PHOSPHORUS MANAGEMENT PLAN

GREEN LAKE ALUM TREATMENT 2016

Prepared for
Seattle Parks and Recreation

Prepared by
Herrera Environmental Consultants, Inc.

In association with
Tetra Tech, Inc.

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EXECUTIVE SUMMARY

Green Lake is an important recreational and aesthetic resource for Seattle residents and park visitors. Although the lake is heavily used, enjoyment of it has been diminished due to poor water quality related to intense blooms of cyanobacteria (blue-green algae), which have plagued the lake since at least 1916. Over the years, various techniques for reducing phosphorus concentrations have been used to reduce the amount of cyanobacteria in Green Lake. The most effective efforts to improve water quality and reduce cyanobacteria were lake-wide applications of aluminum sulfate (alum) in 1991 and 2004.

Alum treatments inactivate the internal cycling of inorganic and organic phosphorus. The alum is applied near the water surface, and it removes phosphorus from the water column as it flocculates and settles. It then covers the bottom sediments to further prevent the internal release of phosphorus from the sediments.

Although water quality goals for Green Lake have been met since the 2004 alum treatment, those goals are based on average summer measurements of total phosphorus (less than 25 micrograms per liter [µg/L]) and Secchi depth (water clarity greater than 2.5 meters [8.2 feet]). In recent years (2012 through 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.

The January 2015 Green Lake Phytoplankton Study (Herrera) documented effects of the 1991 and 2004 alum treatments on the amount and type of phytoplankton (algae and cyanobacteria) in the lake, and identified significant water quality degradation in recent years. The study provided Seattle Parks and Recreation with recommended next steps for controlling cyanobacteria and addressing additional lake needs. The recommendations included preparation and implementation of a plan to treat Green Lake with alum as soon as possible to control cyanobacteria and prevent lake closures.

This phosphorus management plan provides background information about the lake and detailed information on a proposed third alum treatment that is planned for late March 2016. This phosphorus management plan is being submitted to the Washington State Department of Ecology (Ecology) for an Aquatic Plant and Algae Management General Permit to perform the alum treatment.

Sediment phosphorus was recently analyzed to determine the amount of alum needed to inactivate sediment phosphorus in Green Lake and meet water quality goals in the future. In May 2015, sediment cores were collected at four locations, and eight depth intervals were analyzed for six different types of phosphorus down to 30 centimeters (cm). The data were compared to those collected in 1998 (between the 1991 and 2004 alum treatments) and in 2004 (6 months after the 2004 alum treatment). The analysis results show that the 2004 alum treatment substantially reduced concentrations of mobile phosphorus (consisting of labile and iron-bound phosphorus) in the upper 15 to 20 cm of sediment. When combined with the observed increase in aluminum-bound phosphorus, the results also show that mobile phosphorus present at 6 months after the 2004 alum treatment continued to bind with free

aluminum remaining in the sediment and extended inactivation effectiveness for at least 10 years.

Biogenic phosphorus is a portion of organic phosphorus that can be degraded to mobile phosphorus over time. It was not used to calculate the 2004 alum dose, but it is now included along with mobile phosphorus as standard procedure in determining the alum dose. The alum dose calculated for 2016 considered only the "active" fraction of biogenic phosphorus in the top 10 or 20 cm of sediment (depending on location), minus the "inactive" background fraction of lower concentrations below that depth. Background biogenic phosphorus averaged approximately 50 percent of the active biogenic phosphorus in the top 10 to 20 cm of sediment.

In addition, the ratio of aluminum added to phosphorus present was modified slightly from 10:1, which was used to calculate the 2004 alum dose, to 9:1. A 9:1 ratio was recently recommended by Danish scientists when using both mobile and biogenic phosphorus to determine the alum dose. In calculating the proposed 2016 alum dose for Green Lake, the ratio of 9:1 was applied to the upper 20 cm of mobile and active biogenic phosphorus throughout the entire lake to account for mobile phosphorus sources below 20 cm, which are likely present based on the observed formation of aluminum phosphorus below that depth following the 2004 alum treatment.

Using this sediment dose methodology and including a small amount of aluminum (0.4 mg/L) to inactivate 20 µg/L of total phosphorus in the water column, the alum dose proposed for 2016 is 8.2 milligrams per liter (mg/L as aluminum) on a lake-volume basis. The proposed alum dose is approximately one-third of the 23.0 mg/L dose applied in 2004 and is similar to the 8.6 mg/L dose applied in 1991. As done in 2004, liquid alum will be applied concurrently with liquid sodium aluminate at a ratio of 2:1 by volume to ensure that the water pH does not decrease below 6.0. Sodium aluminate has been shown to be an effective buffer at this ratio.

The 2016 alum treatment is planned to occur between March 21 and April 22, 2016, to avoid interference with a rowing regatta on March 19 and 20 and opening day of fishing on April 23, 2016. The treatment is expected to occur in 6 days within a 10-day period. The alum treatment is estimated to cost $460,855, which includes $122,520 for 81,680 gallons of aluminum sulfate; $147,024 for 40,840 gallons of sodium aluminate; $53,909 for material application (20 percent of the material costs); tax (9.6 percent); and contingency (30 percent). Engineering oversight and short-term water quality monitoring will be conducted before, during, and for up to 2 weeks after the treatment to ensure proper material application, prevent potential impacts to fish from low or high pH, and meet permit requirements. In addition, a public involvement plan is included to inform and educate park users and nearby residents of the proposed alum treatment.

The 2016 treatment is expected to meet water quality goals for at least 10 years, based on the long-term effect of the 2004 treatment and assuming external phosphorus inputs to the lake remain relatively low. Long-term water quality monitoring will be continued through the King County Volunteer Monitoring Program and the Washington State Toxic Algae Program to determine if the following water quality goals are met:

- Summer average total phosphorus concentration shall be less than 20 µg/L.
- Summer average Secchi depth (water clarity) shall exceed 2.5 meters (8.2 feet).
- The lake will not be closed to recreational uses due to toxic cyanobacteria.

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, which 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). 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.

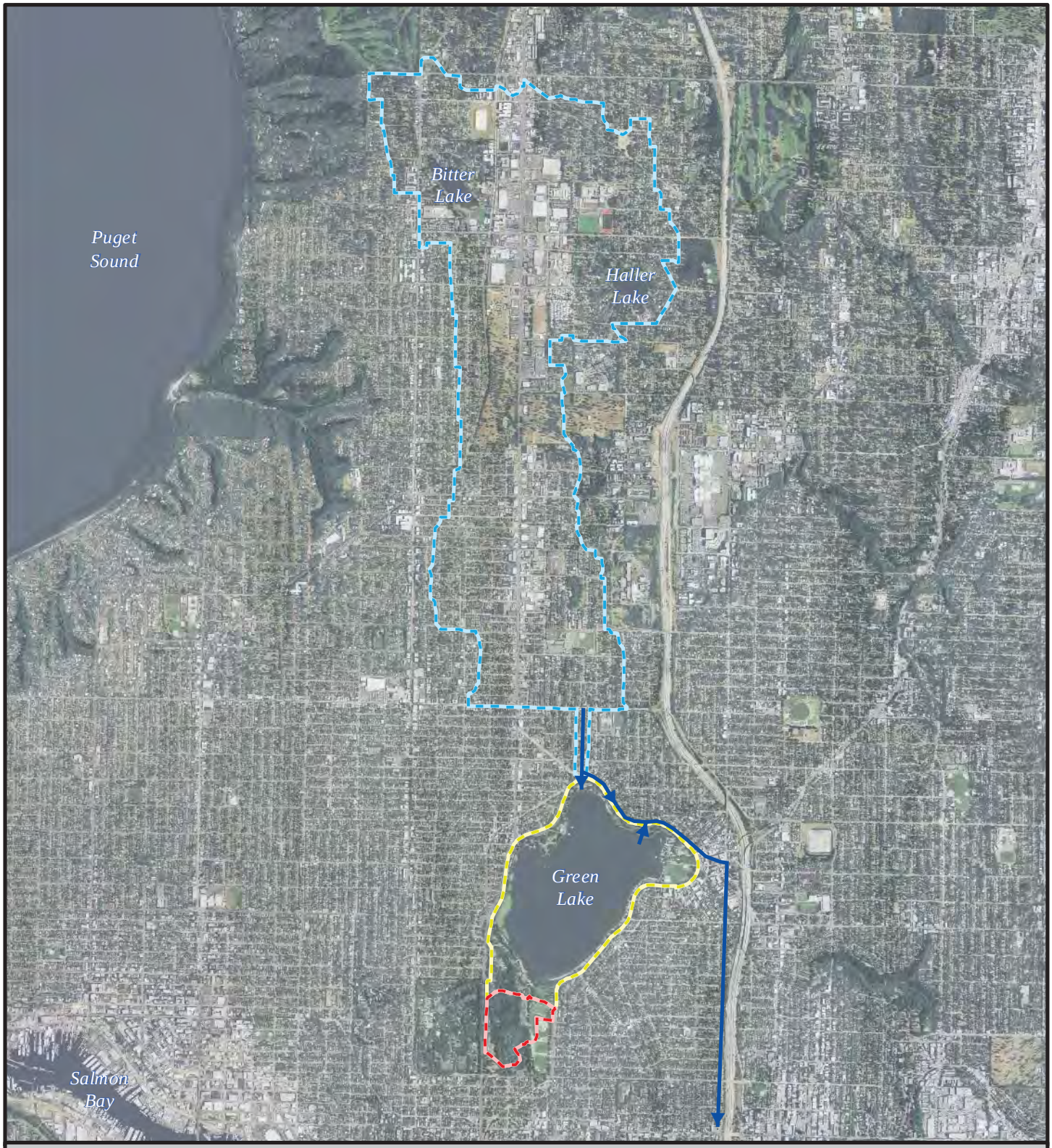
Although water quality goals have been met since the 2004 alum treatment, those goals are based on average lake conditions. During recent years (2012 through 2014), toxic cyanobacteria scums have occurred in isolated areas of the lake. High concentrations of microcystin detected in scum samples have 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.

The Green Lake Phytoplankton Study (Herrera 2015) recently documented effects of the 1991 and 2004 alum treatments on the amount and type of phytoplankton in the lake. The study evaluated nutrient and phytoplankton relationships and trends using data collected since 1959. Cyanotoxin data were analyzed from algae scum samples and beach water samples collected at the lake since 2007, and algae scum accumulation patterns were examined using observation data collected for the lake over the past 2 years. The study also documented current cyanobacteria monitoring protocols, public notification, and lake closure procedures used by Green Lake stakeholders. Finally, the study provided Seattle Parks and Recreation with recommendations on the next steps for controlling phytoplankton and addressing additional lake needs. Those recommendations included preparation and implementation of a plan to treat Green Lake with alum as soon as possible to control cyanobacteria and prevent lake closures.

The purpose of this phosphorus management plan is to provide background information about the lake and detailed information on a third alum treatment planned to occur in late March 2016. This plan is being submitted to the Washington State Department of Ecology (Ecology) for an Aquatic Plant and Algae Management General Permit, which addresses alum treatment restrictions in Table 4 and monitoring requirements in section S6.B (Ecology 2015). In accordance with the permit, this phosphorus management plan is being submitted in lieu of a discharge management plan.

This phosphorus management plan includes the following sections:

- Problem Statement
- Past Phosphorus Management Efforts
- Phosphorus Management Goals
- Watershed and Hydrology
- Lake Characteristics
- Beneficial and Recreational Uses
- Phosphorus Management Alternatives
- Alum Treatment Plan
- Water Quality Monitoring and Treatment Evaluation Plan
- Public Involvement Plan



Legend

- Densmore Basin
- Nearshore Basin
- Woodland Park Basin
- Densmore and Lake Drain

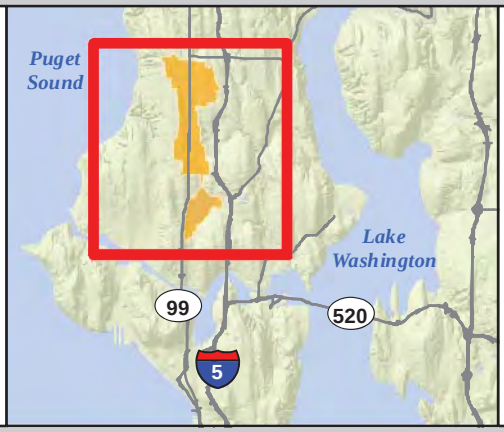


Figure 1.
Green Lake Watershed.

N

0 1,750 3,500 7,000 Feet

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USDA, Aerial (2013)

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2. PROBLEM STATEMENT

Water quality goals established in 1987 by the lake restoration program and updated in 1995 by the Phase IIC restoration project include:

- Summer mean total phosphorus concentration shall be less than 25 micrograms per liter (µg/L).
- Summer mean Secchi depth (measure of water clarity) shall be greater than 2.5 meters (8.2 feet).

As reported in Herrera (2015), the summer mean total phosphorus concentration in Green Lake has been significantly increasing since the 2004 alum treatment to a maximum of 19 µg/L in 2014, which meets the goal of less than 25 µg/L. In addition, the summer mean Secchi depth decreased since the 2004 alum treatment to a minimum value of 2.7 meters in 2014, which meets the goal of greater than 2.5 meters.

Although the total phosphorus and water clarity goals have been met for each of the past 11 years, the growth of cyanobacteria (blue-green algae) has resulted in closures of the lake to contact recreation (swimming) in the late summer of the past 3 years (2012 through 2014) because the state guideline of 6 µg/L for microcystin (a toxin produced by some cyanobacteria) has been exceeded in algae scum samples collected from shore. Because of ongoing summer toxic cyanobacteria blooms, Seattle Parks and Recreation proposes to treat the lake with alum. Alum works by inactivating the sediment phosphorus, thereby reducing internal phosphorus loading and the availability of phosphorus to cyanobacteria.

3. Past Phosphorus Management Efforts

Seattle Parks and Recreation, with grant funding from Ecology and the US Environmental Protection Agency (US EPA) completed a Phase I diagnostic feasibility study in 1983 (URS 1983). The study concluded that phosphorus was the growth-limiting nutrient for algae in the lake. The report of the results outlined recommendations for treating the problem of algal blooms, which included the application of alum to inactivate phosphorus. An environmental impact statement (EIS) was completed to assess the impacts of several management efforts to control lake phosphorus levels including dilution with the City of Seattle's (the City's) drinking water supply, aeration, installation of test wells (for lake dilution), and other measures considered for phosphorus control (KCM 1995).

With additional grant monies awarded to the City from Ecology and US EPA, a Phase IIA plan was completed in 1987. The plan's recommendations included diluting the lake with water from Lake Washington or ground water, and applying alum to control phosphorus released from the bottom sediments (KCM 1995). The City received Phase IIB grant money to complete an EIS for the Green Lake Water Quality Improvement Project, which assessed possible pipeline routes from Lake Washington to accomplish the dilution (URS 1990a). However, Ecology would not issue a permit for this type of consumptive water use; therefore, this management option was abandoned. The EIS also analyzed other possible solutions including dilution of the lake with treated lake water provided by a small onsite treatment plant and alum treatment of the lake (URS 1990a).

In late 1990, the City adopted a program to improve the quality of Green Lake and included the following measures for controlling both the internal and external sources of phosphorus: alum treatment, stormwater management, milfoil harvesting, lake dilution with City water, goose management, water quality monitoring, and public education (KCM 1995). The program adopted by the city council became known as the Phase IIC water quality restoration program. The Phase IIC restoration project completion report concluded that the phosphorus goal should be reduced from a summer mean concentration of less than 30 µg/L to less than 25 µg/L (whole-lake average) (KCM 1995), which has since been adopted. The goal of a summer mean Secchi depth of greater than 2.5 meters has remained unchanged since the water quality improvement plan was adopted in 1990.

Additional phosphorus management measures have been implemented since the Phase IIC water quality restoration program. They include fish stocking to control common carp and Eurasian watermilfoil, drainage improvements to the Densmore basin, upgrades to past stormwater control improvements to the Nearshore basin, a second alum treatment in 2004, water quality monitoring, and public education. These phosphorus management efforts, which are described in the following subsections, either targeted significant sources of phosphorus or conditions that contribute to phosphorus loadings.

3.1. Alum Treatment

A whole-lake alum treatment of Green Lake was performed in 1991 for the Phase IIC restoration program and again in 2004 due to degraded water quality conditions.

In October 1991, Green Lake was treated with 181 tons (67,500 gallons) of liquid alum and 76.5 tons (24,200 gallons) of liquid sodium aluminate to obtain a lake dose of 8.6 milligrams of aluminum per liter of water (mg Al/L) (KCM 1995). Sodium aluminate was added during the treatment as a buffering agent, which maintained the lake's pH above 6.7 and its alkalinity above 27 milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$). One day after the lake's alum treatment, the total phosphorus concentration decreased from 40 to 14 µg/L and water clarity (Secchi depth) increased from 2.0 to 6.1 meters (KCM 1995). Summer mean total phosphorus concentrations after treatment were 20 µg/L in 1992, 26 µg/L in 1993, and 18 µg/L in 1994. The alum treatment was deemed successful at controlling sediment-bound phosphorus for a period of at least 3 years as measured by post-application water quality monitoring. However, by the late 1990s summer toxic bacteria blooms had returned, resulting in lake closures in 1999, 2002, and 2003.

In April to March 2004, Green Lake was treated with 454 tons (169,160 gallons) of liquid alum and 261 tons (82,670 gallons) of liquid sodium aluminate to obtain a lake dose of 23.0 mg Al/L (Herrera 2004). Sodium aluminate was added during the treatment as a buffering agent, which maintained the lake's pH above 6.7 and its alkalinity above 17 mg/L as $CaCO_3$. Two days after completion of the lake's alum treatment, the total phosphorus concentration dropped from 16 to 5 µg/L and water clarity (Secchi depth) increased from 2.5 to 5.4 meters. At 2 weeks after treatment, the phosphorus concentration increased to 14 µg/L and water clarity (Secchi depth) decreased to 2.9 meters. Summer mean total phosphorus concentrations ranged from 11 to 16 µg/L for each of the 10 years following the treatment, and then increased to 19 µg/L in 2014 (Herrera 2015). As predicted, the alum treatment met water quality goals by controlling sediment-bound phosphorus and for over 10 years.

The 2004 alum treatment was predicted to reduce cyanobacteria blooms for 8 to 12 years. Toxic cyanobacteria scums have occurred in isolated areas of the lake during recent years (2012 through 2014) that resulted in closure of the lake to direct contact recreational use (swimming) for substantial periods (Herrera 2015).

3.2. Goose Management

If a large population exists, Canada geese can be a significant contributor of phosphorus to the lake. Because their diet consists mostly of aquatic plants, grass, and other vegetation, phosphorus constitutes a large component of goose excrement. Furthermore, the geese are rather productive in terms of waste generation. Because the vegetation they eat is mostly from the lake and surrounding area, this source of phosphorus is considered internal. However, through digestion, the geese produce a soluble form of phosphorus, which contributes to the lake's total phosphorus concentration (KCM 1995).

Instead of migrating seasonally out of the area, Canada geese have become year-round residents in and near the lake. The grassy areas near the lakeshore attract the birds, which

have found the habitat ideal for feeding. Furthermore, the birds are nesting in the area and are raising their offspring in and near the lake.

To address the increasing number of resident geese at the lake, the City began a Goose Management Program in 1987. The program initially focused on assessing the problem and conducting geese population studies. As a first step, approximately 100 Canada geese were relocated to eastern Washington and northern Idaho from 1990 through 1995 to help reduce the resident population (Stoops 2003a).

In 1993, an egg-addling program was started by the US Department of Agriculture (USDA) to control the number of offspring generated by the resident goose population (Stoops 2003a). In 2003, the program prevented approximately 1,500 eggs per year from hatching in the Puget Sound area and was successful at reducing the number of hatchlings, which potentially contributed to the resident population. No nests were found at Green Lake during spring 2003 (Linnell 2003).

In 1997, the USDA began a capture, removal, and euthanasia program, which removed up to 2,500 geese per year from the Lake Washington basin (Stoops 2003a). Although site-specific data are not available, Green Lake was not a major source of geese for this management program in the early 2000s.

In 2004, the City stopped participating in the lethal goose control program. Also, no egg addling or other non-lethal methods of control have are being implemented at Green Lake. According to the USDA, geese populations at Green Lake have increased in recent years and are expected to increase further because geese in controlled areas use the lake as a safe haven, feeding by park users is not actively discouraged or prevented, and there is an abundance of grass that is particularly attractive because it is cut short (Loucks 2015). Very few (approximately 2 percent) of the geese present on Green Lake actually nest on its shores (Loucks 2015). Lake monitors have observed only two or three geese families on the lake in recent years and that most geese visit the lake during the evening (Fleming 2015). Lake monitors have not noticed an increase in geese activity since the 2004 ban on lethal goose control.

3.3. Milfoil Harvesting

In 1981, when the Phase I diagnostic feasibility study began, a limited occurrence of Eurasian watermilfoil (*Myriophyllum spicatum*) was documented in the lake (Stoops 1996). During the next several years as the milfoil became more abundant, the City mounted hand-pulling efforts to remove the milfoil with the aid of volunteers. However, by 1991 the milfoil growth had covered most of the lake in areas where the water depth was greater than 1.5 meters feet and less than 5.5 meters (Stoops 1996).

The City purchased an aquatic plant harvester in 1992 to control the abundant growth of Eurasian watermilfoil, which at one time covered 75 to 90 percent of the lake between depths of 1.5 and 5.5 meters (KCM 1995). The cutting and removal of Eurasian watermilfoil began in late summer 1992 (KCM 1995). The biomass of the milfoil removed (via harvester) was 483 grams per square meter (g/m^2) in 1991, 87 g/m^2 in 1992, 185 g/m^2 in 1993, 130 g/m^2 in 1994, and 58 g/m^2 in 1995 (Seattle 2001). The amount of milfoil removed from the lake decreased from a high of 1,200 tons in 1992 to only 30 tons in 1995 (Seattle 2001). In addition

to milfoil removal with the harvester, removal of plants that had accumulated at the shoreline occurred in 1992 and 1993 (Stoops 2003b).

From 1995 to 2002, small amounts of milfoil were removed from the lake (via harvester), ranging from approximately 15 to 30 tons/year (Stoops 2003b). Harvester operations declined only 5 to 10 days per year, mostly in the rowing lanes before regattas or other boating events. No milfoil harvesting has been conducted since 2002.

3.4. Stormwater Management

As part of the 1990 lake restoration program, measures were implemented to reduce the amount of stormwater entering the lake. These projects included diverting stormwater runoff in mid-1993 from the Densmore basin to the City's Metro University Regulator storm drain and away from Green Lake (KCM 1995). The Densmore basin consists of 1,698 acres, representing approximately 91 percent of the Green Lake watershed (see Figure 1). The Densmore diversion reduced the stormwater phosphorus loadings by 68 kilograms (kg) annually (86 percent) within the basin (KCM 1995).

Lake phosphorus loadings were further reduced by the addition of stormwater treatment facilities to treat stormwater runoff before it enters the lake from a portion of Green Lake Way and the parking lots at the southwest end of Green Lake Park (Nearshore basin). The stormwater treatment facilities included oil/water separators and biofiltration vaults consisting of either gravel or crushed glass. North of Green Lake, some stormwater was directed to the Licton Springs system for water quality treatment, which includes a wetland and small pond. Based on the results of water quality monitoring associated with the restoration program, these stormwater controls resulted in a reduction in phosphorus loading to the lake of 89 kg, or 55 percent, per year (KCM 1995).

In 2003, Seattle Public Utilities (SPU) conducted an investigation of stormwater drainage and water quality in the Densmore basin. SPU evaluated alternatives for reducing the amount of flooding within the basin, and for improving water quality within the basin through stormwater treatment and pollution prevention. Densmore basin drainage improvement projects include a wet pond located at Midvale Avenue North and North 107th Street to detain and treat stormwater runoff from approximately 40 percent of a 1,100-acre basin (completed in 2013), and a large detention extending south from Licton Springs Park to reduce peak flows in the Densmore drain (to be completed in early 2016) (S. Kelleher 2015). In addition, the Seattle Department of Transportation constructed drainage and water quality swales along Linden Avenue North from North 145th Street to North 130th Street (completed in 2012). Future drainage improvement projects planned to reduce peak flows and improve stormwater quality include a new police precinct at North 130th Street and Aurora Avenue North, and the remodeling of Wilson Pacific School at North 90th Street. These and other development projects required to meet the Seattle Drainage Code are estimated to reduce phosphorus concentrations in stormwater and reduce phosphorus loadings to Green Lake.

In 2004, Seattle Parks and Recreation conducted a stormwater investigation of Woodland Park at the south end of the lake in the Nearshore basin (Herrera 2005a). This investigation identified sources of phosphorus and fecal coliform, inspected and evaluated existing stormwater facilities, and evaluated treatment options for removal of phosphorus in

stormwater. A large wood chip pile on an asphalt surface was identified as a major source of phosphorus and fecal coliform bacteria control, and that source was removed. Other stormwater improvements implemented by the City include removal of sediment from a stormwater vault draining the dirt playfields, construction of a French (infiltration) drain at the tennis court parking lot, and retrofitting catch basins with oil traps while paving two gravel parking lots.

In 2009, the two dirt playfields in Lower Woodland Park were replaced with synthetic turf. Water quality testing in 2010 showed that the replacement significantly reduced total phosphorus concentrations in stormwater runoff from the park (Herrera 2010). For example, the median total phosphorus concentration in eight stormwater samples from a synthetic turf field (Field #7) was only 32 µg/L compared to 148 µg/L in drainage from upstream grass and paved surfaces. Much higher median total phosphorus concentrations were observed downstream of the playfields in 2004 (688 µg/L before wood chip pile removal) and in 1992 to 1995 (502 µg/L).

Other drainage improvements to Woodland Park performed in 2009 by Seattle Parks and Recreation include the installation of a French drain along the tennis court parking lot, and paving of two gravel/dirt parking lots north of the tennis courts.

3.5. Lake Dilution with City Water

Prior to the 1991 alum treatment, water from the City's drinking water supply was directed to Green Lake to dilute the lake water in an attempt to lower the phosphorus levels. This water was discharged from the City's outfalls located near the shore at the lake's surface. From 1976 through 1991, the average annual discharge rate ranged from 1.9 to 6.1 million gallons per day (mgd), average monthly rates ranged from 1.7 mgd in December to 5.2 mgd in May, and the overall average rate was 3.12 mgd (Capron 2003). This average discharge rate is equivalent to an annual volume of 4.32 million cubic meters, or 105 percent, of the lake volume. Intentional dilution of Green Lake with drinking water has not occurred since the 1992 drought (KCM 1995; Capron 2003).

Since the 1991 alum treatment, drinking water has been discharged to Green Lake only when Maple Leaf reservoir or Roosevelt reservoir (formerly known as Green Lake reservoir) required flushing to reduce bacteria concentrations, or when they were drained prior to cleaning (Capron 2003). From 1992 through 1995, the average discharge rate was 0.5 mgd, which is equivalent to 17 percent of the lake volume per year. Due to an inoperable flow meter, discharge monitoring was discontinued in October 1996 (Capron 2003). Average annual discharge rates since 1996 were estimated in 2003 to be similar to the rate of 0.5 mgd for the period from 1992to 1995.

The City installed flow meters and began estimating discharge from the reservoirs in 2007 (Capron 2015). The results show similar discharge rates of approximately 1.1 mgd for 2007 and 2008 when each reservoir was cleaned only once (Maple Leaf in April and Roosevelt in June), but cleaning accounted for less than 30 percent of the total reservoir discharge. The remaining discharge was attributed to overflow of surface waters (and debris) when the reservoirs were full at various times throughout the year.

Reservoir discharge declined in 2009 to 0.6 mgd and continued to decline to a negligible amount of 0.01 mgd in 2014 due to changes in reservoir operations. Maple Leaf Reservoir was taken out of service in July 2009 and subsequently covered, which eliminated overflow and reduced the cleaning frequency from 1 to 2 times per year to once every 3 to 5 years. Roosevelt Reservoir was taken out of service in April 2013. It is not being cleaned and only drains rainwater while the City decides whether to repair or remove the reservoir. Maple Leaf Reservoir required repair of a design flaw that discharged half the reservoir volume in May 2015 and the other half in October 2015, resulting in a total discharge rate of 0.08 mgd for 2015. Thus, Green Lake is currently only diluted with minor amounts of City water on rare cleaning or service events for Maple Leaf Reservoir.

3.6. Fisheries Management

Green Lake fisheries were not managed to control phosphorus until after the Phase IIC restoration program.

To benefit sport fishermen with the possibility of reducing the common carp population, the Washington Department of Fish and Wildlife (WDFW) stocked Green Lake in November 2000 with 150 sterile tiger musky, which is a cross between muskellunge (*Esox masquinongy*) and northern pike (*Esox lucius*) (Herrera 2003). The tiger musky were 18 inches long and expected to grow to 36 inches in 1 year. These predatory fish consume carp and other fish, and provide unusual opportunities for local sport fishermen. Fish surveys conducted by WDFW since the stocking indicated that common carp continued to dominate (75 percent) the fish biomass in the lake, but tiger musky represented the second largest fish population (18 percent of biomass).

In an effort to control Eurasian watermilfoil, Seattle Parks and Recreation stocked Green Lake in August 2001 with 777 triploid (sterile) grass carp. The potential for these grass carp to consume and control Eurasian watermilfoil has not been evaluated by the City or WDFW.

From May 2004 to June 2005, a comprehensive carp survey and removal program was conducted for Seattle Parks and Recreation in Green Lake by WDFW (Herrera 2005b). The capture methods used to remove carp included the use of electrofishing, gillnetting, and fish traps. Using tagging and recapture data collected during the initial phase of the program, carp density was estimated at 120.6 kilograms per hectare (kg/ha) before the removal activities began (Bolding 2005). Upon completion of the carp removal program in June 2005, carp density in the lake was estimated to have been reduced to 74.2 kg/ha. It was estimated that the removal program reduced the carp population by 38 percent, and electroshocking was determined to be the most effective removal method.

A carp bioturbation model was developed to estimate the amount of sediment phosphorus entrained in the water column by foraging carp and the effects of carp control on phosphorus in the lake (Herrera 2005b). It was concluded that carp bioturbation represents a relatively small source of phosphorus and algae growth in Green Lake compared to the total phosphorus loading from other internal and external sources.

3.7. Public Education

Before the 1991 lake alum treatment, the City held an information fair and installed two kiosks to help educate the public about the lake alum treatment and other ongoing lake restoration efforts. The City also distributed written information throughout the watershed and held public meetings to explain the alum treatment and the ongoing restoration program, and to further increase public awareness about urban watershed management issues (KCM 1995). A video was developed at the conclusion of the Phase II project that described the lake restoration program and water quality issues related to Green Lake.

In March 2003, the City met with the Green Lake Community Council to discuss water quality, and the Lake Restoration Committee was formed (Herrera 2003). This group of volunteer citizens submitted a letter to the City Council and Parks Superintendent urging an emergency request of funds for another alum treatment. The committee gathered signatures for a petition that was sent to the mayor and parks superintendent, and eventually formed the Friends of Green Lake.

A public involvement plan was prepared for the 2004 alum treatment (Herrera 2003) that included construction of a project sign, distribution of flyers to all households within a 1/4-mile radius of Green Lake Park, meetings with the general public and specific lake groups to discuss the alum treatment plans, posting of additional signs immediately prior to the alum application, and additional public and group meetings following the treatment to discuss early water quality monitoring results. Seattle Parks and Recreation prepared annual water quality monitoring reports for 10 years after the treatment and shared those findings with the Friends of Green Lake.

The City is using a variety of educational programs to engage the citizens of Seattle in source control and stormwater management (Seattle 2015). These programs provide educational materials, instruction, and designs that citizens can use at their home, business, or in the community at large. The City uses community–based, social marketing approaches to evaluate the audiences' understanding of how their actions can have negative impacts on stormwater and how they can take an active role in the improvement of stormwater quality. The evaluations are used to direct education and outreach programs most effectively and to evaluate changes in the audiences' adoption of the target behavior. City programs protecting water quality through public education include:

- Protect Our Waters Community and Youth Programs
- Doo Diligence – Pet Waste Program
- Auto Maintenance Program
- Natural Soil Building
- Seattle reLeaf
- Spill Kits
- Car Wash Program
- Stormwater Outreach for Regional Municipalities and Puget Sound Starts Here

- Water Quality Hotline
- Green Gardening Program
- Seattle Green Business Program
- RainWise
- Stormwater Construction Controls and On-The-Job Training
- Natural Landscaping Professional Development
- Business Inspection Program
- Stormwater Facility Program

4. PHOSPHORUS MANAGEMENT GOALS

Although water quality goals have been met since the 2004 alum treatment, those goals are based on average lake conditions. During recent years (2012 through 2014), toxic cyanobacteria scums have occurred in isolated areas of Green 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.

Seattle Parks and Recreation proposes to treat the lake with alum again in the spring of 2016 to reduce cyanobacteria blooms by lowering the lake phosphorus levels. It is expected that the treatment will prevent future lake closures due to outbreaks of toxic cyanobacteria, maximizing recreational and aesthetic uses of the lake for the next 10 years.

Water quality goals established in 1987 by the lake restoration program and updated in 1995 by the Phase IIC restoration project include values for summer mean total phosphorus and Secchi depth values. To align with the toxic cyanobacteria bloom prevention goal, the phosphorus goal is reduced from 25 to 20 µg/L and the Secchi depth (water clarity) remains unchanged at 2.5 meters. In addition, a new water quality goal is being established to address lake closures resulting from blooms of toxic cyanobacteria. Thus, water quality goals for the 2016 alum treatment include the following three conditions over the next 10 years (through 2025):

- Summer mean total phosphorus concentration shall be less than 20 micrograms per liter (µg/L).
- Summer mean Secchi depth (water clarity) shall be greater than 2.5 meters (8.2 feet).
- No closures of lake to recreational uses due to toxic cyanobacteria.

5. Watershed and Hydrology

Green Lake is in King County, Washington, in an area just north of downtown Seattle and Lake Union. Green Lake is in Water Resource Inventory Area (WRIA) 8, which includes the Cedar-Sammamish watershed and Lake Washington, Lake Union, Lake Sammamish, and most of Seattle. The Green Lake watershed consists of 4,270 acres (1,728 hectares [ha]) and encompasses three major basins, which are shown in Figure 1. The basins include the Densmore basin with an area of 1,698 acres (687 ha), the Woodland Park basin with an area of 72 acres (29 ha), and the Nearshore basin with an area of 103 acres (42 ha). The Densmore basin only drains to the lake during large storm events (estimated at over 0.75 inch) when stormwater bypasses typical drainage to Lake Union by jumping over a weir and into a large outfall pipe. A fourth basin, the Phinney Ridge basin, contributes base flow of ground water to the lake but does not contribute measurable amounts of stormwater runoff (Herrera 1995). A summary of the average water budget from 1992 through 1994 is presented in Table 1.

Table 1. Green Lake Water Budget, 1992-1994 Average.

	Volume (m^3)	Percent
Inflows		
Precipitation	837,052	35%
Nearshore Runoff	78,840	3%
Densmore Overflow[a]	127,378	5%
Woodland Runoff	63,568	3%
Woodland Base Flow	96,111	4%
Phinney Base Flow	163,083	7%
City Water[b]	690,157	29%
Groundwater (Net Gain)	306,719	13%
Total Inflow	**2,362,908**	**100%**
Outflows		
Outlets (total)	1,474,042	67%
Evaporation	723,624	33%
Total Outflow	**2,197,666**	**100%**
Lake Storage (Net Gain)	165,242	--

Source: Herrera 1995 in KCM 1995

m^3 = cubic meters

[a] Reduced to 58,425 (3 percent) in 1994 due to raising of the Densmore overflow weir.

[b] Reduced to 361,051 m^3 (16 percent) in 1994 due to modified City water management.

Land use in the Green Lake watershed consists largely of single-family and multifamily residences with small commercial developments. However, land use activities vary greatly between the major basins. Most of the development in the Densmore basin is characterized by single-family residential use. However, small areas of the basin are developed for

commercial use, such as the Aurora Avenue North traffic corridor (Herrera 1995). In contrast, the Woodland Park and Nearshore basins are largely undeveloped; approximately 87 percent of the two basins is covered with brush or grass, with pavement covering the remaining 13 percent (Herrera 1995). The immediate surroundings of the lake include park grounds, parking lots of various sizes, small buildings, and residential streets that encircle the lake (KCM 1995).

No natural streams flow into Green Lake (KCM 1995). A small wetland north of Green Lake, known as the Licton Springs wetland, discharges into a small detention pond before ultimately discharging into the Densmore basin drainage system and into Green Lake during large storm events.

Stormwater runoff from the Densmore, Woodland Park, and Nearshore basins contributed a relatively small volume of water to the lake in the 1992 to 1994 Phase IIC study, totaling an average of only 11 percent of the total lake inflow (see Table 1). Although the Densmore basin is much larger than the other basins, runoff from the Densmore basin represented only 47 percent of the total stormwater inflow because most of the runoff from the Densmore basin is diverted away from Green Lake. Before 1993, base flow and most of the runoff from the Densmore basin drained to Seattle's combined sewer system. Upon completion of King County's University Regulator project in 1993, this drainage was diverted from the sewer system to Lake Union, and stormwater discharge to Green Lake was reduced by the construction of a new diversion structure in the Densmore drain. (Inputs of phosphorus from the drainage basins are summarized in the *Lake Characteristics* section.)

Direct precipitation is the major source of inflow to Green Lake. Annual inflows of precipitation were estimated at 35 percent of the total water input from 1992 to 1994, accounting for the largest source of inflow during that time period (see Table 1).

Historically, domestic freshwater inputs from the Maple Leaf drinking water reservoir and the Roosevelt drinking water reservoir (formerly known as the Green Lake reservoir) provided another major source of inflow to Green Lake. Drinking water input accounted for 62 percent of the total inflow in 1981 (KCM 1995) and was approximately three times higher in 1976 than in the 1981 diagnostic study year (Capron 2003). The average drinking water input from 1992 to 1994 was estimated to have reduced to 29 percent of the total lake inflow (see Table 1), but had reduced to only 16 percent by 1994 due to changes in City water management policy (Herrera 1995). Average annual discharge rates remained relatively unchanged until 2009 when they began decreasing to a negligible amount in 2014 due to changes in reservoir operations from the covering of the Maple Leaf reservoir and terminating use of the Roosevelt reservoir (Capron 2015).

The net input of groundwater was estimated at 13 percent for 1992 to 1994 based on differences in estimates of surface inputs and outputs (see Table 1). The total input and output of indirect groundwater sources is unknown. Direct inputs of groundwater as base flow from the Woodland Park and Phinney drains constituted 11 percent of the total lake inflow. Thus, groundwater contributed at least 24 percent of the total inflow to Green Lake in 1992 to 1994. Groundwater input to Green Lake may have changed recently due to large buildings immediately northeast of the lake that are pumping groundwater into the sewer to prevent basement flooding (Fleming 2015).

6. Lake Characteristics

Green Lake covers an area of 259 acres (104 ha) and is considered to be a fairly shallow lake, with a mean depth of 3.9 meters and a maximum depth of 9.1 meters. The deepest area in Green Lake is located near the northeastern shore of the lake (Figure 2). The volume of Green Lake is 4.12 million cubic meters (m^3). A variety of water sources discharge into Green Lake, greatly influencing the flushing rate and residence time of the water. The estimated mean residence time of water in Green Lake ranged from 2.6 years in 1994 to 5.0 years in 1992 (KCM 1995).

6.1. Water Quality

Water quality data were recently compiled and evaluated by Herrera (2015) for the following three summer study periods and associated years of data:

- **Pre 1991 Alum Treatment:** 1959, 1981, 1989, and 1990
- **Post 1991 Alum Treatment:** 1992 through 1995
- **Post 2004 Alum Treatment:** 2004 through 2014

The data are presented in Appendix A. Summer mean values from May through October are presented in Table A1. Summer means were computed separately for water quality samples collected by King County and Seattle Parks and Recreation during the post-2004 alum treatment period. As shown in Table A1, summer means from the King County and Seattle Parks and Recreation 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.

Water quality data are presented as box plots in Figures A1 through A7 showing annual and monthly trends among the three study periods. Figure A8 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.

6.1.1. Water Temperature

Water temperature exhibited a wide range during each summer that was similar among all years (see Figure A1). 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).

Legend

- 2015 sediment station
- 2004 sediment station
- Water quality 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 Sampling Stations.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

K:\Projects\Y2013\13-05709-001\Project\monitoring_stations_2015.mxd (11/9/2015)

6.1.2. 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 (Herrera 2003), compared to a common threshold of less than 1.9 meters for eutrophic lakes. This goal was established in 1991 and is compared to all study years in Figure A2.

The Secchi depth goal was met in every study year except 1959 and 2003 when the summer mean Secchi depth was 2.0 and 1.9 meters, respectively (see Figure A2). (Note: Secchi depth data for 2003 are not shown in Figure A2 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 meters in May to a minimum of approximately 2 meters in October in the pre-1991 and post-1991 alum treatment years, but only decreased from a maximum of 4 meters in May to a minimum of 3 meters 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.

6.1.3. 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) (US EPA 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 A3). 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 A8).

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 A3). The variance in chlorophyll was much lower following the 1991 alum treatment and even lower following the 2004 alum treatment.

6.1.4. 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 A4.

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 A4). 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 A8).

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 A4). The seasonal variance in total phosphorus was much lower following the 1991 and 2004 alum treatments.

6.1.5. 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 A1. 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).

6.1.6. Total Nitrogen

Total nitrogen is the sum of organic nitrogen and dissolved inorganic nitrogen, which is composed 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 A5).

However, total nitrogen has increased each year since 2010 and has exhibited a significant increasing trend during the post-2004 alum treatment period when the summer mean value increased from 210 µg/L in 2005 to 387 µg/L in 2014 (p=0.01, see Figure A8).

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 A5). Similar to total phosphorus, the seasonal variance in total nitrogen was much lower following the 1991 and 2004 alum treatments.

6.1.7. 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. Summer mean nitrate nitrogen was high in 1959 (107 µg/L), but it was unusually low in 1981 (12 µg/L), moderate during the post-1991 alum treatment years (15–27 µg/L), and not detected during the post-2004 treatment years when detection limits ranged from 5 to 20 µg/L (see Table A1).

6.1.8. Ammonia Nitrogen

Ammonia nitrogen is another form of dissolved inorganic nitrogen readily used by phytoplankton and other microbes in lakes. 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 (see Table A1). 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.

6.1.9. 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, the study authors 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 A6) 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 A6). 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. Thee total N:P 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 A3 and A6).

The recent decrease in total N:P ratio was because total phosphorus increased proportionately more than total nitrogen between 2012 and 2014 (see Figures A4 and A5). 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 A8).

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 A6).

6.1.10. 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 it was lowest during the post-2004 alum treatment period (ratio range of 5 to 8) with the exception of one high value for 2014 (ratio of 35) (see Figure A7). 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 dissolved 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 A8).

Monthly mean total N:P typically did not exhibit a seasonal pattern for any period (see Figure A7).

6.2. Phosphorus Loading

The source of the elevated phosphorus concentrations and the associated blooms of cyanobacteria have been linked to both external loading and internal cycling of phosphorus. Numerous external sources have contributed to elevated phosphorus concentrations in Green Lake: surface runoff from the surrounding watershed, City water, direct precipitation, ground water inflow, and several additional sources. As shown by the annual phosphorus budgets in 1992 through 1994 (Table 2), efforts to reduce phosphorus loading from the lake drainage basins were successful during the Phase IIC restoration project, especially in the Densmore basin. However, it is also evident that other input sources, such as waterfowl and aquatic macrophytes, continued to contribute substantial amounts of phosphorus to Green Lake in 1992 through 1994.

Table 2. Comparison of Annual Phosphorus Budgets for Green Lake from 1981 to 1994 with Projected Changes to 2015.

	Total Phosphorus (kilograms)				Projected Change From 1994 to 2015
	1981	**1992**	**1993**	**1994**	
Input Source					
Densmore basin	45	79	41	11	None
Woodland Park basin	30	55	42	39	Decrease due to source control
Nearshore basin	89	21	19	16	None
Phinney basin	11	6	6	6	None
City water	39	9	8	4	Decrease due to reservoir changes
Direct precipitation	21	19	19	20	None
Ground water	NA	10	48	36	Unknown
Waterfowl (new) [a]	NA	16	16	17	None
Waterfowl (transformed) [b]	NA	144	143	154	Decrease due to less macrophytes
Macrophyte	NA	205	283	197	Decrease due to less macrophytes
Vertical migration	NA	33	4	1	None
Internal	3.5	0	0	0	None
Total	**235**	**597**	**629**	**501**	**Decrease**
Output					
Outlet	178	13	43	23	Decrease due to less phosphorus in water
Sedimentation	NA	478	613	478	Decrease due to less phosphorus in water
Ground water	NA	29	14	19	None
Total	**178**	**520**	**670**	**520**	**Decrease**
Lake Storage Change	61	77	–40	–20	None

Source: KCM 1995

NA = not available

[a] Bird dropping-related phosphorus derived from food sources external to Green Lake (e.g., bread and shoreline grasses).

[b] Bird dropping-related phosphorus derived from food sources within the lake (e.g., macrophytes).

Studies have indicated that internal cycling and loading of phosphorus is largely responsible for the intense blooms of cyanobacteria. In 1981, Bolstridge (1982) and Perkins (1983) found that 88 percent of the phosphorus budget during the summer was from internal sources, with lake sediments being the principal source (KCM 1995). Other estimates approximate the internal loading rates at 60 to 70 percent (KCM 1995). Several factors play a role in the internal cycling of phosphorus in Green Lake. A source of internal cycling lies in the life cycle of cyanobacteria; they take up phosphorus from lake sediments before maturing and migrating upward into the water column. The movement of the sediment into the upper portions of the water column has been documented to contribute to significant increases of phosphorus in the lake (KCM 1995). In addition, periodic depletion of dissolved oxygen in the hypolimnion can promote increased phosphorus release from sediments into the water column (KCM 1995), which is referred to as internal loading in Table 2, and has become a negligible source since the 1991 and 2004 alum treatments inactivated sediment phosphorus.

Phosphorus is also released through aquatic plant (macrophyte) senescence and decay, which had been exacerbated by the extremely high biomass accumulations generated by Eurasian watermilfoil in Green Lake in 1992 through 1994 (Table 2). Macrophytes were also estimated to have contributed substantial amounts of phosphorus to the lake from waterfowl foraging, which transformed sediment phosphorus taken up by the plant roots to water phosphorus excreted by waterfowl from the consumed plants. However, the current coverage of Eurasian watermilfoil in Green Lake (see Figure 2) is much less than that measured at 85 percent of the lake area in 1992 through 1995 (KCM 1995). Thus, phosphorus input from macrophyte decay and waterfowl excretion are likely to be less than previous estimates. Finally, the abundance of common carp, although not quantified, is likely to enhance the cycling of phosphorus in the lake.

6.3. Phytoplankton

Phytoplankton data were recently compiled and evaluated by Herrera (2015) for the following three summer study periods and associated years of data:

- **Pre 1991 Alum Treatment:** 1959 and 1981
- **Post 1991 Alum Treatment:** 1992, 1993, and 1994
- **Post 2004 Alum Treatment:** 2008 and 2013

Phytoplankton data are presented in Appendix A as stacked bar charts in Figures A9 and A10, which show annual and monthly trends among the three study periods. Percent composition of phytoplankton groups and biovolume of cyanobacteria species are presented and discussed separately.

Correlation and principal component analyses were performed by Herrera (2015) to identify relationships between phytoplankton and water quality data. Those analyses clearly showed that total phytoplankton and cyanobacteria biomass are most correlated with the concentration of total phosphorus in the lake. While nutrient ratios suggested 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 (Herrera 2015).

6.3.1. Group Composition

Phytoplankton group composition was very similar in the 2 pre-1991 alum treatment years with data (1959 and 1981) (see Figure A9), 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 it 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 3 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 A9). 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 the 2004 treatment than the 1991 alum treatment, and total nitrogen and total N:P ratio were similar among the 4 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 A9). 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.

6.3.2. Cyanobacteria Biovolume

The summer mean total cyanobacteria biovolume varied greatly within and between the three study periods, ranging from a low of 0.04 cubic millimeters per liter (mm^3/L) in 2008 to a high of 5.8 mm^3/L in 1992 (see Figure A10). 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 9 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 those 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 2 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 obtained 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.

6.4. Zooplankton

During the Phase IIC study in 1992 and 1994, zooplankton biomass peaked in the winter or spring, and was dominated by cladocerans (water fleas including *Daphnia* spp., *Ceriodaphnia* sp., and *Bosmia longirostris*) (KCM 1995). Cyclopoid copepods were also most abundant in the winter and spring, and *Diacyclops bicuspidatus thomasi* was the dominant species. Calanoid copepods were most abundant in summer, and included *Diaptomus oregonensis* and *Epischura nevadensis* as the dominant species. Rotifers (*Keratella* and *Polyarthra*) and immature copepods were typically most numerous in the lake, but did not comprise a substantial portion of the zooplankton biomass due to their small size.

Zooplankton populations have not been studied since the Phase II study. Recent increases in trout stocking of the lake (see *Fisheries* section) may have affected the abundance of large zooplankton from increased predation and, as a result, reduced the amount of grazing pressure on phytoplankton.

6.5. Aquatic Plants

Surveys of Green Lake conducted in 1991 through 1994 indicated that Eurasian watermilfoil (*Myriophyllum spicatum*) was the dominant species among Green Lake's vascular plants (KCM 1995). Eurasian watermilfoil is native to Europe, Asia, and North Africa and also occurs in Greenland, but it is not native to the United States (WSNWCB 2005). Eurasian watermilfoil is classified as a nonnative noxious weed, legally defined by Washington's Noxious Weed Control Law (Revised Code of Washington, Chapter 17.10) as a highly destructive, competitive, or difficult plant to control once it becomes established (WSNWCB 2005). This perennial, submersed aquatic plant is characterized by feather-like leaves containing 12 to 16 leaflets on each leaf and often forms dense mats of vegetation just below the water surface (see photographs in Appendix A). It reproduces primarily by auto-fragmentation during the growing season. The plants naturally break apart into small pieces, and fragments are also produced by waves, currents, boating activities, and animal disturbances. Each fragment can root and form a new plant far from its source. In western Washington, Eurasian watermilfoil frequently overwinters and can maintain a substantial biomass entering into the following growing season (WSNWBC 2005).

In 1981, a limited occurrence of Eurasian watermilfoil was documented in Green Lake (Stoops 1996). During the next several years, as the Eurasian watermilfoil became more abundant in

the lake, Seattle Parks and Recreation mounted hand-pulling efforts to remove the Eurasian watermilfoil with the aid of volunteers. However, by 1991, the Eurasian watermilfoil had covered most of the lake in areas where the water depth was greater than 5 feet and less than 20 feet (Stoops 1996).

Surveys of Green Lake in 1994 showed that between 75 and 90 percent of the lake bottom was dominated by Eurasian watermilfoil in areas where the water depth was 1.5 to 5.5 meters (KCM 1995). Additional macrophyte species observed in the lake in 1992 through 1995 include the submersed species coontail (*Ceratophyllum demersum*) and emergent species such as cattails (*Typha latifolia*), rushes (*Juncus* sp. and *Scirpus* sp.), and yellow flag iris. (KCM 1995). Several dense beds of floating waterlilies (*Nuphar* sp. and *Nymphaea* sp.) have also been observed along the southwestern shoreline from 0.5 meter (1.5 feet from the shoreline) to a maximum depth of 2.5 meters (8.2 feet).

Between 1992 and 2000, Seattle Parks and Recreation conducted mechanical harvesting of aquatic plants to control the growth of Eurasian watermilfoil (Stoops 2005). Mechanical harvesting was suspended indefinitely in 2000 because plant height and density had both been reduced to low levels. In August 2001, Green Lake was stocked with 777 triploid (sterile) grass carp in an effort to provide long-term control the amount of Eurasian watermilfoil in the lake (Herrera 2003). WDFW has analyzed grass carp stocking rates that provide effective aquatic plant control in a number of lakes in western Washington. The median stocking rate for lakes where effective control occurred was 24 fish per vegetated acre (Bonar et al. 1999). Assuming 75 percent of the lake was vegetated, Green Lake was stocked with an average of only approximately four fish per vegetated acre. Fish surveys of the lake in 2005 indicate that healthy grass carp were still present in the lake and had grown (e.g., median length increased from approximately 32 centimeters [cm] in 2002 to 66 cm in 2005) (Bolding 2005). It is not known the degree of control provided by these fish, but, as milfoil is the only significant food source in the lake for grass carp, the carp's ongoing presence and growth indicate at least some measure of long-term control.

During the summers of 1999, 2002, and 2003, blooms of toxic blue-green algae prompted the closure of the lake to all contact recreation. Based on qualitative observations between 1999 and 2003, the amount of Eurasian watermilfoil and other submersed aquatic plants appeared to be severely suppressed. A possible explanation for the reduced plant biomass during that period is that the reduced water clarity, caused by the intense algal blooms, restricted the penetration of light through the water column, thereby reducing the growth rate of Eurasian watermilfoil. Likewise, the improved water quality resulting from the 2004 alum treatment would have eliminated this suppressive effect on Eurasian watermilfoil, again putting the lake at risk for reinfestation with milfoil.

Another aquatic plant survey of Green Lake was conducted in August 2005 (Herrera 2005c). The observed plant coverage is shown in Figure 2. Eurasian watermilfoil coverage in Green Lake decreased by approximately 95 percent between 1991 and 2005, from 210 acres to 10.5 acres, respectively. Several dense beds of fragrant water lily (*Nymphaea odorata*) occur along the southwestern shoreline from a depth of 1.5 feet to a depth of 8 feet (see Figure 2). Fragrant water lily is a nonnative plant that covered approximately 4.5 acres in 2005, which was similar to the coverage observed in 1991 (KCM 1995), but the native lily, *Nuphar* sp., was not observed in 2005. Additional submersed macrophyte species observed in the lake during

the August 2005 survey included minor amounts of coontail (*Ceratophyllum demersum*) and common waterweed (*Elodea canadensis*). There are no rare, threatened, or endangered aquatic plant species in Green Lake.

It is likely that Eurasian watermilfoil coverage was even less than 10 acres immediately before the March 2004 alum treatment because of low water clarity resulting from algal blooms. By August 2005, large stands of well-developed plants were distributed along the shoreline in various areas, making further dispersal of milfoil plant fragments by wind and wave action highly likely. The extensive recreational boat traffic also provides abundant opportunities for the distribution of watermilfoil fragments.

Most of the lake area was devoid of aquatic plants in 2005 but of suitable depth for the re-establishment of Eurasian watermilfoil. Therefore, it is concluded that the abundance of source material (i.e., plant fragments) present in several areas of the lake, coupled with improved water clarity, would result in the rapid colonization of large areas of remaining habitat in the lake (Herrera 2005c). It is not known whether the introduction of grass carp in 2001 has had any effect on the biomass of Eurasian watermilfoil or whether carp would provide an effective control of milfoil in the future.

Seattle Parks and Recreation hired a contractor to perform minor amounts of Eurasian watermilfoil control by diver hand-pulling in the vicinity of Duck Island. However, the observed coverage of Eurasian watermilfoil in Green Lake (10.5 acres) was considered to be too extensive for eradication without the use of herbicides. Herbicide use is prohibited for Green Lake, and recent observations indicate that Eurasian watermilfoil has continued to expand its coverage in the lake (Fleming 2015).

6.6. Shoreline Use

Shoreline use of Green Lake is largely confined to public activities relating to the park, which encircles the entire lake. Development includes grassed park grounds, park-related buildings and associated parking lots, two swimming beaches, and several fishing docks. A paved trail for walking and running also encircles the lake, and is very populated with park users year round. Residential and commercial properties dominate the areas adjacent to the park.

6.7. Wetland Areas

Along the lake shoreline, emergent species such as cattails (*Typha latifolia*), soft rush (*Juncus effusus*), bulrush (*Scirpus* sp.), reed canarygrass (*Phalaris arundinacea*), and yellow flag iris (*Iris pseudacorus*) are common (Herrera 2005c). The shoreline also contains a variety of trees and shrubs, including red alder (*Alnus rubra*), birch (*Betula* sp.), willows (*Salix* sp.), and Himalayan blackberry (*Rubus armeniacus*). Portions of the shoreline are unvegetated due to the presence of retaining walls or disturbances by humans and dogs.

The coverage of shoreline plants was mapped by the Seattle Urban Nature Project during its citywide vegetation surveys in 1999 through 2001 (SUNP 2005) and is shown in Figure 2. The general condition and coverage of shoreline plants observed in August 2005 were similar to those previously observed by the Seattle Urban Nature Project. Much of the shoreline was

dominated by either nonnative species (primarily yellow flag iris, reed canarygrass, and Himalayan blackberry) or aggressive native species (cattails).

Very few wetland areas remain in the vicinity of Green Lake due to the development of the surrounding areas for residential, commercial, and park land purposes. One of the only remaining wetlands connected to Green Lake is the Licton Springs wetland. Located at North 97th Street and Ashworth Avenue North, the wetland discharges stormwater into a small pond (0.14 ha in size) before ultimately draining into Green Lake.

6.8. Fisheries

Most of the fish species residing in Green Lake have been introduced by WDFW (Herrera 2003). The lake is stocked with some fish species, such as rainbow trout (*Oncorhynchus mykiss*), on a regular basis to provide increased angling opportunities. In addition, two fish species have recently been introduced in the lake as a means of biomanipulation. In November 2000, the tiger musky, a hybridized fish species that is a cross between northern pike (*Esox lucius*) and muskellunge (*Esox masquinongy*), was introduced as a predator to reduce the population of common carp in the lake. In 2001, triploid (sterile) grass carp were introduced in the lake to reduce the abundance of milfoil.

WDFW conducted 15 electroshocking surveys of fish in Green Lake from July 2001 through March 2003 (Herrera 2003). Results showed that common carp was the dominant species in the lake, constituting approximately 75 percent of the total fish biomass and 30 percent of the total number of fish (Table 3). The second most abundant fish was tiger musky by biomass (18 percent) and largemouth bass by number (18 percent). There are no rare, threatened, or endangered fish species in Green Lake.

Table 3. Green Lake Fish Survey Results from July 2001 through March 2003.

	Weight		Number		Total Length Range (millimeters)	
Type of Fish	**Kilograms**	**Percent**	**Number**	**Percent**	**Minimum**	**Maximum**
Brown bullhead (*Ameiurus nebulosus*)	6.0	0.7	23	1.7	157	390
Brown trout (*Salmo trutta*)	18.0	2.2	221	16.1	93	495
Sculpin (*Cottis* sp.)	2.9	0.4	175	12.8	25	180
Carp (*Cyprinus carpio*)	597.9	74.5	410	29.9	97	679
Grass carp (*Ctenopharyngodon idella*)	1.5	0.2	3	0.2	307	343
Largemouth bass (*Micropterus salmoides*)	13.6	1.7	254	18.5	52	531
Pumpkinseed sunfish (*Lepomis gibbosus*)	2.2	0.3	111	8.1	30	166
Rainbow trout (*Oncorhynchus mykiss*)	7.7	1.0	19	1.4	150	432
Rock bass (*Ambloplites rupestris*)	6.7	0.8	76	5.5	40	316
Tiger musky (hybrid)	143.0	17.8	40	2.9	595	920
Yellow perch (*Perca flavescens*)	2.9	0.4	39	2.8	48	232
Total	**802.3**	**100.0**	**1,371**	**100**		

Species surveys were conducted during 15 electrofishing surveys by the Washington Department of Fish and Wildlife (Herrera 2003). Data have been corrected for an estimated 10 percent catch rate of carp, most of which were released because of limited boat storage capacity.

Trout stocking (planting) rates for Green Lake (WDFW 2015) have been increasing in recent years due to the popular demand (Figure 3). The number of rainbow trout planted in the lake each year increased from approximately 4,000 fish in 2000 to 29,000 fish in 2013. A dramatic increase in the number of fish to more than 93,000 occurred in 2014. This large planting was the result of a lawsuit by Native American tribes to cease the release of rainbow trout from state hatcheries to waters draining to Puget Sound for protection of native steelhead populations.

The total mass of planted trout was converted to total phosphorus based on an average phosphorus content of 230 milligrams (mg) in 3 ounces of rainbow trout (Ipatenco 2015), which is equivalent to 1.23 grams of phosphorus per pound of trout. This conversion yields over 55 kilograms (kg) of phosphorus from trout planted to Green Lake in 2014, which is similar to the total annual phosphorus loading from stormwater to the lake (see Table 3). Although much of that loading is removed by fishermen, the more important impact of trout plantings is from the grazing of zooplankton by the trout and the increase in phytoplankton biomass due to the reduced zooplankton grazing pressure.

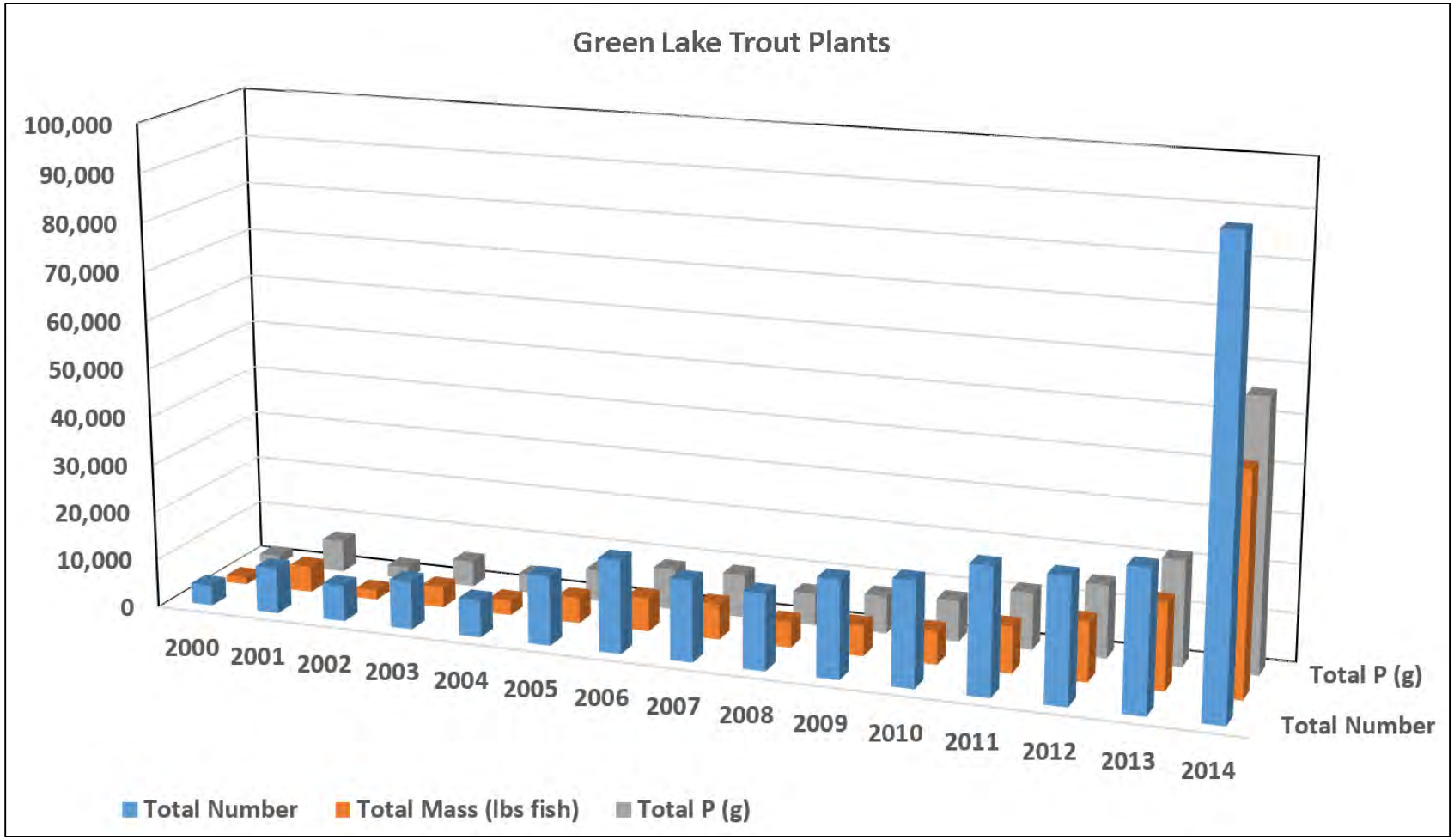

Figure 3. Green Lake Trout Stocking Data, 2000-2014.

7. Beneficial and Recreational Uses

7.1. Aesthetics

Green Lake Park is one of the most heavily used parks in Seattle, with thousands of people using the lakeside path and other park facilities each day. The lakeside path extends 2.8 miles around the lake and is used year-round for walking, running, skating, and bicycling. Path and park use is heaviest during the summer months. The centerpiece of the park is Green Lake itself. Bird watching is an important recreational use for many park users, with volunteers working to restore natural shoreline habitats. Most recreational activities in the park occur on or immediately adjacent to the lake itself, and the aesthetic character of the lake has a determining effect on the quality of the recreational experience of most park users.

7.2. Boating

The public is able to enjoy a variety of recreational non-motorized boating activities on Green Lake. Recreational uses of the lake include rowing, canoeing, kayaking, windsurfing, and sailing. The Green Lake Small Craft Center, located in the southwest area of the lake, provides instructional programs and competitions in such boating activities. Major boating competitions include youth, college, and adult rowing regattas in the spring and fall of each year that include competitors from throughout the Pacific Northwest. Boat access points for hand-carried boats are located at the Green Lake Small Craft Center and at the Green Lake West and Green Lake East beach areas. In addition, the Green Lake Boat Rental, a private company on the eastern side of the lake, offers a variety of canoes and boats for rental by the public. The rental season runs from approximately mid-May to mid-September.

7.3. Swimming

Swimming is a common recreational activity at the East Beach and West Beach, where swimming rafts with 1- and 3-meter diving boards are available. A small wading pool is located on the park grounds near the intersection of North 73rd Street and West Green Lake Drive North. Typically, the beaches are open from Memorial Day to Labor Day, serving over 10,000 swimmers each season. Green Lake has been closed for contact recreation on several occasions because the water quality was deemed unsafe for public use due to blooms of toxic cyanobacteria. The lake was closed to swimming in 2002 and 2003, and then again in 2012 through 2014 since the 2004 alum treatment. The lake was not closed in 2015, as of November 4, 2015.

7.4. Fishing

Fishing is a popular recreational activity at Green Lake. The numerous fish species in the lake provide a variety of fishing opportunities, including both cold (e.g., rainbow trout) and warm

(e.g., bass) fisheries. In addition, the Green Lake Kids Fishing Derby is conducted every April to promote family participation in fishing. Before the derby, the lake is stocked with a large quantity of rainbow trout from WDFW hatcheries.

Three fishing piers are available for public use at Green Lake. The piers are near the following addresses:

- East Green Lake Drive and Latona Avenue Northeast, at the foot of 65th Avenue Northeast
- West Green Lake Drive and Stone Way North, near the south end of the Bathhouse Theater
- West Green Lake Way North, at the Green Lake Small Craft Center

The lakeside path also provides access to the shoreline areas for fisherman.

8. Phosphorus Management Alternatives

As part of the Phase I diagnostic feasibility study (URS 1983), numerous lake management alternatives were considered for the reduction of phosphorus in Green Lake. An EIS completed in 1990 (URS 1990) addressed the feasibility and impacts of the management options identified in the Phase I diagnostic feasibility study. Table 4 presents a summary of the alternatives that were implemented; Table 5 presents a summary of the alternatives that were considered infeasible.

In late 1990, the Seattle City Council adopted a program to improve water quality at Green Lake (Seattle 1990). That water quality improvement program included the following lake management alternatives: lake alum treatment, biomanipulation, aquatic plant management, stormwater controls (Densmore diversion and nearshore treatment), and dilution with City drinking water (on a limited basis). The City implemented the program as summarized in the *Past Phosphorus Management Efforts* section of this plan.

Table 4. Alternative Restoration Methods Considered and Implemented for Green Lake.

Restoration Method	Description
Lake alum treatment	First alum treatment occurred in October 1991 at a reduced alum dose due to budget limitations at a much lower cost than dilution. Lake was treated again at full inactivation dose in April 2004 to remove water column phosphorus and inactivate sediment phosphorus release.
Biomanipulation:	
1. Goose management	Program began in 1987. Methods of control included removal, euthanasia, and egg addling to reduce numbers of resident Canada geese. The program was terminated in 2004.
2. Fish management	Included stocking with tiger musky in 2000 to control common carp, and physical removal of carp in 2004 and 2005.
Aquatic plant management	Harvesting was conducted from 1992 to 2002 to remove Eurasian watermilfoil from boating areas. In 2001, the lake was stocked with 777 triploid grass carp to control Eurasian watermilfoil.
Stormwater management	A new diversion structure was constructed in 1993 that increased the amount of stormwater diverted away from the lake in the Densmore basin. Stormwater treatment facilities were constructed in the Nearshore basin. Phosphorus sources were removed and drainage improvements were made in the Woodland Park basin in 2004 through 2009. Stormwater treatment has occurred since 2012 and will continue to occur with re-development of the Densmore basin.
Dilution with City water	Prior to the 1991 alum treatment, excess City drinking water was delivered to the lake for dilution; this has since been limited to small amounts when reservoirs are drained for maintenance. Current amounts are negligible due to changes in reservoir operations.

Source: Table adapted from URS (1990) and Herrera (2003).

Table 5. Alternative Restoration Methods Considered but Rejected for Green Lake.[a, b]	
Restoration Method	**Description/Considerations**
Reduce external phosphorus sources:	
1. Divert nearshore runoff in park	Rejected due to collection, disposal, and safety concerns and ineffectiveness in reducing summer phosphorus levels.[a]
2. Divert Woodland/Phinney drains	Considered not cost-effective or feasible due to impact on existing storm drain in Aurora Avenue North.
Reduce phosphorus concentration by dilution:	
1. City water	High-quality source (low phosphorus), but sufficient volume not available when needed. High cost compared with other alternatives. Not reliable during shortage conditions.[a, b]
2. Lake Washington water	Rejected because Ecology would not issue a permit for a consumptive use.[a, b]
3. Ground water	Unavailable quantity or quality[a, b]
4. Green Lake water treatment	Not feasible due to high cost and required use of park land.
5. Treated Ship Canal water	Rejected because Ecology would not issue a permit for a consumptive use. In addition, phosphorus concentration was too high to reduce current phosphorus concentrations in Green Lake.
6. Algicides	Rejected due to environmental effects.[a]
Reduce internal phosphorus sources:	
1. RIPLOX method	Prevents conditions needed for phosphorus release by oxidizing sediment. Eliminated due to lack of confidence in its effectiveness for Green Lake and because of high cost.[b] Not recommended for lakes with extensive macrophytes.
2. Aeration	Prevents conditions needed for phosphorus release and prevents rise of bottom-developing algae. Rejected due to adverse impacts on aesthetics and recreation and due to potential vandalism.[a] In addition, redox sediment release of phosphorus is no longer the driving force of phosphorus cycling in the lake. More importantly, 95% of the water column is oxygenated and shallow, indicating that aeration will not improve water quality.
3. Dredging	Removes sediment high in phosphorus. Rejected due to ineffectiveness and high cost due to high phosphorus concentrations deep within sediments.[a]
No action	Continuing current practices. Rejected because of severe aesthetic impacts, potential closures of the lake to recreational activities, and potential public health impacts.

Source: Table adapted from URS (1990) and Herrera (2003).

a Green Lake restoration diagnostic feasibility study (URS 1983)

b Green Lake water quality improvement plan (URS 1987)

Alternatives that were considered in the EIS but not adopted by the Seattle city council include diversion of stormwater from additional basins, diluting the lake with another surface water or ground water source, construction of a lake water treatment plant, application of algicides, the use of RIPLOX (sediment oxidation), aeration, dredging to control internal phosphorus sources, and a no-action alternative of continuing with current practices. These

phosphorus management alternatives were considered to be infeasible and are summarized in the following subsections. Seattle Parks and Recreation since received inquiries about three newer (SolarBee, peroxide, and EcoSOAR) that are also considered to be infeasible and summarized below.

8.1. Dilution

The City pursued the possibility of diluting lake waters with water pumped from Lake Washington (or Lake Union or Union Bay or Licton Springs) or with ground water or with City drinking water to reduce the overall phosphorus concentration in the lake. The City completed an EIS in 1990 that addressed these three dilution options (URS 1990). However, after publication of the final EIS, Ecology determined that a transfer of Lake Washington water to Green Lake was a consumptive use that could not be permitted (KCM 1995). In addition, the total phosphorus concentrations (approximately 30 µg/L) in Lake Union and Union Bay were determined to be too high to provide any dilution benefit to Green Lake (URS 1983).

Ground water wells were drilled at Green Lake Park and in nearby View Ridge Park to serve as sources of ground water for dilution. The well drilled at Green Lake Park did not have a significant water yield. The well drilled at View Ridge Park produced water but had a high total phosphorus concentration (average of 750 µg/L). Dilution with water from the City's drinking water supply was analyzed but proved to be too costly (URS 1983). Dilution with the City's drinking water supply has occurred in the past, but has been reduced to negligible amounts in recent years (see the Past Phosphorus Management Efforts section). The future availability of drinking water for lake dilution is expected to decrease, and its costs will likely increase as the supply decreases.

8.2. Treatment Plant

The City pursued the possibility of building a treatment plant at the lake, which would treat lake water and recycle the clean water back into the lake, thereby reducing the lake phosphorus concentration. This method would provide an effective, long-term solution; however, because this alternative would require the construction, operation, and maintenance of a treatment plant, the cost of this alternative made it infeasible (URS 1983, 1990).

8.3. Stormwater Diversion

In an effort to reduce combined sewer overflows to Lake Union, King County implemented the University Regulator project, which diverted additional stormwater out of the Green Lake watershed from the Densmore basin (discussed in the Past Phosphorus Management Efforts section). However, stormwater from the Woodland Park and Nearshore basins has not been diverted from the lake. The EIS concluded that these projects would be costly and, because the control would target stormwater, mostly a wet-season input, these diversions would likely have minimal effects in reducing summertime phosphorus levels (URS 1990).

8.4. Algicides

Algicides provide partial short-term algae control by killing the algae and cyanobacteria in the water column. However, all algicides also affect other aquatic biota to varying degrees and accelerate recycling of nutrients. Algicides (such as copper sulfate) are effective only while the active ingredient is in the water column and available for uptake by the algae (Cooke et al. 1993). Typically, several applications must occur within the same season to provide effective control of algae and blue-green bacteria. Algicides do not reduce phosphorus concentrations and do not provide long-term control. In fact, they cause recycling of phosphorus. Currently, endothall (Hydrothol® 191) and sodium carbonate peroxyhydrate (see *Peroxide* section below) are the only algicides that can be used in the state of Washington, and Ecology will not issue a permit for the use of copper sulfate. The use of algicides is not a suitable option for controlling algae in Green Lake because of their adverse side-effects and the potential risk to human health and aquatic life (URS 1983).

8.5. RIPLOX (Sediment Oxidation)

Under certain conditions, RIPLOX prevents the release of phosphorus from sediments by reducing the oxygen demand of sediments. The sediments are oxidized by injecting them with calcium nitrate ($Ca[NO_3]_2$) to stimulate denitrification (reduction of nitrates to nitrogen gas). This method is not an option for Green Lake because of the high cost and its lack of known effectiveness (URS 1983), and was not recommended by the method inventor (W. Ripl) due to interference from dense aquatic macrophyte coverage. Although macrophyte coverage has declined, the potential effectiveness of RIPLOX has been reduced because the redox-sensitive phosphorus fractions have been reduced to a low level by the 2004 alum treatment.

8.6. Aeration and Circulation

Aeration would prevent anoxic (oxygen poor) conditions from developing near the lake's bottom, which, in some cases, enhances the release of phosphorus from the sediment. Aeration and circulation devices also may deter cyanobacteria advantages over other algae by increased mixing and reduced pH. URS (1983) determined that lake aeration and circulation devices are not a suitable option for Green Lake because they would interfere with the aesthetic and recreational uses of the lake, and because of the potential for vandalism of the equipment. Also, it is unlikely that aeration or circulation would decrease phytoplankton production or cyanobacteria dominance in Green Lake because the lake is shallow and well mixed, and deep waters are well oxygenated.

8.7. Dredging

One method for removing sediments high in phosphorus is dredging or removing sediments from the lake. However, dredging occurred in 1935 to 1937 and in 1962, and was generally ineffective in improving water quality in the lake (URS 1983). Analysis of sediment core samples has indicated that the phosphorus concentration within the sediments is uniform and that removing the top layer of sediments would not reduce the sediment phosphorus levels (URS 1983). Dredging of lake sediments is not considered an option because of the long-term ineffectiveness and the high cost of removal and sediment disposal (URS 1983), which is estimated to be approximately $800 million in 2015 dollars.

8.8. SolarBee

The SolarBee is a solar-energy–driven, mixing device that is advertised to aerate water column and reduce cyanobacteria by mixing. Cyanobacteria have gas vacuoles that allow them to be buoyant. In order to reduce cyanobacteria production in Green Lake, the induced mixing velocities would have to be high enough to overcome the buoyancy potential of cyanobacteria and to physically "trap" the cyanobacteria at light-limiting depths. However, there is no evidence that SolarBee units can mix the water column at sufficient rates to overcome the buoyancy ability of cyanobacteria. In addition, over 95 percent of the water column in Green Lake is in the photic zone, such that SolarBee units would not induce light limitation on algal production.

8.9. Sodium Carbonate Peroxhydrate

Application of sodium carbonate peroxhyrate (peroxide) has been used as an algicide and to oxidize bottom sediments in lakes and reservoirs. The most common brand names for peroxide algicides are PAK27, GreenCleen, and Phycomycin. As an algicide, peroxide has the same limitation as other algicides in that it increases phosphorus recycling and, therefore, is only and temporal fix. Peroxide use as a sediment oxidant is no longer permitted by Ecology or US EPA at dose rates required to oxidize lake sediments.

8.10. EcoSOAR

There are scores of approaches, methods, and devices to improve water quality in lakes. Very few have received a comprehensive, rigorous, long-term evaluation to demonstrate their effectiveness. The test cases given for EcoSOAR on their website (http://www.premiermaterials.com/kria-water-purification.html) are in this category. For the Grand Lake (St. Mary's, Ohio) example, the implication is that the treatment affected the entire 13,000-acre lake, when its real effect was only a very small area around the EcoSOAR device. EcoSOAR claims that the device ionizes water to increase oxygen and "stimulate bacteria to degrade phosphates and drive phosphorus into the sediments." However, phosphate is an inorganic, oxygenated form of phosphorus that cannot be degraded. While it is true the phosphate is taken up by bacteria and algae and converted to organic phosphorus, this is not enhanced by the EcoSOAR unit or a degradation process. The manufacturer's claim to drive phosphorus to the sediments is also not supported by basic physics.

There is no evidence provided indicating the EcoSOAR device could affect a lake the size of Green Lake, or would reduce phosphorus internal loading and cyanobacteria production as claimed, especially since oxygen levels in the lake are not an issue.

8.11. No Action

The no action alternative for phosphorus management of Green Lake would result in cyanobacteria blooms during the summer that would result in severe aesthetic impacts, potential closures of the lake to recreational activities, and potential public health impacts from the consumption of toxic cyanobacteria by lake users.

9. ALUM TREATMENT PLAN

Since the first lake alum treatment in 1991, the City has undertaken numerous management efforts to help maintain the reduced phosphorus concentrations achieved after that treatment. Such measures have included diverting stormwater, biomanipulation, public education, and milfoil harvesting. However, such measures have not proved effective over the long term at maintaining the total phosphorus concentrations at the recommended summer target level of less than 25 µg/L. Therefore, a second alum treatment was performed in 2004 that effectively reduced the internal sediment loading of phosphorus within the lake for over 10 years. Although the phosphorus goal has been met each year since 2004, cyanobacteria blooms resulted in lake closures in 2012, 2013, and 2014.Because of the success of the 1991 and 2004 alum treatments in controlling sediment phosphorus sources, the City proposes a third alum treatment during the spring of 2016.

Alum treatments inactivate the internal cycling of inorganic and organic phosphorus. The alum is applied near the water surface and it removes phosphorus from the water column as it flocculates and settles. It then covers the bottom sediments to further prevent the internal release of phosphorus from the sediments.

Sediment phosphorus analysis was recently performed to determine the amount of alum needed to inactivate sediment phosphorus in Green Lake and meet water quality goals in the future. The sediment phosphorus analysis, alum treatment design, permit conditions, and a cost estimate are presented separately below for the planned 2016 alum treatment.

9.1. Sediment Phosphorus Analysis

The sediment phosphorus analysis of Green Lake is described in detail in a technical memorandum presented in Appendix B. Methods and results are summarized in the following sections.

9.1.1. Methods

Sediment cores were collected on May 4, 2015, at four previously sampled locations in Green Lake (Index station, Station A, Station B, and Littoral station) (see Figure 2). One core was collected at the deepest portion of the lake (23 feet deep at Index), and one core was collected at each of the three shallow stations (14 feet deep at Station A, 9 feet deep at Station B, and 10 feet deep at Littoral).

Each sediment core was partitioned into eight depth intervals down to 30 cm: 0–2 cm, 2–4 cm. 4–6 cm, 6–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, and 25–30 cm. Each interval sample was obtained by pushing sediment up the core tube with a rod and removing the specified depth of sediment from the top of the core tube with a small, decontaminated spoon. A total of 32 depth-interval samples (and 3 field duplicate samples) were analyzed for the following phosphorus fractions:

- Labile (loosely bound) phosphorus (labile-P)
- Iron bound phosphorus (Fe-P)
- Biogenic phosphorus (biogenic-P)
- Organic phosphorus (organic-P)
- Calcium bound phosphorus (Ca-P)
- Aluminum-bound phosphorus (Al-P)
- Total phosphorus (TP)

The samples were also analyzed for total solids, percent water, and total aluminum, iron, and calcium.

Sediment cores were collected from Green Lake in 1998 and 2004, representing 7 years after the 1991 alum treatment and 6 months after the 2004 alum treatment, respectively. The cores were collected using similar coring techniques, and the samples were analyzed by different laboratories using methods similar to those used in 2015.

The 2004 cores were collected from the same four stations sampled in 2015 (see Figure 1), and were divided into 1 cm intervals down to 10 cm depth and thereafter at 15, 20, 25, 30, 35, and 40 cm depths. Each sample was analyzed for phosphorus fractions and total aluminum (Herrera 2005b).

The precise location of the 1998 cores is unknown, but they were known to be collected near the Index station and Station A. The two 1998 cores were divided into 1 cm intervals down to 15 cm depth and thereafter at 20 and 25 cm depths. Each sample was analyzed for phosphorus fractions.

Upon completion of the technical memorandum in Appendix B, the analyst of the 1998 and 2004 sediment samples (Emil Rydin, Uppsala University) was contacted, and it was determined that the historical results for organic phosphorus are actually biogenic phosphorus. The corrected results are presented below and were used to design the proposed 2016 alum treatment.

9.1.2. Results

Labile phosphorus (labile-P) was not detected in any of the samples (less than a detection limit of 2 milligrams per kilogram [mg/kg] dry weight). Iron bound phosphorus (Fe-P) concentrations were low, ranging from 6.3 to 35 mg/kg in all samples, and displayed no consistent depth or spatial patterns.

Mobile phosphorus (mobile-P) was calculated as the sum of labile-P and Fe-P using the detection limit for undetected values. Mobile phosphorus profiles for 1998, 2004, and 2015 are compared in Figure 4 for Index station and Station A. The results show that the 2004 alum treatment reduced the mobile phosphorus concentrations in the upper 15 to 20 cm of sediment, and this reduction was much more pronounced at the deep Index station than shallow Station A. Mobile phosphorus concentrations were substantially lower in 2015 to uniformly low concentrations throughout all of the cores, suggesting that mobile phosphorus

continued to bind with free aluminum remaining in the sediment since the 2004 alum treatment.

Aluminum bound phosphorus (Al-P) profiles for 1998, 2004, and 2015 are compared in Figure 5 for Index station and Station A. These results show that Al-P concentrations were higher in 2004 than 1998 in the upper 10 cm of sediment at both stations, and even higher in 2015 at most depth intervals in the cores from both stations. The results further indicate that mobile phosphorus present at 6 months after the 2004 alum treatment continued to bind with free aluminum remaining in the sediment, extending inactivation effectiveness for at least 10 years.

Biogenic phosphorus (biogenic-P) profiles for 1998, 2004, and 2015 are compared in Figure 6 for Index station and Station A. The results show that biogenic phosphorus concentrations varied widely but did not exhibit a substantial vertical or temporal trend among the years tested.

9.2. Alum Treatment Design

The sediment analysis results were used to evaluate effects of the 2004 alum treatment and to calculate an appropriate aluminum dose for design of the 2016 alum treatment. A technical memorandum of this evaluation is presented in Appendix C. An addendum to that memorandum was then prepared that reduced the aluminum dose by 48 percent based on additional information obtained from Swedish limnologists.

Sediment core data show that mobile-P, as Fe-P and labile-P, has remained quite low throughout the sediment column at all four coring sites (Appendix B). Figures 4 and 5 show that the effect of the 2004 alum treatment, in terms of decreased mobile-P and increased Al-P, was greater in the intervening 11 years than was the case 6 months after the 2004 treatment, especially between 10 and 30 cm at the Index station. Again, the results show that added aluminum continued to inactivate phosphorus to greater depths in the sediment column well after the treatment and the formed Al-P remained stable. This is a significant indication of the positive, persistent, and intended impact of the 2004 alum treatment.

Biogenic-P is now included with mobile-P (Fe-P + labile-P) as standard procedure in determining the aluminum dose. The low ratio of aluminum added to Al-P formed in Green Lake (~4 and ~8) and other lakes (~11) may be due to a portion of undetermined biogenic-P inactivated by aluminum. Therefore, including biogenic-P, as is done here, may ultimately reduce the ratio used to determine dose. The risk in using too low of a ratio is that it does not account for the mobilization and vertical migration of the phosphorus reserve from deeper sediment layers to the sediment surface; such sediment phosphorus reserve exists in Green Lake.

Biogenic-P concentrations from 1998 and 2004 are similar to those determined in 2015, ranging from 0.300 to 0.445 milligrams per gram (mg/g) at the Index station and from 0.275 to 0.352 mg/g at Station A (see Figure 6). Although biogenic-P was not included in the aluminum dose added to the lake in 2004, the original aluminum dose calculated for 2016 included all of the biogenic-P observed in the top 10 to 20 cm of sediment, along with the small amount of mobile-P that still persists from the 2004 treatment.

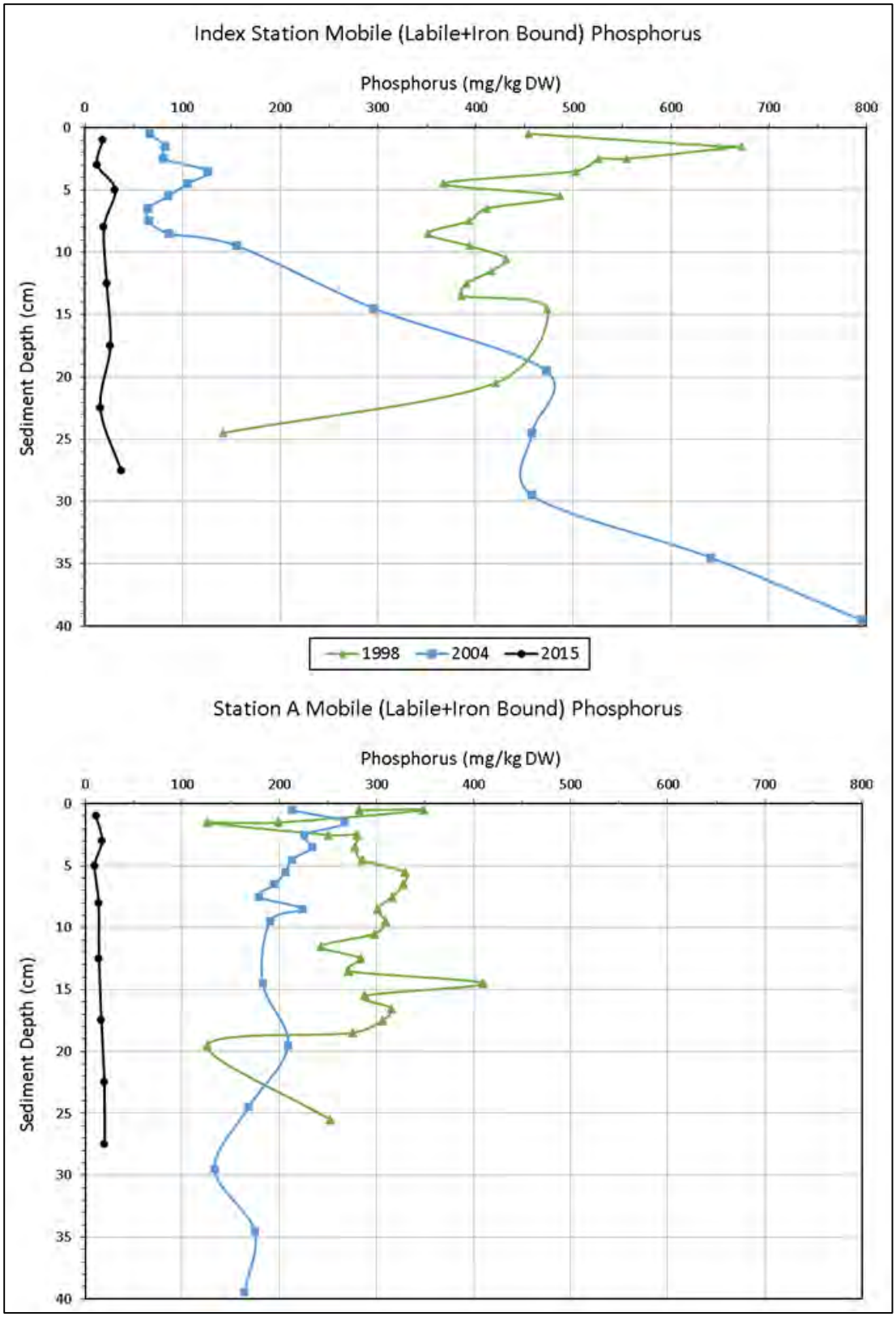

Figure 4. Green Lake Sediment Mobile Phosphorus at Index Station and Station A.

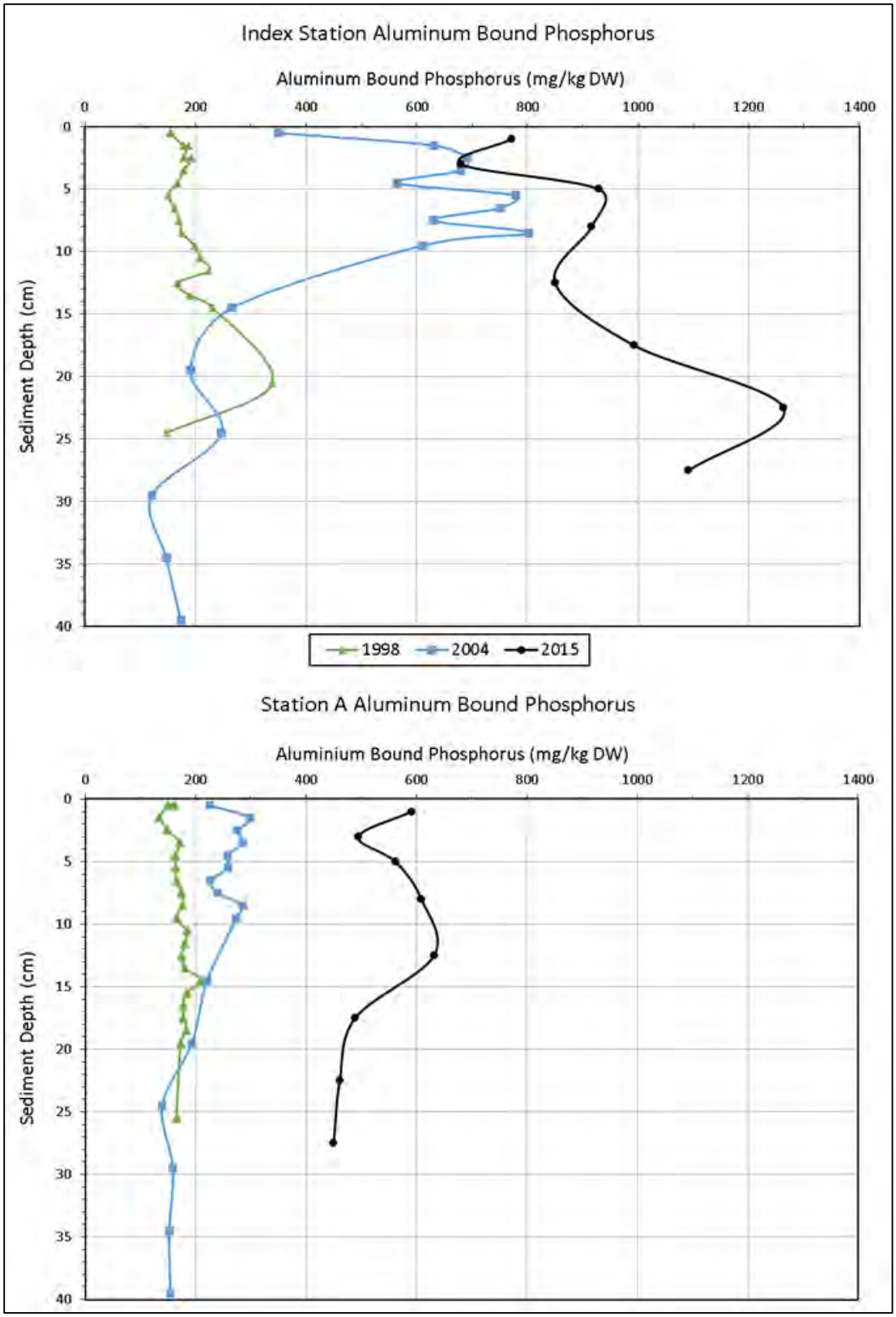

Figure 5. Green Lake Sediment Aluminum Bound Phosphorus at Index Station and Station A.

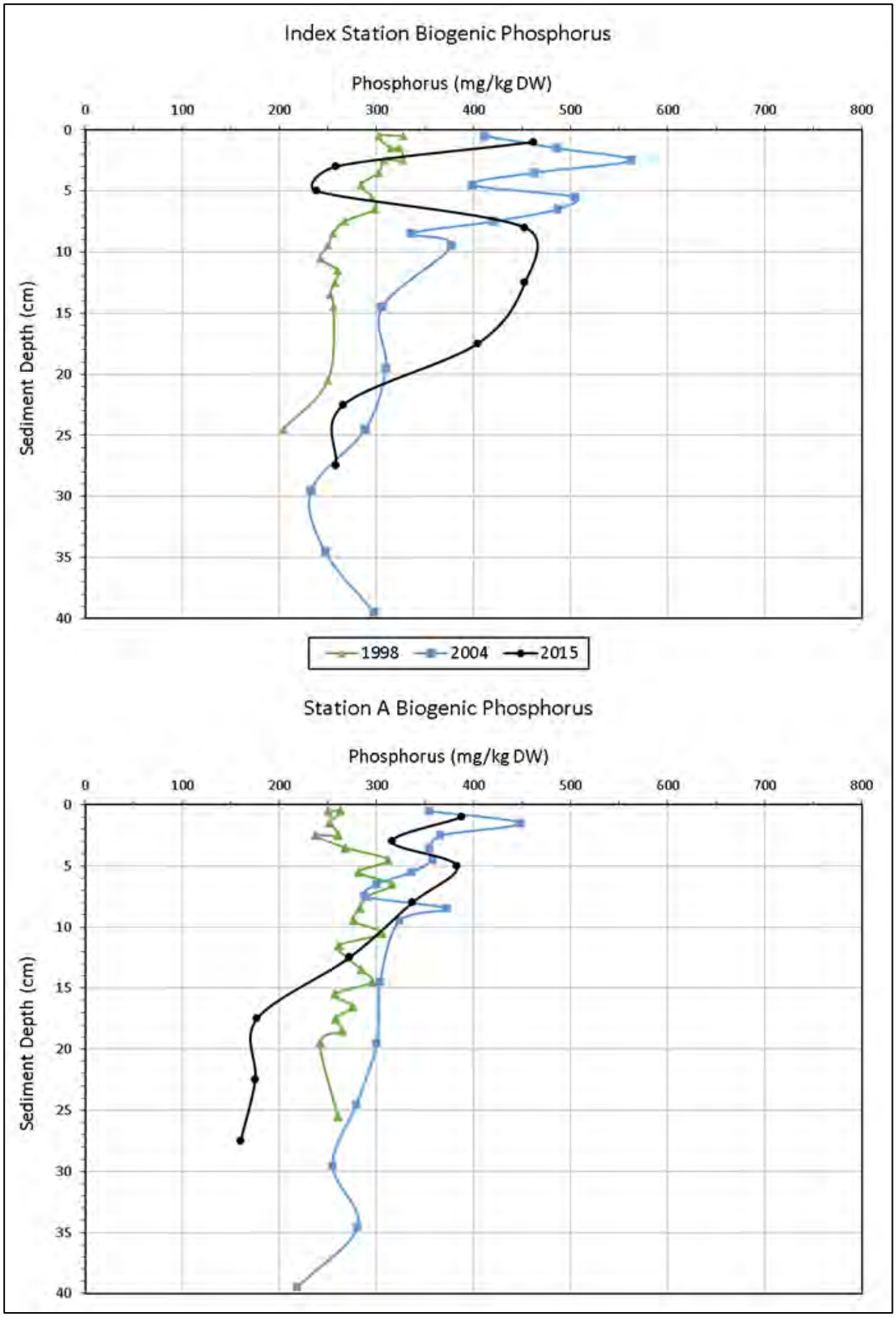

Figure 6. Green Lake Sediment Biogenic Phosphorus at Index Station and Station A.

As recommended by Swedish limnologists Emil Rydin and Brian Huser, the aluminum dose was then revised to consider only the "active" fraction of biogenic-P in the top 10 or 20 cm of sediment, minus the "inactive" background fraction of lower concentrations below that depth (Table 6). Background biogenic-P averaged approximately 50 percent of the biogenic-P in the top 10 cm at Station A and the Littoral station, and in the top 20 cm at the Index station and Station B. Therefore, sediment depths used to compute aluminum dose to inactivate biogenic-P were 10 cm at Station A and the Littoral station, and 20 cm at the Index station and Station B, because those were the depths at which biogenic-P declined to background. In addition, the ratio of aluminum added to phosphorus (mobile-P + biogenic-P) was modified. Instead of using 10:1 and 20:1 ratios of aluminum added to phosphorus for 20 cm and 10 cm depths, respectively, a 9:1 ratio was used regardless of sediment depth. A ratio of 8.8:1 of aluminum added to phosphorus has been recommended by Danish scientists when using both biogenic-P and mobile-P to determine the aluminum dose.

Table 6. Mean Sediment-P Content (mg/g) and Aluminum (Al) Doses for a 9:1 Ratio of Al Added to Mobile+Biogenic-P at 0-10 and 0-20 cm Depth Intervals.

Site	Mobile + Biogenic P (mg/g)		Al Dose (g Al/m^2) at 9:1 Al:P	
	0 – 10 cm	0 – 20 cm	0 – 10 cm	0 – 20 cm
Index Station	--	0.159	--	35.8
Station A	0.167	--	18.3	--
Station B	--	0.250	--	41.2
Littoral Station	0.295	--	26.3	--
		Average sediment Al dose:	30.4	
		+ Water column Al dose:[a]	1.6	
		= Total Al dose:	**32.0**	

[a] Based on an a total phosphorus concentration of 20 µg/L (20 milligrams per cubic meter) in the lake water.

g AL/m^2 = grams of aluminum per square meter

Al:P = aluminum to phosphorus

There is still the uncertainty of phosphorus sources from sediment deeper than 30 cm. Mobile Fe-P remained relatively high at Station A and the Littoral station, and deeper than 15 cm at the Index station following the 2004 treatment (Table 7). By 2015, those levels had decreased to only a few percent of those in 1998, before treatment, and deeper than 15 cm at the Index station (Table 7). Al-P concentrations below 15 cm were also much higher in 2015 than 2004, consistent with the Fe-P decrease. Thus, added Al accessed more mobile-P and at greater depth than anticipated with the dose used in the 2004 treatment. A similar pattern of increased Al-P and decreased Fe-P occurred at the Littoral station below 15 cm. Thus, the use of 9:1 over 20 cm, as well as 10 cm, is to account for mobile-P sources below 20 cm. Additional cores to 0.5- and 1-meter depths would be needed to identify the depth to which the 2004 treatment reached, as well as the quantity of mobile-P that exists and may be available.

Table 7. Mean Iron-P Concentrations in Sediment Cores from Green Lake.			
Site	**Iron–P (mg/g) by Year and Sediment Core Depth**		
	1998 to 25 cm	**2004 to 40 cm**	**2015 to 30 cm**
Index Station	418	23 (< 15 cm)	21.4
		496 (> 15 cm)	
Station A	275	180	14.0
Station B	--	46.4	16.0
Littoral Station	--	87.5	15.2

Using this methodology, the aluminum dose ranges from 18.3 to 41.2 grams of aluminum per square meter (g Al/m^2) and averaged 30.4 g Al/m^2 among the four core stations (see Table 6). An additional 1.6 mg Al/L is added to account for total phosphorus in the water column, which is based on a total phosphorus concentration of 20 µg/L (or 20 milligrams per cubic meter) in the lake at the time of treatment. The total aluminum dose is 32.0 g Al/m^2 on an areal basis, which is equivalent to a total aluminum dose of 8.2 mg Al/L on lake volume basis. The proposed dose of 8.2 mg Al/L is approximately one-third of the 23.0 mg Al/L dose applied in 2004 and similar to the 8.6 mg Al/L dose applied in 1991. The dose recommended for sediment inactivation (7.8 mg Al/L) is much less than that applied in 2004 (17.2 mg Al/L), and the dose planned for water binding (0.4 mg Al/L) is much less than that applied in the 2004 (5.8 mg Al/L) due to the lower amount of total phosphorus present in the water column.

As performed in 2004, liquid alum will be applied concurrently with liquid sodium aluminate at a ratio of 2:1 by volume to ensure that the water pH does not decrease below 6.0. Sodium aluminate has been shown to be an effective buffer at this ratio.

It is recommended that the 2016 treatment occur in March or April when the water temperature is moderate, the amount of aquatic plant (milfoil) and algae growth are relatively low, and recreational activity on the lake is also low. The 2016 alum treatment is planned to occur between March 21 and April 22, 2016, to avoid interference with a rowing regatta on March 19 and 20 and opening day of fishing on April 23, 2016. The treatment should be completed within 10 working days.

The recommended dose is anticipated to meet water quality goals for at least 10 years, based on the long-term effect of the 2004 treatment and assuming external phosphorus inputs to the lake remain relatively low.

More information about treatment procedures and constraints are provided in the Technical Specifications presented in Appendix D.

9.3. Permit Conditions

The alum treatment will be conducted in accordance with Ecology's Aquatic Plant and Algae Management General Permit (Ecology 2015). This permit is currently being revised and the draft permit does not include any revisions to restrictions for alum treatments. Permit restrictions for alum treatments (see Table 4 in Ecology 2015) include:

- Timing restrictions:
  - None for fish or other priority species.
  - Early spring or fall treatment if aquatic plant biomass interferes with inactivation of sediment phosphorus.
- Lake use restrictions or advisories:
  - None.
- Treatment restrictions:
  - Application must cease when wind speed is greater than 15 miles per hour.
  - Powdered alum must be mixed with water to form a slurry before applying to the water surface.
  - The pH of lake water during treatment must remain between 6.0 and 8.5 based on lake average.
  - Only aluminum compounds suitable for water treatment may be used.
  - Buffering materials must be available for use.
- Monitoring requirements:
  - Minimum monitoring is one surface water pH measurement in the morning prior to any alum addition and one surface water pH measurement 1 hour after alum addition has stopped for that day.
  - Monitoring for pH must continue for the duration of the treatment and for 24 hours following treatment completion.
  - Monitoring locations must be representative of water body-wide conditions.
- Other restrictions:
  - A jar test must be completed prior to whole lake treatments only if a buffer other than sodium aluminate is used or a ratio of liquid alum to liquid sodium aluminate differs from 2:1 by volume.
  - An on-site storage facility is required for any treatment requiring 9,000 gallons of alum or more, or the project proponent must have a plan to store any unused alum or buffering products.

The general permit allows for short- and long-term exceedance of Washington State Surface Water Quality Standards (WAC 173-201A) provided that the Permittee complies with any short-term modifications of water quality criteria authorized in writing by Ecology. Water quality degradation is allowed if the degradation does not significantly interfere with or become injurious to existing or designated water uses or cause long-term harm to the environment (WAC-173-201A-410).

9.4. Cost Estimate

Quantities of each chemical, alum and sodium aluminate, were calculated based on the recommended dose of 8.2 mg Al/L. The spring 2016 treatment at a dose of 8.2 mg Al/L will

require 81,680 gallons of alum (estimated 19 tanker trucks) and 82,670 gallons of sodium aluminate (estimated 10 tanker trucks) based on the standard ratio of 2 parts alum to 1 part aluminum sulfate (by volume) and their typical aluminum content. A cost estimate for the spring 2016 treatment is shown in Table 8.

Table 8. Cost Estimate for the 2016 Alum Treatment at Green Lake for the Planned Dose of 8.2 mg Al/L (32.0 g Al/m^2).

Item	Unit Cost	Quantity	Total Cost
Aluminum Sulfate (material cost)	$1.50/gallon	81,680 gallons	$122,520
Sodium Aluminate (material cost)	$3.60/gallon	40,840 gallons	$147,024
Application (applied to material costs)	20%	$269,544	$53,909
		Subtotal 1	**$323,453**
Tax	9.6%	--	$31,051
		Subtotal 2	**$354,504**
Contingency	30%	--	$106,351
		Grand Total Cost	**$460,855**

mg Al/L = milligrams of aluminum per liter

g AL/m^2 = grams of aluminum per square meter

10. Water Quality Monitoring and Treatment Evaluation Plan

Water quality monitoring will be conducted at Green Lake to protect aquatic biota during the 2016 alum treatment, and to evaluate the short-term and long-term effects of the treatment. The goals of water quality monitoring under this plan are to:

- Conduct a jar test before the alum treatment and measure pH in Green Lake during the alum treatment to ensure that pH levels exceed 6.0 for protection of aquatic biota from aluminum toxicity
- Collect water quality data before, during, and after the treatment to evaluate the short-term water quality effects of the alum treatment in the lake to insure that pH criteria (between 6.0 and 8.7) and alkalinity criteria (greater than 12 mg/L) are met for protection of aquatic biota from aluminum toxicity
- Collect post-treatment water quality data to evaluate the long–term effectiveness of the alum treatment in relation to water quality goals that have been established for Green Lake

Treatment monitoring will be performed to determine if the following short-term water quality objectives are met:

- Average lake pH shall be between 6.0 and 8.7
- Average lake alkalinity in the lake shall be greater than 12 mg/L

Post-treatment monitoring will be performed to determine if the following long-term water quality objectives are met for at least 10 years (2016 through 2025):

- Summer average total phosphorus concentration shall be less than 20 µg/L
- Summer average Secchi depth (water clarity) shall exceed 2.5 meters (8.2 feet)
- The lake will not be closed to recreational uses due to toxic cyanobacteria

A detailed monitoring plan is presented in Appendix E. In addition, oversight of the alum treatment will be performed on a full-time basis by an engineer from Tetra Tech, Inc. with extensive alum treatment experience to ensure materials are properly handled and distributed.

Water quality monitoring will include the following three components: jar test, treatment monitoring, and post-treatment monitoring. A jar test using the specified dose will be conducted on site immediately prior to the first day of alum treatment to verify that the lake pH will exceed 6.0 during the treatment. Treatment monitoring will include various elements to evaluate short-term effects of the treatment. Post-treatment monitoring will be conducted during subsequent summers over a period of 10 years to evaluate the long-term effects of

alum treatment. The following sections describe the sampling locations and the design of each monitoring component. The overall monitoring design is summarized in Table 9.

Table 9. Water Quality Monitoring Design for the Green Lake 2016 Alum Treatment.

Monitoring Component	Sampling Locations[a]	Analytical Parameters	Sampling Frequency
Pre-treatment Jar Test	Near Small Craft Center	Alkalinity, pH	One or more tests
Treatment Monitoring			
Short-term impact	Station A, Station B, Index station (surface, bottom)	Alkalinity, dissolved Al, total Al, sulfate, TP, SRP, nitrite + nitrate, ammonia, fecal coliform, chlorophyll *a*, Secchi depth, temperature/DO/pH/conductivity profile	Day before treatment, and 2 days and 2 weeks after treatment
Twice daily	Station A, Station B, Index station (surface, bottom)	Alkalinity (field), dissolved and total Al[b], Secchi depth, temperature/DO/pH/ conductivity profile	Morning before and evening after each day of treatment
Random daily	Treatment sites (surface, bottom)	pH profile and alkalinity (if pH is less than 6.0)	At least every 2 hours during treatment
Post-treatment Monitoring	Index station (surface)	Chlorophyll *a*, TP, TN, Secchi depth, temperature	12 events from May through October for 10 years

Al = aluminum

TP = total phosphorus

SRP = soluble reactive phosphorus

DO = dissolved oxygen

[a] Treatment sampling stations include Index, Composite A, and Composite B at 1 meter below water surface and 1 meter above lake bottom. Post-treatment sampling includes one composite sample from Composite A and Composite B stations for chlorophyll a and TP, and field measurements at the Index station.

[b] Dissolved and total aluminum will be analyzed only if the pH is less than 6.0.

10.1. Lake Monitoring Locations

Water quality monitoring will be conducted at three stations on Green Lake that have been used for previous monitoring projects to allow for comparison to historical data. The monitoring stations include (see Figure 2):

- Index station: Located at the deepest (approximately 9 meters) point in Green Lake, which is near the northeast corner of the lake
- Station A: Located in a moderately deep (approximately 5 meters) portion of Green Lake near the northwest corner of the lake
- Station B: Located in a moderately deep (approximately 4 meters) portion of Green Lake near the south end of the lake

In addition, the pre-treatment jar test will be conducted at the treatment staging area, which is located on the southwest shore of Green Lake near the Small Craft Center.

10.2. Jar Test

Jar tests will be conducted on the first day of alum treatment. This testing will be performed for pH using the alum treatment chemicals, dose, and application method provided by the treatment contractor using water and water quality conditions present at the time of application. This large-scale jar test will be performed at the alum treatment staging area located near the Small Craft Center on the southwest shore of Green Lake.

A testing vessel (e.g., 5-gallon plastic bucket) will be filled with lake water and treated with aluminum sulfate and sodium aluminate directly taken from the supply trucks or storage tanks. The jar test will be conducted using three ratios (1.9:1, 2.0:1, and 2.1:1) of alum and sodium aluminate to ensure correct buffering under current treatment conditions. A control bucket with only lake water will also be tested. The pH of the collected lake water will be tested immediately before treatment after 2 minutes, 15 minutes, 30 minutes, and 1 hour after dosing. Monitoring results will be recorded and immediately reported to the Resident Engineer.

10.3. Treatment Monitoring

Treatment monitoring will be conducted by Herrera Environmental Consultants, Inc. (Herrera) over a 10-day period, which will include the application of alum during approximately 6 days. Water quality monitoring for the treatment component is anticipated to occur in late March to late April 2016.

Treatment monitoring will include the following three elements:

- Monitoring before and after the alum addition to evaluate short-term impacts of the treatment on various water quality parameters at established monitoring stations.
- Twice-daily monitoring (in the morning before treatment begins and in the afternoon or evening when treatment ends) to verify that pH criteria (between 6.0 and 8.7) and alkalinity criteria (greater than 12 mg/L) are met at established monitoring stations.
- Random monitoring of pH during the alum application at treatment sites will be conducted at least once every 2 hours at specific treatment locations and allowing for 1 hour of alum settling.

Short-term impact monitoring will consist of measuring field parameters and collecting water samples from 1 meter below the water surface and 1 meter above the lake bottom at each of the following three stations: Station A, Station B, and Index station. A total of six water samples will be collected from the lake on three occasions: 1) the day before the first day of treatment, 2) 2 days following the last day of treatment, and 3) 2 weeks following the last day of treatment. The collected samples will be analyzed for the following parameters:

- Secchi depth (field measurement)
- Temperature (field measurement at 1-meter intervals)
- Dissolved oxygen (field measurement at 1-meter intervals)
- pH (field measurement at 1-meter intervals)

- Conductivity (field measurement at 1-meter intervals)
- Total alkalinity
- Dissolved aluminum
- Total aluminum
- Sulfate
- Soluble reactive phosphorus
- Total phosphorus
- Nitrate+nitrite nitrogen
- Ammonia nitrogen
- Total nitrogen
- Chlorophyll *a*
- Fecal coliform bacteria (surface grab only).

Twice-daily monitoring will consist of measuring field parameters at the Station A, Station B, and Index station in the morning before treatment begins, and in the afternoon or evening when treatment ends. The field parameters include Secchi depth and vertical profiles of temperature, dissolved oxygen, pH, and conductivity at 1-meter intervals. In addition, total alkalinity will be tested in the field on water samples collected from 1 meter below the water surface and 1 meter above the lake bottom at each of the three stations. If the pH is consistently less than 6.0 at a monitoring station, then the samples collected from that station will be analyzed for dissolved and total aluminum.

Random daily monitoring will consist of measuring pH at the treatment site during the alum application at a frequency of at least once every 2 hours. The pH will be measured at 1-meter intervals at the location where alum was applied approximately 1 hour before the time of sample collection. The 1-hour delay in sampling will allow for settling of the alum floc and stabilization of water quality conditions. If the pH is consistently less than 6.0 at a treatment site, then samples will be collected from 1 meter below the water surface and 1 meter above the lake bottom, and analyzed in the field for total alkalinity.

The alum treatment will be suspended if the pH is consistently less than 6.0 (± 0.05) or greater than 8.7 (±0.05) in samples collected at the treatment sites or at the twice-daily monitoring stations. Additional monitoring will be conducted as necessary to determine when the lake pH and alkalinity have adequately recovered. Treatment may resume if the pH is between 6.2 and 8.4 (± 0.05) and the alkalinity is greater than 12 mg/L (± 0.5 mg/L) at all monitoring locations.

Observations of the alum treatment activities, floc formation, and potential fish and wildlife impacts will be made during random daily monitoring.

In the event that treatment monitoring data do not comply with the permit terms and conditions, Ecology's Northwest Regional Office will be notified immediately. In addition,

observations of fish or wildlife impacts will be immediately reported to the Region 4 (Mill Creek) office of WDFW.

10.4. Post-Treatment Monitoring

Long-term water quality monitoring will be conducted by the King County Volunteer Monitoring Program for a 10-year period after the alum treatment has been completed. The objective of post-treatment monitoring will be to evaluate whether the total phosphorus goal (summer mean value less than 20 µg/L) and Secchi depth goal (summer mean value greater than 2.5 meters) for Green Lake are being met. The design of post-treatment monitoring generally follows that used for Green Lake since the first alum treatment in 1991.

Monitoring will occur on 12 occasions from May through October, beginning in May 2016. Secchi depth will be measured and water samples will be collected from the Index station at a depth of 1 meter. The surface samples will be analyzed for the following parameters:

- Temperature (field measurement)
- Total phosphorus
- Total nitrogen
- Chlorophyll *a*

In addition, mid-depth and near-bottom samples will be collected on two occasions each year and analyzed for these same parameters. Surface samples will also be analyzed for alkalinity, soluble reactive phosphorus, nitrate+nitrite nitrogen, ammonia nitrogen, and ultraviolet absorbance on those two additional occasions each year.

It is expected that additional water quality monitoring of Green Lake will be conducted by others to address public health concerns. If a cyanobacteria bloom is observed in Green Lake, King County or a volunteer will collect a surface scum sample for analysis of cyanotoxin (microcystin and anatoxin-a) concentrations, and phytoplankton species presence. In addition, King County Department of Natural Resources will continue monitoring microcystin and fecal coliform bacteria at the swimming beaches in Green Lake. These additional monitoring procedures are further described by Herrera (2015).

10.5. Treatment Evaluation

Herrera and Tetra Tech will prepare a water quality monitoring report that presents and evaluates data collected for the jar tests, treatment monitoring, and first year of post-treatment monitoring. Field and laboratory results will be tabulated in spreadsheets that include associated data qualifiers for estimated values, rejected values, and values exceeding established thresholds, goals, or water quality criteria. Laboratory reports and quality assurance worksheets will be included in the monitoring report. Data quality assurance reports will be prepared that summarize the following information:

- Changes in the monitoring plan
- Significant quality assurance problems and corrective actions

- Data quality assessment in terms of precision, accuracy, representativeness, completeness, comparability, and detection limits
- Discussion of whether the quality assurance objectives were met, and the resulting impact on decision-making
- Limitations on use of the measurement data.

The monitoring report will describe the monitoring methods, present data tables, and discuss the monitoring results. The pre-treatment jar test results will be discussed relative to test implications for the 2016 alum treatment. Treatment monitoring results will be compared to the permit requirements and the short-term water quality impact of the alum treatment will be discussed. Post-treatment monitoring values will be evaluated by comparison with water quality goals and historical data.

11. PUBLIC INVOLVEMENT PLAN

Green Lake has been closed for contact recreation, such as swimming, in recent years because the water quality was deemed unsafe for public use due to blooms of toxic cyanobacteria. In 2014, in response to those closures and as a result of ongoing water quality monitoring of Green Lake, Seattle Parks and Recreation funded a study (Herrera 2015) of the short- and long-term effects of the 1991 and 2004 alum treatments of Green Lake The study demonstrated that the previous alum treatments reduced phosphorus and cyanobacteria blooms in the lake. As a result of the study, the City allocated $1.5 million to treat Green Lake with alum again. Seattle Parks and Recreation is contracting with Herrera to design, engineer, and permit the alum treatment for Green Lake.

Seattle Parks and Recreation requested that the alum treatment project be moved up 1 year in the Capital Improvement Project list so that the planning and design for the treatment would be done in 2015 and the actual treatment done in 2016. By accelerating the funding by a year, Seattle Parks and Recreation could move forward in 2015 with necessary lake testing and treatment permitting from Ecology, which is required before the alum treatment can begin. In November 2014, the Seattle City Council Budget Committee reallocated $300,000 to fund the initial treatment work. Also, in early 2015, Seattle Parks and Recreation met with the Friends of Green Lake and the Green Lake Community Council to keep them informed of project status.

After a warm winter and early spring, Seattle Parks and Recreation prepared for the possibility of another algae bloom at Green Lake in 2015 by creating new public informational water quality signs and placing them in six locations around the lake. The signs were developed in partnership with the King County Department of Natural Resources and Parks, Health Department of Seattle & King County, Washington State Department of Ecology, and Washington State Department of Health.

Seattle Parks and Recreation has developed a public involvement plan in preparation for the proposed alum treatment at Green Lake in the spring of 2016. The goal of the public involvement is to inform and educate park users and nearby residents of the proposed alum treatment. It will provide answers to questions about why alum treatment is the appropriate lake restoration tool at this time and will address public concerns about the use of alum in the lake environment. The public involvement plan will comply with Seattle Parks and Recreation's Public Involvement Policy and has been through Seattle Parks and Recreation Racial Equity Toolkit Assessment Worksheet.

The public involvement plan for the treatment work includes:

- Three signs, measuring at least 4 feet by 4 feet, will be erected at Green Lake in December 2015 to outline the proposed alum treatment, describe why the treatment is needed, provide the schedule for the proposed treatment in spring 2016, outline anticipated impacts, and announce all the public meetings associated with the proposed treatment. One sign will be placed near the Green Lake Community Center,

one near the Green Lake Bathhouse Theatre, and one near the Aqua Theater. The name of the Seattle Parks and Recreation's project manager, with his phone number and email address, will be provided as the primary contact for the project.

- Informative postcards will be distributed to all households within a 1/4-mile radius of Green Lake Park. The postcards will state why the alum is needed, will provide the proposed schedule for alum treatment in spring 2016, and will announce the public meeting, scheduled for February 2016, that is associated with the proposed treatment. The name, phone number, and email address of the Seattle Parks and Recreation project manager will be included. The postcards will also be sent to representatives of the Green Lake Community Center Advisory Council, the Green Lake Rowing Advisory Council, the Green Lake Community Council, and an additional stakeholder list for Green Lake.
- A public meeting will be held in late February 2016 at the Green Lake Community Center. The purpose of the meeting is to explain the proposed alum treatment and to address public concerns about the proposal. The meeting will be announced in the postcard noted above along with standard public meeting notice (posted on Seattle Parks and Recreation's public calendar, a press release, social media, and flyers posted in the vicinity of Green Lake).
- Seattle Parks and Recreation will endeavor to have the public meeting press release picked up by local media and announced in local blogs and social media outlets in the Green Lake area. The press release will be posted at the six informational water quality signs around the lake.
- The meeting announcement will be posted on Seattle Parks and Recreation's project website. The meeting agenda and notes from the meeting will also be posted on the website, at http://www.seattle.gov/parks/projects/green_lake/alum.htm.
- Seattle Parks and Recreation will host the public meeting at the Green Lake Community Center. Both the Seattle Parks and Recreation project manager and the consultant (Herrera) will make presentations at the meeting.
- A project update will be given to the Board of Parks Commissioners (the official citizen advisory body for Seattle Parks and Recreation) in spring 2016.
- To the degree necessary, the Seattle Parks and Recreation project manager will make presentations in February and March 2016 at meetings of the Green Lake Community Center Advisory Council, the Green Lake Rowing Advisory Council, the Green Lake Community Council, and other appropriate organizations interested in Green Lake. The intent of such efforts is to inform users of the lake and other interested citizens about the proposed alum treatment.
- Seattle Parks and Recreation will notify Ecology and WDFW of all the meetings noted above.
- Just prior to the alum application in the spring of 2016, a project update will be posted on the three project signs, at the Green Lake Community Center, and on the "current lake status signs."

- A press release will be sent out when the alum treatment begins in the spring of 2016. Seattle Parks and Recreation will endeavor to have the press release posted in local blogs and social media outlets in the Green Lake area.
- A large sign, measuring approximately 6 feet by 12 feet, will be erected at Green Lake in the spring of 2016 to educate lake users about the hydrology, phosphorus cycle, cyanobacteria, and restoration of Green Lake. It is anticipated that one sign will be placed near the Green Lake Community Center using simple terms and graphics, and will include Quick Response (QR) codes to obtain additional information.
- After the alum treatment, water quality monitoring results will be reported on the project website by the end of 2016.

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APPENDIX A

Water Quality Data

Table A1. 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 (-)	Cyano-phyta (%)	Chloro-phyta (%)	Chryso-phyta (%)	Other Groups (%)	Total Phyto (mm^3/L)	Total Cyano (mm^3/L)	Micro-cystis (mm^3/L)	Ana-baena (mm^3/L)	Aphani-zomenon (mm^3/L)	Gloeotri-chia (mm^3/L)	Woroni-chinia (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

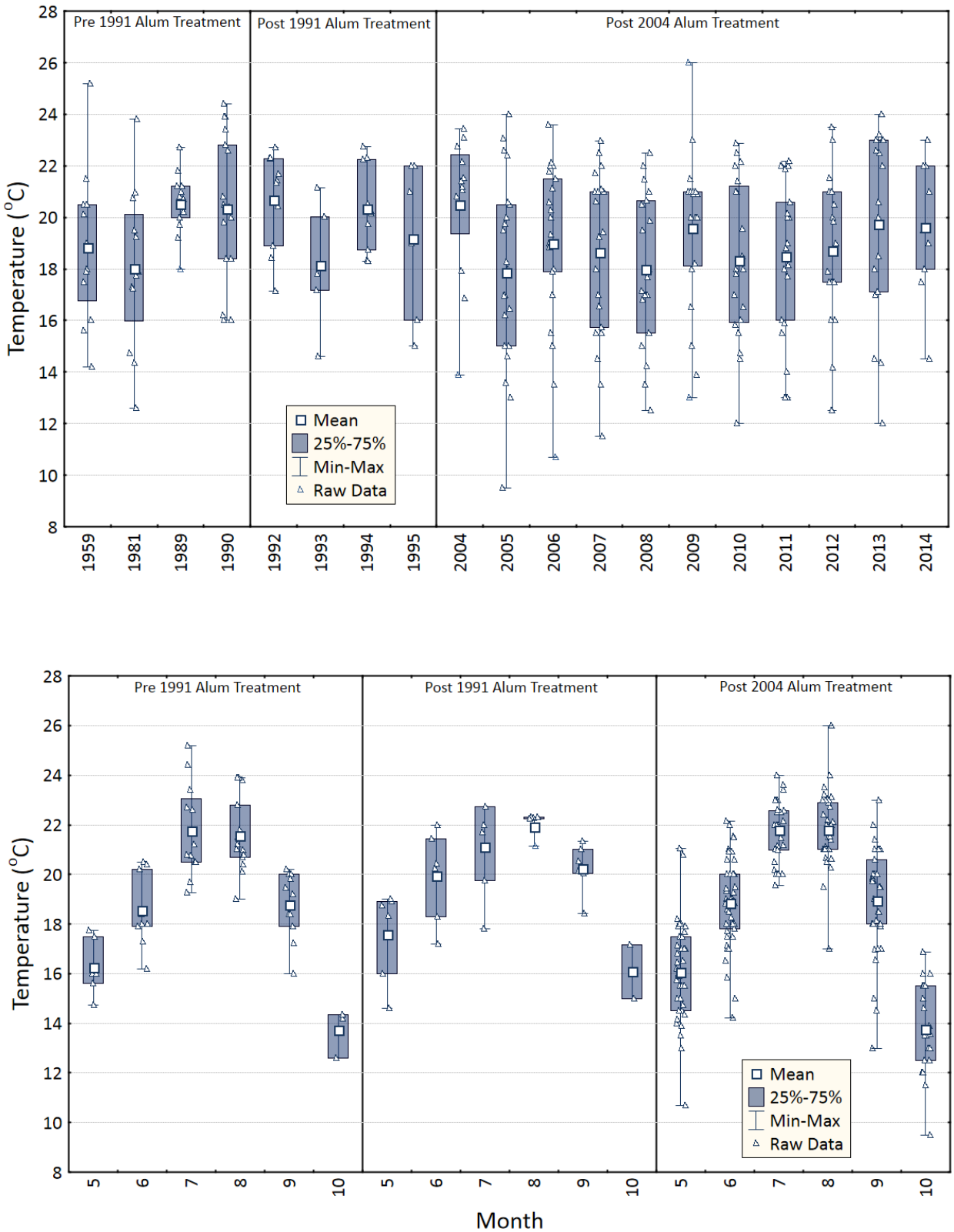

Figure A1. Water Temperature by Study Year and Month for Summer in Green Lake.

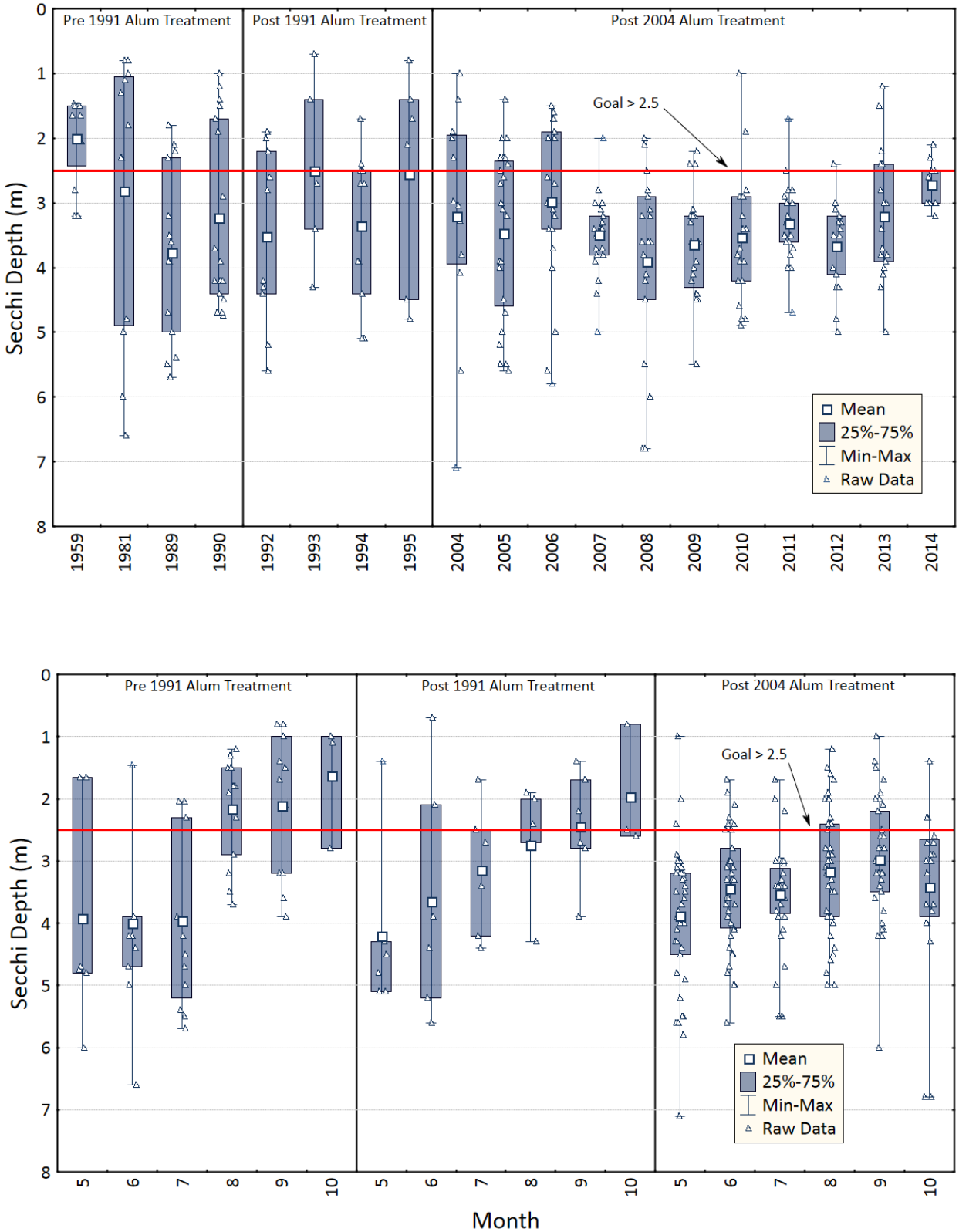

Figure A2. Secchi Depth by Study Year and Month for Summer in Green Lake.

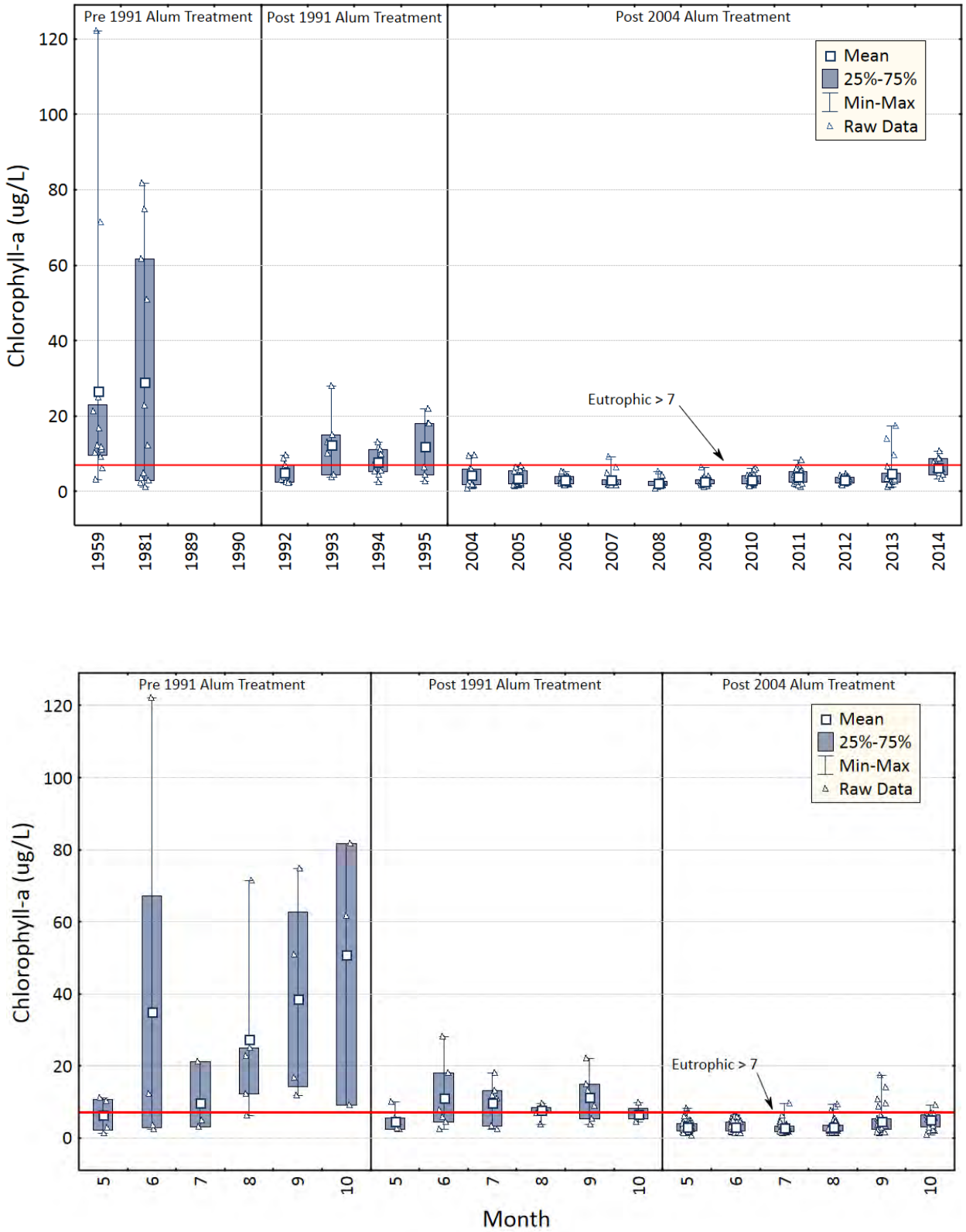

Figure A3. Chlorophyll by Study Year and Month for Summer in Green Lake.

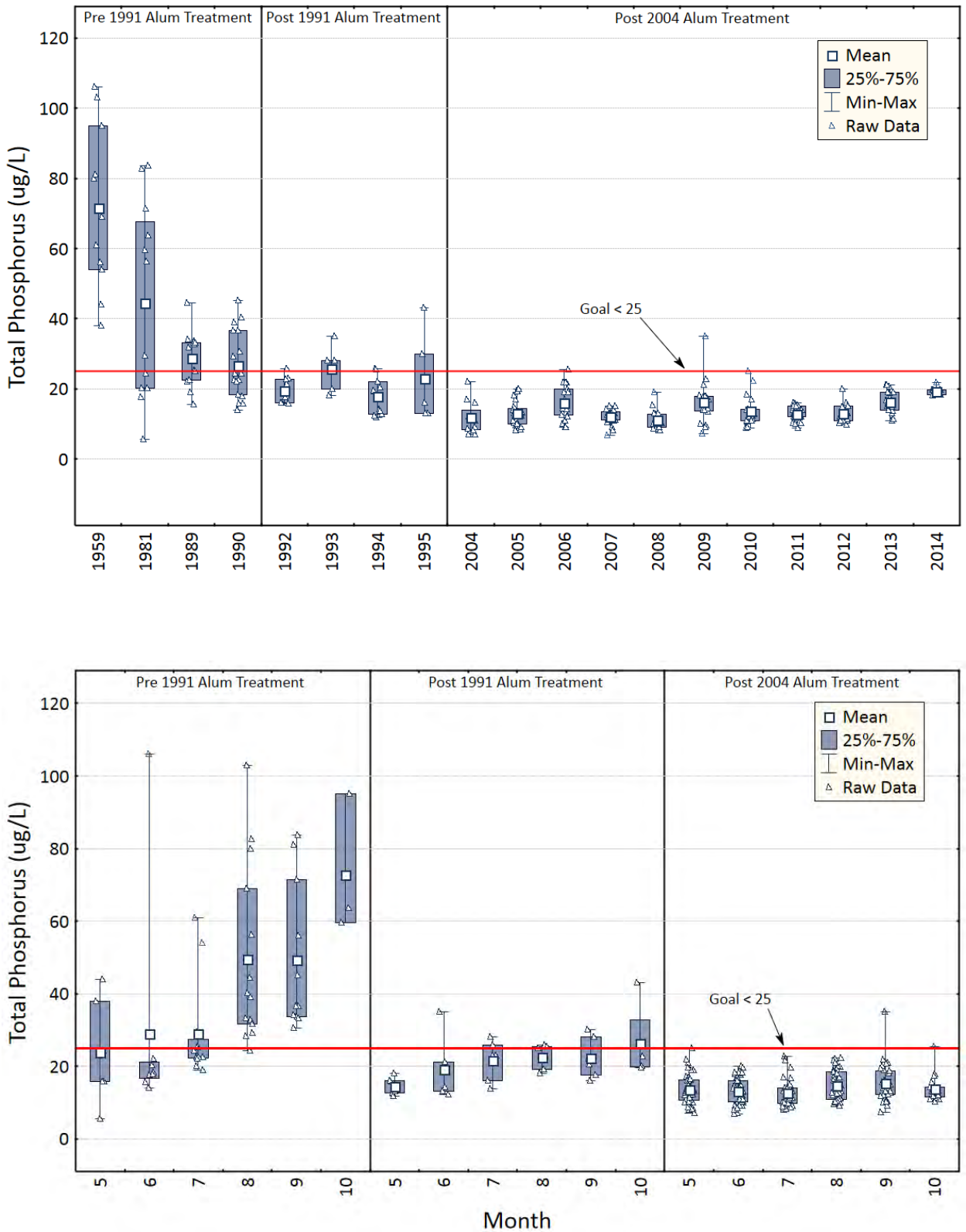

Figure A4. Total Phosphorus by Study Year and Month for Summer in Green Lake.

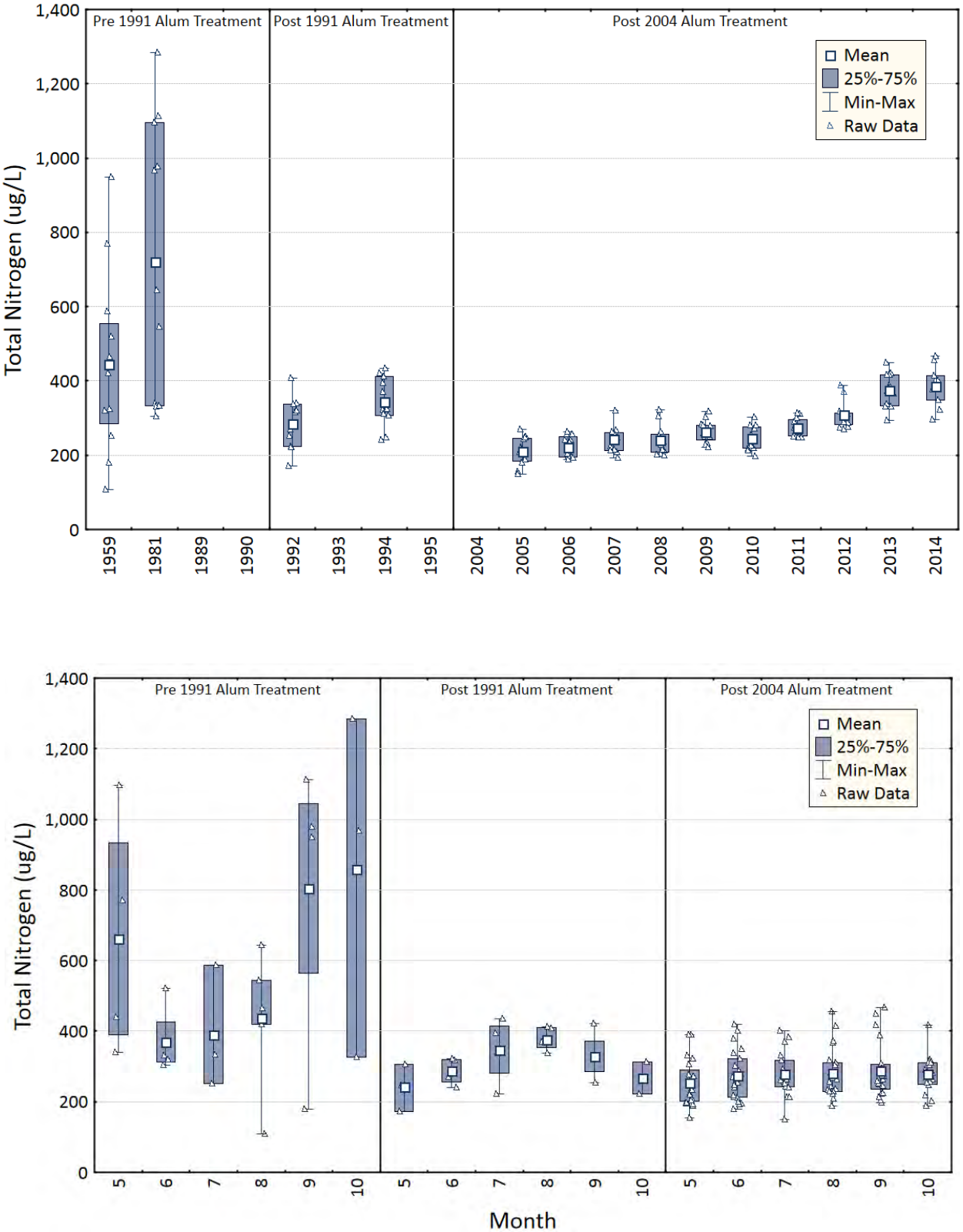

Figure A5. Total Nitrogen by Study Year and Month for Summer in Green Lake.

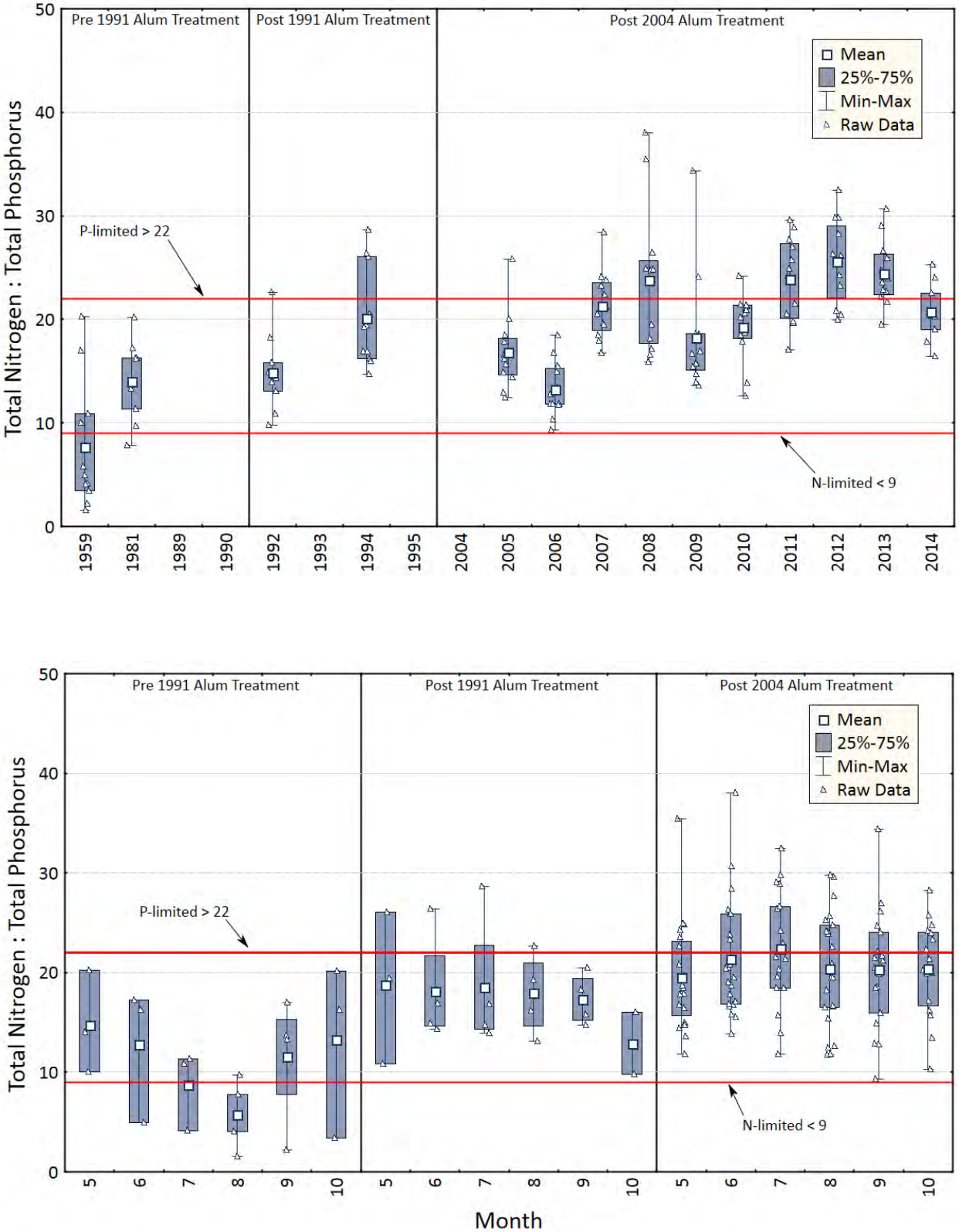

Figure A6. Total Nitrogen to Total Phosphorus Ratio by Study Year and Month for Summer in Green Lake.

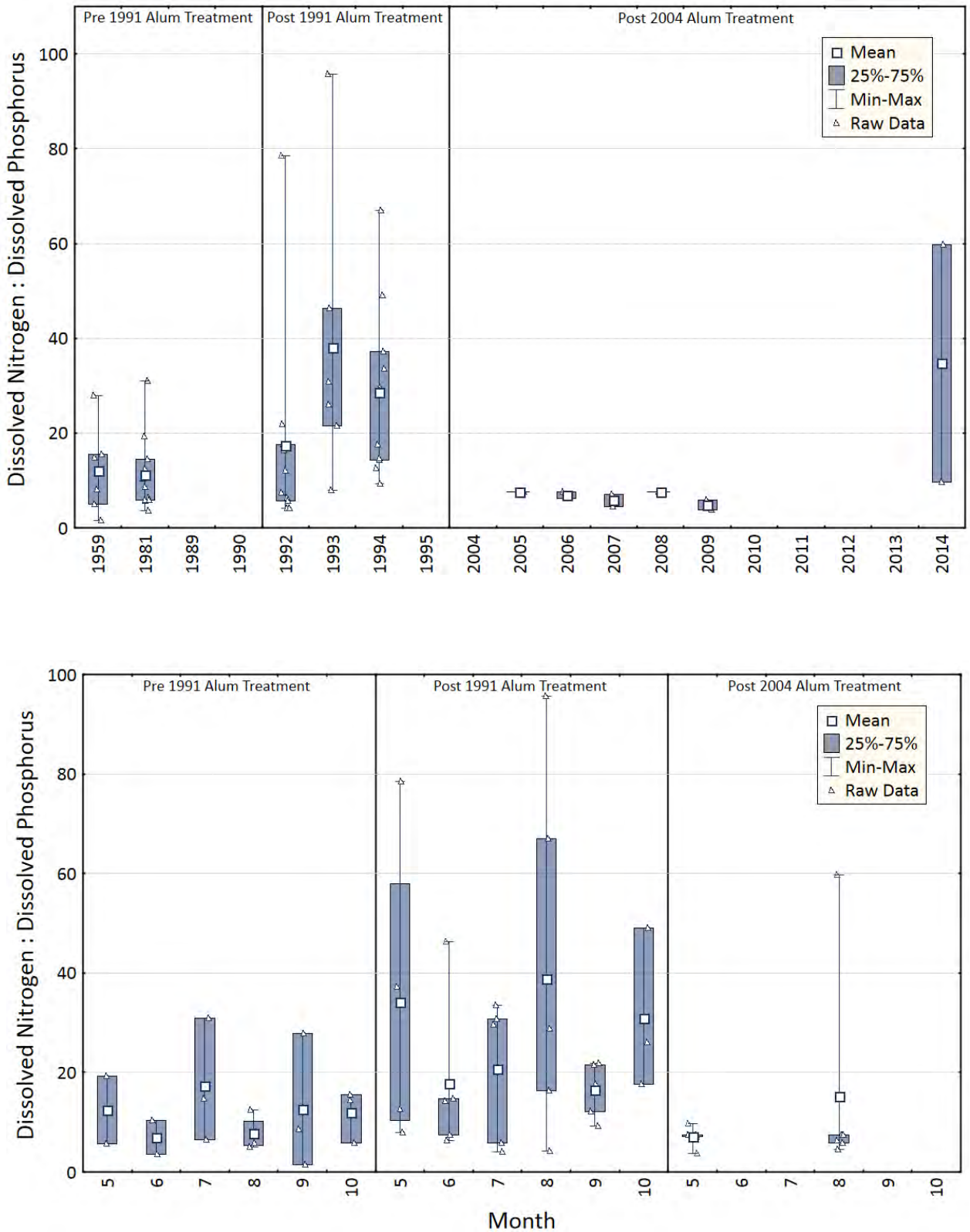

Figure A7. Dissolved Nitrogen to Total Phosphorus Ratio by Study Year and Month for Summer in Green Lake.

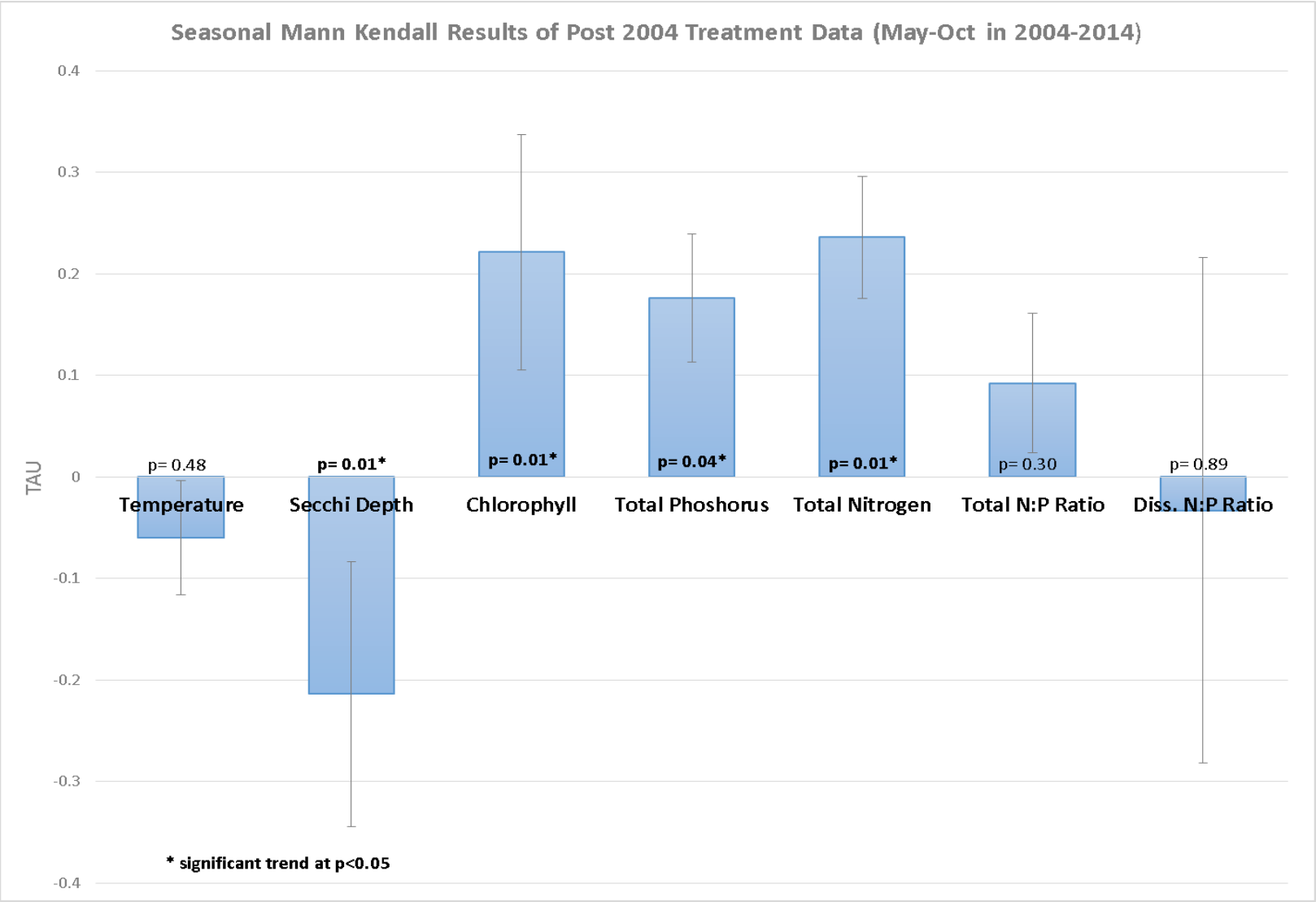

Figure A8. Seasonal Mann Kendall Test Results of Post 2004 Alum Treatment Water Quality Data for Green Lake.

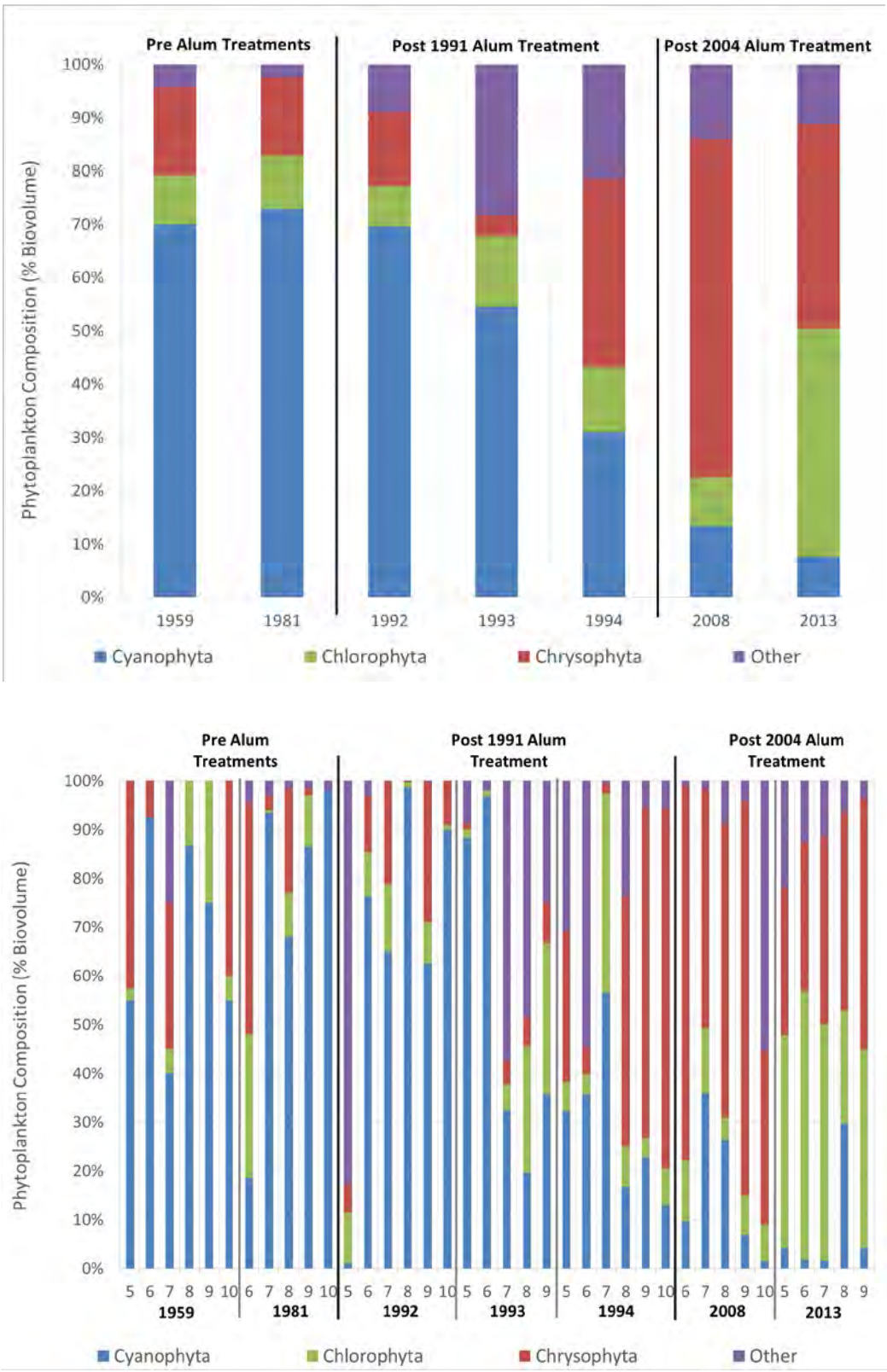

Figure A9. Phytoplankton Group Composition by Study Year and Month for Summer in Green Lake.

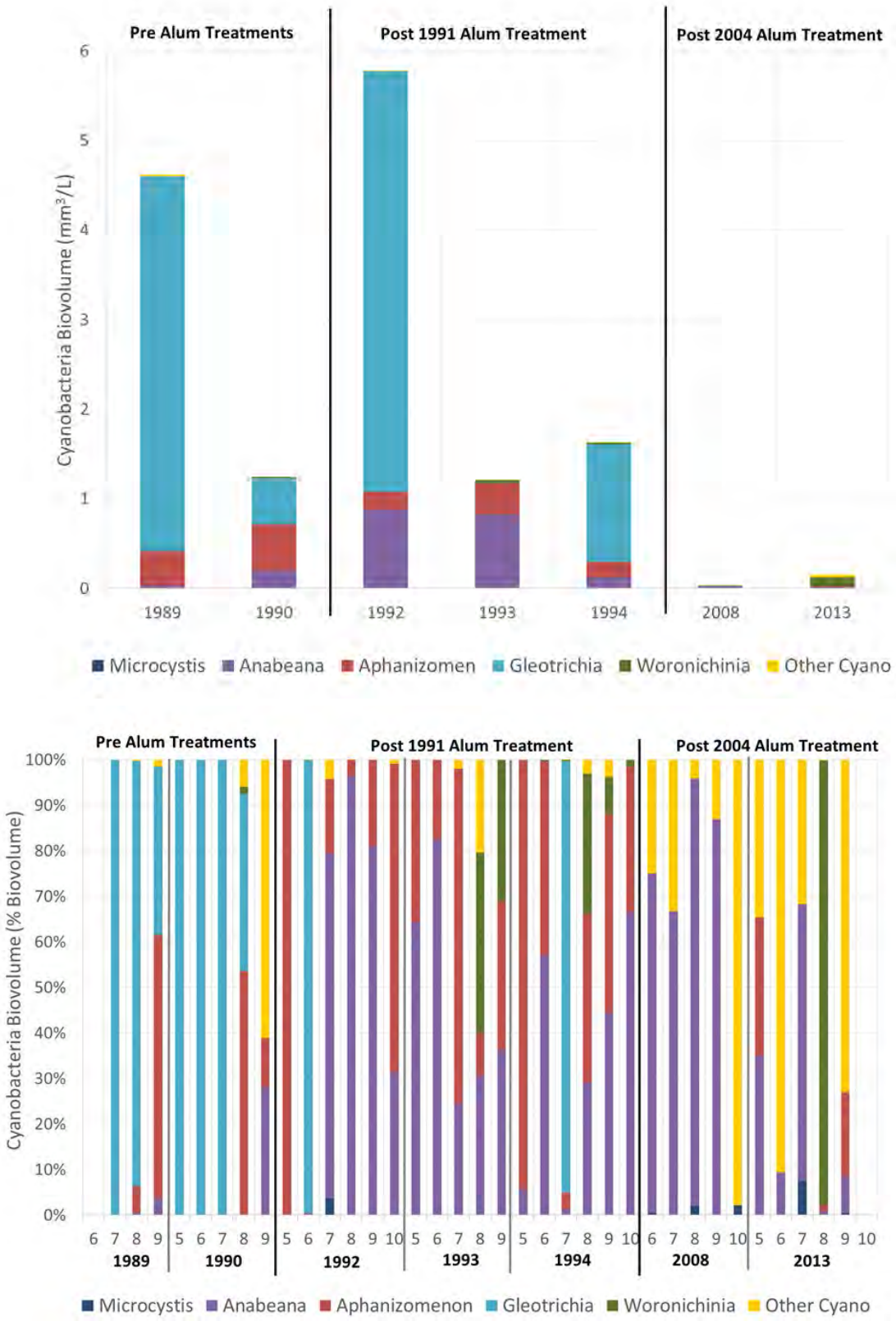

Figure A10. Cyanobacteria Biovolume by Study Year and Composition by Month for Summer in Green Lake.

APPENDIX B

Sediment Phosphorus Analysis

TECHNICAL MEMORANDUM

Date: July 2, 2015

To: Robert E. Lee, Seattle Parks and Recreation

Copy to: Harry Gibbons, Tetra Tech

From: Rob Zisette, Herrera Environmental Consultants

Subject: Green Lake Sediment Phosphorus Analysis

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Figure 1. Green Lake Sediment Sampling Stations, May 4, 2015. 3

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.

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. Seattle Parks is currently planning to treat Green Lake with alum in Spring 2016 to reduce phosphorus and cyanobacteria blooms, and improve recreational use of the lake based on recommendations from the Green Lake Phytoplankton Study (Herrera 2015).

To support the planned alum application, updated information on sediment phosphorus concentrations was needed to refine the treatment design. This memorandum presents methods and results of sediment sampling conducted in May 2015, and compares those results to historical sediment data collected in 1998 and 2004 (before and after the 2004 alum treatment, respectively).This sediment core analysis was performed to evaluate recent changes in sediment phosphorus concentrations, and evaluate alternative alum treatment designs to effectively intercept sediment phosphorus and reduce cyanobacteria growth. This information will be used to design the 2016 alum treatment and prepare a phosphorus management plan, which will contain additional information about the lake and treatment for the required Aquatic Plant and Algae Management General Permit.

Methods

Sediment cores were collected on May 4, 2015 at four previously sampled locations in Green Lake (Index, Station A, Station B, and Littoral) (Figure 1). One core was collected at the deepest portion of the lake (23 feet deep at Index) and one core was collected at each of the three shallow stations (14 feet deep at Station A, 9 feet deep at Station B, and 10 feet deep at Littoral).

Legend

- 2015 sediment station
- 2004 sediment station
- Water quality 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 1.
Green Lake Sediment Sampling Stations, May 4, 2015.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

K:\Projects\Y2013\13-05709-000\Project\Phytoplankton_report\monitoring_stations_features.mxd (7/1/2015)

A scuba diver advanced a 3-foot-long, 2-inch-diameter plastic (polycarbonate) tube slowly into the sediment by gently tapping it down. The diver then placed a cap on the top and bottom of the core, pulled the core from sediment, and transferred it to the boat where it was placed in a bucket with ice, and covered to exclude light. The four cores were stored in a refrigerator until processing the following day. The scuba diver also took underwater video and photographs of each sampling area (submitted separately).

Each sediment core was partitioned into eight depth intervals down to 30 centimeters (cm): 0-2 cm, 2-4 cm. 4-6 cm, 6-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, and 25-30 cm. Three field duplicate samples were also collected and submitted for analysis from the following core depth intervals: 10-15 cm at Index, 15-20 cm at Station A, and 25-30 cm at Station B.

Each interval sample was obtained by pushing sediment up the core tube with a rod and removing the specified depth of sediment from the top of the core tube with a small, decontaminated spoon. Each sample was placed in a new sample jar provided by the laboratory, homogenized with the spoon, and stored in a cooler with ice.

A toal of 32 depth-interval samples and 3 field duplicate samples were submitted to IEH Analytical Laboratories in Seattle, Washington for analysis. The following phosphorus fractions were analyzed by Standard Method 4500PF and EPA Method 365.1:

- Labile phosphorus(loosely bound P)
- Iron bound phosphorus (Fe-P)
- Biogenic phosphorus (biogenic P)
- Organic phosphorus (organic P)
- Calcium bound phosphorus (Ca-P)
- Aluminum-bound phosphorus (Al-P)
- Total phosphorus (TP)

The following supplemental parameters were also analyzed:

- Total solids and percent water by Standard Method 2540B
- Total aluminum, iron, and calcium by EPA Method 6010

Sediment cores were collected from Green Lake in 1998 and 2004, representing seven years after the 1991 alum treatment and six months after the 2004 alum treatment, respectively. These cores were collected using similar coring techniques, and the samples were analyzed using similar methods by different laboratories to those used in 2015.

The 2004 cores were collected from the same four stations sampled in 2015 (see Figure 1), and were divided into 1 cm intervals down to 10 cm depth and thereafter at 15, 20, 25, 30, 35, and 40 cm depths. Each sample was analyzed for the same phosphorus fractions as listed above except biogenic phosphorus, and were also analyzed for total aluminum. The cores were collected by Herrera divers and analyzed by Rebecca Dugopolski (graduate student at the University of Washington Environmental Engineering Department), and the data were

presented in the Year 1 Post-Treatment Monitoring Report for the 2004 alum treatment (Herrera 2005).

The exact location of the 1998 cores is unknown except that they were known to be collected near the Index station and Station A. The two 1998 cores were divided into 1 cm intervals down to 15 cm depth and thereafter at 20 and 25 cm depths. Each sample and four duplicate samples were analyzed for the same phosphorus fractions as listed above, except biogenic phosphorus. The cores were collected and analyzed by Emil Rydin (visiting scientist at the University of Washington Department of Civil Engineering), and the data were presented in the Integrated Phosphorus Management Plan for the 2004 alum treatment (Herrera 2003).

Results

Sediment profile charts are provided in Appendix A. The sediment database is provided in Appendix B. The laboratory data report is provided in Appendix C.

Data Quality Review

A quality assurance review of the sediment data was performed to ensure that the data collected are of known and acceptable quality. The data were reviewed for precision, accuracy, representativeness, and completeness using laboratory method blanks, laboratory control samples (LCS), laboratory duplicate samples, and the three field duplicate samples.

All of the laboratory analyses were conducted as planned and the laboratory results were 100 percent complete. The laboratory (IEH Analytical Laboratories) provided all of the quality control data required by the analytical methods. The following data quality control objectives were met:

- Method blanks did not contain target parameters above the reporting limits
- Laboratory duplicate sample relative percent difference (RPD) values (ranging from 0.9 to 8.7 percent) met the method control limit of less than 20 percent
- LCS percent recovery values (ranging from 90 to 107 percent) met the method control limits of 90 to 110 percent recovery
- Field duplicate RPD values (ranging from 0.1 to 17 percent) met the less than 20 percent control limit, with the exception noted below.

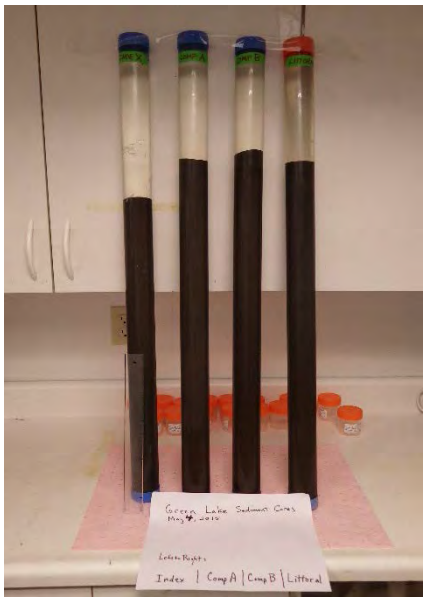
The field duplicate RPD value (122 percent) for sample B-25-30 and field duplicate sample Dup-3 exceeded the less than 20 percent criterion for Fe-P. Only the Fe-P result for sample B-25-30 was qualified (flagged) as estimated (J) because all other quality control criteria were met.

Physical Characteristics

The total depth of sediment obtained from all four locations was 66 cm. The cores were very similar in appearance (see lower photograph). Sediment in the cores was described as watery, dark brown silt in the top 2 cm (see upper photograph) and decreasing water content with

depth to a firm dark brown silt at 30 to 40 cm depth. No alum particles or debris were observed in any of the sediment cores. A single blood worm was observed in each of the following intervals: 15 to 20 cm, 20 to 25 cm, and 25 to 30 cm in the Station A core; and 10 to 15 cm in the Station B core.

Green Lake sediments had a typically high water content (89 percent average) that ranged from 83 to 93 percent and generally decreased with depth in all cores (see Appendix B).



Green Lake Sediment Cores, May 4, 2015.

Phosphorus

The 2015 sediment phosphorus data are presented as profiles in Figure A-1 (Index and Station A) and Figure A-2 (Station B and Littoral). Labile phosphorus was not detected in any of the samples (less than a detection limit of 2 milligrams per kilogram [mg/kg] dry weight). Iron bound phosphorus (Fe-P) concentrations were low, ranging from 6.3 to 35 mg/kg in all samples, and displayed no consistent depth or spatial patterns.

Organic phosphorus concentrations ranged from 321 to 1,055 mg/kg among all samples. Biogenic phosphorus ranged from 160 to 779 mg/kg. Biogenic phosphorus is the portion of organic phosphorus most susceptible to remineralization in which organic fractions are transformed to inorganic fractions by microbial activity. Biogenic and organic phosphorus exhibited similar patterns in the cores. The biogenic to organic phosphorus ratio averaged 0.64 and ranged from 0.47 to 0.77 among all samples. This ratio did not vary consistently with depth indicating that it has not changed appreciably with time in Green Lake.

Biogenic and organic phosphorus concentrations generally decreased with depth at the shallow stations and were highest at the surface of the Littoral station. The higher organic phosphorus at the surface of the Littoral station may be due to organic matter from Eurasian watermilfoil that has been increasingly abundance near this station since the 2004 alum treatment and is not abundant near the other stations (see Figure 1). The biogenic and organic phosphorus profiles were different at the deep Index station where concentrations were depressed just below the surface (i.e., at 2 to 6 cm depth), and somewhat elevated at lower depths (i.e., at 6 to 20 cm depth). This may be due in part to less sedimentation of organic phosphorus from less phytoplankton production following the 2004 alum treatment, based on an approximate sedimentation rate of 0.5 cm per year for Green Lake.

Calcium bound phosphorus (Ca-P) concentrations ranged from 164 to 341 mg/kg and were typically higher in the upper 10 cm of the cores with the exception of a depressed value in the 2-4 cm interval of the deep core from Index.

Aluminum bound phosphorus (Al-P) concentrations exhibited a wide range from 205 to 1,265 mg/kg, with variable depth and spatial patterns among all core samples. Al-P concentrations were much higher in the deep Index station (680 to 1,263 mg/kg) than the three shallow stations (205 to 662 mg/kg), and were highest below 15 cm depth at the deep station and highest above 15 cm depth at the shallow stations (with the exception of an unusually low value for surface 0-2 cm sample from the Littoral station).

Total phosphorus (TP) concentrations ranged from 751 to 1,979 mg/kg among all core samples. TP concentrations were depressed in the 2-4 cm interval of cores from each station except Littoral, due to the depressed organic P and Al-P concentrations at that interval. TP concentrations were highest below 15 cm depth in the deep core and highest above 15 cm depth in the shallow cores, primarily due to the Al-P concentrations.

Cations

The 2015 sediment cation data are presented in Figures A-3 (Index and Station A) and A-4 (Station B and Littoral). Results of all four cores are generally similar for calcium (ranging from 4,524 to 8,828 mg/kg), aluminum (ranging from 15,910 to 29,828 mg/kg), and iron (ranging from 16,557 to 31,521 mg/kg), with the exception of depressed concentrations of all three cations in the 2-4 cm interval at the deep Index station.

The iron to phosphorus (Fe:P) ratio was high, ranging from 14 to 25 among all samples (see database in Appendix B). The Fe:P ratio should exceed 10 if it is to regulate phosphorus release and should exceed 15 to prevent phosphorus release from oxidized sediments (Sondergaard et al. 2003). The high Fe:P ratios observed suggest that phosphorus release from oxidized sediments is low in Green Lake.

Historical Data Comparison

The 2004 sediment phosphorus data collected 6 months after the 2004 alum treatment are presented in Figures A-5 (Index and Station A) and Figure A-6 (Station B and Littoral), and the 1998 sediment phosphorus data are presented in Figure A-7 (Index and Station A). The labile P and Fe-P concentrations in the 2015 sediment samples were lower than both previous years. However, the organic phosphorus, Ca-P, Al-P, and TP concentrations generally increased in 2015.

Mobile phosphorus was calculated as the sum of labile P and Fe-P using the detection limit for undetected values. Mobile phosphorus profiles for 1998, 2004, and 2015 are compared in Figure A-8 for Index and Station A. These results show that the 2004 alum treatment reduced the mobile phosphorus concentrations in the upper 15 to 20 cm of sediment, and this reduction was much more pronounced at the deep Index station than shallow Station A. Mobile phosphorus concentrations were substantially lower in 2015 to uniformly low concentrations throughout all of the cores, suggesting that mobile phosphorus continued to bind with free aluminum remaining in the sediment since the 2004 alum treatment.

Organic phosphorus profiles for 1998, 2004, and 2015 are compared in Figure A-9 for Index and Station A. These results show that organic phosphorus concentrations increased between 1998 and 2004 and were even higher in 2015, with the exception of depressed organic phosphorus concentrations near the surface (2-6 cm depth) of the Index core.

Ca-P profiles for 1998, 2004, and 2015 are compared in Figure A-10 for Index and Station A. These results show that Ca-P concentrations were somewhat lower in 2004 than 1998 at Index but not Station A, and were substantially higher at all depths at both stations in 2015.

Al-P profiles for 1998, 2004, and 2015 are compared in Figure A-11 for Index and Station A. These results show that Al-P concentrations were higher in 2004 than 1998 in the upper 10 cm of sediment at both stations, and even higher in 2015 at most depth intervals in the cores from both stations. These results further suggest that mobile phosphorus present since 2004 continued to bind with free aluminum remaining in the sediment as a result of the 2004 alum treatment.

TP profiles for 1998, 2004, and 2015 are compared in Figure A-12 for Index and Station A. These results show that TP concentrations were substantially higher in 2004 than 1998 throughout both the deep and shallow cores, and even higher in 2015 below 10 cm at Index and above 15 cm at Station A.

Total aluminum profiles for 2004 and 2015 are compared in Figure A-13 for Index and Station A. Total aluminum concentrations throughout the cores from both stations were substantially less in 2015 sediment (ranging from 15,900 to 29,800 mg/kg) than 2004 sediment (ranging from (22,200 to 160,000 mg/kg) (Appendix B). This large discrepancy suggests that either the 2004 results were overestimated or the 2015 results were underestimated because total aluminum concentrations should not have changed much since the 2004 alum treatment. Similar methods were used for both sets of analyses (digestion in hot acid and analysis by inductively coupled plasma [ICP]), but quality control data are not available for the 2004 results to determine if they may be biased high.

Average mobile and biogenic P concentrations in the upper 20 cm of sediment are summarized in Table 1. A depth of 20 cm was selected for averaging because this was the target depth used to inactivate mobile phosphorus for the 2004 alum treatment. Sample values were weighted for the depth of the interval that they represented in the average calculation (e.g., the 0-2 cm sample was given a weight of 2 and the 15-20 cm sample was given a weight of 5). Depth-weighted concentrations are presented for each year and station, and an average value for the three shallow stations in 2004 and 2015 is also included. For comparison, an average mobile P concentration of 370 mg/kg was used to calculate the aluminum dose (17.2 mg Al/L) for the 2004 alum treatment (Herrera 2003). This value was based on an arithmetic (unweighted) mean value of all sample intervals from 0 to 20 cm depth in the deep (Index) and shallow (Station A) cores collected in 1998.

Table 1 shows the substantial decrease in average mobile P from 1998 to 2004 due to 2004 alum treatment, and a continued decrease from 2004 to 2015 apparently due to continued reaction of mobile P with free aluminum. Also evident is the increase in biogenic P from 1998 to 2004 and again from 2004 to 2015. The recent increases in water column phosphorus concentrations in Green Lake (Herrera 2015) may be explained in part by the recycling of increased biogenic P from lake sediments. Thus, both mobile and biogenic P concentrations

will be used for calculating the aluminum dose for the 2016 alum treatment. The sum of mobile and biogenic P fractions decreased from 1998 to 2004 and again from 2004 to 2015. This result suggests that less alum will be needed in 2016 than was applied in 2004.

Table 1. Depth-Weighted Mean Sediment Phosphorus Concentrations in 0-20 cm Core Interval at Green Lake.

Year/Station	Labile P (mg/kg DW)	Fe-P (mg/kg DW)	Mobile P (Labile+Fe-P) (mg/kg DW)	Biogenic P (mg/kg DW)[a]	Mobile+ Biogenic P (mg/kg DW)[a]
1998					
Index	11	427	438	*173*	*611*
Station A	8	277	285	*176*	*461*
2004					
Index	23	215	238	*241*	*479*
Station A	13	192	205	*209*	*414*
Station B	6	41	47	*250*	*297*
Littoral	8	102	110	*242*	*353*
Mean Shallow[b]	9	112	121	*234*	*355*
2015					
Index	2	20	22	401	423
Station A	2	12	14	288	303
Station B	2	14	16	453	470
Littoral	2	14	16	414	430
Mean Shallow[b]	2	14	16	385	401

[a] Biogenic P was estimated as 64% of organic P for 1998 and 2004 (*in italics*) based on the mean ratio in 2015 cores.

[b] Mean shallow = mean of shallow cores at Station A, Station B, and Littoral.

mg/kg DW = milligrams per kilogram dry weight

Conclusions

Based on comparison of sediment cores collected from Green Lake in 2015 to sediment cores collected in 1998 and 2004, the following changes have occurred since the 2004 alum treatment:

- The 2004 alum treatment reduced the mobile phosphorus concentrations in the upper 15 to 20 cm of sediment.
- Mobile phosphorus concentrations were substantially lower in 2015 to uniformly low concentrations throughout the 30 cm core depth, suggesting that mobile phosphorus present since 2004 continued to bind with free aluminum remaining in the sediment due to the 2004 alum treatment.
- Biogenic P concentrations in the upper 20 cm of sediment in were estimated to be higher 2004 than 1998 (based on the amount of organic phosphorus and applying the average ratio of biogenic to organic P measured throughout the core depth in 2015), and biogenic P concentrations were highest in 2015.

- Both mobile and biogenic P concentrations will be used for calculating the aluminum dose for the 2016 alum treatment, and the lower sum of these fractions observed in 2015 than estimated for 1998 suggests that less alum will be needed in 2016 than was applied in 2004.
- Total phosphorus concentrations were higher in 2015 than 2004 primarily due to higher concentrations of organic phosphorus and aluminum phosphorus.
- Total aluminum concentrations were much lower in 2015 than 2004, which suggests possible analytical error with either data set because total aluminum concentrations should not have changed much since the 2004 alum treatment.

References

Herrera. 2003. Green Lake Integrated Phosphorus Management Plan. Prepared for the City of Seattle Parks and Recreation, Seattle, Washington, by Herrera Environmental Consultants, Inc., Seattle, Washington.

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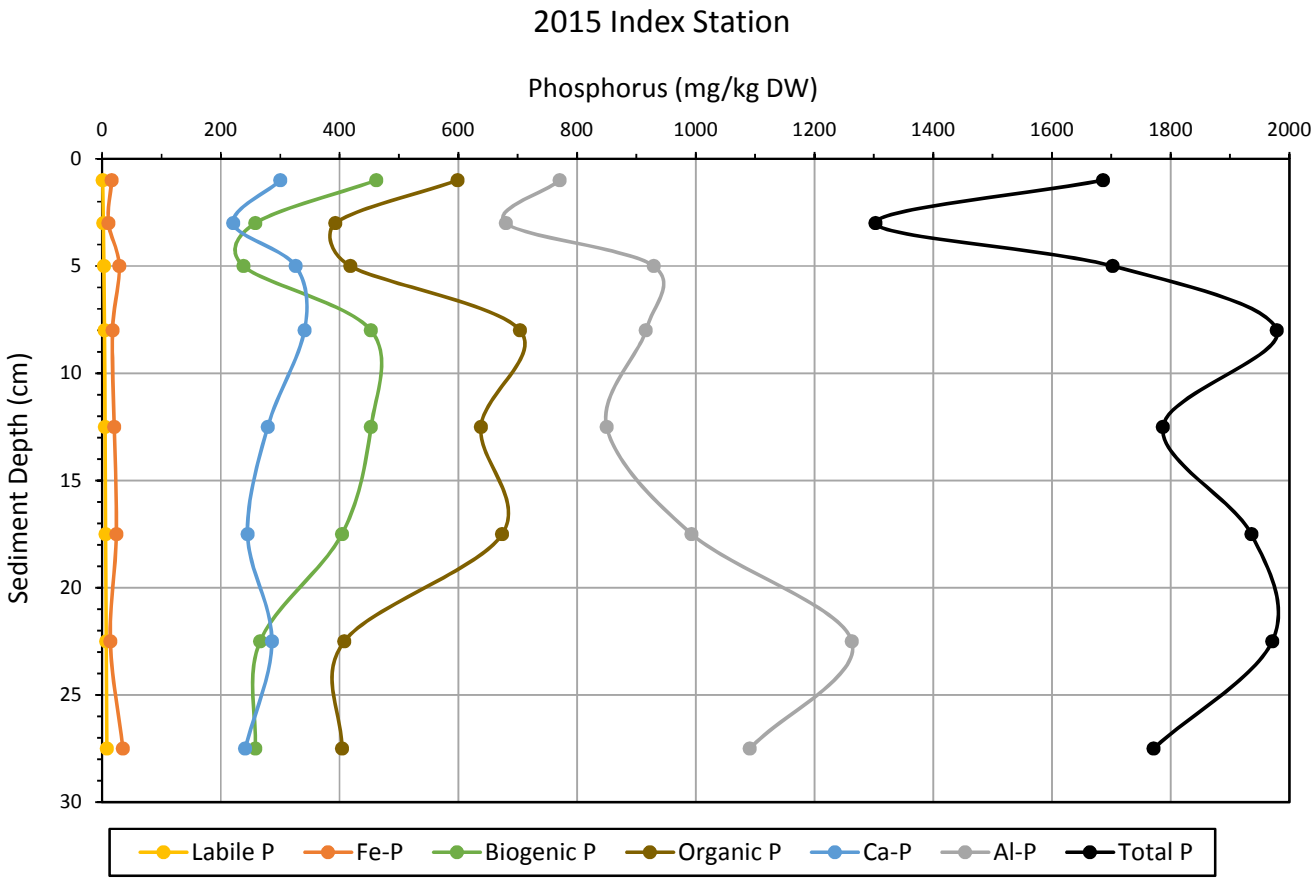
APPENDIX A

Sediment Profile Charts



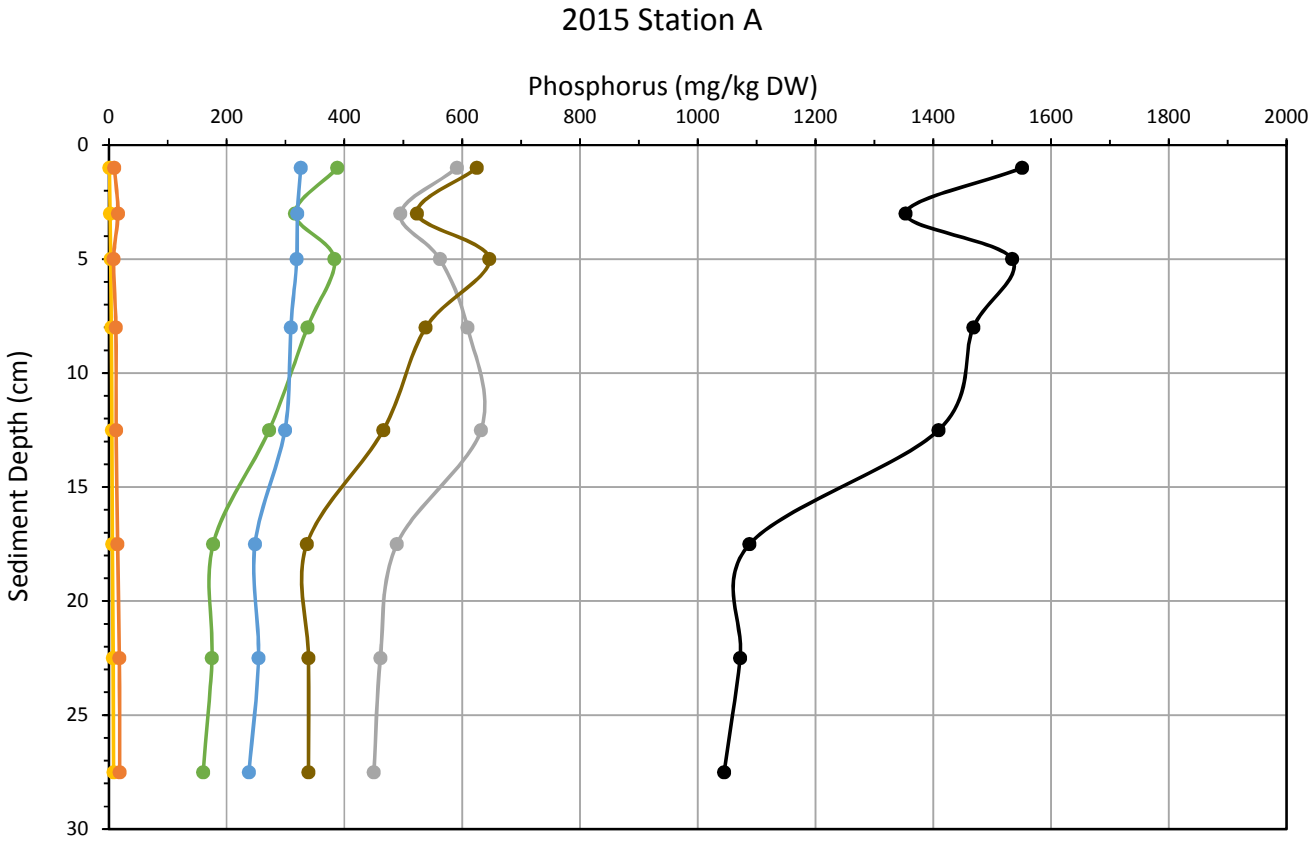
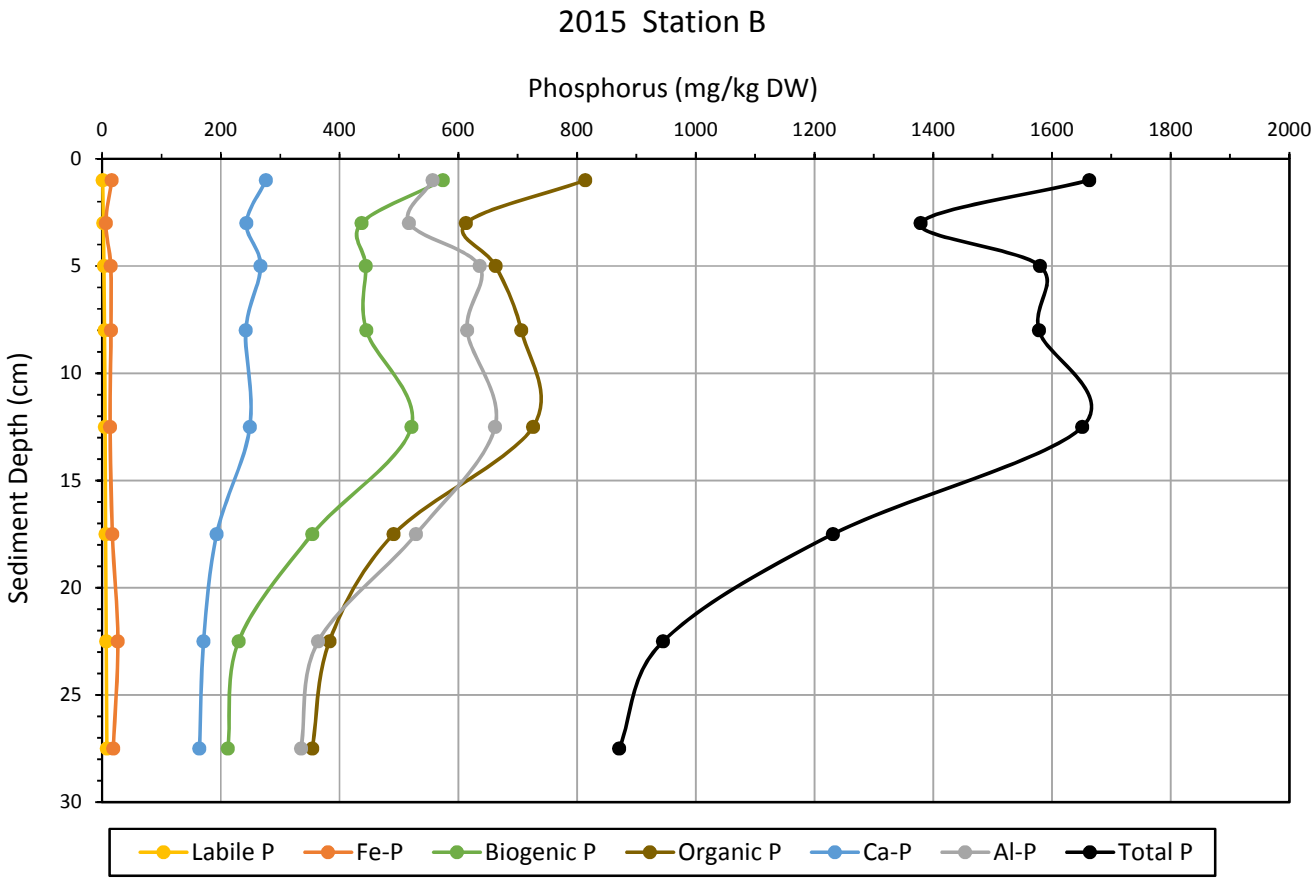


Figure A1. Green Lake Sediment Phosphorus in 2015 at Index and Station A.



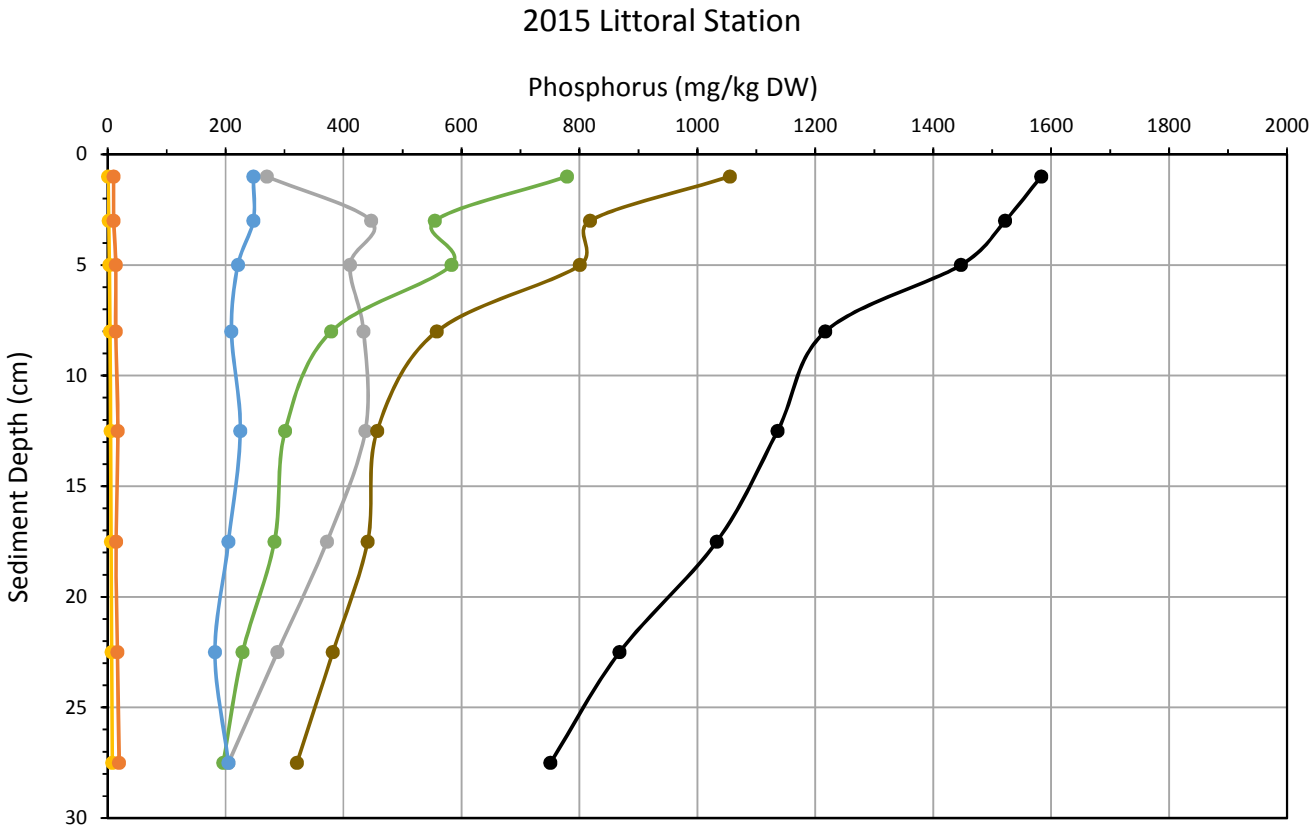
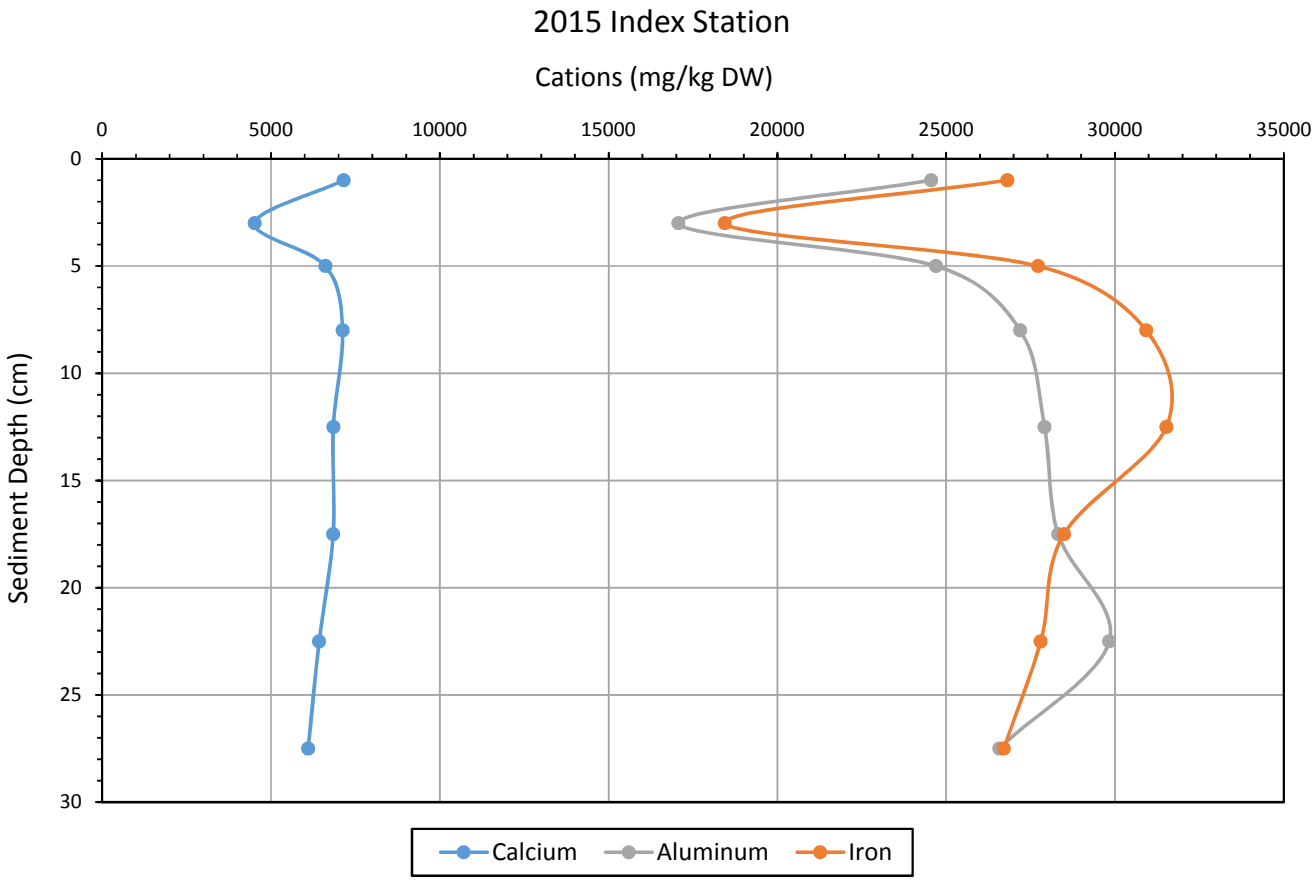


Figure A2. Green Lake Sediment Phosphorus in 2015 at Station B and Littoral Station.



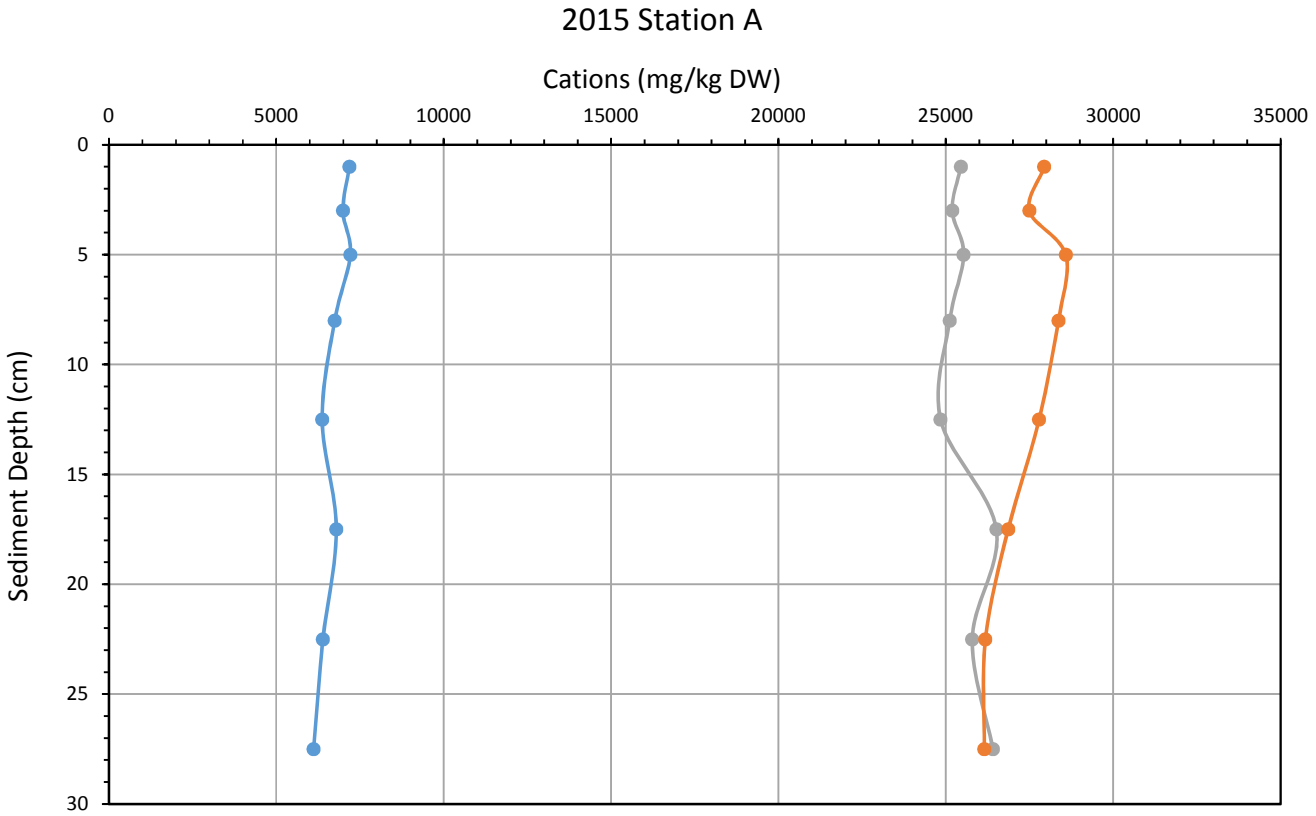
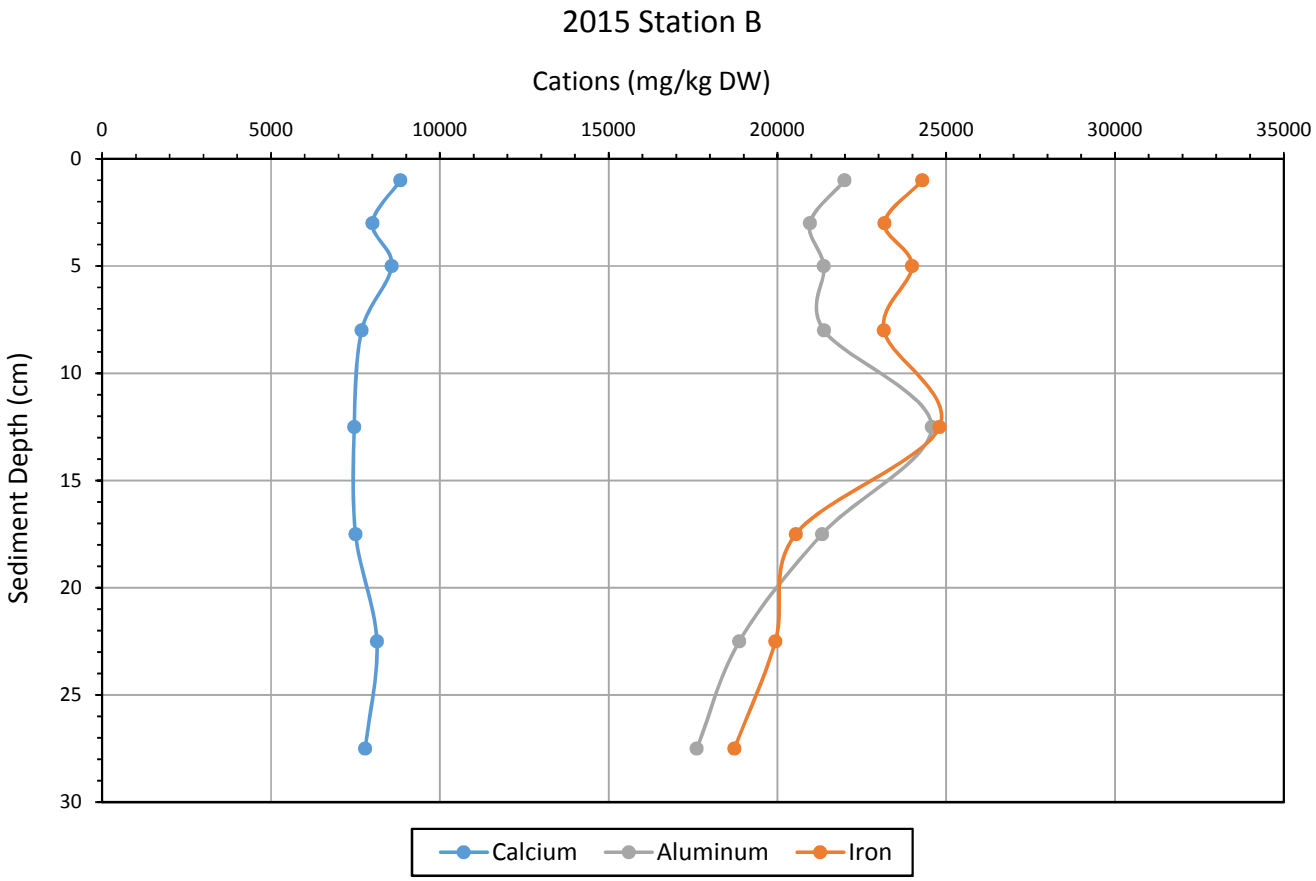


Figure A3. Green Lake Sediment Cations in 2015 at Index and Station A.



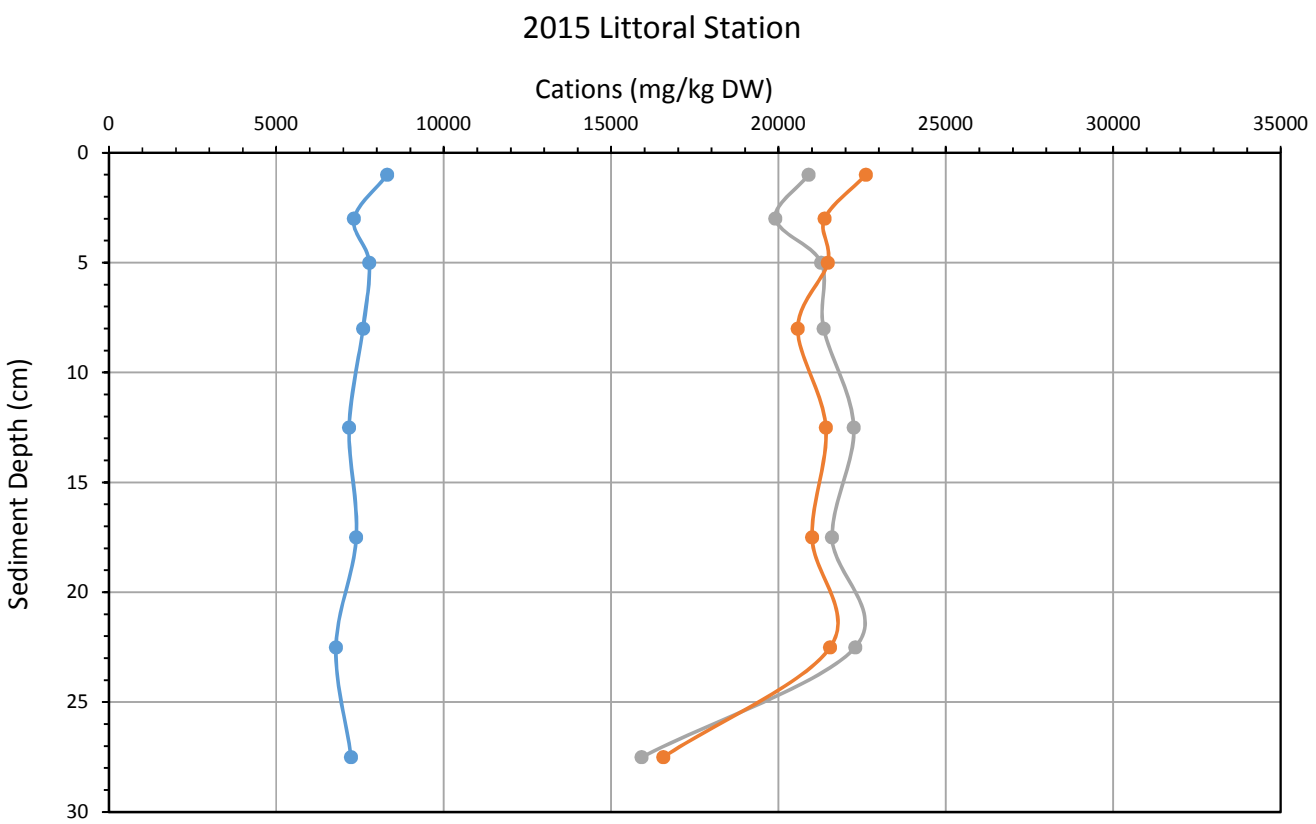
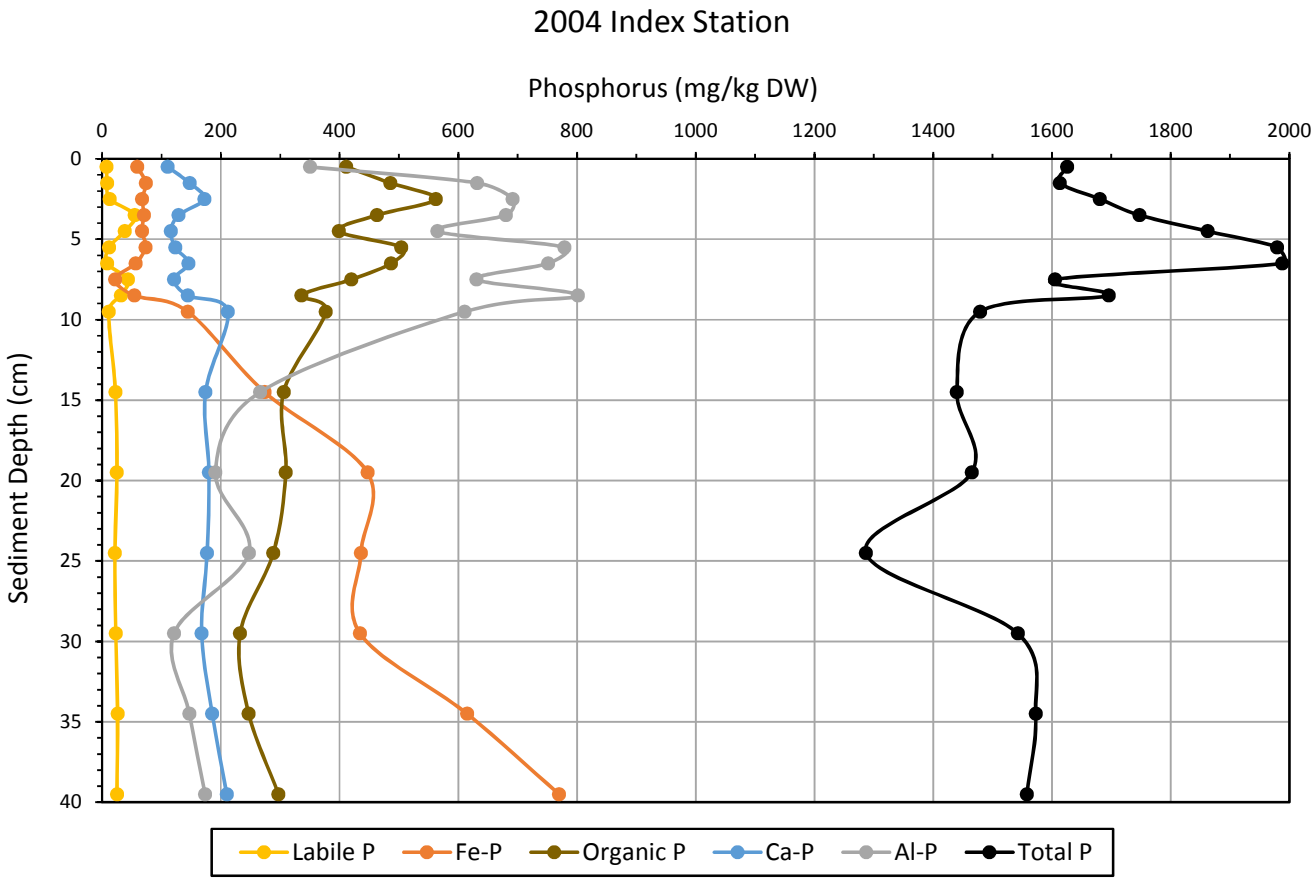


Figure A4. Green Lake Sediment Cations in 2015 at Station B and Littoral Station.



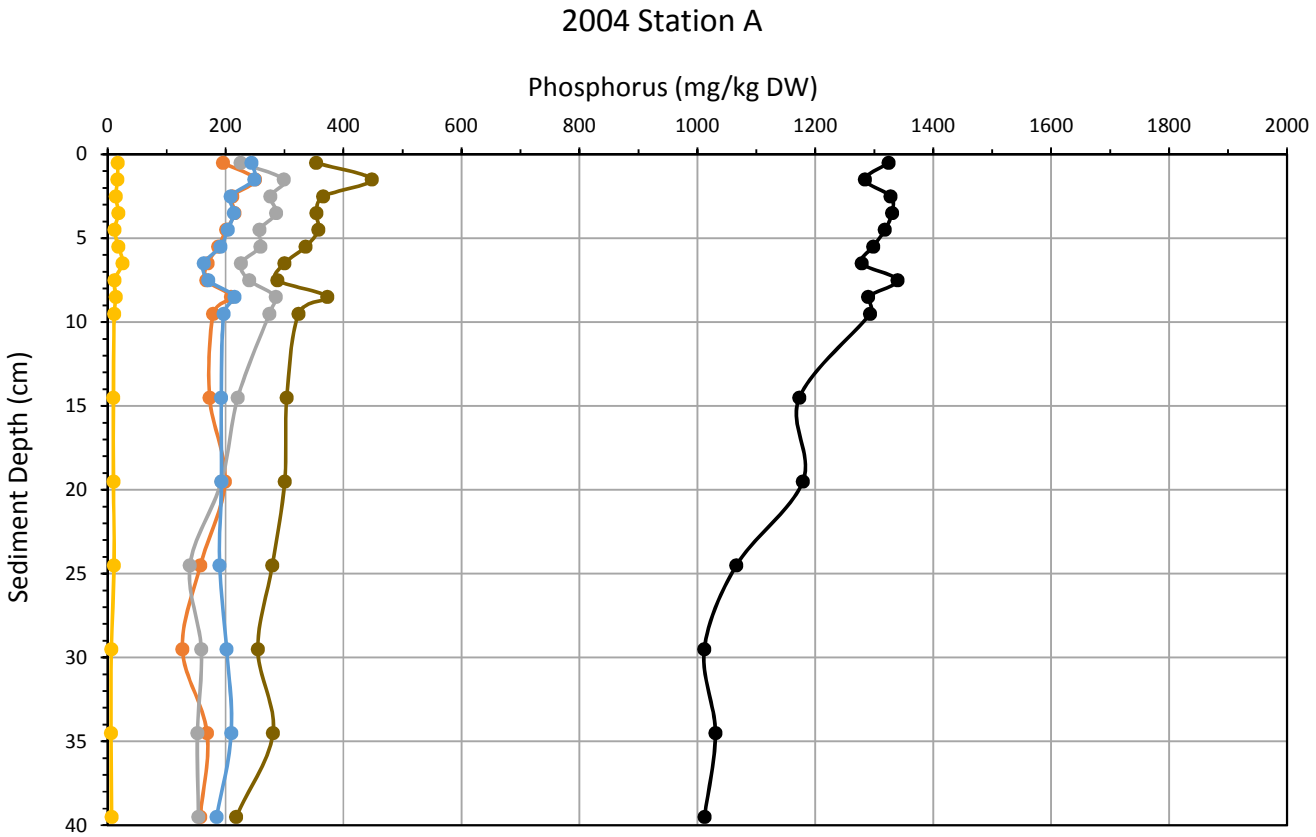
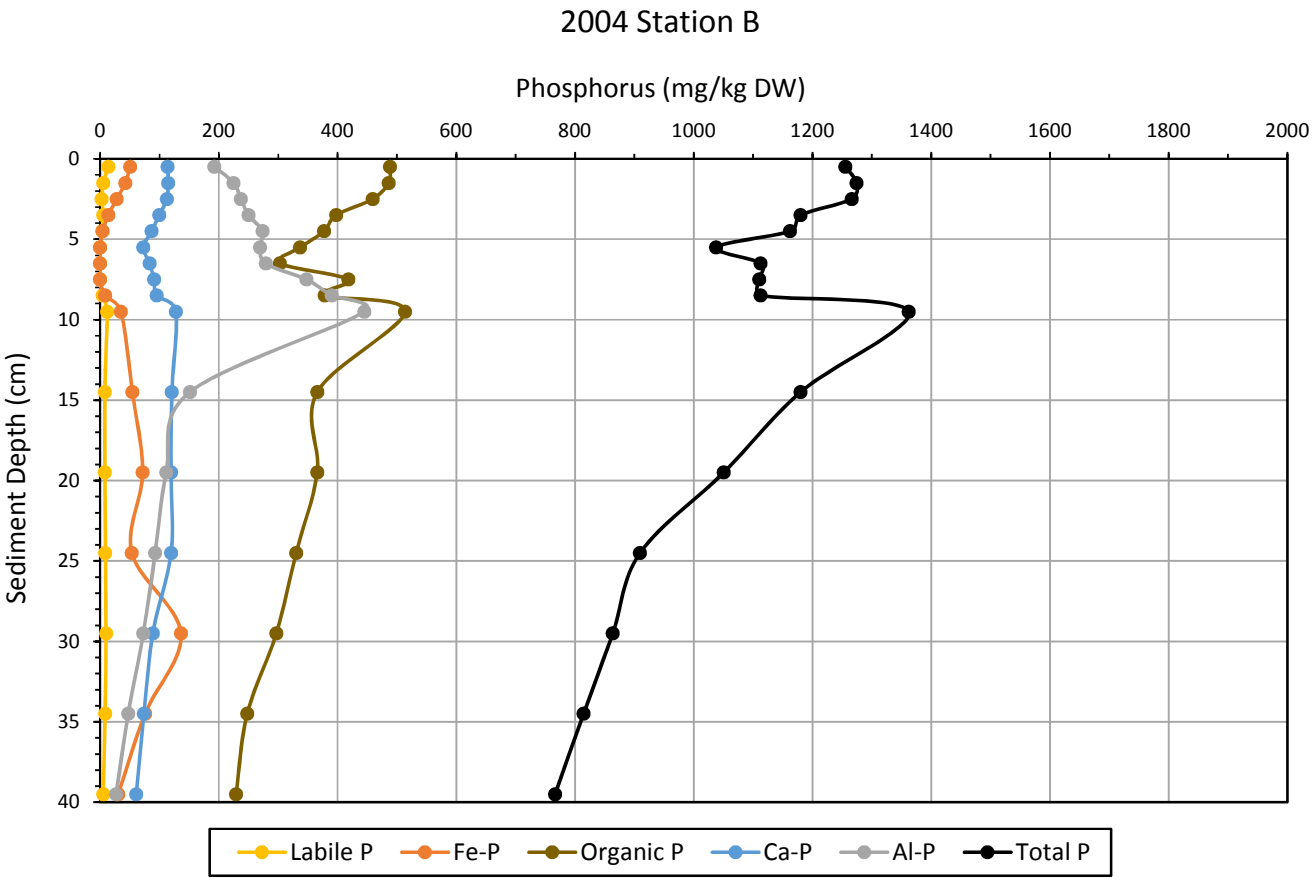


Figure A5. Green Lake Sediment Phosphorus in 2004 at Index and Station A.



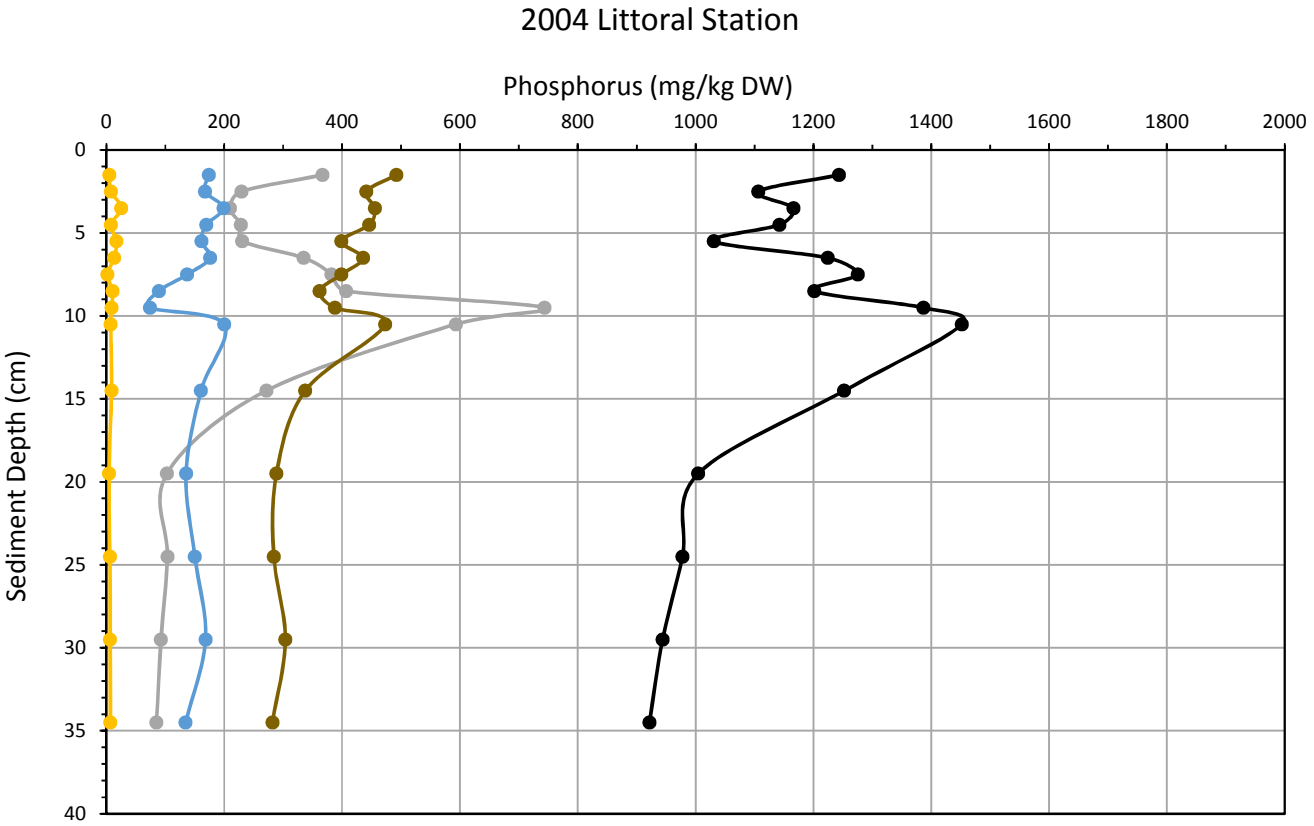
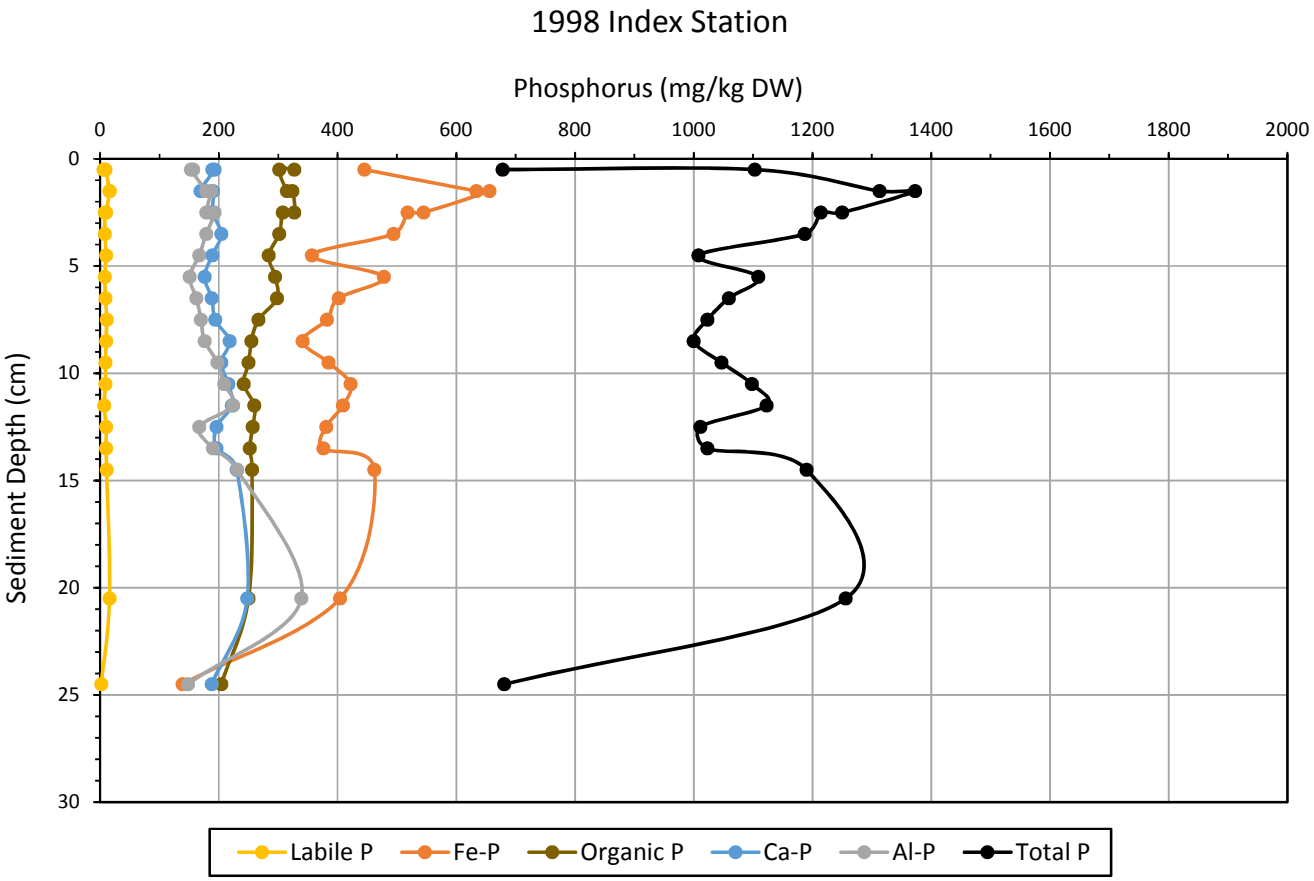


Figure A6. Green Lake Sediment Phosphorus in 2004 at Station B and Littoral Station.



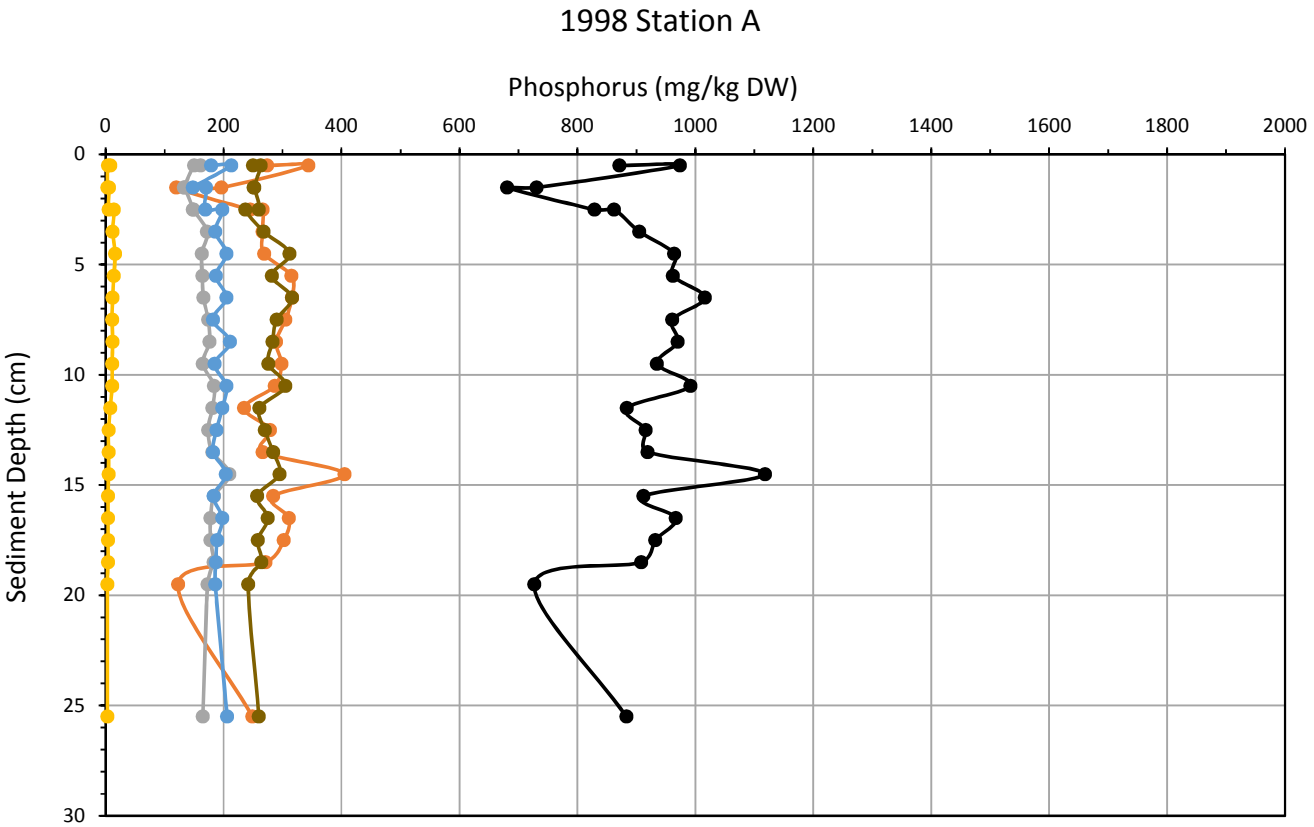
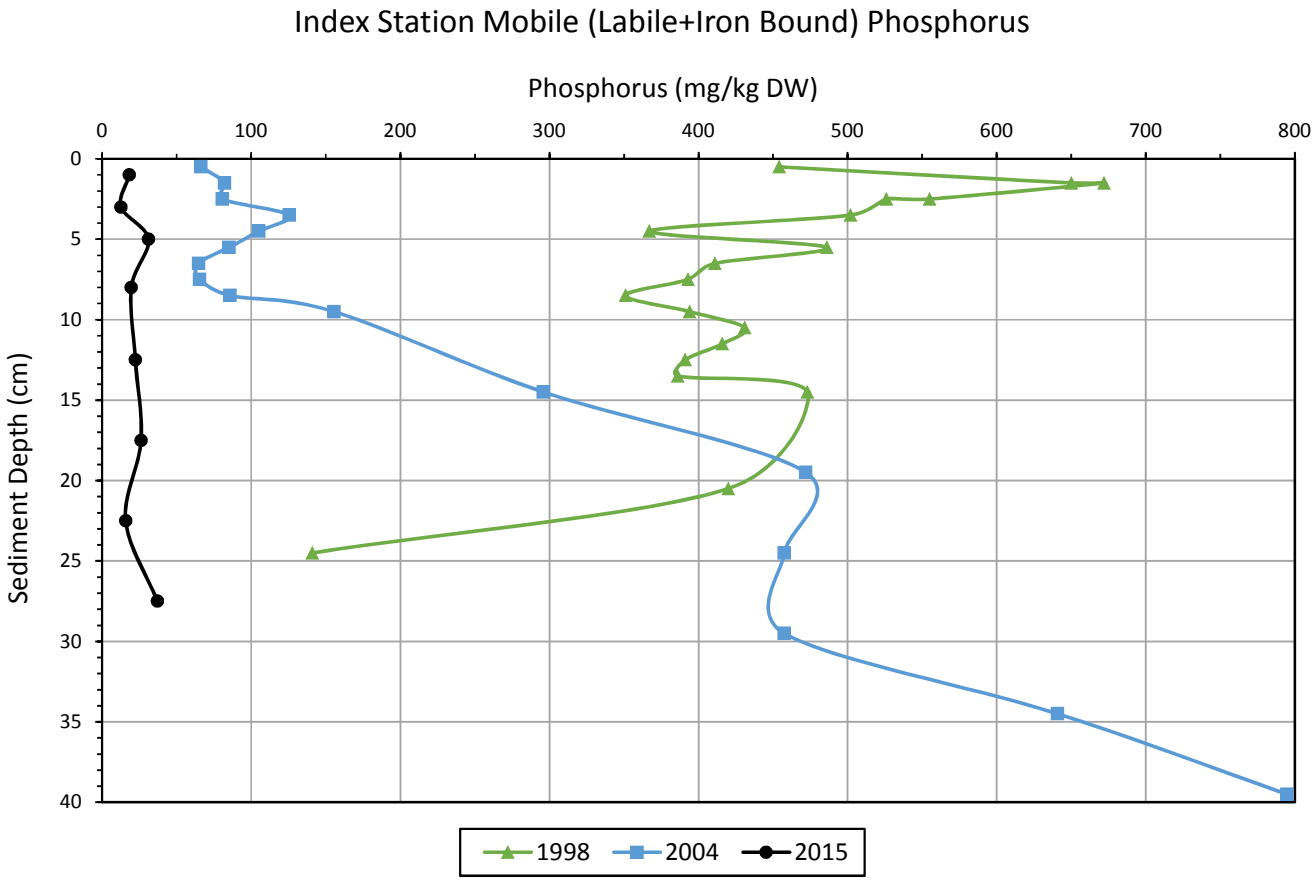


Figure A7. Green Lake Sediment Phosphorus in 1998 at Index and Station A.



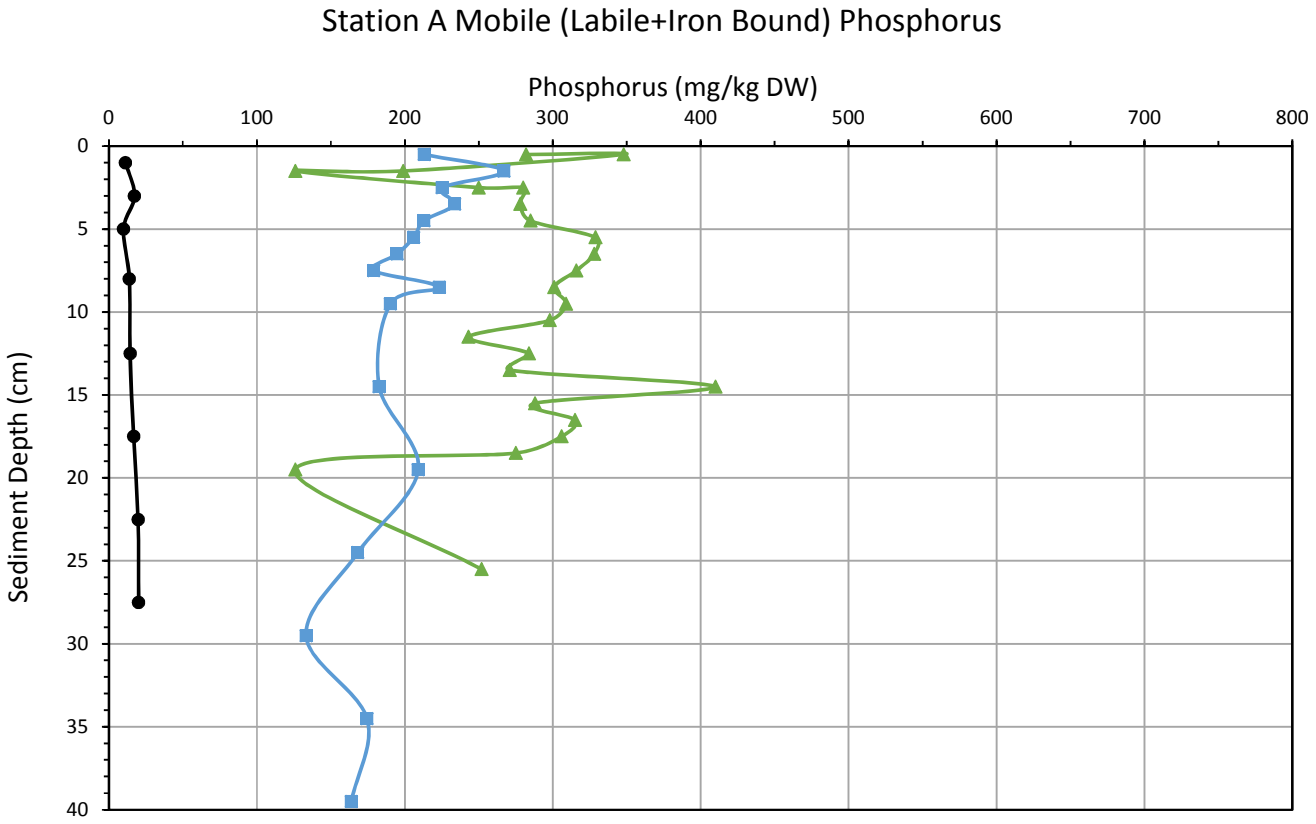
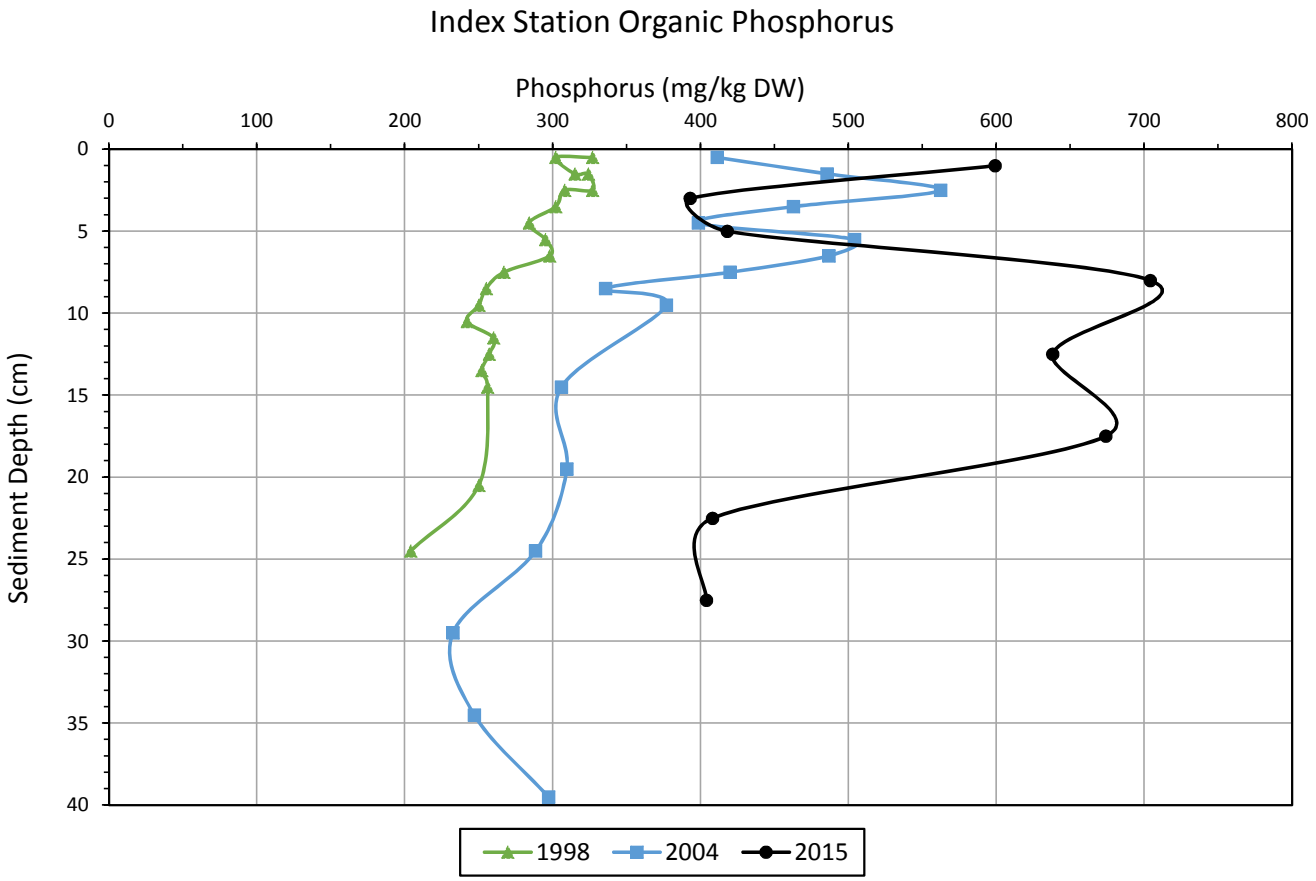


Figure A8. Green Lake Sediment Mobile Phosphorus at Index and Station A.



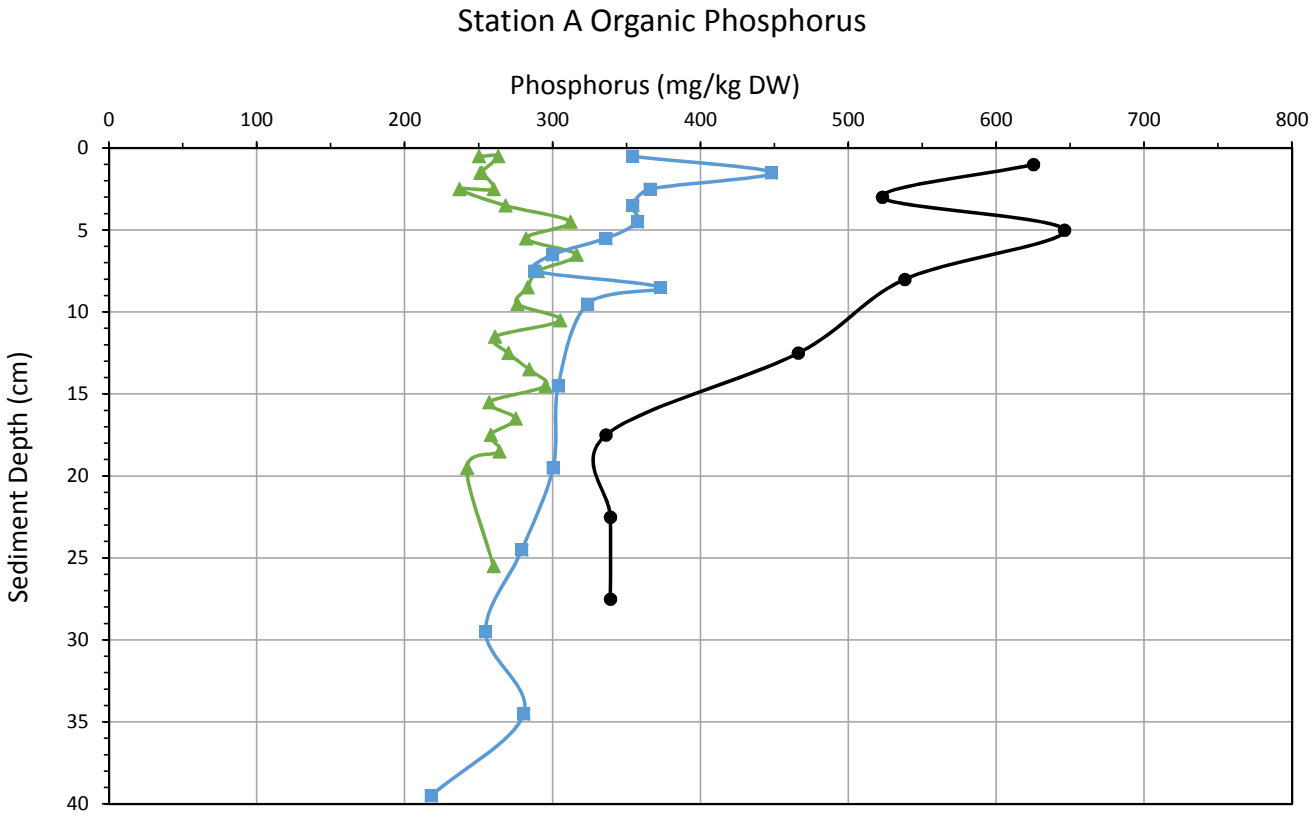
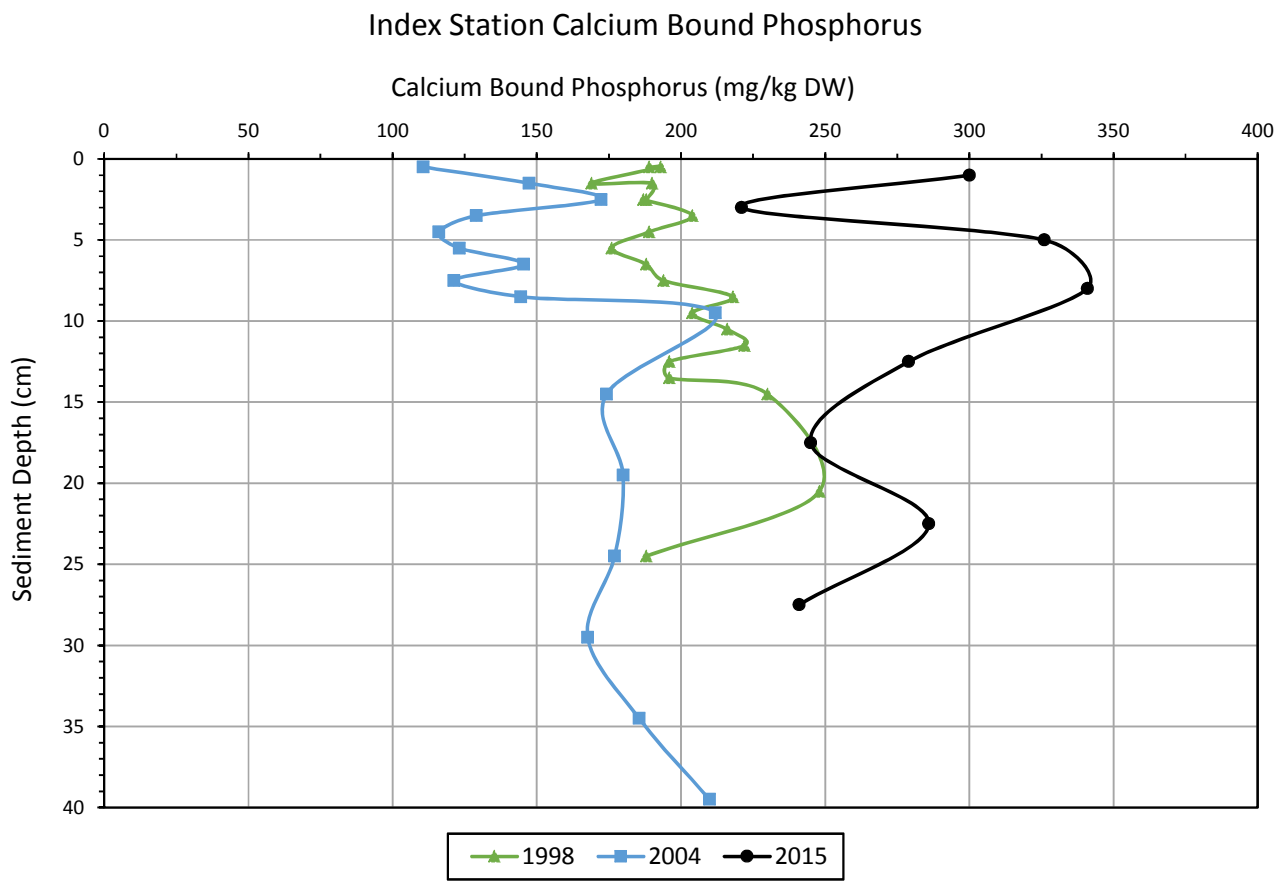


Figure A9. Green Lake Sediment Organic Phosphorus at Index and Station A.



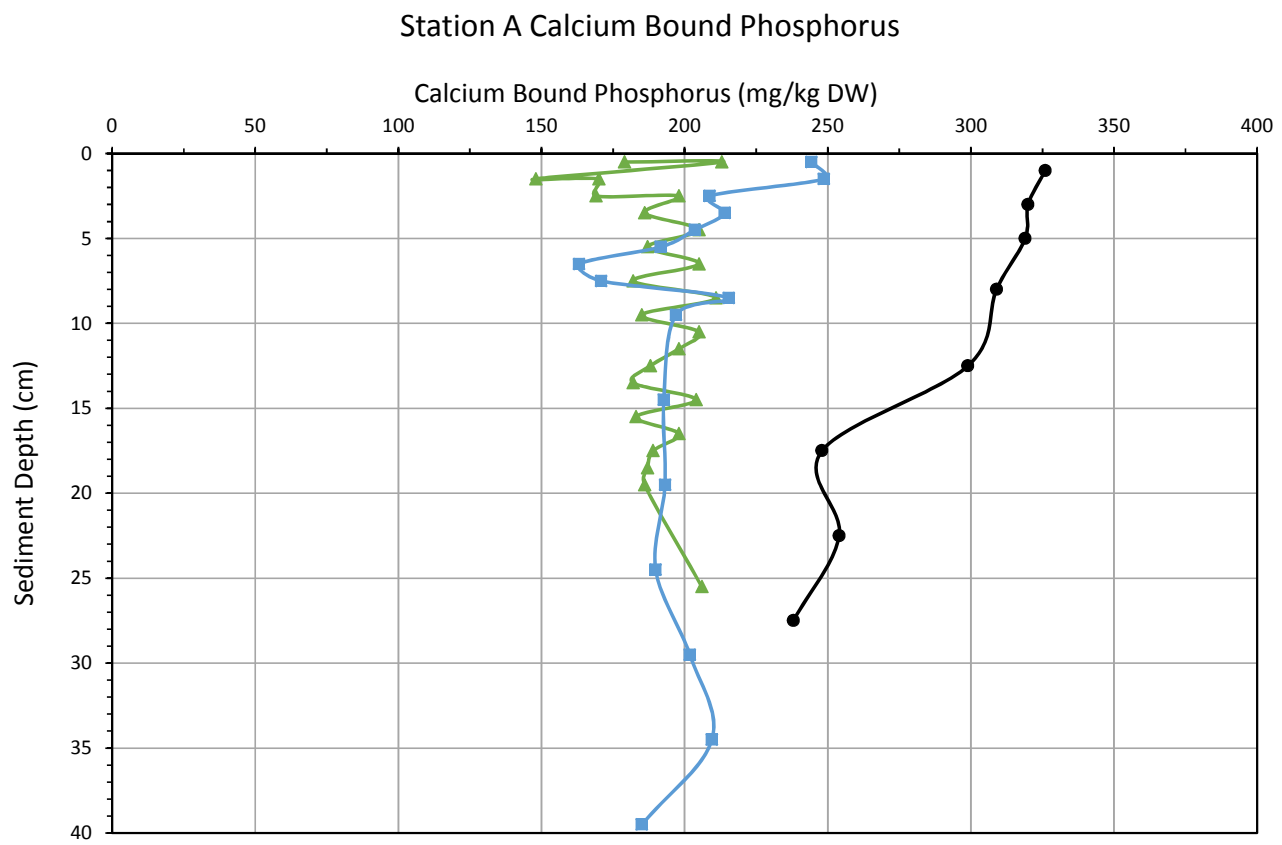
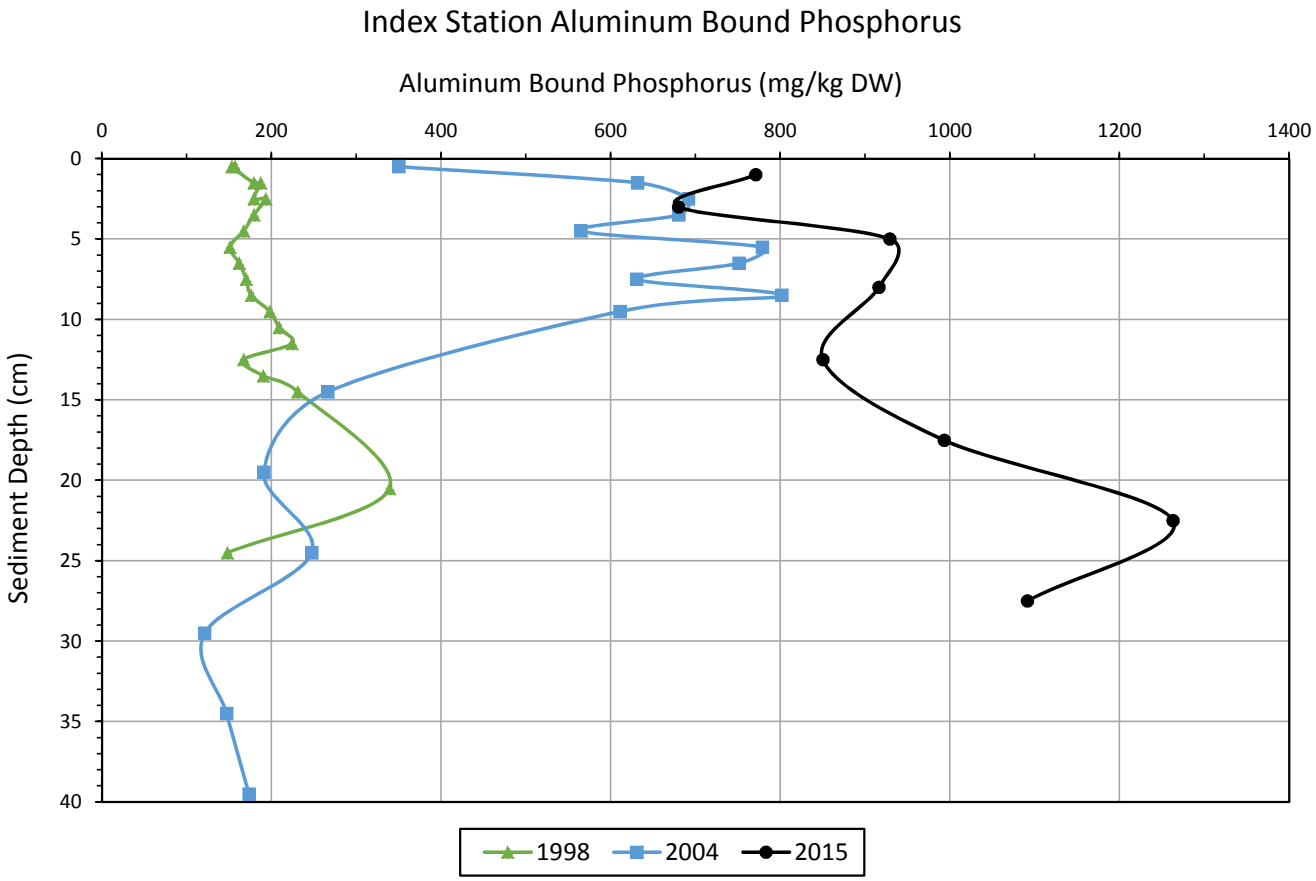


Figure A10. Green Lake Sediment Calcium Bound Phosphorus at Index and Station A, 1998-2015.



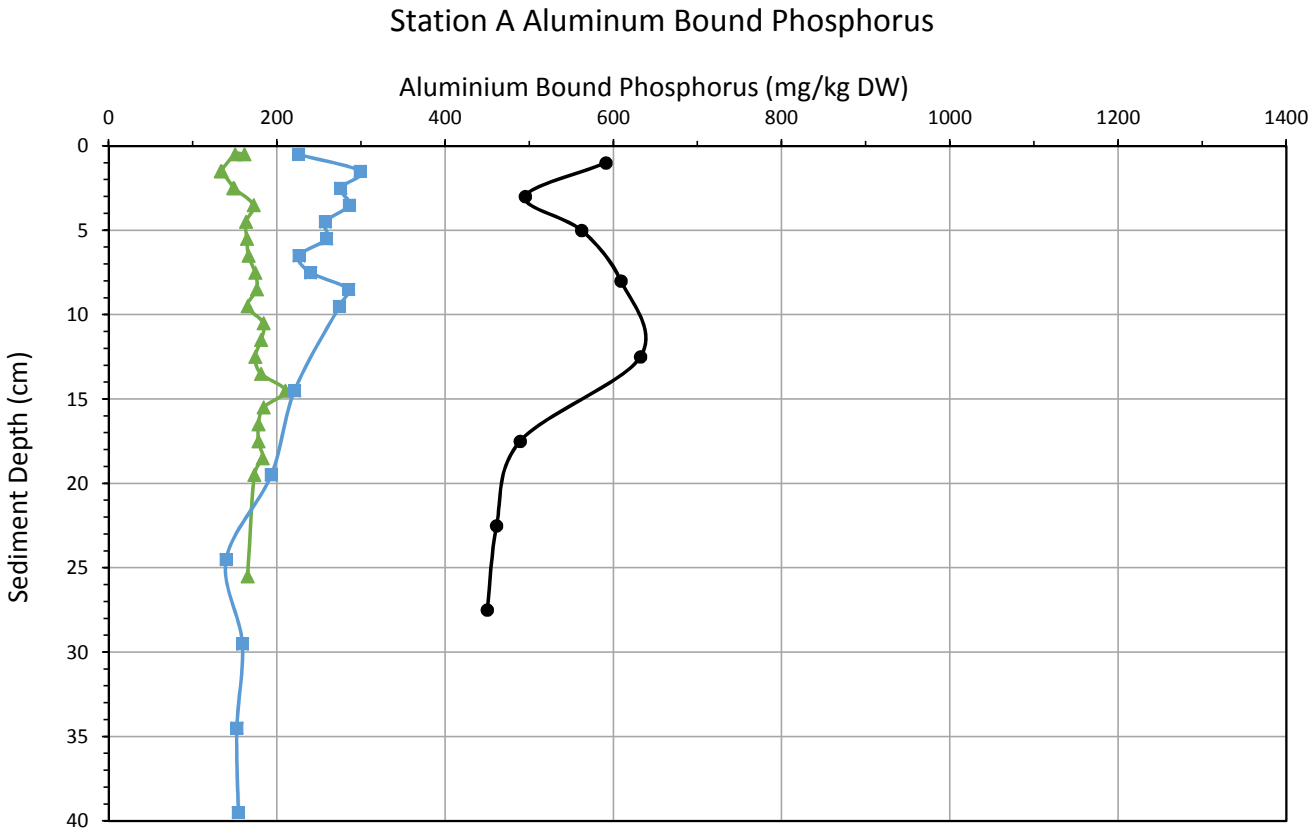
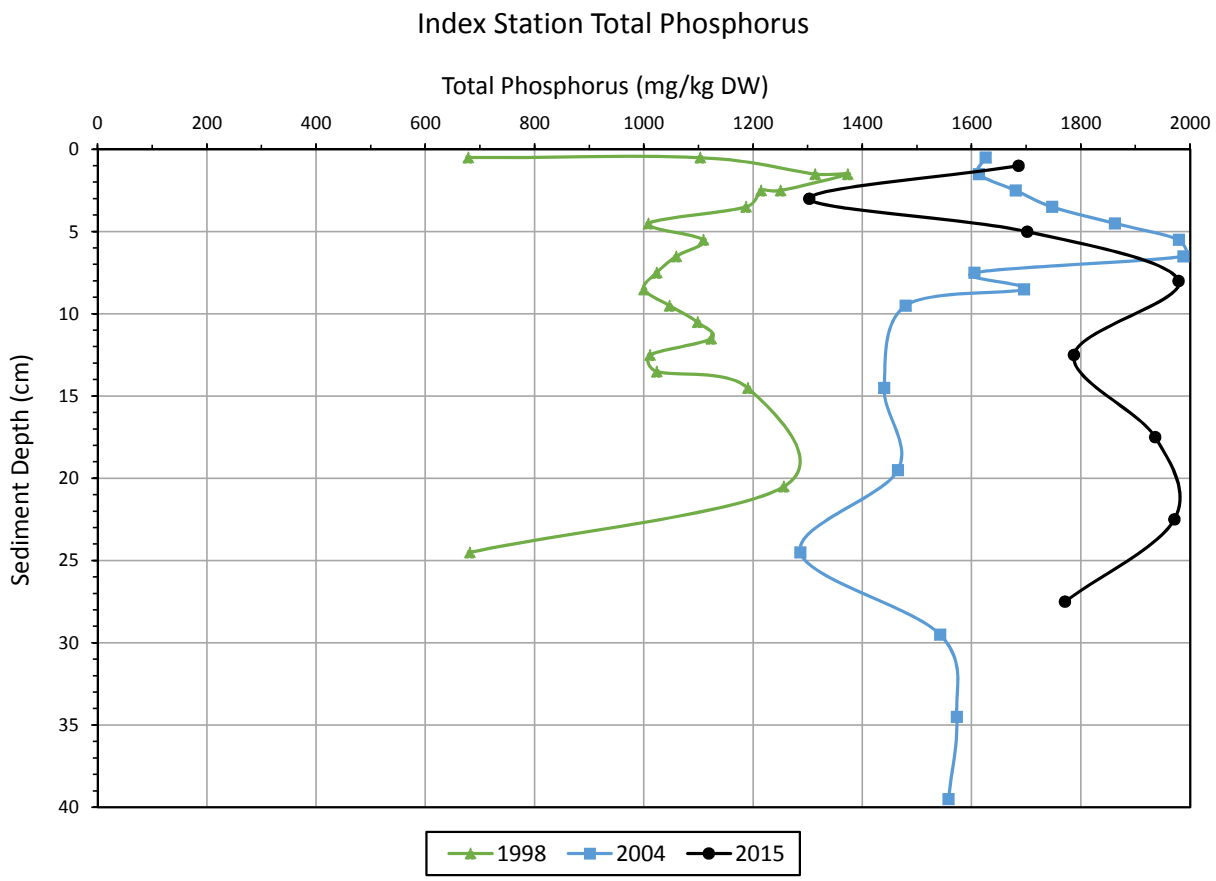


Figure A11. Green Lake Sediment Aluminum Bound Phosphorus at Index and Station A.



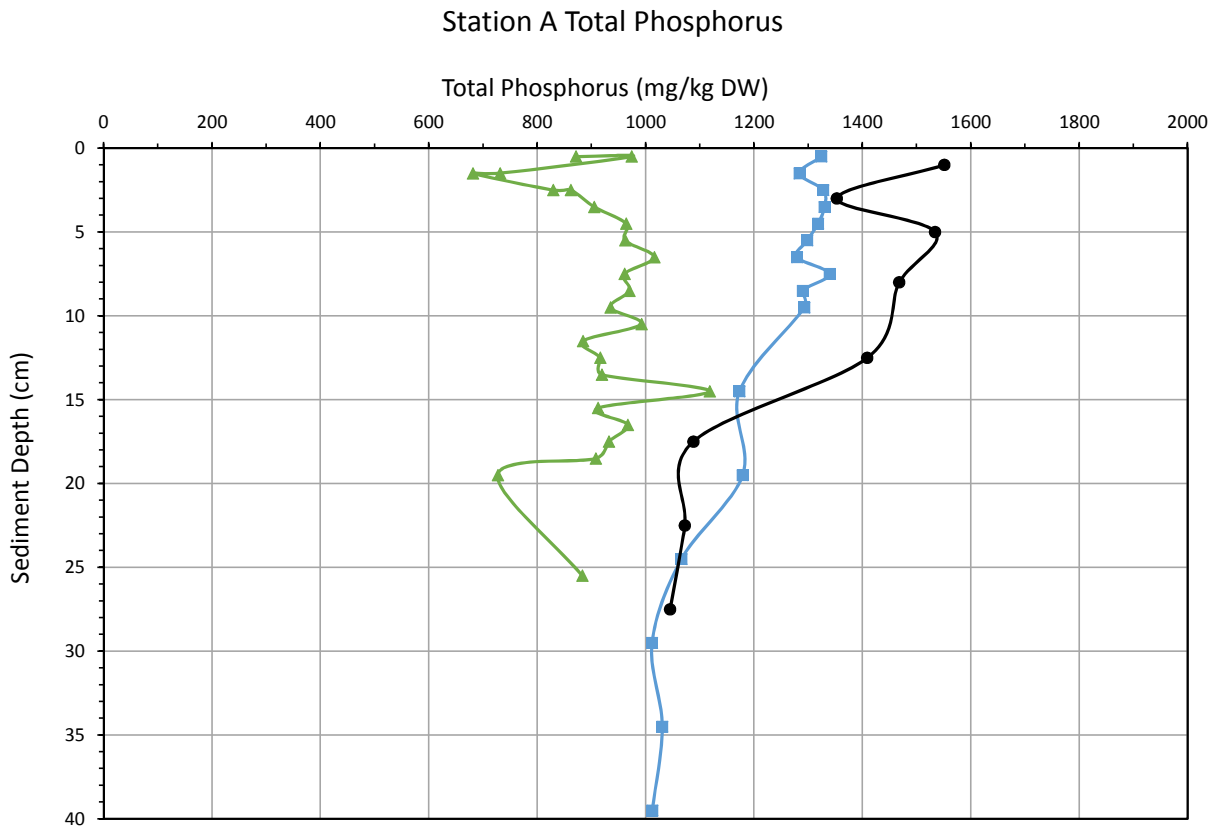
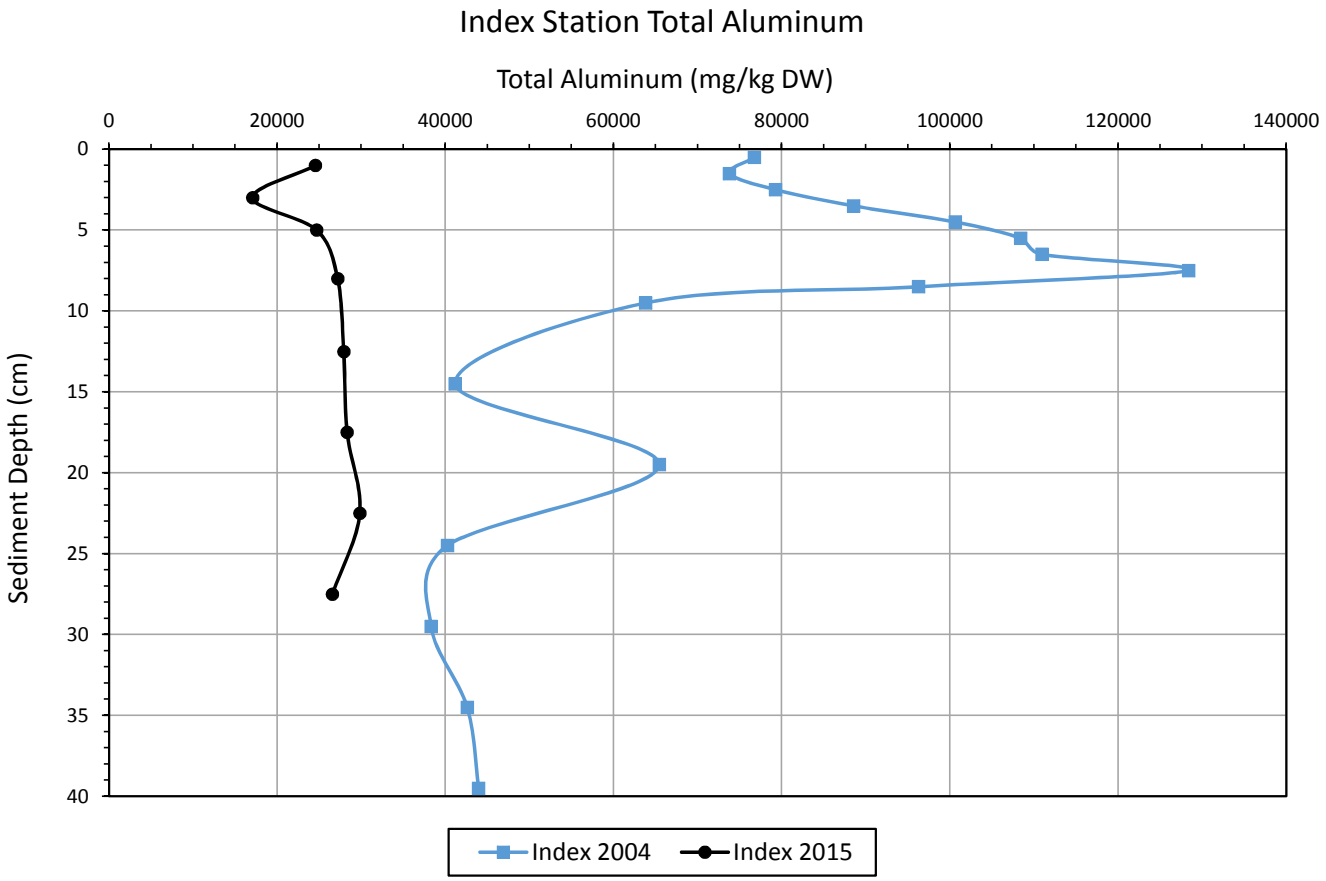


Figure A12. Green Lake Sediment Total Phosphorus at Index and Station A.



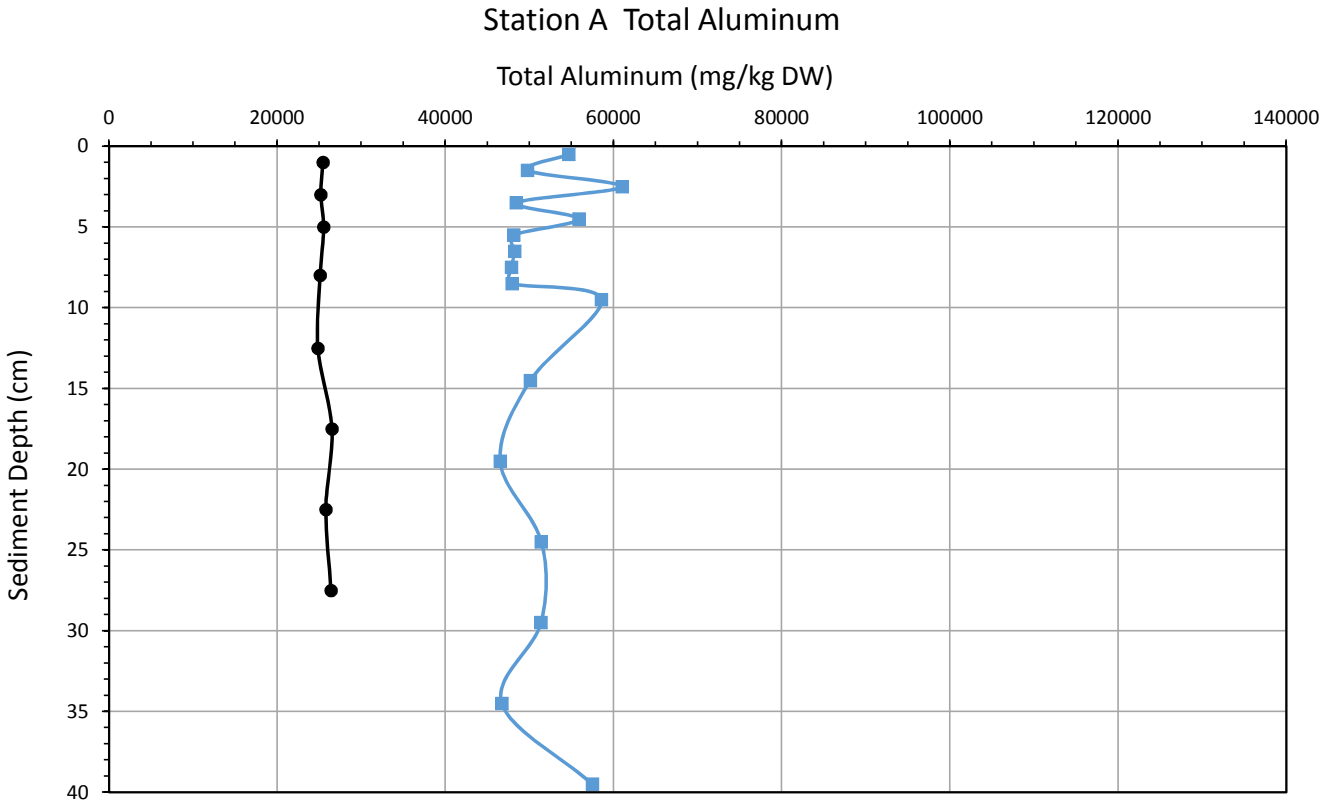


Figure A13. Green Lake Sediment Total Aluminum at Index and Station A.

APPENDIX B

Sediment Database

Table B1. Green Lake Sediment Database.

Year	Station	Sample ID	Sample Date	Sample Depth (cm)	Top Depth (cm)	Bottom depth (cm)	Solids (%)	Water (%)	Total P (mg/kg DW)	Labile P (mg/kg DW)	Fe-P (mg/kg DW)	Al-P (mg/kg DW)	Ca-P (mg/kg DW)	Organic P (mg/kg DW)	Biogenic P (mg/kg DW)	Mobile P (labile+Fe-P) (mg/kg DW)	Mobile+ Biogenic P (mg/kg DW)[a]	Aluminum, total (mg/kg DW)	Calcium, total (mg/kg DW)	Iron, total (mg/kg DW)	Iron:TP Ratio
1998	Index		Summer	0.5	0	1			678	6.0		157	189	327	*209*						
1998	Index		Summer	0.5	0	1			1,103	9.0	445	153	193	302	*193*	454	*647*				
1998	Index		Summer	1.5	1	2			1,313	16.0	634	179	169	315	*202*	650	*852*				
1998	Index		Summer	1.5	1	2			1,373	16.0	656	187	190	324	*207*	672	*879*				
1998	Index		Summer	2.5	2	3			1,250	10.0	545	179	188	327	*209*	555	*764*				
1998	Index		Summer	2.5	2	3			1,214	8.0	518	193	187	308	*197*	526	*723*				
1998	Index		Summer	3.5	3	5			1,187	8.0	494	179	204	302	*193*	502	*695*				
1998	Index		Summer	4.5	4	5			1,008	10.0	357	167	189	284	*182*	367	*549*				
1998	Index		Summer	5.5	5	6			1,109	8.0	478	151	176	295	*189*	486	*675*				
1998	Index		Summer	6.5	6	7			1,059	9.0	402	162	188	298	*191*	411	*602*				
1998	Index		Summer	7.5	7	8			1,023	11.0	382	170	194	267	*171*	393	*564*				
1998	Index		Summer	8.5	8	9			1,000	10.0	341	176	218	255	*163*	351	*514*				
1998	Index		Summer	9.5	9	10			1,047	9.0	385	198	204	250	*160*	394	*554*				
1998	Index		Summer	10.5	10	11			1,098	9.0	422	209	216	242	*155*	431	*586*				
1998	Index		Summer	11.5	11	12			1,123	7.0	409	224	222	260	*166*	416	*582*				
1998	Index		Summer	12.5	12	13			1,011	10.0	381	167	196	257	*164*	391	*555*				
1998	Index		Summer	13.5	13	14			1,023	10.0	376	190	196	252	*161*	386	*547*				
1998	Index		Summer	14.5	14	15			1,190	11.0	462	231	230	256	*164*	473	*637*				
1998	Index		Summer	20.5	20	21			1,256	16.0	404	339	248	250	*160*	420	*580*				
1998	Index		Summer	24.5	24	25			681	2.0	139	148	188	204	*131*	141	*272*				
1998	Station A		Summer	0.5	0	1			871	8.0	274	161	179	250	*160*	282	*442*				
1998	Station A		Summer	0.5	0	1			974	4.0	344	150	213	263	*168*	348	*516*				
1998	Station A		Summer	1.5	1	2			731	3.0	196	133	148	251	*161*	199	*360*				
1998	Station A		Summer	1.5	1	2			681	6.0	120	134	170	252	*161*	126	*287*				
1998	Station A		Summer	2.5	2	3			829	5.0	245	149	169	260	*166*	250	*416*				
1998	Station A		Summer	2.5	2	3			862	14.0	266	148	198	237	*152*	280	*432*				
1998	Station A		Summer	3.5	3	5			905	12.0	266	172	186	268	*172*	278	*450*				
1998	Station A		Summer	4.5	4	5			964	16.0	269	163	205	312	*200*	285	*485*				
1998	Station A		Summer	5.5	5	6			962	14.0	315	164	187	282	*180*	329	*509*				
1998	Station A		Summer	6.5	6	7			1,016	12.0	316	166	205	316	*202*	328	*530*				
1998	Station A		Summer	7.5	7	8			961	11.0	305	174	182	290	*186*	316	*502*				
1998	Station A		Summer	8.5	8	9			970	12.0	289	176	211	283	*181*	301	*482*				
1998	Station A		Summer	9.5	9	10			935	11.0	298	165	185	276	*177*	309	*486*				
1998	Station A		Summer	10.5	10	11			992	11.0	287	184	205	305	*195*	298	*493*				
1998	Station A		Summer	11.5	11	12			884	8.0	235	181	198	261	*167*	243	*410*				
1998	Station A		Summer	12.5	12	13			916	5.0	279	174	188	270	*173*	284	*457*				
1998	Station A		Summer	13.5	13	14			919	5.0	266	181	182	284	*182*	271	*453*				
1998	Station A		Summer	14.5	14	15			1,118	5.0	405	210	204	295	*189*	410	*599*				
1998	Station A		Summer	15.5	15	16			912	4.0	284	184	183	257	*164*	288	*452*				
1998	Station A		Summer	16.5	16	17			967	4.0	311	178	198	275	*176*	315	*491*				
1998	Station A		Summer	17.5	17	18			932	4.0	302	178	189	258	*165*	306	*471*				
1998	Station A		Summer	18.5	18	19			908	4.0	271	183	187	264	*169*	275	*444*				
1998	Station A		Summer	19.5	19	20			727	3.0	123	173	186	242	*155*	126	*281*				
1998	Station A		Summer	25.5	24	25			883	3.0	249	165	206	260	*166*	252	*418*				

Table B1. Green Lake Sediment Database.

Year	Station	Sample ID	Sample Date	Sample Depth (cm)	Top Depth (cm)	Bottom depth (cm)	Solids (%)	Water (%)	Total P (mg/kg DW)	Labile P (mg/kg DW)	Fe-P (mg/kg DW)	Al-P (mg/kg DW)	Ca-P (mg/kg DW)	Organic P (mg/kg DW)	Biogenic P (mg/kg DW)	Mobile P (labile+Fe-P) (mg/kg DW)	Mobile+ Biogenic P (mg/kg DW)[a]	Aluminum, total (mg/kg DW)	Calcium, total (mg/kg DW)	Iron, total (mg/kg DW)	Iron:TP Ratio
2004	Index		Oct-04	0.5	0	1			1,626	7.4	59.0	350	111	411	*263*	66.4	*330*	76,754			
2004	Index		Oct-04	1.5	1	2			1,613	8.4	73.7	632	147	486	*311*	82.1	*393*	73,793			
2004	Index		Oct-04	2.5	2	3			1,681	13.0	67.5	692	172	562	*360*	80.6	*440*	79,247			
2004	Index		Oct-04	3.5	3	4			1,747	55.1	70.4	680	129	463	*296*	125	*422*	88,565			
2004	Index		Oct-04	4.5	4	5			1,862	38.2	67.1	565	116	399	*255*	105	*360*	100,657			
2004	Index		Oct-04	5.5	5	6			1,979	12.0	73.2	779	123	504	*323*	85.2	*408*	108,409			
2004	Index		Oct-04	6.5	6	7			1,988	8.3	56.4	751	145	487	*312*	64.7	*376*	110,941			
2004	Index		Oct-04	7.5	7	8			1,605	43.6	21.8	630	121	420	*269*	65.5	*334*	128,376			
2004	Index		Oct-04	8.5	8	9			1,696	31.6	54.2	802	145	336	*215*	85.8	*301*	96,290			
2004	Index		Oct-04	9.5	9	10			1,479	11.4	144	611	212	377	*241*	156	*397*	63,799			
2004	Index		Oct-04	14.5	14	15			1,440	22.5	274	266	174	306	*196*	296	*492*	41,169			
2004	Index		Oct-04	19.5	19	20			1,465	24.9	447	191	180	310	*198*	472	*670*	65,429			
2004	Index		Oct-04	24.5	24	25			1,287	21.6	436	247	177	288	*185*	458	*642*	40,250			
2004	Index		Oct-04	29.5	29	30			1,542	23.0	434	121	168	233	*149*	457	*606*	38,320			
2004	Index		Oct-04	34.5	34	35			1,573	26.1	615	147	185	247	*158*	641	*799*	42,604			
2004	Index		Oct-04	39.5	39	40			1,558	25.1	770	173	210	297	*190*	795	*985*	43,953			
2004	Station A		Oct-04	0.5	0	1			1,324	17.4	196	226	244	354	*226*	213	*440*	54,678			
2004	Station A		Oct-04	1.5	1	2			1,284	16.9	250	299	249	448	*287*	267	*554*	49,771			
2004	Station A		Oct-04	2.5	2	3			1,328	13.9	211	276	209	366	*234*	225	*459*	61,038			
2004	Station A		Oct-04	3.5	3	4			1,330	18.2	215	286	214	354	*227*	234	*460*	48,443			
2004	Station A		Oct-04	4.5	4	5			1,318	12.0	201	257	204	357	*229*	213	*442*	55,883			
2004	Station A		Oct-04	5.5	5	6			1,298	18.5	188	259	192	336	*215*	206	*421*	48,122			
2004	Station A		Oct-04	6.5	6	7			1,279	25.3	169	226	163	300	*192*	195	*387*	48,248			
2004	Station A		Oct-04	7.5	7	8			1,340	11.6	167	240	171	288	*184*	179	*363*	47,850			
2004	Station A		Oct-04	8.5	8	9			1,290	14.0	209	285	215	373	*239*	223	*462*	47,947			
2004	Station A		Oct-04	9.5	9	10			1,293	11.2	179	274	197	324	*207*	190	*397*	58,567			
2004	Station A		Oct-04	14.5	14	15			1,173	9.8	173	221	193	304	*194*	183	*377*	50,118			
2004	Station A		Oct-04	19.5	19	20			1,179	10.0	199	193	193	300	*192*	209	*401*	46,528			
2004	Station A		Oct-04	24.5	24	25			1,066	10.9	157	140	190	279	*179*	168	*347*	51,423			
2004	Station A		Oct-04	29.5	29	30			1,012	6.4	127	159	202	255	*163*	133	*296*	51,379			
2004	Station A		Oct-04	34.5	34	35			1,031	5.7	169	152	210	280	*180*	174	*354*	46,719			
2004	Station A		Oct-04	39.5	39	40			1,012	6.7	157	154	185	218	*139*	164	*303*	57,483			
2004	Station B		Oct-04	0.5	0	1			1,256	14.0	50.4	193	114	489	*313*	64.4	*377*	41,123			
2004	Station B		Oct-04	1.5	1	2			1,274	5.2	42.7	225	115	486	*311*	47.9	*359*	49,278			
2004	Station B		Oct-04	2.5	2	3			1,266	2.8	27.7	237	112	459	*294*	30.5	*324*	51,029			
2004	Station B		Oct-04	3.5	3	4			1,180	5.6	14.0	250	100	398	*255*	19.6	*274*	67,059			
2004	Station B		Oct-04	4.5	4	5			1,162	3.5	4.3	274	87	377	*242*	7.8	*249*	121,828			
2004	Station B		Oct-04	5.5	5	6			1,038	0.0	0.0	269	73	337	*216*	0.0	*216*	154,364			
2004	Station B		Oct-04	6.5	6	7			1,113	0.0	0.0	279	83	303	*194*	0.0	*194*	127,513			
2004	Station B		Oct-04	7.5	7	8			1,110	0.0	0.0	347	91	418	*268*	0.0	*268*	125,267			
2004	Station B		Oct-04	8.5	8	9			1,113	4.2	8.5	390	95	379	*242*	12.7	*255*	111,146			
2004	Station B		Oct-04	9.5	9	10			1,362	11.8	35.1	445	127	514	*329*	46.9	*376*	57,343			
2004	Station B		Oct-04	14.5	14	15			1,180	7.9	54.4	151	121	366	*234*	62.3	*296*	42,633			
2004	Station B		Oct-04	19.5	19	20			1,051	8.3	71.6	111	119	366	*234*	79.9	*314*	34,322			

Table B1. Green Lake Sediment Database.

Year	Station	Sample ID	Sample Date	Sample Depth (cm)	Top Depth (cm)	Bottom depth (cm)	Solids (%)	Water (%)	Total P (mg/kg DW)	Labile P (mg/kg DW)	Fe-P (mg/kg DW)	Al-P (mg/kg DW)	Ca-P (mg/kg DW)	Organic P (mg/kg DW)	Biogenic P (mg/kg DW)	Mobile P (labile+Fe-P) (mg/kg DW)	Mobile+ Biogenic P (mg/kg DW)[a]	Aluminum, total (mg/kg DW)	Calcium, total (mg/kg DW)	Iron, total (mg/kg DW)	Iron:TP Ratio
2004	Station B		Oct-04	24.5	24	25			909	8.8	53.5	93	120	330	*211*	62.3	*274*	32,520			
2004	Station B		Oct-04	29.5	29	30			864	10.1	136	73	89	297	*190*	146	*336*	27,181			
2004	Station B		Oct-04	34.5	34	35			814	8.3	75.7	47	74	248	*159*	84.1	*243*	23,353			
2004	Station B		Oct-04	39.5	39	40			766	5.4	30.4	27	61	229	*146*	35.9	*182*	22,182			
2004	Littoral		Oct-04	0.5	0	1												53,550			
2004	Littoral		Oct-04	1.5	1	2			1,244	4.8	52.4	367	174	492	*315*	57.2	*372*	69,138			
2004	Littoral		Oct-04	2.5	2	3			1,107	7.8	104	229	167	441	*282*	112	*394*	71,816			
2004	Littoral		Oct-04	3.5	3	4			1,166	25.0	110	210	199	456	*292*	135	*427*	43,262			
2004	Littoral		Oct-04	4.5	4	5			1,142	7.8	97.9	228	170	446	*285*	106	*391*	39,085			
2004	Littoral		Oct-04	5.5	5	6			1,031	16.9	90.3	230	161	399	*255*	107	*362*	45,146			
2004	Littoral		Oct-04	6.5	6	7			1,225	13.1	86.3	335	176	435	*279*	99.4	*378*	47,635			
2004	Littoral		Oct-04	7.5	7	8			1,276	1.5	40.5	382	137	399	*255*	42.1	*297*	91,207			
2004	Littoral		Oct-04	8.5	8	9			1,202	10.3	11.5	407	89	362	*232*	21.8	*253*	139,321			
2004	Littoral		Oct-04	9.5	9	10			1,387	8.5	24.7	744	74	388	*248*	33.1	*281*	160,008			
2004	Littoral		Oct-04	10.5	14	15			1,452	7.3	118	593	200	473	*303*	126	*428*				
2004	Littoral		Oct-04	11.5	11	12									*0*			60,517			
2004	Littoral		Oct-04	14.5	14	15			1,252	8.6	196	272	161	337	*216*	205	421	48,824			
2004	Littoral		Oct-04	19.5	19	20			1,004	4.5	94.3	103	135	289	*185*	98.8	283	44,740			
2004	Littoral		Oct-04	24.5	24	25			978	6.0	99.1	104	150	284	*182*	105	287	40,587			
2004	Littoral		Oct-04	29.5	29	30			944	6.3	84.1	93	168	304	*194*	90.3	285	60,722			
2004	Littoral		Oct-04	34.5	34	35			922	6.8	103	85	134	282	*180*	110	291	40,866			
2015	Index	I-0-2	5/4/2015	1	0	2	8.0%	92.0%	1,686	2.0 U	16.2	771	300	599	462	18.2	480	24,555	7,152	26,815	15.9
2015	Index	I-2-4	5/4/2015	3	2	4	14.2%	85.8%	1,303	2.0 U	10.7	680	221	393	258	12.7	271	17,069	4,524	18,444	14.2
2015	Index	I-4-6	5/4/2015	5	4	6	10.2%	89.8%	1,702	2.0 U	29.1	929	326	418	238	31.1	269	24,698	6,613	27,716	16.3
2015	Index	I-6-10	5/4/2015	8	6	10	10.3%	89.7%	1,979	2.0 U	17.6	916	341	704	453	19.6	473	27,191	7,123	30,921	15.6
2015	Index	I-10-15	5/4/2015	12.5	10	15	11.4%	88.6%	1,787	2.0 U	20.3	850	279	638	453	22.3	475	27,912	6,847	31,521	17.6
2015	Index	I-15-20	5/4/2015	17.5	15	20	11.9%	88.1%	1,936	2.0 U	24.1	993	245	674	404	26.1	430	28,314	6,843	28,486	14.7
2015	Index	I-20-25	5/4/2015	22.5	20	25	12.5%	87.5%	1,971	2.0 U	13.8	1,263	286	408	266	15.8	282	29,828	6,428	27,800	14.1
2015	Index	I-25-30	5/4/2015	27.5	25	30	13.1%	86.9%	1,771	2.0 U	35.0	1,091	241	404	258	37.0	295	26,571	6,103	26,703	15.1
2015	Station A	A-0-2	5/4/2015	1	0	2	8.3%	91.7%	1,551	2.0 U	9.2	591	326	625	388	11.2	399	25,447	7,180	27,937	18.0
2015	Station A	A-2-4	5/4/2015	3	2	4	10.9%	89.1%	1,353	2.0 U	15.3	495	320	523	316	17.3	333	25,191	6,992	27,496	20.3
2015	Station A	A-4-6	5/4/2015	5	4	6	11.3%	88.7%	1,534	2.0 U	7.9	562	319	646	383	9.9	393	25,531	7,212	28,581	18.6
2015	Station A	A-6-10	5/4/2015	8	6	10	11.9%	88.1%	1,468	2.0 U	11.8	609	309	538	337	13.8	351	25,112	6,743	28,363	19.3
2015	Station A	A-10-15	5/4/2015	12.5	10	15	13.2%	86.8%	1,409	2.0 U	12.3	632	299	466	272	14.3	286	24,841	6,370	27,786	19.7
2015	Station A	A-15-20	5/4/2015	17.5	15	20	14.5%	85.5%	1,088	2.0 U	14.7	489	248	336	177	16.7	194	26,508	6,791	26,860	24.7
2015	Station A	A-20-25	5/4/2015	22.5	20	25	15.7%	84.3%	1,072	2.0 U	17.7	461	254	339	175	19.7	195	25,789	6,392	26,180	24.4
2015	Station A	A-25-30	5/4/2015	27.5	25	30	16.8%	83.2%	1,045	2.0 U	18.1	450	238	339	160	20.1	180	26,403	6,112	26,146	25.0
2015	Station B	B-0-2	5/4/2015	1	0	2	6.9%	93.2%	1,663	2.0 U	16.3	557	276	814	574	18.3	592	21,987	8,828	24,291	14.6
2015	Station B	B-2-4	5/4/2015	3	2	4	7.8%	92.2%	1,379	2.0 U	6.3	517	243	613	437	8.3	445	20,960	8,005	23,170	16.8
2015	Station B	B-4-6	5/4/2015	5	4	6	7.9%	92.1%	1,580	2.0 U	14.5	636	267	663	444	16.5	461	21,374	8,575	23,989	15.2
2015	Station B	B-6-10	5/4/2015	8	6	10	8.6%	91.4%	1,578	2.0 U	14.9	615	242	706	445	16.9	462	21,377	7,687	23,152	14.7
2015	Station B	B-10-15	5/4/2015	12.5	10	15	8.4%	91.6%	1,651	2.0 U	13.4	662	249	726	521	15.4	536	24,570	7,467	24,801	15.0
2015	Station B	B-15-20	5/4/2015	17.5	15	20	9.2%	90.8%	1,231	2.0 U	17.3	529	193	491	354	19.3	373	21,320	7,508	20,543	16.7
2015	Station B	B-20-25	5/4/2015	22.5	20	25	9.3%	90.7%	945	2.0 U	26.6	364	171	383	230	28.6	259	18,872	8,138	19,941	21.1

Table B1. Green Lake Sediment Database.

Year	Station	Sample ID	Sample Date	Sample Depth (cm)	Top Depth (cm)	Bottom depth (cm)	Solids (%)	Water (%)	Total P (mg/kg DW)	Labile P (mg/kg DW)	Fe-P (mg/kg DW)	Al-P (mg/kg DW)	Ca-P (mg/kg DW)	Organic P (mg/kg DW)	Biogenic P (mg/kg DW)	Mobile P (labile+Fe-P) (mg/kg DW)	Mobile+ Biogenic P (mg/kg DW)[a]	Aluminum, total (mg/kg DW)	Calcium, total (mg/kg DW)	Iron, total (mg/kg DW)	Iron:TP Ratio
2015	Station B	B-25-30	5/4/2015	27.5	25	30	9.4%	90.6%	871	2.0 U	18.8 J	335	164	354	212	20.8	233	17,611	7,794	18,726	21.5
2015	Littoral	L-0-2	5/4/2015	1	0	2	8.0%	92.0%	1,583	2.0 U	10.2	270	247	1,055	779	12.2	791	20,896	8,310	22,607	14.3
2015	Littoral	L-2-4	5/4/2015	3	2	4	8.5%	91.5%	1,522	2.0 U	10.3	447	247	818	555	12.3	567	19,905	7,321	21,379	14.0
2015	Littoral	L-4-6	5/4/2015	5	4	6	8.9%	91.1%	1,447	2.0 U	13.9	411	221	801	583	15.9	599	21,276	7,774	21,472	14.8
2015	Littoral	L-6-10	5/4/2015	8	6	10	9.8%	90.2%	1,217	2.0 U	13.8	434	210	558	379	15.8	395	21,350	7,590	20,577	16.9
2015	Littoral	L-10-15	5/4/2015	12.5	10	15	10.4%	89.7%	1,136	2.0 U	17.4	437	225	457	301	19.4	320	22,249	7,175	21,414	18.9
2015	Littoral	L-15-20	5/4/2015	17.5	15	20	11.0%	89.0%	1,033	2.0 U	14.4	372	205	441	283	16.4	299	21,601	7,388	21,003	20.3
2015	Littoral	L-20-25	5/4/2015	22.5	20	25	11.6%	88.4%	868	2.0 U	16.5	288	182	382	229	18.5	248	22,292	6,779	21,544	24.8
2015	Littoral	L-25-30	5/4/2015	27.5	25	30	9.8%	90.2%	751	2.0 U	19.6	205	205	321	196	21.6	218	15,910	7,236	16,557	22.0
2015	Index	DUP-1	5/4/2015	12.5	10	15	11.1%	88.9%	1,716	2.0 U	17.3	821	292	586	433	19.3	452	27,285	6,822	30,637	17.9
2015	Station A	DUP-2	5/4/2015	17.5	15	20	14.7%	85.3%	1,084	2.0 U	15.4	464	274	330	209	17.4	226	26,343	6,756	26,720	24.6
2015	Station B	DUP-3	5/4/2015	27.5	25	30	9.5%	90.5%	1,003	2.0 U	77.3	349	172	405	249	79.3	328	17,409	7,261	18,380	18.3

[a] Biogenic P estimated for 1998 and 2004 (italics values) as 64% of organic P based on average ratio observed in 2015

J = Associated sample result is estimated value.

U = Not detected above the associated detection limit.

cm = centimeter

mg/kg DW = milligrams per kilogram dry weight

Empty cell = Not available

APPENDIX C

Laboratory Data Report

IEH ANALYTICAL LABORATORIES

LABORATORY & CONSULTING SERVICES

3927 AURORA AVENUE NORTH, SEATTLE, WA 98103

PHONE: (206) 632-2715 FAX: (206) 632-2417

CASE FILE NUMBER:	**HER080-11A**		**PAGE**	**1**
REPORT DATE:	**06/23/15**			
DATE SAMPLED:	**05/04/15**	**DATE RECEIVED:**		**05/06/15**

FINAL REPORT, LABORATORY ANALYSIS OF SELECTED PARAMETERS ON SEDIMENT SAMPLES FROM HERRERA ENVIRONMENTAL

CASE NARRATIVE

Thirty five sediment samples were received by the laboratory in good condition and analyzed according to the chain of custody. Phosphorus fractions were determined according to the method of Rydin and Welch.. Successive extractions with NH4Cl, Bicarbonate/Dithionate, NaOH, and HCL were performed and analyzed for phosphorus. One part of Organic P was determined by digesting the residue after the inorganic fractions were extracted. Organic P includes the P after the inorganic fractions plus Biogenic P. Total P is the sum of all fractions minus Biogenic P, which is part of the Organic P fraction. No difficulties were encountered in the preparation or analysis of these samples. Sample data follows, while QA/QC data is contained on subsequent pages.

SAMPLE DATA - SEDIMENTS (DRY WT. BASIS)

SAMPLE ID	% SOLIDS	% WATER	TOTAL-P (mg/kg)	LOOSELY BOUND P (NH4CL) (mg/kg)	FE BOUND P (DITHIONATE) (mg/kg)	AL BOUND P (NAOH) (mg/kg)	BIOGENIC P (mg/kg)	CA BOUND P (HCL) (mg/kg)	ORGANIC P (mg/kg)
B-15-20	9.24%	90.8%	1231	<2.00	17.3	529	354	193	491
B-20-25	9.26%	90.7%	945	<2.00	26.6	364	230	171	383
B-25-30	9.43%	90.6%	871	<2.00	18.8	335	212	164	354
L-0-2	8.04%	92.0%	1583	<2.00	10.2	270	779	247	1055
L-2-4	8.54%	91.5%	1522	<2.00	10.3	447	555	247	818
L-4-6	8.92%	91.1%	1447	<2.00	13.9	411	583	221	801
L-6-10	9.80%	90.2%	1217	<2.00	13.8	434	379	210	558
L-10-15	10.3%	89.7%	1136	<2.00	17.4	437	301	225	457
L-15-20	11.0%	89.0%	1033	<2.00	14.4	372	283	205	441
L-20-25	11.6%	88.4%	868	<2.00	16.5	288	229	182	382
L-25-30	9.76%	90.2%	751	<2.00	19.6	205	196	205	321
DUP-1	11.1%	88.9%	1716	<2.00	17.3	821	433	292	586
DUP-2	14.7%	85.3%	1084	<2.00	15.4	464	209	274	330
DUP-3	9.46%	90.5%	1003	<2.00	77.3	349	249	172	405
I-0-2	7.97%	92.0%	1686	<2.00	16.2	771	462	300	599
L-2-4	14.2%	85.8%	1303	<2.00	10.7	680	258	221	393
I-4-6	10.2%	89.8%	1702	<2.00	29.1	929	238	326	418
I-6-10	10.3%	89.7%	1979	<2.00	17.6	916	453	341	704
I-10-15	11.4%	88.6%	1787	<2.00	20.3	850	453	279	638
I-15-20	11.9%	88.1%	1936	<2.00	24.1	993	404	245	674
I-20-25	12.5%	87.5%	1971	<2.00	13.8	1263	266	286	408
I-25-30	13.1%	86.9%	1771	<2.00	35.0	1091	258	241	404
A-0-2	8.30%	91.7%	1551	<2.00	9.17	591	388	326	625
A-2-4	10.9%	89.1%	1353	<2.00	15.3	495	316	320	523
A-4-6	11.3%	88.7%	1534	<2.00	7.88	562	383	319	646
A-6-10	11.9%	88.1%	1468	<2.00	11.8	609	337	309	538
A-10-15	13.2%	86.8%	1409	<2.00	12.3	632	272	299	466
A-15-20	14.5%	85.5%	1088	<2.00	14.7	489	177	248	336
A-20-25	15.7%	84.3%	1072	<2.00	17.7	461	175	254	339
A-25-30	16.8%	83.2%	1045	<2.00	18.1	450	160	238	339
B-0-2	6.85%	93.2%	1663	<2.00	16.3	557	574	276	814
B-2-4	7.81%	92.2%	1379	<2.00	6.34	517	437	243	613
B-4-6	7.92%	92.1%	1580	<2.00	14.5	636	444	267	663
B-6-10	8.58%	91.4%	1578	<2.00	14.9	615	445	242	706
B-10-15	8.41%	91.6%	1651	<2.00	13.4	662	521	249	726

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CASE FILE NUMBER:	**HER080-11A**	**PAGE**	**2**
REPORT DATE:	**06/23/15**		
DATE SAMPLED:	**05/04/15**	**DATE RECEIVED:**	**05/06/15**

FINAL REPORT, LABORATORY ANALYSIS OF SELECTED PARAMETERS ON SEDIMENT SAMPLES FROM HERRERA ENVIRONMENTAL

QA/QC DATA- SEDIMENTS

QC PARAMETER	% SOLIDS	TOTAL-P (mg/kg)	LOOSELY BOUND P (NH4CL) (mg/kg)	FE BOUND P (DITHIONATE) (mg/kg)	AL BOUND P (NAOH) (mg/kg)	BIOGENIC P (mg/kg)	CA BOUND P (HCL) (mg/kg)	ORGANIC P (mg/kg)
METHOD	SM18 2540B	CALCULATED	SM18 4500PF	SM18 4500PF	SM18 4500PF	EPA 365.1	SM18 4500PF	EPA 365.1
DATE PREPARED	06/20/15	06/22/15	06/16/15	06/16/15	06/17/15	06/15/15	06/17/15	06/22/15
DATE ANALYZED	1.00%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
DETECTION LIMIT								
DUPLICATE								
	A-25-30	B-15-20	B-15-20	B-15-20	B-15-20	B-15-20	B-15-20	B-15-20
SAMPLE ID	16.8%	1231	<2.00	17.3	529	354	193	491
ORIGINAL	16.4%	1242	<2.00	16.3	550	325	198	477
DUPLICATE	2.26%	0.88%	NC	5.74%	3.92%	8.70%	2.61%	2.96%
RPD								
SPIKE SAMPLE								
SAMPLE ID								
ORIGINAL								
SPIKED SAMPLE								
SPIKE ADDED	NA	NA	NA	NA	NA	NA	NA	NA
% RECOVERY								
QC CHECK (mg/l)								
FOUND			0.040	0.040	0.040	0.093	0.040	0.092
TRUE			0.039	0.039	0.039	0.090	0.039	0.094
% RECOVERY	NA	NA	102.56%	102.56%	102.56%	103.33%	102.56%	97.87%
BLANK	NA	NA	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00

RPD = RELATIVE PERCENT DIFFERENCE.
NA = NOT APPLICABLE OR NOT AVAILABLE.
NC = NOT CALCULABLE DUE TO ONE OR MORE VALUES BEING BELOW THE DETECTION LIMIT.
OR = RECOVERY NOT CALCULABLE DUE TO SPIKE SAMPLE OUT OF RANGE OR SPIKE TO LOW RELATIVE TO SAMPLE CONCENTRATION.

SUBMITTED BY:

Damien Gadomski

Damien Gadomski
Project Manager

IEH ANALYTICAL LABORATORIES

LABORATORY & CONSULTING SERVICES

3927 AURORA AVENUE NORTH, SEATTLE, WA 98103

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CASE FILE NUMBER:	**HER080-11B**	**PAGE**	**1**
REPORT DATE:	**06/23/15**		
DATE SAMPLED:	**05/04/15**	**DATE RECEIVED:**	**05/06/15**

FINAL REPORT, LABORATORY ANALYSIS OF SELECTED PARAMETERS ON SEDIMENT SAMPLES FROM HERRERA ENVIRONMENTAL

CASE NARRATIVE

Thirty five sediment samples were received by the laboratory in good condition and were sectioned and analyzed according to the chain of custody. No difficulties were encountered in the preparation or analysis of these samples. Sample data follows, while QA/QC data is contained on subsequent pages.

SAMPLE DATA - SEDIMENTS (DRY WT. BASIS)

SAMPLE ID	% SOLIDS	% WATER	ALUMINUM (mg/kg)	IRON (mg/kg)	CALCIUM (mg/kg)
B-15-20	9.24%	90.8%	21320	20543	7508
B-20-25	9.26%	90.7%	18872	19941	8138
B-25-30	9.43%	90.6%	17611	18726	7794
L-0-2	8.04%	92.0%	20896	22607	8310
L-2-4	8.54%	91.5%	19905	21379	7321
L-4-6	8.92%	91.1%	21276	21472	7774
L-6-10	9.80%	90.2%	21350	20577	7590
L-10-15	10.3%	89.7%	22249	21414	7175
L-15-20	11.0%	89.0%	21601	21003	7388
L-20-25	11.6%	88.4%	22292	21544	6779
L-25-30	9.76%	90.2%	15910	16557	7236
DUP-1	11.1%	88.9%	27285	30637	6822
DUP-2	14.7%	85.3%	26343	26720	6756
DUP-3	9.46%	90.5%	17409	18380	7261
I-0-2	7.97%	92.0%	24555	26815	7152
L-2-4	14.2%	85.8%	17069	18444	4524
I-4-6	10.2%	89.8%	24698	27716	6613
I-6-10	10.3%	89.7%	27191	30921	7123
I-10-15	11.4%	88.6%	27912	31521	6847
I-15-20	11.9%	88.1%	28314	28486	6843
I-20-25	12.5%	87.5%	29828	27800	6428
I-25-30	13.1%	86.9%	26571	26703	6103
A-0-2	8.30%	91.7%	25447	27937	7180
A-2-4	10.9%	89.1%	25191	27496	6992
A-4-6	11.3%	88.7%	25531	28581	7212
A-6-10	11.9%	88.1%	25112	28363	6743
A-10-15	13.2%	86.8%	24841	27786	6370
A-15-20	14.5%	85.5%	26508	26860	6791
A-20-25	15.7%	84.3%	25789	26180	6392
A-25-30	16.8%	83.2%	26403	26146	6112
B-0-2	6.85%	93.2%	21987	24291	8828
B-2-4	7.81%	92.2%	20960	23170	8005
B-4-6	7.92%	92.1%	21374	23989	8575
B-6-10	8.58%	91.4%	21377	23152	7687
B-10-15	8.41%	91.6%	24570	24801	7467

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LABORATORY & CONSULTING SERVICES

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CASE FILE NUMBER:	**HER080-11B**	**PAGE**	**2**
REPORT DATE:	**06/23/15**		
DATE SAMPLED:	**05/04/15**	**DATE RECEIVED:**	**05/06/15**

FINAL REPORT, LABORATORY ANALYSIS OF SELECTED PARAMETERS ON SEDIMENT SAMPLES FROM HERRERA ENVIRONMENTAL

QA/QC DATA- SEDIMENTS

QC PARAMETER	% SOLIDS	ALUMINUM (mg/kg)	IRON (mg/kg)	CALCIUM (mg/kg)
METHOD	SM18 2540B	EPA 6010	EPA 6010	EPA 6010
DATE ANALYZED	06/20/15	06/01/15	06/01/15	06/01/15
DETECTION LIMIT	1.00%	3.00	2.00	10.0
DUPLICATE				
SAMPLE ID	A-25-30	B-10-15	B-10-15	B-10-15
ORIGINAL	16.8%	24570	24801	7467
DUPLICATE	16.4%	23800	23947	7709
RPD	2.26%	3.19%	3.50%	3.18%
SPIKE SAMPLE				
SAMPLE ID				
ORIGINAL				
SPIKED SAMPLE				
SPIKE ADDED				
% RECOVERY	NA	NA	NA	NA
QC CHECK **(mg/L)**				
FOUND		4.51	5.36	9.76
TRUE		5.00	5.00	10.0
% RECOVERY	NA	90.20%	107.20%	97.59%
BLANK	NA	<3.00	<2.00	<10.0

RPD = RELATIVE PERCENT DIFFERENCE.
NA = NOT APPLICABLE OR NOT AVAILABLE.
NC = NOT CALCULABLE DUE TO ONE OR MORE VALUES BEING BELOW THE DETECTION LIMIT.
OR = RECOVERY NOT CALCULABLE DUE TO SPIKE SAMPLE OUT OF RANGE OR SPIKE TO LOW RELATIVE TO SAMPLE CONCENTRATION.

SUBMITTED BY:

Damien Gadomski

Damien Gadomski
Project Manager

HER080-11

HERRERA
2200 Sixth Avenue | Suite 1100
Seattle, Washington | 98121
p 206 441 9080 | f 206 441 9108

Chain of Custody Record

Project Name:	Project Number:	Client:
Green Lake Alum Treatment 2016	13-05709-001	Seattle Parks
Report To: Rob Zisette		Copy To:
Sampled By: Rob Zisette		Delivery Method: Hand
Laboratory: Aquatic Research	Requested Completion Date: Standard	Total No. of Containers: 35
Lab Use:		

Sample ID	Date	Time	Sample Type (see codes)	Preser-vative? (Y/N)	Matrix (see codes)	Number of Containers	Loosely Bound P (SM 4500PF)	Fe Bound P (SM 4500PF)	Al Bound P (SM 4500PF)	Ca Bound P (SM 4500PF)	Total and Labile Organic P (SM 4500PF)	Total P (SM 4500PF)	Total Solids (SM 2540B)	Total Iron (EPA 6010)	Total Calcium (EPA 6010)	Total Aluminum (EPA 6010)	Lab ID No.
B-15-20	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-20-25	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-25-30	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-0-2	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-2-4	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-4-6	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-6-10	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-10-15	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-15-20	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-20-25	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
L-25-30	5/4/2015	1200	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
DUP-1	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
DUP-2	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
DUP-3	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	

Comments/Special Instructions:

Note that two forms of organic P are requested, including total organic P and labile organic P (also termed biochemical organic P or mobile organic P)

Relinquished by (Name/CO/	Signature	Date/Time	Received By (Name/CO)	Signature	Date/Time
Rob Zisette/Herrera	[signature]	5/6/15 1535	JAMIE GANDAMSH	[signature]	5/6/15 1535
Relinquished by (Name/CO/	Signature	Date/Time	Received By (Name/CO)	Signature	Date/Time

Sample Type: G=Grab C=Composite **Matrix Codes:** A=Air GW=Groundwater SE=Sediment SO=Soil SW=Surface Water W=Water (blanks) M=Material O=Other (specify)

HERRERA
2200 Sixth Avenue | Suite 1100
Seattle, Washington | 98121
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Chain of Custody Record

Project Name:	Project Number:	Client:
Green Lake Alum Treatment 2016	13-05709-001	Seattle Parks
Report To: Rob Zisette		Copy To:
Sampled By: Rob Zisette		Delivery Method: Hand
Laboratory: Aquatic Research	Requested Completion Date: Standard	Total No. of Containers: 35
Lab Use:		

Sample ID	Date	Time	Sample Type (see codes)	Preser-vative? (Y/N)	Matrix (see codes)	Number of Containers	Analyses Requested: Loosely Bound P (SM 4500PF)	Fe Bound P (SM 4500PF)	Al Bound P (SM 4500PF)	Ca Bound P (SM 4500PF)	Total and Labile Organic P (SM 4500PF)	Total P (SM 4500PF)	Total Solids (SM 2540B)	Total Iron (EPA 6020)	Total Calcium (EPA (6020)	Total Aluminum (EPA 6020)	Lab ID No.
I-0-2	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-2-4	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-4-6	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-6-10	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-10-15	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-15-20	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-20-25	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
I-25-30	5/4/2015	1250	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-0-2	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-2-4	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-4-6	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-6-10	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-10-15	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-15-20	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-20-25	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
A-25-30	5/4/2015	1225	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-0-2	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-2-4	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-4-6	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-6-10	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	
B-10-15	5/4/2015	1130	G	N	SE	1	X	X	X	X	X	X	X	X	X	X	

APPENDIX C

Alum Dose Evaluation

TETRA TECH

MEMO

To:	Herrera Environmental Consultants, ATTN: Rob Zisette
Cc:	
From:	Tetra Tech, Gene Welch, Shannon Brattebo and Harry Gibbons
Date:	8/5/2015
Subject:	Green Lake sediment core data and alum dose

Sediment core data from Green Lake in 1998, 2004, and 2015 presented by Herrera (2015) were reviewed for this technical memorandum. The relative effect of the 2004 treatment was determined by ratios of Aluminum (Al) added to Aluminum-Phosphorus (Al-P) formed at the Index station. Alum doses were also calculated for application in the forthcoming treatment in 2016 with reference to protocols in Cooke et al. (2005) and Osgood et al. (2014), as well as other sources.

Effects of the 2004 Alum Treatment

Aluminum-P concentrations at the Index station averaged 0.172, 0.649 and 0.842 mg/g over the top 10 cm in cores collected in 1998, 2004, and 2015, respectively (Figure 1). These concentrations converted to 1.57, 7.72, and 10.0 g/m^2 for the 3 observation years, respectively. The difference between 1998 and 2004 (after treatment) was 6.15 g/m^2 (the approximate amount of Al-P initially formed by the 2004 alum treatment). The ratio of Al added in 2004 (92 g/m^2) to the Al-P formed (6.15 g/m^2) is 15, which indicates the effect of sediment P initially inactivated with Al by the 2004 treatment.

Additional Al-P was formed at the Index station since the sediment cores were collected after the 2004 treatment (Figure 1). The Al-P concentration in 2015 averaged 0.975 mg/g or 29 g/m^2 through the top 25 cm of sediment. In fact, more Al-P was formed than this amount because cores were not deep enough to determine the depth at which Al-P matched background levels (pre-treatment conditions in 1998; Figure 1). The difference between 29 g/m^2 and the average amount to 25 cm in 1998 (4.35 g/m^2) is 24.7 g/m^2, which gives an Al added:Al-P formed ratio of 3.7 (92/24.7). That ratio is much lower than the ratio of 15 initially observed after the 2004 treatment and would be even lower if the depth at which Al-P returned to pre-treatment levels were known.

Another noteworthy point is that total phosphorus (TP) in the sediments was higher in 2015 than 2004 at the Index station, especially from 10 to 30 cm; 1.76 versus 1.54 mg/g, on average over 30 cm. Much of that increased TP, as well as the increased Al-P, probably came from soluble P diffusing vertically from deeper sediment layers. A similar pattern of increased TP in treated versus untreated areas was shown in Grand Lake St. Marys, Ohio. Although some increased TP may have come from storm runoff, Green Lake sediment is probably enriched to considerable depth and may represent a substantial source of P to the lake. This is reinforced by the deep core taken in 1959 that indicated Green Lake to be naturally eutrophic historically (Sylvester and Anderson, 1964).

The 2004 treatment was less effective at Station A (Figure 1). Aluminum added to Al-P formed ratios of 49 and 26 represent the effect over 10 and 20 cm immediately after the 2004 treatment. Effectiveness increased during the intervening years, with much lower ratios of 16.6 and 7.9 for the 10 and 20 cm sediment depths. As noted for the Index station, the actual ratios at Station A are probably even lower because Al-P formed did not reach background (1998 levels) within the analyzed 30 cm depth (Figure 1).

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The average Al added:Al-P formed ratio observed in eight Washington lakes, at seven to 21 years after alum treatment, was 10.7 ± 0.7 (Rydin et al., 2000). Also, Al-P formed above background occurred at depth intervals less than 10 cm in all eight Washington lakes. Why the depth of Al-P formed was eventually much greater in Green Lake (> 30 cm) is not clear. It may be due to bioturbation by carp because carp are likely much more abundant in Green Lake than the other alum treated lakes studied. For example, a fisheries study in the 1970's showed no carp in Long Lake, Kitsap County, one of the cited eight lakes. A recent study of an alum treated lake with abundant carp and soft sediment measured the average carp bioturbation depth at 13 cm (Huser et al., 2015), which suggests that carp bioturbation would not have been sufficient to mix sediment beyond 30 cm in Green Lake. However, some Danish limnologists have stated that chironomid midges can mix sediment to 20 cm (M. Sondergaard, personal communication). Also, doses were much less in all but two of the other Washington lakes studied– ranging from 11-27 g Al/m^2 – than in Green Lake. Medical Lake is the one other lakes studied with a high dose (122 g Al/m^2 in 1977) and the peak Al-P formed by 1998 was distinctive at only 6.5-7.5 cm (Rydin et al., 2000). Thus, the high Al-P observed at 30 cm in Green Lake is not readily explained by either carp and/or invertebrate bioturbation or the high dose. Note that the other lake was treated at 70 g Al/ m^2 was Long Lake in Kitsap County, but that was in 2007 so it was not included in Rydin's study.

Calculation of the 2016 Alum Dose

Core data show that mobile-P, as Fe-P and labile-P, has remained quite low throughout the sediment column at all four coring sites (Herrera 2015). That indicates the persistent effect of the 2004 treatment. Figures 1 and 2 show that the effect of the 2004 alum treatment, in terms of decreased mobile-P and increased Al-P, was greater in the intervening 11 years than was the case right after the treatment, especially between 10 and 30 cm at the Index site. Again, this shows that added Al continued to inactivate P to greater depths in the sediment column well after the treatment and the formed Al-P remained stable. This is a significant indication of the positive and intended impact of the 2004 alum treatment.

Biogenic-P was not determined in 1998 and therefore was not used to determine the aluminum dose in 2004. Thus, the amount of biogenic-P inactivated with Al in the 2004 treatment cannot be determined. Biogenic-P is now included with mobile-P (Fe-P + labile-P) as standard procedure in determining Al dose. The low ratio of Al added:Al-P formed in Green Lake (~4 and ~8) and other lakes (~11) may be due to a portion of undetermined biogenic-P inactivated by Al. Therefore, including biogenic-P, as is done here, may ultimately reduce the ratio used to determine dose. For example, the dose ratio used for Lake Sønderby (Denmark), which included biogenic-P, was 4:1 (Reitzel et al., 2003). In follow-up work by the Danish group, a dose ratio of 8.8 over 20 cm depth was recommended that included biogenic-P (de Vicente et al., 2008). The initial work determining dose from sediment mobile-P levels in Wisconsin lakes recommended 100:1 Al added to mobile P over 4 cm (Rydin and Welch, 199). That ratio translates to 20:1 over 20 cm. Recent treatment of Lake Ketchum, Snohomish County in 2014 and 2015 was dosed at 20:1 for mobile + biogenic-P (most was biogenic-P). Grand Lake St Marys was also dosed at 20:1 for biogenic-P control in 2011 and 2012. The risk in using too low of a ratio is that it does not account for the mobilization and vertical migration of the P reserve from deeper sediment layers to the sediment surface; such sediment P reserve exists in Green Lake.

Mobile-P plus biogenic-P mean concentrations ranged from 0.303 to 0.549 mg/g, depending on sediment depth and site (Table 1). Three alternative dose ratios (Al added:mobile-P + biogenic-P) and sediment depth combinations were used to calculate Al dose for the 2016 Green Lake treatment that include; 1) 20:1 for the top 10 cm, 2) 10:1 for the top 20 cm, and 3) 7:1 for the top 20 cm of sediment. The reason for using dose ratios of 20:1 over 10 cm and 10:1 over 20 cm (which is roughly the same due to rather uniform biogenic-P profiles) is that this procedure produced a rather high ratio of 15:1 added Al:AL-P formed shortly after the 2004 treatment, and this high dose was necessary to bind mobile-P (and biogenic-P) in the shallow sediments and still have enough left to bind P diffusing from greater sediment depth. A relatively high dose ratio for 2016 also would be a partial safeguard in case proper application protocols are not followed and/or weather conditions preclude an equal distribution of alum, as occurred in the 1991 treatment. The reason for using 7:1 instead of 10:1 for the top 20 cm of sediment is that mobile-P below 10 cm, to at least 30 cm, was eventually inactivated at the Index and Station A sites well after the 2004 treatment using a 10:1 dose ratio and 20 cm sediment depth (Figure 2) that did not include biogenic-P.

The eventual Al added:Al-P formed ratios through 20 cm at the Index and Station A sites were ~4 and ~8, respectively. Also, a ratio of 8.8:1 (10:1 molar) was recommended by de Vicente et al. (2008) that included biogenic-P, as well as substantial mobile Fe-P and labile-P. Therefore, the other reason for recommending a ratio of 7:1 is recommended as a compromise between 4:1 and 10:1, over 20 cm, because mobile-P is now minimal in Green Lake compared to biogenic-P concentrations. Using a lower ratio of 4 may not provide enough Al for treatment longevity effectiveness due to continued diffusion of mobile P from greater sediment depths. Also, using a 10 cm depth, which would reduce the dose roughly in half, is not recommended for the same reason: because results from the 2004 treatment show that mobile P, and likely some biogenic P, was eventually inactivated through at least the top 30 cm, and throughout that depth, P may have been available for internal loading, as a result of upward diffusion of soluble P and/or through bioturbation by carp and invertebrates.

The calculated aluminum dose is presented for each alternative dose and station, and averaged for all stations in Table 1. An additional Al dose of 1.6 g/m^2 was added to each sediment dose to account for binding with total phosphorus, at an average concentration of 20 mg/m^3 in the water column during treatment. This procedure results in total Al doses of 95.2, 94.4 and 66.6 g/m^2 for ratios of 20:1 (10 cm), 10:1 (20 cm), and 7:1 (20 cm) (Table 1 and spreadsheet). Converting the areal Al dose to a concentration results in doses of 24.4, 24.2, and 17.1 mg Al/L for ratios of 20:1 (10 cm), 10:1 (20 cm), and 7:1 (20 cm) (see spreadsheet below).

The 17.1 mg Al/L dose recommended for 2016 is less than the 23.0 mg Al/L dose applied in 2004. The dose recommended for sediment inactivation (16.7 mg Al/L) is similar to that applied in 2004 (17.2 mg Al/L), while the dose recommended for water binding (0.4 mg Al/L) is much less than that applied in the 2004 (5.8 mg Al/L) due to the lower amount of total phosphorus present in the water column. The recommended dose is anticipated to meet water quality goals for at least 10 years based on the long-term effect of the 2004 treatment and assuming external phosphorus inputs to the lake remain relatively low. It is recommended that the 2016 treatment occur in April when the water temperature is moderate, the amount of aquatic plant (milfoil) and algae growth are relatively low, and recreational activity on the lake is also low.

Quantities of each chemical, alum and sodium aluminate, were calculated based on the recommended dose of 17.1 mg Al/L. The spring 2016 treatment at a dose of 17.1 mg Al/L will require 169,160 gallons of alum (estimated 38 tanker trucks) and 82,670 gallons of sodium aluminate (estimated 20 tanker trucks) based on the standard ratio of 2 parts alum to 1 part aluminum sulfate (by volume) and their typical aluminum content. The treatment should be completed within 10 working days. A cost estimate for the spring 2016 treatment is shown in Table 2.

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Rydin, E., and E. B. Welch. 1999. Dosing alum to Wisconsin lake sediments based on possible in vivo formation of aluminum bound phosphorus. Lake and Reserv. Manage. 15:324-331.

Sylvester, R. D. and G. C. Anderson. 1964. A lake's response to its environment. V. Sanit. Eng. Div. ASCE. 90:1-22.

Tables:

Table 1: Mean sediment-P content and alternative aluminum doses for ratios of Al added:mobile + biogenic P at 0–10 and 0–20 cm depth intervals.

Site	Mobile + Biogenic P (mg/g)		Aluminum Dose (g Al/m^2)		
			20:1	10:1	7:1
	0-10 cm	*0-20 cm*	*0-10 cm*	*0-20 cm*	*0-20 cm*
Index Station	0.393	0.423	93.2	105.9	74.2
Station A	0.365	0.303	88.9	85.4	59.8
Station B	0.484	0.470	83.6	86.1	60.2
Littoral Station	0.549	0.430	108.1	93.8	65.7
Average sediment dose:			**93.6**	**92.8**	**65.0**
Water column dose (at 20 mg/m^3 TP):			**1.6**	**1.6**	**1.6**
Total dose:			**95.2**	**94.4**	**66.6**

See spreadsheet calculations attached.

Table 2: Cost Estimate for the Green Lake Spring 2016 Alum Treatment based on the recommended dose of 17.1 mg Al/L.

Item	Unit Cost	Quantity	Total Cost
Aluminum Sulfate (applied cost per gallon)	$1.50	169,160	$ 253,740
Sodium Aluminate (applied cost per gallon)	$3.60	82,670	$ 297,612
Mobilization/Demobilization (applied to material cost)	$0.20	$ 551,352	$ 110,270
Subtotal 1			$ 661,622
Tax	9%	--	$ 59,546
Subtotal 2			$ 721,168
Contingency	30%	--	$ 216,351
Grand Total Cost			**$ 937,519**

Figures:

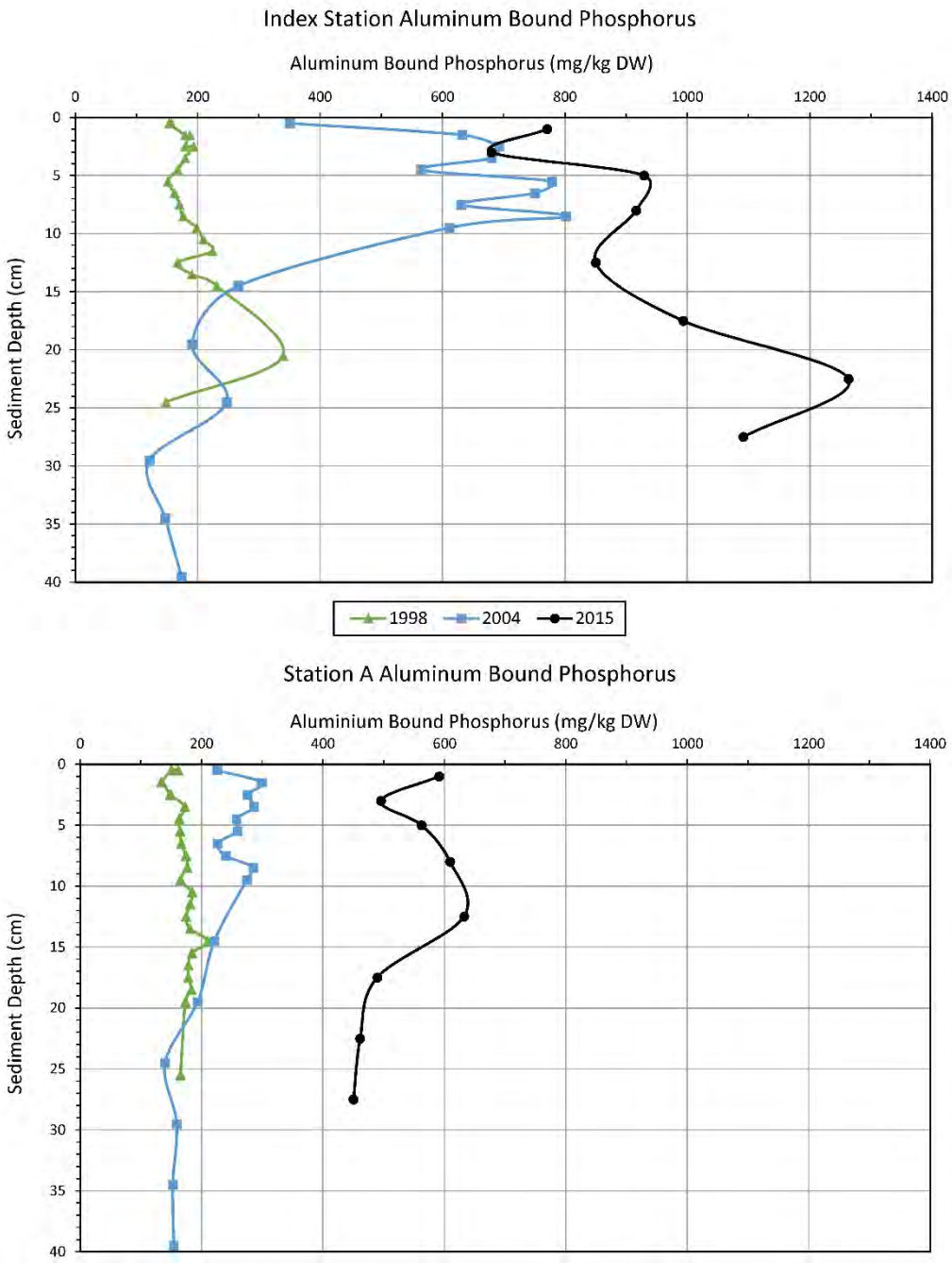

Figure 1 - Green Lake Sediment Aluminum Bound Phosphorus at Index Station and Station A in 1998, 2004 (post- alum treatment), and 2015

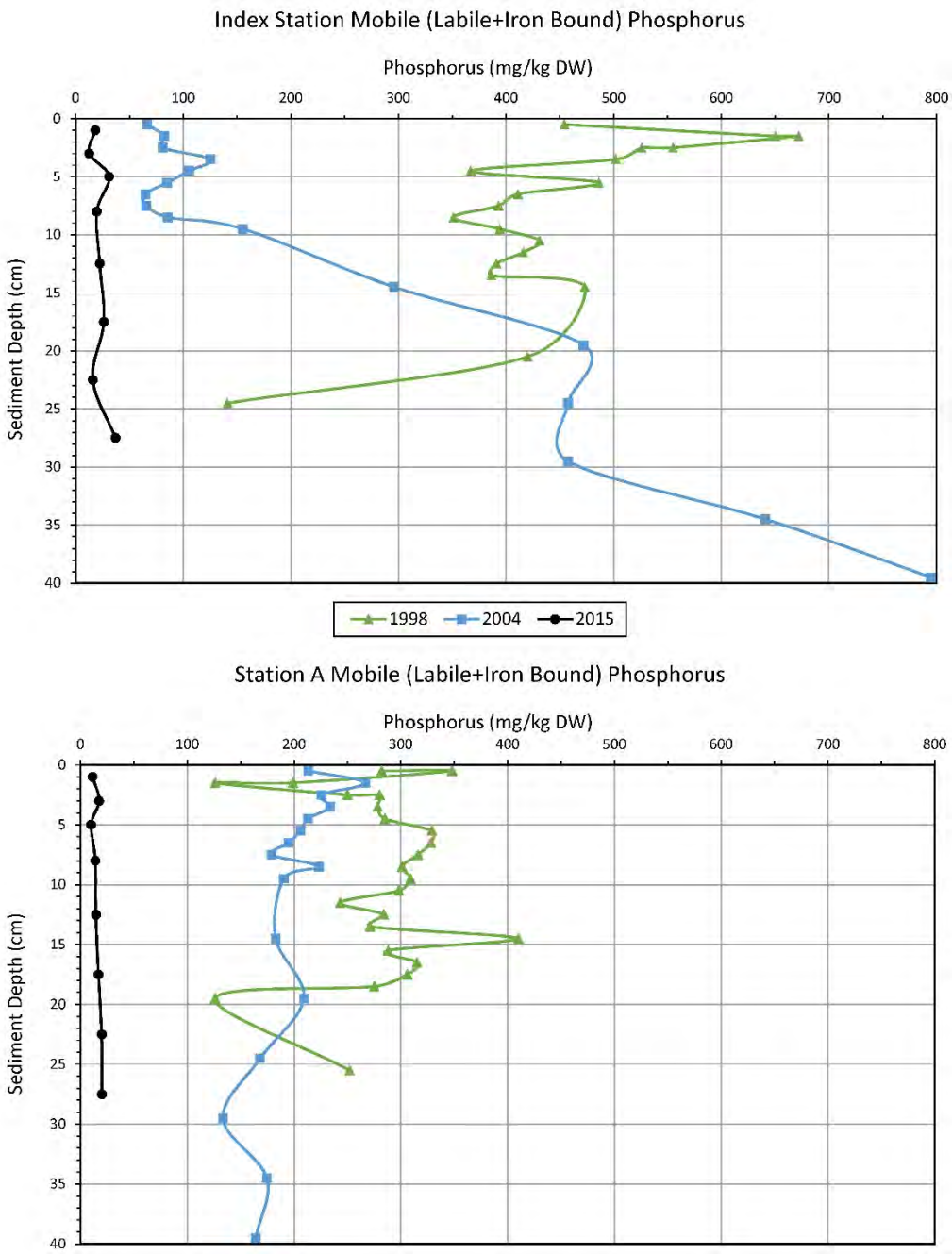

Figure 2 - Green Lake Sediment Mobile Phosphorus at Index Station and Station A in 1998, 2004 (post- alum treatment), and 2015

Spreadsheets:

Green Lake Alum Dose Calculations by Station

INDEX STATION (all averages depth weighted)

Mobile P + Biogenic P (mg/g)	% Water	% Solids	Sediment Bulk Density (g/cm^3)	Solids concentration (g/cm^3)	Sediment Depth (cm)	Al added:Al-P formed ratio	Al dose, mg/cm^2	Al dose, g/m^2
0.393	89.4%	10.6%	1.119	0.119	10	20	9.3	93.2
0.423	88.9%	11.1%	1.125	0.125	20	10	10.6	105.9
0.423	88.9%	11.1%	1.125	0.125	20	7	7.4	74.2
0.423	88.9%	11.1%	1.125	0.125	20	4	4.2	42.4

STATION A (all averages depth weighted)

Mobile P + Biogenic P (mg/g)	% Water	% Solids	Sediment Bulk Density (g/cm^3)	Solids concentration (g/cm^3)	Sediment Depth (cm)	Al added:Al-P formed ratio	Al dose, mg/cm^2	Al dose, g/m^2
0.365	89.1%	10.9%	1.122	0.122	10	20	8.9	88.9
0.303	87.7%	12.4%	1.141	0.141	20	10	8.5	85.4
0.303	87.7%	12.4%	1.141	0.141	20	7	6.0	59.8
0.303	87.7%	12.4%	1.141	0.141	20	4	3.4	34.2

STATION B (all averages depth weighted)

Mobile P + Biogenic P (mg/g)	% Water	% Solids	Sediment Bulk Density (g/cm^3)	Solids concentration (g/cm^3)	Sediment Depth (cm)	Al added:Al-P formed ratio	Al dose, mg/cm^2	Al dose, g/m^2
0.484	92.1%	8.0%	1.086	0.086	10	20	8.4	83.6
0.470	91.6%	8.4%	1.091	0.092	20	10	8.6	86.1
0.470	91.6%	8.4%	1.091	0.092	20	7	6.0	60.2
0.470	91.6%	8.4%	1.091	0.092	20	4	3.4	34.4

LITTORAL (all averages depth weighted)

Mobile P + Biogenic P (mg/g)	% Water	% Solids	Sediment Bulk Density (g/cm^3)	Solids concentration (g/cm^3)	Sediment Depth (cm)	Al added:Al-P formed ratio	Al dose, mg/cm^2	Al dose, g/m^2
0.549	91.0%	9.0%	1.099	0.099	10	20	10.9	108.8
0.430	90.2%	9.8%	1.109	0.109	20	10	9.4	93.8
0.430	90.2%	9.8%	1.109	0.109	20	7	6.6	65.7
0.430	90.2%	9.8%	1.109	0.109	20	4	3.8	37.5

Water Column Stripping Dose

Average TP Concentration (mg/L)	Al added:Al-P formed ratio	Al dose, mg/L	Al dose, g/m2
0.020	20	0.40	1.56

Average Sediment Dose (all stations)

Al added:Al-P formed ratio	Al dose, g/m^2	Lake Mean Depth (m)	Al dose, mg/L	Water Column Stripping Dose, mg/L	Total Dose, mg Al/L
20	93.6	3.9	24.0	0.40	24.4
10	92.8	3.9	23.8	0.40	24.2
7	65.0	3.9	16.7	0.40	17.1
4	37.1	3.9	9.5	0.40	9.9

TETRA TECH

MEMO

To:	Herrera Environmental Consultants, ATTN: Rob Zisette
Cc:	
From:	Tetra Tech
Date:	10/21/2015
Subject:	Addendum to 8/5/15 memo from Tetra Tech

The alum dose proposed for 2016 is herein modified after conferring with Swedish limnologists on August 18, 2015 (Rydin and Huser, pers. comm). Results of sediment analyzed and/or supervised by them in 1998 and 2004 were reexamined. Also, a procedure for assessing biogenic-P to determine alum dose was recommended. Incorporating that procedure resulted in 48% of the alum dose proposed earlier (Tetra Tech, 2015).

Reexamined past data showed that biogenic-P from 1998 and 2004 and those determined in 2015 were similar, ranging from 0.30 to 0.445 at the index site and 0.275 to 0.352 at site A. Biogenic-P was not included in the dose added to the lake in 2004, but it was part of the dose, determined for 2016, along with the small amount of mobile-P that still persists from the 2004 treatment (Tetra Tech, 2015). However, the new dose proposed here considers only the “active” fraction of biogenic-P in the top 10 or 20 cm of sediment, minus the “inactive” background fraction of lower concentrations below that depth, as recommended by Rydin and Huser (Table 1). Background averaged 50% of the biogenic-P in the top 10 cm at sites A and littoral, and the top 20 cm at the index and B sites. Therefore, sediment depths used to compute dose were 10 cm at the littoral and A sites and 20 cm at the index and B sites, because those were the depths at which biogenic-P declined to background. Instead of using 10:1 and 20:1 ratios of Al added to P for 20 cm and 10 cm depths, respectively, 9:1 was used regardless of sediment depth. A ratio of 8.8:1 of Al added to Al-P formed has been recommended by Danish scientists when using both biogenic-P and mobile-P to determine dose.

There is still the uncertainty of P sources from sediment deeper than 30 cm. Mobile Fe-P remained relatively high at site A and the littoral site, and deeper than 15 cm at the index site following the 2004 treatment (Table 2). By

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2015, those levels had decreased to only a few percent of those in 1998, before treatment, and > 15 cm at the index site (Table 2). Al-P concentrations below 15 cm were also much higher in 2015 than 2004, consistent with the Fe-P decrease. Thus, added Al accessed more mobile-P and at greater depth than anticipated with the dose used in the 2004 treatment. A similar pattern of increased Al-P and decreased Fe-P occurred at the littoral site below 15 cm. Thus, the use of 9:1 over 20 cm, as well as 10 cm, is to account for mobile-P sources below 20 cm. Additional cores to 0.5 m and 1 m would identify the depth to which the 2004 treatment reached, as well as the quantity of mobile-P that exists and may be available.

References:

Rydin, Emil - Uppsala Univ., and Brian Huser - Swedish Agricultural Univ., Uppsala, Sweden, pers. comm.

Tetra Tech Inc. 2015. Technical memo to Herrera Assoc. 8/5/2015

Tables:

Table 1: Mean sediment-P content (mg/g) and alum doses for ratio of Al added: mobile + biogenic P of 9:1 at 0-10 and 0-20 cm depth intervals.

Site	Mobile + Biogenic P (mg/g)		Dose (g Al/m^2) 9:1	
	0 – 10 cm	*0 – 20 cm*	*0 – 10 cm*	*0 – 20 cm*
Index Station	--	0.159	--	35.8
Station A	0.167	--	18.3	--
Station B	--	0.250	--	41.2
Littoral Station	0.295	--	26.3	--
Average sediment dose:			**30.4**	
Water column dose (at 20 mg/m^3 TP):			**1.6**	
Total dose:			**32.0**	

See spreadsheet calculations attached

Table 2 - Iron-P concentrations in sediment at respective sites. Depth is depth of core and sediment column.

	Depth	*25 cm*	*40 cm*	*30 cm*
	Year	**1998**	**2004**	**2015**
Site	A	275	180	14.0
	B	--	46.4	16.0
	Index	418	23 (< 15 cm) 496 (> 15 cm)	21.4
	Littoral	--	87.5	15.2

Table 3: Cost estimate for the Green Lake Spring 2016 Alum Treatment based on the recommended dose of 8.2 mg Al/L (32.0 g Al/m^2).

Item	Unit Cost	Quantity	Total Cost
Aluminum Sulfate (applied cost per gallon)	$1.50	81,680	$122,520
Sodium Aluminate (applied cost per gallon)	$3.60	40,840	$147,024
Mobilization/Demobilization (applied to material cost)	$0.20	$269,544	$53,909
Subtotal 1			$323,453
Tax	9%	--	$29,111
Subtotal 2			$352,564
Contingency	30%	--	$105,769
Grand Total Cost			$458,333

APPENDIX D

Treatment Specifications

TECHNICAL SPECIFICATIONS: GREEN LAKE ALUM TREATMENT 2016

PART 1 GENERAL

1. DESCRIPTION

It is the intent of these specifications to describe the minimum acceptable performance standards for the application of aluminum sulfate (alum) and sodium aluminate to inactivate sediment phosphorous in Green Lake, Seattle, WA.

A. BACKGROUND

Green Lake is located in King County, Washington, just north of downtown Seattle and Lake Union. The lake is 259 acres in surface area and has an estimated volume of 4,037 acre-feet (4.98 million cubic meters). A bathymetry map of the lake is included in Exhibit A of this document. Green Lake is an important recreational and aesthetic resource for Seattle residents. The lake is surrounded by public park. A lakeside path extends 2.8 miles around the lake and is used year-round for walking, running, skating and bicycling. Recreational uses of the lake include rowing, canoeing, kayaking, windsurfing, and sailing. Boat access points for hand carried boats are located at the Green Lake Small Craft Center and at the Green Lake West and Green Lake East beach areas. Fishing is another recreational activity at Green Lake. Three fishing piers are available for public use at the lake as well as access to shorelines areas via the lakeside path.

Green Lake has been closed to recreation for cyanobacteria accumulations and blooms several times in its history. Most recently, accumulations along downwind shorelines have produced toxins, and scums tested in 2012 – 2014 have produced values that could be harmful to children and pets. This resulted in warnings being posted at these accumulation locations advising recreational users to avoid all areas of algae accumulation and scum along the shorelines.

The lake was treated with aluminum sulfate (alum) to reduce available phosphorus and inactivate sediment phosphorus in 1991 and in again in 2004. The most recent treatment reduced nutrients and immediately improved water quality of the lake. Water quality goals have been met in Green Lake since the 2004 treatment although there has been an increase in toxic cyanobacteria accumulations in isolated locations around the lake in the past few years.

Seattle Parks and Recreation in response to the increased presence of toxic cyanobacteria accumulations decided to treat Green Lake with alum in the spring of 2016 to reduce phosphorus and cyanobacteria blooms, and improve recreational use of the lake. This decision was based on the recommendations from the Green Lake Phytoplankton Study conducted by Herrera (2015). The recommended alum dose for the spring 2016 treatment is 8.2 mg Al/L (7.8 mg Al/L for sediment P inactivation and 0.4 mg Al/L for water column P inactivation).

2. PROJECT SPECIFIC REQUIREMENTS

Below is a list of project specific requirements for the 2016 Green Lake alum treatment.

A. The Contractor shall perform all work necessary to apply liquid aluminum sulfate (alum) and liquid sodium aluminate (buffer) simultaneously at a volumetric ratio of 2:1 (alum: sodium aluminate) for phosphorus control in Green Lake. A ratio of 2:1 will provide 0.44 kg Al from two gallons of liquid alum and 0.58 kg Al from one gallon of liquid sodium aluminate, given a concentration of 32 percent for the available soluble sodium aluminate. Materials shall be applied to the whole lake, beginning with the shallower southwestern portion of the lake, then the shallow periphery of the lake, and finishing in the deeper section of the lake at the northeast end. Note: Seattle Parks and Recreation/City of Seattle holds permit coverage under the Washington State Department of Ecology Aquatic Plant and Algae Management General Permit for this treatment. The Contractor shall adhere to all the requirements of Ecology General Permit.

B. The Contractor shall provide all equipment, labor, and materials necessary to perform the work, including application equipment, and all other equipment necessary to mobilize and demobilize. This shall include:

1. The specified amounts and qualities of aluminum sulfate and sodium aluminate
2. Boat(s) or barge(s) capable of traversing the lake and applying the alum and buffer at appropriate rates to all portions of the lake. Both chemicals are to be applied to the water directly and simultaneously so that they mix immediately upon entering the water but not before (see Exhibit C for illustration of appropriate application boom set up). The alum and sodium aluminate should NOT come in contact with one another outside of the water.
3. On-shore chemical storage tanks and associated spill containment equipment (On-shore storage tanks are recommended but not required if the rate of application can keep pace with delivery of chemicals.)
4. On-board chemical storage tanks and spill containment equipment
5. The appropriate pumps, boom and spreader applicators to control and evenly distribute chemical dosing for both liquid aluminum sulfate and sodium aluminate simultaneously (See Exhibit C for illustration of appropriate boom set up. Note that the chemicals are to be delivered to the lake water at an approximate depth of 1 to 2 inches below the water surface from a minimum of 12 pairs, up to a maximum of 24 pairs, of alum and sodium aluminate injection tubes (nozzles or small hoses) spaced 8 to 12 inches between pairs and with the alum and sodium aluminate injection tubes within each pair spaced 2 to 4 inches apart. The injection tubes shall be alternating so that the closest tubes in each direction are always tubes of the other chemical. The treatment shall not begin until the application system is approved on-site by the construction manager representing Seattle Parks.)
6. A GPS-linked computer system for barge (boat) guidance that is integrated with real-time bathymetric measurements and provides chemical dosing control for both aluminum sulfate and sodium aluminate pumping rates

based on real-time depth as well as maps/documents areas of the lake already treated

7. Trained staff to safely and effectively implement the alum treatment

8. Temporary ramp structure that meets ADA accessible route requirements, to facilitate normal and continued use of the park's lake perimeter path and walkways during treatment application activities

C. Environmental conditions may exist at Green Lake that may require delay or temporary interruption of work on the project. The Seattle Parks on-site representative and construction manager will make a final determination on whether to initiate, suspend, or re-start the treatment, based on having acceptable environmental conditions for treatment. These conditions shall include but are not limited to: dissolved oxygen, pH, temperature, wind, intensity of phytoplankton bloom, and fish kill. Delays or postponements may be measured in hours or days, depending on the length of time necessary for conditions to improve. All work shall comply with conditions of the permit coverage for this project.

The general configuration of the lake and bathymetry, and the staging area are shown on Exhibit A and Exhibit B, respectively.

3. SUBMITTALS

The Contractor shall submit the following for review and approval by Seattle Parks and their on-site representative.

A. Plan of Work – shall be submitted prior to the procurement of materials and shall include, at a minimum, the following items:

1. Explanation of plans and schedule for the timely delivery, storage and transfer of all chemicals

2. Description of any temporary on-shore chemical storage facilities, including a spill prevention, control, and contingency plan (Spill Prevention and Chemical Control Plan), and proposed location for security fencing and/or other measures necessary to deter vandalism and prevent tampering with chemical storage facilities

3. Photographs and/or drawings and description of the application equipment to be used on the lake, including application boom set up, width of application path, on-board storage capacity of both chemicals, and means of locomotion

4. Description of approach to application in the shallow areas of the lake, with specific reference to how to move the treatment boat around in these areas and the application technique to apply the chemicals within these shallower areas (treatment shall be to all areas of the lake 3 feet and deeper), if different than the application technique to be used in deeper areas of the lake

5. Method of chemical distribution, documenting the control of chemical pumping rate into the lake based on application vessel speed, real-time GPS navigation, and real-time bathymetric measurements to ensure an effective dose of 8.2 mg Al/L throughout the lake

6. Description of any proposed backup systems to minimize down time
7. Description of land-to-vessel chemical transfer method(s), including spill prevention and response protocols to be employed
8. Anticipated treatment capacity (acre/hour and gallons/day)
9. Plan for decontaminating all equipment prior to bringing equipment to the lake to prevent the introduction of any aquatic invasive species into the lake. This includes, but is not limited to, de-contamination of barge(s), boat(s), boat and vehicle trailers and tires, all on-board gear, hoses, pumps, spreader lines, booms, barge/boat motors, personal gear such as boots, and any on-shore equipment or gear, including storage tanks, that could come in contact with lake water or allow aquatic invasive species to be washed into the lake. Minimum decontamination procedures are the Washington State Department of Fish and Wildlife Invasive Species Management Protocols, Level 1 Decontamination Protocol – Basic and, if the equipment is known to have been exposed to aquatic invasive species, Special Protocols – Boats and Other Large Aquatic Conveyances Transported Overland. These protocols may be found at http://wdfw.wa.gov/publications/01490/wdfw01490.pdf
10. Spill prevention, control, and contingency plan. (SPCC Plan)
11. Emergency contact information
12. Shop drawings for temporary path bridge/ramp structure
13. Product data for all products used per Section 01 33 10

B. Application Log – Shall include, at a minimum, the following items to be submitted to the on-site Seattle Parks representative and construction manager daily:

1. Date of work
2. Daily starting time and ending time, hours of application
3. Workforce
4. Weather conditions
5. Quantity of material applied (gallons); computer data indicating application of liquid alum and sodium aluminate in the specified dose ratio
6. Approximate location (on map) and acreage of treatment
7. Summary of truck deliveries, including percent Al in both alum and sodium aluminate delivered as well as the percent of soluble sodium aluminate in the liquid sodium aluminate delivered
8. The Contractor shall provide Seattle Parks and their on-site representative with the manufacturer's material quality assurance certification with each truck delivery to show that procurement meets specifications. The alum and sodium aluminate in each delivery shall be approved by the Seattle Parks on-site representative prior to any offloading or applying the alum and/or sodium aluminate in Green Lake.

These logs shall be submitted to the on-site Seattle Parks representative at the end of each day except for item 8 that will be submitted at the time of chemical truck delivery for both alum and sodium aluminate to site for each truck before any offloading can occur.

4. QUALIFICATIONS

A. To be awarded this project, the Bidder shall provide satisfactory evidence that the Bidder meets the qualification requirement listed below. Such evidence must be submitted within three days of Seattle Parks request and should include names and contact information for project references.

1. The Contractor must have conducted buffered, whole-lake alum treatments in a minimum of two lakes that are 200 surface acres or more in size, within the last five years. Chemical application experience on projects should include application of alum as the nutrient inactivation and sodium aluminate as the buffering agent.

PART 2 PRODUCTS AND MATERIALS

1. ALUM (ALUMINUM SULFATE)

A. Upon approval by Seattle Parks, the Contractor shall procure 81,680 gallons of liquid aluminum sulfate ($Al_2(SO_4)_3*14H_2O$) for the spring 2016 treatment of Green Lake. Alum shall meet the following specifications:

1. Grade = Drinking Water Treatment Grade
2. pH = 2.0 to 2.4
3. Specific Gravity at 70°F= 1.333 to 1.337
4. Freezing Point = -16°C
5. Boiling Point = 101°C (214°F)
6. Total Water-Soluble Aluminum of 4.2 to 4.4 percent or as Al_2O_3, 8.0 to 8.4 percent

B. The total water-soluble iron (expressed as Fe_2O_3) content of aluminum sulfate shall be no more than 0.02 percent, on a basis of 8.1 percent Al_2O_3 in liquid alum. In liquid alum, the water-insoluble matter shall not exceed 0.02 percent. At a minimum, aluminum sulfate shall conform with the "American National Standards Institute/National Sanitation Foundation" (ANSI/NSF) Standard 60 Drinking Water Treatment Chemicals – Health Effects (2005 and previous), or Standard 61 Drinking Water System Components – Health Effects (2005 and previous) for use in drinking water.

C. The aluminum sulfate supplied shall contain no soluble mineral or organic substances in quantities that are capable of producing deleterious or injurious effects on public health or water quality, and shall be drinking water treatment grade.

D. The Contractor shall provide Seattle Parks and their on-site representative with the manufacturer's material quality assurance certification with each truck delivery to show that procurement meets specifications. The alum in each delivery shall be approved by the Seattle Parks on-site representative prior to applying the alum in Green Lake.

2. SODIUM ALUMINATE

A. Upon approval by Seattle Parks, the Contractor shall procure 40,840 gallons of sodium aluminate at 32 percent available soluble sodium aluminate for the spring 2016 treatment of Green Lake.

B. Sodium aluminate ($NaAlO_2$) is produced from the reaction of alumina tri-hydrate with caustic soda. Liquid sodium aluminate shall contain no more than 0.5 percent insoluble matter. Liquid sodium aluminate shall contain a minimum of 32 percent available soluble sodium aluminate to a maximum of 38 percent. If liquid sodium aluminate procured by the Contractor contains more or less than 32 percent available sodium aluminate, the application ratio of alum and sodium aluminate will need to be modified and quantities of sodium aluminate revised. Liquid sodium aluminate shall have excess sodium oxide of at least 4 percent to ensure complete combination with the aluminum oxide.

C. The sodium aluminate supplied in accordance with this standard shall contain no substances in quantities capable of producing deleterious or injurious effects on public health or water quality, and shall be water treatment grade.

D. The Contractor shall provide Seattle Parks and their on-site representative with the manufacturer's material quality assurance certification with each truck delivery to show that procurement meets specifications. The sodium aluminate in each delivery shall be approved by the Seattle Parks on-site representative prior to applying the chemical in Green Lake.

3. ALUM AND SODIUM ALUMINATE STORAGE TANKS

A. The use of temporary on-shore storage tanks for staging the chemicals is recommended, but not required, to insure that the application of alum and sodium aluminate is successfully completed in the required applications time frame of 6 working days.

B. If on-shore storage tanks are used, separate tanks shall be provided for each chemical.

C. All on-shore storage tanks shall be fabricated out of HDPE or other suitable material, i.e. stainless steel that is tolerant of temperature in excess of 200 degrees F.

D. The Contractor shall check and confirm the volume of alum/sodium aluminate required for the specified dose prior to procurement of any storage tanks.

E. The Contractor shall provide secondary containment to help prevent spills or uncontrolled leakage of materials from on-shore storage facilities. Spill containment must provide the following features and be equal to or better than "Spillguards":

1. Puncture resistant
2. One piece, no assembly required
3. Wind resistant
4. Approved for a temperature range of -40 to 160 degrees Fahrenheit

4. ALUM AND SODIUM ALUMINATE DISTRIBUTION SYSTEM

A. The Contractor shall procure alum and sodium aluminate distribution lines, pumps, injector units, and all other pertinent equipment necessary to deliver the prescribed liquid alum and sodium aluminate.

B. All piping shall be heavy duty HDPE tubing or appropriate material to avoid dissimilar metals corrosion and to provide safety relative to chemical temperature and potential leaks.

C. Type 316 stainless-steel fittings shall be used in areas where contact with liquid alum and/or sodium aluminate is anticipated. All couplings and connectors used for alum and sodium aluminate distribution lines, storage tank, pumps, and injector units must meet corrosion resistance standards for alum and sodium aluminate, i.e. type 316 stainless-steel fittings at minimum.

PART 3 EXECUTION

1. PREPARATION

A. The Contractor shall protect structures, utilities, sidewalks, roadways, pavements, and other facilities from damage caused by settlement, lateral movement, undermining, washout, or other hazards created by work associated with the application of liquid alum and sodium aluminate, including but not limited to, the transport and delivery of chemicals, chemical storage tanks, and chemical spills. During and at the completion of the application of liquid alum and sodium aluminate, the Contractor shall conduct all operations in such a way as to:

1. Comply with any and all permit conditions for this project.
2. Prevent damage to the lake, equipment, and surrounding properties.
3. Prevent damage to the aquatic environment by using a biodegradable hydraulic fluid.
4. Prevent damage to the lake by ensuring that no aquatic invasive species are introduced into the lake. This shall include decontaminating all equipment and gear that will come into contact with lake water prior to bringing such equipment to the staging area.
5. Maintain orderly appearance at the work site while the treatment is occurring.
6. Prevent damage to the aquatic environment by implementing temporary erosion and sediment control measures, if directed by Seattle Parks.
7. Prevent damage to the aquatic environment if temporary on-shore storage tanks are used.

2. STAGING AREA

A. The Contractor shall be responsible for all staging area setup, security, cleanup, and restoration to its original condition following completion of the application. The staging area will be left in the same condition as before the operation began, photo-documented and verified by Seattle Parks and their on-site representative prior to the acceptance of work.

B. The staging area is located at the parking lot and boat ramp area on the west side of the Aqua Theatre off West Green Lake Way (Exhibit B). Specific park user access restrictions plus temporary traffic controls (i.e., when chemical truck arrives at the site), as well as, park user area restrictions may be modified on-site based upon the direction by Seattle Park's project representative. The staging area is located within a public park and near a residential area. The Contractor shall take steps to minimize impacts to nearby residents, park, and lake users in noise, parking, safety, equipment and supply storage, smells, chemical contact and general condition of the site. The Contractor shall place security fencing around all equipment and storage tanks remaining on-site during non-working hours.

3. APPLICATION

A. Application of the alum and sodium aluminate shall take place after the lake water temperature has risen to over 5.5°C (42° F) throughout the first 4 meters of the water column. The preferred time frame for application is between March 28 and April 22, 2016, to avoid interference with a rowing regatta on March 19–20 and opening day of fishing on April 23, 2016. The application from start to finish shall be completed within 6 working days, with 2 additional days for mobilization and another additional 2 days for demobilization. Application will take place only when the wind speed is less than 17 mph at the lake surface.

B. A mixture of water treatment grade liquid aluminum sulfate (alum as $Al_2(SO_4)^3*14H_2O$) and liquid sodium aluminate ($Na_2Al_2O_4$) shall be applied to the lake surface or injected into the lake from a moving barge or boat. The barge/boat position in the lake shall be controlled by a satellite guiding system (GPS) with computer integrated depth sonar to continuously adjust the application rate of liquid alum and sodium aluminate mixture (2 gallons alum to 1 gallon sodium aluminate, assuming 32 percent soluble sodium aluminate concentration) based on changing lake depth and boat speed. All areas of the lake will be treated at 8.2 mg Al/L. This will ensure complete and uniform chemical coverage during application.

C. The Contractor shall employ a treatment barge (boat) with on-board chemical storage tanks and applicator for even chemical distribution. The system of chemical distribution shall have a minimum application rate of 40,000 gallons per day of combined alum and sodium aluminate. The boom system for chemical distribution shall be substantially similar to the illustration in Exhibit C. The chemicals are to be delivered to the lake water at an approximate depth of 1 to 2 inches below the water surface from a minimum of 12 pairs, up to a maximum of 24 pairs, of alum and sodium aluminate injection tubes (nozzles or small hoses) spaced 8 to 12 inches between pairs and with the alum and sodium aluminate injection tubes within each pair spaced 2 to 4 inches apart. The injection tubes shall be alternating so that the closest tubes in each direction are always tubes of the other chemical. The treatment shall not begin until the boom system is approved on-site by the on-site Seattle Parks representative.

D. The Contractor shall apply a full chemical allotment of liquid alum and liquid sodium aluminate to Green Lake. The effective dose of aluminum to be applied to the lake shall be 8.2 mg Al/L within the water column of the entire lake.

E. The full chemical allotment, as defined above, shall be applied in a ratio of 2 gallons alum to 1 gallon sodium aluminate (assuming 32 percent concentration) with an accuracy of ± 3 percent. The chemicals must be simultaneously distributed so that the entire treatment area is uniformly covered, starting with the shallow areas and finishing in the deeper section of the lake. Computerized barge (boat) guidance and chemical metering control shall be used to ensure that the chemicals are distributed simultaneously and in the correct ratio.

F. In accordance with the alum treatment permit coverage issued to Seattle Parks by the Washington State Department of Ecology, the lake pH, and if needed, alkalinity will be monitored by Seattle Parks on-site representatives in surface water samples collected one (1) meter below the lake surface and at one (1) meter above the lake bottom each morning before application begins, and one (1) hour following application each day.

G. Prior to beginning the lake alum treatment (0.5 to 48 hours before), Seattle Parks representative will conduct a jar test at the lake in a bucket or barrel using alum and sodium aluminate at 8.2 mg Al/L to verify that treated water is above pH 6.0 after addition and mixing (0.25 to 0.5 hours after being dosed).

H. Work shall be suspended if the pH of lake water is consistently less than 6.0 (± 0.05) or greater than 8.7 (± 0.05) in the collected water samples.

I. The threshold for re-starting treatment shall be a pH between 6.2 and 8.4 (± 0.05) and an alkalinity of at least 12 mg/L (± 0.5 mg/L).

J. The Contractor shall apply the full chemical allotment of alum and sodium aluminate as defined above. If there is a remaining supply of chemical after the Contractor has applied the specified dose due to minor deviations in dosage or in lake bathymetry, the Contractor shall be responsible for applying the remaining amount of chemicals to the lake uniformly in areas between 3 and 6 feet depth at the specified ratio of 2 gallons alum to one gallon sodium aluminate. Note: if at any time the pH of the lake water is less than 6.0, treatment is to be immediately stopped until pH is greater than 6.2 and the on-site representative of Seattle Parks gives approval to proceed with the application.

K. The Contractor shall submit the Application Log at the end of each day for review by Seattle Parks and their on-site representative.

4. HAZARDS

A. Because the application of liquid alum and sodium aluminate will take place in a lake, several potential hazards exist, including docks, boats, and underwater hazards such as sunken logs, debris, boats, or utilities. The Contractor should use caution and good judgement during the application. The Contractor is encouraged to produce a site-specific Green Lake Alum Treatment Health and Safety Plan and implement that plan with its employees. The Contractor needs to have a plan to address any hazardous condition or other unforeseen site conditions that may be encountered. The Contractor is responsible and holds sole liability for safe execution of the alum treatment.

Exhibit A. Green Lake Bathymetry.

Legend

- 2015 sediment station
- 2004 sediment sampling
- Water quality 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 1.
Green Lake Sediment Sampling Stations, May 4, 2015.

N

0 325 650 1,300 Feet

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USDA, Aerial (2013)

K:\Projects\Y2013\13-05709-000\Project\Phytoplankton_report\monitoring_stations_features.mxd (6/24/2015)

Exhibit B. Staging Area.

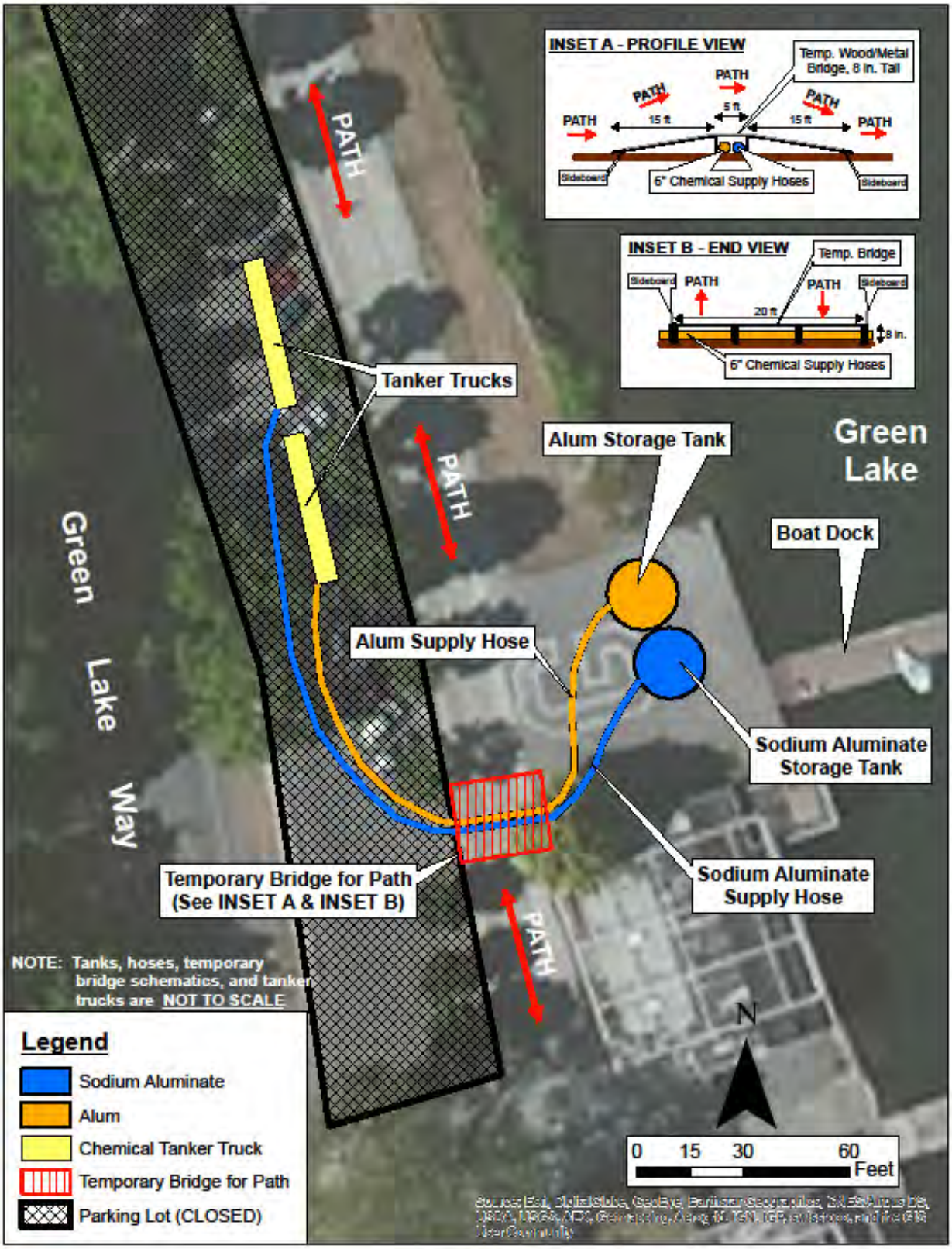
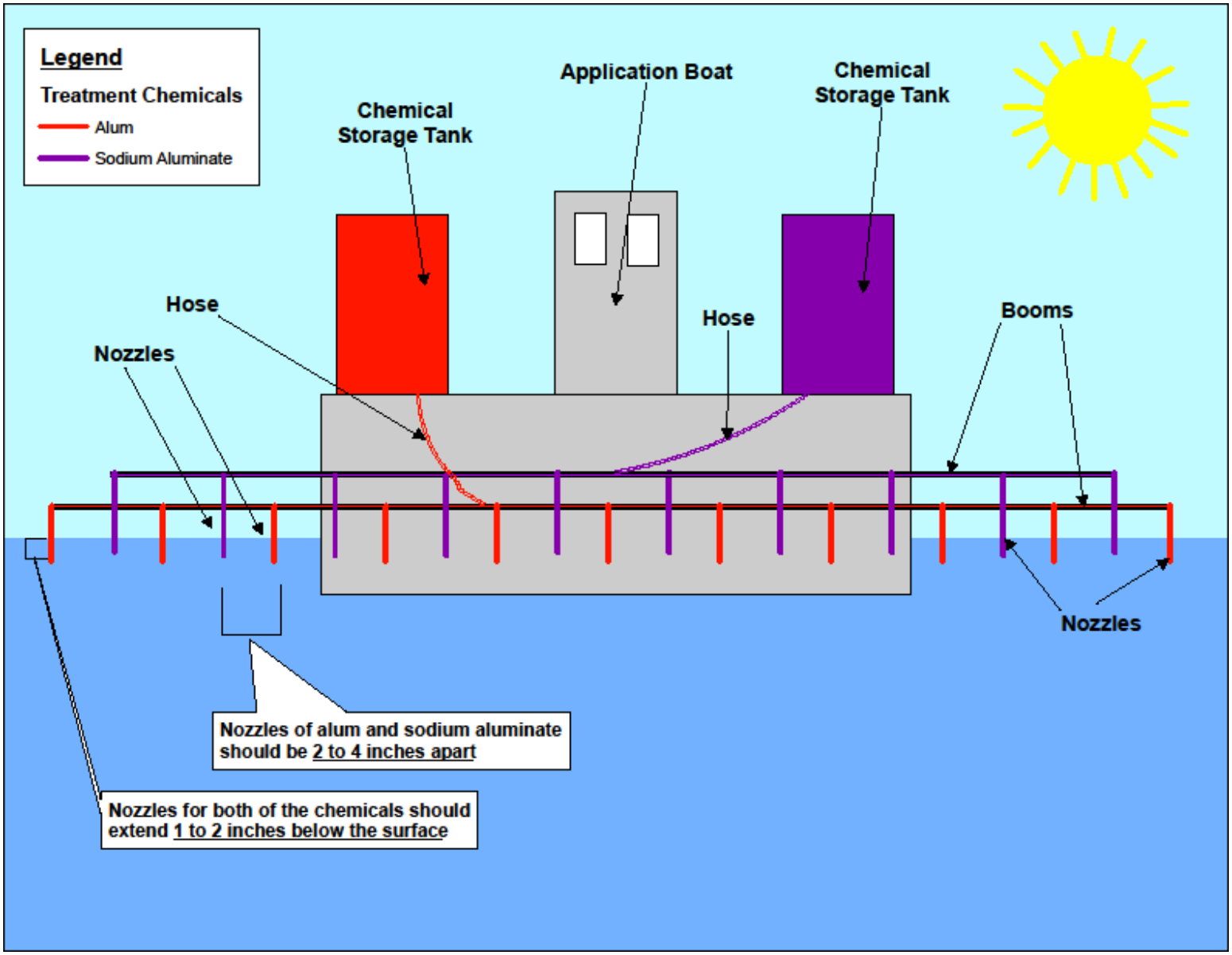


Exhibit C. Chemical Distribution System Illustration.



APPENDIX E

Water Quality Monitoring Plan

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WATER QUALITY MONITORING PLAN

GREEN LAKE ALUM TREATMENT 2016

Prepared for
Seattle Parks and Recreation

Prepared by
Herrera Environmental Consultants, Inc.

HERRERA

Note:
Some pages in this document have been purposely skipped or blank pages inserted so that this document will copy correctly when duplexed.

WATER QUALITY MONITORING PLAN

GREEN LAKE ALUM TREATMENT 2016

Prepared for
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1. INTRODUCTION

Green Lake is a shallow eutrophic lake located just north of downtown Seattle. 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). 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 through 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.

The Green Lake Phytoplankton Study (Herrera 2015) recently documented effects of the 1991 and 2004 alum treatments on the amount and type of phytoplankton in the lake. This study evaluated nutrient and phytoplankton relationships and trends using data collected since 1959. Cyanotoxin data were analyzed from algae scum samples and beach water samples collected at the lake since 2007, and algae scum accumulation patterns were examined using observation data collected for the lake over the past 2 years. This study also documented current cyanobacteria monitoring protocols, public notification, and lake closure procedures used by Green Lake stakeholders. Finally, the study provided Seattle Parks and Recreation with recommendations on the next steps for controlling phytoplankton and addressing additional lake needs. Those recommendations included preparation and implementation of a plan to treat Green Lake with alum as soon as possible to control cyanobacteria and prevent lake closures.

This water quality monitoring plan has been written in support of the Green Lake Phosphorus Management Plan (PMP). Additional background information is provided in the PMP. This monitoring plan was prepared in accordance with Guidelines and Specifications for Preparing Quality Assurance Project Plans (Ecology 2004), and includes monitoring elements specified in Ecology's Aquatic Plant and Algae Management General Permit (Ecology 2015). This monitoring plan includes the following sections:

- Project description
- Project organization and responsibilities
- Data quality objectives
- Water quality monitoring design
- Sample collection procedures
- Analytical procedures
- Quality control
- Data management procedures
- Audits and reports
- Data verification and validation
- Data assessment (usability) assessment.

2. Project Description

As performed in 2004, liquid alum will be applied concurrently with liquid sodium aluminate at a ratio of 2:1 by volume to ensure that the water pH does not decrease below 6.0. Sodium aluminate has been shown to be an effective buffer at this ratio.

It is recommended that the 2016 treatment occur in March or April when the water temperature is moderate, the amount of aquatic plant (milfoil) and algae growth are relatively low, and recreational activity on the lake is also low. The 2016 alum treatment is planned to occur between March 21 and April 22, 2016, to avoid interference with a rowing regatta on March 19 and 20 and opening day of fishing on April 23, 2016. The treatment should be completed within 10 working days, which will include the application of alum during approximately 6 days.

The total recommended dose of aluminum (Al) to be applied to Green Lake is 8.2 mg A/L on a lake volume basis. This will require 81,680 gallons of liquid alum and 40,840 gallons of liquid sodium aluminate. The materials will be delivered in tanker trucks to a parking lot and pumped to holding tanks staged on the north side of the small craft center, located on the southwest shore of Green Lake. Each material will be injected into the lake surface waters from a barge at a specified rate to insure an even application at the recommended dose. The recommended dose is similar to that applied in 1991 (8.6 mg Al/L) and much less than that applied in 2004 (23.0 mg Al/L), and all water quality criteria were met or no fish kills were observed for either treatment.

The recommended dose is anticipated to meet water quality goals for at least 8 years, based on the long-term effect of the 2004 treatment and assuming external phosphorus inputs to the lake remain relatively low.

2.1. Permit Restrictions and Relevant Criteria

The alum treatment will be conducted in accordance with Ecology's Aquatic Plant and Algae Management General Permit (Ecology 2015). This permit is currently being revised and the draft permit does not include any revisions to restrictions for alum treatments. Permit restrictions for alum treatments (see Table 4 in Ecology 2015) include:

- Timing restrictions:
  - None for fish or other priority species.
  - Early spring or fall treatment if aquatic plant biomass interferes with inactivation of sediment phosphorus.
- Lake use restrictions or advisories:
  - None.

- Treatment restrictions:
  - Application must cease when wind speed is greater than 15 miles per hour.
  - Powdered alum must be mixed with water to form a slurry before applying to the water surface.
  - The pH of lake water during treatment must remain between 6.0 and 8.5 based on lake average.
  - Only aluminum compounds suitable for water treatment may be used.
  - Buffering materials must be available for use.
- Monitoring requirements:
  - Minimum monitoring is one surface water pH measurement in the morning prior to any alum addition and one surface water pH measurement 1 hour after alum addition has stopped for that day.
  - Monitoring for pH must continue for the duration of the treatment and for 24 hours following treatment completion.
  - Monitoring locations must be representative of water body-wide conditions.
- Other restrictions:
  - A jar test must be completed prior to whole lake treatments only if a buffer other than sodium aluminate is used or a ratio of liquid alum to liquid sodium aluminate differs from 2:1 by volume.
  - An on-site storage facility is required for any treatment requiring 9,000 gallons of alum or more, or the project proponent must have a plan to store any unused alum or buffering products.

The general permit allows for short- and long-term exceedance of Washington State Surface Water Quality Standards (WAC 173-201A) provided that the Permittee complies with any short-term modifications of water quality criteria authorized by Ecology in writing. Water quality degradation is allowed if the degradation does not significantly interfere with or become injurious to existing or designated water uses, or cause long-term harm to the environment (WAC-173-201A-410).

As for all undesignated lakes in Washington, Green Lake is to be protected for the designated uses of: core summer salmonid habitat and extraordinary primary contract recreation. The following parameters with associated surface water quality criteria will be monitored to evaluate short-term water quality impacts:

- Water temperature – The 7-day average of the daily maximum temperatures (7-DADMax) shall not exceed 16 °C, and human actions considered cumulatively shall not increase the 7-DADMax temperature more than 0.3 C if the natural temperature exceeds 16 °C.
- Dissolved oxygen: The 1-day minimum dissolved oxygen concentration shall exceed 9.5 mg/L, and human actions considered cumulatively shall not decrease the dissolved oxygen concentration more than 0.2 mg/L

- pH: The pH shall be within the range of 6.5 to 8.5, with a human-caused variation within this range of less than 0.2 units
- Fecal coliform bacteria: Fecal coliform bacteria concentrations shall not exceed a geometric mean of 50 colony forming units per 100 milliliters (CFU/100 mL), with no more than 10 percent of the samples (or any single sample for less than ten samples) obtained for calculating the geometric value exceeding 100 CFU/100 mL

In addition, the National Recommended Water Quality Criteria for the protection of freshwater aquatic life (EPA 2015a) include the following criteria for total aluminum:

- Criteria maximum concentration (acute criterion) of 0.750 mg/L
- Criteria continuous concentration (chronic criterion) of 0.087 mg/L.

2.2. Project Goals and Objectives

Water quality monitoring will be conducted at Green Lake to protect aquatic biota during the 2016 alum treatment, and to evaluate the short-term and long-term effects of the treatment. The goals of water quality monitoring under this plan are to:

- Conduct a jar test before the alum treatment and measure pH in Green Lake during the alum treatment to ensure that pH levels exceed 6.0 for protection of aquatic biota from aluminum toxicity
- Collect water quality data before, during, and after the treatment to evaluate the short-term water quality effects of the alum treatment in the lake to insure that pH criteria (between 6.0 and 8.7) and alkalinity criteria (greater than 12 mg/L) are met for protection of aquatic biota from aluminum toxicity
- Collect post-treatment water quality data to evaluate the long–term effectiveness of the alum treatment in relation to water quality goals that have been established for Green Lake

Treatment monitoring will be performed to determine if the following short-term water quality objectives are met:

- Average lake pH shall be between 6.0 and 8.7
- Average lake alkalinity in the lake shall be greater than 12 mg/L

Post-treatment monitoring will be performed to determine if the following long-term water quality objectives are met for at least 10 years (2016 through 2025):

- Summer average total phosphorus concentration shall be less than 20 µg/L
- Summer average Secchi depth (water clarity) shall exceed 2.5 meters (8.2 feet)
- The lake will not be closed to recreational uses due to toxic cyanobacteria

3. Project Organization and Responsibilities

This section describes how the project is organized, key personnel, and the project schedule.

3.1. Organization and Key Personnel

Seattle Parks and Recreation (Seattle Parks) is responsible for oversight of the PMP and the alum treatment project. Herrera Environmental Consultants (Herrera) is responsible for implementing this water quality monitoring plan, including pre-treatment jar testing and treatment monitoring activities. IEH Analytical Laboratories is responsible for conducting the laboratory analysis for the treatment monitoring samples, and is certified by Ecology for all of the identified analytical procedures. Tetra Tech is responsible for engineering oversight of the alum treatment. King County is responsible for long-term monitoring through the Lake Stewardship Program. Specific responsibilities of key personnel are identified below:

Seattle Parks and Recreation
800 Maynard Avenue South
Seattle, Washington 98134-1336
(206) 684-7053

Robert E. Lee, Seattle Parks Project Manager

Herrera Environmental Consultants
2200 Sixth Avenue, Suite 1100
Seattle, WA 98121
(206) 441-9080

Rob Zisette, Herrera Project Manager
Alex Svendsen, Water Quality Monitoring Lead
Gina Catarra, Data Quality Assurance Officer

Tetra Tech
1420 Fifth Avenue, Suite 550
Seattle, WA 98101
(206) 728-9655

Harry Gibbons, Ph.D, Tetra Tech Project Manager

King County
Lake Stewardship Program
201 South Jackson Street – Suite 600
Seattle, WA 98104-3855
(206) 477-4845

Rachael Gravon, King County Program Manager

IEH Analytical Laboratories
3927 Aurora Avenue North
Seattle, WA 98103
(206) 632-2715

Damien Gadomski, Ph.D, Laboratory Project Manager

3.2. Schedule

Water quality monitoring activities for the 2016 Green Lake alum treatment project will begin in March 2016 and continue for a period of approximately 10-years. Herrera will complete the jar test and treatment monitoring tasks. Post-treatment monitoring will be completed by the King County Lake Stewardship Program (under contract with Seattle Public Utilities) that uses citizen volunteers to collect samples for analysis by the King County Environmental Laboratory. The following monitoring activities will occur according to the schedule indicated:

- Jar Test: March or April 2016 (day prior to alum application).
- Treatment Monitoring: March through April 2016
  - Short-term Impact: Day before the first day of treatment, 2 days following last day of treatment, and 2 weeks following the last day of treatment.
  - Twice Daily: Morning and afternoon from first to last day of treatment.
  - Hourly: During alum application.
- Post-treatment Monitoring: Twice monthly from May through October for 10 years (2016 through 2025).

4. Data Quality Objectives

The goal of this monitoring plan is to ensure that the data collected for this study are scientifically accurate, useful for the intended analysis, and legally defensible. To achieve this goal, the collected data will be evaluated relative to the following indicators of quality assurance:

- **Precision**: A measure of the variability in the results of replicate measurements due to random error
- **Bias**: The systematic or persistent distortion of a measurement process that causes errors in one direction (for example the measured mean is different from the true value)
- **Representativeness**: The degree to which the data accurately describe the conditions being evaluated based on the selected sampling locations, sampling frequency and duration, and sampling methods
- **Completeness**: The amount of data obtained from the measurement system
- **Comparability**: The ability to compare data from the current study to data from other similar studies, regulatory requirements, and historical data

Measurement quality objectives (MQOs) are performance or acceptance criteria that have been established for each of these quality assurance indicators. These MQOs are described below and summarized in Table 1. Note that the term "reporting limit" in this document refers to the practical quantification limit established by the laboratory, not the method detection limit.

4.1. Precision

$$RPD = \left(\frac{\left| C_1 - C_2 \right|}{C_1 + C_2} \right) \times 200\%$$

Precision will be assessed by laboratory duplicates. These will be assessed using relative percent difference (*RPD*) as calculated using the following equation:

Where: *RPD* = Relative percent difference

C_1 and C_2 = Concentration values

If either the sample or duplicate sample is at or below the reporting limit the MQO cannot be calculated. *RPD* values exceeding those identified in Table 1 will trigger an assessment as to whether there are any problems with laboratory methodology, which might warrant remediation.

Table 1. Measurement Quality Objectives for Water Quality Data.								
Parameter	**Analytical Method**	**Method Number**	**Maximum Holding Time**	**Reporting Limit Target and Unit**	**Method Blank**	**Control Standard Recovery**	**Matrix Spike Recovery**	**Laboratory Duplicate RPD**
Laboratory Analysis								
Total alkalinity	Titrimetric, pH 4.5	EPA 310.1	14 days	1.0 mg/L $CaCO_3$	≤ RL	80–120%	NA	≤ 20%
Dissolved aluminum	ICP-MS	EPA 200.8	6 months[b]	0.003 mg/L	≤ RL	85–115%	80–120%	≤ 20%
Total aluminum	ICP	EPA 200.7	6 months	0.100 mg/L	≤ RL	90–110%	75–125%	≤ 20%
Sulfate	Turbidimetric	EPA 375.4	28 days	1.00 mg/L	≤ RL	80–120%	75–125%	≤ 20%
Soluble reactive phos.	Auto. ascorbic acid	EPA 365.1	48 hours[b]	0.001 mg/L	≤ RL	80–120%	75–125%	≤ 20%
Total phosphorus	Auto. ascorbic acid	EPA 365.1	28 days	0.002 mg/L	≤ RL	80–120%	75–125%	≤ 20%
Nitrate+nitrate nitrogen	Auto. cadmium red.	EPA 353.2	28 days	0.010 mg/L	≤ RL	80–120%	75–125%	≤ 20%
Ammonia nitrogen	Automated phenate	EPA 350.1	28 days	0.010 mg/L	≤ RL	80–120%	75–125%	≤ 20%
Total nitrogen	UV Spectrophoto.	SM 4500 NC	28 days	0.050 mg/L	≤ RL	80–120%	75–125%	≤ 20%
Chlorophyll *a*	Spectrophotometric	SM 10200 H	28 days	0.1 µg/L	≤ RL	NA	NA	≤ 20%
Fecal coliform bacteria	Membrane filter	SM 9222 D	36 hours	1 CFU/100 mL	≤ RL	NA	NA	≤ 35%
Field Analysis								
Total alkalinity	Titrimetric, pH 4.5	EPA 310.1	1 day	1.0 mg/L $CaCO_3$	NA	NA	NA	NA
Secchi depth	20-cm disc	NALMS 1995	*in situ*	0.1 m	NA	NA	NA	NA
Temperature	Electrode	Field meter	*in situ*	± 0.2 °C	NA	NA	NA	NA
Dissolved oxygen	Electrode	Field meter	*in situ*	± 0.2 mg/L	NA	NA	NA	NA
pH	Electrometric	Field meter	*in situ*	± 0.2 std. units	NA	NA	NA	NA
Conductivity	Platinum electrode	Field meter	*in situ*	± 0.005 mS/cm	NA	NA	NA	NA

[a] Method numbers from APHA 1998 and EPA 1983).

[b] Samples must be filtered within 48 hours.

NA = not applicable, RL = reporting limit, RPD = relative percent difference.

4.2. Bias

Bias will be assessed based on analyses of method blanks, matrix spikes, and laboratory control samples (LCS). The values for method blanks will not exceed the reporting limit. The acceptable percent recoveries for matrix spikes and LCS are identified for each parameter in Table 1. Percent recovery will be calculated using the following equation:

$$\%R = \frac{(S - U)}{C_{sa}} \times 100\%$$

Where:

%R	=	Percent recovery
S	=	Measured concentration in spike sample
U	=	Measured concentration in unspiked sample
C_{sa}	=	Actual concentration of spike added

If the analyte is not detected in the unspiked sample, then a value of zero will be used in the equation.

Percent recovery for LCS will be calculated using the following equation:

$$\%R = \frac{M}{T} \times 100\%$$

Where:

%R	=	Percent recovery
M	=	Measured value
T	=	True value

4.3. Representativeness

Sample representativeness will be ensured by employing consistent and standard sampling procedures.

4.4. Completeness

Completeness will be assessed based on the percentage of specified samples (listed in this QAPP) collected. The completeness goal shall be 90 percent. Completeness for acceptable data is defined as the percentage of acceptable data out of the total amount of data generated. Acceptable data is either data that passes all QC criteria, or data that may not pass all QC criteria but has appropriate corrective actions taken.

4.5. Comparability

Standard sampling procedures, analytical methods, units of measurement, and reporting limits will be applied in this study to meet the goal of data comparability. The results will be tabulated in standard spreadsheets to facilitate analysis and comparison with water quality threshold limits (e.g., permit restrictions and water quality criteria), where appropriate.

5. Water Quality Monitoring Design

Water quality monitoring will include the following three components: jar test, treatment monitoring, and post-treatment monitoring. A jar test using the specified dose will be conducted on site immediately prior to the first day of alum treatment to verify that the lake pH will exceed 6.0 during the treatment. Treatment monitoring will include various elements to evaluate short-term effects of the treatment. Post-treatment monitoring will be conducted during subsequent summers over a period of 10 years to evaluate the long-term effects of alum treatment. The following sections describe the sampling locations and the design of each monitoring component. The overall monitoring design is summarized in Table 2.

Table 2. Water Quality Monitoring Design for the Green Lake 2016 Alum Treatment.

Monitoring Component	Sampling Locations[a]	Analytical Parameters	Sampling Frequency
Pre-Treatment Jar Test	Small Craft Center	Alkalinity, pH	One or more tests
Treatment Monitoring			
Short-term impact	Station A, Station B, Index station (surface, bottom)	Alkalinity, dissolved Al, total Al, sulfate, TP, SRP, nitrite + nitrate, ammonia, fecal coliform, chlorophyll a, Secchi depth, temperature/DO/pH/conductivity profile	Day before treatment, and 2 days and 2 weeks after treatment
Twice daily	Station A, Station B, Index station (surface, bottom)	Alkalinity (field), dissolved and total Alb, Secchi depth, temperature/DO/pH/conductivity profile	Morning before and evening after each day of treatment
Random daily	Treatment sites (surface, bottom)	pH profile and alkalinity (if pH is less than 6.0)	At least every 2 hours during treatment
Post-Treatment Monitoring	Index station (surface)	Chlorophyll a, TP, TN, Secchi depth, temperature	12 events from May through October for 10 years

Al = aluminum

TP = total phosphorus

SRP = soluble reactive phosphorus

DO = dissolved oxygen

[a] Treatment sampling stations include Index, Composite A, and Composite B at 1 meter below water surface and 1 meter above lake bottom. Post-treatment sampling includes one composite sample from Composite A and Composite B stations for chlorophyll a and TP, and field measurements at the Index station.

[b] Dissolved and total aluminum will be analyzed only if the pH is less than 6.0.

5.1. Lake Monitoring Locations

Water quality monitoring will be conducted at three stations on Green Lake that have been used for previous monitoring projects to allow for comparison to historical data. The monitoring stations include (Figure 1):

- Index station: Located at the deepest (approximately 9 meters) point in Green Lake, which is near the northeast corner of the lake
- Station A: Located in a moderately deep (approximately 5 meters) portion of Green Lake near the northwest corner of the lake
- Station B: Located in a moderately deep (approximately 4 meters) portion of Green Lake near the south end of the lake

In addition, the pre-treatment jar test will be conducted at the treatment staging area, which is located on the southwest shore of Green Lake near the Small Craft Center.

5.2. Jar Test

Jar tests will be conducted on the first day of alum treatment. This testing will be performed for pH using the alum treatment chemicals, dose, and application method provided by the treatment contractor using water and water quality conditions present at the time of application. This large-scale jar test will be performed at the alum treatment staging area located near the Small Craft Center on the southwest shore of Green Lake (see Figure 1).

A testing vessel (e.g., 5-gallon plastic bucket) will be filled with lake water and treated with aluminum sulfate and sodium aluminate directly taken from the supply trucks or storage tanks. As shown in Table 3, the jar test will be conducted using three ratios (1.9:1, 2.0:1, and 2.1:1) of alum and sodium aluminate to ensure correct buffering under current treatment conditions. A 1,000 microliter pipet will be used to inject the materials into 16 liters of lake water to achieve the 8.2 mg Al/L dose. The material amounts in Table 3 are based on a concentration of 8.1 percent of soluble Al_2O_3 for the alum and 32 percent of soluble $NaAlO_2$ for the sodium aluminate, and will be adjusted as necessary if different material concentrations are obtained. A control bucket with only lake water will also be tested.

Table 3. Jar Test Ratios and Amounts.

Sample ID	Test Ratio[a]	Water (L)	Aluminum Sulfate (mL)	Sodium Aluminate (mL)
Test 1	2.1:1	16	1.05	0.50
Test 2	2.0:1	16	1.00	0.50
Test 3	1.9:1	16	0.95	0.50
Control	NA	16	0.00	0.00

[a] Ratio of liquid aluminum sulfate to sodium aluminate.

L = liters.

The pH of the collected lake water will be tested immediately before treatment and after 2 minutes, 15 minutes, 30 minutes, and 1 hour after dosing. Monitoring results will be recorded and immediately reported to the Resident Engineer (Tetra Tech).

5.3. Treatment Monitoring

Treatment monitoring will be conducted by Herrera over a 10-day period, which will include the application of alum during approximately 6 days. Water quality monitoring for the treatment component is anticipated to occur in late March to late April 2016.

Legend

- 2015 sediment station
- 2004 sediment station
- Water quality 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 1.
Green Lake Sampling Stations.

N

0 325 650 1,300 Feet

HERRERA

USDA, Aerial (2013)

K:\Projects\Y2013\13-05709-000\Project\Phytoplankton_report\monitoring_stations_features.mxd (11/9/2015)

Treatment monitoring will include the following three elements:

- Monitoring before and after the alum addition to evaluate short-term impacts of the treatment on various water quality parameters at established monitoring stations.
- Twice-daily monitoring (in the morning before treatment begins and in the afternoon or evening when treatment ends) to verify that pH criteria (between 6.0 and 8.7) and alkalinity criteria (greater than 12 mg/L) are met at established monitoring stations.
- Random monitoring of pH during the alum application at treatment sites will be conducted at least once every 2 hours at specific treatment locations and allowing for 1 hour of alum settling.

Short-term impact monitoring will consist of measuring field parameters and collecting water samples from 1 meter below the water surface and 1 meter above the lake bottom at each of the following three stations: Station A, Station B, and Index station. A total of six water samples will be collected from the lake on three occasions: 1) the day before the first day of treatment, 2) two days following the last day of treatment, and 3) two weeks following the last day of treatment. The collected samples will be analyzed for the following parameters:

- Secchi depth (field measurement)
- Temperature (field measurement at 1-meter intervals)
- Dissolved oxygen (field measurement at 1-meter intervals)
- pH (field measurement at 1-meter intervals)
- Conductivity (field measurement at 1-meter intervals)
- Total alkalinity
- Dissolved aluminum
- Total aluminum
- Sulfate
- Soluble reactive phosphorus
- Total phosphorus
- Nitrate+nitrite nitrogen
- Ammonia nitrogen
- Total nitrogen
- Chlorophyll a
- Fecal coliform bacteria (surface grab only).

Twice-daily monitoring will consist of measuring field parameters at the Station A, Station B, and Index station in the morning before treatment begins, and in the afternoon or evening when treatment ends. The field parameters include Secchi depth and vertical profiles of temperature, dissolved oxygen, pH, and conductivity at 1-meter intervals. In addition, total

alkalinity will be tested in the field on water samples collected from 1 meter below the water surface and 1 meter above the lake bottom at each of the three stations. If the pH is consistently less than 6.0 at a monitoring station, then the samples collected from that station will be analyzed for dissolved and total aluminum.

Random daily monitoring will consist of measuring pH at the treatment site during the alum application at a frequency of at least once every 2 hours. The pH will be measured at 1-meter intervals at the location where alum was applied approximately 1 hour before the time of sample collection. The 1 hour delay in sampling will allow for settling of the alum floc and stabilization of water quality conditions. If the pH is consistently less than 6.0 at a treatment site, then samples will be collected from 1 meter below the water surface and 1 meter above the lake bottom, and analyzed in the field for total alkalinity.

The alum treatment will be suspended if the pH is consistently less than 6.0 (± 0.05) or greater than 8.7 (± 0.05) in samples collected at the treatment sites or at the twice-daily monitoring stations. Additional monitoring will be conducted as necessary to determine when the lake pH and alkalinity have adequately recovered. Treatment may resume if the pH is between 6.2 and 8.4 (± 0.05) and the alkalinity is greater than 12 mg/L (± 0.5 mg/L) at all monitoring locations.

Observations of the alum treatment activities, floc formation, and potential fish and wildlife impacts will be made during random daily monitoring.

In the event that treatment monitoring data do not comply with the permit terms and conditions, Ecology's Northwest Regional Office will be notified immediately. In addition, observations of fish or wildlife impacts will be immediately reported to the Region 4 (Mill Creek) office of Washington Department of Fish and Wildlife (WDFW).

5.4. Post-Treatment Monitoring

Long-term water quality monitoring will be conducted by the King County Volunteer Monitoring Program for a 10-year period after the alum treatment has been completed. The objective of post-treatment monitoring will be to evaluate whether the total phosphorus goal (summer mean value less than 20 µg/L) and Secchi depth goal (summer mean value greater than 2.5 meters) for Green Lake are being met. The design of post-treatment monitoring generally follows that used for Green Lake since the first alum treatment in 1991.

Monitoring will occur on 12 occasions from May through October, beginning in May 2016. Secchi depth will be measured and water samples will be collected from the Index station at a depth of 1 meter. The surface samples will be analyzed for the following parameters:

- Temperature (field measurement)
- Total phosphorus
- Total nitrogen
- Chlorophyll *a*

In addition, mid-depth and near-bottom samples will be collected on two occasions each year and analyzed for these same parameters. Surface samples will also be analyzed for alkalinity,

soluble reactive phosphorus, nitrate+nitrite nitrogen, ammonia nitrogen, and ultraviolet absorbance on those two additional occasions each year.

It is expected that additional water quality monitoring of Green Lake will be conducted by others to address public health concerns. If a cyanobacteria bloom is observed in Green Lake, King County or a volunteer will collect a surface scum sample for analysis of cyanotoxin (microcystin and anatoxin-a) concentrations, and phytoplankton species presence. In addition, King County Department of Natural Resources will continue monitoring microcystin and fecal coliform bacteria at the swimming beaches in Green Lake. These additional monitoring procedures are further described by Herrera (2015).

6. Sample Collection Procedures

Measurements for field parameters will be made prior to the collection of water samples during treatment and post-treatment monitoring. Water temperature, dissolved oxygen, pH, and conductivity will be measured *in situ* by lowering the probe of a portable, multi-parameter water quality meter from a boat to record values at 1-meter intervals from the water surface to the lake bottom. The water quality meter will be calibrated according to the manufacturer's directions and following standard measurement procedures (APHA 1998).

Secchi depth will be measured by using a Secchi disk measuring 20 centimeters in diameter according to standard measurement procedures (NALMS 1995). The Secchi disk will be lowered from the sunny side of the boat to the depth where the disk disappears from view and raised to the depth where the disk reappears. Secchi depth is the average depth of the disk disappearance and reappearance. An underwater viewer (viewscope) will not be used during the measurement because it has not been used historically at Green Lake.

Water samples will be collected by deploying a clean Van Dorn sampler or similar sampling device from a boat. The sampler will be opened, lowered to the desired depth, and then closed by releasing the messenger.

For treatment monitoring, water samples will be collected from 1 meter below the lake surface and 1 meter above the lake bottom at treatment sites and three monitoring stations. Sample bottles will be filled directly from the Van Dorn sampler. Bacteria sample bottles will be filled directly from the lake by submerging the sample bottle below the water surface to avoid contamination by hands or equipment.

For post-treatment monitoring, water samples will be collected from 1 meter below the lake surface at the Index station on each sampling event, and at mid-depth and near the lake bottom on two sampling events per year. Sample bottles will be filled directly from the Van Dorn sampler.

The following quality control procedures will be used in the field to ensure that data quality objectives are met.

6.1. Equipment Decontamination

The Van Dorn water sampler and any other sampling equipment will be decontaminated before each day of use. The equipment will be scrubbed with a brush and phosphate-free detergent (e.g., Liquinox®), and thoroughly rinsed with potable water followed by deionized water. Cleaned sampling equipment will be protected from contamination and will be rinsed with lake water prior to the collection of each sample.

6.2. Field Notes

At each water quality monitoring station, the following information will be recorded in a waterproof bound field notebook:

- Sample identification (ID)
- Sampling date
- Name of sampler
- Time of sample collection, measurement, or observation
- Station location
- Weather conditions
- Calibration results for field instruments
- Field measurements
- Number and type of samples collected
- Unusual conditions (e.g., oily sheen, odor, color, fish kill)
- Modifications of or unusual sampling procedures.

6.3. Sample Containers, Preservation, and Holding Times

Pre-cleaned sample containers will be obtained from the analytical laboratory for the required analyses. Spare sample containers will be carried by the sampling team in case of breakage or possible contamination. Sample containers, preservation techniques, and holding times will follow the analytical method requirements and US EPA guidelines (EPA 2015b).

6.4. Sample Identification and Labeling

Each sample will be identified by its station number and the date of collection. Prior to filling, sample containers will be labeled with the following information using indelible ink:

- Station ID
- Date of collection (month/day/year)
- Time of collection (military format)
- Project ID (Green Lake)
- Company/sampler initials.

Labels on glass containers will be secured with clear adhesive tape.

6.5. Sample Handling

To minimize contamination, laboratory containers without preservative will be rinsed twice with sample water before filling. Samples will be stored at 4° C in a cooler and transported to the laboratory within 12 hours of collection. A chain-of-custody record will accompany the samples that clearly identifies the analytical parameters and methods.

7. Analytical Procedures

Analytical methods are presented in Table 1 for field and laboratory parameters. Also included in Table 1 are the target reporting limits, units of measurement, and maximum sample holding times.

Field measurements of Secchi depth will be conducted using a 20-centimeter Secchi disk according to standard measurement procedures (NALMS 1995) (see Section 6). Field measurements of temperature, dissolved oxygen, pH, and conductivity will be conducted using a portable meter operated according to the manufacturer's directions and following standard measurement procedures (APHA 1998).

Laboratory analytical procedures will follow US EPA approved methods (APHA 1998; EPA 1983, 2015b). These methods provide detection limits that are below the state and federal regulatory criteria or guidelines, and will enable direct comparison of analytical results with these criteria.

The laboratory identified for this project (IEH Analytical Laboratories) is certified by Ecology for each of the analytical parameters, and participates in audits and inter-laboratory studies by Ecology and EPA. These performance and system audits have verified the adequacy of the laboratory standard operating procedures, which include preventative maintenance and data reduction procedures.

The laboratory will report the analytical results within 30 days of receipt of the samples. If necessary, the laboratory will provide draft results within hours of receipt of the samples. Sample and quality control data will be reported in a standard format. The reports will also include a case narrative summarizing any problems encountered in the analyses.

8. QUALITY CONTROL

Quality control procedures are identified below for laboratory activities. The overall objective of these procedures is to ensure that data collected for this project are of a known and acceptable quality. Quality control procedures that will be implemented in the laboratory are described in the following subsections. The frequency and type of quality control samples to be analyzed by the laboratory are summarized in Table 4.

Table 4. Quality Control Requirements and Frequency for Water Quality Sample Analyses.

Parameter	Laboratory Method Blanks	Laboratory Control Standard	Matrix Spike	Lab Duplicates
Total alkalinity	1/batch[a]	1/batch[a]	NA	1/batch[a]
Dissolved aluminum	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Total recoverable aluminum	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Sulfate	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Soluble reactive phosphorus	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Total phosphorus	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Nitrate + nitrate nitrogen	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Ammonia nitrogen	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Total nitrogen	1/batch[a]	1/batch[a]	1/batch[a]	1/batch[a]
Chlorophyll *a*	1/batch[a]	NA	NA	1/batch[a]
Fecal coliform bacteria	1/batch[a]	NA	NA	1/batch[a]

NA = not applicable.

[a] Laboratory quality assurance samples will be analyzed with each batch of samples submitted to the laboratory for analysis. A laboratory batch will consist of no more than 20 samples.

8.1.1. Method Blanks

Method blanks consisting of deionized and micro-filtered pure water will be analyzed with every laboratory sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Blank values will be presented in each laboratory report.

8.1.2. Control Standards

Control standards for each parameter will be analyzed by the laboratory with every sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Control standard values and percent recovery will be presented in each laboratory report.

8.1.3. Matrix Spikes

For applicable parameters, matrix spikes will be analyzed by the laboratory with every sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Matrix spike values and percent recovery will be presented in each laboratory report.

8.1.4. Laboratory Duplicates

Laboratory duplicate samples will be analyzed by the laboratory with every sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Laboratory duplicate values and percent recovery will be presented in each laboratory report.

9. Data Management Procedures

This section discusses data management, which addresses the path of data from recording in the field or laboratory to final use and archiving. The data management and documentation strategy provides for consistency when collecting, assessing, and documenting environmental data and electronic storage of all documents and records on servers that are regularly backed up.

9.1. Data Management

The laboratory will report the analytical results within 30 days of receipt of the samples. The laboratory will provide sample and quality control data in standardized reports that are suitable for evaluating the project data. These reports will include all data including raw quality assurance results, and all quality control results associated with the data. The reports will also include a case narrative summarizing any problems encountered in the analyses, corrective actions taken, changes to the referenced method, and an explanation of data qualifiers. Laboratory analytical and quality assurance sample results will be delivered from the laboratory in both electronic and hard copy form.

Both the laboratory and Herrera will retain project related data for 5 years after completion of the project.

9.2. Documentation and Records

Four types of documentation will be managed: 1) field operation records, 2)laboratory records, 3) data handling records, and 4) QAPP revision documentation.

9.2.1. Field Operation Records

Field operation records may include data sheets and field notes, and photographs taken of the described activities (when taken).

9.2.2. Laboratory Records

Laboratory records will include a data package (lab report in Excel® format). Hard copy laboratory reports will not be issued by the project laboratory.

9.2.3. Data Handling Records

All documents associated with a sampling event will be stored electronically. Paper copies will not be archived. Each sampling event will be documented with the following records:

- Chain-of-Custody (COC)
- Field Reports (field notes)
- Data Package

All documents will be provided in portable document format (PDF) with the exception of the lab reports, which will be in Excel® format.

9.2.4. Revisions to the WQMP

In the event that significant changes to this WQMP are required prior to the completion of the study, a revised version of the document (with changes tracked) shall be prepared and submitted to the Seattle Parks Project Manager for review. The approved version of the WQMP shall remain in effect until the revised version has been approved. Justifications, summaries, and details of expedited changes to the WQMP will be documented in the monitoring report.

10. Audits and Reports

The following section describes the procedures used to ensure that this WQMP is implemented correctly and that the data generated is of sufficient quality to meet the project objectives, and that corrective actions, if necessary, are implemented in a timely manner. The procedures include audits and response actions; deficiencies, nonconformances, and corrective actions; and reports to management.

10.1. Audits and Response Actions

Audits will be conducted for field, laboratory, and data management activities, following the schedule outlined below in Table 5.

Table 5. Quality Assurance Audit Schedule and Response Actions.

Assessment Activity	Approximate Schedule	Responsible Party	Scope	Response Requirements
Field Measurement Audit	Within 7 days of completion of sampling event	Data QA Officer	Review of field notes and data	Annotate field notes and notify field staff within 1 day
Laboratory Measurement Audit	Within 2 days of receiving laboratory data reports	Data QA Officer	Review analytical and quality control procedures employed at laboratory	Laboratory to respond in writing within 3 days to address corrective actions
Data Entry Audit	Within 7 days of data entry	WQ Monitoring Lead	Review all data entry values	Correct errors and repeat audit until no error found

10.2. Deficiencies, Nonconformance, and Corrective Action

The Herrera Project Manager is responsible for implementing and tracking corrective action procedures as a result of audit findings by the Data QA Officer. Records of audit findings and corrective actions are maintained by the Data QA Officer in the project file. Documentation of quality assurance issues will be made by the Data QA Officer in the project file and in quality assurance worksheets, if applicable.

Upon completion of an audit, the results will be reviewed to determine if a deficiency has occurred, and whether the deficiency is classified as a nonconformance. Deficiencies are defined as unauthorized deviations from procedures documented in the WQMP. Nonconformances are deficiencies which affect data quality and render the data unacceptable or indeterminate. Deficiencies related to field and laboratory measurement systems include but are not limited to instrument malfunctions and quality control sample failures.

The Herrera Project Manager, in consultation with the Data Quality Assurance Officer (and other affected individuals/organizations), will determine if the deficiency constitutes a nonconformance. If it is determined a nonconformance does exist, the Herrera Project

Manager, in consultation with the QA Officer, will determine the disposition of the nonconforming data or activity and necessary corrective action(s). Corrective actions may include the qualification of the data as estimates (J) or rejected (R). If the data is qualified as rejected (R), additional corrective actions may include collection of additional samples or reanalysis of the existing samples as authorized by the Seattle Parks Project Manager.

10.3. Reporting

10.3.1. Data Quality Assurance Report

The Herrera Data Quality Assurance Officer (see Project Organization and Schedule section) will provide an independent review of the laboratory QC data from each sampling event using the MQOs that have been identified in this WQMP. A data quality assurance report will be prepared that summarize the following information:

- Changes in the monitoring plan
- Significant quality assurance problems and corrective actions
- Data quality assessment in terms of precision, accuracy, representativeness, completeness, comparability, and detection limits
- Discussion of whether the quality assurance objectives were met, and the resulting impact on decision-making
- Limitations on use of the measurement data.

10.3.2. Monitoring Report

Herrera will prepare a water quality monitoring report that presents and evaluates data collected for the jar tests, treatment monitoring, and first year of post-treatment monitoring. Field and laboratory results will be tabulated in spreadsheets that include associated data qualifiers for estimated values, rejected values, and values exceeding established thresholds, goals, or water quality criteria. Laboratory reports and quality assurance worksheets will be included in the monitoring report.

11. Data Verification and Validation

Data will be reviewed and audited within 14 business days of receiving the results from the laboratory (see *Audits and Reports* section). This review will be performed to ensure that all data are consistent, correct and complete, and that all required quality control information has been provided. Specific quality control elements for the data (see Table 1) will also be examined to determine if the MQOs for the project have been met. Values associated with minor quality control problems will be considered estimates and assigned *J* qualifiers. Values associated with major quality control problems will be rejected and qualified *R*. Estimated values may be used for evaluation purposes, while rejected values will not be used. The following sections describe in detail the data validation procedures for these quality control elements:

- Completeness
- Methodology
- Holding times
- Method blanks
- Reporting limits
- Duplicates
- Matrix spikes
- Control standards
- Sample representativeness

11.1. Completeness

Completeness will be assessed by comparing valid sample data with this WQMP and the chain-of-custody records. Completeness will be calculated by dividing the number of valid values by the total number of values. If fewer than 95 percent of the samples submitted to the laboratory are judged to be valid, then more samples will be collected until at least 95 percent are judged to be valid.

11.2. Methodology

Methodologies for analytical procedures will follow US EPA approved methods (APHA et al. 1992; US EPA 1983) specified in Table 1. Field procedures will follow the methodologies described in this WQMP. Any deviations from these methodologies will be documented in an addendum to the monitoring report.

11.3. Holding Times

Holding times for each analytical parameter in this study are summarized in Table 1. Holding time compliance will be assessed by comparing sample collection dates and times analytical dates and times.

Data from samples that exceed the specified maximum holding times by less than 2 times the holding time will be considered estimates (*J*). Data from samples that exceed the maximum holding times by more than 2 times holding time will be rejected values (*R*).

11.4. Method Blanks

Method blank values will be compared to the MQOs that have been identified for this project (see Table 1). If an analyte is detected in a method blank at or below the reporting limit, no action will be taken. If blank concentrations are greater than the reporting limit, the associated method blank data will be labeled with a *U* (in essence increasing the reporting limit for the affected samples), and associated project samples within 5 times the de facto reporting limit will be flagged with a *J*.

11.5. Reporting Limits

Reporting limits will be presented in each laboratory report. If the proposed reporting limits are not met by the laboratory, the laboratory will be requested to reanalyze the samples or revise the method, if time permits. Proposed reporting limits for this project are summarized in Table 1.

11.6. Duplicates

Duplicate results exceeding the MQOs for this project (see Table 1) will be noted, and associated values may be flagged as estimates (*J*). If the objectives are severely exceeded (such as more than twice the objective), then associated values may be rejected (*R*).

11.7. Matrix Spikes

Matrix spike results exceeding the MQOs for this project (see Table 1) will be noted, and associated values may be flagged as estimates (*J*). However, if the percent recovery exceeds the MQOs and a value is less than the reporting limit, the result will not be flagged as an estimate. Non-detected values will be rejected (*R*) if the percent recovery is less than 10 percent.

11.8. Control Standards

Control standard results exceeding the MQOs for this project (see Table 1) will be noted, and associated values will be flagged as estimates (*J*). If the objectives are severely exceeded (such as more than twice the objective), then associated values will be rejected (*R*).

11.9. Sample Representativeness

The data collected for this study will be labeled with unique quality assurance flags for both laboratory and field data quality issues. Table 6 presents the flagging scheme that will be used in the reports produced for this project.

Table 6. Data Qualifier Definitions and Usage Criteria.

Data Qualifier	Definition	Criteria for Use
J	Value is an estimate based on analytical results.	MQOs for field duplicates, laboratory duplicates, matrix spikes, laboratory control samples, holding times, or blanks have not been met.
R	Value is rejected based on analytical results.	Major quality control problems with the analytical results.
U	Value is below the reporting limit.	Based on laboratory method reporting limit.
UJ	Value is below the reporting limit and is an estimate based on analytical results.	Based on laboratory method reporting limit; MQOs for analytical results have not been met.

12. Data Quality (Usability) Assessment

Data quality assessment for this project will include applying the data quality objectives and sampling design, preparing summary tables, and drawing conclusions from the data. Conclusions from this monitoring project will be drawn based on comparisons with water quality standards and historical values.

13. REFERENCES

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