Internal Phosphorus Load Study:
Kohlman and Keller Lakes

Prepared for
Ramsey-Washington Metro Watershed District

October 2005

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Executive Summary

Internal phosphorus loading was investigated in Kohlman and Keller Lakes. Sediment cores were collected and analyzed for mobile phosphorus content; results were used to predict internal phosphorus loading from the sediment of each lake and the amount of aluminum sulfate (alum) necessary to inactivate the phosphorus, thereby inhibiting internal loading. Other internal phosphorus loading mechanisms were investigated as well. Both *Potamogeton crispus* (Curlyleaf pondweed) senescence and benthivorous rough fish activity can increase phosphorus loading within a lake during the summer months. Curlyleaf pondweed is present in both lakes, and is capable of contributing phosphorus loads as it senesces in the lakes each summer. Benthivorous rough fish (i.e. carp and bullheads) are also present in both lakes, however, the extent to which they contribute phosphorus to the water column is difficult to quantify at present.

Two management options were investigated to control internal phosphorus loading from the sediment: (1) alum treatment, and (2) sediment dredging. The costs associated with each option are listed below and are considered conservative. The dredge cost estimate is the midpoint of the range detailed in the Dredging section of the report.

	Kohlman	**Keller**
Alum Addition	$ 141,000	$ 50,000
Sediment Dredging	$1,322,000	$858,000

Due to the elevated sediment internal loading rate estimated for Kohlman Lake (an average of 9.7 $mg{\cdot}m^{-2}\ d^{-1}$), alum addition is recommended; but only after feasible reductions in external phosphorus loading to the lake are made. Elevated external loading will limit the longevity and effectiveness of internal phosphorus reduction.

Internal phosphorus load from the sediment in Keller Lake (2.2 $mg{\cdot}m^{-2}\ d^{-1}$) is lower and comparable to the internal load contribution from Curlyleaf pondweed. Due to the relatively low sediment internal phosphorus loading rate and the low water residence time of the lake, alum treatment is not recommended at this time.

Before measures to limit internal phosphorus loading from the sediment are taken in Kohlman and Keller Lakes, a macrophyte management plan should be implemented. The focus of the plan should be placed upon on the removal of Curlyleaf pondweed due to its contribution to internal phosphorus loading during the summer months. The plan should also consider the potential increase in growth of other species (especially Eurasian watermilfoil) due to increased water clarity in these lakes. The costs associated with removal of Curlyleaf pondweed are conservative and are estimated at $84,000 and $116,000 for Kohlman and Keller Lakes respectively. It is expected that four years of treatment will be needed to eliminate the species.

Internal Phosphorus Load Study: Kohlman and Keller Lakes

Table of Contents

List of Tables

List of Figures

List of Appendices

1.0 Introduction

The *Strategic Lake Management Plan for the Phalen Chain of Lakes* (draft, Barr 2004) indicates that reducing the internal load of phosphorus in Kohlman and Keller Lakes is important in order to significantly reduce the lakes' summer phosphorus concentrations. The purpose of this study was to further analyze the factors that affect the internal loading of phosphorus in the lakes in order to better define a treatment plan.

The main component of this study was to determine the amount of sediment phosphorus that contributes to internal loading in the lakes, otherwise known as mobile phosphorus. Aluminum sulfate (alum) doses were then estimated based on the amount of mobile phosphorus in the sediment and were designed to inhibit the internal release of phosphorus in the lakes. Other parts of this study included a macrophyte survey of the lakes (focusing on Curlyleaf pondweed), and evaluation of other factors that could both affect the existing internal load of phosphorus, as well as the viability of future treatments of the lakes' sediments to reduce internal phosphorus loading.

There are two parts to this report: (1) the calculation of mobile phosphorus contributing to internal phosphorus loading and effective alum dosing needed to inactive the phosphorus; and (2) the evaluation of other processes that can affect internal phosphorus loading, and the management thereof.

The treatment measures recommended in this report should be considered preliminary recommendations that represent the best options in terms of treating the internal phosphorus loads of Kohlman and Keller Lakes. These treatment measures will not be considered final until the entire suite of 2005 Phalen Chain of Lakes feasibility studies are completed later this year. At that time, the preliminary recommendations from all of the feasibility studies will be compiled and evaluated in reference to the new lake goals (established based on the lake user survey results that are currently being compiled.) In this manner, meaningful, holistic lake management decisions can be made for the Phalen Chain of Lakes based on all of the detailed studies that have been conducted this year, which include:

- Internal Phosphorus Load Study for Kohlman and Keller Lakes (described in this report)
- Phalen Chain of Lakes Untreated Tributary Drainage Areas Study
- Phalen Chain of Lakes Carp Population Study
- Phalen Chain of Lakes Wetland Enhancement Study
- Ramsey Washington Metro Watershed District Phosphorus Sources Assessment Study

2.0 Determination of Aluminum Sulfate Dose for Kohlman and Keller Lakes

Alum doses were designed to inactivate mobile phosphorus directly contributing to internal loading from the sediments of Kohlman and Keller Lakes. The dose of alum necessary to inhibit internal loading in Kohlman and Keller Lakes was based upon the amount of excess mobile phosphorus in the sediment. Designing an alum treatment based on mobile sediment phosphorus ensures the entire pool of phosphorus available for release and uptake by algae is considered.

2.1 Background-Introduction to Alum

Internal phosphorus loading is a common problem in lakes that have received elevated external inputs of phosphorus. In shallow lakes, it is often associated with mid- to late summer algal blooms that can have detrimental effects on lake aesthetics; as well as fisheries through decreased food quality of phytoplankton species. In order to reduce internal phosphorus loading, the phosphorus binding capacity of the sediment must be increased. Alum functions as a phosphorus sorption component through the addition of aluminum, enhancing the ability of lake sediment to bind phosphorus and prevent it from reaching the water column where it can become available for uptake by phytoplankton (algae). Once phosphorus is bound by aluminum, it is considered permanently bound and removed from the in-lake phosphorus cycle as it becomes incorporated with the sediment over time. Previous studies have shown that aluminum continues to bind phosphorus decades after alum treatment (Rydin et al. 2000). Medical Lake in Washington State was treated with 122 $g \cdot m^{-2}$ alum (as aluminum) in 1977 and the aluminum-bound phosphorus formed from alum treatment can be seen clearly between 6 and 8 cm sediment depth (Figure 1). The excess aluminum and aluminum-bound phosphorus resulting from treatment with alum are present at these depths due to burial with new sediment over time.

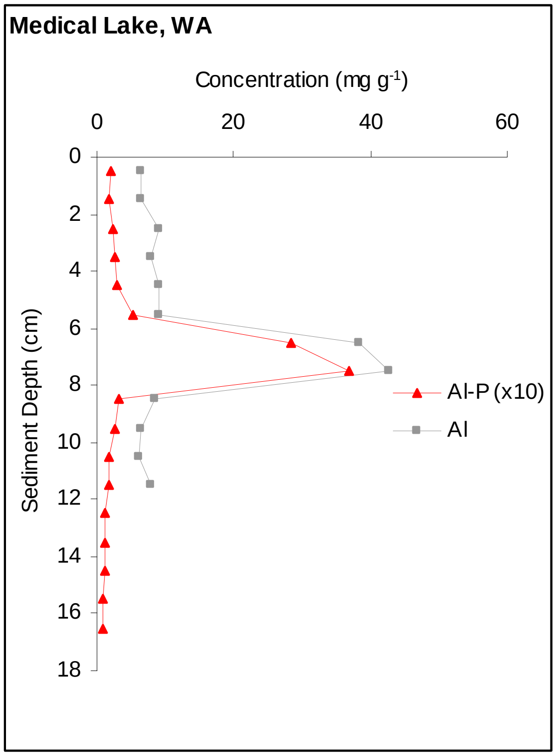


Figure 1 Aluminum and Aluminum-Bound Phosphorus in the Sediment of Medical Lake, WA

2.1.1 Sediment Chemistry

Both aluminum and iron are naturally present in sediment where they can bind phosphorus. Aluminum and iron also react similarly in sediment with the exception being iron is redox sensitive and will release phosphorus under low oxygen (anoxic) conditions. The reduction of iron can occur not only in deep, stratified lakes, but also in shallow lakes and wetlands even though the water is generally mixed and oxygenated. As sediment buildup occurs, oxygen diffusion is limited in the lower sediment layers creating the conditions for anoxic release of phosphorus from iron. Additionally, micro-zones of anaerobic activity can develop during stagnation of the water column, especially during the summer months when biological activity is high. When the water is mixed, the phosphorus is immediately available for use by algae.

2.1.2 Use of Alum

Aluminum, the third most abundant element in the earth's crust, is naturally present in the sediment of lakes where it binds with organic material and elements like phosphorus. Aluminum salts (mainly alum and sodium aluminate) are used in water and wastewater treatment processes for suspended solids removal and phosphorus reduction, and alum is a commonly used aluminum salt for lake restoration that has been used for over three decades in projects around the world (Landner 1970; Garrison and Knauer 1984; Welch and Cooke 1999; Lewandowski et al., 2003).

Longevity of alum treatment is a concern when annualizing cost for restoration alternatives. An extensive review of alum treatment longevity is available in Welch and Cooke (1999). In this study, the authors state that expected longevity of alum treatment in shallow lakes is 10 years and in deep lakes 15 years. All the lakes included in this study, however, were dosed based on internal phosphorus loading rate or alkalinity (lake water buffering capacity), which generally under-estimates alum dose needed to inactive the entire sediment pool of mobile phosphorus available for release (Huser 2005; Rydin and Welch 1999).

2.1.3 Toxicity

Aluminum can be problematic once the water pH drops below 5.5 (Stumm and Morgan 1996) and the main form becomes the soluble Al^{3+} ion. When aluminum is soluble in high concentrations, it can interfere with the respiratory systems in fish. Therefore, as long as the lake water pH remains above 6 during treatment with alum, fish mortality is not expected to occur. Monitoring of two alum treatments in 2001, conducted directly behind the application barge, showed the operator was able to maintain pH levels well above 6 and no fish mortality was observed directly after treatment or in the following days (Mike Perneil, Mpls. Park and Rec. Board, personal communication). Zero mortality of trout between pH 6 and 10 was seen in an experiment using alum treated sludge from a wastewater facility as sediment (Ramamoorthy 1988). This is expected as aluminum is in the particulate phase within this pH range.

Bottom dwelling, benthic organisms have not been affected greatly by previous lake alum treatments except that diversity increases in some cases (Conner et al. 1989; Narf 1989). The increase in diversity was attributed to more oxygen in the deep water due to lower algal production, increasing the quality of habitat. In Liberty Lake, WA, alum treatment appeared to negate toxic effects of a previous rotenone treatment, as crayfish, absent previous to alum treatment, were found 5 days after treatment (Funk et al. 1982).

Generally, studies have shown short-term, initial impacts from alum treatment on phytoplankton, zooplankton and benthic species. These effects are mainly due to physical properties of the aluminum floc once it has entered the water. However, due to the increase in water quality following treatment; abundance and diversity generally increase.

2.1.4 Post Alum Treatment In-Lake Conditions

Lakes Harriet and Calhoun were treated with alum in 2001 and provide an example of in-lake aluminum concentrations after treatment. Lake Harriet, treated in early May 2001, had elevated total aluminum concentrations in the surface water shortly after treatment up to 0.298 $mg \cdot L^{-1}$ (Figure 2). By the June sampling period, surface concentration was back near the pre-treatment condition. Lake Calhoun was treated in the autumn of 2001, but no aluminum sampling was conducted immediately after treatment. By the early spring of 2002, however, aluminum concentrations were low and comparable to pre-treatment levels, especially in the water just above the alum treated sediment near the bottom of the lake. By June of 2003, both lakes had total aluminum concentrations below pre-treatment levels throughout the water column. It should be noted that the acute and chronic limits for total aluminum currently set by the EPA are 750 and 87 $\mu g \cdot L^{-1}$. The study that determined the chronic limit was done under low pH and low hardness, both of which can substantially limit the impact of aluminum. Because of this, the EPA is currently revising the aluminum standard. Both pH and hardness are substantially higher in most MN lakes than the conditions present in the EPA study referenced above. The current standards are met, however, in both Lake Harriet and Calhoun.

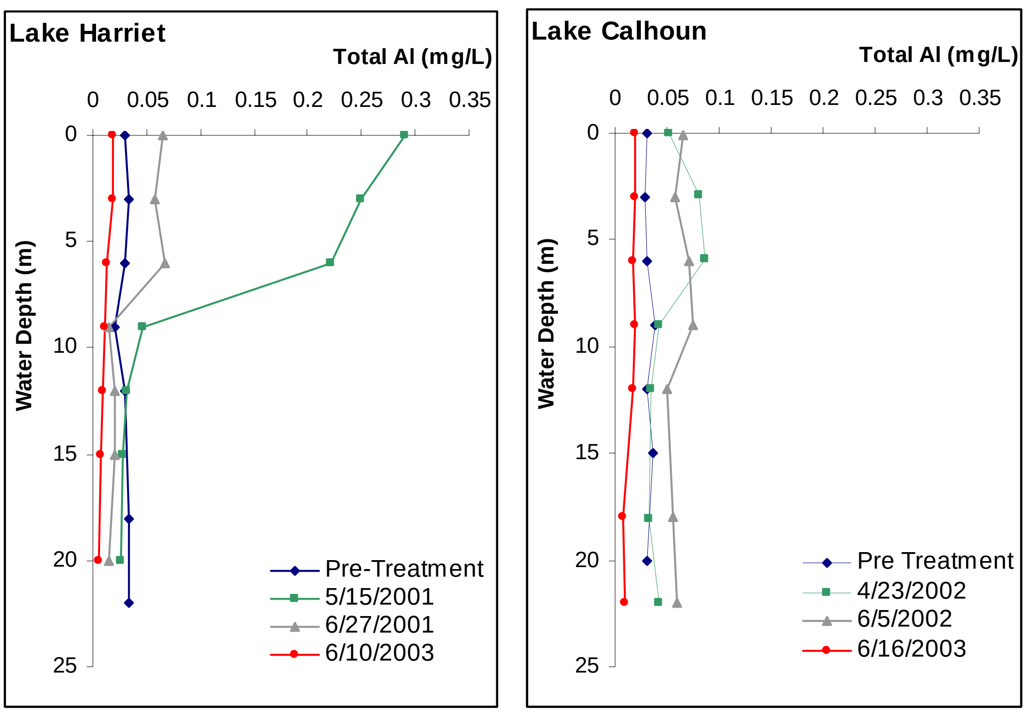


Figure 2 Aluminum Concentrations in Lakes Harriet and Calhoun Before and After Treatment With Alum

2.2 Design Methods

In the past, release rate experiments were conducted to help estimate an appropriate alum dose to control internal phosphorus loading in lakes. Recently, more effective methods have been developed to determine the amount of phosphorus available for release from the sediment. Rather than measuring phosphorus release rate of sediments indirectly in stratified lake water or directly in sediment core laboratory experiments, a detailed analysis of sediment mobile phosphorus content is conducted (Reitzel et al. 2003; Rydin and Welch 1999). In this manner, the entire pool of phosphorus available for release into the water column is determined and used to estimate an effective alum dose. This procedure allows for a less complex experimental approach that offers more detailed dosing information and has proved useful in recent alum dosing studies designed to inactivate phosphorus in other lakes (i.e. Lakes Harriet and Calhoun, Huser 2005; Green Lake, Seattle Dept. of Parks and Recreation 2003), and is described below.

Initially, mobile phosphorus concentration is calculated and used to determine the depth extent of elevated phosphorus in the sediment. Then the total mass of mobile phosphorus is calculated on a volume basis. Based on the amount of mobile phosphorus in the sediment, it is possible to estimate the expected internal loading rate of phosphorus in a lake. This is accomplished by using the linear relationship determined by Pilgrim, et al. (2005) between mobile phosphorus in the sediment and internal phosphorus loading rate to the water column for 17 Twin Cities metro area lakes (Equation 1). It is a useful tool for estimating in-lake conditions before alum treatment, and can also be used to judge if mobile phosphorus reductions will help achieve lake phosphorus management goals. However, it is recommended that alum dose be calculated based on reducing mobile phosphorus to its background concentration found deeper in the sediment, because this is the lowest level considered naturally attainable in any lake under consistent external input conditions.

Equation 1. The relationship between internal phosphorus (P) loading rate and mobile phosphorus in the sediment (Pilgrim. et al. 2005).

$$\text{Internal P release rate } (\text{mg}\bullet\text{m}^{-2}\bullet\text{d}^{-1}) = 15.1*(\text{mobile P } (\text{g}\bullet\text{m}^{-2}\bullet\text{cm}^{-1})) - 0.7$$

2.2.1 Sediment Sampling

It is important to properly characterize the mobile phosphorus content in the sediment of a lake both horizontally and vertically to avoid under- or over-dosing an alum treatment. Therefore, multiple sediment cores were collected from each lake to better define the spatial distribution of mobile phosphorus in the sediment. Using a gravity sediment coring device, sediment cores were collected from the deep spot as well as representative shallower areas in both lakes. Sediment cores were sliced into 2-cm increments down to 16 cm (10-14 cm samples were not analyzed) to determine sediment depth of excess mobile phosphorus (Table 1). An additional sample at 20-22 cm was collected and analyzed to use for the dredge cost estimate and to confirm background estimates.

Table 1 Analysis Design for Alum Treatment Experiments on Kohlman and Keller Lakes

Lake	Cores	Sediment Intervals (cm)	Alum Ratios
Kohlman	2	0-2, 24, 4-6, 6-8, 8-10, 14 16	0, 25, 50, 100, 150:1
Keller	3	0-2, 2-4, 4-6, 6-8, 8-10, 14-16	0, 25, 50, 100, 150:1

2.2.2 General Observations

Sediments from Kohlman and Keller Lakes physically appeared similar to sediments collected from other Twin Cities metro area lakes. The deep core collected from Kohlman was typical of accumulation type sediments and was flocculent and low density (high water content) in nature. The shallow cores collected from Kohlman Lake were similar to other shallow, transitional type sediment consisting of coarser material and higher overall density. The cores collected from Keller Lake were transitional in nature consisting of denser, sandy type sediment.

2.2.3 Sediment Analysis

Sediment samples from each lake were initially analyzed for mobile phosphorus content down to a depth of 22 cm (Figure 3). As Figure 3 indicates, elevated mobile phosphorus in the surficial sediments was detected in all cores and mobile phosphorus concentrations were generally higher in the sediment collected from Kohlman Lake.

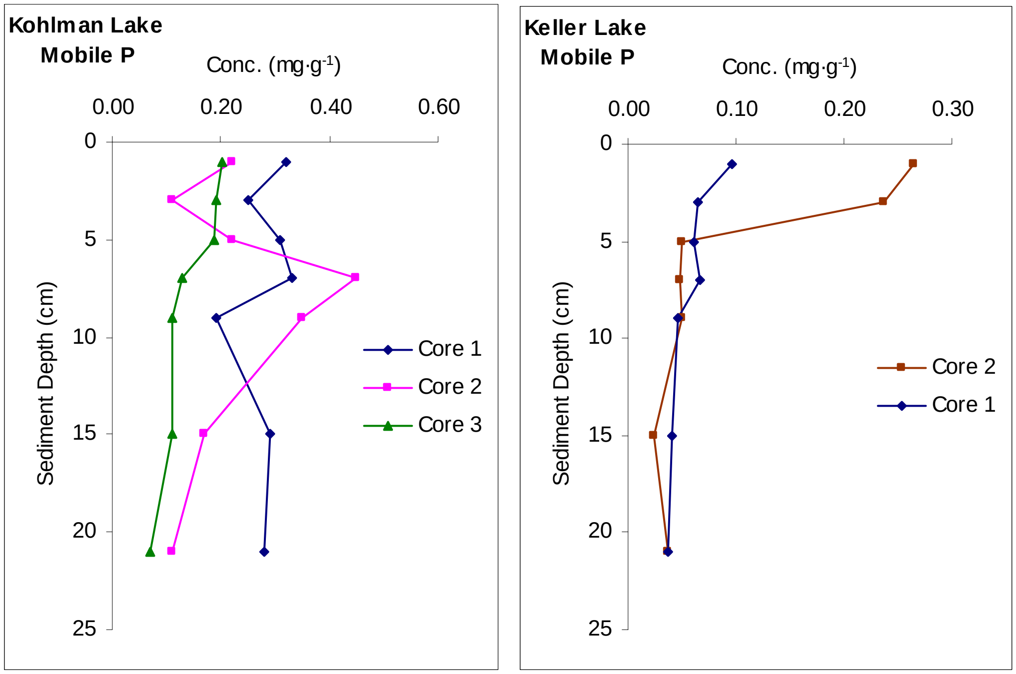


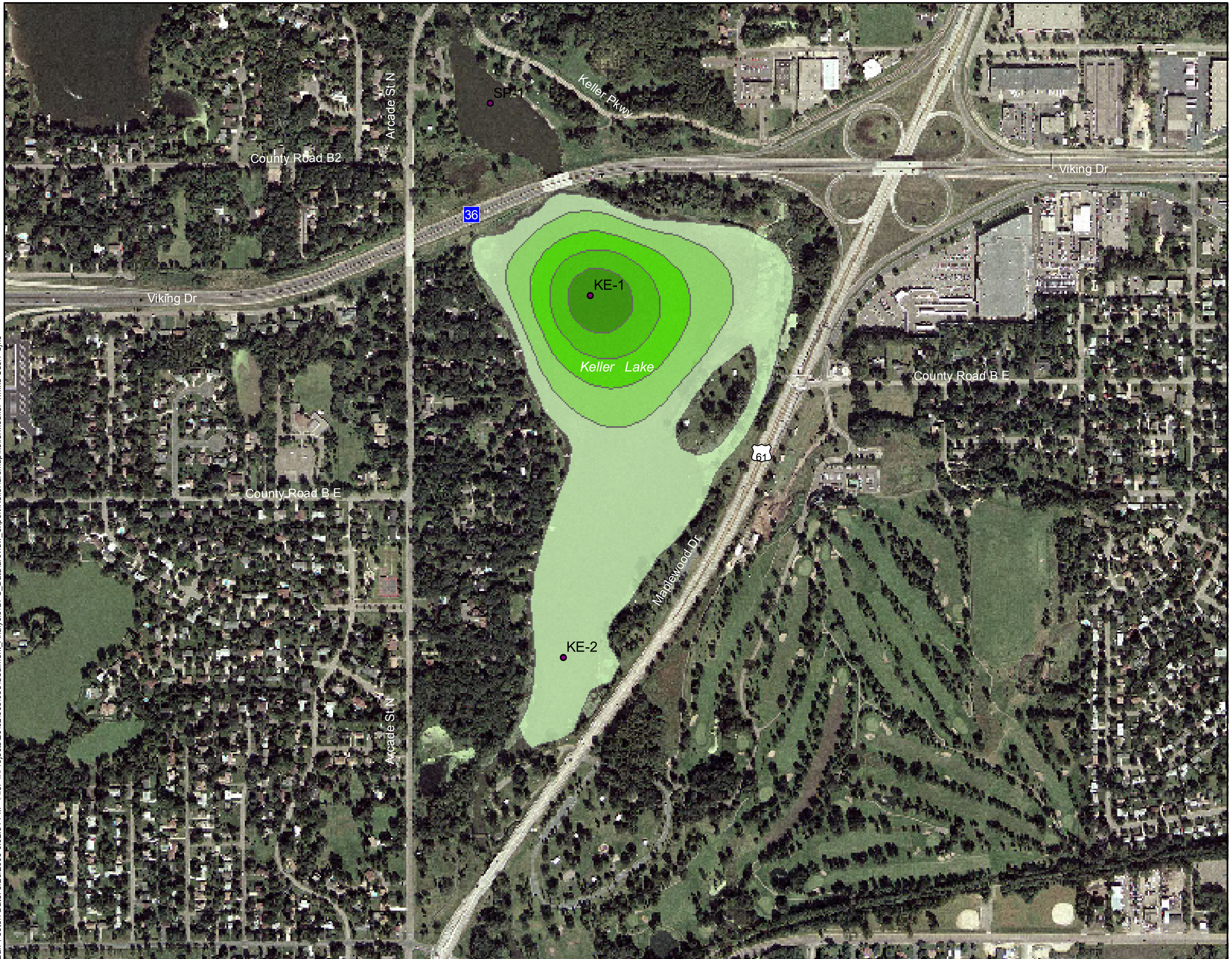
Figure 3 Mobile Phosphorus Concentrations in Sediment Collected from Kohlman and Keller Lakes

Based on the observed mobile phosphorus concentrations in the cores, alum was added to the collected sediment at four ratios of alum (as aluminum) to mobile phosphorus ranging from approximately 25:1 to 150:1 (See Table 1 for more detail). A control for each lake, with no alum added, was analyzed for each core as well. The sediments with the added alum were shaken and allowed to equilibrate for 48 hours. Changes in mobile phosphorus and aluminum-bound phosphorus were then analyzed and used to determine the alum dose necessary to reduce excess mobile phosphorus in the lake sediment.

2.3 Results, Dose Recommendations, and Cost

2.3.1 Results of Sediment Analysis

The mass of mobile phosphorus was considerably higher in Kohlman Lake when compared with Keller Lake. In Kohlman and Keller Lakes, mobile phosphorus ranged from 0.25 to 1.17 $g \bullet m^{-2} \bullet cm^{-1}$, and 0.10 to 0.28 $g \bullet m^{-2} \bullet cm^{-1}$, respectively (Table 2). Three core samples were taken from Kohlman Lake and two from Keller Lake and the results were input into the Surfer data modeling program to estimate average mobile phosphorus mass across the lake. As Figures 4A and B show, mobile phosphorus was highest in the northwest corner of Kohlman Lake and the north central portion of Keller Lake.



Mobile Phosphorus (g/m2/cm)

- 0.09-0.1
- 0.1-0.13
- 0.13-0.17
- 0.17-0.21
- 0.21-0.28

Sediment Sample Points

0 300 600 1,200
Feet

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Figure 4B

KELLER LAKE:
Mobile Phosphorus Concentrations
Based on Sediment Cores Collected
from Keller Lake

Kohlman and Keller Lakes
Internal Phosphorus Loading Study

Estimates of the internal phosphorus loading rate due to release of mobile phosphorus from the sediment ranged from 3.20 to 17.01 mg•m^{-2}•d^{-1} in Kohlman Lake and from 0.88 to 3.53 mg•m^{-2}•d^{-1} in Keller Lake. These estimates were derived from a linear relationship developed by Pilgrim, et al. (2005) that related mobile sediment phosphorus to internal release rate in 17 Minnesota lakes (Equation 1).

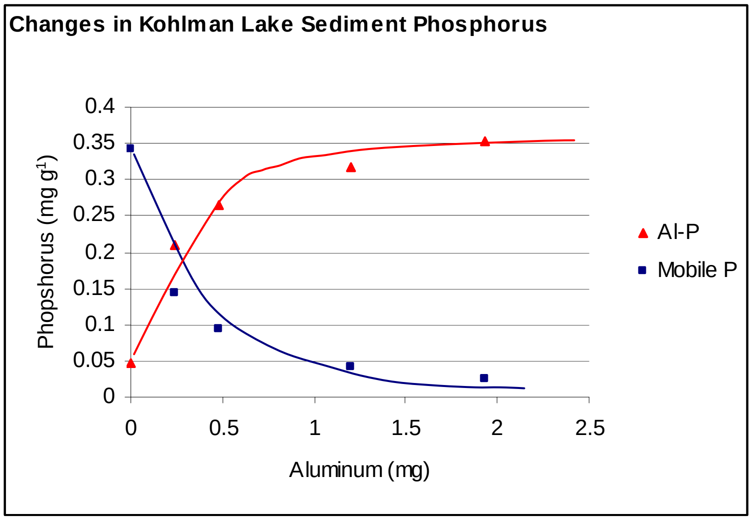
Table 2 Total Sediment Mobile Phosphorus and Corresponding Internal Phosphorus Loading Rates Estimated Using the Linear Relationship Determined by Pilgrim et al. (2005).

	Kohlman		Keller	
	Mobile P g·m^{-2}·cm^{-1}	**Internal Release mg·m^{-2}·d^{-1}**	**Mobile P g·m^{-2}·cm^{-1}**	**Internal Release mg·m^{-2}·d^{-1}**
Core 1	0.58	7.99	0.10	0.88
Core 2	1.17	17.01	0.28	3.53
Core 3	0.25	3.02		

Depth of excess mobile phosphorus extended between 6 and 8 cm into the sediment in Kohlman Lake and between 4 and 8 cm into the sediment in Keller Lake (Figure 3). This is similar to what was found in the study by Pilgrim et al. (2005) and other data collected by Huser (2005) where mobile phosphorus ranged in sediment depth from 4 to 7 cm in lakes in the Twin Cities metro area.

2.3.2 Alum Dose Calculation

Alum doses were estimated based on removing excess mobile phosphorus in the upper sediment and the depth to which it extended into the sediment, thus inactivating the phosphorus pool available for release into the water column. As larger alum doses were applied to sediment collected from the lakes, more mobile phosphorus was converted to aluminum-bound phosphorus (Figure 5).



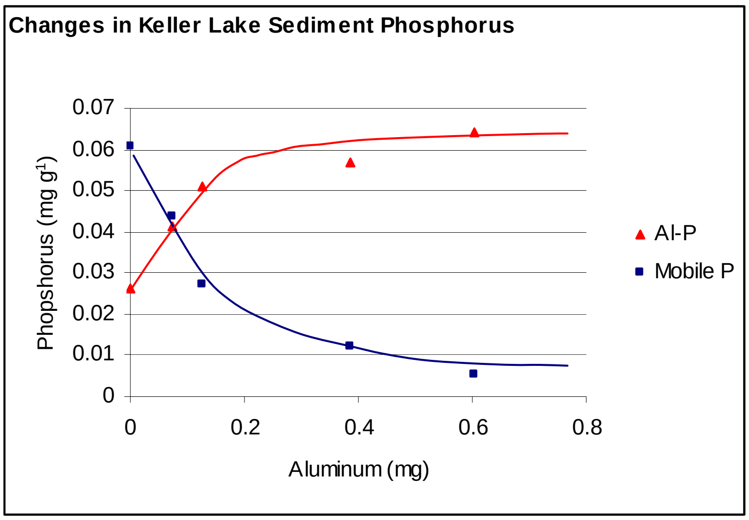


Figure 5 Changes in Mobile and Aluminum-Bound Phosphorus (Al-P) as Increasing Amounts of Alum Were Added to the Sediment from Kohlman and Keller Lakes.

Alum doses, as aluminum, were then calculated based on the resulting lab data on changes in mobile phosphorus. A whole lake alum dose was then estimated across both lakes to determine the average dose on an aerial basis (Figure 6). Converting the data contained in Figure 6 on alum dose, an applicator would be able to adjust dose "on the fly" based on position in the lake to apply the alum in a manner that is most effective at targeting mobile phosphorus.

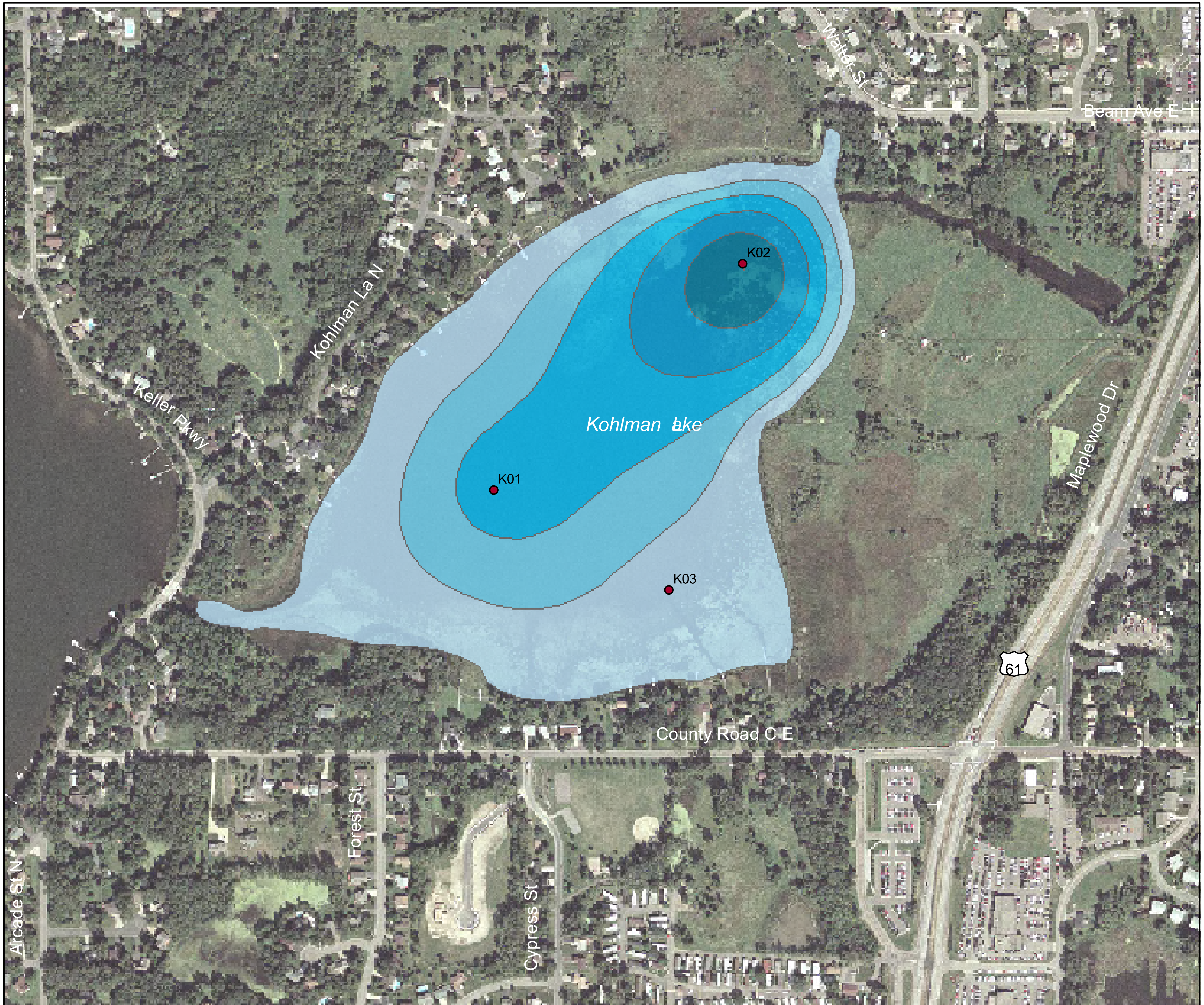
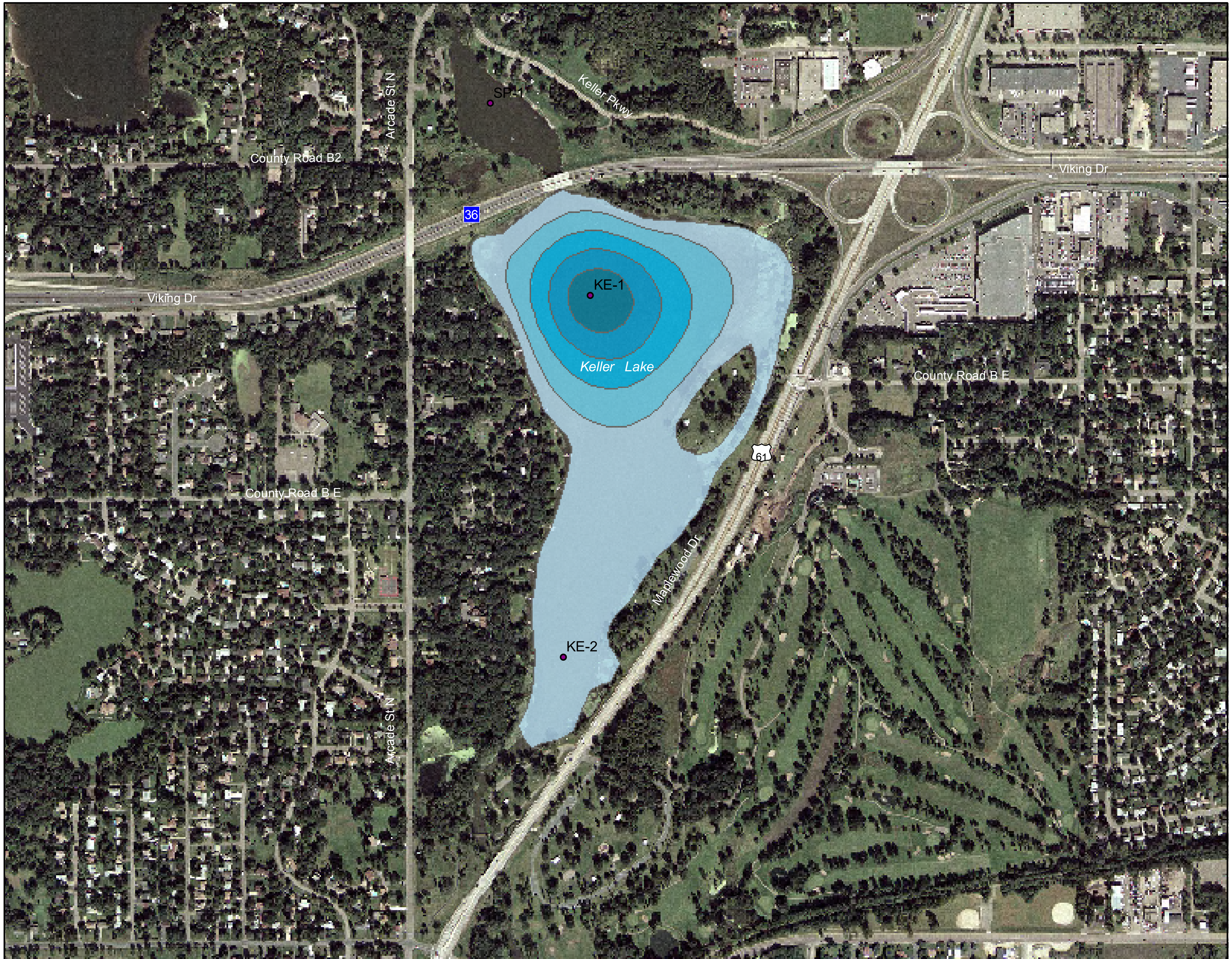


Figure 6A

KOHLMAN LAKE:
Alum Doses Needed to
Inactivate Mobile Phosphorus
in Kohlman Lake

Kohlman and Keller Lakes
Internal Phosphorus Loading Study



Alum Dose (g Al/m2)

- 14-20
- 20-30
- 30-42
- 42-57
- 57-83

Sediment Sample Points

0 300 600 1,200
Feet

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Figure 6B

KELLER LAKE:
Alum Doses Needed to
Inactivate Mobile Phosphorus
in Keller Lake

Kohlman and Keller Lakes
Internal Phosphorus Loading Study

To eliminate excess mobile phosphorus in Kohlman Lake sediment, an average, area-weighted dose of alum (as aluminum) was determined to be 78.4 g·m-^{2}. This dose will need to be applied in multiple phases because the amount of lake water available for buffering is insufficient. This will increase the cost slightly ($5,000) but will have the additional benefit of creating more contact between the added alum and newly deposited sediment. In Keller Lake, the dose was lower, because mobile phosphorus in the sediment was lower, and averaged 28.4 g·m^{-2} as aluminum (Table 3). These alum doses will inactivate mobile phosphorus in the upper sediment of Kohlman and Keller Lakes, permanently converting it to aluminum-bound phosphorus. The reduction in mobile sediment phosphorus will reduce internal loading, thereby reducing the overall phosphorus load to the lake. Data for these experiments can be found in Appendix A.

Table 3 Required Alum Doses (As Aluminum) Necessary to Inactivate Excess Mobile Phosphorus in Kohlman and Keller Lakes. Averages are Area Weighted Means.

	Kohlman		**Keller**	
	Mobile P g·m^{-2}·cm^{-1}	Alum (as Al) g·m^{-2}	Mobile P g·m^{-2}·cm^{-1}	Alum (as Al) g·m^{-2}
Core 1	0.58	95.4	0.10	14.3
Core 2	1.17	205.2	0.28	83.3
Core 3	0.33	40.9		

2.3.3 Expected Cost

The cost of alum treating Kohlman and Keller Lakes was estimated based on aerial doses calculated in this study, lake area and an estimated cost of $1.30 per gallon of alum added (including mobilization). Alum dose specifications are shown in Table 4.

- Kohlman Lake alum dose @ 78.4 g Al·m^{-2} $141,000
- Keller Lake alum dose @ 28.4 g Al·m^{-2} $ 50,000

Table 4 Alum Dose Specifications

Keller Lake	Units	P-Fractionation Dose
Area	m^2	291376.8
Area	acres	72.0
Al^{3+}	lbs/acre	258.2
Al^{3+}	**g/m^2**	**28.4**
Al^{3+}	lbs	18589.1
Alum	lbs	421972.4
Alum	Gallons	37977.5
Alum	Gallons/acre	527.5
Cost per Gallon	Dollars	1.3
Total Cost		**$50,000.0**

Kohlman Lake	Units	P-Fractionation Dose
Area	m^2	299470.6
Area	acres	74.0
Al^{3+}	lbs/acre	712.7
Al^{3+}	**g/m^2**	**78.4**
Al^{3+}	lbs	52741.8
Alum	lbs	1197239.3
Alum	Gallons	107751.5
Alum	Gallons/acre	1456.1
Cost per Gallon	Dollars	1.3
Total Cost		**$141,000.0**

3.0 Factors to Consider In Managing Internal Phosphorus Loading to Kohlman and Keller Lakes

3.1 Invertebrates

It has been hypothesized that the density, size and type of invertebrate species in lakes can undermine in-lake alum treatments through bioturbation (the disturbance of sediments due to displacement by living things.). To investigate this potential issue in the success of future alum treatments in Kohlman and Keller Lakes, the scope of this study originally included an invertebrate study of Kohlman and Keller Lakes. Specifically, invertebrate samples were to be collected with the sediment cores so that the density, size and type of the invertebrate communities in Kohlman and Keller Lakes could be characterized and discussed relative to the viability of future in-lake alum treatments.

At the time this scope was written, the invertebrate study was recommended in response to the theory presented in numerous lake water quality books that benthic invertebrates can significantly disturb an alum floc layer, undermining its effectiveness. After searching the literature for substantiation of this theory, however, it appears that there is no scientific basis for this allegation at present. The current body of academic literature was searched for studies that show a positive correlation between invertebrate activity and the release of soluble phosphorus from alum treated sediments. No such studies were found. The literature was also searched for any indication of the density of species that would indicate a threat to an alum treatment. Likewise, no such studies were found.

In fact, recent research indicates that benthic invertebrates may not, after all, pose such a threat. Research indicates that alum can pull phosphorus out of the water column, out of the sediment pore water and even off of iron-bound complexes in the sediment whether the alum floc is above or below the sediment (Sposito 1996). If benthic activity displaces alum floc, even to the point of exposing patches of sediment, it is likely that the phosphorus released from the exposed sediment would still be pulled into the alum floc nearby as the phosphorus travels into the water column. As long as the alum is dosed correctly (i.e., taking into account the stores of mobile phosphorus in the sediment), the sediment phosphorus will be removed by the alum.

A recent invertebrate bioturbation study supports this description of alum's treatment mechanism. Alan Steinman, 2004 (Director of the Annis Water Research Institute at Grand Valley State University, Michigan) tested the theory that benthic activity by invertebrates can affect the release rate of phosphorus from sediments treated with alum. Six sediment cores were collected from each of four sites in Spring Lake (Grand Haven, Michigan.) For each site's collection of cores, half of the cores' invertebrates were poisoned with formaldehyde. Cores were treated with 0, 5 or 10 mg/L aluminum to simulate an alum treatment. The release rate of phosphorus in cores with and without invertebrates was compared. Although the release of total phosphorus was higher in the cores with invertebrate activity (due to suspension of sediment), there was no difference in the release rates of soluble phosphorus in the sediment cores with and without invertebrates. Because soluble phosphorus is the form that alum can control, and the form that is readily available for algal uptake, this result is significant.

Although benthic invertebrates certainly can and do move sediment on lake bottoms, it appears that this activity does not significantly affect the viability of an alum floc layer. For this reason, the invertebrate survey of Kohlman and Keller Lakes was put on hold until research shows that an invertebrate survey would provide meaningful information that assists in decisions regarding management of a lake's internal phosphorus load.

3.2 Macrophytes

During sediment sampling in early May 2005, Barr Engineering Co. staff noticed the presence of Curlyleaf pondweed and Eurasian watermilfoil (EWM), both of which are invasive, nuisance species. Due to this observation, a basic macrophyte survey was deemed necessary to identify the extent of macrophyte growth in Kohlman and Keller Lakes during the late spring, early summer. Although macrophyte surveys have been conducted previously on both lakes, information was needed during the height of the Curlyleaf pondweed growing season (through mid-June). Curlyleaf pondweed typically dies back by July and can go undetected in mid- to late summer macrophyte surveys.

A macrophyte survey was conducted on both lakes in mid-June 2005. Barr staff visually surveyed the littoral areas for submerged vegetation of both lakes noting plant species and densities from the boat. A grappling hook was used on a number of transects to quantitatively identify species and determine plant density. Maps were then created base on both quantitative and qualitative results. Estimated densities of individual species are as follows:

- **Low**—less than 25 percent of substrate covered or 0 to 24 percent presence during hook tosses
- **Medium—**25 to 75 percent of substrate covered or 25 to 75 percent presence during hook tosses
- **High**—greater than 75 percent of substrate covered or more than 75 percent presence during hook tosses

3.2.1 Observations

From the sediment sampling trip in May to the macrophyte survey conducted in mid-June, there was a visually noticeable increase in macrophyte coverage and density in Kohlman Lake. Macrophyte coverage was dense in most areas of the lake where water depth was less than approximately 5 to 6 feet (approximately 52 acres of the lake were vegetated).

In Keller Lake it was more difficult to notice changes in macrophyte coverage and density due to macrophyte management ongoing within the lake. Macrophytes were still present throughout the lake with the highest densities found in the southern part of the lake. A lakeshore owner commented that EWM was less abundant than it had been in previous years.

Curlyleaf pondweed was visually observed at medium density in both lakes.

3.2.2 Macrophyte Survey

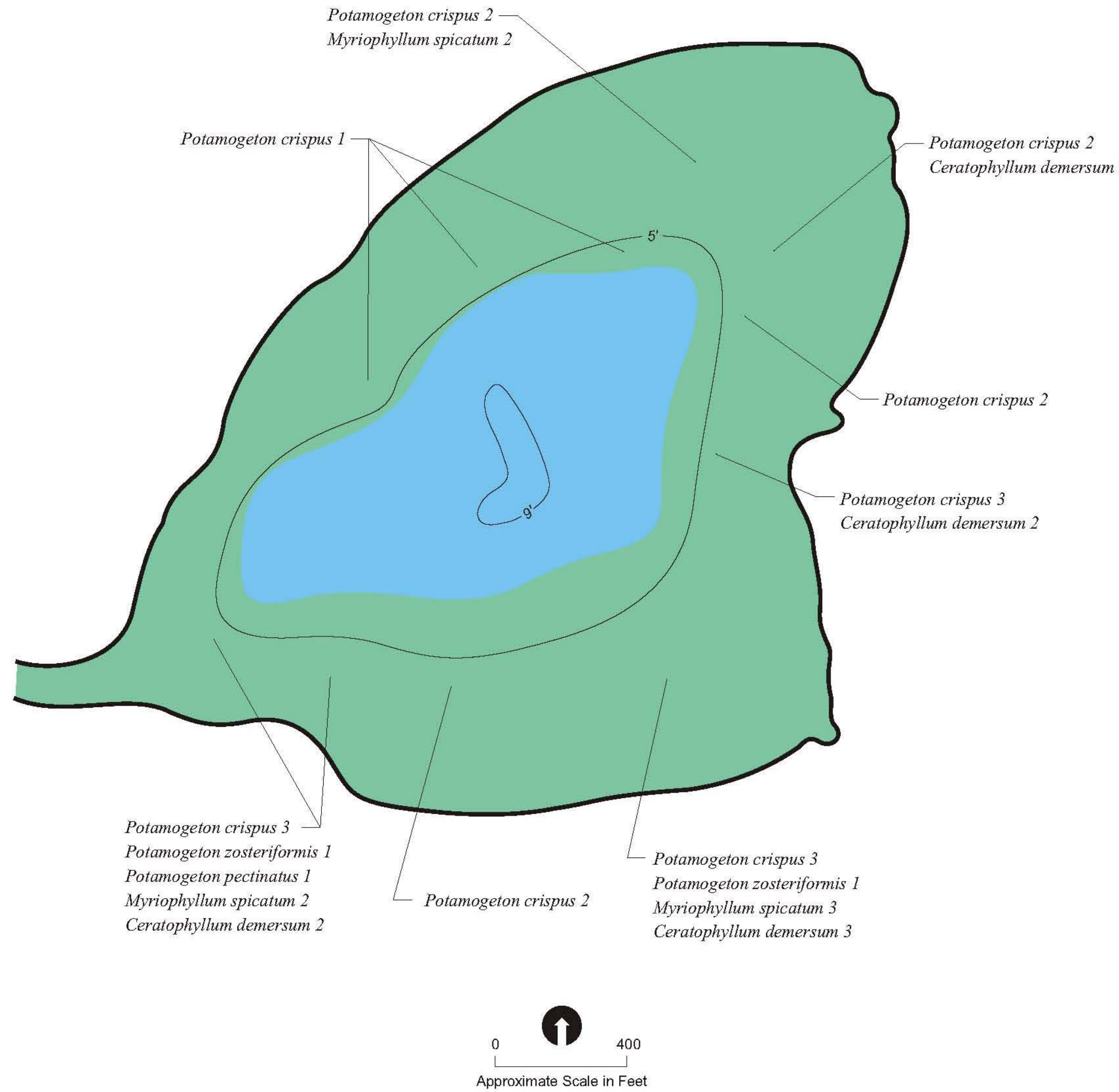
The macrophyte survey conducted by Barr Engineering Co. showed substantial growth of Curlyleaf pondweed in both Kohlman and Keller Lakes (Figures 7A and 7B). All submersed species detected in the lakes are detailed in Table 5.

Table 5 Macrophyte Species Present in Kohlman and Keller Lakes. ND = Not detected

Species	Common Name	Kohlman	Keller
Potamogeton crispus	Curlyleaf Pondweed	69.6	82.6
Myriophyllum spicatum	Eurasian Watermilfoil	65.2	30.4
Ceratophyllum demersum	Coontail	87.0	83.0
Potamogeton zostriformus	Flatstem Pondweed	39.1	30.0
Potamogeton pectinatus	Sago Pondweed	4.3	ND
Nymphaea odorata	White Water Lily	34.8	4.3
Elodea canadensis	Elodea	ND	56.5

- No Macrophytes Found In Water >5' - 6'
- Macrophyte Densities Estimated As Follows: 1 = low; 2 = medium; 3 = high

		Common Name	Scientific Name
Submerged Aquatic Plants:	(green)	Curlyleaf pondweed	*Potamogeton crispus*
		Flatstem pondweed	*Potamogeton zosteriformis*
		Sago pondweed	*Potamogeton pectinatus*
		Eurasian watermilfoil	*Myriophyllum spicatum*
		Coontail	*Ceratophyllum demersum*
No Aquatic Vegetation Found:	(blue)		



KOHLMAN LAKE
MACROPHYTE SURVEY
JUNE 2005

P:\23\62\905\035\Macrophyte Surveys\Kohlman Lake Macrophyte Survey 2005.CDR RLG 08-10-05

Figure 7A Plant Species and Density Based on Macrophyte Survey on Kohlman Lake

- Macrophytes Found In Entire Lake
- Macrophyte Densities Estimated As Follows: 1 = low; 2 = medium; 3 = high

		Common Name	Scientific Name
Submerged Aquatic Plants:		Curlyleaf pondweed	*Potamogeton crispus*
		Flatstem pondweed	*Potamogeton zosteriformis*
		Sago pondweed	*Potamogeton pectinatus*
		Eurasian watermilfoil	*Myriophyllum spicatum*
		Coontail	*Ceratophyllum demersum*
		Elodea	*Elodea canadensis*
No Aquatic Vegetation Found:			

P:\23\62\905\035\Macrophyte Surveys\Keller Lake Macrophyte Survey 2005.CDR RLG 08-10-05

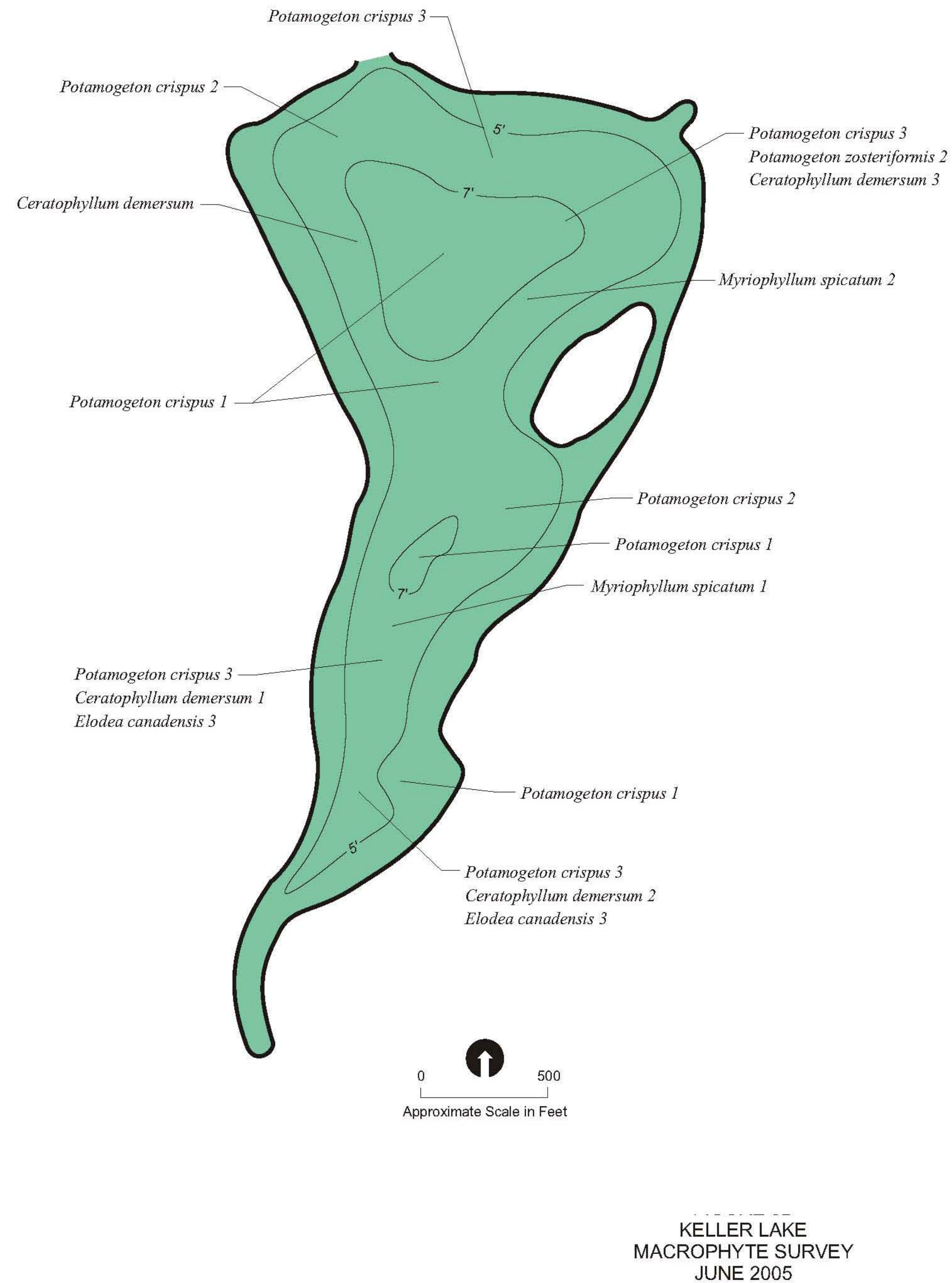


Figure 7B Plant Species and Density Based on Macrophyte Survey on Keller Lake

Medium densities of Curlyleaf pondweed were present in both lakes according to hook sampling (Table 6) indicating that management of this aquatic plant would be necessary before attempts to limit sediment internal loading are initiated. The reason for this is due to the contribution of Curlyleaf pondweed to the lake's internal phosphorus load during the growing season (see Section 4.1 of this report). In addition, if water clarity is increased through management activities in the lake, the area of lakebed exposed to light during the growing season will increase, potentially increasing growth of macrophytes in these lakes. This is especially a concern with the invasive species EWM and Curlyleaf pondweed present in both lakes.

Table 6 Macrophyte Density Based on Hook Data Collected from Kohlman and Keller Lakes

Scores were averaged on a 0-5 rating system ranging from no plants on hooks on any throws to plants on all hooks on all throws (Jessen and Lound 1962). ND = not detected.

Species	Kohlman	Keller
Potamogeton crispus	2.83	3.67
Myriophyllum spicatum	2.50	1.33
Ceratophyllum demersum	3.83	3.50
Potamogeton zostriformus	1.67	0.83
Potamogeton pectinatus	0.17	ND
Nyphaea odorata	1.33	0.17
Elodea canadensis	ND	2.50

3.3 Water Current through Kohlman and Keller Lakes

A concern with alum treatment is that strong water current may translocate the floc of aluminum hydroxide that forms and settles on the sediment surface before it is incorporated with the sediment. Because of Keller Lake's morphology and short residence time (less than 1 year), testing of the water current through the lake was warranted. The flow was measured near the exit to Lake Phalen to assure that maximum, in-lake current would be detected. However, even after a storm event the evening before, water current was measured between 0.05 and 0.08 feet per second. We were unable to detect measurable flow in other areas of the lake.

A related issue, with regard to water quality within Keller Lake, is the hydraulic residence time of the water. Hydraulic residence time is defined as the time required for the lake to entirely flush. Because

Keller Lake has an average hydraulic residence time of less than a year (based on 2001 data), lake water quality is tied heavily to Gervais Lake. 2002 data show that average total phosphorus concentrations between Keller and Gervais Lakes were similar (29 and 33 $\mu g \cdot L^{-1}$, respectively). However, in drier than normal years, the impact of internal loading will be greater due to lower external flows through the lake.

Kohlman Lake is in a similar situation. Though Kohlman Lake has a higher average internal loading rate, external flows are high as well and keep the average hydraulic residence time below 1 year. Under high external loading conditions during wet years, beneficial impacts of phosphorus inactivation may be overwhelmed by high external inputs of phosphorus. This scenario can be seen in the 2002 data for the lake when average, in-lake total phosphorus concentration was only 10 $\mu g \cdot L^{-1}$ higher than the concentration of direct inputs to the lake. However, in drier than normal years, the effect of internal phosphorus loading in Kohlman Lake will be higher due to lower external inputs of phosphorus and any reduction of internal loading will have a greater impact.

3.4 Bioturbation from Benthivorous Fish

It is generally assumed that bottom-feeding fish, such as carp and bullhead, tend to disturb the lake bottom (bioturbation) and possibly undermine the effectiveness of an alum treatment. However, there is little to support this assumption in the current body of literature. In fact, a recent study, 2004, by Dr. Alan Steinman on Spring Lake, Michigan suggests otherwise. As mentioned in Section 3.1 of this report, generally, bioturbation had relatively little impact on increasing phosphorus release and that resuspension increased total phosphorus but not soluble reactive phosphorus. This is to be expected because the bond between aluminum and phosphorus is strong and even if the sediment becomes re-suspended, the phosphorus remains inactivated. The author of the paper concludes:

> "*When alum was present, it appeared to sorb [bind] P very effectively, irrespective of the role of bioturbation. Resuspension of sediments at the conclusion of the alum concentration experiment resulted in significant increases in TP compared to the pre-resuspension concentrations, irrespective of alum concentration. However, SRP concentrations remained very low in the water column during resuspension, suggesting bioavailable P will be in short supply, even during sediment mixing events, provided alum is present.*"

4.0 Factors that Cause Additional Internal Load to Kohlman and Keller Lakes

Sediment phosphorus is generally the main component of internal loading in lakes but it is not always the only one. Shallow lakes are especially vulnerable to inputs of phosphorus from certain species of macrophytes and benthivorous fish as discussed below.

4.1 Macrophytes

Curlyleaf pondweed is an invasive plant that has infested numerous Minnesota lakes. The life cycle of the macrophyte presents a lake management problem due to initial decay of the plant early in the growing season (late May through July) that contributes substantial amounts of phosphorus to the water column. Estimates of internal phosphorus loading from Curlyleaf pondweed senescence using data collected during the macrophyte study indicate a rate of up to 2.2 $mg{\cdot}m^{-2}\ d^{-1}$ (James et al., 2002). Thus, any management plan that incorporates the reduction of internal phosphorus loading, like alum treatment for example, runs the risk of being “short-circuited” or less effective than planned if the potential loading from Curlyleaf pondweed is not taken into account.

4.2 Benthivorous Rough Fish

Although many authors allude to the effect of benthivorous fish on lake water quality, only one has attempted to quantify it (LaMarra, 1975). In this study, long-term experiments were conducted to demonstrate the effects of various carp densities on the total phosphorus and chlorophyll concentrations of the overlying water. The study completed by LaMarra shows that carp can contribute up to 15.42 $mg{\cdot}m^{-2}\ d^{-1}$ under very high population density.

Although current, specific fish density is unavailable, it is instructive to consider an estimated impact of carp populations on the internal phosphorus load for Kohlman and Keller Lakes. A somewhat reasonable fish density of benthivorous fish is approximately 100 kg ha^{-1}. According to LaMarra’s study, the corresponding release rate of total phosphorus would be 1.07 mg $m^{-2}\ d^{-1}$. This value is significantly lower than the maximum sediment release rates of phosphorus for Kohlman and Keller Lakes (17 mg $m^{-2}\ d^{-1}$ and 3.5 mg $m^{-2}\ d^{-1}$, respectively). The number, however, is similar to estimated internal phosphorus loading from Curlyleaf pondweed that can be up to 2.2 m $m^{-2}\ d^{-1}$.

These results indicate that management of the benthivorous fish population may be a reasonable approach to consider in improving the lakes’ water quality. It is important to note, however, that the fish density numbers considered here are estimates that may or may not reflect the true magnitude of the actual population in the lakes, leaving the true water quality impact of removing benthivorous fish unknown. In addition, the study by LaMarra is the only one that was found on the subject of fish induced phosphorus loading. Further study of this potential phosphorus source should be considered. One possible option is to work jointly on a project with the Fisheries department at the University of Minnesota.

5.0 Alternative Phosphorus Removal Options

Chemical inactivation of phosphorus is one of a number of methods available to reduce in-lake phosphorus levels. Dredging is an alternative option to chemical inactivation, although this method is generally more expensive due to high labor and disposal costs. The removal of phosphorus contributing macrophytes and rough fish are other options to consider along with sediment phosphorus removal. Another, more experimental option (Solarbees) is also described in the next section.

5.1 Dredging

Dredging was investigated as an option to remove excess phosphorus in the surficial sediment of Kohlman and Keller Lakes. The cost of removal and disposal was based on the depth of excess total phosphorus in the sediment and sediment volume. It should be noted that the cost estimates determined in this study are mainly for comparison purposes with other management alternatives and if dredging was decided upon as a desired option, a feasibility study would need to be conducted to determine the actual costs of dredging including, but not limited to, dredging method, precise dredge delineation, staging site design, spoil storage site design, and transportation costs. Also, if contaminants were detected in the sediment, cost would increase substantially due mainly to disposal restrictions. One additional benefit to dredging of the lakes would be the potential increase in water depth achieved through sediment removal.

5.1.1 Cost Estimate

The depth of sediment needed for removal of phosphorus was estimated using the data collected for the alum dosing portion of this study. Excess total phosphorus was determined down to a depth of 22 cm. Based on Figure 8, estimated dredge cut depths for Kohlman and Keller Lakes were 15 cm and 10 cm, respectively.

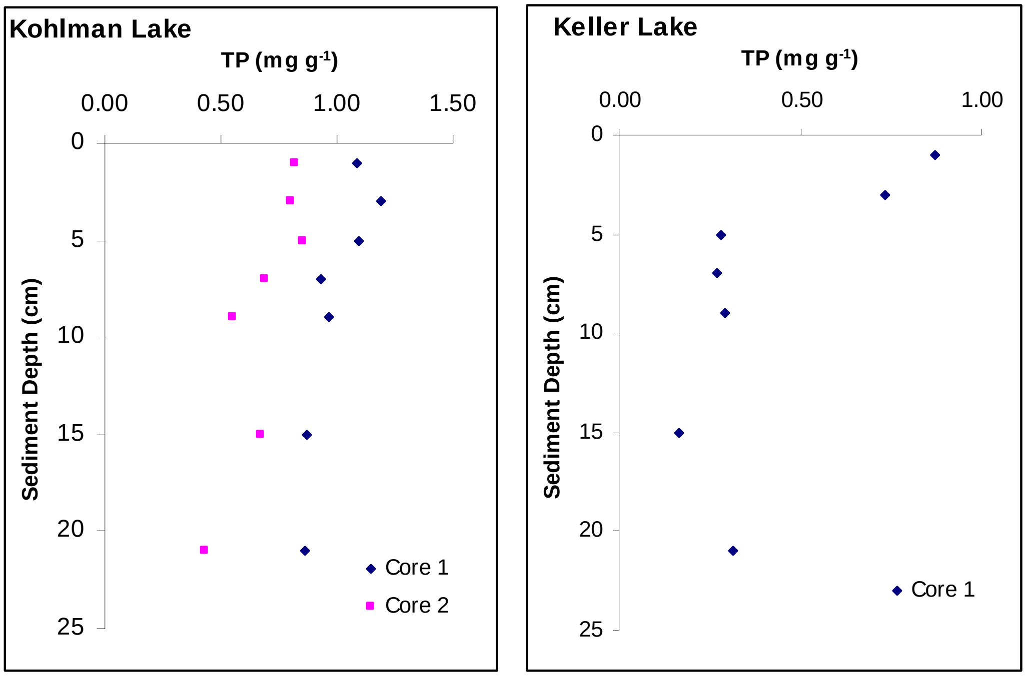


Figure 8 Depth Distribution of Total Phosphorus (TP) in the Sediment of Kohlman and Keller Lakes.

Costs associated with removal of lake sediment were estimated based on a range from $4 to $11 per cubic yard, in 2005 dollars, as recommended by Judy Mader (2005) at the MPCA (Table 7). The cost to dewater and dispose of the sediment will be an additional $10 to $20. Disposal cost may be reduced if "beneficial use" status can be obtained through the MPCA.

Table 7 Cost Estimates for Dredging Kohlman and Keller Lakes Based on Depth of Excess Total Phosphorus (TP) in the Sediment

	Kohlman	**Keller**
Depth of excess TP (feet)	0.49	0.33
Volume removed (yard^3)	59,000	39,000
Dredge cost range	$236,000-$647,000	$153,000-$420,000
Disposal cost range	$588,000-$1,176,000	$382,000-$763,000
Total cost range	$824,000-$1,823,000	$535,000-$1,183,000

5.2 Curlyleaf Pondweed Management

In order to manage internal phosphorus loading in Kohlman and Keller Lakes, the macrophyte community should be taken into consideration to avoid "short-circuiting" restoration activities. *Potamogeton crispus* (Curlyleaf pondweed) presents a problem due to senescence of the macrophyte during the growing season. The decay of Curlyleaf pondweed will contribute phosphorus to the water column during late June to early July, potentially supplying algae with an additional nutrient source. Information from the macrophyte surveys conducted on these lakes indicates medium densities of Curlyleaf pondweed in both lakes. Thus, Curlyleaf pondweed will need to be managed in order for a successful internal loading management program to succeed. Treatment of this macrophyte will occur for up to four years because of the need to eliminate all turions in the sediment that can lead to new plant growth. One of the options for treatment of Curlyleaf pondweed is the herbicide Endothall. It is fast acting and non-selective at high doses but has been shown to be selective for invasive species, such as Curlyleaf pondweed, at lower doses. Another method involves the application of lime but this process is currently in the experimental stage. If this treatment method proves successful, however, it would be both beneficial as a herbicide and as a buffer during alum treatment to ensure the pH of the water remains in the optimal range for phosphorus inactivation.

Cost of treatment is estimated to be $400 per acre for treatment with Endothall. Based on estimated 2004 macrophyte coverage in Kohlman (52.2 acres) and Keller (72 Acres) Lakes (see Figures 7A and 7B), control costs will be approximately $84,000 and $116,000 respectively for treatments conducted over a four year period. The overall costs could be lower due to the possibility of smaller treatment areas following the initial, first-year treatments.

5.3 Removal of Rough Fish

The extent to which benthivorous fish affect the water quality of the Phalen Chain of Lakes has not been quantified. MDNR fishery reports and staff opinions do not indicate a large benthivorous fish population in the lakes. However, large numbers of carp are often observed, particularly during the spawning season. Anglers, in particular, report frequent encounters with large carp. Even if a benthivorous fish population size could be agreed upon, the current body of literature does not offer much guidance in translating fish population densities into phosphorus loading rates. Only one relevant paper (LaMarra, 1975) was found in the literature regarding internal phosphorus loading rates.

Due to the limited amount of carp collected in recent MDNR studies (Draft: *Phalen Chain of Lake Carp Population Study*, Barr 2005), it is not known whether fish harvesting will have a substantial impact on internal phosphorus loading in Kohlman and Keller Lakes. Cost estimates can also be found in the *Carp Population Study* report and indicate an approximate cost of $3,000 per lake. Repeat applications are expected every 3 to 5 years.

6.0 Alternative Management Option-Solarbees

Solarbees are a new technology when it comes to lake management and, as of yet, are an unproven alternative. The Solarbees main function is physical mixing of the surface water, which basically dilutes the chlorophyll *a* over a greater volume. They do help erode the buoyancy advantage the cynobacteria have over other types of algae by mixing all types of algae present in the water column. Cyanobacteria contain gas vacuoles that inflate or deflate allowing them to migrate to more favorable environments. Therefore, the potential exists to increase the food quality of the algae (fewer cyanobacterium), which may benefit the fisheries in the long run if successful. However, other processes common to shallow lakes are likely to be more important (Welch and Cooke, 1995)

Solarbees may be helpful in reducing phosphorus concentration in lakes under certain circumstances. Circulation of the water column will mix surface water containing elevated oxygen concentration with bottom water that is oxygen deficient. This will oxygenate water above the sediment helping iron to bind with phosphorus. However, sediment routinely exposed to anoxic conditions (low oxygen) may be low in iron and thus, not be able to bind additional phosphorus. In oxic lakes (high oxygen) with excess sediment phosphorus relative to iron, oxygenation of bottom water will have less beneficial impact in terms of phosphorus reduction. In order to increase the sorption capacity of the sediment to increase phosphorus retention, either iron or aluminum would need to be added. In addition, if iron is used, once the Solarbees are removed or stop functioning, it is likely that a substantial portion of the iron-bound phosphorus would eventually be re-released.

Because Kohlman and Keller are shallow lakes, it is doubtful that Solarbees will benefit water quality by reducing phosphorus levels unless additional phosphorus-binding components are added to the sediment (i.e., aluminum or iron). If additional sediment amendments are not added, there is a potential that Solarbees could actually increase phosphorus loading to the lake water through increased diffusion of phosphorus from the sediment pore water.

One advantage to this option is that Solarbee Company has been willing to rent circulating units. Solarbee Company is currently attempting to study the potential for macrophyte control with these devices as well. The hypothesis is that the physical mixing of the water helps to oxidize ammonia in the pore water, thereby limiting plant growth. Testing is still needed to confirm this however, and therefore implementation for macrophyte control is not recommended at this time.

Solarbee units generally cover 40 acres of surface area so two would be needed in either Kohlman or Keller Lakes. Costs for purchase and rental of Solarbee equipment (per lake) is as follows:

Table 8 Cost Estimates for Purchase and Rental of Solarbee Circulating Units for Each Lake

Quantity	Description	Cost Each	Total Cost
2—Purchase	SB100000v12	$38,000	$76,000
	Delivery, installation, startup		$10,000
	Total Purchase Cost		**$86,000**
2—Rent	SB100000v12-Rental cost per month		$3,000
	Delivery, installation, startup		$10,000
	Total Cost, First Year		**$46,000**

7.0 Conclusions and Recommendations

Reducing internal phosphorus release from the sediment through means such as alum addition will permanently remove a prescribed amount of phosphorus from the system. The nutrient related water quality effects of such a reduction will not only be dependant on the amount of phosphorus inactivated, but other factors influencing overall lake water quality as well. These factors include:

- External Loading
- Macrophyte community
- Benthivorous rough fish
- Water residence time (water flow through the lake)
- Use of other phosphorus reduction strategies (e.g. dredging)

These factors, along with the expected reduction in internal phosphorus release, were considered in the following recommendations.

7.1 Kohlman Lake

The average internal phosphorus release rate in Kohlman Lake is estimated at 9.3 mg m^{-2} d^{-1} and is thus, a considerable phosphorus load to the lake. Therefore, an alum treatment is recommended to limit internal phosphorus release in order to substantially decrease the phosphorus loading from the sediment. External loading is also high to Kohlman Lake (Figure 9), approximately 90 percent of which is delivered through Kohlman basin. Growing season averages of external phosphorus input in Figure 9 were determined through modeling. Curlyleaf pondweed phosphorus contribution was calculated using 2005 data collected by Barr and internal loading was estimated through deduction and is similar to the data collected in 2005. During wet seasons when external phosphorus loading is high and residence time is low, the beneficial effects of decreased internal phosphorus loading resulting from phosphorus inactivation with alum will be limited. Thus, before an alum treatment is applied to the lake, external sources should be reduced to the maximum extent possible.

The presence of both *P crispus* (Curlyleaf pondweed) and *M. spicatum* (EWM) indicates that an increase in water clarity due to in-lake phosphorus reduction increase the density and biomass of these species. Therefore, we also recommend that a macrophyte management plan be established and implemented previous to any internal phosphorus load reduction activities. The costs of both Curlyleaf pondweed control and alum treatment are listed in Table 9.

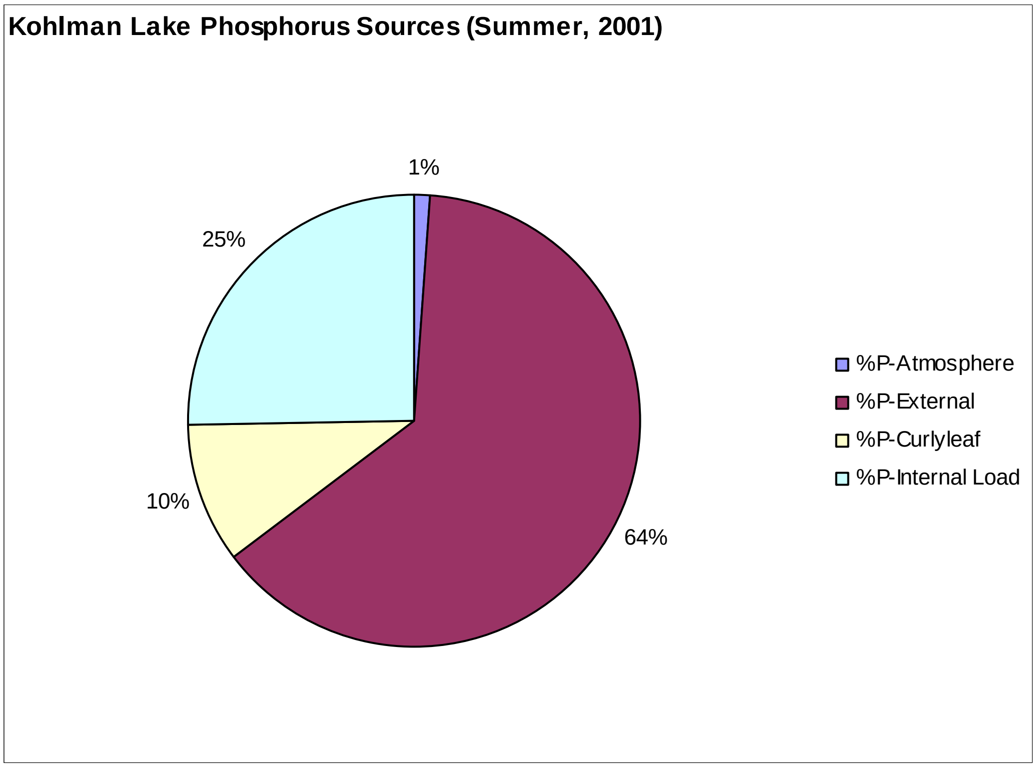


Figure 9 Phosphorus sources in Kohlman Lake by percentage of total input

Table 9 Summary of Costs for Internal Phosphorus Control in Kohlman Lake

Curlyleaf pondweed management (4 year application)	$ 84,000
Alum Treatment	$141,000

7.2 Keller Lake

Due to the comparatively low rate of internal sediment phosphorus loading estimated in this study (average of 2.2 $g \cdot m^{-2} d^{-1}$) and the short hydraulic residence time of the lake, alum treatment alone is not expected to have a great impact on water clarity or surface water total phosphorus. In addition, Curlyleaf pondweed contributes a similar amount of phosphorus to the water column when compared to sediment release in Keller Lake (Figure 10). Phosphorus inputs to the lake were calculated in the same manner as Figure 9 for Kohlman Lake and the external phosphorus load includes input from Gervais Lake. Therefore, we recommend a phased approach to control internal loading in Keller Lake, with the initial phase consisting of Curlyleaf pond weed management. If in-lake phosphorus goals are not met, application of alum could then be used to further reduce phosphorus concentration in the lake. The costs of both Curlyleaf pondweed control and alum treatment are listed in Table 10.

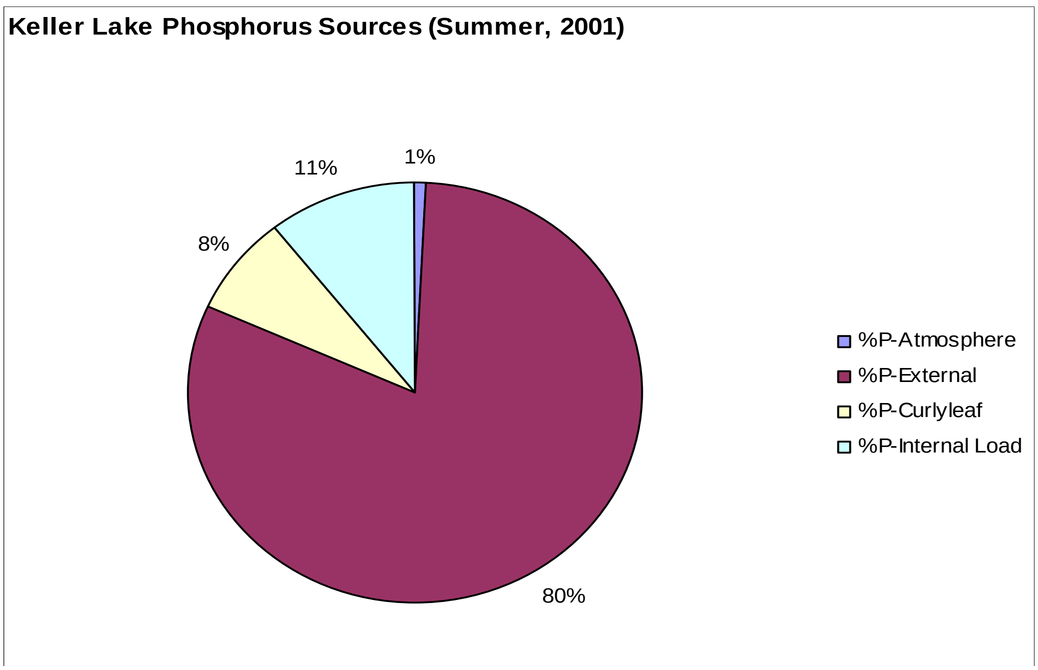


Figure 10 Approximate Percentages of Phosphorus Sources in Keller Lake

Table 10 Summary of costs for internal phosphorus control in Keller Lake

Curlyleaf pondweed management (4 year application)	$ 116,000
Alum Treatment	$ 50,000

7.3 Other Considerations

Rough fish removal will have some benefit to the lake but due to the low numbers of benthivorous fish collected by MNDNR staff in previous years, the magnitude may be limited. If benthivorous rough fish increase in density in the future, the management of these species will be necessary to limit internal loading of phosphorus.

If alum treatment is not a desired option and the cost of dredging is not considered feasible, Solarbee circulators may be considered for Kohlman Lake. It is not likely that phosphorus concentration will decrease, however, without addition of phosphorus binding elements such as iron or aluminum to the sediment. Implementation would require a feasibility study involving sediment cores (to determine available iron and aluminum for phosphorus sorption), pre- and post-installation evaluation of zooplankton and phytoplankton populations, as well as detailed pre and post-treatment macrophyte surveys. These studies would help define the potential improvements to the fisheries status achieved by the Solarbee circulators.

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Appendices

Appendix A

Data

Sediment Data

Mobile Phosphorous

Kohlman Lake

Kohlman Phosphorus Fractionation					
Sample	Depth	H2O	Density	Sample	Mobile P
	cm	%	$g \cdot cm^{3}$	mg	$mg \cdot g^{-1}$
KO1 0-2	1	87	1.1	173.3	0.32
.2-4	3	84	1.2	175	0.25
.4-6	5	83	1.2	177.8	0.31
.6-8	7	82	1.2	163.8	0.33
.8-10	9	80	1.2	167.2	0.19
14-16	15	78	1.2	166.5	0.29
20-22	21	76	1.3	153	0.28
KO2 0-2	1	73	1.3	205.5	0.22
.2-4	3	71	1.3	168.7	0.11
.4-6	5	68	1.4	152	0.22
.6-8	7	73	1.3	149.3	0.45
.8-10	9	71	1.3	181.6	0.35
14-16	15	69	1.5	145.3	0.17
20-22	21	64	1.4	174	0.11
KO3 0-2	1	87.6	1.30	129.2	0.20
.2-4	3	86.6	1.31	150.9	0.19
.4-6	5	85.9	1.36	112.7	0.19
.6-8	7	83.4	1.31	173.8	0.13
.8-10	9	81.5	1.35	160.2	0.11
14-16	15	77.5	1.48	123.3	0.11
20-22	21	74.2	1.41	168.7	0.07

Keller Lake

Keller Phosphorus Fractionation					
Sample	Depth	H2O	Density	Sample	Mobile P
	cm	%	$g \cdot cm^{3}$	mg	$mg \cdot g^{-1}$
KE1 0-2	1	89.0	1.10	173.3	0.10
.2-4	3	82.0	1.17	175.0	0.06
.4-6	5	79.0	1.20	177.8	0.06
.6-8	7	75.0	1.23	163.8	0.07
.8-10	9	73.0	1.26	167.2	0.05
14-16	15	67.0	1.38	166.5	0.04
20-22	21	78.0	1.21	153.0	0.04
KE1B 0-2	1	84.9	1.07	131.1	0.26
.2-4	3	79.3	1.10	122.8	0.24
.4-6	5	74.9	1.12	140.4	0.05
.6-8	7	72.6	1.14	133.3	0.05
.8-10	9	73.6	1.13	133.9	0.05
14-16	15	64.9	1.19	171.2	0.02
20-22	22	74.7	1.13	133.4	0.04

Alum Experiments

Kohlman Lake

Kohlman Alum Addition								
Composite	H2O	Density	Al added	Al-P	Mobile P	Al added	Al-P	Mobile-P
mg	%	$g \cdot cm^3$	$mg \cdot g^{-1}$	$mg \cdot g^{-1}$	$mg \cdot g^{-1}$	$g \cdot m^{-2} \cdot cm^{-1}$	$g \cdot m^{-2} \cdot cm^{-1}$	$g \cdot m^{-2} \cdot cm^{-1}$
183.2	71.99	1.31	0.00	0.05	0.34	0.00	0.17	1.25
132.8	72.08	1.30	6.50	0.21	0.14	23.70	0.77	0.53
137.5	71.94	1.31	12.50	0.27	0.10	45.81	0.97	0.35
133.8	71.89	1.31	32.07	0.32	0.04	117.73	1.16	0.15
142	72.11	1.30	48.72	0.35	0.03	177.25	1.29	0.09

Keller Lake

Keller Alum Addition								
Composite	H2O	Density	Al	Al-P	Mobile-P	Al	Al-P	Mobile-P
mg	%	$g \cdot cm^3$	$mg \cdot g^{-1}$	$mg \cdot g^{-1}$	$mg \cdot g^{-1}$	$g \cdot m^{-2} \cdot cm^{-1}$	$g \cdot m^{-2} \cdot cm^{-1}$	$g \cdot m^{-2} \cdot cm^{-1}$
150.8	82.53	1.08	0.00	0.03	0.06	0.00	0.05	0.12
183.3	81.86	1.09	2.18	0.04	0.04	4.28	0.08	0.09
129.1	82.64	1.08	5.60	0.05	0.03	10.50	0.10	0.05
171.6	81.98	1.08	12.48	0.06	0.01	24.39	0.11	0.02
160.9	82.24	1.08	21.10	0.06	0.01	40.59	0.12	0.01

Macrophyte Survey

Kohlman Lake

Hook Data

Macrophytes 6/22/2005			6 Prong Hook Number of hooks					
Station	Depth (m)	Throw #	*P. crispus*	*M. spicatum*	*C. demersum*	*P. zosteriformis*	*P. pectinatus*	*N. odorata*
KO1-A	1.25	1	5	6	4			2
		2	1	6	6			
		3	4		6			
		4	1	3	6			
KO1-B	1.52	1	1	5	6			
		2	1		6	1		
		3			6			
		4		6	6	3		
KO2-A	1	1		6	6	2		
		2	2	5	6	3		
		3		3	4	6		
		4	1	6	6	2		
KO2-B	1.5	1			6			2
		2			6			
		3	1	3	6			
		4		3	6			
KO3-A	0.5	1	6	3		6		4
		2	4	5	1	3		1
		3	6	4		3	4	
		4	6	2				4
KO3-B	1	1	2		6			3
		2	6		6			3
		3	6		4			6
		4	6		6	2		1
% of throws present			69.6	65.2	87.0	39.1	4.3	34.8

Kohlman Lake

Density

Density						
	Present in all 4 throws, hooks full	5	Present in 2 throws	2		
	Present in all 4 throws, hooks not full	4	Present in 1 throw	1		
	Present in 3 throws	3	Present in 0 throws	0		

Station	Density *P. crispus*	*M. spicatum*	*C. demersum*	*P. zosteriform*	*P. pectinatus*	*N. odorata*
KO1-A	4	3	4	0	0	1
KO1-B	2	2	5	2	0	0
KO2-A	2	4	4	4	0	0
KO2-B	1	2	5	0	0	1
KO3-A	4	4	1	3	1	2
KO3-B	4	0	4	1	0	4
Average	2.83	2.50	3.83	1.67	0.17	1.33

Keller Lake

Hook Data

Macrophyte Data 6/22/2005			6 Prong Hook Number of hooks					
Station	Depth (m)	Throw #	Number of hooks *P. crispus*	*M. spicatum*	*E. canadensis*	*C. demersum*	*P. zosteriformis*	*N. odorata*
KE1-1	1.5	1	6			6		
		2	6			6		
		3	6			6		
		4	6			6	1	
KE1-2	2	1	6	3	1		3	
		2	6	6	3			
		3	6	4		1		
		4	5	3	2	3	3	
KE1-3	1.125	1				5		
		2			1	3	3	
		3				4		
		4	2			4		
KE2-1	1.25	1	6		6	1	2	
		2	1					1
		3	6		6	1		
		4	6		6	2		
KE2-2	1.5	1	1		6	1	1	
		2	6			2		
		3	2	1	6	6		
		4			6	2		
KE2-3	1.75	1	1	1	6	1		
		2	5		6			
		3	5	1	6	1	2	
		4	6	1	6	2		
% of throws present			82.6	30.4	56.5	83	30	4.3

Keller Lake

Density

Density Rating Key						
Present in all 4 throws, hooks full	5	Present in 2 throws	2			
Present in all 4 throws, hooks not full	4	Present in 1 throw	1			
Present in 3 throws	3	Present in 0 throws	0			

Station	Density *P. crispus*	*M. spicatum*	*E. canadensis*	*C. demersum*	*P. zosteriformis*	*N. odorata*
KE1-1	5	0	0	5	0	0
KE1-2	5	4	3	2	1	0
KE1-3	1	0	1	4	1	0
KE2-1	4	0	3	3	1	1
KE2-2	3	1	3	4	1	0
KE2-3	4	3	5	3	1	0
Average	3.67	1.33	2.50	3.50	0.83	0.17