Lake Stevens Sediment Quality Investigation
Technical Memorandum

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Prepared For:

Snohomish County Public Works
Surface Water Management

Snohomish County
WASHINGTON

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INTRODUCTION

In many lakes, including Lake Stevens, internal loading (the release of phosphorus from lake sediments into the water column) is a significant source of nutrients that contribute to nuisance algal growth and impaired water quality. Internal loading is in part controlled when phosphorus is held in the sediments by iron under oxidative or aerobic conditions which are characterized by the presence of dissolved oxygen. Since 1994, an aeration system has been operating in Lake Stevens to provide aerobic conditions in the hypolimnion and help control internal phosphorus loading. In order to define the current phosphorus release potential and possible need for additional treatment of the sediments, Tetra Tech, Inc. conducted a sediment quality investigation of Lake Stevens, the largest recreational lake in Snohomish County.

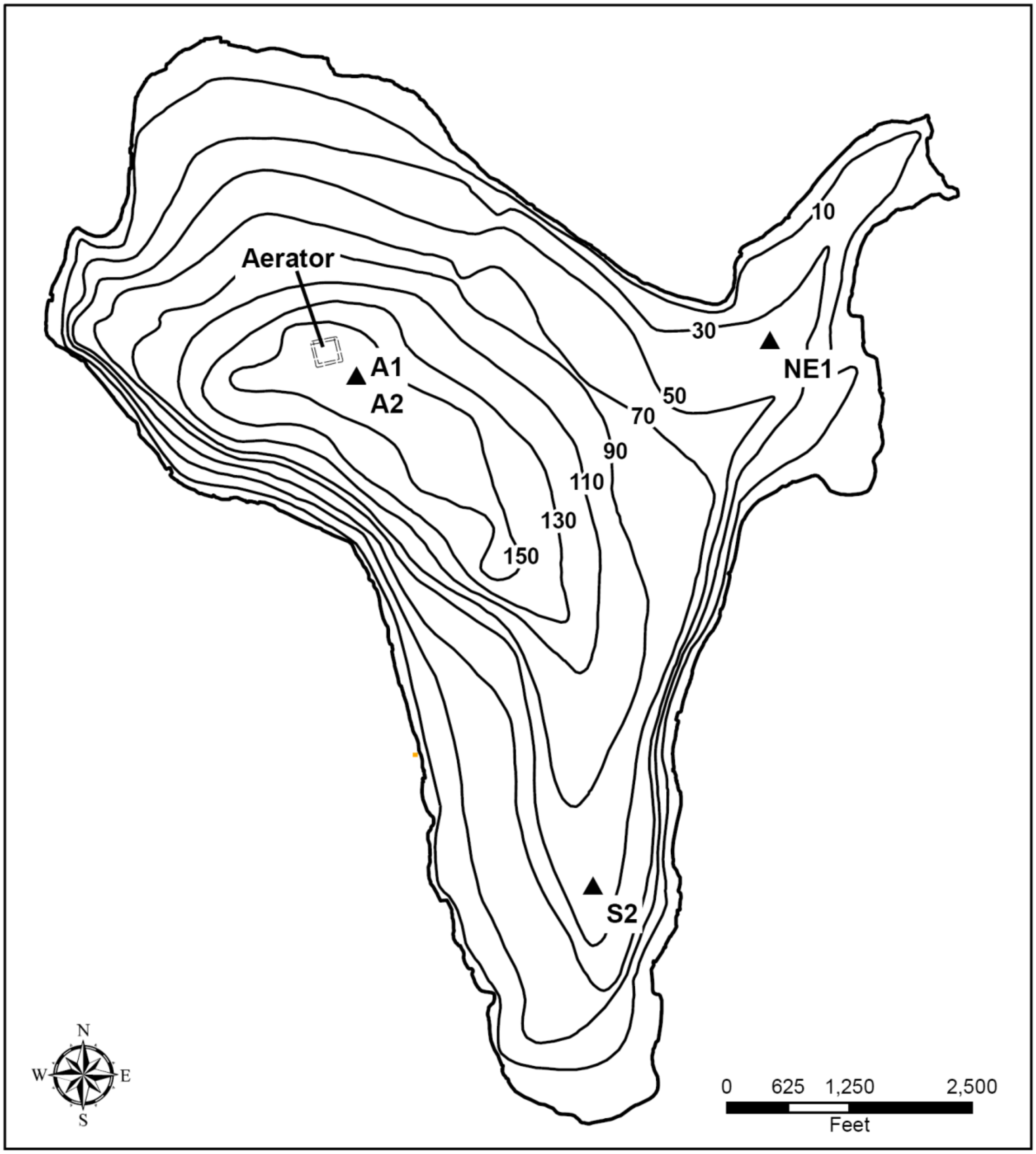
On July 8th, 2009, five sediment cores were collected from Lake Stevens (Map 1). The sediment cores were collected from three regions of the lake: two cores (A1, A2) from the deepest hypolimnetic sediment near the aeration system (water depth of 145 feet), two cores from the south end of the lake (S1, S2) at a water depth of 80 feet, and one core (NE 1) from the outlet bay at a water depth of 40 feet. The sediment cores were sent to Aquatic Research laboratory and analyzed for the following parameters at depths of 0-2, 2-4, 4-6, 6-10, 10-15, 15-20, 20-25, 25-30 cm:

- % solids
- % water
- % volatile solids
- Organic-Phosphorus
- Total-Phosphorus (TP)
- Loosely Sorbed Phosphorus
- Iron bound-Phosphorus (Fe-P)
- Aluminum bound-Phosphorus (Al-P)
- Aluminum
- Iron

One sediment core collected from the south end of the lake (S1) was not analyzed at depth intervals but was used as a composite core for analytical QA/QC purposes and will not be discussed. Analyses performed on core S1 followed all the same quality control protocols as the other cores. The data from S1 were used in an overall QA/QC post-analytical assessment to provide a test for consistency for overall laboratory sediment analysis and core sampling uniformity.

STUDY OBJECTIVE

The purposes of this study are to evaluate the present characteristics of the lake sediments, to better understand the past performance of the hypolimnetic aeration system, and to assess the future management activities needed to control internal loading and maintain the water quality and beneficial uses of Lake Stevens.



Map 1: Lake Stevens Sediment Study 2009

▲ Sediment Core Sites

—— Depth Countours

Snohomish County

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RESULTS

Sediment core analytical results were completed on August 26th, 2009. Total phosphorus, iron, and aluminum profiles were compared to sediment data from Lake Stevens taken in 1981 (Reid, Middleton & Assoc., 1983). The 1981 profile is assumed to begin at the 15 cm depth of the current cores based on the estimated sedimentation rate between 1981 and 2009 that would result in the burial of the older sediments. The 2009 sediment profiles were also compared to sediment profile concentrations from four eutrophic lakes in Western Washington—Green Lake (Tetra Tech, 2003), Long Lake in Thurston County, (Tetra Tech, 2006), Wapato Lake (Tetra Tech, 2007), and Long Lake in Kitsap County, (Tetra Tech, 2008). These four lakes were used for comparison with Lake Stevens because they represent a gradient of phosphorus concentrations (from high to low) bound in bottom sediments. The comparison indicated a relative level of nutrient contribution to sediments from loading sources (i.e. nonpoint) and the potential mechanisms for impairment based on known sources from the four lakes.

Total Phosphorus

Phosphorus is present in several forms in sediment cores and is collectively examined as total phosphorus. TP concentrations in Lake Stevens are high in the surface sediments (0 to 4 cm) in all four cores (S2, A1, A2, NE 1) as shown in Figure 1. The highest TP concentrations were found in the surface sediments at stations A1 and A2, located at the deepest point of the lake near the aerators. The average TP concentration at stations A1 and A2 in the top 4 cm was 3,540 mg/kg, which is twice as high as that seen in the surface sediments at Wapato Lake and much higher than what was observed at the other lakes (Figure 2). These high concentrations are evidence that Lake Stevens is receiving excess nutrients from its watershed. This is consistent with the sediments of highly eutrophic lakes that are known to reach TP concentrations of 10,000 mg/kg because they are stressed by nutrients coming from their watersheds. TP concentrations were somewhat lower at station NE 1, which was located near the outlet zone of the lake. At depths greater than 4 cm, TP concentrations in Lake Stevens decrease and remain fairly consistent to the lower end of the cores. The one exception is the A2 sediment core which showed increases at 15 – 20 cm and 30 cm. Overall, the TP concentrations below 4 cm in Lake Stevens are similar to concentrations observed in other lakes in the region (Figure 2).

The high TP concentrations in the Lake Stevens surface sediments found in 2009 (2,500-7,500 mg/kg) are actually lower than those measured in 1981 (10,000-15,000 mg/kg) (see Figure 1). The higher concentrations in the 1970s through 1980s were caused in part by agricultural runoff (i.e. poultry waste) and large numbers of waterfowl residing on the lake from a nearby solid waste landfill. Both of those sources were subsequently eliminated or dramatically reduced. Interestingly, there are no consistent markers in the current A1 and A2 cores to match the high concentrations measured in 1981. These higher levels should have occurred around 15 cm sediment depth in the 2009 cores based on the sedimentation rate determined in the mid 1980s of 0.5 cm/yr.

Sediment-bound Phosphorus

Sediment-bound phosphorus comprises the majority of the total phosphorus, and its different forms can be analyzed to understand how much phosphorus is biologically available. Phosphorus is held in the sediments by three basic means, iron bound phosphorus (Fe-P), aluminum bound phosphorus (Al-P), and organic bound phosphorus. The sediment profiles for these three forms of sediment-bound phosphorus are shown in Figures 3, 4, and 5. Only Al-P is biologically inactivated, meaning it is not available to aquatic biota under normal conditions within the sediments of Western Washington lakes. Under certain conditions, both Fe-P and organic bound phosphorus (at a slower rate) can become unbound resulting in the release and biological availability of phosphorus for algal growth. This release and instability is shown in the variable Fe-P sediment profile in Figure 3. There is less variation in Al-P and organic bound phosphorus profiles (Figures 4 and 5). The deeper sediments in all three profiles (representing longer term conditions) reflect greater stability.

Mobile Phosphorus

Mobile phosphorus, the sum of Fe-P and loosely sorbed phosphorus, is another fraction of the total phosphorus that is critical to understanding internal phosphorus loading of lakes. Under oxidative conditions (characterized by the presence of dissolved oxygen), iron exists in a form (trivalent) that chemically binds to phosphorus. However, if reducing conditions develop (in the absence of dissolved oxygen), iron's chemical form is reduced (divalent) and releases the bound phosphorus. This results in an upward migration of phosphorus through the sediments to the overlying water, causing internal loading of phosphorus.

Mobile phosphorus concentrations in Lake Stevens are high, particularly in the first 4 cm of sediment. Mobile phosphorus was highest in the sediment cores collected at the south end and at the deepest point of the lake (Figure 6). The sediment core collected at station NE 1 had the lowest mobile phosphorus concentrations, which remained nearly constant with depth. The average in the top 4 cm of sediment at the deep point of the lake was 452 mg/kg. This is slightly lower than the average mobile phosphorus concentrations in the top 4 cm of the Green Lake deep water sediment core, 560 mg/kg, but higher than the mobile phosphorus concentrations observed at other lakes. The elevated mobile phosphorus concentrations in the sediments of Lake Stevens indicate a high potential for phosphorus release and internal loading.

Iron and Phosphorus

The relative concentrations of iron and phosphorus determine the ability of a lake to successfully bind external phosphorus. In the Lake Stevens sediments, the measured average iron to phosphorus ratios (the concentration of Fe compared to the concentration of P) are about 11:1 (Figures 1 and 8). This ratio is well below the 15:1 ratio associated with phosphorus control by iron when enough iron is available to bind the phosphorus. The 15:1 ratio is well established from research in lakes around the world (Cooke, et al, 2005). Below this Fe:P ratio, iron is not the primary control over phosphorus internal loading potential.

Recent water quality data (Snohomish County, unpublished data, 2008-2009) also show a lack of available iron in the water column necessary to precipitate phosphorus out of the water, based on the 15:1 ratio of iron to phosphorus in the sediments. Because of the high TP concentrations in the surface sediments and the lack of sufficient iron in the sediments, some phosphorus is probably being released from the sediments into the water column. This conclusion is supported by water quality monitoring data that show that summer average TP concentrations in the hypolimnion of Lake Stevens have been steadily increasing in recent years (Figure 9). The excess phosphorus exceeds the capacity of iron in the water column based on the low sediment to phosphorus ratio to bind effectively with phosphorus and precipitate out into the sediments as Fe-P.

The 1981 sediment analysis also found that the Fe:P ratios in the surface sediments (0-4 cm) averaged only 4.6, less than half the current ratio of 11. This corresponds with the greater amount of internal phosphorus loading that was occurring at that time. The higher ratio in 2009 suggests that phosphorus loading from the watershed to the lake, although still too high, has probably decreased at a faster rate than iron loading. Also, the 1981 analysis found that deeper sediments, corresponding to the period from 1960 back to 1863, had much lower and rather constant TP concentrations of 1,000-2,000 mg/kg.

Aluminum and Phosphorus

The major importance of aluminum to phosphorus dynamics in a lake is that under the typical pH ranges (6.0 to 7.8) found in the sediments of the lowland lakes in the Puget Sound area, aluminum binds chemically with phosphorus. This renders phosphorus inactive relative to its bioavailability, regardless of the dissolved oxygen concentrations (Cooke, et al., 2005. and Osgood, et al., 2004, 2005, 2006, 2007, 2009). Figure 4 presents the aluminum bound phosphorus (Al-P) data from the sediment cores. Examining these data together with the data in Figure 1, it is clear that aluminum-phosphorus is a very important portion of the total phosphorus in the sediments. This is especially true for the shallow surface sediments. The relatively high Al-P in the surface sediments is most-likely related to watershed inputs of both phosphorus and aluminum (i.e. from soil erosion). The ratios of aluminum to phosphorus in the Lake Stevens sediments range between about 5:1 to 10:1, depending on the depth. Overall, the supply of aluminum needed to truly control phosphorus internal loading from the sediments is less than the ideal ratio of 11:1 (Cooke, et al., 2005). Comparing the Al-P levels in Lake Stevens' sediments to the data from other lakes, all of which are aluminum deficient, leads to the conclusion that Lake Stevens does not have aluminum concentrations sufficient to provide long-term control over internal phosphorus loading from the sediments.

ANALYSIS

The high TP concentrations in the surface sediments (the top 4 cm) at Lake Stevens are an indicator of excessive external loading of phosphorus from the lake watershed. The increasing trend toward higher TP concentrations in the lake hypolimnion is an indicator that phosphorus is being released from the sediments. These indicators are warning signs of potential future problems in Lake Stevens.

It appears that the external loading is exceeding and overloading the capacity of the aeration system to control the release of phosphorus from the buildup of organic bound phosphorus in the surface sediments and the release of iron-phosphorus from the sediments. This is because insufficient iron is available to bind with phosphorus and because of the high levels of phosphorus being delivered to the sediments. Phosphorus then becomes available to migrate into the water column, especially if iron is not in an oxidized form to bind with the released phosphorus. Also, organic material contains phosphorus within its molecular structure and can adsorb phosphorus onto its surface. As organic materials are metabolically broken down through microbial decay (mineralization), phosphorus is released from both the adsorbed phosphorus on organic particulate surfaces as this surface area is reduced and by the chemical release of phosphorus as organic carbon is converted to carbon dioxide.

The phosphorus release is occurring even under the aerobic conditions provided by operation of the aeration system. However, it is likely that a much greater release of phosphorus from the sediments would occur if the aerators were turned off or malfunctioned and anaerobic (reducing) conditions were to occur. In addition, the operation of the aeration system provides an aerobic habitat that promotes a fast microbial metabolism that breaks down organic phosphorus into a more stable (refractory) organic compounds that retain phosphorus longer in the organic chemical form than under anaerobic metabolism, thus allowing the sediments to trap and hold more phosphorus (serve as a phosphorus sink) better than if the hypolimnion were anaerobic.

In summary, the phosphorus concentrations in the sediments of Lake Stevens are high and relatively unstable, indicating excess loading from the watershed and suggesting that phosphorus release from the sediments is occurring. Without the operation of the aeration system, the phosphorus concentrations in the lake would likely be even higher than measured in recent years. However, because there has been an increasing trend in the hypolimnetic build-up of phosphorus over the last few years, and because iron levels are lower than needed to fully bind the phosphorus, the conclusion is that aeration alone may not be enough in the future to maintain the water quality of the lake. Continuing inputs of phosphorus from the surrounding watershed coupled with internal release of phosphorus from the sediments are a threat to the health of Lake Stevens.

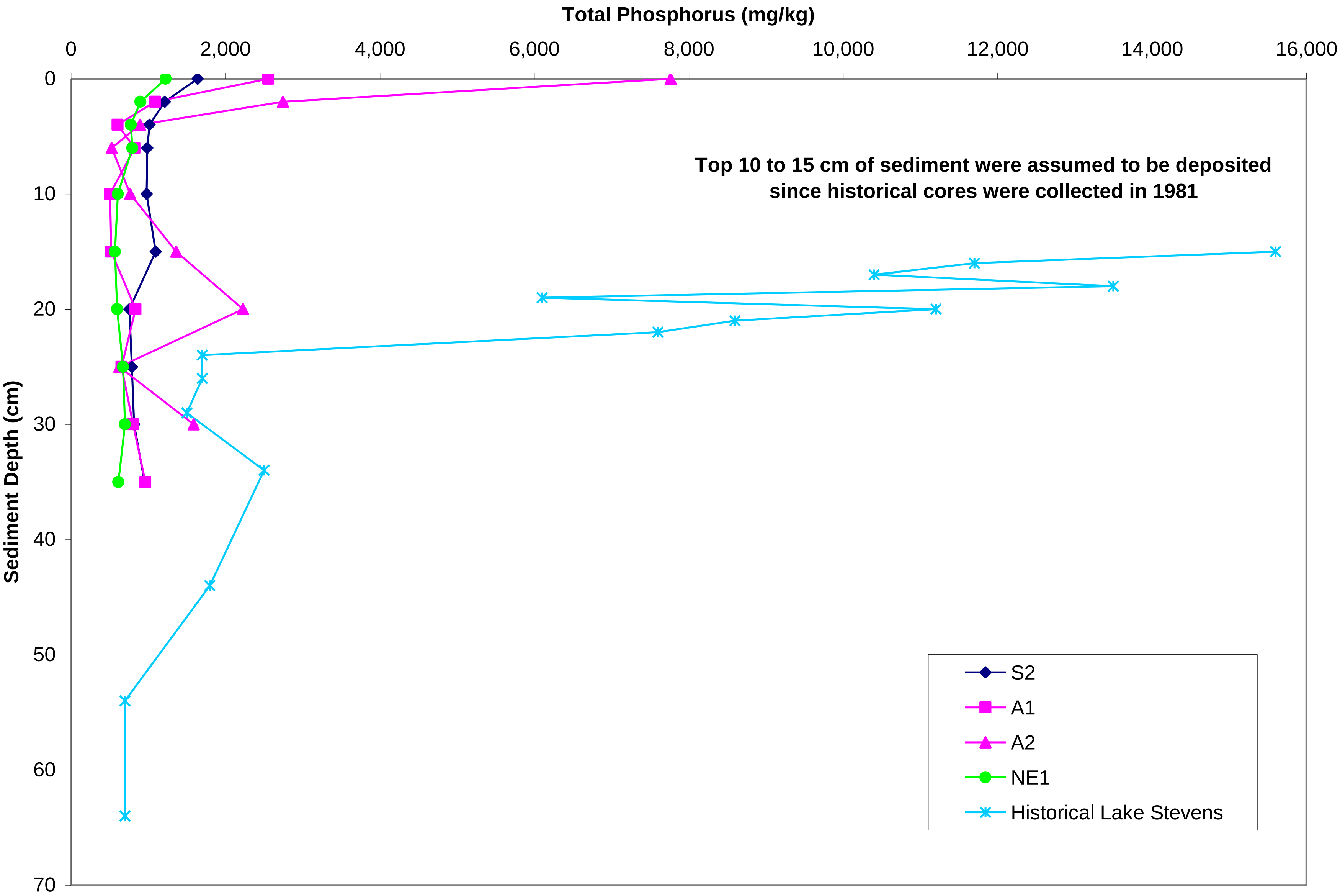

Figure 1. Sediment TP Profiles in Lake Stevens (2009, 1981).

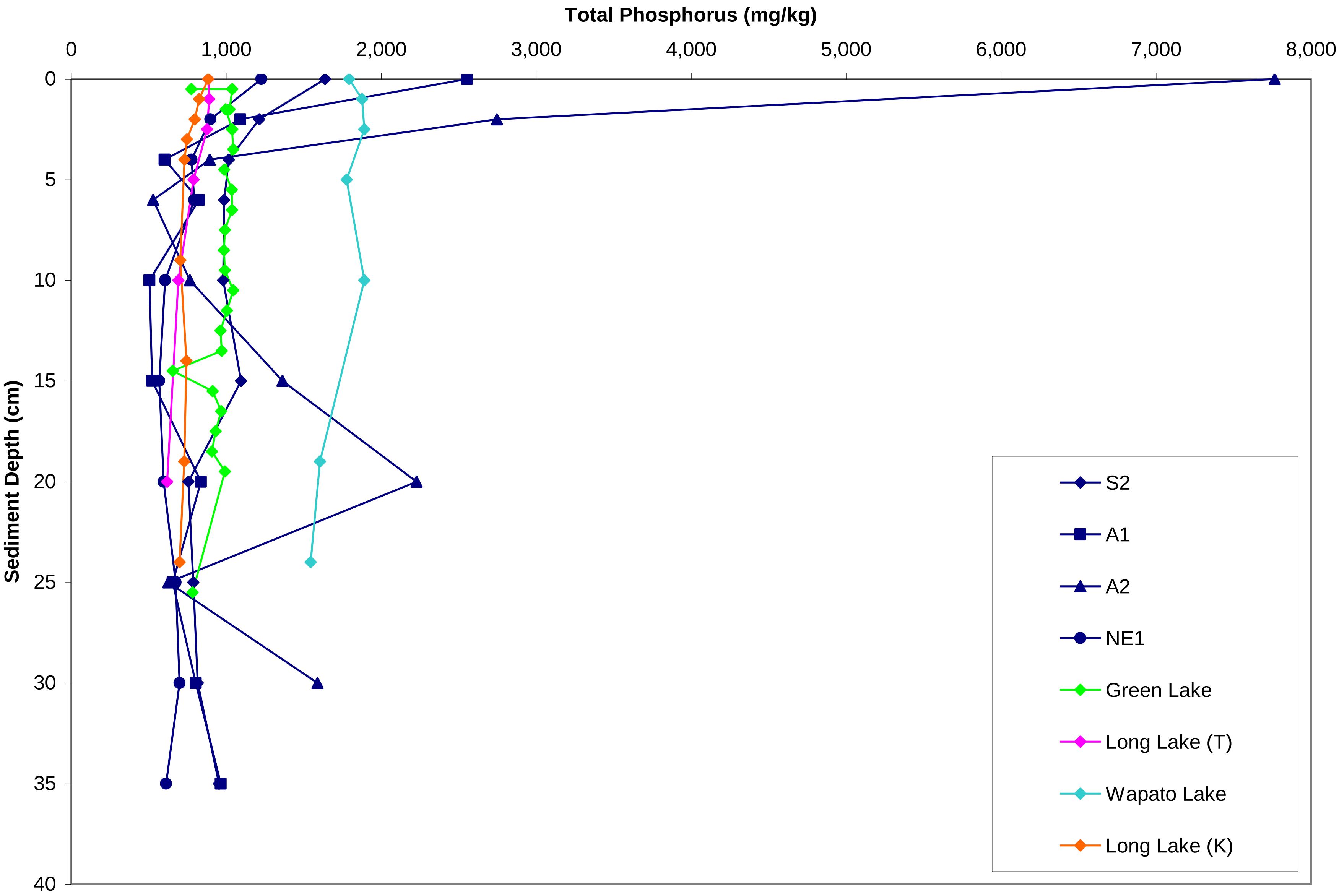

Figure 2. Sediment TP profiles in Lake Stevens (2009) compared to Green Lake, Long Lake-Thurston County, Wapato Lake, and Long Lake-Kitsap County.

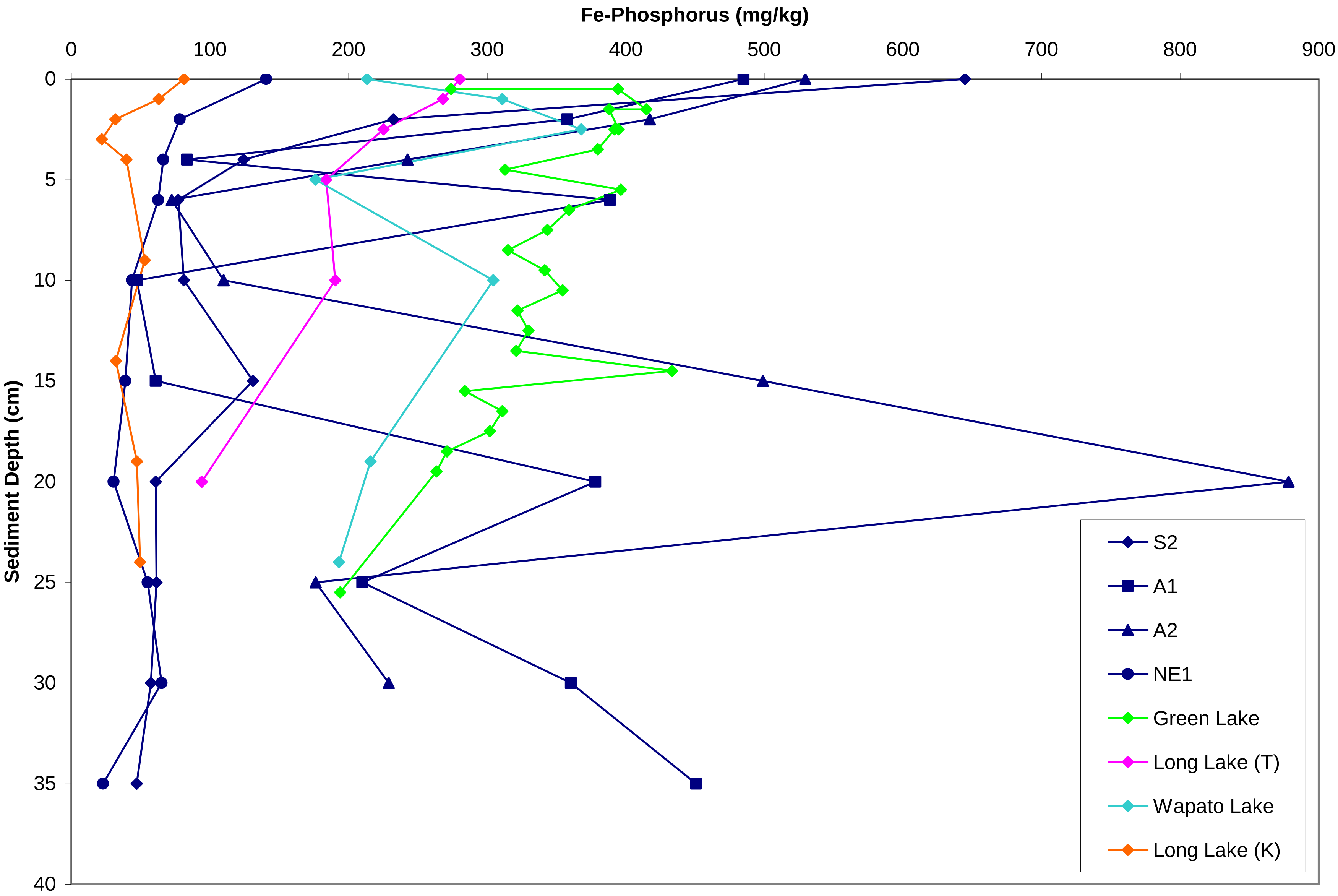

Figure 3. Sediment Fe-P profiles in Lake Stevens (2009) compared to Green Lake, Long Lake-Thurston County, Wapato Lake, and Long Lake-Kitsap County.

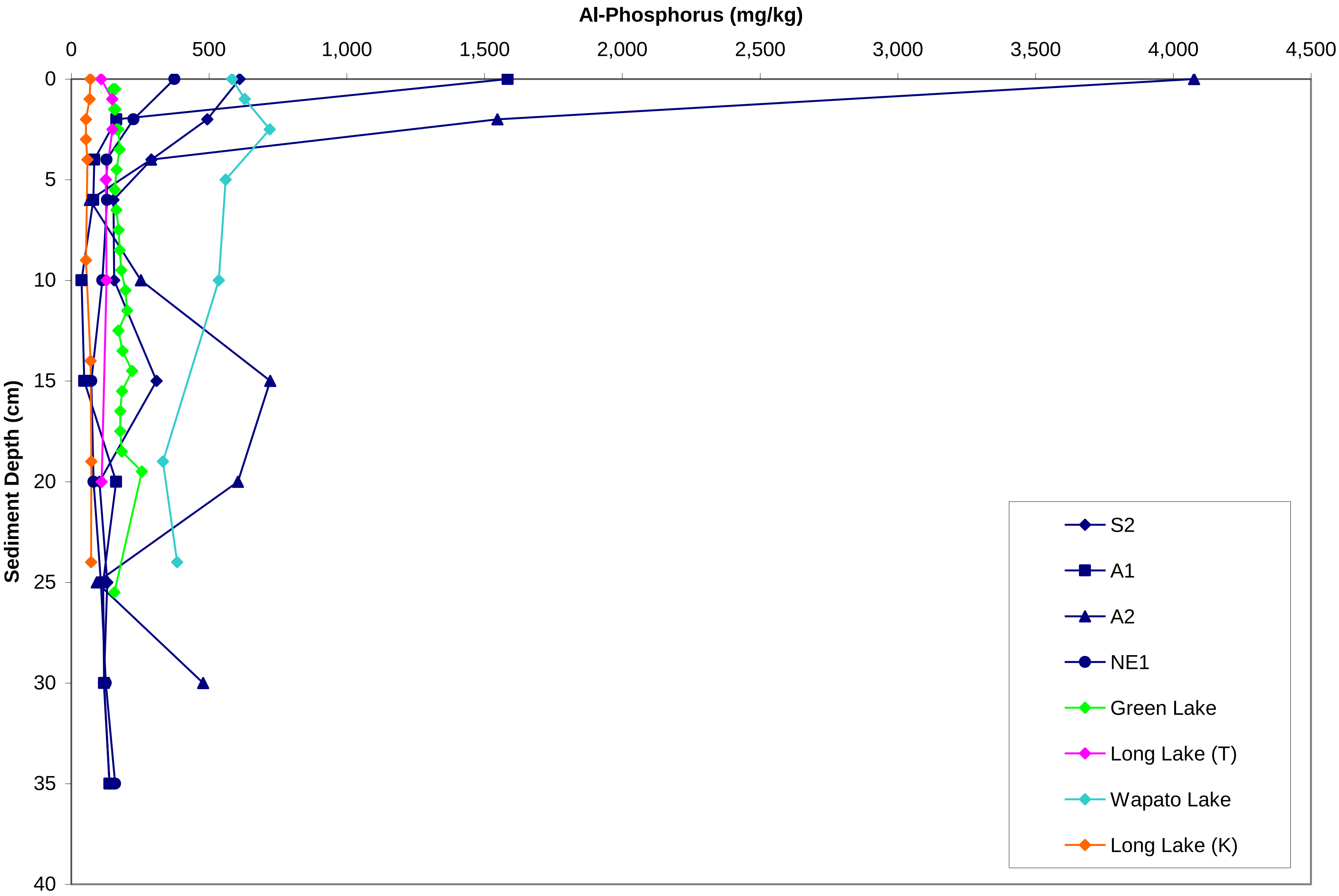

Figure 4. Sediment Al-P profiles in Lake Stevens (2009) compared to Green Lake, Long Lake-Thurston County, Wapato Lake, and Long Lake-Kitsap County.

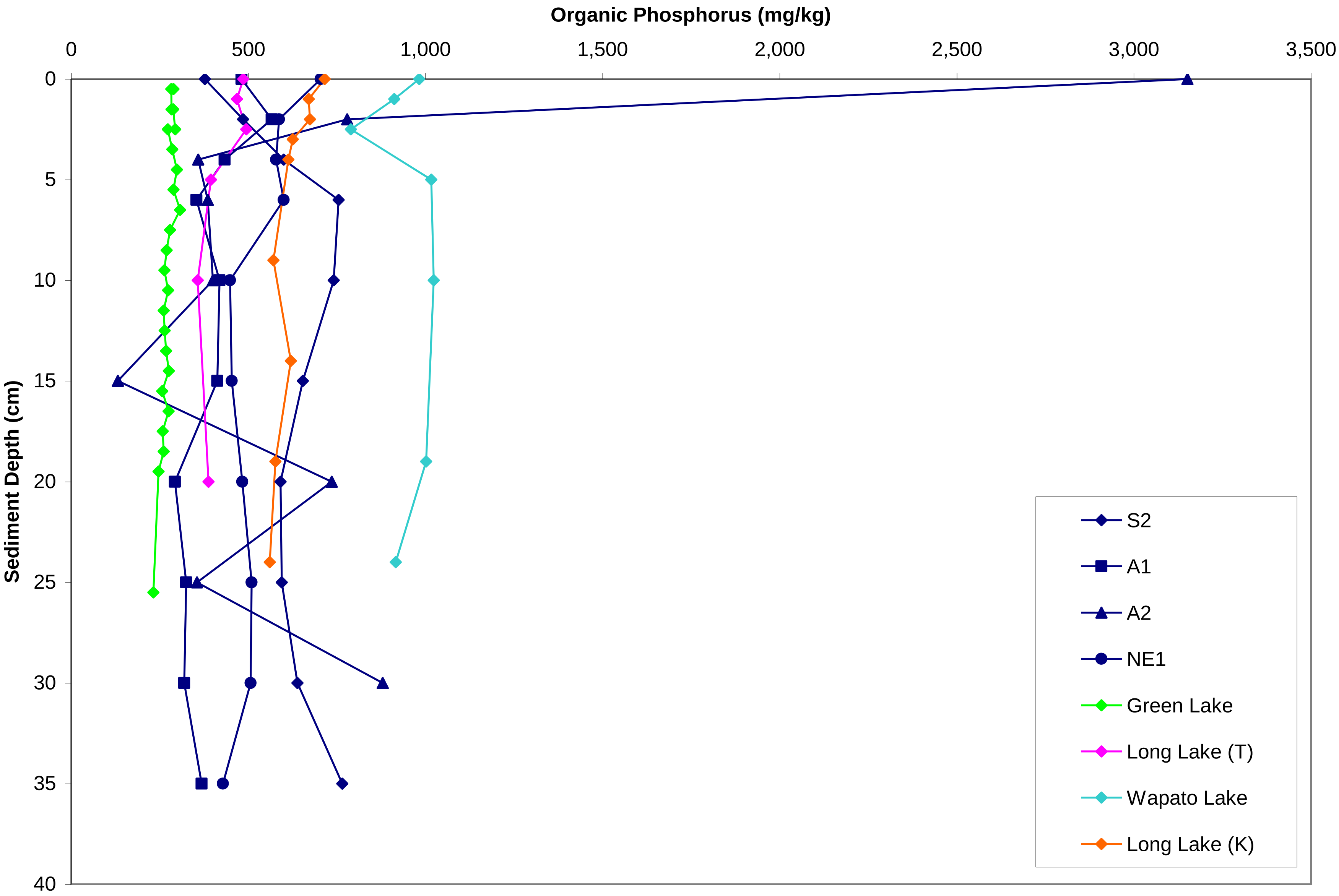

Figure 5. Sediment Organic-P profiles in Lake Stevens (2009) compared to Green Lake, Long Lake-Thurston County, Wapato Lake, and Long Lake-Kitsap County.

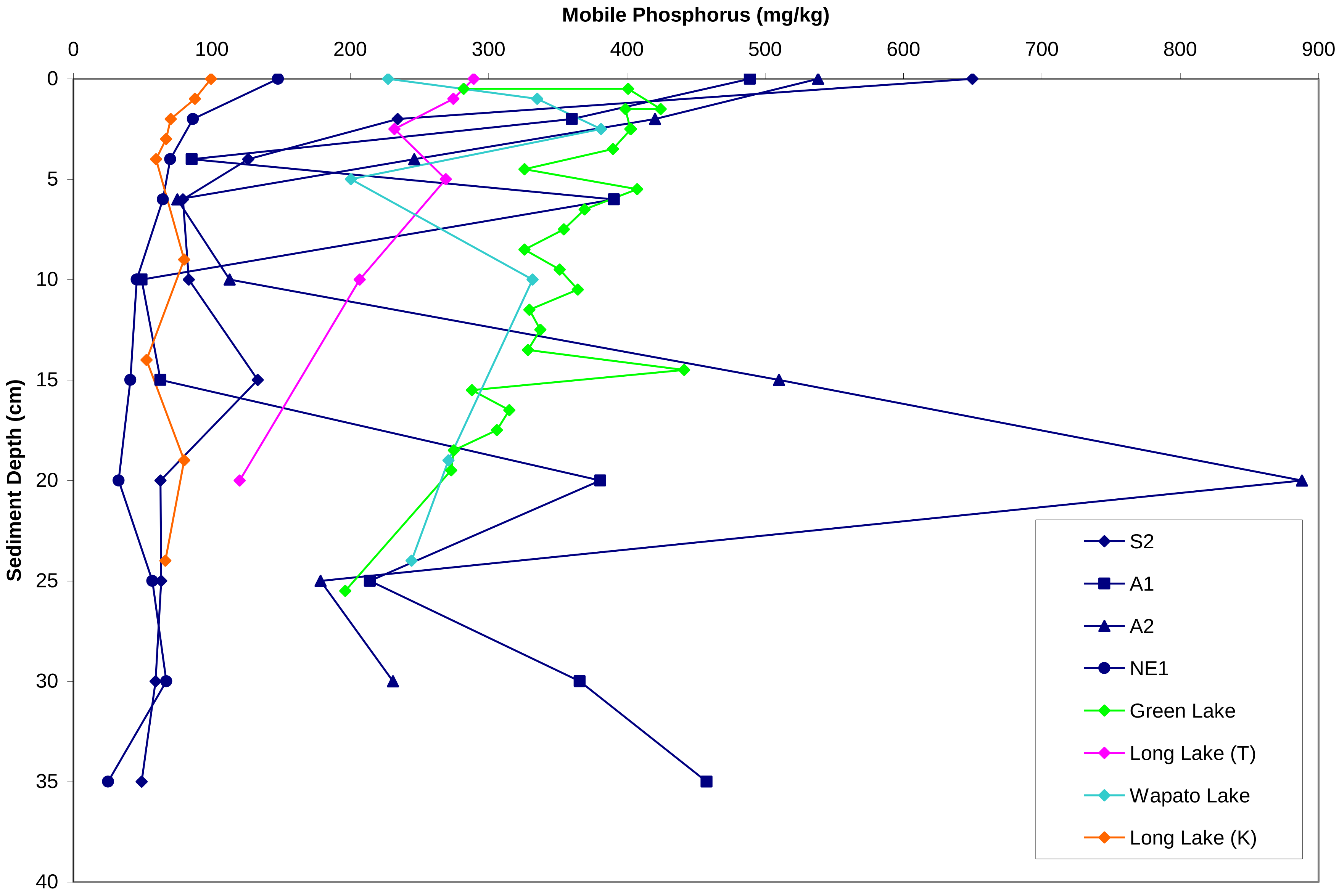

Figure 6. Sediment Mobile-P (Fe-P plus Loosely Sorbed P) profiles in Lake Stevens (2009) compared to Green Lake, Long Lake-Thurston County, Wapato Lake, and Long Lake-Kitsap County.

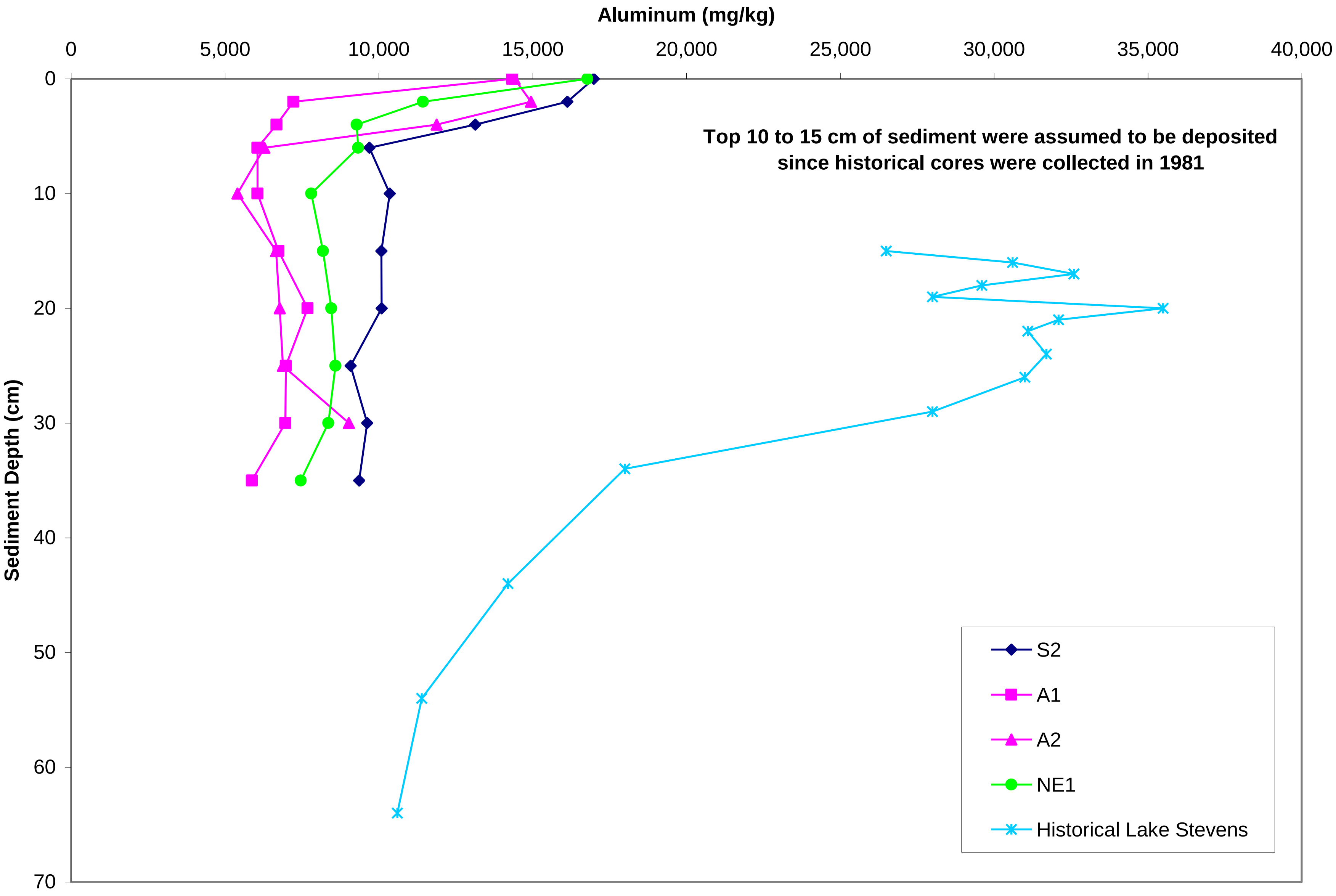

Figure 7. Sediment Aluminum Profiles in Lake Stevens (2009, 1981).

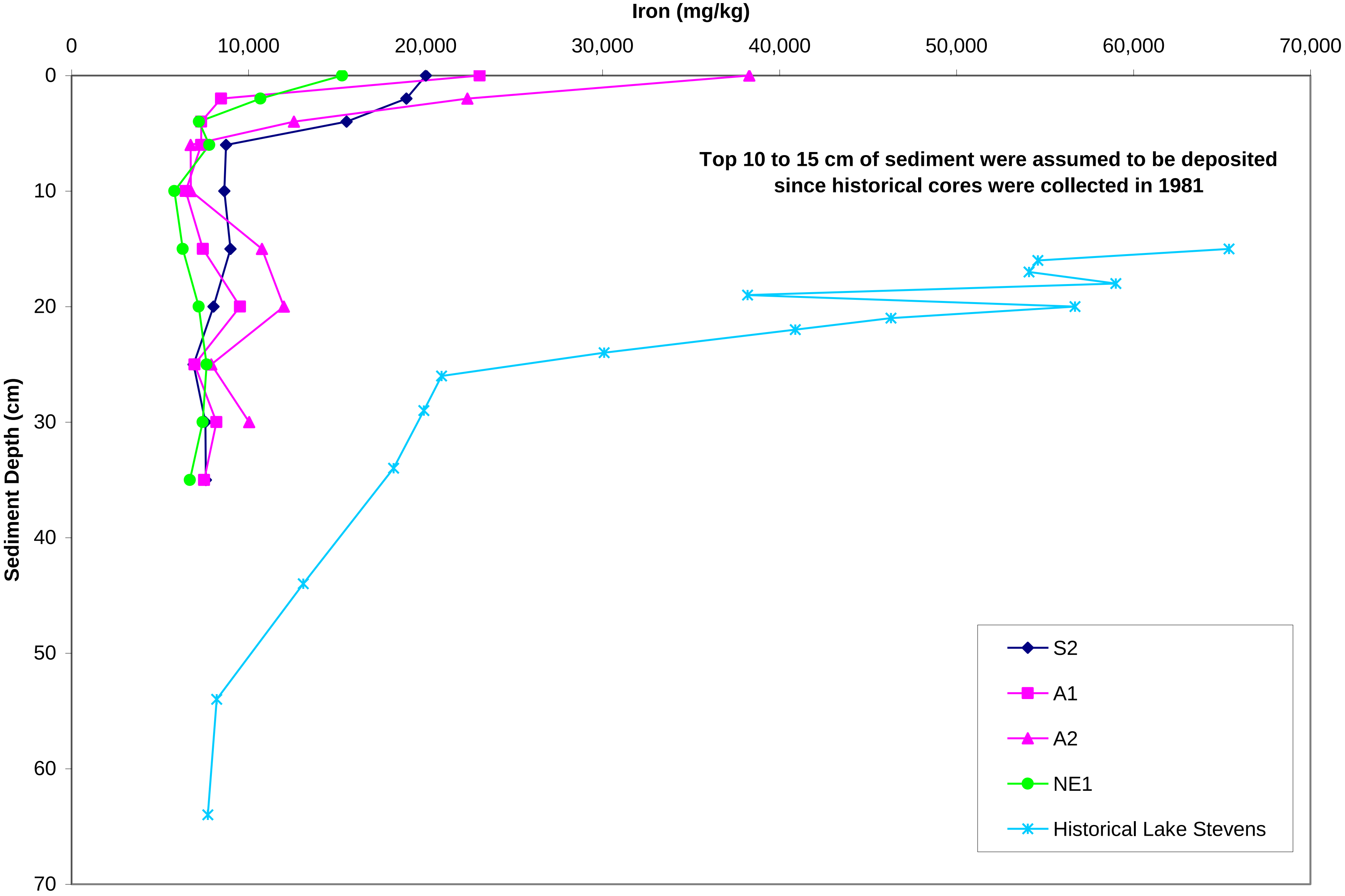

Figure 8. Sediment Iron Profiles in Lake Stevens (2009, 1981).

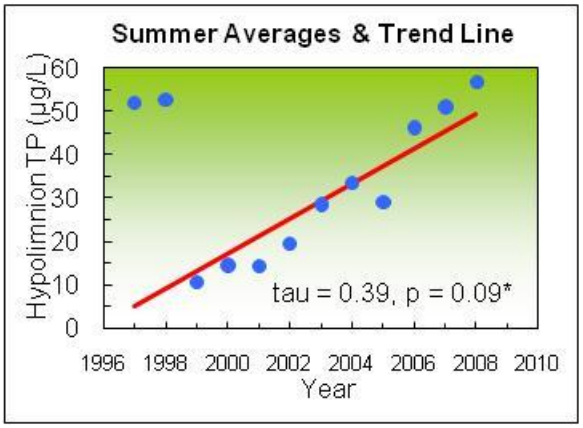

Figure 9. Hypolimnetic Total Phosphorus (40 meters) in Lake Stevens 1997 – 2008.

VALUE OF THE HYPOLIMNETIC AERATION SYSTEM

Although the aeration system alone may not be able to maintain and improve the water quality of Lake Stevens, the system does provide positive environmental benefits to Lake Stevens. First, the depth of available high-concentration phosphorus in the sediments prior to aeration has been reduced to a narrower depth range so that migration of "deep phosphorus" to the surface water is severely limited. Second, the concentration of phosphorus in the water column is less than before aeration, and severe algal blooms are much less frequent. Third, the aerobic aquatic habitat in the lake has been expanded by 200% compared to conditions before aeration. It can be anticipated that continued operation of the aeration system will, without any other in-lake restoration actions, continue to provide 5 to 10 years of additional benefits. However, beyond that 10-year horizon, in-lake restoration actions in addition to the current aeration system may be needed to meet the goals for water quality and beneficial uses.

TREATMENT ALTERNATIVES

Two treatment alternatives, iron addition and aluminum addition (using aluminum sulfate or alum), were evaluated for the control of sediment phosphorus in Lake Stevens. The evaluation was based on the presumption that external loading of phosphorus will most likely continue at current or greater levels for the foreseeable future.

Iron Addition

Iron addition has been used in the wastewater industry for years to remove phosphorus, but its use to inactivate and control phosphorus in lakes is much less common than the use of aluminum. Specifically, iron treatments are more expensive than alum treatments, require additional safety precautions, and depend upon an oxidative environment to be effective. There have been some examples of iron addition to control both water column and sediment phosphorus, mostly in Europe and British Columbia. Iron injection at Lake

Stevens would occur at the deepest point in the lake, near the aerator, in the form of ferric chloride. The iron dose needed to control phosphorus in the top 20 cm of sediment is 43 mg Fe/L. This dose would supplement existing iron concentrations and provide a whole lake concentration that would result in an iron to phosphorus ratio of 15:1.

There are several concerns with using iron addition in Lake Stevens to control phosphorus. One concern is that iron injection will only treat the deeper zone of the lake (because iron may rapidly precipitate out of the water column by combining with competing compounds other than phosphorus and the relative low ratio of iron-phosphorus in the sediments is not high enough to overcome this competition, leaving the south and north ends of the lake untreated. Although sediment phosphorus concentrations were lower in these zones of the lake, there is still the potential for significant release of phosphorus from the sediments if these areas are left untreated. The second major concern is that aerobic conditions are necessary to prevent the Fe-P in the sediments from solubilizing and releasing phosphorus into the water column. In other words, the aeration system would have to continue operating to provide aerobic conditions in the hypolimnion. If the aerator were to malfunction or be turned off for any reason, there would be a risk of anoxic conditions developing that would lead to phosphorus release from the sediments. Handling requirements of ferric chloride, as well as a possible increase in lake salinity, are also concerns that would need to be addressed with any iron injection treatment in Lake Stevens.

Because of the concerns and uncertainties associated with iron addition and the fact that transportation and application costs would be more expensive than aluminum addition, iron addition is not recommended as the preferred method for controlling sediment phosphorus in Lake Stevens.

Aluminum Addition

The addition of aluminum via an alum treatment has frequently been used to control phosphorus in lakes and has been one of the most successful lake management techniques world-wide. Alum treatments work by precipitating phosphorus from the water column and inactivating phosphorus in the sediments. Phosphorus precipitation focuses on removal of phosphorus from the water column at the time of application. Phosphorus inactivation focuses on long-term control of sediment phosphorus release as well as precipitation from the water column.

For Lake Stevens, several alum treatment options were considered for control of phosphorus, both in the water column and in the sediments. Table 1 summarizes the aluminum dose for each treatment option, the amount of chemical needed for that dose, and an estimate of applied chemical costs plus permitting, required monitoring, and planning/design costs.

The first alum treatment option considered for Lake Stevens is a whole-lake alum treatment to inactivate phosphorus in the sediments as well as precipitate phosphorus from the water column. This treatment option would inactivate phosphorus in the sediments up to 36 cm in depth, effectively immobilizing all mobile-P in the sediment and controlling recent external loading of phosphorus to the lake. The aluminum dose determined for this treatment option was calculated based on the average mobile-P concentration in sediment cores collected near the aerator, the deepest point in the lake. The aluminum dose to inactivate mobile-P was calculated to be 9.9 mg Al/L. An additional 0.5 mg Al/L would be needed to precipitate and remove phosphorus from the water column at the time of treatment.

The aluminum dose for the phosphorus precipitation was determined based on the long-term TP concentrations in the epilimnion (13 µg/L) and in the hypolimnion (32 µg/L) of Lake Stevens. Assuming that the hypolimnion is approximately 50% of the lake volume, the whole-lake volume-weighted average TP concentration would be 22.5 µg/L. This concentration was used along with the ideal ratio of aluminum to phosphorus of 11:1 to determine a precipitation dose of 0.5 mg Al/L. Because this treatment option requires the maximum amount of aluminum addition, a buffer (sodium aluminate) would also be needed in conjunction with alum to minimize stress to the lake system.

A whole-lake alum treatment with this combined aluminum dose of 10.4 mg Al/L would provide a high level of control of the phosphorus in the sediments for 5 years, with somewhat less control over the next 5 to 10 years. For planning purposes, effectiveness is assumed to be approximately 10 to 15 years. Longer effectiveness would be achieved if external loading of phosphorus to the lake from the watershed could be significantly reduced and controlled. However, without greatly improved control of watershed phosphorus loading, another alum treatment likely would be needed in the future even with an alum treatment of this magnitude. The retreatment would need to occur in approximately 10 years without continued aeration operation and in 15 to 20 years with continued operation.

The second alum treatment option is a whole-lake alum treatment to precipitate or remove phosphorus just from the water column of Lake Stevens. This option would target phosphorus specifically coming from the watershed and would not address internal loading of phosphorus from the sediments. However, once precipitated, the phosphorus from the water column would be bound to aluminum and not available for internal loading if anoxic conditions were to occur. The aluminum dose for this option, as described above, would be 0.5 mg Al/L. Because the alkalinity of the lake provides enough buffering capacity for an aluminum dose of 0.5 mg Al/L, sodium aluminate is not needed for this treatment option. For optimal effectiveness, an alum treatment specifically designed for phosphorus precipitation from the water column would need to be repeated approximately every 2 years without the aeration system and every 3 to 4 years with the continued operation of the aeration system.

The final alum treatment option considered for Lake Stevens is a whole-lake treatment to inactivate phosphorus in just the top 4 cm of sediment, as well as precipitate phosphorus from the water column. This treatment option would not only address phosphorus from watershed loading in the water column, but also control mobile-P in the surface sediments where the highest concentrations are observed. Similar to the first treatment option, the aluminum dose was calculated based on the average mobile-P concentration in sediment cores collected at the deepest point in the lake, however the concentration was determined only for the top 4 cm of sediment. The aluminum dose required to inactivate mobile-P in the surface sediments was calculated to be 1.6 mg Al/L. This dose is much smaller than the dose calculated for the first treatment option because of the depth of sediment being treated. As with the previous two alternatives, an additional 0.5 mg Al/L is needed to remove phosphorus from the water column at the time of treatment, making the total dose for this option 2.1 mg Al/L. Because the aluminum dose is small, potentially no additional buffer would be needed during treatment. However, this would have to be verified with jar tests before treatment. This alum treatment option would provide approximately 5 years of phosphorus control without the operation of the aeration system and between 8 to 10 years of phosphorus control with the continued operation of the aeration system.

With repeated alum treatments under all three options, the aeration system in Lake Stevens may no longer be needed except for increasing the time between alum treatments and for maintaining aquatic habitat. Any decisions on continuing aerator operation would have to be determined through analysis of monitoring data. Longer effectiveness for all alum treatment options would also be achieved if external loading of phosphorus from the watershed could be controlled simultaneously.

Table 1. Lake Stevens Alum Treatment Options

Whole-Lake Treatment Option	Total Aluminum Dose (mg Al/L)	Alum (gallons)	Sodium Aluminate (gallons)	Estimated Total Chemical Cost	Permitting and Monitoring Cost	Planning and Design Cost	Total Project Costs	Duration & Costs without Aeration (years & annualized cost)	Duration & Costs with Aeration (years & annualized cost***)
Option 1: Treatment of 36 cm of sediment and precipitation from water column	10.4	1,637,000	818,500	$4,911,000	$8,000 $55,000	$38,000	$5,012,000	10 years $501,000	15-20 years $434,000 to $351,000
Option 2: Treatment of water column only to precipitate phosphorus	0.5	180,000	Not needed	$180,000	$8,000 $18,000	$32,000	$238,000	2 years $119,000	3-4 years $179,000 to $160,000
Option 3: Treatment of top 4 cm of sediments and precipitation from water column	2.1	756,000	If not needed	$756,000	$8,000 $25,000	$38,000	$827,000	5 years $165,000	8-10 years $203,000 to $183,000
		370,000	189,000	$1,247,000	$8,000 $38,000	$38,000	$1,331,000	5 years $266,000	8-10 years $266,000 to $233,000

******* Annualized costs "with aeration" include the costs of alum treatment plus the costs of aeration, assuming that aeration (O/M plus normal repairs) is $100,000 per year. Major repairs to the aeration system would push costs higher.

DISCUSSION

The selection of a recommended alternative for Lake Stevens is not simple because of two major unknowns. First, there is the uncertainty of the success of long-term watershed management efforts that address the current external phosphorus loading to the lake. There have been reductions in watershed pollution since the 1980s, but without intensive outreach efforts to target the use of fertilizers, pet wastes, septic system maintenance, runoff from paved areas, and shoreline vegetation buffers, it is unlikely that further significant reductions in external loading will occur.

Second, the aeration system is sixteen years old and in need of continuing repairs. It is unknown how long the aerators can continue without major investments. Either elements of the aeration system must be repaired as they reach the end of their useful lives in the next few years, or it may not be possible to continue operating the system. Decisions about the aeration system directly affect the choice of an in-lake treatment alternative as well as the length of effectiveness that can be expected from each treatment option.

Some things that have contributed to maintaining and improving the water quality of Lake Stevens are apparent, however. Three of the major sources of nutrients to the lake in the 1970s and 1980s have been curtailed—septic systems near the lake, agricultural pollution, and a large bird population. However, this sediment analysis makes it clear that there still remains significant phosphorus loading to the lake from the watershed, as indicated by the high TP concentrations in the top 4 cm of sediments. The operation of the aeration system has mitigated the occurrence and duration of blue-green algal blooms and has contributed to a reduction in phosphorus release from the sediments. The aeration system has also enhanced habitat by re-establishing an oxygenated hypolimnion.

The question now is will continued operation of the aeration system keep up with the on-going external phosphorus loading from the watershed without additional controls on phosphorus. Unfortunately, without a much more involved analysis of all of the available data and construction of a mass balance loading model, that question cannot be answered completely. What can be concluded from this study is two-fold. If operation of the aeration system does not continue, lake conditions will deteriorate unless an alternative is employed. The current benefits to the hypolimnetic habitat will also be lost. However, hypolimnetic aeration by itself does not appear to be a sustainable management strategy for the long-term (more than 10 years) without implementation of an in-lake sediment treatment alternative.

The alternative that best addresses the problems in Lake Stevens appears to be phosphorus inactivation with alum to control the in-lake phosphorus concentration. Based on review of the data, both in-lake and sediment, and considering life-cycle costs, it would appear that the third option for alum treatment of the shallow sediments (top 4 cm) provides the greatest value (balancing cost with effectiveness) for phosphorus control if conducted every 5 to 8 years. Continued operation of the aeration system will allow this option to be effective for the longer end of this range, while ending aeration will reduce the effectiveness to the shorter time period.

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APPENDIX

Sediment Quality Data

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CASE FILE NUMBER: **SNO004-64** **PAGE** **1**
REPORT DATE: **08/26/09**
DATE SAMPLED: **07/08/09** **DATE RECEIVED:** **07/10/09**
FINAL REPORT, LABORATORY ANALYSIS OF SELECTED PARAMETERS ON SEDIMENT SAMPLES FROM TETRATECH

CASE NARRATIVE

Five sediment cores were received by the laboratory in good condition . The cores were frozen then sectioned 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, and NaOH were performed and analyzed for phosphorus. 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	VOLATILE SOLIDS (%)	TOTAL-P (mg/kg)	LOOSLY BOUND P (NH4CL) (mg/kg)	FE BOUND P (DITHIONATE) (mg/kg)	AL BOUND P (NAOH) (mg/kg)	ALUMINUM (mg/kg)	IRON (mg/kg)
S1	18.42%	81.58%	26.98%	937	<2.00	110	252	13447	14134
S2 0-2	16.42%	83.58%	31.23%	1638	4.85	645	611	16989	20020
S2 2-4	16.91%	83.09%	27.94%	1213	<2.00	232	494	16134	18912
S2 4-6	15.96%	84.04%	28.99%	1017	<2.00	124	291	13134	15542
S2 6-10	15.71%	84.29%	30.24%	987	<2.00	77.1	153	9695	8728
S2 10-15	16.47%	83.53%	28.84%	980	<2.00	81.3	155	10361	8625
S2 15-20	16.73%	83.27%	32.46%	1096	<2.00	131	309	10088	8980
S2 20-25	16.00%	84.00%	29.44%	756	<2.00	60.9	102	10092	8026
S2 25-30	16.32%	83.68%	30.18%	788	<2.00	61.4	131	9086	6893
S2 30-35	16.51%	83.49%	36.12%	816	<2.00	57.5	118	9628	7560
S2 35-40	17.58%	82.42%	27.62%	953	<2.00	47.2	139	9363	7590
A1 0-2	15.12%	84.88%	26.75%	2555	3.96	485	1585	14339	23060
A1 2-4	14.20%	85.80%	28.72%	1091	2.48	358	164	7229	8457
A1 4-6	13.93%	86.07%	28.99%	603	<2.00	83.6	83.9	6683	7323
A1 6-10	13.76%	86.24%	26.93%	824	<2.00	389	80.1	6057	7321
A1 10-15	14.36%	85.64%	25.41%	505	<2.00	47.4	37.0	6061	6455
A1 15-20	14.09%	85.91%	25.82%	522	<2.00	61.0	47.0	6744	7427
A1 20-25	16.35%	83.65%	26.12%	836	2.61	378	162	7687	9522
A1 25-30	16.48%	83.52%	23.50%	655	4.29	210	116	6981	6943
A1 30-35	14.97%	85.03%	28.57%	804	5.43	361	119	6968	8187
A1 35-38	14.11%	85.89%	28.28%	964	6.89	451	138	5879	7489
A2 0-2	14.35%	85.65%	28.87%	7765	8.69	530	4076	14419	38299
A2 2-4	16.62%	83.38%	26.40%	2746	3.14	417	1547	14950	22371
A2 4-6	16.34%	83.66%	27.64%	894	3.71	243	289	11886	12565
A2 6-10	14.20%	85.80%	28.94%	528	2.59	72.4	67.5	6285	6730
A2 10-15	14.08%	85.92%	25.23%	765	2.85	110	252	5412	6742
A2 15-20	14.23%	85.77%	26.69%	1363	10.9	499	722	6663	10764
A2 20-25	14.45%	85.55%	24.73%	2229	9.83	878	605	6780	11989
A2 25-30	14.53%	85.47%	25.99%	626	2.37	176	92.5	6887	7901
A2 30-34	14.77%	85.23%	29.54%	1589	<2.00	229	479	9032	10031
NE1 0-2	16.33%	83.67%	29.65%	1227	7.26	141	375	16783	15285
NE1 2-4	13.97%	86.03%	32.64%	899	8.05	78.3	226	11435	10681
NE1 4-6	12.54%	87.46%	31.44%	776	3.39	66.5	128	9289	7196
NE1 6-10	13.93%	86.07%	32.52%	795	<2.00	62.7	130	9330	7778
NE1 10-15	13.62%	86.38%	33.10%	606	<2.00	43.8	113	7810	5806
NE1 15-20	14.38%	85.62%	32.38%	567	<2.00	39.1	73.1	8192	6282
NE1 20-25	15.07%	84.93%	32.22%	597	<2.00	30.6	81.0	8456	7182
NE1 25-30	16.46%	83.54%	30.92%	674	<2.00	55.1	107	8591	7633
NE1 30-35	15.84%	84.16%	32.89%	699	<2.00	65.2	125	8366	7404
NE1 35-40	14.99%	85.01%	33.98%	613	<2.00	23.0	159	7468	6681

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CASE FILE NUMBER:	**SNO004-64**	**PAGE**	**2**
REPORT DATE:	**08/26/09**		
DATE SAMPLED:	**07/08/09**	**DATE RECEIVED:**	**07/10/09**

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

QA/QC DATA- SEDIMENTS

QC PARAMETER	% SOLIDS	VOLATILE SOLIDS (%)	TOTAL-P (mg/kg)	LOOSLY BOUND P (NH4CL) (mg/kg)	FE BOUND P (DITHIONATE) (mg/kg)	AL BOUND P (NAOH) (mg/kg)	ALUMINUM (mg/kg)	IRON (mg/kg)
METHOD	SM18 2540B	SM18 2540E	SM18 4500PF	SM18 4500PF	SM18 4500PF	SM18 4500PF	EPA6010	EPA6010
DATE PREPARED	07/31/09	07/31/09	08/15/09	07/30/09	07/30/09	07/30/09	08/06/09	08/06/09
DATE ANALYZED	1.00%	1.00%	5.00	2.00	2.00	2.00	2.00	2.00
DETECTION LIMIT								
DUPLICATE								
	NE1 35-40	NE1 35-40	A1 6-10	A1 6-10	A1 6-10	A1 6-10	S1	S1
SAMPLE ID	14.99%	33.98%	824	<2.00	389	80.1	13447	14134
ORIGINAL	15.06%	34.77%	792	3.89	309	83.8	13063	13439
DUPLICATE	0.47%	2.31%	4.00%	NC	22.84%	4.54%	2.90%	5.04%
RPD								
SPIKE SAMPLE								
SAMPLE ID								
ORIGINAL								
SPIKED SAMPLE								
SPIKE ADDED	NA	NA	NA	NA	NA	NA	NA	NA
% RECOVERY								
QC CHECK								
(mg/l)								
FOUND			0.900	0.033	0.033	0.033	0.959	1.06
TRUE			0.950	0.033	0.033	0.033	1.00	1.00
% RECOVERY	NA	NA	94.74%	99.62%	99.62%	99.62%	95.91%	105.59%
BLANK	NA	NA	<5.00	<2.00	<2.00	<2.00	<25.0	<25.0

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.

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CASE FILE NUMBER:	**SNO004-64**	**PAGE**	**3**
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FINAL REPORT, LABORATORY ANALYSIS OF SELECTED PARAMETERS ON SEDIMENT SAMPLES FROM TETRATECH

QA/QC DATA- SEDIMENTS

QC PARAMETER	% SOLIDS	VOLATILE SOLIDS (%)	TOTAL-P (mg/kg)	LOOSLY BOUND P (NH4CL) (mg/kg)	FE BOUND P (DITHIONATE) (mg/kg)	AL BOUND P (NAOH) (mg/kg)	ALUMINUM (mg/kg)	IRON (mg/kg)
METHOD	SM18 2540B	SM18 2540E	SM18 4500PF	SM18 4500PF	SM18 4500PF	SM18 4500PF	EPA6010	EPA6010
DATE PREPARED	07/31/09	07/31/09	08/15/09	07/30/09	07/30/09	07/30/09	08/06/09	08/06/09
DATE ANALYZED	1.00%	1.00%	5.00	2.00	2.00	2.00	2.00	2.00
DETECTION LIMIT								
DUPLICATE								
	NE1 35-40	NE1 35-40	NE1 35-40	NE1 35-40	NE1 35-40	NE1 35-40	NE1 0-2	NE1 0-2
SAMPLE ID	14.99%	33.98%	613	<2.00	23.0	159	16783	15285
ORIGINAL	15.06%	34.77%	630	<2.00	28.0	158	16243	14896
DUPLICATE	0.47%	2.31%	2.85%	NC	19.55%	0.97%	3.27%	2.58%
RPD								
SPIKE SAMPLE								
SAMPLE ID								
ORIGINAL								
SPIKED SAMPLE								
SPIKE ADDED	NA	NA	NA	NA	NA	NA	NA	NA
% RECOVERY								
QC CHECK (mg/l)								
FOUND			0.900	0.033	0.033	0.033	0.959	1.06
TRUE			0.950	0.033	0.033	0.033	1.00	1.00
% RECOVERY	NA	NA	94.74%	99.62%	99.62%	99.62%	95.91%	105.59%
BLANK	NA	NA	<5.00	<2.00	<2.00	<2.00	<25.0	<25.0

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:

Steven Lazoff
Laboratory Director