APPENDIX A

Green Lake Alum Treatment Study

TECHNICAL REPORT

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Prepared for

Seattle Department of Parks and Recreation

June 2003

TECHNICAL REPORT

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Prepared for

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Introduction

Green Lake is a shallow eutrophic lake that is very productive due to high concentrations of dissolved nutrients such as nitrogen and phosphorus that promote algae and plant growth. Located just north of downtown Seattle, the lake is an important recreational and aesthetic resource for city residents. Although the lake remains heavily used, enjoyment of it has been diminished by its poor water quality. Intense blooms of blue-green bacteria (formerly known as blue-green algae) have plagued the lake since at least 1916. In addition, the rooted aquatic plant Eurasian watermilfoil (*Myriophyllum spicatum*) expanded during the 1980s to cover over 90 percent of the lake surface area, further restricting enjoyment and use of the lake (KCM 1995).

Physical and chemical processes within the lake, as well as drainage to the lake from the surrounding watershed, supply the nutrients that support the blue-green bacteria blooms. Phosphorus is the main nutrient causing the problem. Previous studies have found that most of the phosphorus in Green Lake during the summer can be attributed to the internal processes, with sediments on the lake bottom identified as the most likely source. The movement of blue-green bacteria from the sediments to the water has also been identified as a significant source of internal phosphorus loading (Barbiero 1991; Barbiero and Welch 1992). However, other processes common to shallow lakes are probably more important (Welch and Cooke 1995).

Green Lake is listed by the Washington Department of Ecology (Ecology) as an impaired water body for total phosphorus (Ecology 1998). The action required to address this impairment is the establishment of a total maximum daily load (TMDL) for Green Lake. Presently, Ecology is scoping and prioritizing TMDLs for water bodies located in water resource inventory area (WRIA) 8, which includes Green Lake.

The Seattle Department of Parks and Recreation, with funding assistance from Ecology and the U.S. Environmental Protection Agency, implemented a lake restoration program for Green Lake (URS 1987) based on the Phase I diagnostic/feasibility study of the lake in 1981 (URS 1983) and subsequent restoration analyses (URS 1990a, 1990b, 1990c). Goals of the lake restoration program included reducing the average total phosphorus concentrations in the summer to 30 micrograms per liter (μg/L) and increasing the average water clarity in the summer to 2.5 meters (8.2 feet).

The cornerstone of the Phase II restoration project was the application of aluminum sulfate (i.e., alum) to inactivate sediment phosphorus, thereby reducing internal phosphorus loading and availability to blue-green bacteria. Green Lake was treated with alum and the buffering agent sodium aluminate in October 1991. Following the treatment, a 3-year limnological monitoring program was conducted for the lake (KCM 1995). Additional elements of the lake restoration program included harvesting Eurasian watermilfoil, treatment and diversion of stormwater inflow, dilution of the lake with excess drinking water, management of the resident Canada goose population, and public education. Recent lake management activities also include stocking the lake with sterile tiger musky in 2000 to control common carp and with sterile grass carp in 2001 to control Eurasian watermilfoil. In addition, Seattle Public Utilities is currently preparing a stormwater management plan for the Densmore drainage basin, which is the largest basin in the Green Lake watershed.

Although the alum treatment improved water clarity for a few years, Green Lake has suffered from blue-green bacteria blooms on several occasions in recent summers. In the summers of 1999 and 2002, blooms of blue-green bacteria resulted in potentially toxic levels of microcystin produced by the bacteria and closure of the lake to all contact recreation. The Seattle Department Parks and Recreation is interested in treating the lake again with alum to help prevent toxic bacteria blooms in the future. The 1995 project completion report recommended treating the lake with alum every 5 to 8 years to maintain the water quality goals (KCM 1995).

This report presents the results of a study conducted to determine the optimal approach for treating Green Lake with alum. This study includes a water quality and fisheries data compilation, alum literature review and dose calculation, alum dose testing, alum treatment technical specifications, permit requirements, and cost estimate. The study findings are presented below for each of these elements.

Water Quality and Fisheries Data Compilation

Recent water quality and fisheries data for Green Lake were compiled from various monitoring efforts conducted since the KCM (1995) restoration analysis. The compiled data are presented in Appendix A. Table 1 summarizes the monitoring parameters and collection procedures for each source of data. The compiled data are briefly summarized below for each parameter or group of parameters. Monitoring locations are also depicted in Figure 1.

Table 1. Green Lake water quality and fisheries data collected since 1995.

Data Source	Monitoring Parameters	Monitoring Periods	Monitoring Locations
Seattle Department of Parks and Recreation (Seattle Parks 2003)	Lake level Secchi depth Temperature Soluble reactive phosphorus Total phosphorus Chlorophyll *a*	May 1995 – July 2000 (18 sample dates)	Boathouse (lake level) Index (temperature and Secchi) Composites A and B (composite for phosphorus and chlorophyll *a*)
Seattle Public Utilities (SPU 2003)	Microcystin Phytoplankton identification Nutrients and field parameters (1 date)	August 2002 – January 2003 (13 sample dates)	East Green Lake Beach and various other shore locations
Seattle University Seattle University 2003)	Microcystin	August and October 1999 (4 sample dates)	East Green Lake Beach and various other shore locations
King County Department of Natural Resources (King County 2003)	Fecal coliform bacteria *E. coli* bacteria Enterococcus bacteria Temperature	May – September of 1998 - 2002 (92 sample dates)	East Green Lake (near swimming beach)
Washington Department of Fish and Wildlife (WDFW 1998; WDFW 2000; WDFW 2003)	Fish assemblage Field water quality parameters Continuous temperature	September 1997, June and September 1999, July 2000 to September 2002, and May to December 2002 (continuous temperature)	Various shore locations (fish) South of Index (water quality)

Water Quality Field Parameters

Water quality field parameters include water temperature, dissolved oxygen, pH, and conductivity. (Secchi depth is also a water quality field parameter that is discussed along with trophic state indicators in the following section.) Instantaneous measurements of surface water temperature were made by Seattle Parks and Recreation (Seattle Parks 2003) and King County Department of Natural Resources (King County 2003) during sample collection. Seattle Public Utilities measured dissolved oxygen, pH, and conductivity near the Index station on August 29, 2002 (SPU 2003). The Washington Department of Fish and Wildlife (WDFW) measured all four field parameters at 1-meter-depth intervals at three locations on September 24, 1997 (WDFW 1998) and only near the Index station on September 21, 1999 (WDFW 2000). In

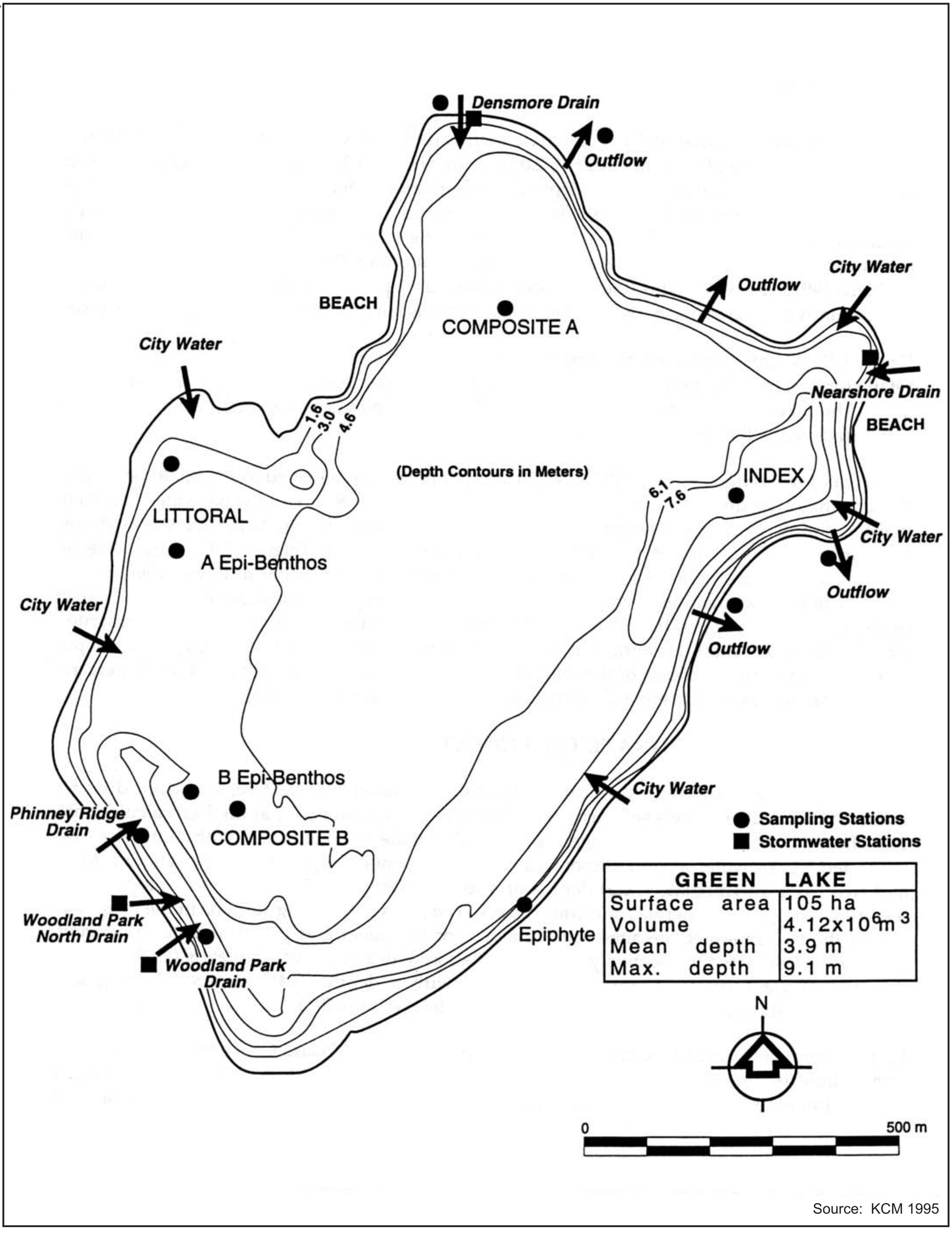


Figure 1. Locations of sampling stations in Green Lake.

addition, WDFW recorded surface water temperature continuously at 2-hour intervals at an undisclosed location from May 17 to December 2, 2002 (WDFW 2003).

The 2002 continuous temperature data collected by WDFW exhibited a range of 8 to 25 degrees Celsius (°C; see graph in Appendix A-6), which is similar to the range of instantaneous measurements (8 to 24°C) reported for the post-treatment monitoring period (KCM 1995). The maximum temperature recorded by KCDNR during five summers of weekly monitoring was 27°C on July 23, 2002.

Dissolved oxygen concentrations ranged from 4 milligrams per liter (mg/L) at the lake bottom to 12 mg/L at the lake surface during the September 1997 and 1999 surveys by WDFW. SPU observed anoxic conditions (0 mg/L) at depths greater than or equal to 5 meters near the Index station on August 29, 2002.

The pH values ranged from 7.8 at the lake bottom to 9.3 at the lake surface at various locations during the September 1997 and 1999 surveys by WDFW. SPU observed the pH to range from 7.1 at the lake bottom to 9.1 at the lake surface near the Index station on August 29, 2002.

Conductivity values reported by WDFW varied widely between the sampling dates, but exhibited little variation with depth (i.e., ranging from 102 to 107 microsiemens per centimeter [µS/cm] on September 21, 1999 and from 62 to 65 µS/cm on September 24, 1999). Conductivity values reported by SPU were elevated at the lake bottom (147 µS/cm) compared to the lake surface (117 µS/cm).

Trophic State Indicators

Secchi depth, total phosphorus, and chlorophyll *a* are the three primary parameters used as trophic state indicators for evaluating the water quality of lakes. Seattle Department of Parks and Recreation monitored these and additional parameters (i.e., lake level, water temperature, and soluble reactive phosphorus) on 18 sampling dates from May 1995 through July 2000 (Seattle Parks 2003) (Table 2). Secchi depth and surface water temperature were measured at the Index station, and phosphorus and chlorophyll *a* were measured from a composite sample collected from multiple depths at the Composite A and B stations (see Figure 1).

Table 3 compares the mean and range of trophic state indicator values for the recent (1995–2000) monitoring period to those for the post-treatment (1992–1994) monitoring period. Total phosphorus and chlorophyll *a* concentrations have generally increased, and Secchi depths have decreased since the post-treatment period. Soluble reactive phosphorus concentrations did not exhibit a substantial change. The minimum Secchi depth (0.5 meters) and maximum total phosphorus (51 µg/L) and chlorophyll *a* (68 µg/L) concentrations were observed during an intense bacterial bloom on September 13, 1999. These minimum/maximum values exceed those reported during the post-treatment period (see Table 3) and are similar to those observed during the pre-treatment period (i.e., less than 1 meter Secchi depth, 50 to 80 µg/L total phosphorus, and 52 µg/L chlorophyll *a*) (KCM 1995).

Table 2. Green Lake data collected since 1994 by Seattle Department of Parks and Recreation.

Date	Lake Level (feet)	Secchi Depth (meters)	Temperature (degrees C)	SRP (µg/L)	TP (µg/L)	Chlorophyll *a* (µg/L)
5/5/95	155.0	4.8	16	3	16	2.6
5/22/95	154.9	4.5	19	9	13	4.5
6/27/95	154.7	2.1	22	1	13	18
7/14/95	154.6	1.7	22	2	23	18
9/1/95	154.5	1.4	21	3	30	22
10/12/95	155.1	0.8	15		43	6.4
3/13/96	154.9	1.6	8	2	43	27
4/9/96	155.0	2.1	14	3	17	13
5/7/96	155.0	2.9	14	2	17	5.9
6/12/96	154.9	2.2	19	15	26	6.7
7/9/96	155.0	3.4	21	2	13	3.9
8/9/96	154.7	3.5	22	2	16	5.6
3/30/98	154.9	2.2	10	3	25	8.5
4/28/98	154.7	2.6	15	2	17	5.7
9/13/99	–	0.5	20	2	51	68
5/4/00	154.7	1.1	15	2	28	6.4
6/13/00	154.5	2.4	16	4	28	9.1
7/17/00	154.6	3.1	22	3	23	3.8
Overall mean	154.8	2.4	17.3	3.5	24.6	13.1
Summer mean [a]	154.7	2.3	20.6	3.8	25	17.2

Source: Seattle Parks (2003).
SRP = soluble reactive phosphorus.
TP = total phosphorus.
[a] Mean value for samples collected June through September.

Table 3. Comparisons of water quality data for depth-composited samples from Composite A and B stations in Green Lake.

	Post-treatment (1992–1994) [a]			Recent (1995–2000) [b]		
	mean	min.	max.	mean	min.	max.
Secchi depth (meters)	3.7	1.2	7.8	2.4	0.5	4.8
Soluble reactive phosphorus (µg/L)	3.4	1	11	3.5	1	15
Total phosphorus (µg/L)	18.7	7	38	24.6	13	51
Chlorophyll *a* (µg/L)	7.0	1	24	13.1	2.6	68

[a] Data source: KCM (1995) (49 sampling dates).
[b] Data source: Seattle Parks (2003) (18 sampling dates).

Table 4 compares mean summer (June through September) values of Secchi depth and total phosphorus to the goals established by the lake restoration project (KCM 1995). This comparison suggests that the Secchi depth goal of greater than 2.5 meters was met during the post-treatment period, but has not been met in recent years. The total phosphorus goal of less than 30 µg/L was met in both the post-treatment and recent monitoring periods.

Table 4. Comparisons of mean summer Secchi depth and total phosphorus values to restoration goals for Green Lake.

	Restoration Goal	Pre-treatment [a]			Post-treatment [a]			Recent [b]
		1981	1989	1990	1992	1993	1994	1995 – 2000
Secchi depth (meters)	>2.5	2.8	–	–	3.4	2.9	3.0	2.3
Total phosphorus (µg/L)	<30	52	29	28	20	26	18	25

– No data available.
[a] Data source: KCM (1995).
[b] Data source: Seattle Parks (2003).

It is important to recognize that sampling methods varied widely among the pre-treatment, post-treatment, and recent monitoring years. For example, samples were collected on a regular and frequent (bimonthly) basis during the post-treatment period, but were collected on an irregular and infrequent (e.g., a maximum of only three times per summer and most often in the spring and early summer when water quality is historically good) basis during the recent monitoring period. In addition, mean total phosphorus values for pre-treatment and post-treatment periods include volume-weighted mean values for the Index station (see Figure 1), which was not sampled in recent years and may exhibit higher total phosphorus concentrations in the summer than those for the Composite A and B stations due to anoxic conditions and higher total phosphorus concentrations in the hypolimnion at the Index station. These differences in post-treatment and recent sample collection suggest that the decline in late summer water quality in recent years shown in Table 3 is probably underestimated.

Seattle Public Utilities (SPU 2003) collected nutrient samples from depths of 1 meter (surface) and 7.5 meters (bottom) near the Index station on August 29, 2002. The total phosphorus concentration ranged from 57.6 µg/L at 1 meter to 212 µg/L at 7.5 meters. The surface total phosphorus concentration exceeded the maximum previously observed in Green Lake since the 1991 alum treatment (see Table 3). Soluble reactive phosphorus concentrations were also elevated at the surface (11.3 µg/L) and the bottom (83.5 µg/L). Nitrate+nitrite nitrogen was analyzed but not detected at a limit of 10 µg/L. Secchi depths were between 1.1 and 1.2 meters throughout the lake.

Microcystin

Microcystin is a hepatotoxin (liver toxin) produced by several species of freshwater blue-green bacteria. The World Health Organization (WHO) has established a guideline of 1 µg/L for microcystin in drinking water that includes both the free and cell-bound forms of the toxin. The first known tests of microcystin in Green Lake were conducted on water samples collected at various shore locations in August 1999 (three sample dates) and October 1999 (one sample date)

(Seattle University 2003 in Appendix A-2). Microcystin concentrations ranged from 0.6 µg/L to 32 µg/L, and exceeded 1 µg/L in three of five samples. The samples were analyzed for free and cell-bound toxin.

Seattle Public Utilities measured microcystin concentrations and identified the dominant species of blue-green bacteria in water samples collected at various shore locations on 13 sampling dates from August 2002 to January 2003 (SPU 2003 in Appendix A-1). Samples were analyzed for microcystin before and after the bacteria cells had been crushed (sonicated) for comparison to the WHO guideline for free and cell-bound toxin. Several of the uncrushed samples exhibited microcystin concentrations above the WHO guideline for drinking water and all crushed samples exceeded the guideline. The maximum microcystin concentration in a crushed sample was approximately 100 µg/L on October 12, 2002, and the second highest microcystin concentration (approximately 80 µg/L) was observed very late in the season on December 7, 2002.

Dominant blue-green bacteria observed during periods of high microcystin levels in 2002 include *Microcystis*, *Gloeotrichia*, *Anabaena*, and *Aphanizomenon* (see Appendix A-1). *Microcystis* and *Gloeotrichia* are known to produce microcystin. Although *Anabaena* and *Aphanizomenon* were the dominant species in each of the two samples exhibiting the highest microcystin concentrations (collected on October 12 and December 7, respectively), *Microcystis* was also present in the samples.

Bacteria

King County Department of Natural Resources monitored levels of fecal coliform, enterococcus, and *Escherichia coli* bacteria on a weekly basis from May to September each year from 1998 to 2002 (King County 2003 in Appendix A-3). Fecal coliform bacteria concentrations ranged from 1 to 2,350 organisms per 100 milliliters (mL). The Washington state surface water quality criterion for fecal coliform bacteria (50 organisms/100 mL) was exceeded in approximately 25 percent of the 92 samples collected. The east Green Lake swimming beach was not closed by the Seattle-King County Public Health Department in spite of the high bacteria levels observed during this period.

Fisheries

Fish surveys conducted in Green Lake since 1993 indicate that common carp (*Cyprinus carpio*) and largemouth bass (*Micropterus salmoides*) have been the dominant species (WDFW 2000; see Appendix A-5). During the 1997 and 1999 fish surveys conducted by Washington Department of Fish and Wildlife (WDFW), common carp was the dominant species by biomass, and largemouth bass was the most dominant by number. Common carp have been described as one of two impediments to improved water quality in Green Lake (KCM 1995), and the population is thriving. Electrofishing catch rates for common carp increased four-fold from 1997 to 1999. Relative weights of common carp in Green Lake were high when compared to 25 other western Washington lakes (WDFW 2000), likely indicating an ample food supply. Common carp are known to thrive in phytoplankton and/or nutrient rich environments.

In an effort to control common carp populations, WDFW stocked Green Lake in November 2000 with 150 sterile tiger musky, which are a cross between muskellunge (*Esox masquinongy)* and northern pike (*Esox lucius*). The tiger musky were 18 inches long and expected to grow to 36 inches in 1 year. WDFW has conducted 15 fish surveys since the stocking and the combined results show that that common carp is still the dominant species, comprising approximately 75 percent of the total fish biomass and 30 percent of the total fish numbers (WDFW 2003 in Appendix A). The second most abundant fish is tiger musky by biomass (18 percent) and largemouth bass by number (18 percent). These recent relative abundance estimates are based on electroshocking data provided by WDFW that have been corrected for the exclusion of approximately 90 percent of the common carp catch due to a limited capacity in the boat. The potential impact of tiger musky on common carp has not been evaluated.

In an effort to control Eurasian watermilfoil, Seattle Parks and Recreation stocked Green Lake in August 2001 with 777 triploid (sterile) grass carp. Grass carp represented 15 percent by weight and 3 percent by numbers in the recent electroshocking effort by WDFW (2003). The potential impact of grass carp on Eurasian watermilfoil has not been evaluated.

Alum Literature Review and Dose Calculation

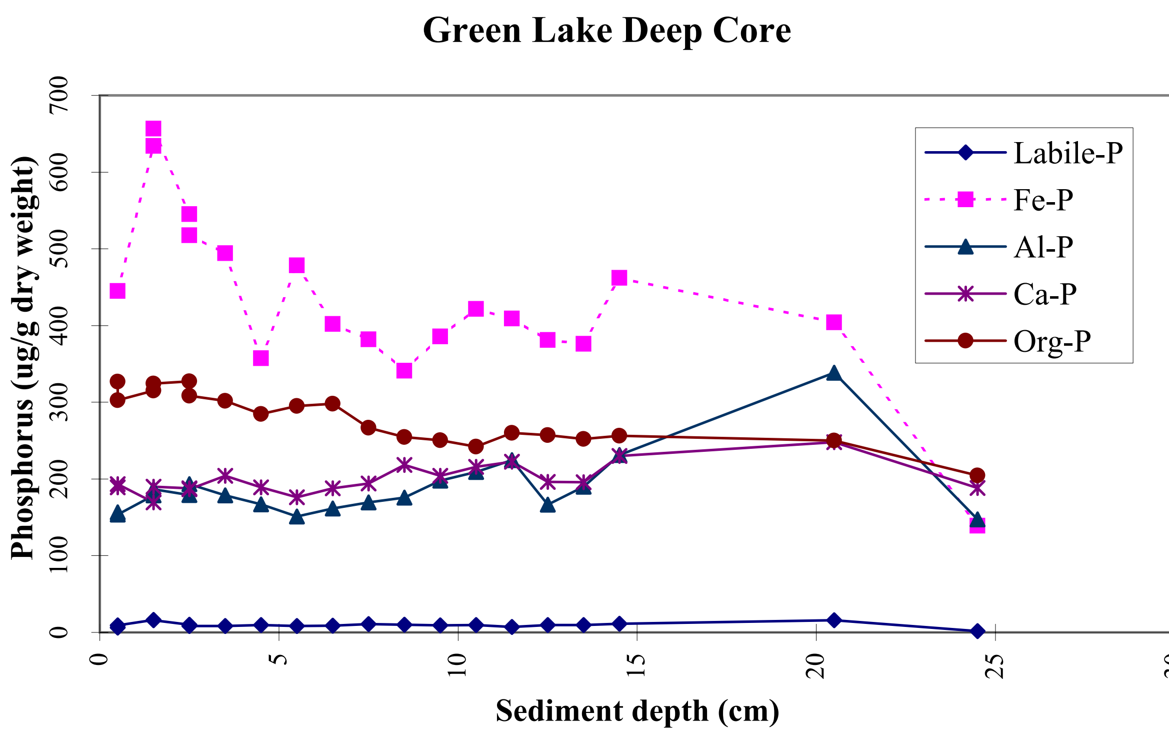
Alum treatment has proven to be a highly effective technique to reduce internal phosphorus loading in both stratified and unstratified lakes (Cooke et al. 1993; Welch and Cooke 1999). Green Lake is a polymictic lake with no anoxic bottom layer except for a relatively small hole on the east side. The lake was treated with alum in 1991 with the effectiveness lasting 3 to 5 years (Jacoby et al. 1994).

Two sediment cores were collected by University of Washington scientists (E. Rydin and B. Huser) in 1998, one from the deep (8-meter) hole near the Index station and another from a depth of 4 meters near the Composite A station in the northwest portion of the lake (see Figure 1). Sediment characteristics were determined in those cores according to methods described by Rydin (et al. 2000) and, contrary to other treated lakes in western Washington (Rydin et al. 2000), there was no aluminum marker from the 1991 treatment visible in the Green Lake sediment profiles. The 1998 sediment analysis provides pertinent data with which to determine an appropriate alum dose. The 1998 sediment phosphorus data are presented in Figure 2 and Tables 5 and 6.

Sodium aluminate would be added along with alum to ensure proper buffering during application. As long as a pH above 6.0 can be maintained, adverse impacts on aquatic life can be avoided (Cooke et al. 1993). The objective of phosphorus inactivation is to add enough aluminum compounds to immediately inactivate mobile phosphorus in lake sediments by converting the mobile phosphorus to aluminum-bound phosphorus. The dose should also be adequate to bind phosphorus, which migrates up from lower sediment depths over time.

The total phosphorus concentration in Green Lake sediment is only about 1 milligram per gram (mg/g); most lakes that have received alum treatments contain more than 2 mg/g (i.e., Campbell Lake, Erie Lake, Long Lake, Pattison Lake, and Wapato Lake, in Washington; Mirror Lake in Wisconsin; Dollar Lake in Ohio; Kezae Lake in New Hampshire; Annabessacook Lake in Maine) (Welch and Cooke 1999). The mobile phosphorus fraction in Green Lake sediments is relatively constant with depth to 26 centimeters, which is the maximum depth of the 1998 core samples. Iron-bound phosphorus averaged 450 µg/g and 272 µg/g over that depth in each of the two cores, while loosely sorbed phosphorus was 10 and 8 µg/g. The mean of total mobile phosphorus (iron-bound phosphorus and loosely sorbed phosphorus) was 370 µg/g for the two cores.

While alum has been a successful and popular treatment to reduce internal loading, lakes have usually been underdosed. The average longevity of seven well-documented cases was 10.5 years (ranging from just over 4 to more than 13 years) at an average dose of 30 grams alum (as aluminum) per square meter (g/m^2) with a range of 10 to 40 g/m^2 of alum (as aluminum). As seen from the estimates calculated for Green Lake, many of these doses were probably too low because they were estimated based on the lake's alkalinity (Welch and Cooke 1999). That is, the dose must be lower if alkalinity is low, in order to maintain a pH above 6.0.



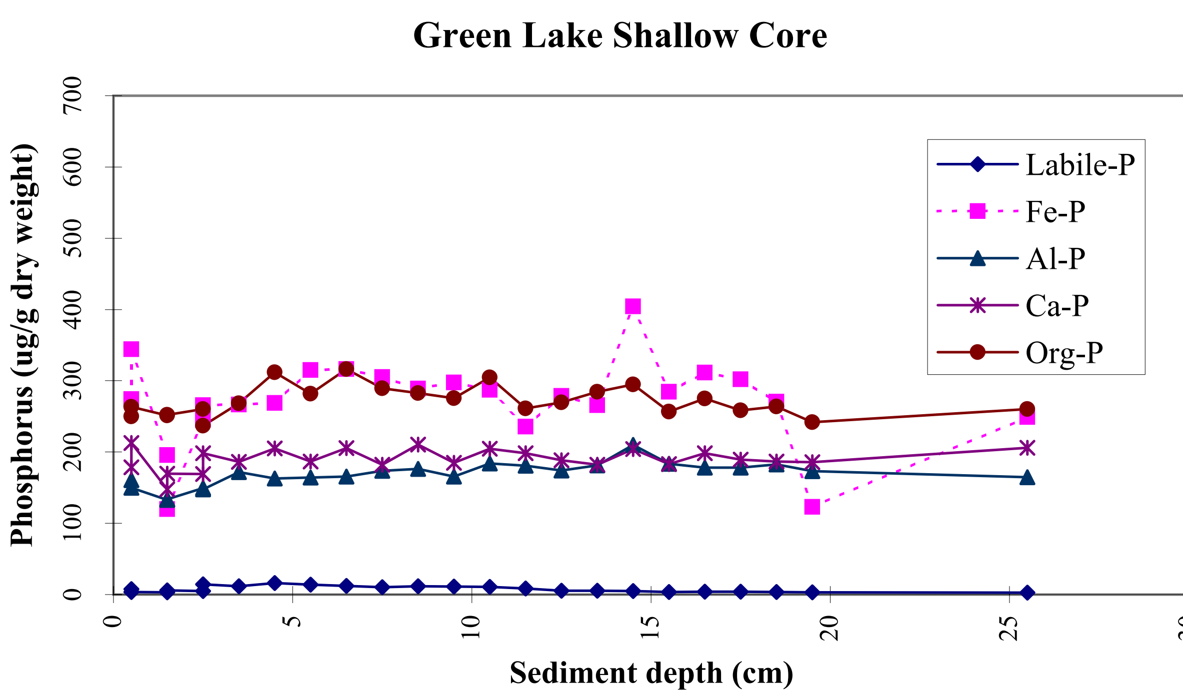


Figure 2. **Green Lake sediment phosphorus concentrations in cores collected by the University of Washington (2003) near the Index station (deep core) and the Composite A station (shallow core) during summer 1998.**

Table 5. Green Lake sediment phosphorus concentrations in a core collected near the Index station (deep core) during summer 1998.

Depth (cm)	Phosphorus Concentration (μg/g dry weight)						
	Labile-P	Fe-P	Al-P	NaOH-TP	Ca-P	Org-P	Total P
0.5	6	–	157	483	189	327	678
0.5	9	445	153	456	193	302	1,103
1.5	16	634	179	494	169	315	1,313
1.5	16	656	187	511	190	324	1,373
2.5	10	545	179	506	188	327	1,250
2.5	8	518	193	502	187	308	1,214
3.5	8	494	179	481	204	302	1,187
4.5	10	357	167	451	189	284	1,008
5.5	8	478	151	446	176	295	1,109
6.5	9	402	162	460	188	298	1,059
7.5	11	382	170	436	194	267	1,023
8.5	10	341	176	431	218	255	1,000
9.5	9	385	198	448	204	250	1,047
10.5	9	422	209	451	216	242	1,098
11.5	7	409	224	485	222	260	1,123
12.5	10	381	167	424	196	257	1,011
13.5	10	376	190	442	196	252	1,023
14.5	11	462	231	487	230	256	1,190
20.5	16	404	339	589	248	250	1,256
24.5	2	139	148	352	188	204	681

Labile-P = loosely sorbed phosphorus.
Fe-P = iron-bound phosphorus.
Al-P = aluminum-bound phosphorus.
NaOH-TP = sodium hydroxide extractable total phosphorus.
Ca-P = calcite phosphorus.
Org-P = organic phosphorus (calculated difference of NaOH-TP and Al-P).
Total P = total phosphorus (calculated sum of labile-P, Fe-P, NaOH-TP, and Ca-P).
Data source: University of Washington (2003).

Table 6. Green Lake sediment phosphorus concentrations in a core collected near the Composite A station (shallow core) during summer 1998.

Depth (cm)	Phosphorus Concentration (µg/g dry weight)						
	Labile-P	Fe-P	Al-P	NaOH-TP	Ca-P	Org-P	Total P
0.5	8	274	161	411	179	250	871
0.5	4	344	150	413	213	263	974
1.5	3	196	133	384	148	251	731
1.5	6	120	134	386	170	252	681
2.5	5	245	149	410	169	260	829
2.5	14	266	148	384	198	237	862
3.5	12	266	172	440	186	268	905
4.5	16	269	163	475	205	312	964
5.5	14	315	164	446	187	282	962
6.5	12	316	166	482	205	316	1,016
7.5	11	305	174	463	182	290	961
8.5	12	289	176	459	211	283	970
9.5	11	298	165	441	185	276	935
10.5	11	287	184	489	205	305	992
11.5	8	235	181	442	198	261	884
12.5	5	279	174	444	188	270	916
13.5	5	266	181	466	182	284	919
14.5	5	405	210	505	204	295	1,118
15.5	4	284	184	440	183	257	912
16.5	4	311	178	453	198	275	967
17.5	4	302	178	436	189	258	932
18.5	4	271	183	447	187	264	908
19.5	3	123	173	415	186	242	727
25.5	3	249	165	425	206	260	883

Labile-P = loosely sorbed phosphorus.
Fe-P = iron bound phosphorus.
Al-P = aluminum bound phosphorus.
NaOH-TP = sodium hydroxide extractable total phosphorus.
Ca-P = calcite phosphorus.
Org-P = organic phosphorus (calculated difference of NaOH-TP and Al-P).
Total P = total phosphorus (calculated sum of labile-P, Fe-P, NaOH-TP, and Ca-P).
Data source: University of Washington (2003).

Achieving the proper aluminum dose is extremely important, not so much for potential toxicity from aluminum and pH—because this will minimized or eliminated with adequate buffering—but to ensure inactivation of all mobile phosphorus in the effective sediment layer.

As with any chemical treatment of water and wastewater, treatment effectiveness is dependent on the dose of the chemical used. For phosphorus inactivation of lake sediments, dose has been estimated in three ways:

- Alkalinity method: Dose is proportional to alkalinity or buffering capacity of the lake, which is progressively lost as the alum dose increases, and is associated with a decrease in pH and an increase in soluble Al^{+3}, the toxic aluminum form. A dose is selected from batch assays that prevent pH from falling below approximately 6.0 to protect aquatic organisms from potentially toxic concentrations of dissolved aluminum (Cooke and Kennedy 1981; Cooke et al. 1993).

- Internal loading method: Dose is estimated from internal phosphorus loading, which is multiplied by a nominal ratio of 1.0 for aluminum added: aluminum-bound phosphorus formed and the years of expected phosphorus inactivation.

- Sediment phosphorus method: Mobile phosphorus (iron-bound phosphorus and loosely sorbed or labile phosphorus) in sediments, the source of internal loading, is used directly with the ratio of aluminum added to aluminum-bound phosphorus formed to estimate the dose (Rydin and Welch 1998, 1999). The sediment depth over which to treat requires some judgment with this method.

The alkalinity method was the principal dose procedure used until recently. This method typically resulted in effective treatments if the lake had a relatively high alkalinity. In such cases, doses were usually greater than 20 mg/L aluminum (Welch and Cooke 1999). However, in soft water lakes, like many treated in Washington state, doses were on the order of 5 mg/L and it is now apparent that these lakes were underdosed (Rydin et al. 2000). The 1991 treatment dose in Green Lake was 8.6 mg/L aluminum.

Using the internal loading rate allows a more direct estimate of aluminum needed. However, an aluminum added: aluminum-bound phosphorus formed ratio of 1.0 is unrealistically low and does not account for all the other ligands besides phosphorus (e.g., organic matter) competing for binding sites in the aluminum hydroxide floc. In Green Lake, macrophytes represent a substantial source of organic matter, whose demand for binding sites must be incorporated into the dose calculations.

Recently, Rydin and Welch (1999) developed a dosing method based on mobile phosphorus in sediments. Aluminum addition experiments showed that iron-bound phosphorus and loosely sorbed phosphorus were increasingly converted to aluminum-bound phosphorus as the aluminum dose was increased. Resulting ratios of aluminum added: aluminum-bound phosphorus formed in treated lake sediments ranged from 5:1 in Wisconsin lake sediments (Rydin and Welch 1999) to 11:1 in Washington state lake sediments (Rydin et al. 2000). Further, in order to treat all mobile phosphorus throughout the sediment profile of three Wisconsin lakes, a ratio of 100:1 was recommended, using an arbitrary sediment depth of 4 cm. A lower ratio is considered reasonable, however, if a greater sediment depth is used.

For Green Lake, a ratio of 10:1 is considered reasonable, along with a sediment depth of 20 cm. The 20 cm depth is selected because mobile phosphorus is relatively constant with depth. The substantially greater sediment depth than that used in the Wisconsin lakes (4 cm) justifies using a lower ratio (10:1). This is also consistent with the aluminum added: aluminum-bound phosphorus ratio formed that was observed for western Washington treated lakes (Rydin et al. 2000). To estimate dose, bulk sediment density (0.0912 g/cm^3) is multiplied by sediment depth (20 cm) and mean mobile phosphorus content (370 µg/g), which yields 675 µg mobile P/cm^2 or 6.75 g P/m^2. That value times the 10:1 ratio and divided by the lake mean depth (3.93 meters) yields 17.2 g Al/m^3, which is the recommended dose to inactivate mobile phosphorus in Green Lake sediments. Mobile phosphorus averaged 460 µg/g in the deep-water core and 280 µg/g in the shallow-water core. While the shallow-water core is probably more representative of sediments throughout the lake, a mean of these values (370 µg/g) is used to calculate the dose to minimize the risk of underdosing the lake.

Given that there is a fair amount of competing anions to bind with aluminum in Green Lake, it is prudent to dose the lake with enough alum to satisfy the sediment exchangeable phosphorus as well as the demand for aluminum in the water column. To satisfy this additional water column demand for aluminum, the alum dose must also meet the water column aluminum demand. Based on the jar test results discussed below, the water column aluminum demand is estimated to be approximately 5 mg Al/L. Hence, the total dose of alum and sodium aluminate will be 23 mg Al/L. This level of aluminum addition is necessary to control internal cycling of phosphorus and to overcome the competing water column demand in the lake (e.g., organic compounds, aquatic plant interference, and recyclable water column phosphorus). Given that treatments in Campbell, Erie, and Long (Kitsap County, WA) lakes were effective for 10 years, even though they were probably underdosed, the recommended dose for Green Lake should have a longevity of greater than 10 years.

Alum Dose Testing

Two jar tests were conducted to determine the appropriate dose of alum and sodium aluminate for the treatment of Green Lake. Data provided by the jar test was used to determine the amount of phosphorous in the water column that will bind alum, subsequently reducing the effectiveness of the alum at binding sediment phosphorous at the bottom of the lake. In addition, pH, alkalinity, and dissolved aluminum were measured to ensure that the water quality would not be compromised and adversely affect fish populations in the lake after application of the alum and sodium aluminate mixture.

Two tests were conducted to analyze the effects of alum and sodium aluminate on water samples taken from Green Lake. Test 1 analyzed the effects of five different dose rates of alum and sodium aluminate. However, it was subsequently discovered that the lake water sample for Test 1 was collected at the end of a 3-day discharge cycle in which drinking water from the Roosevelt reservoir (formerly known as the Green Lake reservoir) was flushed into Green Lake, enough to dilute the lake by approximately 5 percent. Furthermore, the discharge drain for the drinking water is located within 100 feet of one of the two lake sampling locations, which likely resulted in a disproportionate fraction of drinking water inflow in the composite lake water sample.

A second test (Test 2) was conducted 3 weeks after Test 1 to allow Green Lake to equilibrate and return to more natural water conditions. The alum dose rates were changed for Test 2 to include fewer dose rates (i.e., three doses in Test 2 versus five doses in Test 1) and to increase the maximum dose (i.e., 30 mg Al/L in Test 2 versus 23 mg Al/L in Test 1). In addition, liquid alum and sodium aluminate were used for Test 2 versus the granular material used for Test 1 because liquid material was proposed for use in Green Lake.

Additional jar tests will be conducted immediately prior to the alum treatment to evaluate the effects of using the chemicals and lake water present at the time of the treatment. It is anticipated that the treatment jar tests will be on a larger scale (e.g., 20 gallons of lake water) and will test only for pH and alkalinity using the prescribed doses of alum and sodium aluminate. Results of the treatment jar test will be used, if necessary, to adjust the application rate and allow more time for the lake alkalinity to recover.

Methods

Sample Collection

Composite water samples were taken from Green Lake at 8 a.m. on April 1, 2003 for Test 1 and at 8 a.m. on April 23, 2003 for Test 2. Approximately 2.5 gallons were collected from the offshore end of the dock located adjacent to the east beach and from the dock located adjacent to the boathouse on the southwest shore (near the Woodland Park drain exhibited in Figure 1) for a total of 5 gallons for each test. The water samples were collected in precleaned, 5-gallon plastic containers. Immediately after collecting each water sample, a subsample of untreated lake water was delivered to the analytical laboratory (Aquatic Research, Inc.) for analysis of total alkalinity, soluble reactive phosphorus, total phosphorous, and dissolved aluminum. Aquatic Research is certified by Ecology to perform these analyses.

Dose Solution Preparation

Separate alum and sodium aluminate dose solutions were prepared for Tests 1 and 2. The dose solutions for Test 1 were prepared by Aquatic Research using the granular stock materials used for the 1991 Green Lake alum jar test. These solutions were prepared by dissolving reagent-grade alum and technical grade sodium aluminate in deionized water. The alum and sodium aluminate dose solutions contained aluminum concentrations of 10.00 and 25.98 g Al/L, respectively.

Dose solutions for Test 2 were made using liquid stock materials that are equivalent to those proposed for use at Green Lake. The liquid alum stock solution, containing 8.27 percent aluminum as Al_2O_3, was provided by General Chemical Corporation located in Vancouver, Washington. The liquid sodium aluminate stock solution, containing 20 percent aluminum as Al_2O_3, was provided by the Delta Chemical Corporation located in Baltimore, Maryland. Both of the stock solutions were diluted prior to use in Test 2 to increase the accuracy of the dose applications. The alum dose solution was prepared by diluting 44.9 grams of the stock solution in 1 liter of deionized water, resulting in an alum dose solution of 1.97 g Al/L. The sodium aluminate dose solution was prepared by diluting 29.9 grams of liquid stock solution in 1 liter of deionized water, forming a sodium aluminate dose solution of 3.17 g Al/L.

Shortly after Test 2 was initiated, a typographical error was observed in the written procedure for Test 2. Instead of using the correct amount of 23.9 grams, the procedure called for 29.9 grams of sodium aluminate stock solution to be mixed with 1 liter of water. Thus, the sodium aluminate dose solution contained 25 percent more aluminum than was designed. This error resulted in doses having a higher proportion of sodium aluminate buffer than the intended ratio of 2 parts liquid alum to 1 part liquid sodium aluminate by volume.

Test Procedure

Each jar test was performed within 2 hours of collecting the composite Green Lake water samples. A total of 1.5 liters of Green Lake water was poured into each new, half-gallon plastic container (jar). The pH of the water was measured in each jar prior to commencing Test 1 and was measured in the composite water sample prior to commencing Test 2. The pH was measured using a Hanna Instruments Model 9023 pH meter that was response tested using tap water and calibrated using pH 4 and 7 buffers prior to use.

Five rates of alum and sodium aluminate were used in Test 1 and three rates of the aluminum mixture were used in Test 2. In both tests, all of the treatments were conducted in duplicate. Tables 7 and 8 present the alum and sodium aluminate doses for Tests 1 and 2, respectively. It should be noted that the sodium aluminate dose concentrations shown in Table 8 are the actual amounts used in Test 2 and not the amounts originally planned.

Table 7. Green Lake Jar Test 1 alum and sodium aluminate dose concentrations and volumes added to 1.5 liters of Green Lake water.

Jar Number	Total Aluminum Dose in Jar (mg Al/L)	Alum Dose (mg Al/L)	Sodium Aluminate Dose (mg Al/L)	Alum Dose Solution Added (mL) [a]	Sodium Aluminate Dose Solution Added (mL) [b]
1A	7.66	5.00	6.49	0.50	0.250
1B	7.66	5.00	6.49	0.50	0.250
2A	11.50	7.50	9.74	0.75	0.375
2B	11.50	7.50	9.74	0.75	0.375
3A	15.33	10.00	12.98	1.00	0.500
3B	15.33	10.00	12.98	1.00	0.500
4A	19.16	12.50	16.24	1.25	0.625
4B	19.16	12.50	16.24	1.25	0.625
5A	22.99	15.00	19.48	1.50	0.750
5B	22.99	15.00	19.48	1.50	0.750

[a] Based on an alum dose solution containing 10.00 g/L aluminum made from granular reagent grade alum.
[b] Based on a sodium aluminate dose solution containing 25.98 g/L aluminum made from granular technical grade sodium aluminate.

Table 8. Green Lake Jar Test 2 alum and sodium aluminate dose concentrations and volumes added to 1.5 liters of Green Lake water.

Jar Number	Total Aluminum Dose in Jar (mg Al/L)	Alum Dose (mg Al/L)	Sodium Aluminate Dose (mg Al/L)	Alum Dose Solution Added (mL) [a]	Sodium Aluminate Dose Solution Added (mL) [b]
1A	11.41	4.37	7.04	3.33	3.33
1B	11.41	4.37	7.04	3.33	3.33
2A	22.81	8.74	14.03	6.67	6.67
2B	22.81	8.74	14.03	6.67	6.67
3A	34.24	13.11	21.13	10.0	10.0
3B	34.24	13.11	21.13	10.0	10.0

[a] Based on an alum dose solution containing 1.97 g Al/L, which is made by diluting 44.9 grams of liquid stock solution containing 4.38 percent aluminum (8.27 percent as Al_2O_3) into 1 liter of deionized water.
[b] Based on a sodium aluminate dose solution containing 3.17 g Al/L, which is made by diluting 29.9 grams of liquid stock solution containing 10.6 percent aluminum (20 percent as Al_2O_3) into 1 liter of deionized water.

In Tests 1 and 2, the alum and sodium aluminate were added consecutively to each jar using a graduated pipette. Each jar was mixed immediately after the alum and sodium aluminate was added by capping the jar and inverting it repeatedly for 1 minute. Vigorous shaking was avoided during mixing to prevent excessive quantities of air bubbles from forming in the water. For Test 1, each treated sample was tested for pH at 5 minutes and at 1, 4, 8, 12, 16, 20, and 24 hours after mixing. For Test 2, each treated sample was tested for pH at 5 minutes and at 1, 4, 8, and

24 hours after mixing. A small flashlight was also used to improve visual observations of the alum floc in each jar.

After measuring pH at 24 hours, subsamples were collected from each jar for laboratory analysis. The subsamples were withdrawn from approximately one third of the total water depth using a 50-mL pipette. Careful attention was taken to avoid mixing and incorporating any floc with the subsample. Several subsamples were collected to fill a 250-mL plastic sample bottle. Immediately after filling, the bottles were labeled and placed in a small cooler with ice.

The sample bottles were immediately delivered to Aquatic Research for analysis of total alkalinity, soluble reactive phosphorus, total phosphorous, and dissolved aluminum using methods approved by the U.S. Environmental Protection Agency (U.S. EPA). In addition, the dose solutions used for Test 2 were tested for total aluminum. All requested analyses for Test 1 were canceled because the decision was made to conduct another jar test due to the potential influence of the drinking water discharge on the water sample collected from the lake for Test 1.

Results

Observations of floc formation and the test results are presented and discussed separately below. Data quality was reviewed by comparing results of quality control sample analyses to quality control limits established by the laboratory. Low detection limits were achieved using U.S EPA-approved methods, and no analytes were detected in the preparation blanks. The relative percent difference between laboratory duplicates ranged from 1 to 11 percent and met the control limit of less than 20 percent. Percent recoveries of for laboratory control samples ranged from 92 to 106 percent and met the control limit of between 90 and 110 percent. Percent recoveries for matrix spike samples ranged from 94 to 102 percent and met the control limits of between 80 and 120 percent. Thus, all analytical results exhibit a high degree of precision and accuracy, and are acceptable for use without qualification.

Floc Formation

The presence of floc was closely observed in Tests 1 and 2 over a 24-hour period. The floc was characterized by a slightly off-colored gel that oftentimes contained pinhead sized air bubbles.

In Test 1, small amounts of floc were observed throughout the water column at 5 minutes after mixing in all of the treatments. One hour after mixing, increased amounts of floc had accumulated at the surface of all of the treatments, with the largest surface accumulations in treatments 4 and 5. Four hours after mixing, all of the treatments appeared to have slightly increased floc accumulations at the surface, except treatment 5, which appeared to have less floc at the surface. By eight hours after mixing, most of the floc had settled out onto the bottom of the jar in treatment 5, but the remaining treatments exhibited little change in floc accumulations. One day (24 hours) after mixing, the floc accumulations in treatments 3 through 5 had settled out onto the bottom of the jars, but little change was apparent in the floc accumulations in treatments

1 and 2. These results show that highest doses of alum and sodium aluminate form the largest amount of floc faster than the lower doses, resulting in faster rates at which the floc settles out of the water column.

In Test 2, small amounts of floc were observed in each of the treatment doses (11, 23, and 34 mg Al/L) throughout the water column of the jars. One hour after mixing, increased accumulations of floc were observed at the surface of the jars in all treatments. The thickness of the floc layer ranged from 1 to 2 cm. Four hours after mixing, increased accumulations of floc were observed at the water surface in treatments 1 and 2, but very little floc was observed at the surface of treatment 3 because the floc had settled to the bottom of the jar. One day after mixing, little change in floc accumulations was observed in treatments 1 and 3, but most of the surface floc had settled to the bottom in treatment 2. These results are similar to the pattern observed in Test 1 in which the highest doses of alum and sodium aluminate resulted in the fastest accumulations of floc at the surface and bottom of the jar.

pH

The pH was measured in all of the treatments in Test 1 over a 24-hour period. Table 9 presents the pH results for Test 1 at each time of measurement. The initial (untreated) pH decrease from 7.37 to a range of 6.07 to 6.71 in the treated samples tested over the 24-hour period. The pH generally decreased with increasing doses of alum and sodium aluminate, but little change in pH was observed during the treatment. The pH did not decrease below the 6.0 threshold considered protective of aquatic organisms (Cooke and Kennedy 1981) in any of the treatments. During a lake treatment, the pH would not decrease to the these observed levels because of the additional buffering from lake sediments that is not simulated in the jar tests over a 24-hour period.

Table 9. Green Lake Jar Test 1 pH results.

Jar	Initial [a]	5 Minutes	1 Hour	4 Hours	8 Hours	24 Hours
1A	7.38	6.60	6.65	6.67	6.67	6.71
1B	7.36	6.66	6.67	6.66	6.66	6.69
2A	7.37	6.48	6.48	6.49	6.49	6.51
2B	7.36	6.44	6.47	6.48	6.48	6.50
3A	7.37	6.34	6.30	6.29	6.29	6.29
3B	7.37	6.34	6.34	6.34	6.34	6.35
4A	7.37	6.23	6.23	6.22	6.22	6.23
4B	7.37	6.21	6.21	6.20	6.20	6.22
5A	7.37	6.18	6.15	6.17	6.17	6.20
5B	7.37	6.10	6.08	6.07	6.07	6.11

[a] The pH was measured in each jar immediately prior to treatment.

The pH was measured in all of the treatments in Test 2 over a 24-hour period. Table 10 presents the pH results for Test 2 at each time of measurement. The initial (untreated) pH decrease from 7.70 to a range of 7.00 to 7.20 in the treated samples tested over the 24-hour period. The pH results exhibited low variation among the different treatments and measurement times. The initial and treated pH in Test 2 treatments were higher than those in the Test 1 treatments. The higher initial pH was likely due to increased bacterial productivity in the lake and the higher treated pH was likely due to inadvertent increase in the proportion of sodium aluminate buffer. These results indicate that the pH would not decrease below the 6.0 threshold for protection of aquatic organisms if the sodium aluminate buffer dose was reduced by the 25 percent needed to meet the proposed treatment dose specified in the following section of this report.

Table 10. Green Lake Jar Test 2 pH results.

Jar	Initial [a]	5 Minutes	1 Hour	4 Hours	8 Hours	24 Hours
1A	7.70	7.17	7.14	7.13	7.15	7.11
1B	7.70	7.16	7.12	7.13	7.12	7.12
2A	7.70	7.00	7.08	7.07	7.08	7.14
2B	7.70	7.03	7.05	7.09	7.10	7.19
3A	7.70	7.07	7.03	7.02	7.02	7.11
3B	7.70	7.10	7.10	7.11	7.10	7.20

[a] The pH was measured in the composite water sample prior to pouring subsamples into each jar.

Alkalinity

Total alkalinity was analyzed in the samples collected at 24 hours in Test 2 (Table 11). These results show a decrease in alkalinity from 25 mg/L in the untreated sample to between 19 and 22 mg/L in the treated samples. Total alkalinity decreased with the increased alum dose. These results indicate that lake alkalinity would not exhibit a substantial change during an alum treatment. Although a greater decrease in alkalinity would be anticipated because a lower proportion of sodium aluminate is proposed for the treatment than that tested, lake sediments would add some buffering to the treatment that was not present in the jar tests.

Phosphorus

Soluble reactive phosphorus (SRP) and total phosphorus (TP) were analyzed in the samples collected at 24 hours in Test 2 (see Table 11). SRP was present at the detection limit of 1 µg/L in the untreated and treated samples (with the exception of 2 µg/L detected in Jar 2A). TP decreased from 13 µg/L in the untreated sample to at or below the detection limit of 2 µg/L in the treated samples (with the exception of 4 µg/L detected in Jar 1A. Thus, all of the alum treatments removed nearly all of the phosphorus present in the lake water sample. The initial SRP and TP concentrations are at the low end of the range previously observed since 1994 during the spring season (i.e., ranges of 2 to 9 µg/L SRP and 13 to 25 µg/L TP in March through May of 1995 through 2000 as shown in Table 2).

Table 11. Green Lake Jar Test 2 laboratory analysis results.

Sample	Total Aluminum Dose (mg/L)	Total Alkalinity (mg $CaCO_3$/L)	Soluble Reactive Phosphorus (µg/L)	Total Phosphorus (µg/L)	Dissolved Aluminum (mg/L)	Total Aluminum (mg/L)
Untreated	0.00	24.7	1	13	0.0087	–
Jar 1A	11.41	22.5	1	4	0.0405	–
Jar 1B	11.41	21.7	1	2	0.0460	–
Jar 2A	22.81	20.1	2	2	0.0466	–
Jar 2B	22.81	20.4	1	<2	0.0456	–
Jar 3A	34.24	18.8	1	<2	0.0421	–
Jar 3B	34.24	18.8	1	2	0.0480	–
Alum Dose Solution	1,970	–	–	–	–	2,085
Sodium Aluminate Dose Solution	3,170	–	–	–	–	3,291

– Not analyzed.

Dissolved Aluminum

Dissolved aluminum was analyzed in the samples collected at 24 hours in Test 2 (see Table 11). The dissolved aluminum concentration increased from 0.009 mg/L in the untreated sample to between 0.040 and 0.048 mg/L in the treated samples (see Table 11). The dissolved aluminum concentrations did not vary consistently among the treated samples. The observed aluminum concentrations do not exceed either the acute (0.750 mg/L) or chronic (0.087 mg/L) criteria recommended by U.S. EPA (2002).

Total Aluminum

Total aluminum was analyzed in the alum and sodium aluminate dose solutions used in Test 2 to check the accuracy of their preparation (see Table 11). The relative percent difference between the calculated and measured values is 5.6 percent for the alum dose solution and 3.7 percent for the sodium aluminate dose solution. These results are well within the analytical control limits (i.e., less than 20 percent).

Alum Treatment Specifications

An alum treatment will inactivate the internal cycling of phosphorus and aid in the prevention of toxic algal blooms in Green Lake. For optimal results, the alum treatment will be applied to the lake from the beginning of January to March 2004. This period of time was chosen for application because the biomass of rooted aquatic plants will be relatively low compared to other times of the year. For alum to be effective, it must be allowed to settle directly onto the sediment surface and not be intercepted and held suspended by plants above the lake bottom.

The alum treatment will consist of the application of two compounds, aluminum sulfate and sodium aluminate. These two compounds will be applied at a ratio of 2 gallons of alum to one gallon of sodium aluminate. A mixture of liquid alum and sodium aluminate will be applied to the lake surface or injected into the lake from a moving barge. The barge position in the lake will be controlled by a global positioning system (GPS) with computer-integrated sonar to continuously adjust the flow of alum, based on changing lake volume and boat speed.

As previously noted, determining the proper dose of alum and sodium aluminate to be applied to the lake is extremely important. The dose of alum and sodium aluminate, in mg/L of aluminum (Al), is calculated so toxicity effects are avoided and sediment inactivation of all mobile phosphorus is achieved. The dose of alum to be applied to Green Lake was calculated based on the amount of aluminum needed to inactivate sediment-exchangeable phosphorus as well the amount of aluminum needed to overcome the demand in the water column. This additional demand in the water column is primarily due to the presence of humic organic compounds.

The jar tests were conducted to determine the amount of aluminum needed to overcome the additional water column demand, which is added onto the dose determined to inactivate phosphorus in the sediments to calculate the total dose of aluminum needed. The total dose of aluminum to be applied to Green Lake was determined to be 23 mg Al/L, which includes 17.2 mg Al/L applied to inactivate mobile phosphorus in the sediments and 5.8 mg Al/L applied to overcome the demand throughout the water column. The amount of aluminum sulfate and sodium aluminate to be applied to achieve this aluminum dose is 605 and 357 tons, respectively, at a lake volume of 4.98×10^6 cubic meters. On a liquid basis, this dose is equivalent to 225,470 gallons of alum and 112,922 gallons of sodium aluminate.

It is estimated that the alum treatment will require a total of seven days to deliver the alum and sodium aluminate to the lake working at full capacity of the treatment equipment available. This estimate is based on a treatment equipment capacity to deliver 50,000 gallons of material per day. Given the time of year for the treatment (January to March), there is a potential for weather conditions to delay and interfere with this optimum treatment rate. Therefore, it is estimated that the treatment may take up to 21 days to fully apply the alum to the lake.

Because only a portion of the lake will be treated each day, the lake's alkalinity is protected from permanent alteration by inputs of alkalinity from the lake sediments, by inputs of carbon dioxide from the atmosphere, and through the use of the buffer sodium aluminate. The treatment dose is buffered by sodium aluminate and the dose is calculated so that it will ensure that the pH and lake's alkalinity will not be compromised during or after the treatment. This can be stated with confidence because the results from the two jar tests conducted in 2003 and the jars tests conducted before the 1991 alum treatment, demonstrated that the pH and alkalinity of the lake are, in fact, preserved. Also, the 1991 alum treatment of the lake demonstrated the limited impact of the buffered alum treatment on the lake's alkalinity (KCM 1995).

Presented below are technical specifications for the proposed alum treatment of Green Lake. These specifications are intended to be used as a technical resource to base contractor bid documents on. The specifications include the following three sections:

- Alum Application Description
- Technical Material Specification
- Alum Application Specification.

Alum Application Description

The Green Lake alum treatment project will apply alum to Green Lake to inactivate phosphorus and to reduce internal phosphorus loading and the resulting toxic bacterial blooms. The alum and sodium aluminate shall be applied according to the following specifications:

1. The application period is January 1, 2004 through March 15, 2004 and shall not exceed 75 consecutive calendar days and shall include weekends.

2. The contractor shall provide all equipment, labor and materials necessary to perform the work including application equipment, and equipment necessary to mobilize and demobilize.

3. The lake access and application staging area is located at the parking lot near the Aqua Theatre off West Green Lake Way.

4. The contractor shall submit the following items for approval by the engineer prior to the start of work:

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

   b. Description of the temporary lakeshore chemical storage facilities including a spill prevention and spill contingency plan.

   c. Photographs and/or drawings and description of the application equipment to be used on Green Lake, including width of application path, on-board storage capacity of both chemicals, and means of locomotion.

d. Method of chemical distribution to ensure dose accuracy within the tolerances required.

e. Explanation of GPS navigation system linked to on-board GIS including real-time bathymetric measurement to be used to ensure complete and uniform coverage.

f. Explanation of lake depth detection system and equipment and linkage to pump distribution system for chemical delivery.

g. Description of all backup systems to minimize down time.

h. Land-to-vessel chemical transfer method.

i. Anticipated treatment capacity (acre/hour).

5. The contractor shall demonstrate performance in completing three similar jobs and shall have been in business for a minimum of 3 years. The contractor must have performed an alum treatment on at least three jobs of 100 acres or more.

6. The base bid shall include all equipment, material, work and labor required to complete the application described.

Technical Material Specification

The aluminum sulfate (alum) shall comply with the following specifications:

1. The alum applied to Green Lake will be aluminum sulfate, which is the product of the reaction between sulfuric acid and a mineral rich in aluminum, such as bauxite or liquid alum, which is a nearly saturated solution of aluminum sulfate.

2. The aluminum sulfate supplied under this standard shall contain no soluble mineral or organic substances in quantities capable of producing deleterious or injurious effects on public health or water quality.

3. Liquid alum shall contain water-soluble aluminum of 4.4 percent as Al^{3+} or 8.1 percent as Al_2O_3.

4. The total water-soluble iron (expressed as Fe_2O_3) content of aluminum sulfate shall be no more than 0.35 percent, on a basis of 8.1 percent Al_2O_3 in liquid alum. In liquid alum, the water-soluble matter shall not exceed 0.2 percent.

The sodium aluminate shall comply with the following specifications:

1. Sodium aluminate is a produced from the reaction of alumina trihydrate with caustic soda. Liquid sodium aluminate shall contain no more than 0.5 percent insoluble matter. Liquid sodium aluminate shall contain a minimum of 30 percent available soluble sodium aluminate. Liquid sodium aluminate shall have excess sodium oxide of at least 4 percent to ensure complete combination with the aluminum oxide.

2. 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.

Alum Application Specification

The application of alum and sodium aluminate to Green Lake shall comply with the following specifications:

1. Liquid aluminum sulfate (alum as $Al_2(SO_4)_3*14H_2O$) and sodium aluminate ($NaAlO_2$) will be applied to the lake surface or injected into the lake simultaneously from a moving barge. The barge position in the lake will be controlled by a satellite guiding system with computer integrated sonar to continuously adjust the flow of alum, based on changing lake volume and boat speed. All areas with depths greater than 5 feet will receive the alum/sodium aluminate application.

2. The total dose of aluminum to be applied to Green Lake was determined to be 23 mgAl^{3+}/L, with 17.2 mg Al^{3+}/L applied to inactivate mobile phosphorus in the sediments and 5.8 mg Al^{3+}/L applied to overcome the demand throughout the water column. The amount of aluminum sulfate and sodium aluminate to be applied to achieve this aluminum dose is 605 and 357 tons, respectively, at a lake volume of $4.98x10^6$ cubic meters. On a liquid basis this is equivalent to 225,470 gallons of alum and 112,922 gallons of sodium aluminate.

3. The chemicals shall be applied in a ratio of 2 gallons alum to 1 gallon sodium aluminate to an accuracy of ±5 percent. The chemicals must be simultaneously distributed at this ratio so that the entire treatment area is uniformly covered. Computerized equipment on the barge will ensure that the chemicals are distributed simultaneously and in the correct ratio. The application rate shall be such that the pH of the lake does not decrease below 6.0 as determined by the engineer.

4. The contractor shall be responsible for the purchase, delivery, scheduling and application of the chemicals, including all labor.

5. The contractor shall keep daily logs stating the following minimum items:

    a. Hours of application

    b. Quantity of material applied; computer data indicating application of liquid alum and sodium aluminate in the specified dose ratio

    c. Approximate acreage treated

    d. Approximate location (on map) of area treated

    e. Summary of truck deliveries.

6. The contractor shall be responsible for all staging area setup, security, cleanup, and restoration to its original condition following completion of the application.

7. The contractor shall comply with all of the conditions of the permits with the exception of the monitoring requirements. Water quality monitoring shall be conducted by the engineer.

8. The contractor will adjust the delivery rate of alum and sodium aluminate as specified by the engineer. If environmental conditions develop that require the suspension of the alum treatment, the contractor shall comply with the instructions of the engineer.

Permit Requirements

The proposed Green Lake alum treatment would require coverage under Ecology's aquatic nuisance plant and algae control National Pollutant Discharge Elimination System (NPDES) general permit, which took effect June 13, 2002 (Ecology 2002). Prior to this permit, alum treatments of lakes required a water quality modification permit from Ecology and compliance with the aluminum sulfate treatment policy (Ecology 1991). The alum policy is still in effect and is in the process of being updated (Moore 2003). In addition, the City of Seattle may require a shoreline substantial development permit, if deemed necessary. The NDPES permit, alum policy, and shoreline permit are described below.

Aquatic Nuisance Plant and Algae Control NPDES General Permit

Indirect bacteria (or algae) control through the application of aluminum sulfate (alum) to control phosphorus requires coverage under Ecology's general NPDES permit for aquatic nuisance plant and bacteria control. Under this general permit, the City of Seattle applies for coverage by submitting an application form (also known as a notice of intent [NOI]) requesting coverage under Ecology's general permit (No. WAG 994000). The NPDES permit requires preparation of an integrated aquatic vegetation management plan (IAVMP) for aquatic plant control, or an equivalent plan for using alum to manage phosphorus.

To date, an alum treatment application with an accompanying IAVMP (or equivalent) has not been processed by the Ecology Northwest Regional Office (NWRO) under this new NPDES permit. Therefore, the summary below represents the best interpretation of requirements listed in the permit and discussions with Ecology staff. The NPDES permit is presented in Appendix C.

Permit coverage should be requested at least 38 days prior to the planned activity that results in a discharge to waters of the state. The application form (or NOI) for direct applications, titled *Application for Coverage Aquatic Pest General Permit to Control Nuisance Vegetation and Algae,* is available online at the following Ecology website: <http://apps.ecy.wa.gov/AquaticPestApp/applogin.asp>.

This application can be completed and submitted online by following the instructions on the web site. Currently, no fee is required to submit the application, but a permit fee would be billed to the permittee after the permit is issued. At the present time, the estimated permit fee is $300 (Shoblom 2003b).

Integrated Phosphorus Management Plan

Prior to receiving coverage under the general permit, an Integrated Aquatic Vegetation Management Plan (or equivalent), must be submitted to and approved by Ecology. Per Ecology's guidance, an integrated phosphorus management plan (IPMP) would be prepared in lieu of an IAVMP for phosphorus control in Green Lake because phosphorus, not aquatic vegetation, is targeted for control (Moore 2003). Similar to the IAVMP, the elements of the IPMP would include the following (as identified in Appendix A of the general permit):

I. A description of the problem (problem statement).

II. Past management efforts.

III. Management goals.

IV. Water body and watershed characteristics.

V. Current and potential beneficial and recreational uses of the water body

VI. Map aquatic plants (including depth contours, wetlands, threatened or endangered species of plants or animals).

VII. Identify the aquatic plant control alternatives, their effectiveness, environmental impacts, human health risks, and costs.

VIII. Identify the plant problems in specific locations by assessing the control levels in each of the areas identified on the use map.

IX. Choose the best combination of options of site-specific levels of control using these criteria.

X. Public involvement plan.

XI. SEPA Review (checklist).

XII. Develop an action strategy, which implements the integrated aquatic plant management plan.

XIII. Monitoring and evaluation of plan.

The Green Lake restoration project report (KCM 1995) and this report contain elements I through IX and element XII. Thus, the IPMP would need to summarize existing information for these elements and would also need to include a public involvement plan, SEPA checklist, and monitoring plan. The IPMP would be submitted to Ecology's NWRO for review and approval. This process could take several months and involves a public comment period (Shoblom 2003a). Therefore, the IPMP should be submitted to Ecology by August 2003 to receive coverage under the NPDES general permit for treatment in January 2004.

Modifications can be made to an approved IPMP but must be submitted to Ecology for approval at least 38 days prior to application. However, major modifications to the IPMP would require another SEPA review (Ecology 2002).

Aluminum Application Restrictions for Reduction of Phosphorus

The NPDES permit outlines the following restrictions for aluminum applications (Ecology 2002):

- Whole lake treatments. Whole lake treatments are allowed only as a component of an approved IAVMP (This project proposes to complete an Integrated Phosphorus Management Plan in lieu of an IAVMP for phosphorus control in Green Lake). This plan should address control of nutrients to the lake and include the results of jar tests to determine the proper application rate. The plan must also address monitoring during application to assure the pH and alkalinity requirements are not exceeded.

- Partial lake treatments. Partial lake treatments conducted without prior jar tests shall not exceed 50 µg/L dissolved aluminum.

- Powdered alum. Powdered alum must be mixed with water to form a slurry prior to application. Lake water may be used to make the slurry and for spray application(s).

- Early morning application. The application shall begin as early as possible each morning to avoid complications due to the natural decrease in pH after nightfall.

- Buffering material. For whole lake treatments, buffering material such as sodium carbonate or sodium aluminate shall be available to use with alum if a decrease in pH is observed.

- Wind limit. If the wind speed exceeds 5 mph then application shall cease (whole lake treatments). This wind restriction applies only to powder alum applications (Moore 2003).

- Fish kill or distress. If any fish are killed or distressed during application, the permittee shall cease treatment and immediately notify the appropriate Ecology (Bellevue) and Fish and Wildlife (Mill Creek) Offices.

- pH. The lake pH must remain between 6.0 and 8.5 during the application.

- Aluminum compounds. Only aluminum compounds suitable for water treatment (i.e., containing low concentrations of heavy metals) may be used.

Notification and Posting Requirements

Public Notification

This permit requires that two public notices be published at least one week apart in a local newspaper of general circulation in the area of the application. The permit further requires that the public notice state “an application for coverage has been pursuant to Section 173-226-130(5)

WAC. The date of second publication constitutes completion of public notice. The 30-day comment period starts on the date of the second publication."

The permit requires that public notices (with coverage with an approved IAVMP, or equivalent) include (Ecology 2002):

- The names of the applicant
- The water body name
- The chemicals (aluminum sulfate and sodium aluminate) expected to be used during the coarse of the permit coverage
- The availability of the IPMP for public review.

After the 30-day comment period, Ecology reviews all comments prior to granting coverage under this permit and intends to notify applicants by mail regarding coverage under this permit. However, if the applicant does not receive notification of coverage from Ecology, coverage will commence on the 38th day following the Ecology's acceptance of an application form or publication of the second public notice, whichever occurs later (Ecology 2002).

Length of coverage under this permit varies with the type of application. The City of Seattle would seek coverage for a one-time alum treatment, which would occur over approximately two months.

Agency Notification Requirements

The applicator is required to notify the appropriate Ecology Regional Office by FAX (425-649-7098) by close of the business day (5:00 p.m.) prior to the day of application. The required information to provide Ecology includes:

- The name of the water body
- Estimated time when the application will begin (hour)
- Location on the water body where the treatment will begin
- The chemicals to be used.

The applicator must notify the appropriate Ecology regional office on the day following completion of treatment by fax with information about any modifications of the treatment plan or cancellation of the treatment and if the treatment was cancelled, the expected new treatment date, location, and chemicals (Ecology 2002).

Noncompliance Notification

If the permittee is unable to comply with the terms and conditions of the permit then the permittee is required to "immediately take action to stop, contain, and clean up unauthorized discharges or otherwise stop the noncompliance, and correct the problem." The permittee must also notify Ecology immediately of the failure to comply with the permit.

Posting Requirements

The applicator is required to post signs prior to the application event, but no more than 24 hours prior to application. The applicator is required to use good faith and reasonable effort to ensure that the posted signs remain in place until the end of the period of water use restrictions. Warning signs are required to be posted in English and the language commonly spoken by the community who uses the area.

The specifications and guidelines for posting signs in public shoreline areas are described in the general permit and include requirements for:

- Sign sizing
- Letter sizing
- Sign color
- Sign placement.

Posting signage on the water is not required because alum does not have swimming and/or fish consumption restrictions or precautions.

Monitoring

A monitoring plan is required and would be included as part of the IPMP, which is submitted to Ecology for its review and approval. Lake monitoring would occur before, during, and after treatment, and would occur in at least three lake locations. Parameters sampled may include pH, alkalinity, Secchi depth, dissolved aluminum, dissolved oxygen, total phosphorus, and soluble reactive phosphorus. Monitoring requirements are described further in Ecology's aluminum sulfate treatment policy (Ecology 1991) and the NPDES permit (Ecology 2002).

The permit requires that monitoring data be prepared by an accredited or registered laboratory, under the provisions of Accreditation of Environmental Laboratories (Chapter 173-50 WAC), except for field parameters such as dissolved oxygen, pH, and Secchi depth. Sampling and analytical methods used to meet the monitoring requirements are required to conform to the current version of the *Guidelines Establishing Test Procedures for the Analysis of Pollutants* (40 CFR Part 136) or the current edition of *Standard Methods for the Examination of Water and Wastewater* unless otherwise specified by Ecology.

Laboratory reports for sample analyses are required to include: sampling date, sample location, date of analysis, parameter name, CAS number, analytical method/number, method detection limit (MDL), laboratory practical quantitation limit (PQL), reporting units, and concentration detected.

During each measurement or sample analysis, the following information shall be recorded:

- The date, exact place, method, and time of sampling measurement
- The individual who performed the sampling or measurement
- The dates the analyses were performed
- The analytical techniques or methods used
- Results of all analyses.

Reporting and Record-Keeping Requirements

An annual monitoring report must be submitted to Ecology. Reports for the previous calendar year shall be received by Ecology (Northwest Regional Office) no later than February 1 of the year following the completed monitoring period.

If the permittee monitors a pollutant more frequently than required by the permit, then the results of this monitoring are required to be included in the calculation and reporting of the data submitted in the permittee's annual report (Ecology 2002).

The permittee is required to retain all monitoring records for a minimum of 5 years. Information retained shall include: all calibration and maintenance records, all original recordings for continuous monitoring instrumentation, copies of all reports required by the permit, records of all data used to complete the application for this permit. The record retention period will be extended if any unresolved litigation regarding the discharge of pollutants by the permittee or when requested by the Ecology director.

Ecology requires that all applications, reports, or information submitted to Ecology be signed and certified. For the Green Lake alum treatment, these materials must be signed by a ranking elected official or by a duly authorized representative in accordance with general conditions (G15.B of the NPDES permit). The permit allows for changes in authorization as specified in the condition G15.C. The person signing documents related to this permit is required to make the declaration found in general condition G15.D.

Spill Prevention and Control

The permit requires that spills be reported to the appropriate Ecology regional office (NWRO in Bellevue at 425-649-7000). The contractor should be required to develop a Spill Response and Prevention Plan that would be available on-site during the treatment.

Aluminum Sulfate Treatment Policy

Ecology's aluminum sulfate treatment policy (Ecology 1991) lists guidelines for alum use to treat high nutrient concentrations in lakes and is presented in Appendix D for reference. This policy further outlines water quality monitoring requirements to be followed before, during, and after an alum treatment. Ecology is currently in the process of updating this policy, which has been in effect since 1991 (Moore 2003). These monitoring requirements, along with those outlined in the general permit would be incorporated into the monitoring plan developed for this project and submitted as part of the IPMP (discussed above).

Shoreline Substantial Development Permit

For the 1991 alum treatment of Green Lake, the Seattle Department of Design, Construction, and Land Use (DCLU) issued a Shoreline conditional use permit rather than a shoreline substantial development permit (Seattle Municipal Code [SMC] 23.60). Since the 1991 treatment, an exemption for aquatic noxious weed control has been added to Seattle's shoreline code. DCLU recently indicated that the proposed alum treatment would be exempt for a shoreline permit if it is used to control algae (or bacteria) on the Washington state noxious weed list and an approved treatment method is used, as discussed in SMC 23.60.210 C (McKim 2003 personal communication). However, blue-green bacteria are not weeds, and only vascular plants are included on the Washington state noxious weed list. Thus, the noxious weed control exemption may not apply because the alum treatment is not used for the control or removal of a noxious weed.

Upon review of the current shoreline permit requirements, a shoreline permit may not be required for the proposed Green Lake alum treatment because there is no specific section of the permit code that addresses alum treatments and the treatment is a maintenance activity for which there is a general exemption. It may also be possible to have the project recognized as a watershed restoration effort, which would afford another avenue for exemption from the shoreline permit.

The Green Lake Phase I study was initiated in 1981 and included a diagnostic/feasibility study of the lake (URS 1983). The Phase II lake restoration project included a lake alum treatment in 1991. The Phase II project completion report recommends alum treatments every 5 to 8 years to maintain lake water quality goals (KCM 1995). Both the Phase I study and Phase II restoration program, and implementation of future management recommendations could be deemed by the city as either maintenance activities or watershed restoration projects meeting the permit exemption criteria.

Cost Estimate

Table 12 summarizes the estimated cost to complete the proposed alum treatment of Green Lake. The total estimated costs are based on a total aluminum dose of 23 mg Al/L. The total cost of the alum treatment comes to $1.5 million. Benefits of the alum treatment will most likely last for at least 10 years.

In comparison with the past practice of adding dilution water to the lake, at the rate of 300 acre-feet of city water each summer for the next 10 years, the alum treatment cost is relatively small. The annual cost of adding 300 acre-feet of city water into Green Lake is approximately $437,800 (in 2004 dollars). This was calculated based on the general service commodity charge during the peak usage period for 2004 ($3.35 per 100 cubic feet). Over a 10-year period, this would translate to approximately $4.4 million, not adjusted for inflation. This is approximately three times the cost of a 10-year effective alum treatment.

Table 12. Green Lake alum treatment cost estimate.

Description	Estimated Quantity	Units	Unit Price	Estimated Amount
Alum Chemical Treatment Contract Costs				
Access area site preparation	1	ea	$5,000.00	$5,000
Barges, pumps and boats; ownership and operating expenses	21	days	$450.00	$9,450
Chemical treatment labor	21	days	$1,500.00	$31,500
Liquid alum/sodium aluminate holding facilities	1	LS	$20,000.00	$20,000
Liquid alum purchase	605	dry tons	$500.00	$302,500
Liquid sodium aluminate purchase	357	dry tons	$1,200.00	$428,400
Liquid alum transport	187,800	ton-mile	$0.02	$3,756
Liquid sodium aluminate transport	684,000	ton-mile	$0.02	$13,680
Site Restoration	1	LS	$5,000.00	$5,000
Subtotal 1				**$819,286**
Contractor mobilization/demobilization (8% of Subtotal 1)				$65,543
Subtotal 2				**$884,829**
Contractor's insurance, fees, overhead and profit (20% of Subtotal 2)				$176,966
Subtotal 3				**$1,061,795**
Taxes (8.8% of Subtotal 3)				$93,438
Alum Chemical Treatment Contract Costs Subtotal				**$1,155,233**
Associated Costs				
Parks Department project management	1	LS	$30,000.00	$30,000
Permitting and public involvement	1	LS	$40,000.00	$40,000
Engineering design and bid assist	1	LS	$18,000.00	$18,000
On-site jar test	1	LS	$7,500.00	$7,500
Construction management	55	days	$1,000.00	$55,000
Treatment monitoring	35	days	$2,100.00	$73,500
Post-treatment monitoring	24	days	$2,100.00	$50,400
Contingency (10% of Contract Costs Subtotal)				$115,523
Associated Costs Subtotal				**$353,923**
TOTAL COST OF ALUM TREATMENT				**$1,509,156**

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