Spring Lake Sediment Core Analysis, Alum Dose Determination and Application Plan

Prepared for
Prior Lake – Spring Lake Watershed District (PLSLWD)

September 2012

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Executive Summary

A total of 12 sediment cores were collected in Spring Lake on June 15, 2012 to determine the concentration of phosphorus fractions in the lake's sediment and calculate an alum dose for a whole lake alum treatment. Sediment was analyzed for the following phosphorus fractions; mobile phosphorus (mobile-P), organic phosphorus (organic-P), aluminum bound phosphorus, and calcium bound phosphorus. The mobile-P fraction represents the iron bound phosphorus fraction, as well as the loosely-sorbed phosphorus fraction. A summation of these four fractions is considered to be an estimate of total phosphorus in sediment. Mobile-P and organic-P were highest in the deep areas of Spring Lake. In general, mobile-P and organic-P were highest in the top six centimeters of sediment. Compared to other lakes in the Twin Cities Metropolitan Area, mobile-P and organic-P were not notably elevated, with concentrations comparable to Bryant Lake in Hennepin County and Lake McCarrons in Ramsey County; however, concentrations were lower than Lake Harriet in Hennepin County and Como Lake in Ramsey County.

An alum dose for Spring Lake was calculated using the methods of Pilgrim et al. (Water Research, Volume 41, Issue 6, March 2007, Pages 1215–1224). The alum dose was calculated using the concentration of mobile-P in the Spring Lake sediment, as well as the labile organic phosphorus concentration in the sediment. The labile organic phosphorus fraction represents the portion of the total organic-P fraction that will decompose into mobile-P. For the purposes of this study, the labile organic-P concentration was estimated to be 25% of the total organic-P concentration. The dose was based upon treatment of the upper 6 centimeters of lake sediment with alum and the formation of a 75 to 1 ratio of aluminum to aluminum bound phosphorus in the sediment. Labile organic-P was included as part of the "releasable phosphorus" pool because organically bound phosphorus becomes part of the mobile-P pool when it decays. For the purposes of discussing the pool of phosphorus that would be targeted for an alum treatment, we will define the term "Releasable Phosphorus" (Releasable-P) as the sum of the existing mobile-P fraction and the labile organic-P fraction, which will decompose into mobile-P over time. The organic-P pool is important because it has about twice the mass of the mobile-P pool in Spring Lake sediments, and it is a future source of internal loading to Spring Lake. To bind mobile-P phosphorus and to bind organic-P when it decays in the future, it is recommended that the alum treatment be split in half or three separate portions, and applied in two to three events that are each spaced by three or more years, depending on the need for further watershed loading reductions. Based upon the spatial distribution of mobile-P and organic-P in Spring Lake, two alum application zones are prescribed (see Figure Ex-1). In Zone 1 the alum dose is 1,900 gallons of alum per acre of lake bottom (total area 194 acres, total volume of alum is 369,000 gallons, and the areal mass of alum applied is 103 grams aluminum per square meter of lake bottom), and in Zone 2 the alum dose is 1,000 gallons of alum per acre of lake (total area of 215 acres, total volume of alum is 215,000 gallons, and the areal mass of alum applied is 56 grams aluminum per square meter of lake bottom).

To initiate the alum treatment, it is recommended that half of the alum dose is applied to each of the respective zones (described above). An adaptive management approach should then follow during the next three years to further evaluate the in-lake phosphorus response and potential interferences from the external (and other internal) phosphorus loading sources. Depending on the necessary or expected pace of any other phosphorus loading source reductions, the second alum application could involve the remainder of the total dose or a quarter of the alum dose, with the expectation that the final quarter of the dose would be applied following another three-year period to further evaluate the in-lake phosphorus response and potential interferences from the external (and other internal) phosphorus loading sources. In summary, the following alum treatment schedule is recommended for Spring Lake:

Year	Recommended Management Action
1	Apply Half of Total Alum Dose
2	Conduct Intensive Watershed and In-Lake Water Quality Monitoring
3	Conduct Intensive Watershed and In-Lake Water Quality Monitoring
4	Apply Quarter of Total Alum Dose
5	Conduct Intensive Watershed and In-Lake Water Quality Monitoring
6	Conduct Intensive Watershed and In-Lake Water Quality Monitoring
7	Apply Quarter of Total Alum Dose
8	Conduct Intensive Watershed and In-Lake Water Quality Monitoring
9	Conduct Intensive Watershed and In-Lake Water Quality Monitoring
10	Repeat Sediment Core Sampling and Analysis, If Necessary

1.0 Introduction

Sediment cores were collected from 12 different locations in Spring Lake to measure the concentrations of phosphorus fractions in lake sediment and determine an appropriate alum dose to bind the phosphorus that has the potential to cause internal phosphorus loading in the lake. The sediment coring locations and sediment sampling intervals were selected to account for potential spatial differences in phosphorus in lake sediments (across the lake bottom), and to identify the depth distribution of phosphorus within the sediment (e.g., change in phosphorus within the sediment (see Section 2.0). The alum dose described in this report (section 3.0) follows the approach of Pilgrim et al. (Water Research, Volume 41, Issue 6, March 2007, Pages 1215–1224) whereby the alum dose is a function of the concentration of mobile-P and organic-P in lake sediment. The alum dosing, prescribed in Section 3.0, was designed to target the releasable-P (mobile-P plus labile organic-P) pool in the sediment which is based upon areas of the lake that have different concentrations of releasable-P. The dose was also designed, in part, to target the internal loading reduction percentage determined in the TMDL report (Wenck, 2011), and ultimately meet the State water quality criteria that apply to Spring Lake. This study also provides an estimate of the cost and schedule to apply the prescribed alum dose, including an evaluation of any potential pH effects with the application of a full or partial dose.

2.0 Sediment Coring and Analytical Results

A total of 12 sediment cores were collected in Spring Lake on June 15, 2012 to provide an estimate of the spatial distribution of phosphorus concentrations in the bottom sediments of the lake. The cores were collected using a Willner Gravity Corer. Each core was sliced into nine sections consisting of 2 to 5 centimeter intervals of sediment, to a total depth of 35 centimeters, with the exception of cores S1 and S12. Cores S1 and S12 were at locations with sandy, more consolidated sediment, which limited the depth to which the coring device could penetrate.

For each sediment sample collected, the following analyses were conducted: percent water, loss on ignition (LOI) at 550 ^{o}C (LOI is a measure of the combustible organic matter content), mobile-P, aluminum-bound phosphorus, calcium bound phosphorus, and organic-P. A summary of the sediment analytical results is provided in Table 1. The phosphorus fractionation results are provided in Table 1 on both a “dry weight” basis and a “volumetric” basis. The dry weight basis is the more traditional approach of displaying sediment chemistry data and is simply a measurement of the phosphorus mass divided by the mass of dry solids in the sediment. We have found that the volumetric basis (grams of phosphorus divided by the volume of sediment sampled) provides a more accurate estimate of aluminum binding and hence alum dosing. The volumetric approach also provides a more accurate estimate of internal phosphorus release after alum treatment.

Organic phosphorus is an important contributor to the potentially releasable phosphorus fraction, especially for relatively shallow lakes where organic phosphorus is found at a higher concentration than the mobile phosphorus fraction. We took sediment cores from several lakes and measured organic phosphorus in the core at different sediment depths and measured organic phosphorus. We were able to correlate the rate of organic phosphorus loss to the age of the core to determine the rate of organic-P decay. Decay of the organic-P pool contributes to the mobile-P phosphorus pool over time at an estimated rate of 5 percent per year. If the organic-P pool is not targeted, then the longevity of an alum treatment could be compromised. If the alum treatment is split and applied over a 3-6 year period, then approximately 25% of the organic-P will be targeted by the alum treatment and ensure that fresh alum (aluminum) is available to bind the phosphorus release by organic-P decay.

One of the most challenging and unfortunately poorly researched aspects of phosphorus in sediment is the determination of the layer of sediment that is active (e.g., the sediment layer in which phosphorus release occurs) and the layer that the alum can be expected to reside after application. Figure 1, which shows the distribution of phosphorus by depth within the sediment, provides some indication of the active layer. Overall, it can be seen that mobile-P and particularly organic-P is more concentrated in the top 6 centimeters of sediment. This suggests that most of the phosphorus release occurs in the top 6 centimeters of the sediment and that the amount of alum that is added should be enough to bind the mass of mobile-P within the top 6 centimeters of sediment. Other sediment core sampling studies have indicated that as much as 10 centimeters of the sediment may contribute to sediment phosphorus release. A summary of the average concentration of each fraction of phosphorus in the top 6 centimeters of the core samples is provided in Table 2. It should be noted that "releasable phosphorus" (Releasable-P) is estimated as mobile-P plus the labile (reactive or readily available) organic-P fraction (estimated at 25% the total organic-P fraction).

Phosphorus concentrations measured in Spring Lake sediment were also mapped using GIS to better understand the spatial distribution of phosphorus concentrations in the sediment. It can be seen in Figures 2, 3 and 4 that mobile-P, organic-P, and releasable-P are more concentrated in the deeper areas of the lake. Alum doses prescribed in Section 3.0 were based upon the spatial distribution of sediment displayed in these maps.

3.0 Alum Dosing and Costs

3.1 Alum Dosing

Using the releasable-P map shown in Figure 4, general areas of high, medium and low sediment phosphorus concentrations were identified. The high phosphorus area includes lake sediment found at water column depths greater than 20 feet. The medium phosphorus area includes sediment found at water column depths between 10 to 20 feet. Because phosphorus levels are relatively low in sediment found at depths less than 10 feet, and because oxygen levels at these depths typically remain higher and do not become anoxic, alum treatment is not recommended for areas with water depth less than 10 feet. Oxygen or the lack of oxygen is important for internal loading, when there is not oxygen, iron can no longer effectively bind phosphate. Alum doses have been provided for sediment found between 10 to 20 feet and for sediment found deeper than 20 feet (see Figure Ex-1). Doses prescribed by these treatment areas (identified as Zone 1 and Zone 2 in Figure Ex-1) are based upon estimated average releasable-P concentrations in these zones (see Table 3).

The alum dose (see calculations in Table 3) for Zone 1 is based upon an average releasable-P concentration of 0.31 grams of releasable-P per square meter-centimeter in the top 6 centimeters of lake sediment. The alum dose (see calculations in Table 3) for Zone 2 is based upon an average releasable-P concentration of 0.20 grams of releasable-P per square meter-centimeter in the top 6 centimeters of lake sediment. Alum ($Al_2(SO_4)_3$*14.3H_20) doses for both zones were calculated using a 75:1 aluminum to aluminum bound phosphorus ratio and assuming a sediment treatment depth of 6 centimeters. The 75:1 alum dose was chosen for efficiency and to approximate the internal loading reduction target of the TMDL (Wenck, 2011). With respect to treatment effectiveness, it can be seen in Figure 5 that with alum doses greater than 1,900 gallons/acre for Zone 1 and 1,000 gallons/acre for Zone 2 the percentage removal of releasable-P per addition gallon of alum applied begins to decline (e.g., the most efficient doses are 1,000 and 1,900 gallons per acre). It is estimated that for the doses prescribed there will be an 89% reduction in releasable-P in Zone 1 and a 75% reduction in releasable-P in Zone 2. Using the internal phosphorus release rate of 17 milligrams of phosphorus released per square meter of lake bottom per day used to model Spring Lake as part of the TMDL (Wenck, 2011), it is estimated that with a 75% to 89% reduction in releasable-P, internal loading would be reduced to 2 to 4 milligrams of phosphorus per square meter per day. This rate is similar to the TMDL-prescribed internal load rate for meso-trophic lake systems.

3.2 Costs

A summary of the prescribed alum doses is provided in Table 4. The total recommended gallons of alum to be applied are 584,000 gallons. The current estimated costs to conduct the alum treatment are provided in Table 5, which total $986,000 for a one-time full application. Approximately $46,000 (or less than 5 percent) of the costs, including a $20,000 estimate for contractor mobilization and demobilization, would need to be paid each time if a split application is considered. If the alum treatment is split into three separate applications, the additional project costs could total approximately $100,000 (or 10 percent), depending on inflation and the amount of time between applications. Because there is a minimal difference in the cost to apply the full dose or to apply a fraction of the total dose in stages, it is recommended that the alum application occur in stages. This will avoid the need to use an alum and sodium aluminate mixture (discussed in Section 3.3), and it will provide additional benefits with respect to organic phosphorus binding from each of the subsequent applications.

3.3 pH Effects

Alum is an acid with low pH, and therefore will temporarily reduce the pH of the lake when added in large quantities. In general, lake pH should not be allowed to drop below 6.5 with an alum treatment. A chemical model (called PHREEQC) was used to estimate the effect of the prescribed alum treatment on lake pH. The model was used to estimate the change in lake pH with a range of alum doses up to the full dose prescribed. The modeling effort was conducted assuming that the beginning lake pH was 8.4 and alkalinity was assumed to be in the range of 134 and 164 mg/L (pH and alkalinity were from Spring Lake monitoring data). The results of the model are provided in Figure 6, which shows that if the full alum dose prescribed in Table 4 is applied, pH will likely decline below 6.0. There are two potential approaches to mitigate this: (1) apply a mixture of alum and sodium aluminate since sodium aluminate is a base and neutralizes the acidic alum, and (2) split the dose is half or thirds and apply alum over subsequent years. To mitigate against potential pH effects and to improve the long-term effectiveness of the treatment, it is recommended that the alum dose be split in half or three separate portions and applied over subsequent years until the full alum dose is applied to Spring Lake. The in-lake phosphorus mass balance analysis and implications for the long-term effectiveness of alum treatment are discussed in Section 4.0 to guide the alum treatment process in Spring Lake.

4.0 Mass Balance Analysis and Alum Treatment Plan

4.1 Lake Phosphorus Mass Balance Analysis

Using the phosphorus modeling conducted as part the TMDL study for Spring Lake (Wenck, 2011); a simple predictive phosphorus balance was conducted for the water column and sediment of Spring Lake, assuming the application of the recommended alum dose. The effect of the recommended alum dose on in-lake total phosphorus levels was estimated using all of the total phosphorus load and in-lake water column phosphorus model results that were provided as part of the TMDL documentation. Assuming that the reduction in internal phosphorus load is proportional to the percentage reduction in releasable-P with alum treatment (see Table 6), it is estimated that in-lake total phosphorus concentration would be reduced on average to 85 micrograms per liter (based on all of the 1998 through 2006 annual loading and lake response modeling data provided in the TMDL report) after the full dose alum treatment. The estimated in-lake total phosphorus concentrations for individual years between 1998 and 2006 ranged from 53 and 128 micrograms per liter, in 2003 and 1998, respectively.

Ultimately the longevity of an alum treatment will be dependent upon the long term control of external phosphorus loads. Alum treatments are designed to treat phosphorus in sediment that has accumulated as part of historical phosphorus loading. The total mass of phosphorus in a lake's sediment compared to the total mass of phosphorus that is deposited into a lake's sediment due to external loading should provide an indication of the potential longevity of an alum treatment. According to the TMDL document, approximately 8,000 pounds of the 9,900 pounds of incoming total phosphorus load is deposited in the sediment of Spring Lake each year (based on median values shown from 1998 through 2006), which translates to an 81 percent sedimentation rate. The TMDL document also indicates that 5,161 pounds, or 52 percent, of the total phosphorus load originates from internal loading. Subtracting 4,200 pounds (from Table 6) of the internal load (after applying the sedimentation rate) from the 8,000 pounds of total deposited phosphorus, approximately 3,800 pounds of the sediment phosphorus would originate from watershed loading sources each year. From the sediment coring results conducted as part of this study, the top six centimeters of Spring Lake contains an estimated total of 6,900 pounds of releasable-P (see Table 6). However, the phosphorus deposited in the lake sediments each year is not all readily available for release and consists of aluminum bound, calcium bound, and recalcitrant organic phosphorus, as well as the releasable phosphorus fraction. As a result, it would be more accurate to compare the total phosphorus mass in the top 6 to 10 centimeters of Spring Lake, which is estimated to be 40,000 to 76,000 pounds of phosphorus (as shown in Table 6). Comparing the phosphorus mass to the annual watershed phosphorus load undergoing sedimentation indicates that it may take 11 to 20 years to accumulate the same mass of phosphorus currently found in the top layer of sediment in Spring Lake.

Since the settled alum floc remains reactive and can tie up phosphorus for a couple of years after each alum application, split treatments could improve the long-term cost-effectiveness by increasing the treatment efficiency and allowing for future loading reductions from the watershed and other internal sources of phosphorus.

Using an annual load reduction of 4,200 pounds and the total capital cost from Table 5, and assuming a 3 percent inflation rate and the life-span range from above, the annualized cost for an alum treatment ranges from $16 to $25 per pound removed. Since the annualized costs for implementation and maintenance of watershed Best Management Practices are one to two orders of magnitude higher than this range of costs, an in-lake alum treatment will be the most cost-effective option available to meet the water quality standards for Spring Lake.

4.2 TMDL Modeling Limitations/Implications for Alum Effectiveness

Based on the comparison of the sediment data with available modeling data in the TMDL report, more significant watershed load reductions might be required to ensure that an alum treatment is effective for more than 20 years. However, in the process of completing the lake phosphorus mass balance analysis, two separate concerns involving the TMDL modeling were identified that would account for an underestimate of the effectiveness of an alum treatment for Spring Lake. The initial concern was identified from a review of Appendix A of the TMDL report, which indicates that the TMDL modeling consistently over-predicts the in-lake phosphorus concentration (which occurred for seven of the nine years that were modeled). In addition, the average annual model predicted TP concentration is 20 percent different than the observed TP concentration. Comparing the model predicted minus observed TP residuals with the corresponding residence times from Appendix A indicates that there is a positive bias under higher flow conditions. This suggests that the TMDL modeling overestimates the watershed loading under higher flow conditions and underestimates the internal load under lower flow conditions.

A detailed review of the TMDL report revealed that the watershed modeling was set up to correspond to with phosphorus loads at an upstream monitoring location in the County Ditch 13 (CD-13) watershed. The concern with this is that no attempt was made to compare the watershed modeling results for any of the nine years with the available monitoring data from the downstream stations. In 2003, PLSLWD hired Barr to complete an analysis of the ferric chloride treatment system and corresponding estimates of watershed and internal loading sources of phosphorus for Spring Lake based on FLUX modeling prepared for the CD-13 stations (based on 1999-2002 monitoring data, including the outfall to the lake) and Bathtub modeling of in-lake phosphorus concentrations during 1999 and 2000. Comparing the results of our analysis to the TMDL study data reported for 1999 and 2000 indicates that the TMDL study underestimated the internal load by 2,450 pounds and 13,600 pounds, respectively. Comparing the total external loadings from each study for 1999 and 2000 indicates that the TMDL study overestimated the watershed load by 2,400 pounds and 350 pounds, respectively. Since 1999 represents a wet year and 2000 a drier year, it is expected that the average overestimate of the watershed loading is 1,400 pounds.

Taken together, these concerns indicate that the watershed loading is overestimated while the internal load is underestimated. As a result, the discussion presented in Section 4.1 likely underestimates the long-term effectiveness of an alum treatment for Spring Lake. Applying the same approach discussed in Section 4.1, the estimated lifespan of an alum treatment for Spring Lake could be closer to the range of 17 to 32 years.

4.3 Alum Treatment Process Recommendations

Barr understands that PLSLWD has recently been conducting more-detailed watershed monitoring that could be used to further evaluate the relative contributions of phosphorus from sources that are both internal to the lake and external. This would allow PLSLWD to weigh the long-term costs and treatment efficiency versus attempting to achieve improvements in the short term with less efficient use of alum. Still, the releasable amount of phosphorus in the upper sediment layer determined from this study confirms that no amount of external phosphorus load reduction will allow Spring Lake (and Upper Prior Lake by extension) to meet the water quality standards.

To bind mobile-P phosphorus and to bind organic-P when it decays in the future, it is recommended that the alum treatment be split in half or three separate portions, and applied in two to three events that are each spaced by three or more years, depending on the need for further watershed loading reductions. To initiate this management option, it is recommended that half of the alum dose is applied to each of the respective zones described in Section 3.1. An adaptive management approach should then follow during the next three years to further evaluate the in-lake phosphorus response and potential interferences from the external (and other internal) phosphorus loading sources. Depending on the necessary or expected pace of any other phosphorus loading source reductions, the second alum application could involve the remainder of the total dose or a quarter of the alum dose, with the expectation that the final quarter of the dose would be applied following another three-year period to further evaluate the in-lake phosphorus response and potential interferences from the external (and other internal) phosphorus loading sources.

Tables

Table 1. Sediment characterisitcs and phosphorus fractions in Spring Lake.

Sediment Core	Sample Interval (cm)	% Moisture	% Loss on Ignition	Density (g/cm^3)	Dry Weight Phosphorus Fractions					Mass Per Volume Wet Sediment Phosphorus Fractions				
					Mob	Al	Ca	Org	Total	Mob	Al	Ca	Org	Total
					(mg phosphorus)/(g dry weight sediment)					(mg phosphorus)/(cm^3 wet sediment)				
S1	0-2	35.5	1.8	1.64	0.018	0.010	0.21	0.036	0.27	0.019	0.010	0.22	0.038	0.29
	2-4	31.4	1.6	1.71	0.011	0.008	0.38	0.029	0.43	0.012	0.009	0.45	0.034	0.51
	4-6	25.3	1.1	1.83	0.013	0.008	0.23	0.019	0.27	0.017	0.011	0.31	0.027	0.37
	6-8	25.6	2.2	1.81	0.006	0.004	0.29	0.013	0.31	0.008	0.005	0.39	0.018	0.42
	8-9	23.2	0.9	1.88	0.009	0.005	0.45	0.008	0.47	0.013	0.008	0.65	0.011	0.68
S2	0-2	91.0	28.2	1.04	0.097	0.064	0.40	0.29	0.84	0.009	0.006	0.037	0.027	0.079
	2-4	89.7	28.8	1.05	0.066	0.056	0.45	0.24	0.81	0.007	0.006	0.048	0.026	0.088
	4-6	88.6	29.2	1.05	0.069	0.065	0.38	0.27	0.78	0.008	0.008	0.045	0.032	0.094
	6-8	87.9	28.4	1.06	0.054	0.062	0.52	0.20	0.83	0.007	0.008	0.066	0.026	0.11
	8-10	86.8	27.9	1.06	0.042	0.046	0.32	0.18	0.59	0.006	0.006	0.046	0.025	0.083
	10-15	87.4	32.0	1.06	0.047	0.058	0.38	0.16	0.64	0.006	0.008	0.050	0.021	0.085
	15-20	88.3	33.5	1.05	0.080	0.063	0.68	0.16	0.98	0.010	0.008	0.083	0.019	0.12
	25-26	91.6	42.0	1.03	0.11	0.072	0.84	0.16	1.18	0.010	0.006	0.073	0.014	0.10
S3	0-2	92.0	22.5	1.04	0.092	0.058	0.32	0.27	0.74	0.008	0.005	0.026	0.023	0.061
	2-4	89.7	21.7	1.05	0.070	0.059	0.34	0.25	0.72	0.008	0.006	0.037	0.027	0.078
	4-6	88.5	21.6	1.06	0.057	0.052	0.33	0.24	0.68	0.007	0.006	0.040	0.029	0.082
	6-8	87.9	20.1	1.06	0.064	0.058	0.36	0.25	0.74	0.008	0.008	0.046	0.033	0.10
	8-10	87.8	21.8	1.06	0.070	0.063	0.39	0.25	0.77	0.009	0.008	0.051	0.032	0.10
	10-15	86.7	22.0	1.07	0.078	0.059	0.37	0.19	0.70	0.011	0.008	0.053	0.027	0.10
	15-20	85.1	21.7	1.08	0.070	0.056	0.38	0.16	0.67	0.011	0.009	0.061	0.026	0.11
	25-28.5	82.8	22.0	1.09	0.086	0.055	0.36	0.12	0.62	0.016	0.010	0.067	0.023	0.12
S4	0-2	89.8	20.9	1.05	0.13	0.079	0.47	0.32	1.00	0.014	0.008	0.050	0.035	0.11
	2-4	88.4	21.9	1.06	0.089	0.068	0.39	0.27	0.82	0.011	0.008	0.048	0.033	0.10
	4-6	90.9	22.4	1.05	0.092	0.081	0.47	0.34	0.98	0.009	0.008	0.045	0.032	0.094
	6-8	86.9	22.0	1.07	0.060	0.047	0.40	0.22	0.73	0.008	0.007	0.056	0.031	0.10
	8-10	86.5	22.0	1.07	0.052	0.053	0.33	0.21	0.65	0.008	0.008	0.048	0.030	0.093
	10-15	85.6	21.4	1.07	0.066	0.055	0.34	0.18	0.65	0.010	0.008	0.053	0.028	0.10
	15-20	83.6	21.0	1.09	0.053	0.041	0.35	0.14	0.59	0.009	0.007	0.063	0.025	0.10
	25-27.5	90.8	84.0	1.01	0.080	0.048	0.37	0.15	0.65	0.007	0.004	0.034	0.014	0.060
S5	0-2	92.2	19.9	1.04	0.19	0.097	0.38	0.41	1.08	0.016	0.008	0.031	0.033	0.088
	2-4	90.7	20.0	1.05	0.17	0.095	0.34	0.39	1.01	0.017	0.009	0.033	0.038	0.098
	4-6	89.7	19.9	1.05	0.14	0.074	0.35	0.30	0.87	0.016	0.008	0.038	0.033	0.095
	6-8	89.0	19.8	1.06	0.13	0.068	0.35	0.30	0.84	0.015	0.008	0.041	0.035	0.098
	8-10	88.4	19.5	1.06	0.12	0.059	0.33	0.32	0.83	0.015	0.007	0.041	0.039	0.10
	10-15	87.5	19.1	1.07	0.13	0.062	0.34	0.27	0.80	0.018	0.008	0.046	0.036	0.11
	15-20	86.7	20.5	1.07	0.11	0.057	0.37	0.25	0.79	0.016	0.008	0.053	0.035	0.11
	25-30	83.7	20.7	1.09	0.097	0.059	0.40	0.18	0.74	0.017	0.011	0.071	0.031	0.13

Mob=Mobile phosphorus

Al=Aluminum bound phosphorus

Ca=Calcium bound phosphorus

Org=Organic phosphorus

Total=Sum of Mob, Al, Ca, and Organic bound phosphorus fractions

Table 1. Continued.....Sediment characterisitcs and phopshorus fractions in Spring Lake.

Sediment Core	Sample Interval (cm)	% Moisture	% Loss on Ignition	Density (g/cm^3)	Dry Weight Phosphorus Fractions (mg phosphorus)/(g dry weight sediment)					Mass Per Volume Wet Sediment Phosphorus Fractions (mg phosphorus)/(cm^3 wet sediment)				
					Mob	Al	Ca	Org	Total	Mob	Al	Ca	Org	Total
S6	0-2	93.8	19.2	1.03	0.29	0.16	0.34	0.67	1.46	0.018	0.010	0.022	0.043	0.093
	2-4	91.4	17.5	1.05	0.25	0.094	0.32	0.35	1.02	0.023	0.008	0.029	0.032	0.092
	4-6	90.6	17.3	1.05	0.20	0.094	0.29	0.29	0.87	0.020	0.009	0.028	0.029	0.086
	6-8	89.6	17.4	1.06	0.16	0.076	0.32	0.27	0.83	0.018	0.008	0.035	0.030	0.091
	8-10	87.9	15.6	1.07	0.16	0.074	0.32	0.23	0.79	0.021	0.010	0.042	0.030	0.10
	10-15	87.6	18.7	1.07	0.11	0.063	0.33	0.22	0.73	0.015	0.008	0.044	0.029	0.096
	15-20	86.2	18.7	1.07	0.11	0.062	0.36	0.21	0.74	0.017	0.009	0.053	0.030	0.11
	25-30	83.8	18.7	1.09	0.11	0.053	0.37	0.16	0.69	0.019	0.009	0.065	0.028	0.12
S7	0-2	94.0	19.3	1.03	0.27	0.18	0.34	0.67	1.46	0.017	0.011	0.021	0.042	0.091
	2-4	91.6	17.6	1.04	0.23	0.10	0.30	0.30	0.93	0.020	0.009	0.026	0.026	0.082
	4-6	89.4	16.9	1.06	0.17	0.089	0.33	0.26	0.86	0.020	0.010	0.038	0.029	0.10
	6-8	88.3	17.7	1.06	0.15	0.069	0.33	0.21	0.76	0.019	0.009	0.041	0.026	0.095
	8-10	87.6	19.5	1.07	0.12	0.082	0.38	0.21	0.79	0.015	0.011	0.050	0.028	0.10
	10-15	86.8	19.0	1.07	0.12	0.061	0.35	0.22	0.75	0.017	0.009	0.050	0.030	0.11
	15-20	85.5	18.3	1.08	0.14	0.081	0.34	0.17	0.73	0.021	0.013	0.053	0.027	0.11
	25-30	82.4	19.6	1.10	0.088	0.067	0.35	0.14	0.64	0.017	0.013	0.068	0.026	0.12
S8	0-2	93.7	21.4	1.03	0.35	0.17	0.28	0.73	1.53	0.023	0.011	0.018	0.047	0.099
	2-4	91.0	19.9	1.05	0.21	0.084	0.31	0.38	0.97	0.020	0.008	0.029	0.035	0.092
	4-6	89.0	18.9	1.06	0.18	0.076	0.34	0.29	0.89	0.021	0.009	0.040	0.033	0.10
	6-8	88.8	19.4	1.06	0.16	0.068	0.35	0.26	0.84	0.019	0.008	0.041	0.031	0.099
	8-10	88.6	19.5	1.06	0.11	0.070	0.35	0.27	0.80	0.014	0.008	0.042	0.032	0.096
	10-15	87.0	20.4	1.07	0.11	0.064	0.35	0.23	0.76	0.015	0.009	0.049	0.033	0.11
	15-20	85.6	20.2	1.08	0.091	0.060	0.41	0.21	0.77	0.014	0.009	0.063	0.033	0.12
	25-30	82.0	19.7	1.10	0.11	0.065	0.37	0.15	0.70	0.023	0.013	0.074	0.029	0.14
S9	0-2	85.4	17.8	1.08	0.056	0.046	0.34	0.20	0.65	0.009	0.007	0.054	0.032	0.10
	2-4	80.3	16.5	1.11	0.031	0.033	0.36	0.12	0.54	0.007	0.007	0.079	0.025	0.12
	4-6	79.6	17.9	1.12	0.040	0.032	0.35	0.14	0.56	0.009	0.007	0.080	0.031	0.13
	6-8	75.0	12.9	1.15	0.032	0.019	0.33	0.10	0.48	0.009	0.005	0.094	0.030	0.14
	8-10	74.2	12.5	1.16	0.035	0.028	0.35	0.098	0.51	0.011	0.008	0.11	0.029	0.15
	10-15	64.9	8.6	1.25	0.027	0.018	0.68	0.052	0.78	0.012	0.008	0.30	0.023	0.34
	15-20	80.0	18.4	1.11	0.041	0.027	0.29	0.027	0.39	0.009	0.006	0.064	0.006	0.085
	25-30	78.7	18.9	1.12	0.032	0.023	0.35	0.026	0.43	0.008	0.005	0.083	0.006	0.10

Mob=Mobile phosphorus
Al=Aluminum bound phosphorus
Ca=Calcium bound phosphorus
Org=Organic phosphorus
Total=Sum of Mob, Al, Ca, and Organic bound phosphorus fractions

Table 1. Continued.....Sediment characterisitcs and phopshorus fractions in Spring Lake.

Sediment Core	Sample Interval (cm)	% Moisture	% Loss on Ignition	Density (g/cm^3)	Dry Weight Phosphorus Fractions (mg phosphorus)/(g dry weight sediment)					Mass Per Volume Sediment Phosphorus Fractions (mg phosphorus)/(cm^3 wet sediment)				
					Mob	Al	Ca	Org	Total	Mob	Al	Ca	Org	Total
S10	0-2	93.7	21.2	1.03	0.41	0.33	0.31	1.51	2.56	0.026	0.021	0.020	0.098	0.17
	2-4	92.0	17.9	1.04	0.41	0.17	0.27	0.71	1.57	0.034	0.014	0.023	0.059	0.13
	4-6	89.9	14.9	1.06	0.40	0.10	0.26	0.32	1.08	0.043	0.011	0.027	0.034	0.11
	6-8	88.8	13.9	1.06	0.34	0.091	0.29	0.25	0.98	0.041	0.011	0.035	0.029	0.12
	8-10	89.0	14.0	1.06	0.31	0.088	0.27	0.25	0.92	0.037	0.010	0.031	0.030	0.11
	10-15	88.9	14.3	1.06	0.27	0.082	0.27	0.24	0.86	0.032	0.010	0.032	0.028	0.10
	15-20	87.6	14.1	1.07	0.24	0.087	0.30	0.20	0.83	0.032	0.012	0.041	0.026	0.11
	25-30	84.8	14.8	1.09	0.21	0.075	0.31	0.17	0.76	0.034	0.012	0.051	0.029	0.13
	30-35	82.6	16.1	1.10	0.22	0.085	0.33	0.16	0.80	0.043	0.016	0.063	0.031	0.15
S11	0-2	93.1	20.1	1.04	0.40	0.26	0.34	0.89	1.88	0.029	0.019	0.024	0.064	0.14
	2-4	91.3	18.1	1.05	0.32	0.12	0.27	0.39	1.10	0.029	0.011	0.024	0.036	0.10
	4-6	90.3	17.2	1.05	0.29	0.099	0.26	0.28	0.93	0.030	0.010	0.026	0.029	0.095
	6-8	88.5	15.7	1.06	0.34	0.096	0.29	0.22	0.95	0.041	0.012	0.036	0.027	0.12
	8-10	87.9	14.7	1.07	0.27	0.088	0.29	0.23	0.88	0.035	0.011	0.038	0.030	0.11
	10-15	86.7	15.3	1.07	0.28	0.088	0.32	0.18	0.87	0.040	0.013	0.046	0.026	0.12
	15-20	86.7	16.0	1.07	0.23	0.095	0.30	0.21	0.84	0.033	0.013	0.043	0.030	0.12
	25-30	84.2	16.4	1.09	0.21	0.091	0.32	0.17	0.79	0.037	0.016	0.055	0.029	0.14
	30-35	82.6	14.2	1.10	0.21	0.10	0.32	0.13	0.76	0.040	0.019	0.062	0.026	0.15
S12	0-6	30.2	1.2	1.74	0.011	0.006	0.19	0.015	0.22	0.013	0.007	0.23	0.018	0.27

Mob=Mobile phosphorus
Al=Aluminum bound phosphorus
Ca=Calcium bound phosphorus
Org=Organic phosphorus
Total=Sum of Mob, Al, Ca, and Organic bound phosphorus fractions

Table 2. Summary of phosphorus fraction average concentrations in top 6 cm for each sediment core in Spring Lake.

Core	Mobile Phosphorus (g/m^2-cm)	Organic Phosphorus (g/m2-cm)	Releasable Phosphorus (g/m2-cm)
S1	0.16	0.33	0.24
S2	0.082	0.28	0.15
S3	0.074	0.26	0.14
S4	0.11	0.33	0.20
S5	0.16	0.35	0.25
S6	0.20	0.34	0.29
S7	0.19	0.32	0.27
S8	0.21	0.39	0.31
S9	0.082	0.30	0.16
S10	0.34	0.64	0.50
S11	0.29	0.43	0.40
S12	0.13	0.18	0.18
Overall Average	0.17	0.35	0.26

Notes:

g/m2-cm=grams of phosphorus per square meter per centimeter

Releasable phosphorus=mobile phosphorus+0.25*organic phosphorus

Table 3. Summary of alum dose calculations for the prescribed alum treatment zones in Spring Lake. Highlighted cells show the prescribed alum treatment dose.

(a) Treatment Zone 1

Releasable Phosphorus (g/m^2-cm)	Ratio of Aluminum to Aluminum Bound Phosphorus	Aluminum Dose (g Al/m^2-cm)	Treatment Depth (cm)	Aluminum Dose (Gallons at Treatment Depth)	Aluminum Bound Phosphorus Formed (g Al-P/m^2-cm)	Releasable Phosphorus Converted to Al-P (g/m^2-cm)	Remaining Mobile Phosphorus (g Mob-P/m^2-cm)	% Releasable Phosphorus Removal
0.31	0	0	---	---	---	---	0.311	0
0.31	25	4.1	6	450	0.16	0.20	0.114	63
0.31	50	10.8	6	1,200	0.22	0.26	0.052	83
0.31	75	17.2	6	1,900	0.23	0.27	0.036	89
0.31	100	24.5	6	2,700	0.24	0.29	0.017	95
0.31	150	37.9	6	4,200	0.25	0.30	0.007	98

(b) Treatment Zone 2

Releasable Phosphorus (g/m^2-cm)	Ratio of Aluminum to Aluminum Bound Phosphorus	Aluminum Dose (g Al/m^2-cm)	Treatment Depth (cm)	Aluminum Dose (Gallons at Treatment Depth)	Aluminum Bound Phosphorus Formed (g Al-P/m^2-cm)	Releasable Phosphorus Converted to Al-P (g/m^2-cm)	Remaining Mobile Phosphorus (g Mob-P/m^2-cm)	% Releasable Phosphorus Removal
0.20	0	0	---	---	---	---	0.200	0
0.20	25	2.0	6	220	0.08	0.10	0.102	49
0.20	50	6.1	6	700	0.12	0.15	0.055	73
0.20	75	9.4	6	1,000	0.13	0.15	0.049	75
0.20	100	13.9	6	1,500	0.14	0.17	0.034	83
0.20	150	22.1	6	2,400	0.15	0.18	0.023	88

Table 4. Summary of Spring Lake alum dosing parameters.

Treatment Zone	**Treatment Area** (Acres)	**Aluminum Dose Ratio** (Aluminum Added per Aluminum Bound Phosphorus Molecule Formed)	**Alum Dose** (Grams Aluminum Per Square Meter of Lake Bottom)	**Gallons of Alum** (to Be Applied Per Acre)	**Total Gallons** of Alum to Be Applied
Zone 1	194	75:1	103	1,900	369,000
Zone 2	215	75:1	57	1,000	215,000
Total	409				584,000

Units

Aluminum Dose Ratio=Aluminum Added per Alumnum Bound Phosphorus Molecule Formed

Table 5. Cost estimate for a full dose application of alum to Spring Lake. It is estimated that the applied per gallon cost of alum is $1.60. This includes the cost of the contractor to apply the alum.

Task	**Cost Estimate**
Prepare Bidding Document, Bidding	$10,000
Treatment Oversight	$10,000
Administration	$2,000
Public Relations	$2,000
Meetings/Administration	$2,000
Alum Treatment Contractor Costs (includes mobilization and demobilization)	$960,000
Total	$986,000

Table 6. Summary of phosphorus mass in Spring Lake sediment.

a. Phosphorus Balance in Sediment

Lake Area	Area (acres)	**Average Releasable Phosphorus Concentration in Top 6 cm of Sediment** (grams P/meter^2 - centimeter)	**Average Total Phosphorus Concentration in Top 6 cm of Sediment** (grams P/meter^2 - centimeter)	Total Mass (pounds) of **Releasable Phosphoru**s in the Top 6 Centimeters	Total Mass (pounds) of Total Phosphorus in the Top 6 Centimeters	Total Mass (pounds) of Total Phosphorus in the Top 10 Centimeters
Treatment Area 1	194	0.310	---	3,200	---	---
Treatment Area 2	215	0.200	---	2,300	---	---
Untreated Area of Lake	178	0.150	---	1,400	---	---
Whole Lake	587	0.221	1.26	6,900	40,000	76,000

Note: Total phosphorus includes the sum of the following phopshorus fractions: mobile + organic + aluminum bound + calcium bound

b. Phosphorus Balance for Water Column

Treatment Zone	Average Total Releasable-P in Sediment (grams P/ meter^2-centimeter)		% Reduction in Releasable-P with Treatment	Estimated Internal Loading Rate(1) (mg P/m^2/day)	Estimated Reduction in Phosphorus Loading with Alum Treatment (pounds/year)(2)	Estimated Average Phosphorus Concentration in Lake Water Column with Alum Treatment (ug/L)(3)
	Before Treatment	After Treatment				
Area 1	0.310	0.036	89	1.9	---	---
Area 2	0.200	0.049	75	4.3	---	---
Weighted Average	0.252	0.043	82	3.1	4,200	85

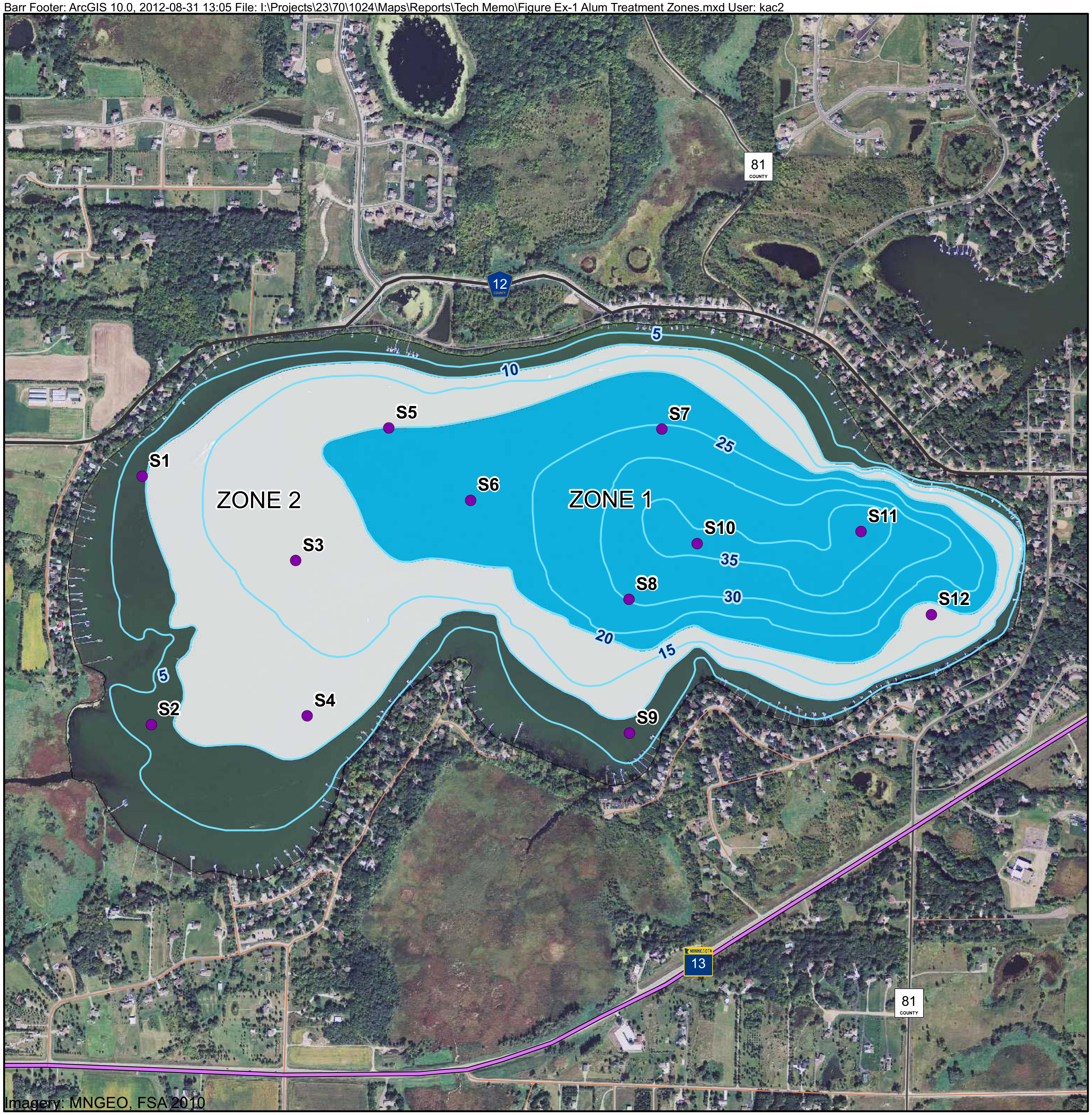
(1) Internal phosphorus loading rate after alum treatment estimated from the TMDL-determined internal loading rate 17 mg/m2/day. Internal phosphorus loading after treatment = Internal Loading Rate *(100- % Reduction in Releasable P)/100.

(2) Internal phosphorus loading after alum treatment estimated from the TMDL-determined internal loading of 5,161 pounds phosphorus used for all modeling years. Internal phosphorus loading after treatment = Internal Loading *(100- % Reduction in Releasable P)/100. Internal loading at depths of 10 feet or less assumed negligible.

(3) In-lake total phosphorus concentration estimated from the 1998 through 2006 annual average lake response modeling based on the relationship between total loading and in-lake phosphorus concentrations in the TMDL report (example calculations from 1998 and 2000 are shown in Figure 7).

Figures

Barr Footer: ArcGIS 10.0, 2012-08-31 13:05 File: I:\Projects\23\70\1024\Maps\Reports\Tech Memo\Figure Ex-1 Alum Treatment Zones.mxd User: kac2



S1 Sediment Core Location

Bathymetric Contours (ft)

Treatment Zones

Zone 1 1,900 gallons/acre

Zone 2 1,000 gallons/acre

N

Feet

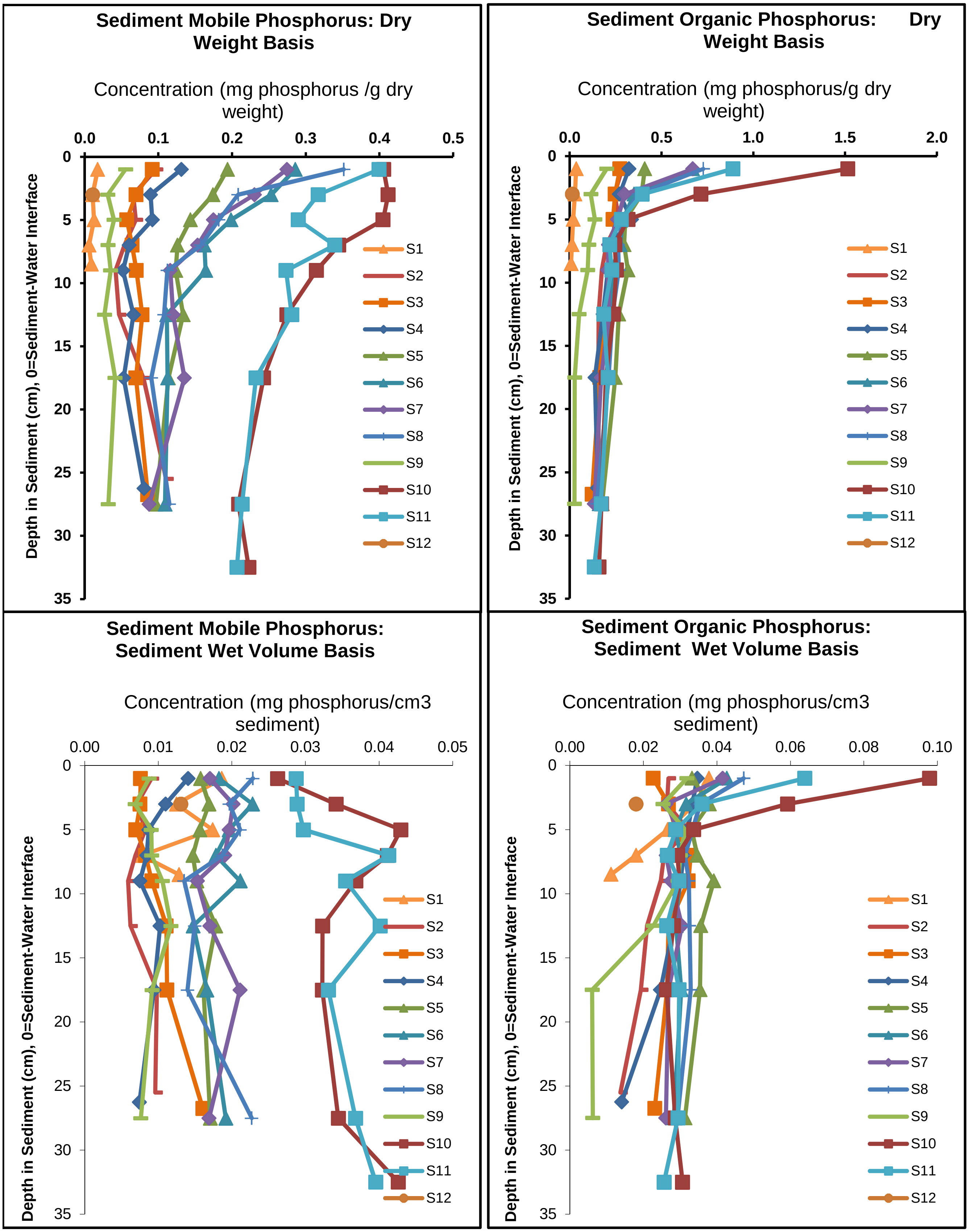
0 1,200 2,400

BARR

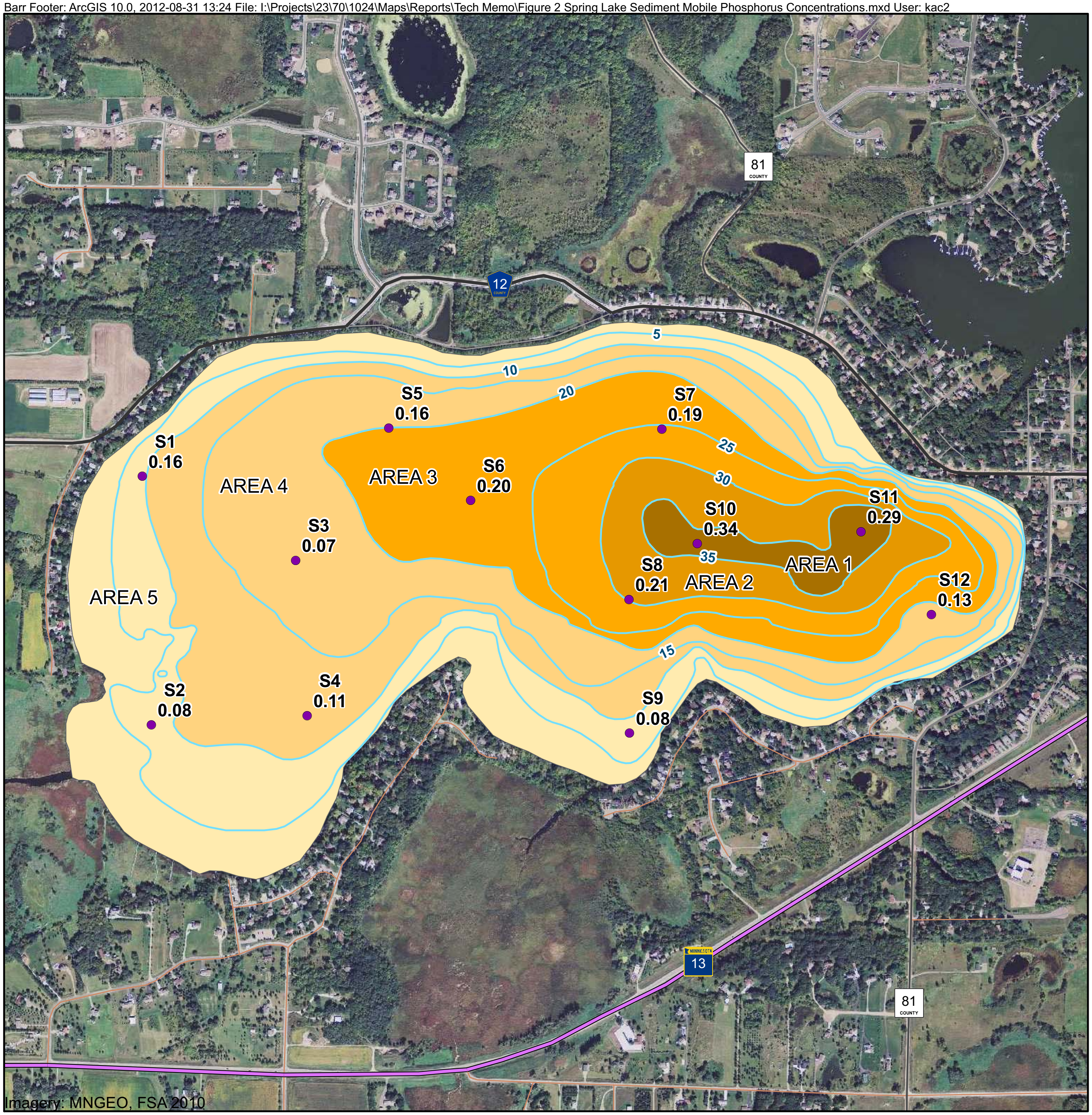
Figure Ex -1

SPRING LAKE ALUM
TREATMENT ZONES
Prior Lake - Spring Lake
Watershed District

Figure 1. Demonstration of the depth distribution of mobile and organic phosphorus in Spring Lake sediment for sediment cores S1 through S12.



Barr Footer: ArcGIS 10.0, 2012-08-31 13:24 File: I:\Projects\23\70\1024\Maps\Reports\Tech Memo\Figure 2 Spring Lake Sediment Mobile Phosphorus Concentrations.mxd User: kac2



S1 Sediment Core Location

0.16 Mobile-P ($g\ m^{-2}\ cm^{-1}$)

Bathymetric Contours (ft)

Estimated Mobile Phosphorus Concentration ($g\ m^{-2}\ cm^{-1}$)

- 0.08 - 0.10
- 0.10 - 0.16
- 0.16 - 0.21
- 0.21 - 0.29
- 0.29 - 0.34

Area	Area (Acres)
Area 1	17
Area 2	43
Area 3	134
Area 4	214
Area 5	178

N

Feet

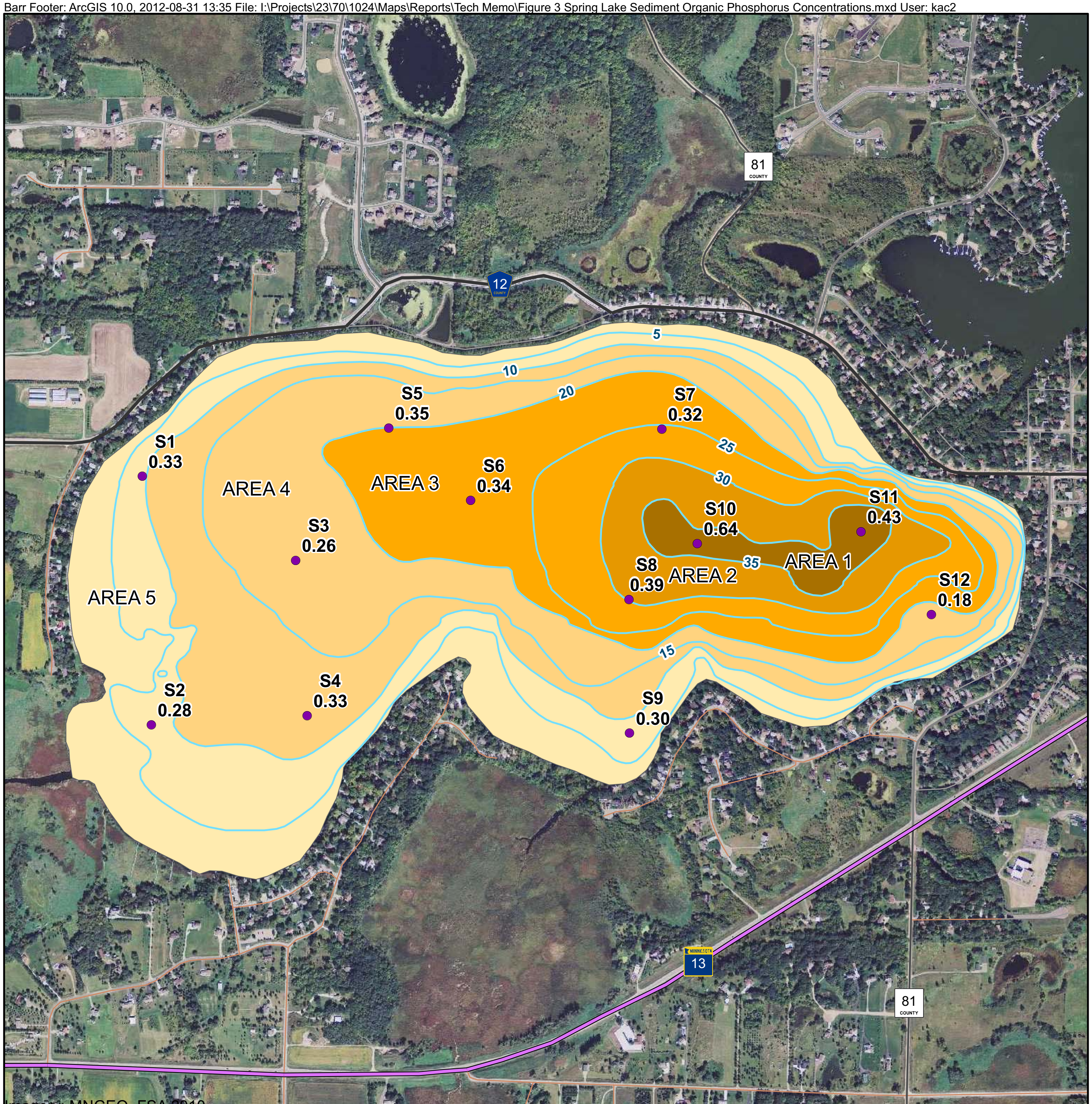
0 1,200 2,400

BARR

Figure 2

SPRING LAKE SEDIMENT MOBILE PHOSPHORUS CONCENTRATIONS

Prior Lake - Spring Lake Watershed District



S1 Sediment Core Location
0.33 Organic-P (g m^{-2} cm^{-1})
Bathymetric Contours (ft)

Estimated Organic Phosphorus Concentration (g m^{-2} cm^{-1})

- 0.18 - 0.26
- 0.26 - 0.32
- 0.32 - 0.39
- 0.39 - 0.43
- 0.43 - 0.64

Area	Area (Acres)
Area 1	17
Area 2	43
Area 3	134
Area 4	214
Area 5	178

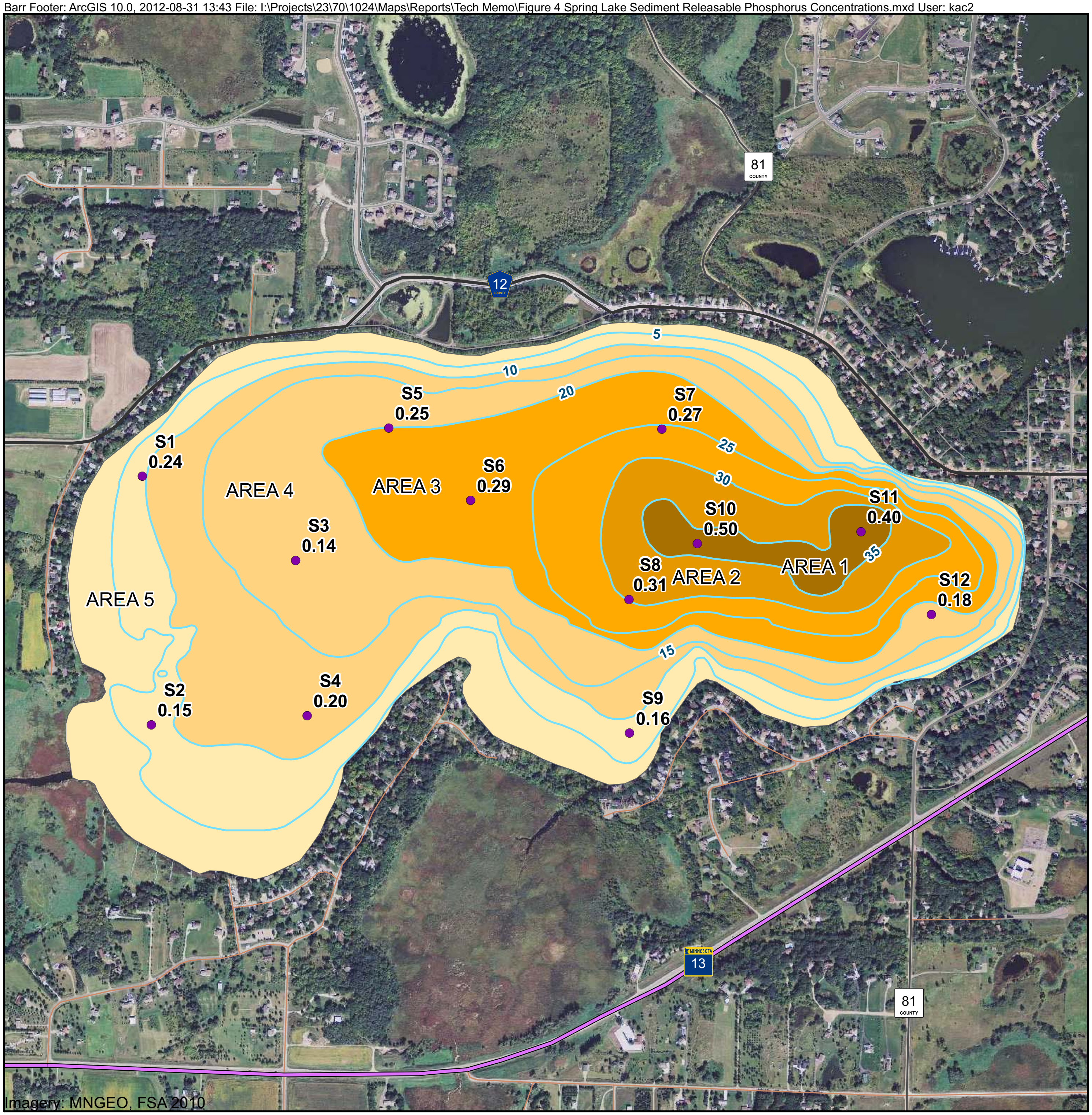
N

Feet
0 1,200 2,400

BARR

Figure 3

SPRING LAKE SEDIMENT ORGANIC PHOSPHORUS CONCENTRATIONS
Prior Lake - Spring Lake Watershed District



S1 Sediment Core Location
0.24 Releasable-P (g m^{-2} cm^{-1})

Bathymetric Contours (ft)

Estimated Releasable Phosphorus Concentration (g m^{-2} cm^{-1})

- 0.15 - 0.16
- 0.16 - 0.25
- 0.25 - 0.31
- 0.31 - 0.40
- 0.40 - 0.50

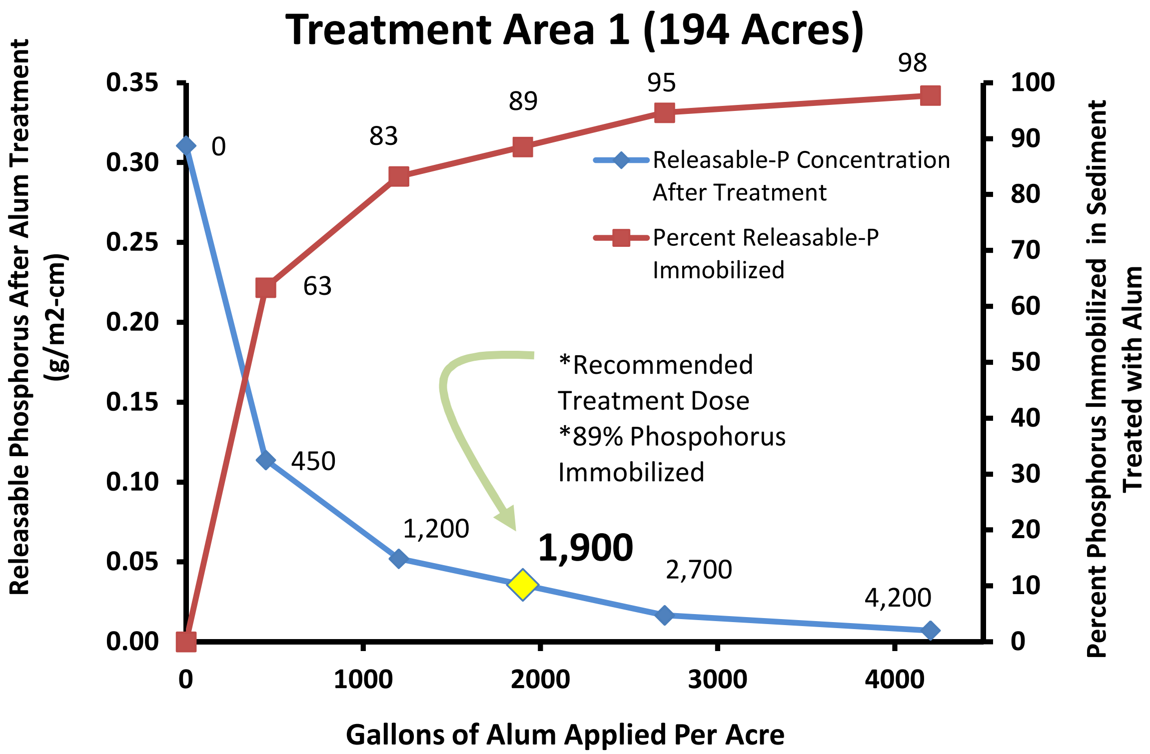
Area	Area (Acres)
Area 1	17
Area 2	43
Area 3	134
Area 4	214
Area 5	178

Feet
0 1,200 2,400

Figure 4

SPRING LAKE SEDIMENT RELEASABLE PHOSPHORUS CONCENTRATIONS
Prior Lake - Spring Lake Watershed District

Figure 5. Predicted reduction in releasable phosphorus with alum treatment for a range of alum doses, Spring Lake.



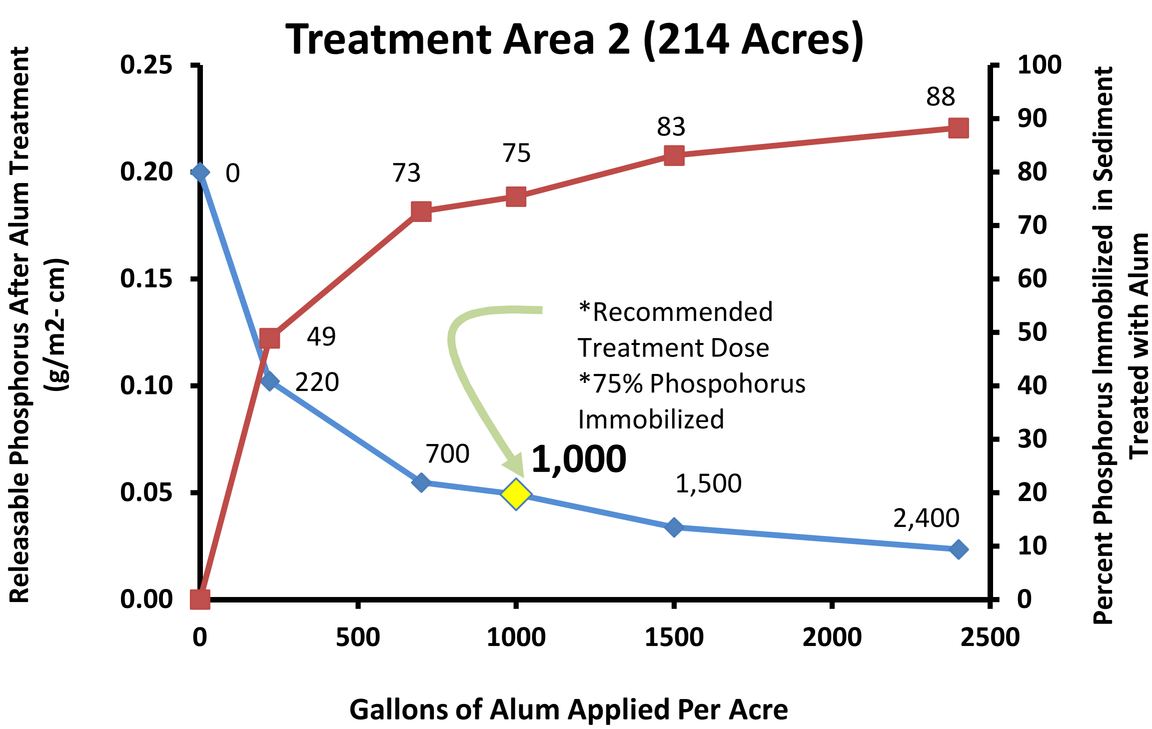
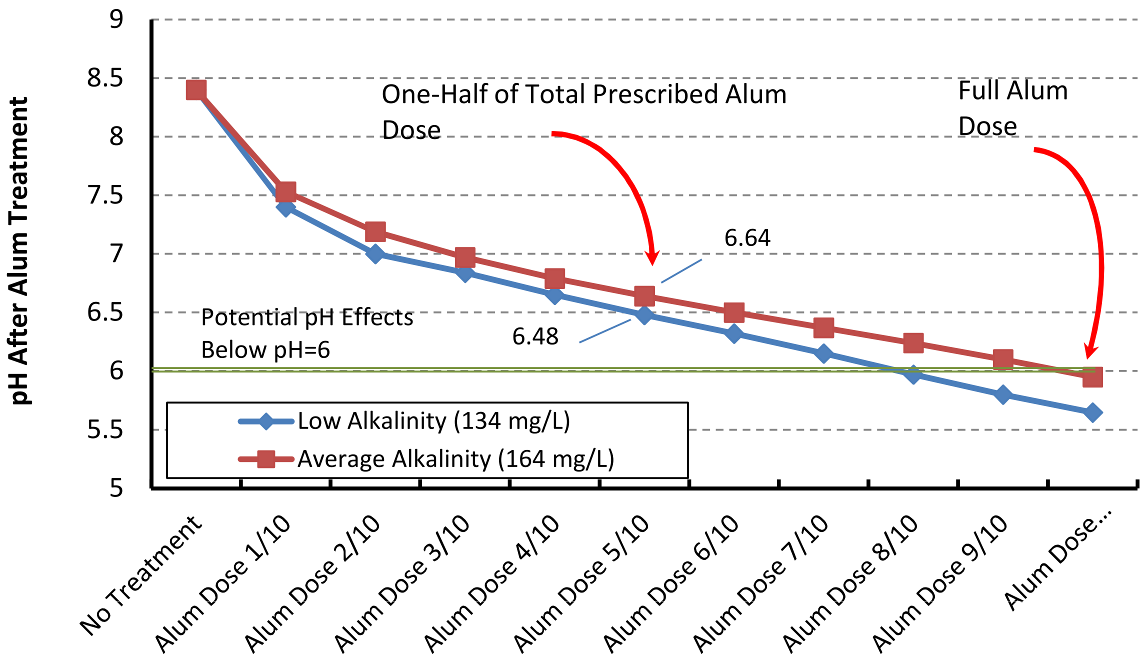


Figure 6. pH reduction with the application of alum. pH effect is shown with a range of alum doses. The full prescribed dose (Alum Dose 10/10) is 584,000 gallons of alum. Each dose shown is a fraction of the total dose. The expected pH after alum treatment is based upon pH levels in Spring Lake expected in the fall or spring, low and average alkalinity levels measured in the lake, and temperatures of 11 deg C. pH was modeled using the chemical speciation model PHREEQC.



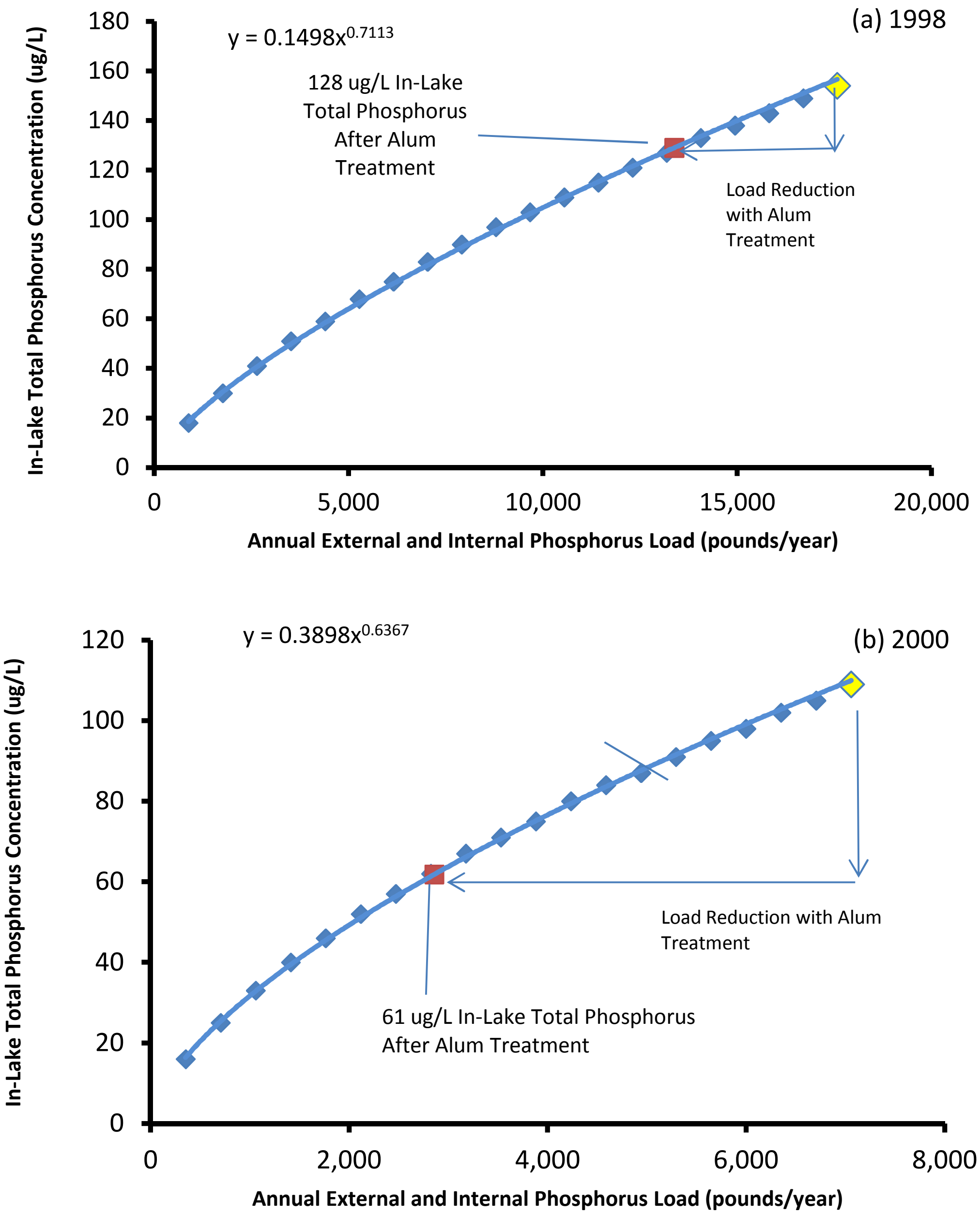


Figure 7. Estimated change in in-lake total phosphorus concentration with the recommended alum dose. Estimate based upon the 1998 (a) and 2000 (b) load reduction table for Spring Lake provided in the 2011 TMDL document (Wenk, 2011). Change in in-lake total phosphorus based upon a 75:1 alum dose (1,000-1,900 gallons alum/acre) and a reduction in the internal loading rate from 5,161 to 929 pounds per year.