae in Green Lake.
- The 2004 alum treatment effectively met water quality goals for total phosphorus and Secchi depth by reducing total phosphorus concentrations and phytoplankton growth in Green Lake for 10 years, achieving its design goal.
- Total phosphorus and toxic cyanobacteria concentrations substantially increased in both of the past two years (2013 and 2014). Toxic cyanobacteria caused lake closures over 2- to 3-month periods and substantial impacts to recreational uses of Green Lake in 2013 and 2014, but no closures occurred in the first 9 years following the 2004 alum treatment. Prior to the 2004 alum treatment, the lake was closed to primary contact recreation for a 1- to 5-month period in the late summer/fall of 1999, 2002, and 2003.
- Goals specific to prevention of cyanobacteria blooms and lake closures have not been established for Green Lake. Current water quality goals are based on average summer values that were established in 1991 before cyanotoxins were monitored or a concern. These goals do not adequately protect public health or prevent recreational impacts from toxic cyanobacteria.
- Microcystin has been the only cyanotoxin of concern in Green Lake. All lake closures were based the microcystin concentration in algae scum samples that exceeded the state guideline of 6 µg/L. Anatoxin-a is the only other cyanotoxin that has been measured in Green Lake and it has never exceeded the state guideline of 1 µg/L.

- Microcystin concentrations in algae scum samples increased in 2012 and again in 2014. The highest microcystin concentration of 25,000 μg/L observed in scum on September 11, 2014, is thought to be the highest ever recorded in Washington State.
- Microcystin was much lower in samples collected outside the algae scum and the state guideline was only exceeded on one occasion in outside scum samples (6.7 μg/L on September 11, 2014). Consumption of algae scum is a much higher public health threat to Green Lake users and their dogs than consumption of waters outside algae scum. Risks associated with microcystin consumption are much higher for children and dogs than adult users because of their greater risk for consumption of scum and lower tolerance to microcystin due to low body mass.
- Microcystin concentrations measured weekly at the swimming beaches since 2007 did not exceed the state guideline until 2014 when the guideline was exceeded on three occasions from late August to early October, and those concentrations varied greatly on the same date at the two beaches located on opposite shores of the lake. The dramatic increase in microcystin at the swimming beaches in 2014, along with the steady increase in phosphorus and chlorophyll over the past 3 years, suggests that concentrations may further increase and result in more extensive beach closures in 2015 if cyanobacteria are not controlled.
- Anabaena and Microcystis were the dominant phytoplankton species and primary producers of microcystin in algae scum samples collected from shore locations at Green Lake. Algae scum did not contain toxic concentrations of microcystin except when Microcystis or Anabaena were observed in the scum sample. Although more scum samples were dominated by Anabaena (18) than Microcystis (4), the median microcystin was higher for Microcystis than Anabaena for all categories of relative abundance. Quantitative analysis of phytoplankton in scum samples would be necessary to determine if Microcystis actually produces more microcystin than Anabaena in Green Lake.
- Daily algae scum ratings recorded by a volunteer at 30 shore stations over the past 2 years were typically higher in the summer than winter months (November through April). The amount of scum was often higher during periods of low wind speed regardless of the prevailing wind direction, but varied greatly and was unpredictable on a daily basis.
- The highest scum accumulation was typically observed at sheltered locations in the northwest area of lake (Duck Island Beach) during the winter and northeast area of the lake during the summer (vicinity of East Beach). Signage warning avoidance of algae scums by Green Lake users is particularly important in the vicinity of East Beach, Duck Island Beach, and Densmore Inlet due to the high frequency of scum observations and common access to the lake in these areas.
- Although the scum rating data greatly enhanced the understanding of algae scum patterns in Green Lake, algae scum ratings have not been consistent enough to determine when to close specific areas of the lake to primary contact recreation due to the highly variable wind conditions and scum accumulation, and unknown species composition of the scum.

9. RECOMMENDATIONS

Based on the study findings, the following is recommended:

- Treat Green Lake with alum as soon as possible to control cyanobacteria and prevent lake closures anticipated to recur in the summer of 2015. The alum treatment should be designed to cost effectively reduce water column phosphorus and inactivate any sediment phosphorus that has been deposited in the lake from external loading over the past 10 years.

- Prepare an Algae Control Plan for the alum treatment that includes the following tasks and provides the associated information:

    - Reassess and develop new water quality goals to better align with protection of public and pet health, and prevention of lake closures from toxic cyanobacteria. These goals may include revision of existing criteria for summer mean phosphorus and Secchi depth, new criteria based on other water quality parameters or statistics, warning levels to initiate planning for control activities or investigation, and/or objectives based on an acceptable frequency or duration of lake closure.

    - Collect and analyze sediment cores for phosphorus fractions and other parameters of interest. Sediment analysis results should be used to evaluate recent changes in phosphorus loading, and to evaluate alternative alum treatment designs to effectively intercept internal and external phosphorus loadings.

    - Update the lake phosphorus budget to account for potential changes in internal and external phosphorus loadings. The detailed phosphorus budget developed for the 1991 alum treatment should be modified to account for recent changes in inputs from the Woodland Park and the Densmore drains, recent increases in milfoil coverage and biomass, and potential groundwater flow modifications from recent subgrade dewatering of large new buildings. The revised phosphorus budget should be based on available information and should not require additional monitoring to assess the relative magnitude of change in phosphorus inputs. Based on preliminary information, changes in phosphorus loading may be substantial for milfoil and surface water drainage, and small for groundwater drainage. Recent changes in lake level, groundwater flow, outlet operations, and city water input should also be evaluated to estimate the magnitude of changes in the lake water budget affecting the phosphorus budget.

    - Evaluate alternatives and recommend a preferred alternative for controlling toxic cyanobacteria. The control alternatives evaluation should focus on variations in alum treatment dose, timing, application technique, and application strategy. An alternative to long-term treatment strategy of 2004 should include smaller, periodic treatments to prevent pulses of phosphorus in the water column and the associated blooms of toxic cyanobacteria. The control alternatives evaluation should include qualitative analysis of internal control methods that have been previously evaluated for Green Lake (dilution, aeration, circulation, treatment, and dredging), and those that have been developed since the previous evaluation (scum removal by vactoring, treatment with Phoslock®, and circulation by SolarBee®). Recommendations should be made for reducing external phosphorus loading where appropriate and feasible.

  - Prepare a lake water quality monitoring plan to evaluate short-term and long-term effects of the proposed alum treatment. The water quality monitoring plan should specify the project objectives, and outline sampling and analytical methods that are compatible with those used historically. Phytoplankton composition analysis should be conducted in addition to the parameters monitored as part of the King County Lake Stewardship Program. Lake level should be monitored with a continuously recording lake gauge. Algae scum and cyanotoxin monitoring should be continued, and modified as appropriate, if scums are observed before or after the alum treatment.
  - Prepare a public education and outreach plan to identify stakeholders, and describe methods for informing and obtaining feedback from stakeholders on the Algae Control Plan. This plan should include recommendations for modification of existing cyanobacteria signs and protocols, and development of additional signs or other materials explaining lake issues and actions.

- Implement the Algae Control Plan to include the following tasks and provide the associated information:
  - Prepare the application and obtain an Aquatic Plant and Algae Management General Permit for an alum treatment. The permit application requires a Discharge Management Plan and SEPA Addendum because the treatment would cover more than 5 acres. Alternatively, the Algae Control Plan may be submitted in lieu of a Discharge Management Plan and SEPA Addendum if it contains the required elements.
  - Prepare contractor specifications for an alum treatment.
  - Procure a contractor to perform the alum treatment in 2015 or 2016 depending on the available funding and schedule.
  - Prepare and distribute signs and other education materials.
  - Provide technical oversight and water quality monitoring of the alum treatment.

If funding is available, preparation of the Algae Control Plan should be expedited in anticipation of performing an alum treatment by early summer 2015 to mitigate impacts from a cyanobacteria bloom anticipated to occur in the late summer of 2015. It is anticipated that it would require approximately 3 months to prepare the plan from January through March 2015, and a maximum of 3 months to obtain a permit and secure a contractor via public bidding from April through June 2015. Treatment during a cyanobacteria bloom in the late summer or fall of 2015 is not preferred due to additional alum and potential water quality impacts of performing a treatment during a cyanobacteria bloom when an excessive amount of algae scum is present on the lake surface. Alternatively, an alum treatment should be successfully performed in the spring of 2016 to control phosphorus and subsequent cyanobacteria blooms. At this time, funding is only available for design and permitting in 2015, and for treatment in 2016.

Upon completion of the Algae Control Plan and treatment of the lake with alum in 2015 or 2016, Seattle Parks and Recreation should consider future study and preparation of a Lake Management Plan to address additional needs for Green Lake:

- **Eurasian Watermilfoil Management** – Eurasian watermilfoil coverage has increased in recent years to a level that impacts lake users by direct entanglement within the lake and accumulation of decaying plants along the shoreline. Friends of Green Lake uses volunteers for milfoil cleanup in the fall of each year because it is not performed by Seattle Parks and Recreation. Increased water clarity resulting from another alum treatment may further increase the spread of Eurasian watermilfoil. An increase in Eurasian watermilfoil would increase internal phosphorus loading and may shorten the effectiveness of an alum treatment.

- **Shoreline Vegetation Management** –Seattle Parks and Recreation manages shoreline vegetation in accordance with an outdated plan that may to conflict with current public interest and waterfowl needs. The Friends of Green Lake have been actively restoring areas of shoreline vegetation using volunteers without a written plan. These restoration areas are impacted by intensive human and pet use. Properly restored shoreline vegetation would reduce soil erosion and nutrient input from adjacent land, and may prolong the effectiveness of an alum treatment. A shoreline vegetation management plan should balance aesthetic, wildlife, and water quality benefits with recreational fishing and boating needs.

- **Fisheries Management** – Washington State Department of Fish and Wildlife has dramatically increased the number of trout planted in recent years in Green Lake without consideration of potential impacts on phytoplankton from zooplankton grazing or phosphorus loading. With consideration of the recreational benefit of trout plants, their potential impacts on phytoplankton should be evaluated in terms of consumption of large zooplankton by trout (which may impact phytoplankton amount or composition by less grazing) and trout excretion (which may increase internal phosphorus loading). In addition, a large population of common carp is present in Green Lake that may be impacting water quality from sediment disturbance and phosphorus loading.

- **Stormwater Management** – A drainage plan for the Densmore basin is being implemented by Seattle Public Utilities to reduce basin flooding. These drainage improvements may be increasing overflow of stormwater runoff to Green Lake from the basin, and an increase in the frequency of overflows has been observed by citizens. Monitoring of inflow amounts and phosphorus loading from the Densmore drain should be evaluated to determine if they impact Green Lake and can be reduced by adjustment of the overflow weir or some other means. Stormwater drainage from the Green Lake Community Center parking lot discharges to the east swimming beach without treatment. Seattle Parks will coordinate with Seattle Public Utilities to reduce external phosphorus loading to the lake where feasible, and potentially extend the effectiveness of the alum treatment.

- **Outlet Control -** Outflow from Green Lake is intentionally directed only to the Meridian Outlet because this outlet drains via a large capacity pipe to Lake Union. However, this outlet structure may be in disrepair and other outlets may be inadvertently discharging to the combined sewer system based on citizen observations. Seattle Parks will coordinate with Seattle Public Utilities and King County to reduce lake drainage to the combined sewer system and costs associated with sewage treatment.

- **Sediment and Fish Contamination** – Lake sediments are contaminated with various metals and organic chemicals at levels exceeding freshwater sediment guidelines for protection of benthic (bottom dwelling) organisms (Seattle 2007). Common carp are contaminated with high levels of PCBs and the pesticides chlordane and dichlorodiphenyldichloroethylene (DDE which is a degradation product of DDT). Green Lake is listed by Ecology as impaired for these parameters in fish tissue based on carp tissue samples collected in 2001. The current status and risks of sediment and fish tissue contamination to recreational fishers and other users is unknown, and public education about the contamination is limited to a few signs around the lake.

- **Public Education** – Green Lake is used by a large number and variety of citizens, and provides an excellent opportunity for public education about lake conditions and environmental issues. A public education plan should be prepared that addresses important elements of the algae control and lake management plans, and protection of public health and recreational benefits.

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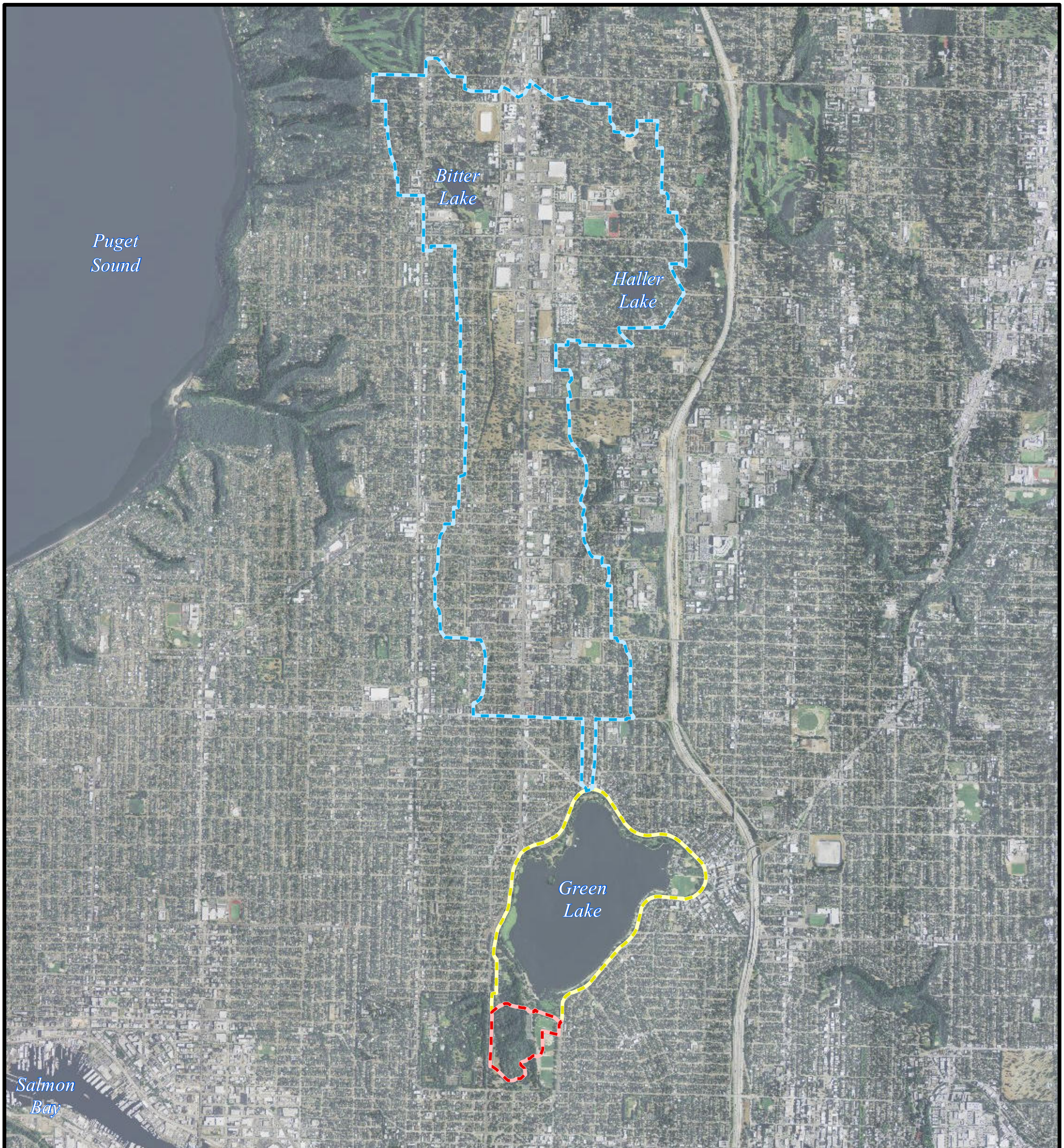
FIGURES



Legend

- Densmore Basin
- Nearshore Basin
- Woodland Park Basin

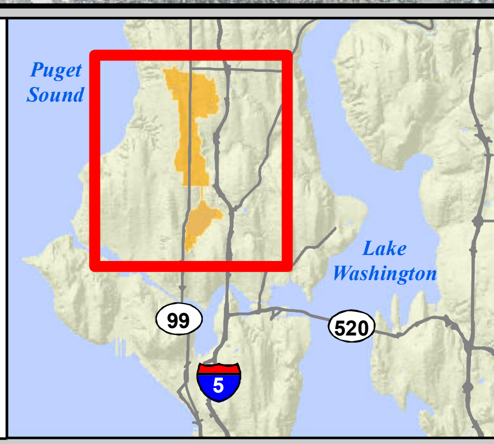


Figure 1.
Green Lake Watershed.

N

0 1,750 3,500 7,000 Feet

HERRERA

USDA, Aerial (2013)

K:\Projects\Y2013\13-05709-000\Project\Phytoplankton_Study\vicinity_map.mxd (11/6/2014)

Legend

- Lake station
- Algae scum station
- Inlet
- Outlet
- Bathymetry contour (5-ft)

Aquatic Plants (Herrera 2005)

- Dense Eurasian watermilfoil
- Sparse Eurasian watermilfoil
- White water lillies

Wetlands (SUNP 2005)

- Palustrine Forested Wetland
- Palustrine Scrub-Shrub Wetland

Figure 2.
Green Lake Monitoring Stations and Features.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

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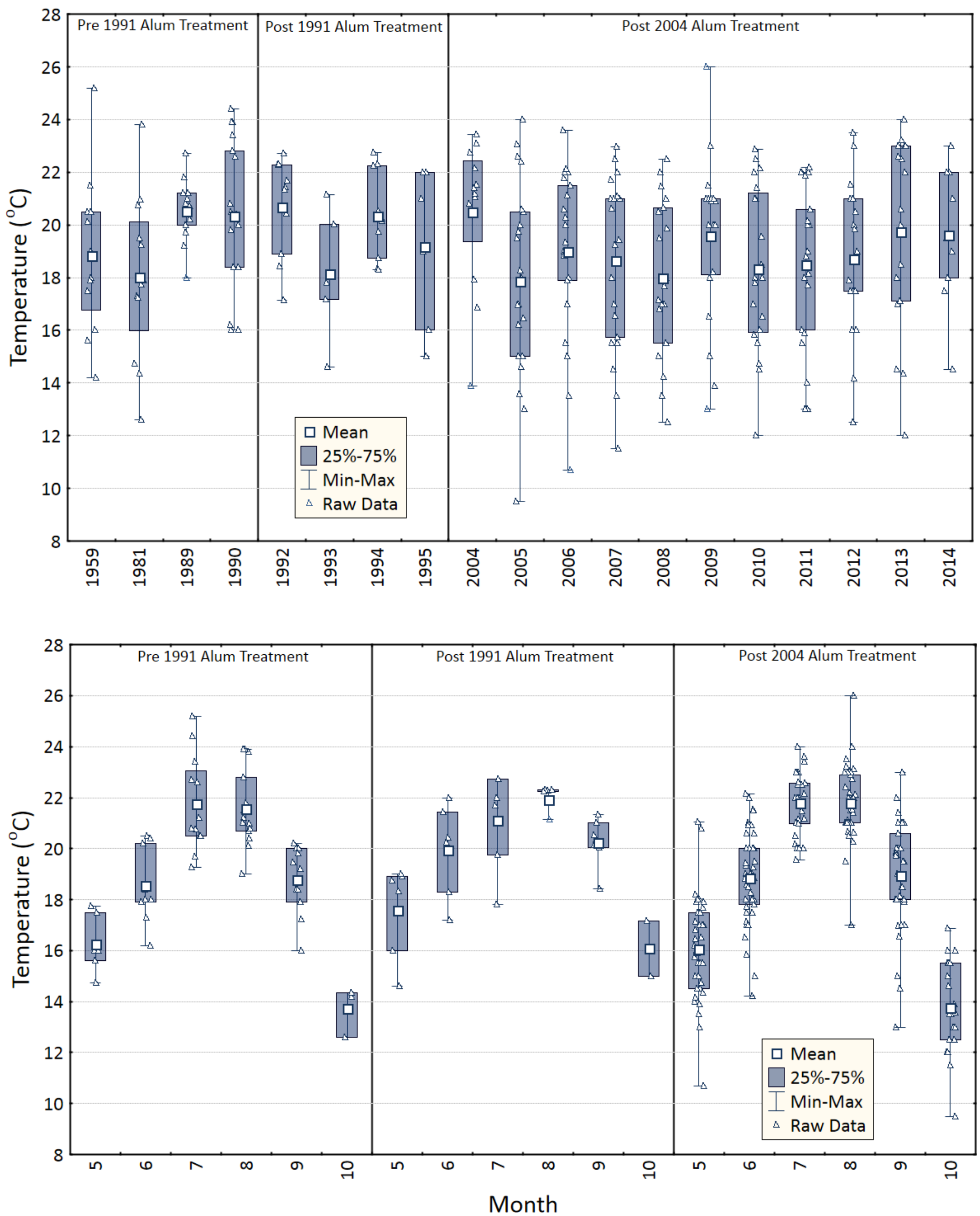


Figure 3. Water Temperature by Study Year and Month for Summer in Green Lake.

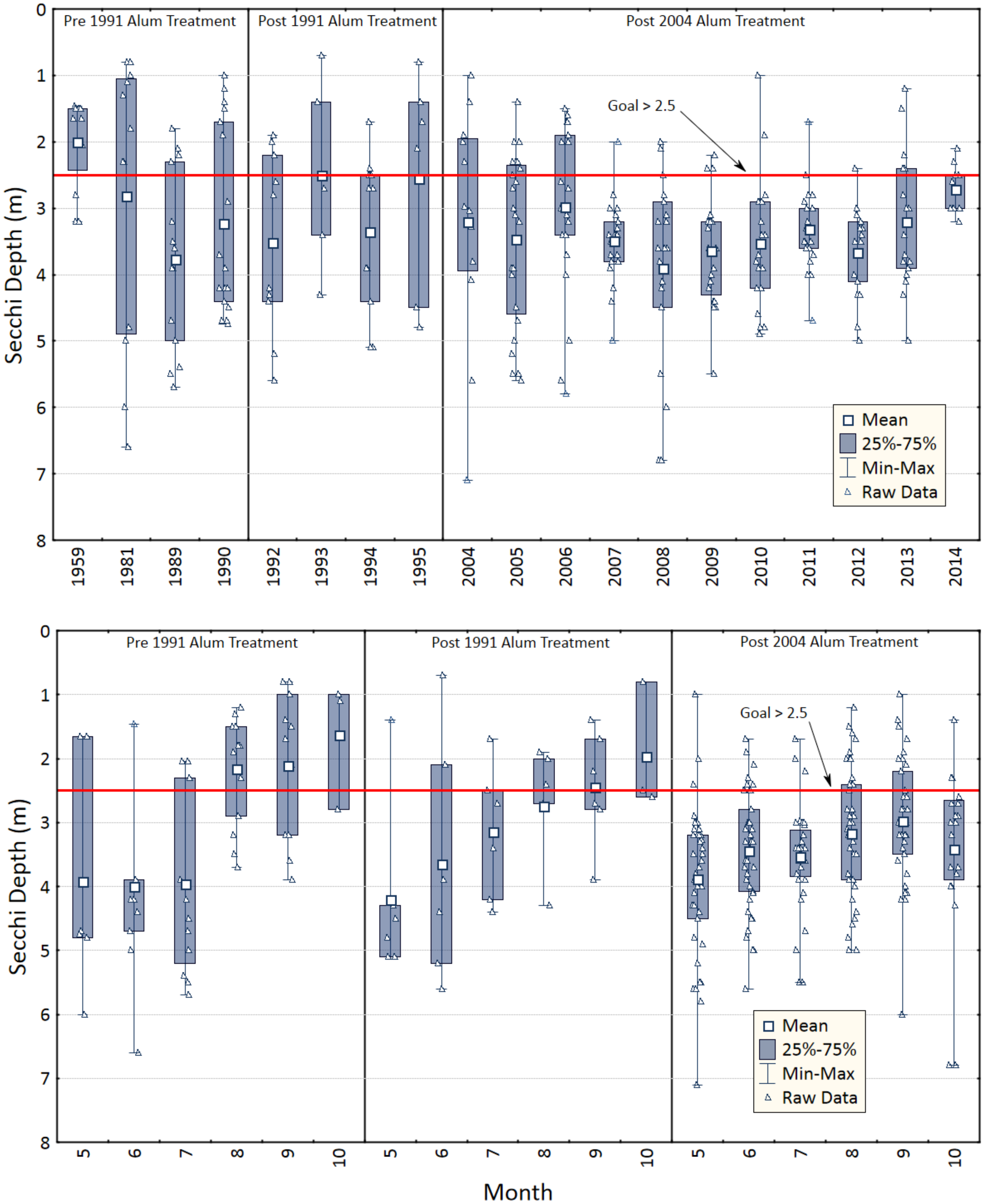
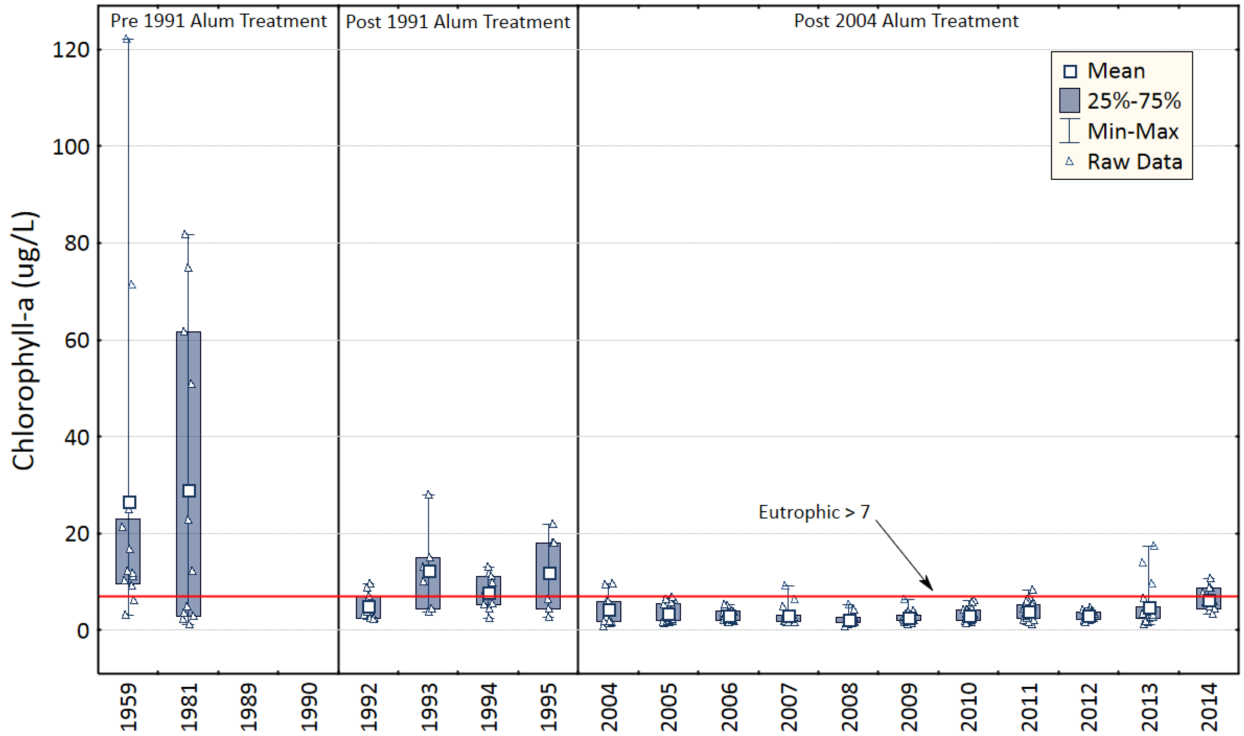


Figure 4. Secchi Depth by Study Year and Month for Summer in Green Lake.



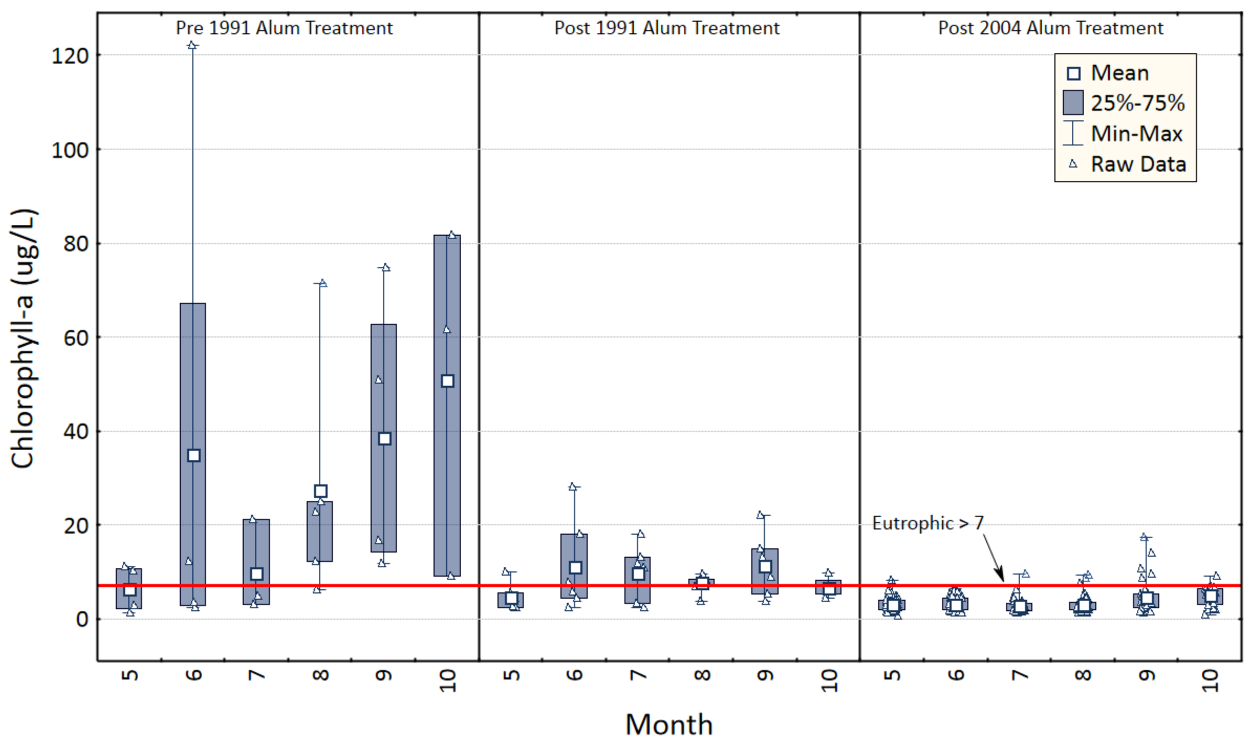


Figure 5. Chlorophyll by Study Year and Month for Summer in Green Lake.

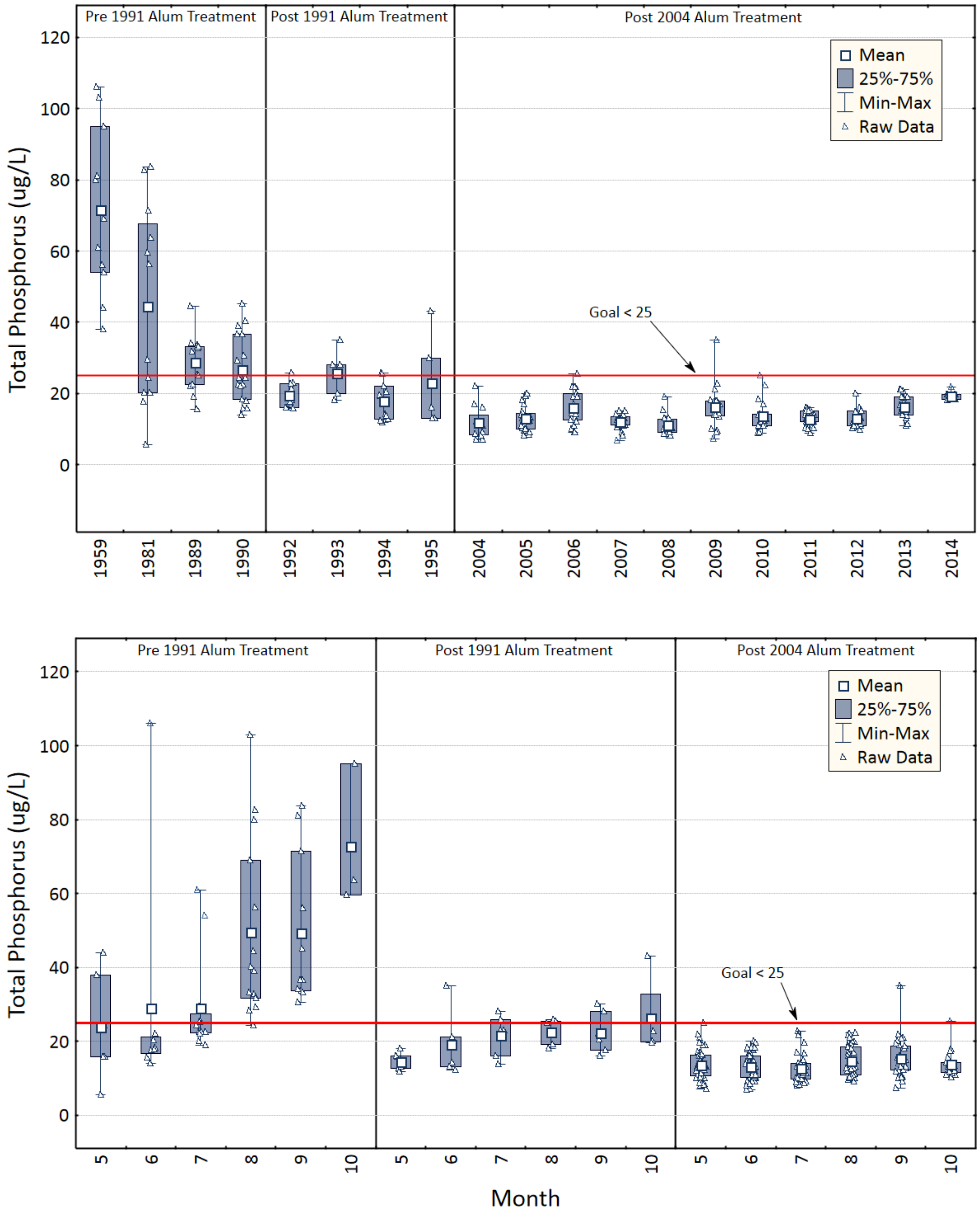
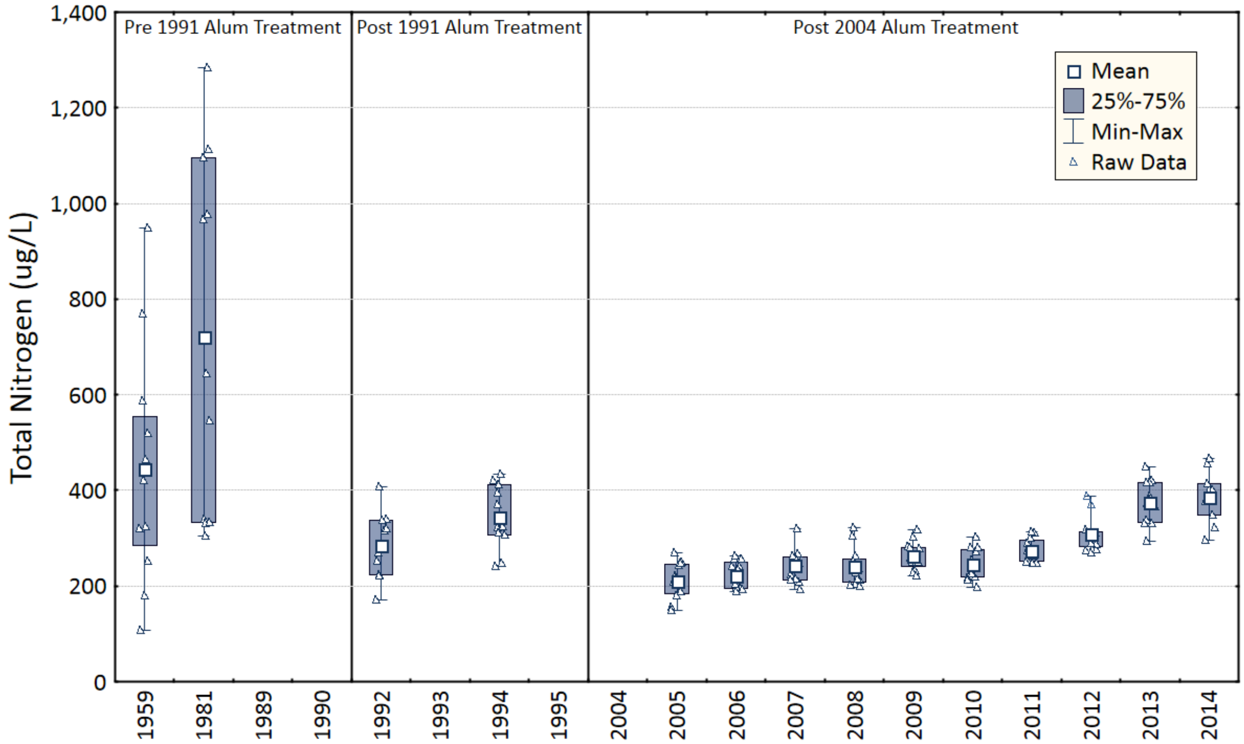


Figure 6. Total Phosphorus by Study Year and Month for Summer in Green Lake.



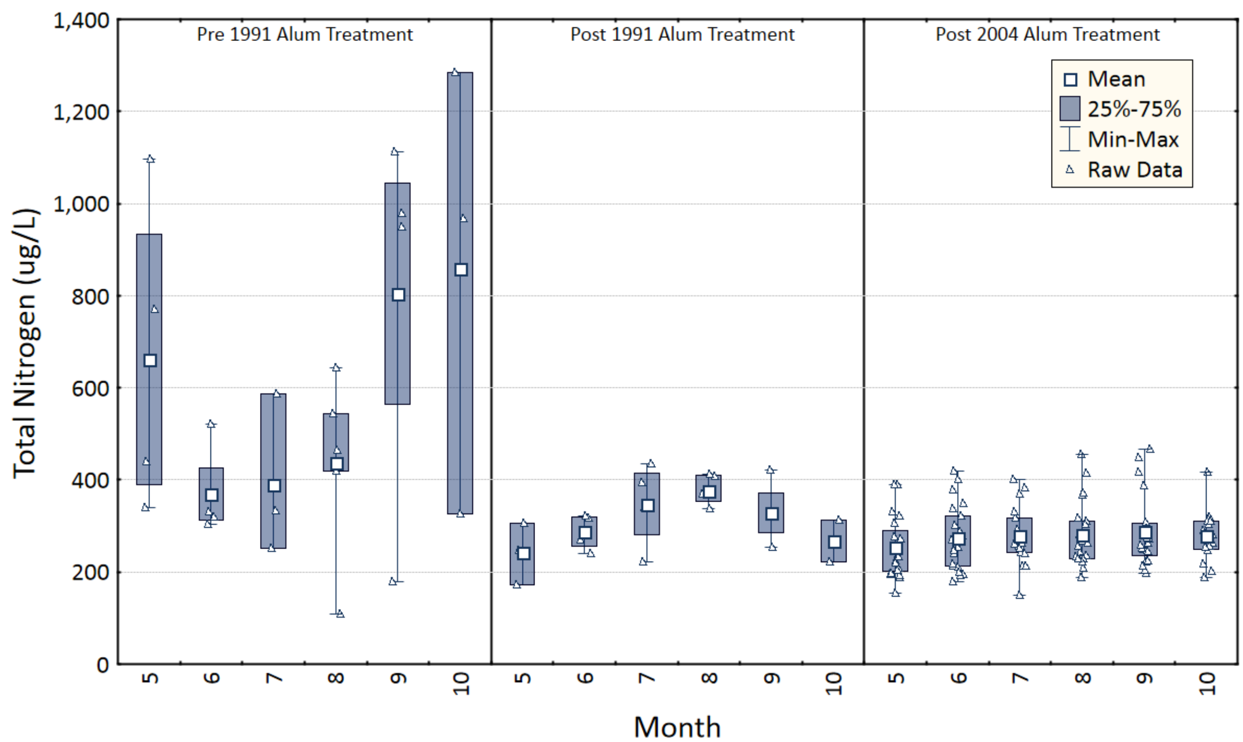
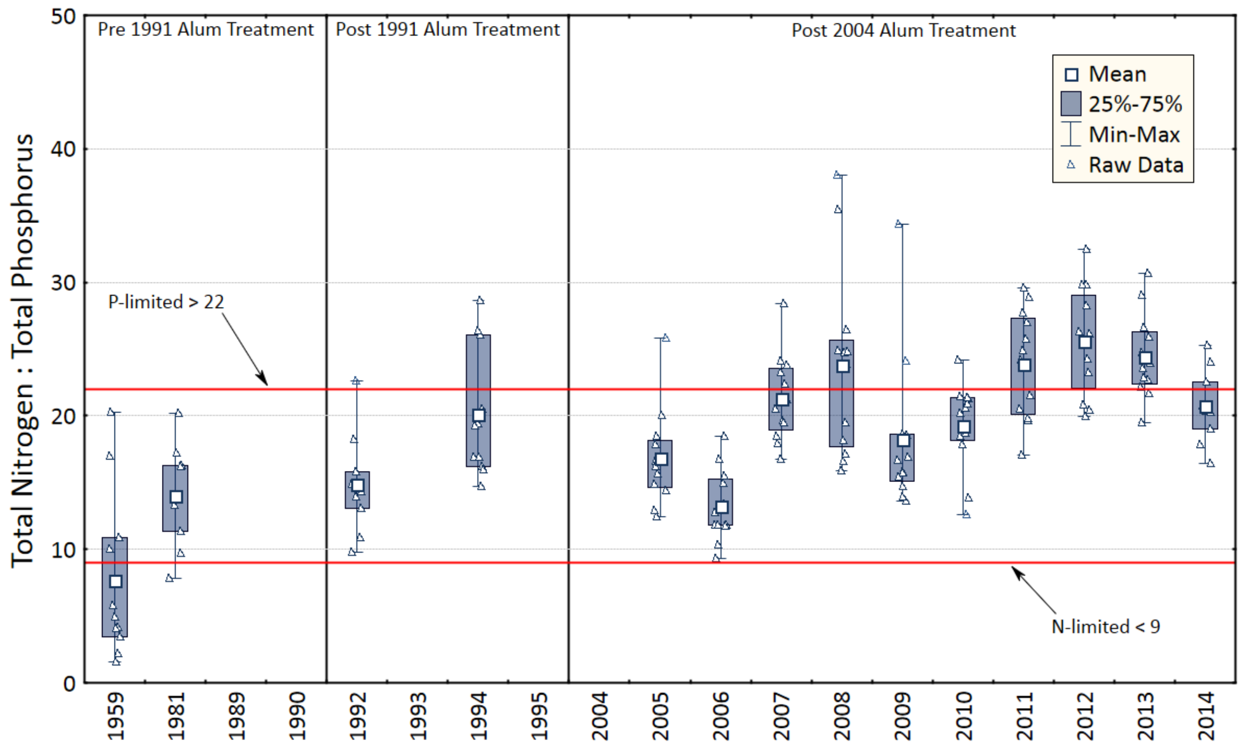


Figure 7. Total Nitrogen by Study Year and Month for Summer in Green Lake.



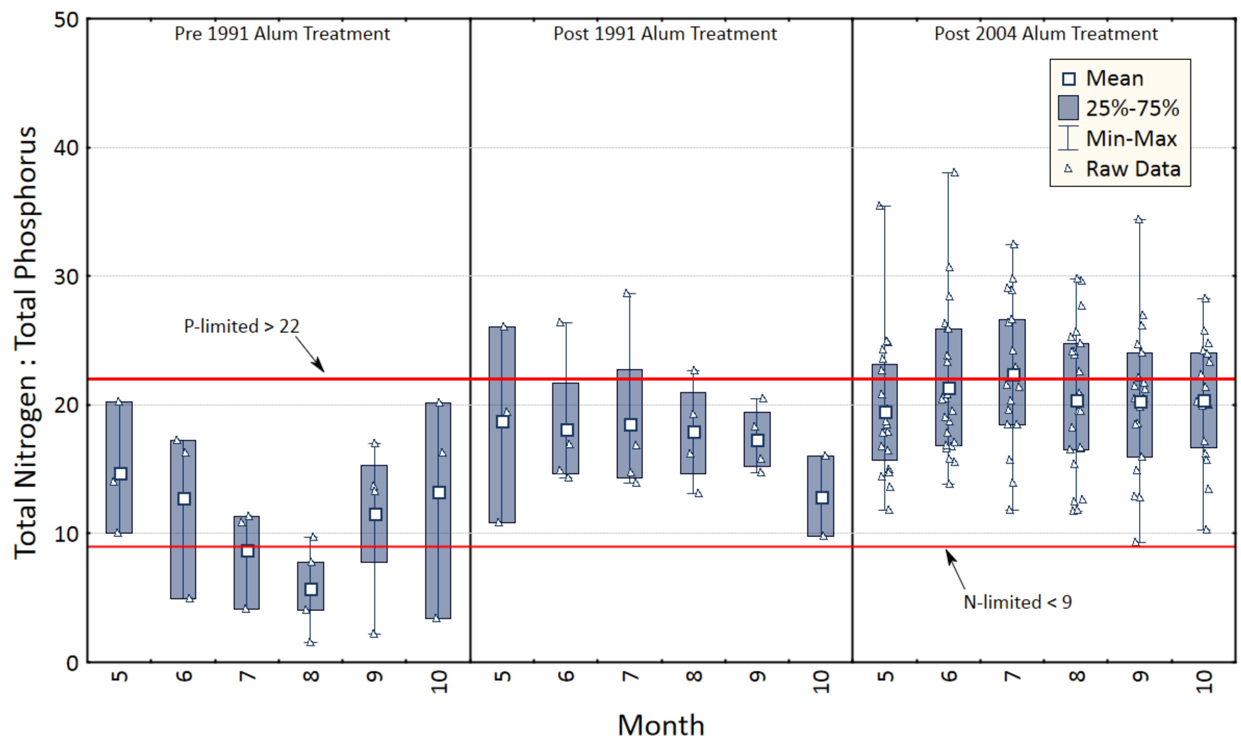


Figure 8. Total Nitrogen to Total Phosphorus Ratio by Study Year and Month for Summer in Green Lake.

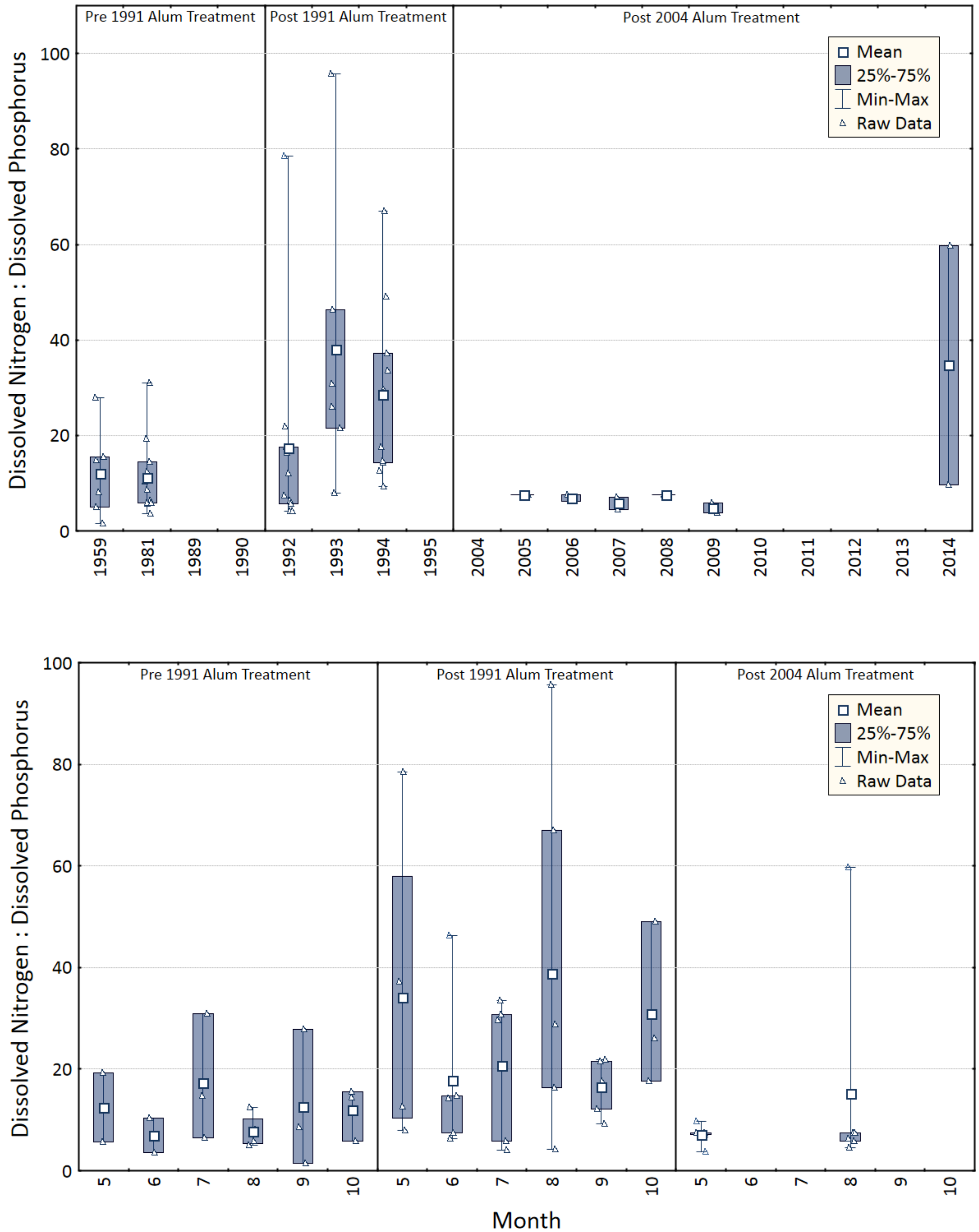


Figure 9. Dissolved Nitrogen to Total Phosphorus Ratio by Study Year and Month for Summer in Green Lake.

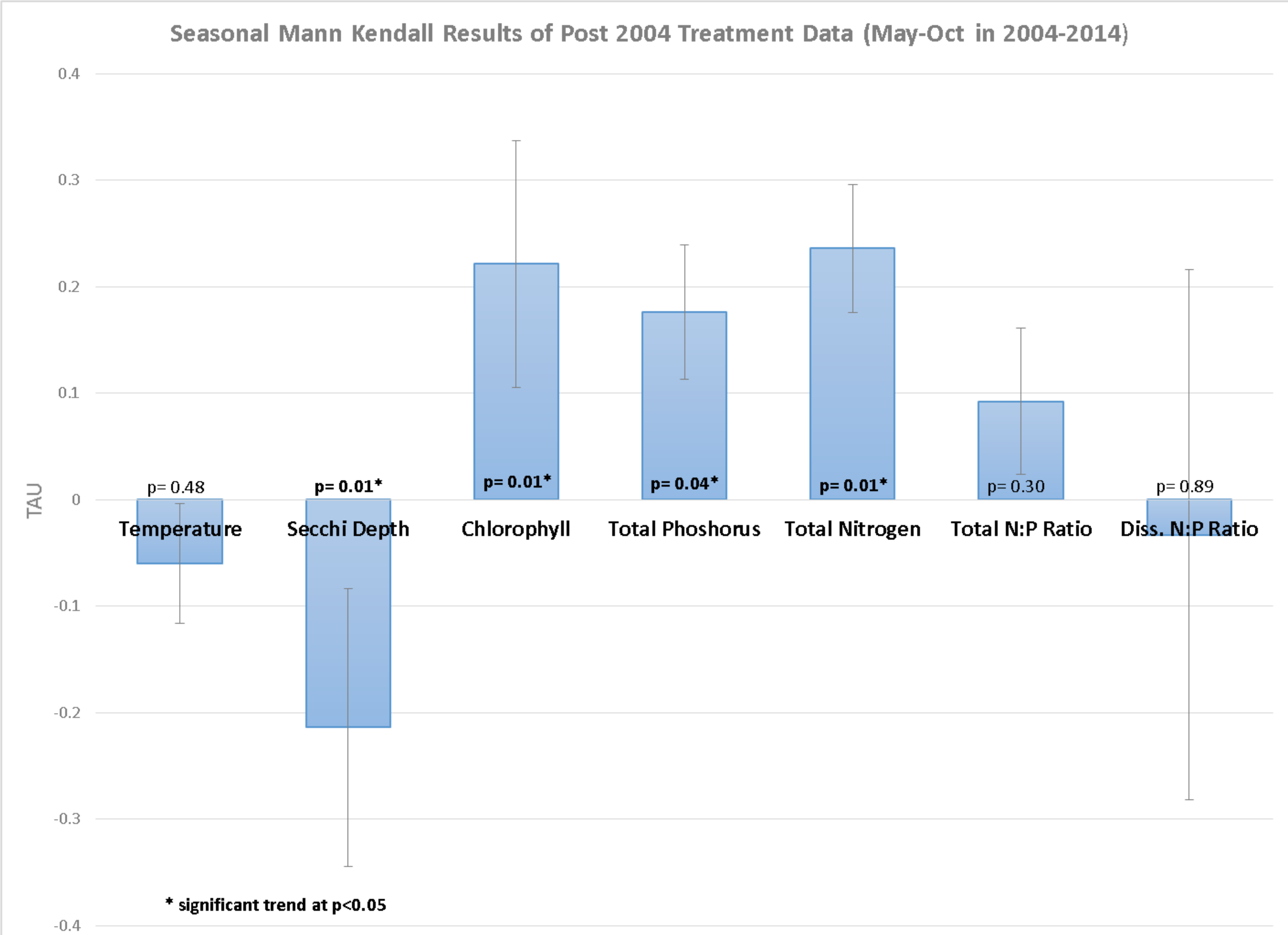


Figure 10. Seasonal Mann Kendall Test Results of Post 2004 Alum Treatment Water Quality Data for Green Lake.

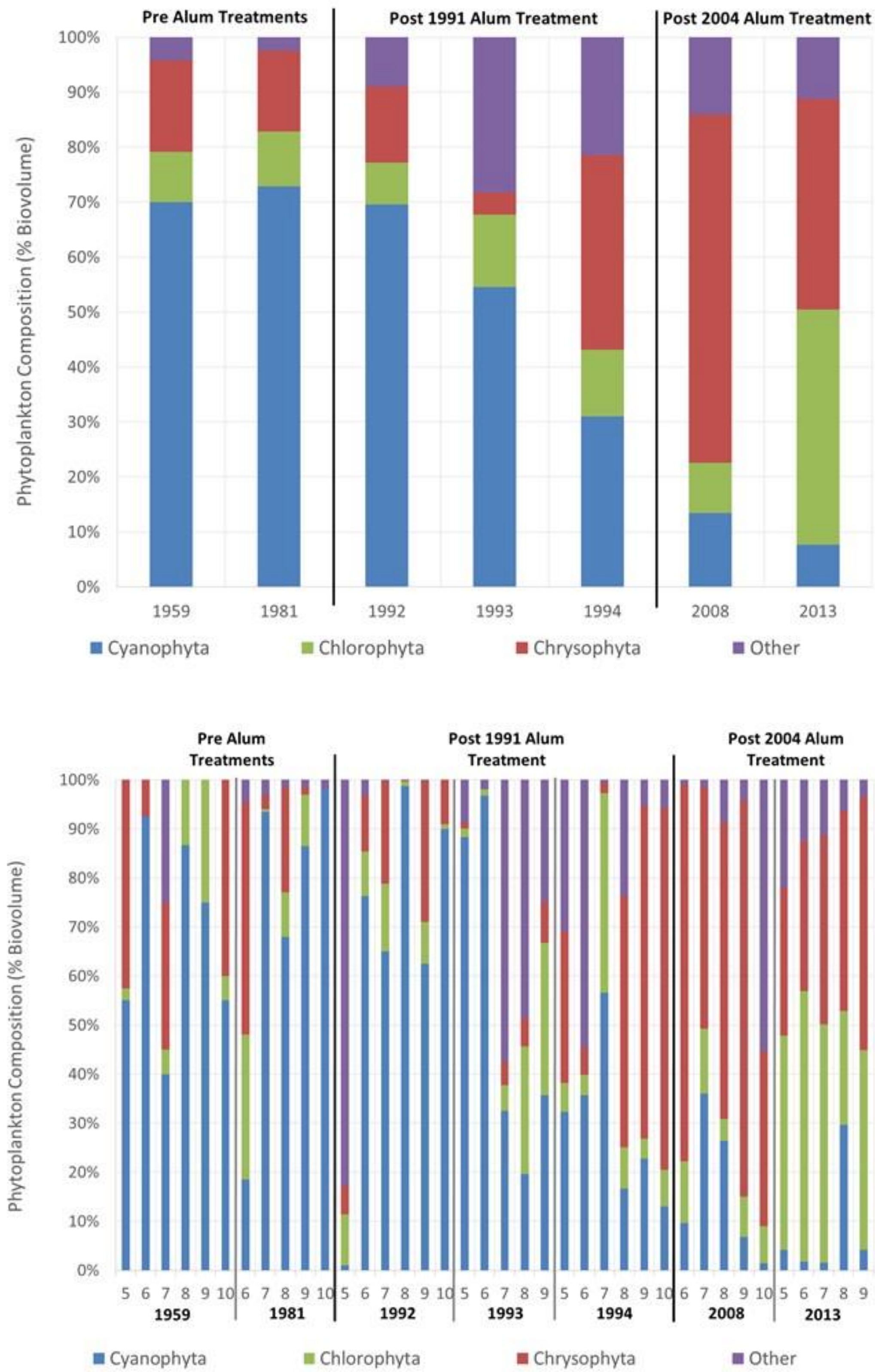


Figure 11. Phytoplankton Group Composition by Study Year and Month for Summer in Green Lake.

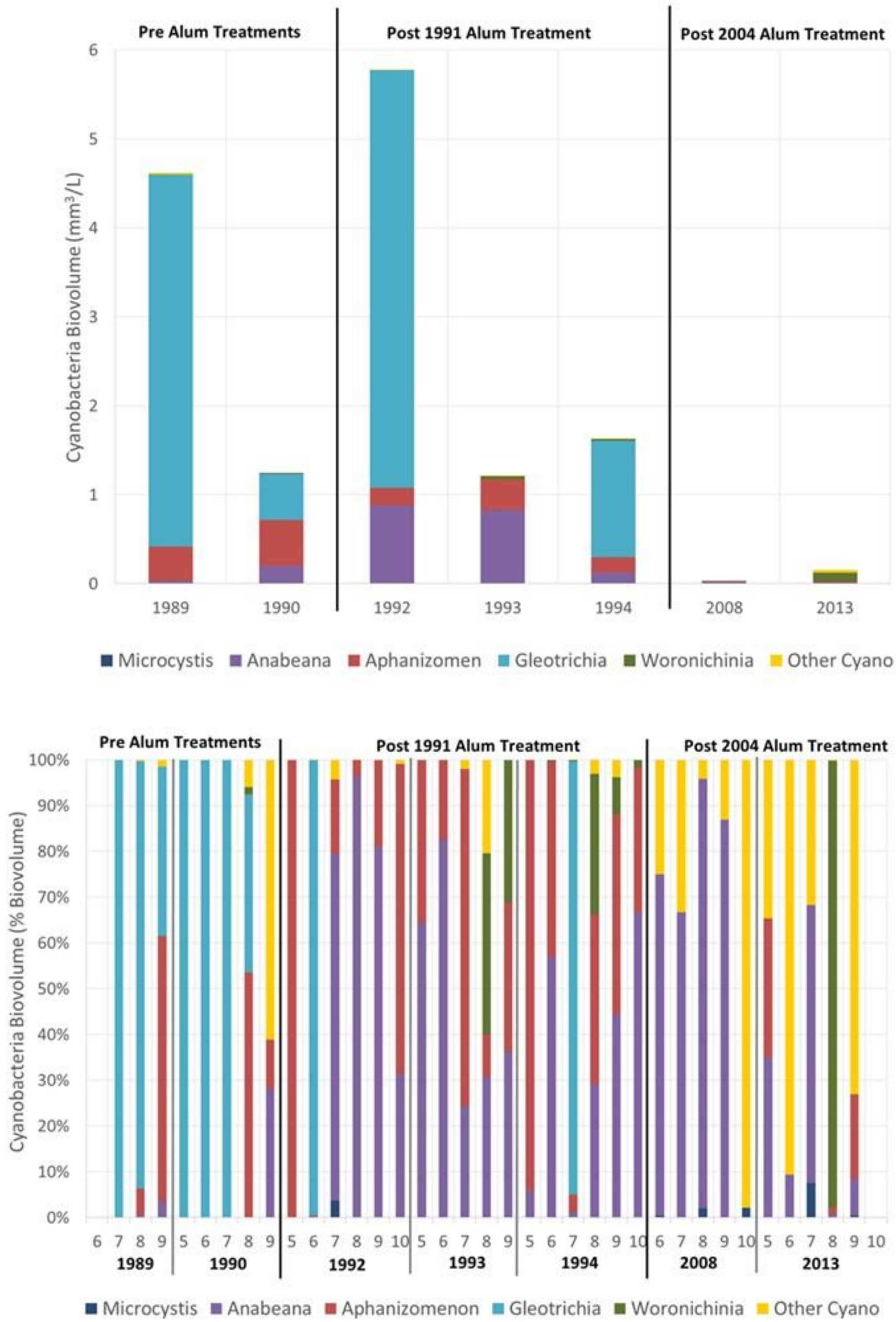


Figure 12. Cyanobacteria Biovolume by Study Year and Composition by Month for Summer in Green Lake.

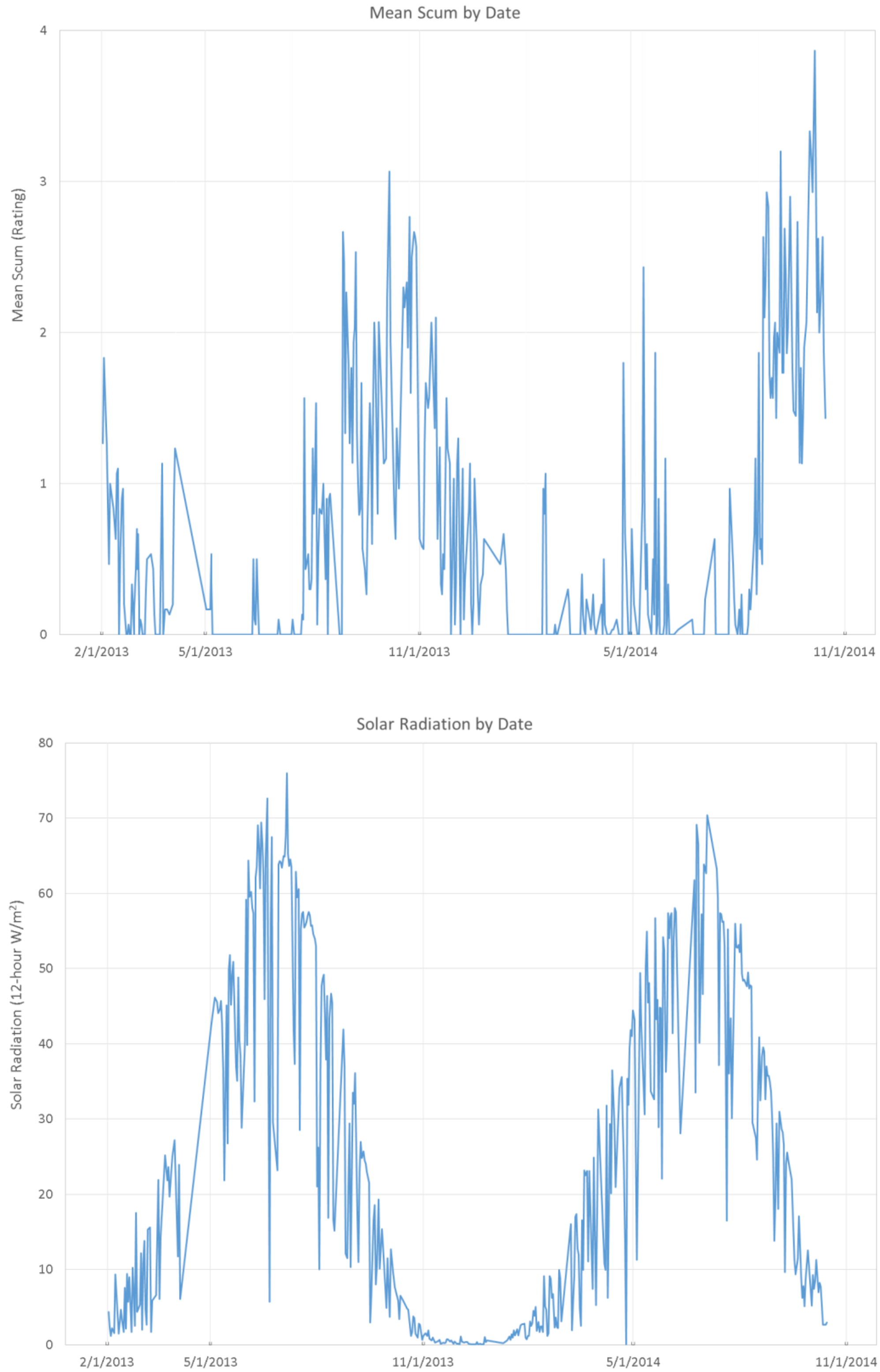


Figure 13. Mean Algae Scum Ratings and Solar Radiation for 12 Hours Before Each Observation at Green Lake.

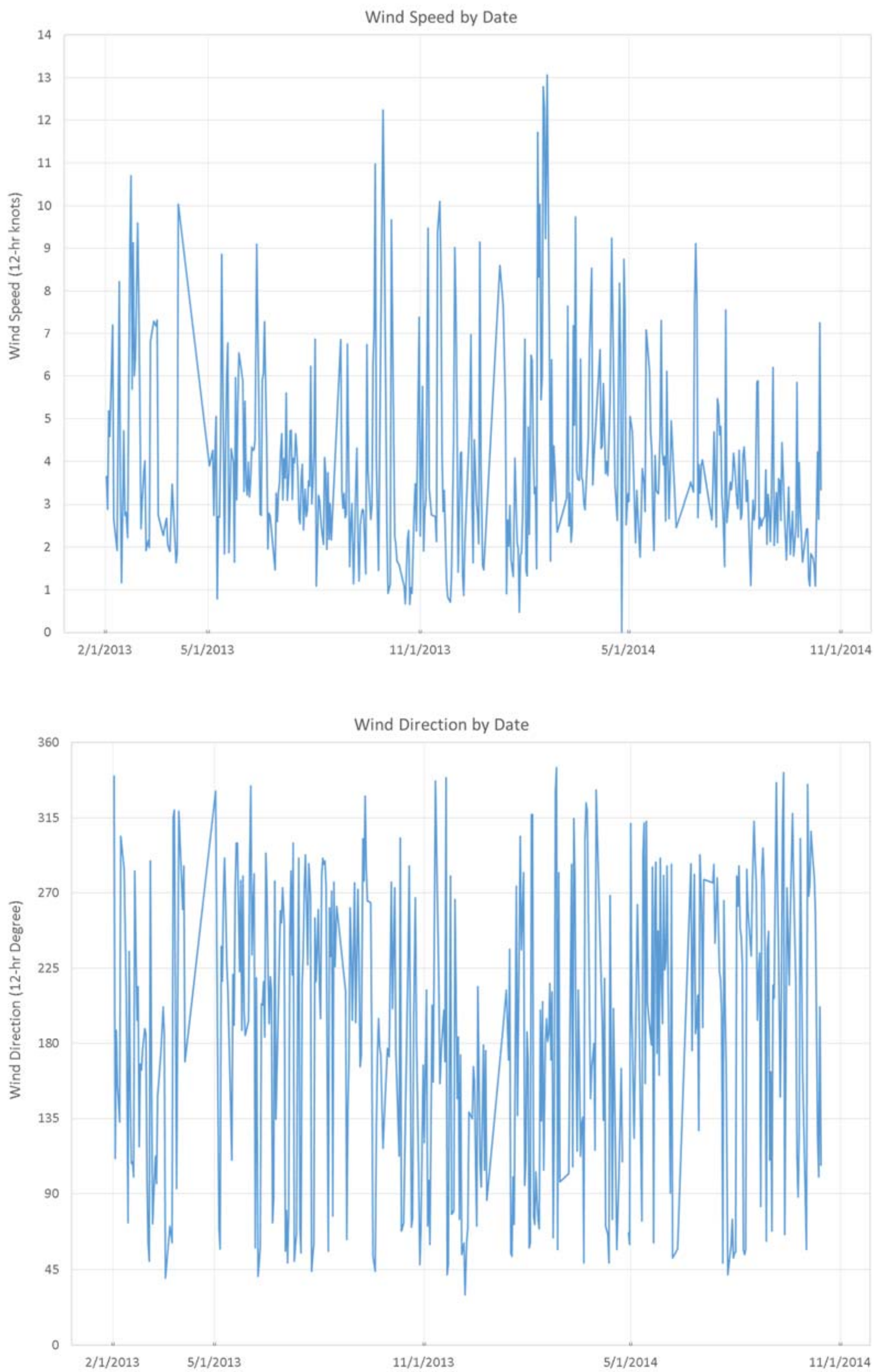
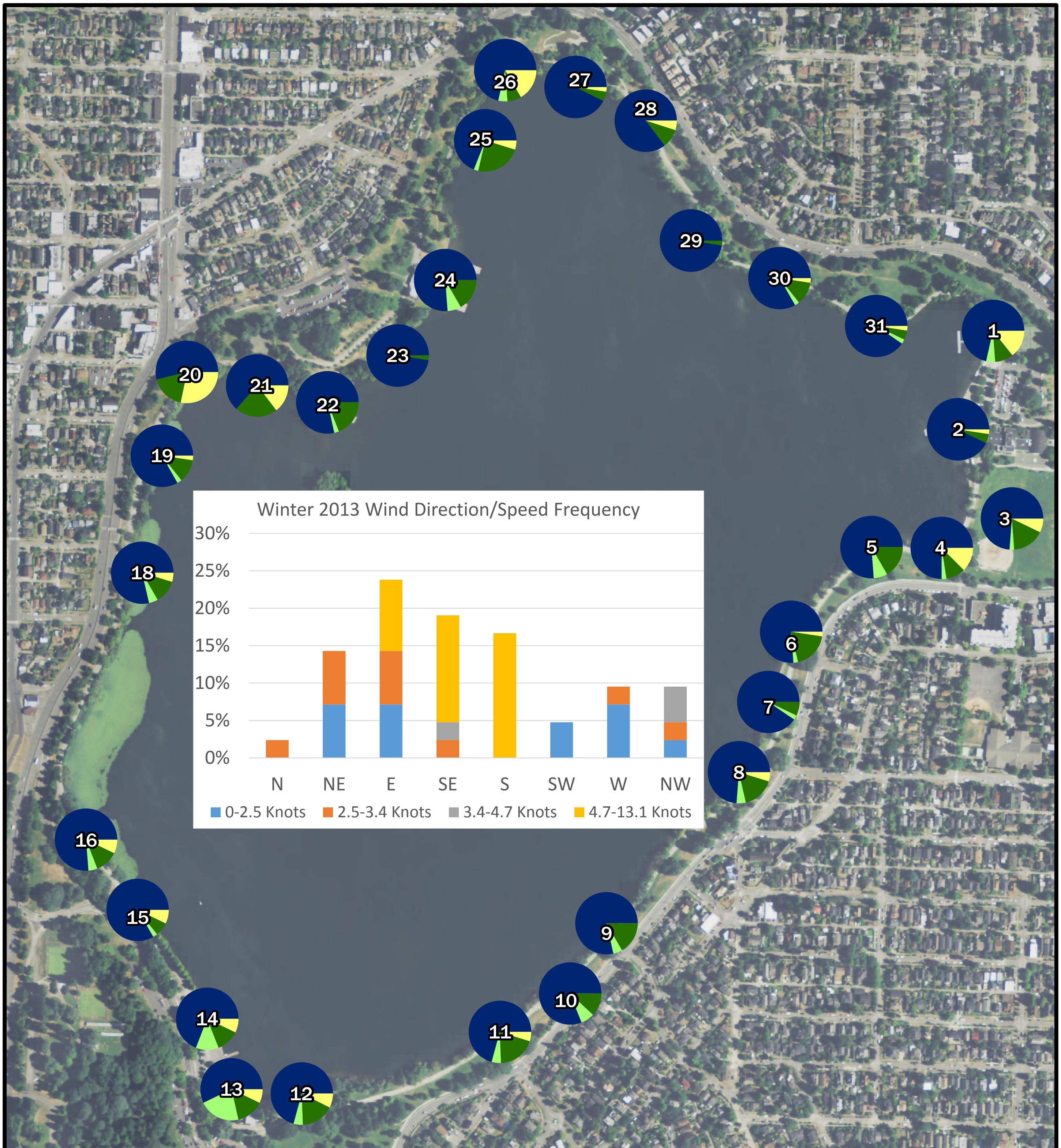


Figure 14. Mean Wind Speed and Median Wind Direction for 12 Hours Before Each Algae Scum Observation at Green Lake.

Figure 15. Mean Algae Scum Versus Wind Speed and Direction at Green Lake.



Legend

Scum Rating (0-8)

0	3
1	4
2	5
	6
	7
	8

Figure 16. Winter (February through April) 2013 Algae Scum Rating Frequency at Green Lake.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

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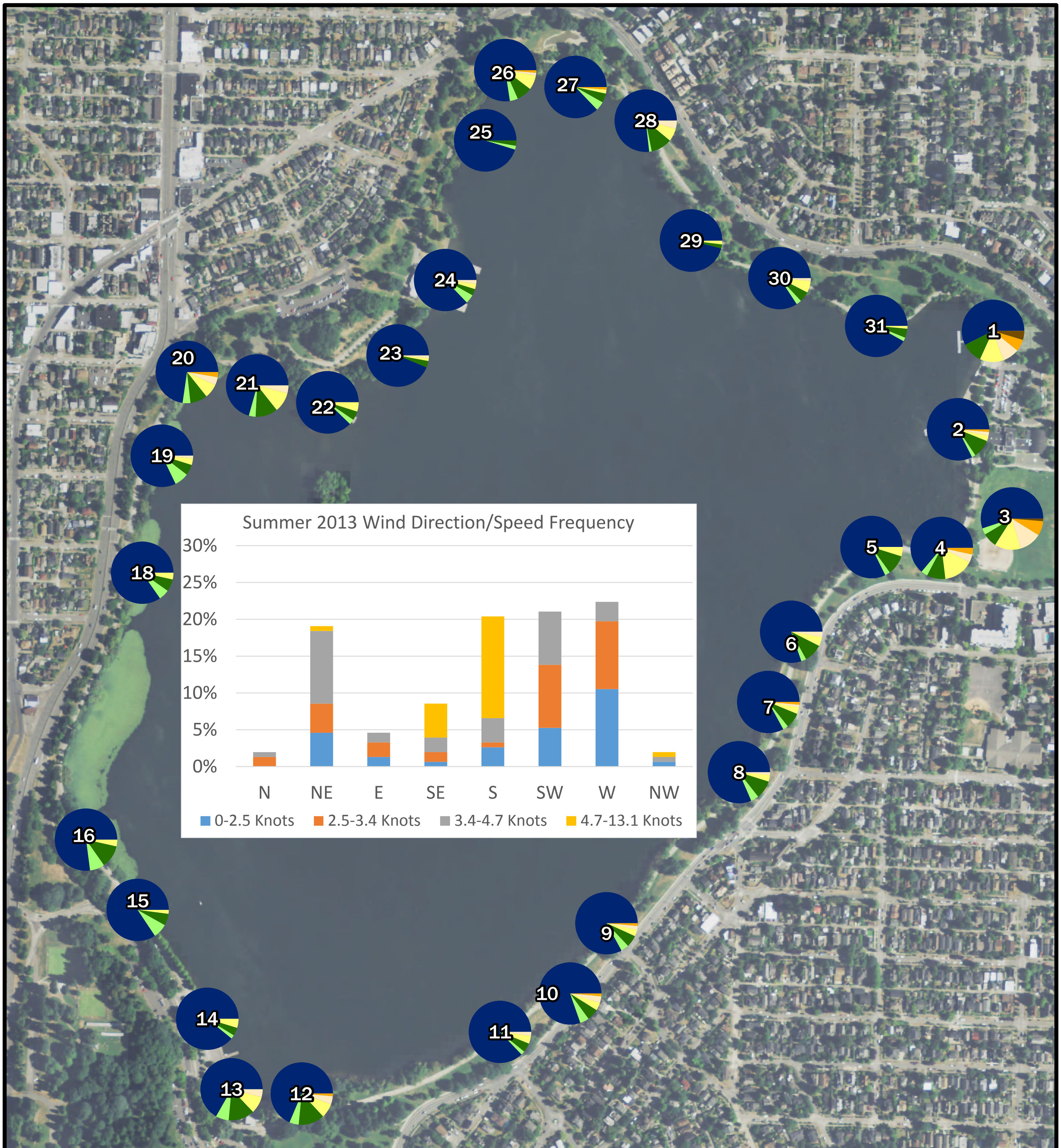

Legend

Scum Rating (0-8)

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Figure 17. Summer (May through October) 2013 Algae Scum Rating Frequency at Green Lake.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

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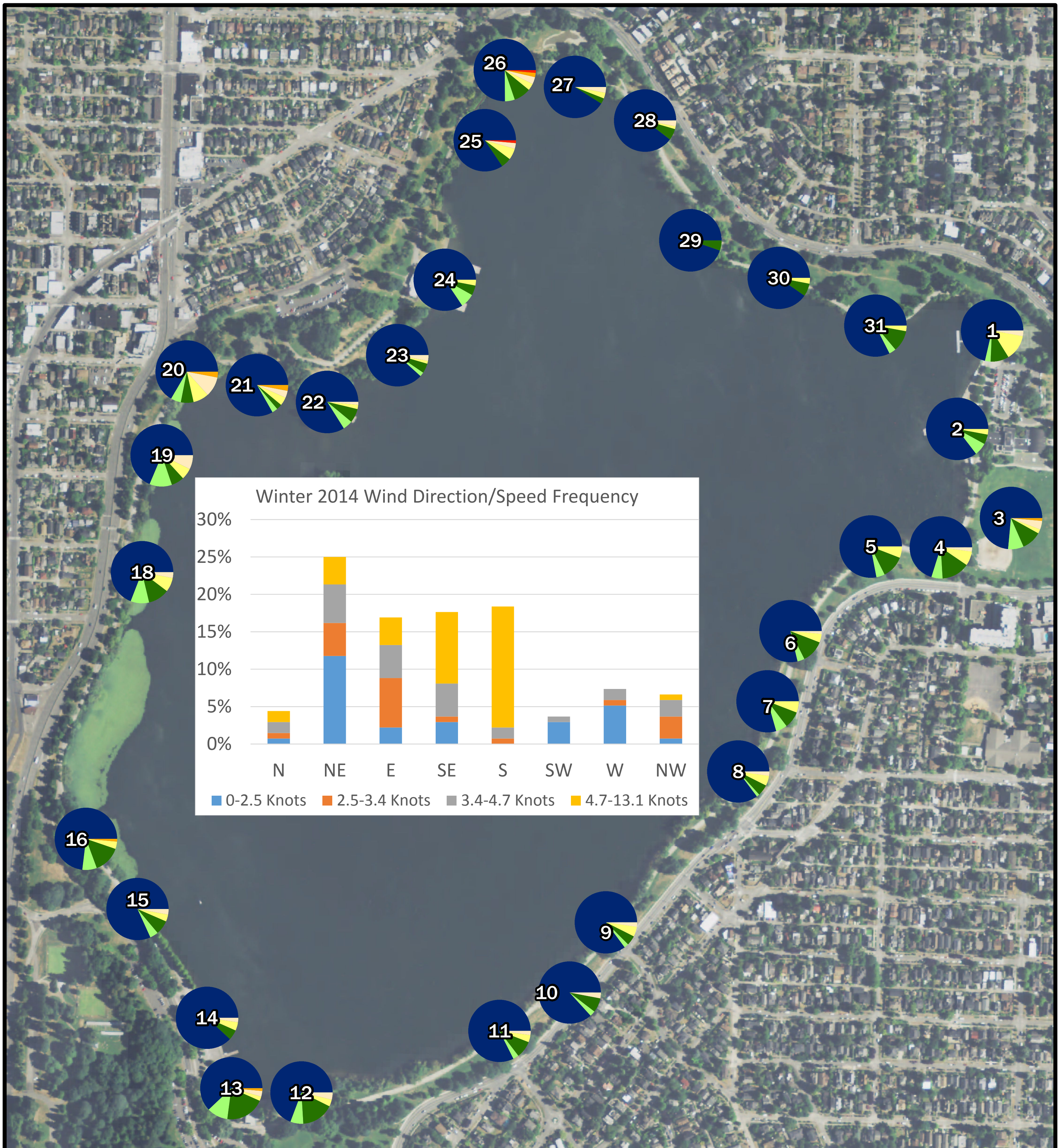

Legend

Scum Rating (0-8)

0
1
2
3
4
5
6
7
8

Figure 18. Winter (November through April) 2014 Algae Scum Rating Frequency at Green Lake.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

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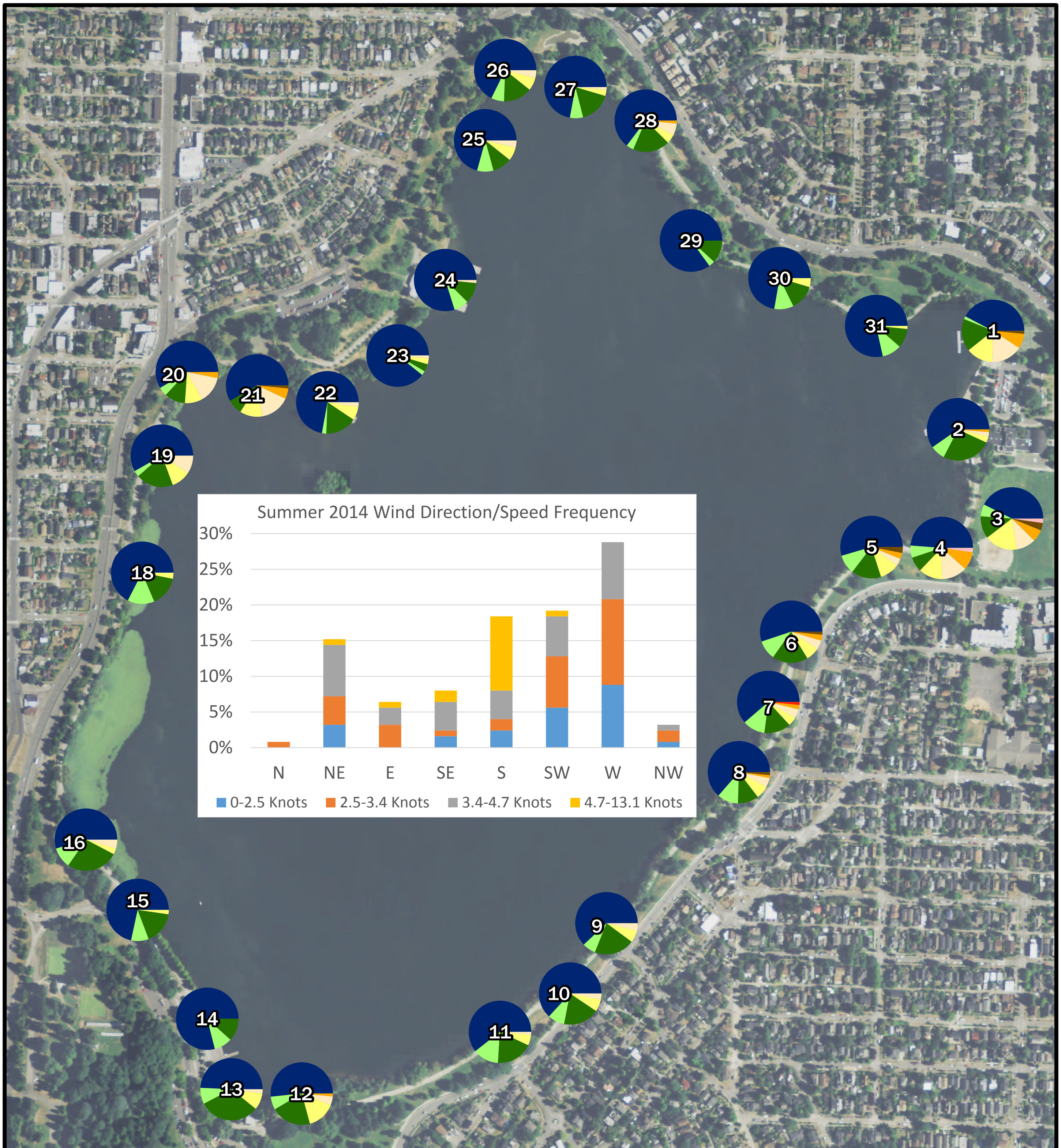

Legend

Scum Rating (0-8)

0
1
2
3
4
5
6
7
8

Figure 19. Summer (May through October) 2014 Algae Scum Rating Frequency at Green Lake.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

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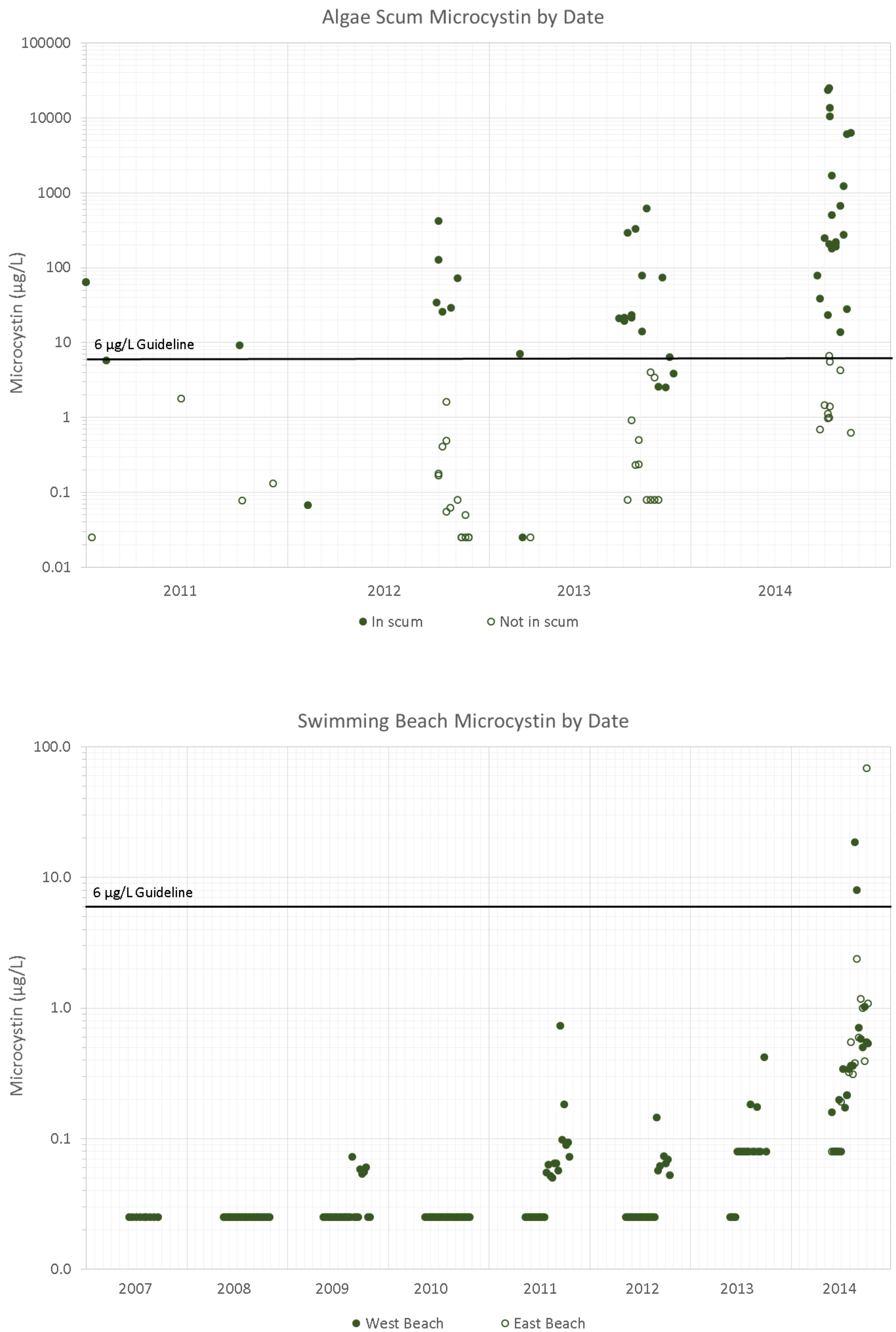


Figure 20. Microcystin in Algae Scum and Swimming Beach Samples from Green Lake.

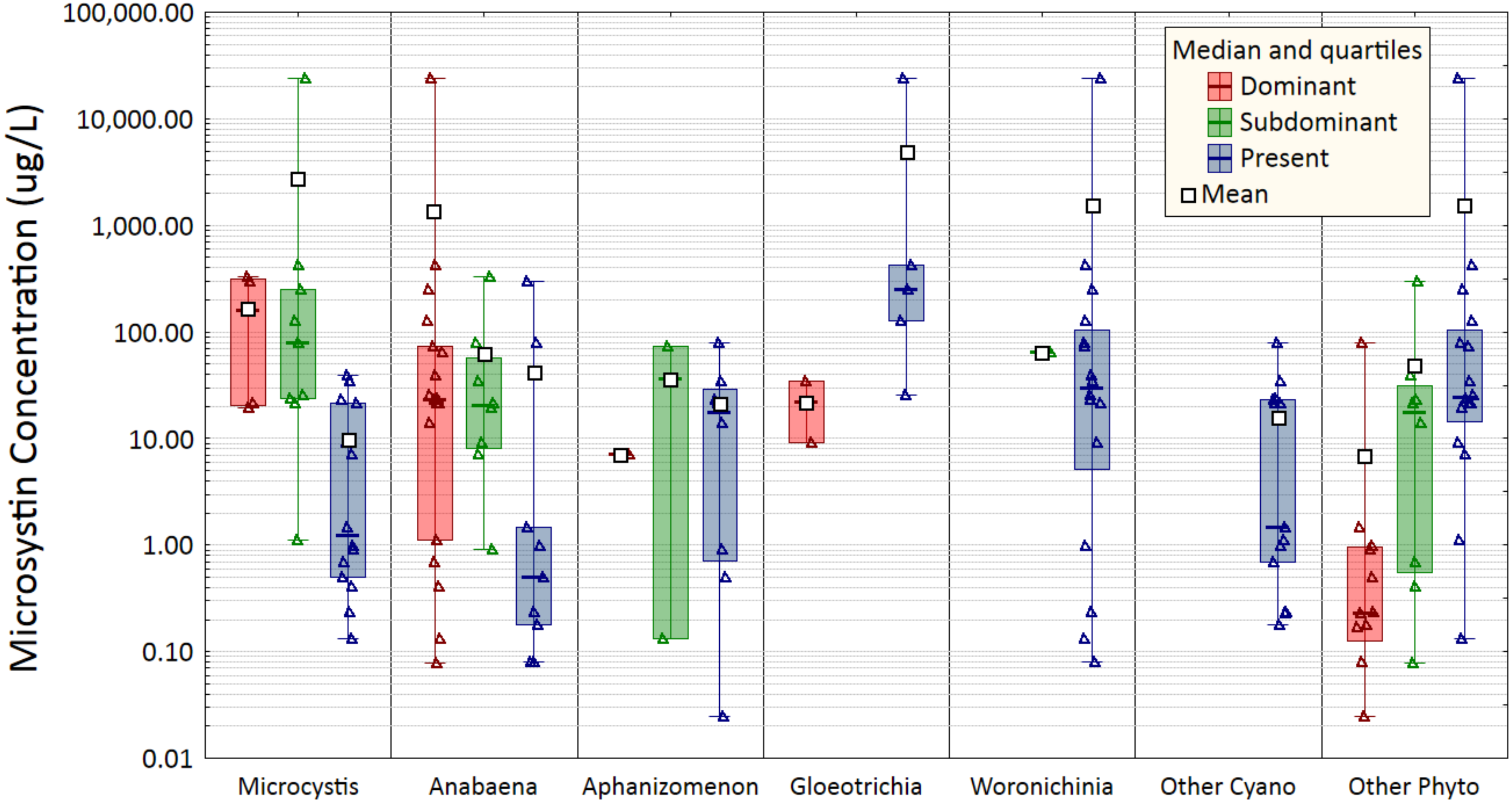


Figure 21. Microcystin by Phytoplankton Abundance in Algae Scum Samples from Green Lake.

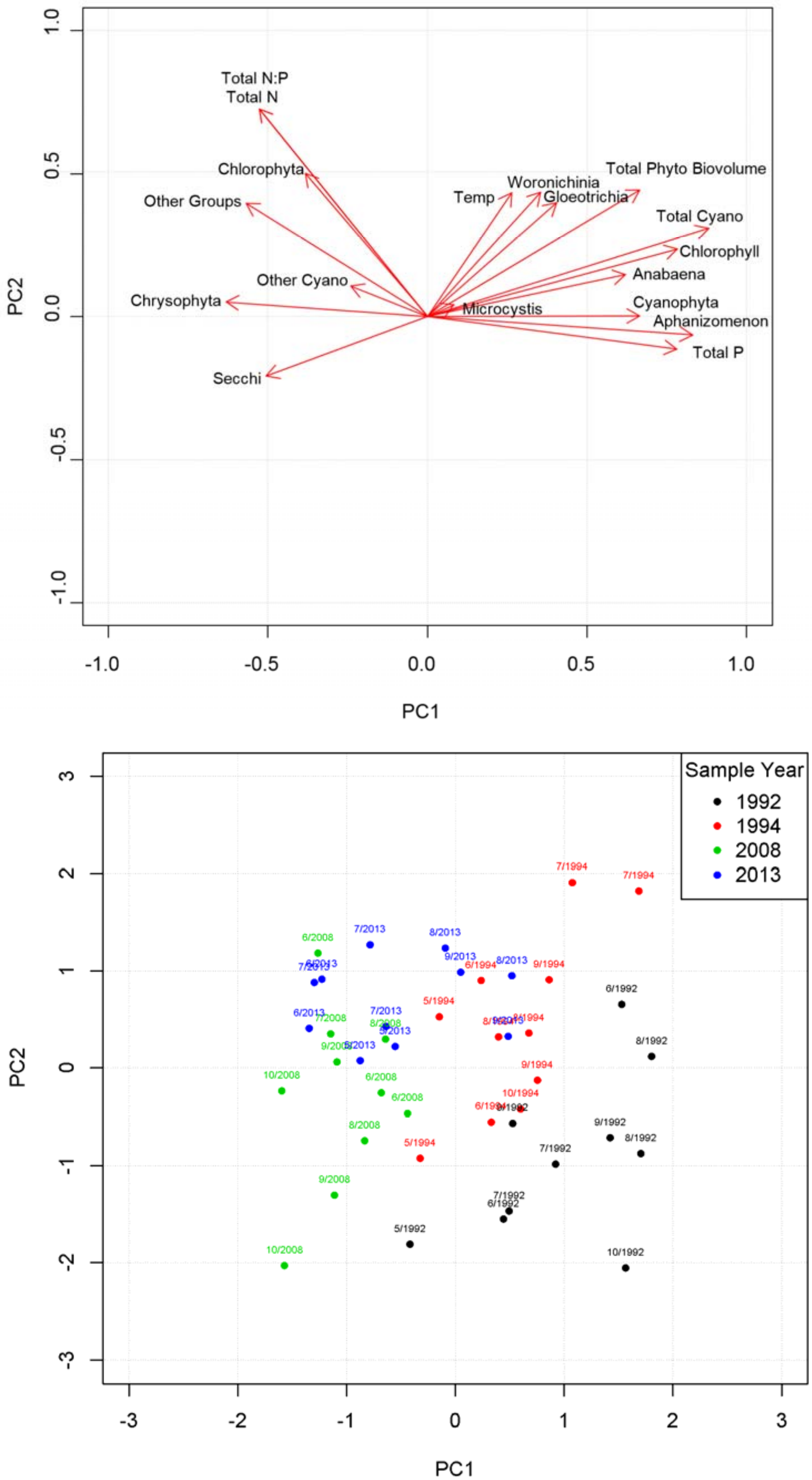
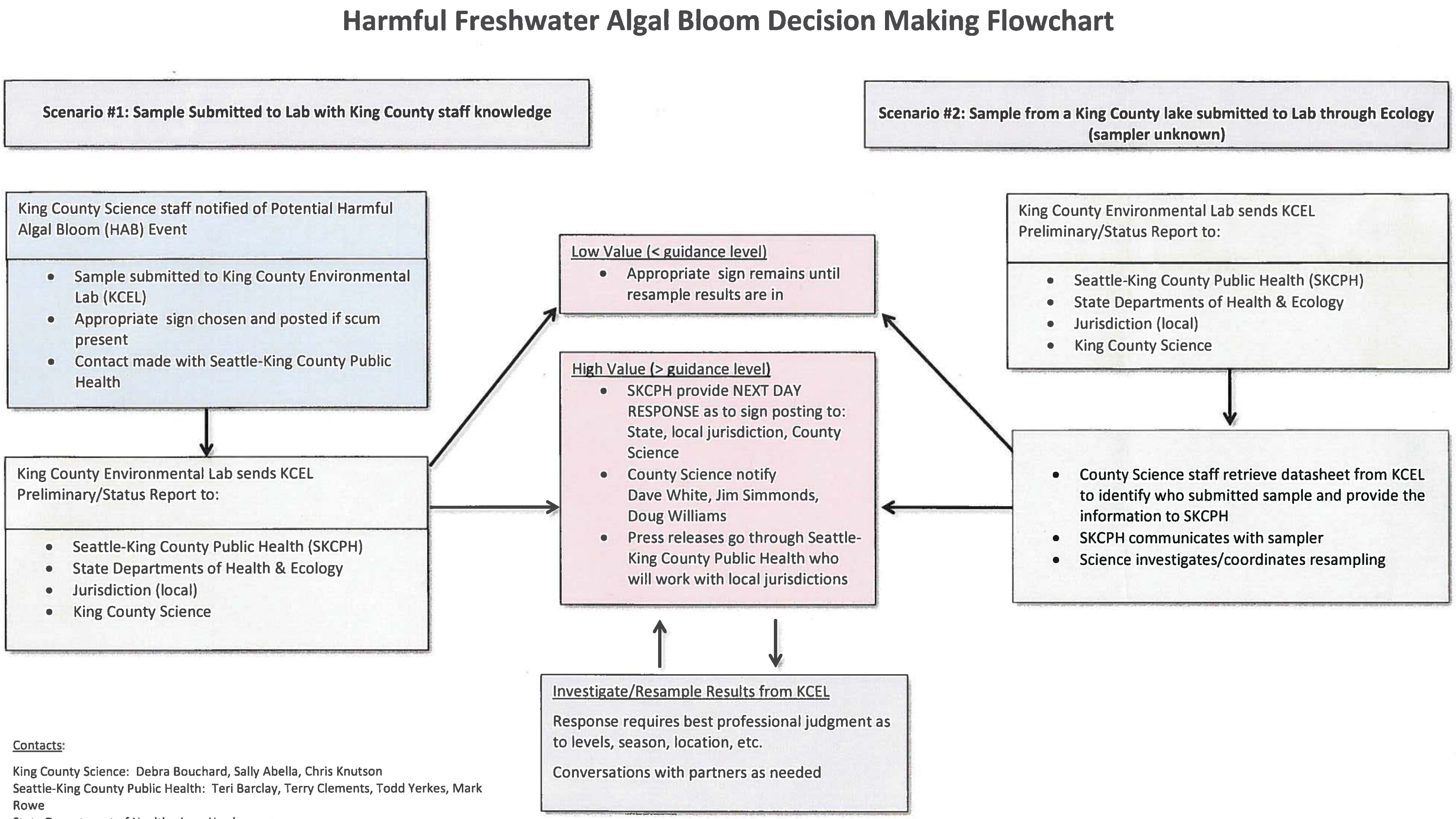


Figure 22. Principal Component Analysis Results of Factors for Water Quality and Phytoplankton Parameters in 1992, 1994, 2008, and 2013 at Green Lake.



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State Department of Health: Joan Hardy
State Department of Ecology: Lizbeth Seebacher

Figure 23. King County Harmful Freshwater Algal Bloom Decision Making Flowchart.

March 21, 2013

Closure Signs

Education Signs

Figure 24. Toxic Algae Signs Available for Use at Green Lake.

TABLES

Table 1. Number of Parameter Values by Year for Summer (May-October) in Green Lake.

Parameter	Pre 1991 Alum Treatment[a]					Post 1991 Alum Treatment[b]					Not Analyzed[c]				
	1959	1981	1989	1990	Total	1992	1993	1994	1995	Total	1996	1999	2000	2002	2003
Sample Dates	12	12	14	17	**55**	10	6	12	6	**34**	4	1	3	1	11
Water Quality															
Water Temperature	12	12	14	17	**55**	10	6	11	6	**33**	4	1	3	1	0
Secchi Depth	12	12	14	17	**55**	10	5	12	6	**33**	4	1	3	1	11
Chlorophyll a	12	11	0	0	**23**	10	6	12	6	**34**	4	1	3	0	0
Total Phosphorus	11	12	14	17	**54**	10	6	12	6	**34**	4	1	3	1	0
Soluble Reactive Phosphorus	12	12	14	17	**55**	10	6	12	5	**33**	4	1	3	1	0
Total Nitrogen	12	11	0	0	**23**	10	0	12	0	**22**	0	0	0	0	0
Nitrate+Nitrite Nitrogen	12	11	0	0	**23**	10	6	12	0	**28**	0	0	0	1	0
Ammonia Nitrogen	7	11	0	0	**18**	10	6	12	0	**28**	0	0	0	0	0
Total N:P Ratio	11	10	0	0	**21**	10	0	12	0	**22**	0	0	0	0	0
Dissolved N:P Ratio	6	11	0	0	**17**	10	6	12	0	**28**	0	0	0	0	0
Phytoplankton															
Group Percent Composition[e]	12	10	0	0	**22**	10	5	12	0	**27**	0	0	0	0	0
Total Phytoplankton Biovolume	0	10	0	0	**10**	10	5	12	0	**27**	0	0	0	0	0
Total Cyanombacteria Biovolume	0	0	14	17	**31**	10	5	12	0	**27**	0	0	0	0	0
Cynaobacteria Species Biovolume[f]	0	0	14	17	**31**	10	5	12	0	**27**	0	0	0	0	0

Parameter	Post 2004 Alum Treatment[d]											
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Sample Dates	0+12	12+12	12+8	12+9	12+7	12+8	12+8	12+9	12+6	12+6	10+0	**203**
Water Quality												
Water Temperature	12	22	20	21	19	20	20	21	18	18	10	**201**
Secchi Depth	12	24	20	21	19	20	20	21	18	18	10	**203**
Chlorophyll a	12	24	20	21	19	20	20	21	18	18	10	**203**
Total Phosphorus	12	24	20	21	19	20	20	21	18	18	9	**202**
Soluble Reactive Phosphorus	0	13	10	11	9	10	10	11	8	8	2	**92**
Total Nitrogen	0	12	12	12	12	12	12	12	12	12	10	**118**
Nitrate+Nitrite Nitrogen	0	2	2	2	2	2	0	0	0	0	2	**12**
Ammonia Nitrogen	0	2	2	2	2	2	2	2	2	2	2	**20**
Total N:P Ratio	0	12	12	12	12	12	12	12	12	12	9	**117**
Dissolved N:P Ratio	0	2	2	2	2	2	0	0	0	0	2	**12**
Phytoplankton												
Group Percent Composition[e]	0	0	0	0	10	0	0	0		11	0	**21**
Total Phytoplankton Biovolume	0	0	0	0	10	0	0	0		11	0	**21**
Total Cyanombacteria Biovolume	0	0	0	0	10	0	0	0		11	0	**21**
Cynaobacteria Species Biovolume[f]	0	0	0	0	10	0	0	0		11	0	**21**

[a] Sources: 1959 (Sylvester and Anderson 1960), 1981 (URS 1983, Bolstridge 1982), 1989-1990 (Barbiero 1991)

[b] Sources: 1992-1994 (KCM 1995), 1995 (Herrera 2003)

[c] Sources: 1996-2002 (Herrera 2003), 2003 (FOGL 2003)

[d] Sources: 2004-2014 (King County 2014) + (Seattle Parks 2014)

[e] Parameters: Cyanophyta, Chlorophyta, Chrysophyta, Other Groups

[f] Parameters: Microcystis, Anabaena, Aphanizomenon, Gloeotrichia, Woronichinia, Other Cyano

Table 2. Green Lake Water Quality and Phytoplankton Summer Means.

Sample Year	No. of Dates	Temp (°C)	Secchi (m)	Chlor *a* (µg/L)	Total P (µg/L)	SRP (µg/L)	Total N (µg/L)	NO2+3 N (µg/L)	NH3 N (µg/L)	Total N:P (-)	Diss N:P (-)	Cyanophyta (%)	Chlorophyta (%)	Chrysophyta (%)	Other Groups (%)	Total Phyto (mm^3/L)	Total Cyano (mm^3/L)	Microcystis (mm^3/L)	Anabaena (mm^3/L)	Aphanizomenon (mm^3/L)	Gloeotrichia (mm^3/L)	Woronichinia (mm^3/L)	Other Cyano (mm^3/L)
1959	12	18.8	2.0	26.7	71.5	19.4	445	107	224	7.7	12.1	70.0	9.2	16.7	4.2	-	-	-	-	-	-	-	-
1981	12	18.0	2.8	29.0	44.5	4.5	721	11.5	22.1	14.0	11.2	72.9	9.9	14.7	2.5	17.35	-	-	-	-	-	-	-
1989	14	20.5	3.8	-	28.6	4.0	-	-	-	-	-	-	-	-	-	-	4.6173	0.0000	0.0319	0.3865	4.1839	0.0000	0.0150
1990	17	20.3	3.2	-	26.7	2.9	-	-	-	-	-	-	-	-	-	-	1.7317	0.0000	0.2009	0.5179	0.5151	0.0129	0.4849
1992	10	20.7	3.5	5.1	19.5	3.4	286	15.1	20.0	14.8	17.4	69.6	7.6	13.8	9.0	6.25	5.7808	0.0027	0.8781	0.1989	4.6960	0.0000	0.0052
1993	6	18.2	2.5	12.4	25.7	3.7	-	27.3	101	-	38.0	54.6	13.1	4.0	28.3	1.77	1.2130	0.0000	0.8278	0.3469	0.0000	0.0317	0.0066
1994	12	20.3	3.4	8.0	17.9	2.0	344	15.4	30.8	20.1	28.5	31.0	12.2	35.4	21.4	8.53	1.6321	0.0000	0.1264	0.1755	1.3056	0.0192	0.0055
1995	6	19.2	2.6	11.9	23.0	3.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2004	12	20.5	3.2	4.4	11.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2005a	12	17.1	3.2	3.3	12.9	2.0	210	10.0	5.0	16.8	7.5	-	-	-	-	-	-	-	-	-	-	-	-
2005b	12	18.8	3.8	3.6	12.9	1.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2005	24	17.9	3.5	3.5	12.9	1.2	210	10.0	5.0	16.8	7.5	-	-	-	-	-	-	-	-	-	-	-	-
2006a	12	18.8	2.7	3.0	17.5	2.2	222	10.0	5.0	13.2	6.9	-	-	-	-	-	-	-	-	-	-	-	-
2006b	8	19.2	3.3	3.2	14.0	0.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2006	20	19.0	3.0	3.1	16.0	0.9	222	10.0	5.0	13.2	6.9	-	-	-	-	-	-	-	-	-	-	-	-
2007a	12	18.2	3.5	3.3	11.7	3.6	244	10.0	11.0	21.3	5.8	-	-	-	-	-	-	-	-	-	-	-	-
2007b	9	19.2	3.5	2.7	12.7	1.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2007	21	18.6	3.5	3.0	12.1	2.0	244	10.0	11.0	21.3	5.8	-	-	-	-	-	-	-	-	-	-	-	-
2008a	12	17.8	4.0	1.8	10.6	2.0	240	10.0	5.0	23.8	7.5	13.4	9.1	63.4	14.1	0.49	0.0392	0.0004	0.0303	0.0000	0.0000	0.0000	0.0085
2008b	7	18.3	3.8	2.9	12.0	1.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2008	19	18.0	3.9	2.2	11.1	1.3	240	10.0	5.0	23.8	7.5	13.4	9.1	63.4	14.1	0.49	0.0392	0.0004	0.0303	0.0000	0.0000	0.0000	0.0085
2009a	12	19.3	3.7	2.4	15.5	2.0	263	5.0	4.6	18.2	4.8	-	-	-	-	-	-	-	-	-	-	-	-
2009b	8	20.0	3.6	3.0	17.5	1.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2009	20	19.6	3.6	2.6	16.3	1.3	263	5.0	4.6	18.2	4.8	-	-	-	-	-	-	-	-	-	-	-	-
2010a	12	17.8	3.3	3.4	13.2	2.1	245	-	9.3	19.3	-	-	-	-	-	-	-	-	-	-	-	-	-
2010b	8	19.1	3.8	2.9	14.3	1.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2010	20	18.3	3.5	3.2	13.6	1.7	245	-	9.3	19.3	-	-	-	-	-	-	-	-	-	-	-	-	-
2011a	12	18.3	3.4	4.0	11.8	2.0	275	-	7.8	23.9	-	-	-	-	-	-	-	-	-	-	-	-	-
2011b	9	18.8	3.2	4.0	14.1	0.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2011	21	18.5	3.3	4.0	12.8	1.1	275	-	7.8	23.9	-	-	-	-	-	-	-	-	-	-	-	-	-
2012a	12	18.7	3.8	3.1	12.3	2.0	309	-	6.8	25.6	-	-	-	-	-	-	-	-	-	-	-	-	-
2012b	6	18.8	3.5	3.0	14.5	1.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2012	18	18.7	3.7	3.1	13.0	1.5	309	-	6.8	25.6	-	-	-	-	-	-	-	-	-	-	-	-	-
2013a	12	19.8	3.4	4.8	15.6	1.3	375	-	13.0	24.4	-	7.6	42.9	38.3	11.2	2.38	0.1578	0.0009	0.0110	0.0102	0.0000	0.1005	0.0352
2013b	6	19.6	2.9	5.2	17.7	1.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2013	18	19.7	3.2	4.9	16.3	1.1	375	-	13.0	24.4	-	7.6	42.9	38.3	11.2	2.38	0.1578	0.0009	0.0110	0.0102	0.0000	0.1005	0.0352
2014	10	19.6	2.7	6.4	19.2	0.7	387	2.5	21.8	20.7	34.7	-	-	-	-	-	-	-	-	-	-	-	-

a = King County, b = Seattle Parks

Table 3. Kendall Tau Correlation Coefficients for Green Lake Water Quality and Phytoplankton Data Analysis.

Variable by Period	Temperature				Secchi Depth				Total P				SRP				Total N				NO3 N				NH3 N				Total N:P				Diss N:P				Chlorophyll a				Total Phyto Biovolume			
	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All
Temperature	1.00	1.00	1.00	1.00	0.04	-0.03	0.03	0.02	-0.01	0.07	-0.04	0.03	-0.02	-0.09	-0.08	-0.01	-0.17	0.42	0.12	0.10	0.19	0.04	-0.19	0.11	-0.09	-0.19	0.42	0.02	-0.38	-0.03	0.15	0.07	-0.04	-0.19	0.12	0.03	0.11	0.05	-0.18	-0.11	-0.07	0.02	0.06	-0.03
Secchi Depth	0.04	-0.03	0.03	0.02	1.00	1.00	1.00	1.00	-0.62	-0.37	-0.33	-0.34	-0.13	0.15	0.11	-0.05	-0.33	-0.37	-0.05	-0.18	-0.25	-0.17	-0.13	-0.23	0.01	0.01	-0.06	-0.03	0.03	-0.05	0.26	0.27	0.05	-0.07	-0.24	-0.04	-0.61	-0.56	-0.45	-0.49	-0.52	-0.42	-0.37	-0.46
Total P	-0.01	0.07	-0.04	0.03	-0.62	-0.37	-0.33	-0.34	1.00	1.00	1.00	1.00	0.36	0.12	0.02	0.41	0.06	0.33	0.27	0.36	0.30	0.04	-0.50	0.24	0.26	0.30	0.09	0.32	-0.46	-0.33	-0.43	-0.52	-0.24	0.14	0.03	0.00	0.52	0.30	0.30	0.43	0.29	0.15	0.51	0.48
SRP	-0.02	-0.09	-0.08	-0.01	-0.13	0.15	0.11	-0.05	0.36	0.12	0.02	0.41	1.00	1.00	1.00	1.00	-0.05	-0.03	-0.32	0.11	0.17	-0.01	0.65	0.17	0.47	0.12	0.01	0.30	-0.27	-0.19	-0.23	-0.27	-0.32	-0.39	-0.60	-0.28	-0.06	-0.08	-0.14	0.21	-0.20	0.08	-0.82	0.17
Total N	-0.17	0.42	0.12	0.10	-0.33	-0.37	-0.05	-0.18	0.06	0.33	0.27	0.36	-0.05	-0.03	-0.32	0.11	1.00	1.00	1.00	1.00	0.02	-0.01	-0.33	0.14	0.10	0.11	0.30	0.30	0.40	0.33	0.31	0.11	0.23	0.04	0.23	0.15	0.23	0.45	0.26	0.36	0.61	0.31	0.45	0.46
NO3 N	0.19	0.04	-0.19	0.11	-0.25	-0.17	-0.13	-0.23	0.30	0.04	-0.50	0.24	0.17	-0.01	0.65	0.17	0.02	-0.01	-0.33	0.14	1.00	1.00	1.00	1.00	0.24	0.29	0.00	0.30	-0.19	0.04	-0.12	-0.20	-0.07	0.31	-0.13	0.18	0.17	0.10	-0.62	0.27	0.34	0.14		0.00
NH3 N	-0.09	-0.19	0.42	0.02	0.01	0.01	-0.06	-0.03	0.26	0.30	0.09	0.32	0.47	0.12	0.01	0.30	0.10	0.11	0.30	0.30	0.24	0.29	0.00	0.30	1.00	1.00	1.00	1.00	-0.12	0.02	0.21	-0.11	0.13	0.47	0.10	0.39	-0.09	0.20	0.05	0.27	-0.08	0.08	1.00	0.04
Total N:P	-0.38	-0.03	0.15	0.07	0.03	-0.05	0.26	0.27	-0.46	-0.33	-0.43	-0.52	-0.27	-0.19	-0.23	-0.27	0.40	0.33	0.31	0.11	-0.19	0.04	-0.12	-0.20	-0.12	0.02	0.21	-0.11	1.00	1.00	1.00	1.00	0.12	0.04	0.23	0.12	-0.10	0.32	-0.06	-0.19	0.00	0.16	-0.14	-0.21
Diss N:P	-0.04	-0.19	0.12	0.03	0.05	-0.07	-0.24	-0.04	-0.24	0.14	0.03	0.00	-0.32	-0.39	-0.60	-0.28	0.23	0.04	0.23	0.15	-0.07	0.31	-0.13	0.18	0.13	0.47	0.10	0.39	0.12	0.04	0.23	0.12	1.00	1.00	1.00	1.00	-0.05	0.09	0.00	0.14	0.22	-0.10		-0.14
Chlorophyll a	0.11	0.05	-0.18	-0.11	-0.61	-0.56	-0.45	-0.49	0.52	0.30	0.30	0.43	-0.06	-0.08	-0.14	0.21	0.23	0.45	0.26	0.36	0.17	0.10	-0.62	0.27	-0.09	0.20	0.05	0.27	-0.10	0.32	-0.06	-0.19	-0.05	0.09	0.00	0.14	1.00	1.00	1.00	1.00	0.72	0.56	0.60	0.59
Total Phyto Biovol	-0.07	0.02	0.06	-0.03	-0.52	-0.42	-0.37	-0.46	0.29	0.15	0.51	0.48	-0.20	0.08	-0.82	0.17	0.61	0.31	0.45	0.46	0.34	0.14		0.00	-0.08	0.08	1.00	0.04	0.00	0.16	-0.14	-0.21	0.22	-0.10		-0.14	0.72	0.56	0.60	0.59	1.00	1.00	1.00	1.00
Cyanophyta	0.07	0.06	0.23	0.01	-0.36	-0.12	-0.12	-0.33	0.20	0.06	-0.21	0.37	-0.15	0.33	-0.82	0.15	0.22	-0.04	0.02	0.19	-0.13	0.03		0.05	-0.18	-0.15	0.33	-0.09	-0.03	-0.18	0.24	-0.31	0.19	-0.37		-0.21	0.52	0.00	-0.03	0.39	0.58	0.03	-0.07	0.24
Chlorophyta	-0.07	0.11	0.39	0.14	0.18	0.17	0.08	0.22	0.21	0.15	0.10	-0.15	0.36	-0.10	0.00	0.09	-0.13	0.12	0.32	-0.05	0.03	0.12		0.06	0.33	0.18	0.33	0.19	-0.19	-0.01	0.39	0.22	-0.26	0.24		0.09	-0.12	-0.11	0.13	-0.22	-0.29	-0.27	0.28	-0.19
Chrysophyta	0.03	-0.12	-0.23	-0.01	0.25	0.15	-0.19	0.21	-0.34	-0.20	0.02	-0.36	-0.23	-0.38	0.00	-0.31	-0.18	0.00	-0.19	-0.17	0.07	-0.16		-0.08	-0.09	0.04	-0.33	-0.05	0.11	0.19	-0.33	0.25	0.05	0.23		0.16	-0.35	-0.05	0.04	-0.31	-0.55	-0.18	-0.09	-0.30
Other Groups	0.03	-0.22	-0.20	-0.03	0.03	0.21	0.34	0.31	-0.39	-0.05	0.04	-0.29	-0.06	-0.15	0.00	-0.16	0.27	-0.08	0.06	-0.09	-0.47	-0.01		-0.21	-0.11	0.29	0.33	0.14	0.41	0.24	0.07	0.32	0.02	0.34		0.28	-0.15	0.06	-0.03	-0.23	-0.30	-0.07	-0.14	-0.19
Microcystis		0.23	0.13	0.06		-0.06	-0.24	-0.09		0.22	0.07	-0.14		0.08	-1.00	-0.11		0.17	0.04	0.04		-0.15		-0.14		-0.14	0.82	-0.15		-0.25	-0.05	0.01		-0.23		-0.22		-0.15	0.27	-0.03		-0.04	0.32	0.07
Anabaena	-0.15	-0.08	0.17	-0.03	-0.46	-0.46	-0.16	-0.34	0.40	0.17	-0.29	0.07	0.22	0.18	0.50	0.10		0.19	-0.10	0.06		-0.01		0.02		-0.16	-0.82	-0.01		-0.02	0.15	-0.16		-0.24		-0.19		0.31	-0.09	0.37		0.33	0.08	0.32
Aphanizomenon	0.21	-0.35	0.01	0.04	-0.62	-0.23	-0.24	-0.40	0.65	-0.06	0.55	0.44	0.24	0.13	-0.50	0.19		0.00	0.44	0.13		0.01		0.05		0.15	0.82	0.25		0.38	-0.23	-0.27		-0.06		-0.01		0.34	0.49	0.57		0.17	0.48	0.36
Gloeotrichia	0.27	0.20		0.20	0.01	0.09		0.12	0.08	0.03		0.31	0.10	0.08		0.15		0.27		0.18		0.14		0.14		0.20		0.22		0.12		-0.03		0.03		0.03		0.16		0.20		0.44		0.34
Woronichinia	0.38	0.23	0.25	0.27	-0.29	-0.12	-0.21	-0.22	0.24	0.24	0.28	0.17	-0.05	-0.25	-1.00	-0.21		0.51	0.18	0.33		0.09		0.11		0.22	0.82	0.20		0.24	-0.07	-0.02		0.31		0.33		0.24	0.26	0.29		0.02	0.28	0.21
Other Cyano	-0.11	0.29	-0.07	0.01	-0.57	0.00	0.03	-0.26	0.50	0.46	-0.05	0.09	0.17	0.14	0.82	0.16		0.33	0.10	0.15		-0.14		-0.16		0.04	-0.33	0.00		-0.28	0.10	0.04		-0.07		-0.08		-0.06	-0.02	-0.15		0.04	0.25	0.01
Total Cyano	0.19	0.02	0.25	0.18	-0.46	-0.32	-0.31	-0.28	0.51	0.18	-0.01	0.50	0.28	0.24	-0.82	0.29		0.32	0.14	0.23		0.04		0.07		0.07	1.00	0.16		0.11	0.08	-0.17		-0.18		-0.12		0.40	0.19	0.50		0.62	0.41	0.54
Total Significant	3	3	4	4	10	6	6	15	11	6	7	15	4	3	3	10	3	9	7	10	2	2	3	7	1	4	1	6	4	4	6	12	0	6	1	4	5	8	7	18	5	6	6	14
% Significant	14	14	19	19	48	29	29	71	52	29	33	71	19	14	14	48	14	43	33	48	10	10	14	33	5	19	5	29	19	19	29	57	0	29	5	19	24	38	33	86	24	29	29	67

Variable by Period	Cyanophyta				Chlorophyta				Chrysophyta				Other Groups				Microcystis				Anabaena				Aphanizomenon				Gloeotrichia				Woronichinia				Other Cyano				Total Cyano			
	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All	Pre	Post1	Post2	All
Temperature	0.07	0.06	0.23	0.01	-0.07	0.11	0.39	0.14	0.03	-0.12	-0.23	-0.01	0.03	-0.22	-0.20	-0.03		0.23	0.13	0.06	-0.15	-0.08	0.17	-0.03	0.21	-0.35	0.01	0.04	0.27	0.20		0.20	0.38	0.23	0.25	0.27	-0.11	0.29	-0.07	0.01	0.19	0.02	0.25	0.18
Secchi Depth	-0.36	-0.12	-0.12	-0.33	0.18	0.17	0.08	0.22	0.25	0.15	-0.19	0.21	0.03	0.21	0.34	0.31		-0.06	-0.24	-0.09	-0.46	-0.46	-0.16	-0.34	-0.62	-0.23	-0.24	-0.40	0.01	0.09		0.12	-0.29	-0.12	-0.21	-0.22	-0.57	0.00	0.03	-0.26	-0.46	-0.32	-0.31	-0.28
Total P	0.20	0.06	-0.21	0.37	0.21	0.15	0.10	-0.15	-0.34	-0.20	0.02	-0.36	-0.39	-0.05	0.04	-0.29		0.22	0.07	-0.14	0.40	0.17	-0.29	0.07	0.65	-0.06	0.55	0.44	0.08	0.03		0.31	0.24	0.24	0.28	0.17	0.50	0.46	-0.05	0.09	0.51	0.18	-0.01	0.50
SRP	-0.15	0.33	-0.82	0.15	0.36	-0.10	0.00	0.09	-0.23	-0.38	0.00	-0.31	-0.06	-0.15	0.00	-0.16		0.08	-1.00	-0.11	0.22	0.18	0.50	0.10	0.24	0.13	-0.50	0.19	0.10	0.08		0.15	-0.05	-0.25	-1.00	-0.21	0.17	0.14	0.82	0.16	0.28	0.24	-0.82	0.29
Total N	0.22	-0.04	0.02	0.19	-0.13	0.12	0.32	-0.05	-0.18	0.00	-0.19	-0.17	0.27	-0.08	0.06	-0.09		0.17	0.04	0.04		0.19	-0.10	0.06		0.00	0.44	0.13		0.27		0.18		0.51	0.18	0.33		0.33	0.10	0.15		0.32	0.14	0.23
NO3 N	-0.13	0.03		0.05	0.03	0.12		0.06	0.07	-0.16		-0.08	-0.47	-0.01		-0.21		-0.15		-0.14		-0.01		0.02		0.01		0.05		0.14		0.14		0.09		0.11		-0.14		-0.16		0.04		0.07
NH3 N	-0.18	-0.15	0.33	-0.09	0.33	0.18	0.33	0.19	-0.09	0.04	-0.33	-0.05	-0.11	0.29	0.33	0.14		-0.14	0.82	-0.15		-0.16	-0.82	-0.01		0.15	0.82	0.25		0.20		0.22		0.22	0.82	0.20		0.04	-0.33	0.00		0.07	1.00	0.16
Total N:P	-0.03	-0.18	0.24	-0.31	-0.19	-0.01	0.39	0.22	0.11	0.19	-0.33	0.25	0.41	0.24	0.07	0.32		-0.25	-0.05	0.01		-0.02	0.15	-0.16		0.38	-0.23	-0.27		0.12		-0.03		0.24	-0.07	-0.02		-0.28	0.10	0.04		0.11	0.08	-0.17
Diss N:P	0.19	-0.37		-0.21	-0.26	0.24		0.09	0.05	0.23		0.16	0.02	0.34		0.28		-0.23		-0.22		-0.24		-0.19		-0.06		-0.01		0.03		0.03		0.31		0.33		-0.07		-0.08		-0.18		-0.12
Chlorophyll a	0.52	0.00	-0.03	0.39	-0.12	-0.11	0.13	-0.22	-0.35	-0.05	0.04	-0.31	-0.15	0.06	-0.03	-0.23		-0.15	0.27	-0.03		0.31	-0.09	0.37		0.34	0.49	0.57		0.16		0.20		0.24	0.26	0.29		-0.06	-0.02	-0.15		0.40	0.19	0.50
Total Phyto Biovol	0.58	0.03	-0.07	0.24	-0.29	-0.27	0.28	-0.19	-0.55	-0.18	-0.09	-0.30	-0.30	-0.07	-0.14	-0.19		-0.04	0.32	0.07		0.33	0.08	0.32		0.17	0.48	0.36		0.44		0.34		0.02	0.28	0.21		0.04	0.25	0.01		0.62	0.41	0.54
Cyanophyta	1.00	1.00	1.00	1.00	-0.37	-0.28	-0.09	-0.37	-0.61	-0.56	-0.10	-0.55	-0.01	-0.57	-0.07	-0.38		0.25	-0.11	-0.07		0.48	0.38	0.53		0.30	0.16	0.49		0.01		0.15		-0.33	0.32	0.06		-0.03	0.00	-0.21		0.39	0.52	0.58
Chlorophyta	-0.37	-0.28	-0.09	-0.37	1.00	1.00	1.00	1.00	-0.03	0.19	-0.50	0.10	-0.20	0.14	0.03	0.10		0.02	-0.06	0.08		-0.29	-0.07	-0.30		-0.23	0.07	-0.35		0.09		-0.01		0.33	-0.03	0.10		0.08	0.19	0.23		-0.19	0.05	-0.26
Chrysophyta	-0.61	-0.56	-0.10	-0.55	-0.03	0.19	-0.50	0.10	1.00	1.00	1.00	1.00	0.08	0.30	-0.37	0.16		-0.29	-0.01	0.03		-0.37	0.12	-0.35		-0.08	-0.12	-0.36		-0.24		-0.25		0.36	-0.03	0.09		-0.08	-0.11	0.14		-0.44	-0.10	-0.42
Other Groups	-0.01	-0.57	-0.07	-0.38	-0.20	0.14	0.03	0.10	0.08	0.30	-0.37	0.16	1.00	1.00	1.00	1.00		-0.30	-0.03	-0.14		-0.32	-0.35	-0.27		-0.13	0.13	-0.09		-0.04		-0.08		0.25	-0.01	0.11		-0.14	0.00	-0.05		-0.27	-0.18	-0.22
Microcystis		0.25	-0.11	-0.07		0.02	-0.06	0.08		-0.29	-0.01	0.03		-0.30	-0.03	-0.14	1.00	1.00	1.00	1.00		0.26	0.19	0.09		-0.25	0.07	-0.17		-0.10		-0.22		-0.20	0.10	-0.06		0.29	-0.04	0.19		0.12	0.22	-0.12
Anabaena		0.48	0.38	0.53		-0.29	-0.07	-0.30		-0.37	0.12	-0.35		-0.32	-0.35	-0.27		0.26	0.19	0.09	1.00	1.00	1.00	1.00	0.32	0.36	-0.02	0.37	0.04	-0.14		-0.25	-0.23	-0.13	-0.14	0.03	0.51	0.04	0.22	0.22	0.41	0.56	0.51	0.27
Aphanizomenon		0.30	0.16	0.49		-0.23	0.07	-0.35		-0.08	-0.12	-0.36		-0.13	0.13	-0.09		-0.25	0.07	-0.17	0.32	0.36	-0.02	0.37	1.00	1.00	1.00	1.00	0.14	-0.10		0.04	0.49	-0.09	0.45	0.28	0.45	-0.19	0.09	0.13	0.63	0.37	0.45	0.53
Gloeotrichia		0.01		0.15		0.09		-0.01		-0.24		-0.25		-0.04		-0.08		-0.10		-0.22	0.04	-0.14		-0.25	0.14	-0.10		0.04	1.00	1.00	1.00	1.00	0.05	0.11		0.00	-0.20	0.07		-0.23	0.51	0.47		0.48
Woronichinia		-0.33	0.32	0.06		0.33	-0.03	0.10		0.36	-0.03	0.09		0.25	-0.01	0.11		-0.20	0.10	-0.06	-0.23	-0.13	-0.14	0.03	0.49	-0.09	0.45	0.28	0.05	0.11		0.00	1.00	1.00	1.00	1.00	0.16	0.17	-0.35	0.01	0.23	-0.10	0.38	0.16
Other Cyano		-0.03	0.00	-0.21		0.08	0.19	0.23		-0.08	-0.11	0.14		-0.14	0.00	-0.05		0.29	-0.04	0.19	0.51	0.04	0.22	0.22	0.45	-0.19	0.09	0.13	-0.20	0.07		-0.23	0.16	0.17	-0.35	0.01	1.00	1.00	1.00	1.00	0.40	0.02	0.28	0.03
Total Cyano		0.39	0.52	0.58		-0.19	0.05	-0.26		-0.44	-0.10	-0.42		-0.27	-0.18	-0.22		0.12	0.22	-0.12	0.41	0.56	0.51	0.27	0.63	0.37	0.45	0.53	0.51	0.47		0.48	0.23	-0.10	0.38	0.16	0.40	0.02	0.28	0.03	1.00	1.00	1.00	1.00
Total Significant	5	9	3	13	2	3	4	9	4	6	3	13	3	6	3	11	0	3	1	3	5	9	3	11	6	6	6	13	2	2	0	9	3	5	4	10	5	4	1	6	7	9	6	15
% Significant	24	43	14	62	10	14	19	43	19	29	14	62	14	29	14	52	0	14	5	14	24	43	14	52	29	29	29	62	10	10	0	43	14	24	19	48	24	19	5	29	33	43	29	71

Table 4. Principal Component Analysis Results of Post 1991 (1992 and 1994) and Post 2004 (2008 and 2013) Alum Treatment Data for Green Lake.

Parameter	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**
Total Cyanobacteria Biovolume	**0.88**	0.31	-0.16	-0.09	0.13	-0.03	0.16	0.05	0.06	-0.10
Aphanizomenon Biovolume	**0.83**	-0.06	0.07	-0.31	-0.18	0.08	-0.04	-0.14	0.20	0.07
Chlorophyll a	**0.78**	0.24	0.31	-0.06	-0.15	-0.25	-0.10	-0.09	0.06	0.21
Total Phosphorus	**0.78**	-0.11	0.41	0.20	0.07	0.22	-0.10	-0.13	0.07	0.08
Total Phytoplankton Biovolume	**0.66**	0.44	0.38	0.02	0.26	-0.27	-0.10	-0.03	-0.01	0.05
Cyanophyta Percent	**0.66**	0.00	-0.56	-0.13	-0.09	0.22	0.30	0.08	0.13	-0.16
Chrysophyta Percent	**-0.63**	0.05	0.46	-0.06	-0.23	0.13	0.42	0.00	0.13	0.12
Anabaena Biovolume	**0.62**	0.15	-0.42	0.17	-0.12	-0.23	0.31	-0.21	0.04	0.24
Other Groups Percent	**-0.57**	0.40	0.48	-0.33	0.01	-0.02	0.06	0.19	0.00	0.17
Secchi Depth	**-0.51**	-0.21	-0.29	-0.42	0.41	0.18	0.08	0.05	0.24	0.33
Total Nitrogen	-0.53	**0.73**	-0.29	-0.08	-0.15	-0.20	-0.01	-0.07	0.01	-0.03
Total N:P Ratio	-0.53	**0.73**	-0.29	-0.08	-0.15	-0.20	-0.01	-0.07	0.01	-0.03
Chlorophyta Percent	-0.38	**0.50**	0.01	0.29	0.16	0.37	-0.24	-0.29	0.40	-0.11
Woronichinia Biovolume	0.35	**0.44**	0.42	-0.21	-0.39	0.42	0.14	0.12	-0.07	-0.12
Microcystis Biovolume	0.08	0.04	0.01	**0.75**	-0.11	-0.16	0.00	0.54	0.30	0.05
Other Cyanobacteria Biovolume	-0.24	0.11	0.24	**0.66**	0.35	0.07	0.39	-0.25	-0.16	0.00
Gloeotrichia Biovolume	0.40	0.40	0.08	-0.28	**0.67**	0.00	0.10	0.23	-0.04	-0.13
Temperature	0.26	0.43	-0.39	0.28	-0.02	**0.50**	-0.18	0.15	-0.30	0.30
Component Statistics										
Standard Score Loadings	6.06	2.44	2.02	1.79	1.19	1.03	0.71	0.67	0.52	0.44
Proportion Variance	0.34	0.14	0.11	0.10	0.07	0.06	0.04	0.04	0.03	0.02
Cumulative Variance	0.34	0.47	0.58	0.68	0.75	0.81	0.85	0.88	0.91	0.94
Proportion Explained	0.36	0.14	0.12	0.11	0.07	0.06	0.04	0.04	0.03	0.03
Cumulative Proportion	0.36	0.50	0.62	0.73	0.80	0.86	0.90	0.94	0.97	1.00

Table 5. Microcystin Statistics (µg/L) for Microcystis and Anabaena in Algae Scum at Green Lake.

	No. of Samples	Median	Minimun	25th Percentile	75th Percentile	Maximum
Microcystis						
Dominant	4	158	19.4	19.9	322	331
Subdominant	9	79.2	1.1	22.5	335	23800
Present	14	1.2	0.1	0.5	21.8	38.8
Not Present	11	0.2	0.0	0.1	64.4	78.1
Anabaena						
Dominant	18	23.4	0.1	1.0	86.8	23800
Subdominant	8	20.4	0.9	7.6	68.0	331
Present	9	0.5	0.1	0.1	39.8	295
Not Present	4	0.1	0.0	0.0	0.2	0.2
No Microcystis or Anabaena	4	0.1	0.0	0.0	0.2	0.2