Upper Prior Lake

In-Lake Phosphorus Management Plan

Prepared for the Prior Lake Spring Lake Watershed District

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Executive Summary

Addressing poor water quality in Upper Prior Lake has been identified in the Watershed's Plan as a key focus area. With upstream treatment of Spring Lake with alum to reduce internal nutrient loading, lower concentrations of phosphorus are reaching Upper Prior Lake. However, as past studies have indicated, there is still an internal reservoir of phosphorus in Upper Prior Lake that continues to hinder the improvement of water quality in the Lake. Water quality data collected from 2002 to 2015 shows that average annual surface water phosphorus and chlorophyll-a concentrations are decreasing; however, summertime spikes in phosphorus and chlorophyll-a concentrations are still noted annually which are correlated with algae blooms and perceived poor water quality. These seasonal trends are heavily correlated with loads derived from internal sources including loads derived from the release of phosphorus from the sediment in areas of the lake that go anoxic during the summer. It is also important to note that near-shore water quality can vary substantially from the open water areas where surface water monitoring takes place. Algae blooms and detached aquatic plants can blow and congregate in certain areas within the lake making water quality appear worse than it is.

In early 2016, the PLSLWD Board authorized further investigations into the extent and how to address internal phosphorus loads impacting the lake. The interconnected lake dynamics necessitated looking at the interactions of inactivating phosphorus release from bottom sediments, carp, and appropriate native aquatic plant re-establishment. Improving the water quality of Upper Prior Lake will require both management of anoxic P release in the lake sediment, in addition to re-establishing submerged vegetation throughout more of the shallow depths to maintain a clear water state. Carp management is also needed to increase the effectiveness and longevity of the alum treatment and re-establishment of aquatic vegetation as carp can disturb the alum floc layer and negatively impact aquatic vegetation growth.

The September, 2016 Upper Prior Lake In-Lake Phosphorus Management Plan identified several potential sediment P management options most applicable to Upper Prior Lake, including:

- **Phosphorus Cycling**
    - **Alum (in-lake)**
    - Hypolimnetic aeration (not recommended)
    - Sediment dredging (not recommended)
- **Carp Management**
    - **Harvest**
    - **Exclusion**
- **Vegetation Management**
    - **Herbicide of invasive aquatic plants**

The options in bold in the list above represent those recommended based on the analyses presented in the Management Plan. These options were investigated in further detail in the Management Plan which includes an examination of the benefits, challenges, and cost-benefit of each option. Analyses completed as part of this study included a) collection of 12 lake sediment cores by St. Croix Watershed Research Station in 2016 to confirm potential for internal P loading from bottom sediments and to determine appropriate alum dosing rates and distribution, and b) review of current and historic fisheries surveys (carp population numbers) and aquatic vegetation surveys to determine appropriate fish and aquatic plant management techniques.

We identified the following combined approach of three management activities to be the most practical and cost-effective way to address internal phosphorus loading to Upper Prior Lake:

1. Alum (in-lake): Alum treatment of lake areas with the high sediment P concentrations
2. Carp Management – Harvest and Exclusion: Reduction of common carp population through harvest and elimination of migration from adjacent waterbodies
3. Vegetation Management – Herbicide of invasives: Management of invasive plant species through targeted herbicide applications to allow natives to establish in shallow areas

These activities should follow a chronological progression whereby carp numbers are first reduced (through harvest) and stabilized (by eliminating migration to the lake using fish barriers). Carp management will be undertaken as per the current PLSLWD funded program which includes harvest and electro-fishing surveys of carp to allow radio- and PIT (passive integrated transponder) tagging to determine Upper Prior population numbers and distribution as well as the extent of migration to and from adjacent waterbodies. As a result of tagging activities, installation of one or more barriers is expected to be necessary (in addition to the barrier already installed at Arctic Lake). One potential barrier location is the channel that connects Spring and Upper Prior Lakes. Reducing the carp population is an important step to reduce disturbance of the layer of alum-treated bottom sediment that can result in decreased alum effectiveness as well as foster re-establishment of native vegetation that carp often impede. Further, a large carp population can, in and of itself, contribute to internal P loading by disturbing bottom sediments.

Once the carp population is under control, the lake will be treated with at least two or more alum doses to bind releasable P in the lake-bottom sediments. Once releasable P in the water column has been reduced and lake clarity improves, the density and distribution of emergent vegetation will increase. Because Upper Prior Lake already has significant populations of two undesirable invasive species, curly leaf pondweed and Eurasian watermilfoil, it is very likely that these species will proliferate and dominate in a clearer water environment created by the alum treatment. As a result, on-going management of these invasive species with herbicide treatments will be necessary.

The Spring Lake alum treatment achieved the upstream lake load reductions identified by the TMDL. Prior to the alum treatment, Spring Lake contributed 38% of total load to Upper Prior Lake; equivalent to approximately 1,982 pounds. The total load reduction from Spring Lake as a result of the alum treatment + ferric chloride treatment is equivalent to 1,426 pounds, assuming the in-lake concentration for Spring Lake remains at 40 ug/L. The summer average P concentration in Spring Lake was around 40 ug/L in 2014 and 2015; however, the summer average P concentration in 2016 was 60 ug/L. The anticipated impact of another alum treatment on Spring Lake would be to increase the longevity of the alum treatment with an ultimate goal of maintaining a summer average P concentration at/or near 40 ug/L.

The management activities of the treatment plan with associated timing and costs are presented in Table 11 below. Adoption of the in-lake management plan would be expected to achieve all of the internal load reductions identified by the Upper Prior Lake TMDL. It is also important to note that these proposed activities are conservative estimates of the cost and effort to achieve Upper Prior Lake phosphorus goals; as these management activities are undertaken iteratively, an adaptive management approach may allow us to forego some proposed activities/costs.

Table 1. Recommended Management Plan Activities

	2017		2018		2019	2020	2021
Management Activity	**Winter**	**Spring**	**Winter**	**Spring**			
Carp harvests[1]	**$4,000***		**$4,000***				
Electrofishing survey with radio and/or PIT tagging to evaluate carp population and migration		**$7,250[2]***		**$4,000[3]***			
Design/Install carp migration barriers[4]				**$4,000***	**$4,000***		
Alum treatments[5]				**$420,000**		**$420,000**	
Invasive plant management[6]		**$25,000**		**$25,000**	**$25,000**	**$25,000**	**$25,000**
Total	**$4,000**	**$32,250**	**$4,000**	**$453,000**	**$29,000**	**$445,000**	**$25,000**
						Grand Total	**$992,250**

* Covered by existing grant funding and budgeted matching dollars; costs as per PLSLWD 2013 Carp Management Plan except where noted

1 Two winter seining harvests: $4,000 each

2 Setup and operation of PIT tagging antennae and data collection equipment; assumes $12,425 cost in fall 2016 for electro-fishing and tagging activities. Costs as per WSB Aug. 22, 2016 memo plus $2,000 assumed District staff time.

3 Electro-fishing carp survey for updated population assessment

4 Assumes installation of up to two additional barriers based on carp migration analysis: $4,000 each

5 Two alum doses (273 acres at 231,000 gallons each): $420,000 each. Based on same cost per gallon ($1.76) and no buffering solution as Spring Lake alum application.

6 Assumes 15% of vegetated acres (Up to 54.5 acres) treated per year: $25,000 each

1 Introduction

The purpose of this report is to identify an in-lake management plan for reducing internal phosphorus (P) loading from bottom sediments to Upper Prior Lake. The report consists of a detailed overview of the recommended in-lake management plan with a 5-year schedule and annual costs, followed by individual sections discussing each in-lake P management option identified as most applicable to Upper Prior Lake based on options outlined in the January 12, 2016 EOR memo to the Prior Lake Spring Lake Watershed District (PLSLWD) Board.

Existing data was compiled to assist with analyzing in-lake treatment options. Lake P sampling data through June 2016 as well as carp surveying data were provided courtesy of the Prior Lake Spring Lake Watershed District (PLSLWD). Aquatic vegetation data from the ongoing annual BioBase data collection as well as point intercept surveys conducted by Blue Water Science provided insights into the current distribution and density of emergent and invasive vegetation, respectively. Of principal importance for evaluating internal P loading and the cost feasibility of alum treatments in Upper Prior Lake was core sampling of the lake bottom sediments. The morphometry of Upper Prior Lake is unique in that it contains two relatively deep basins yet is mostly littoral (Figure 1). These data are discussed in detail in the following sections.

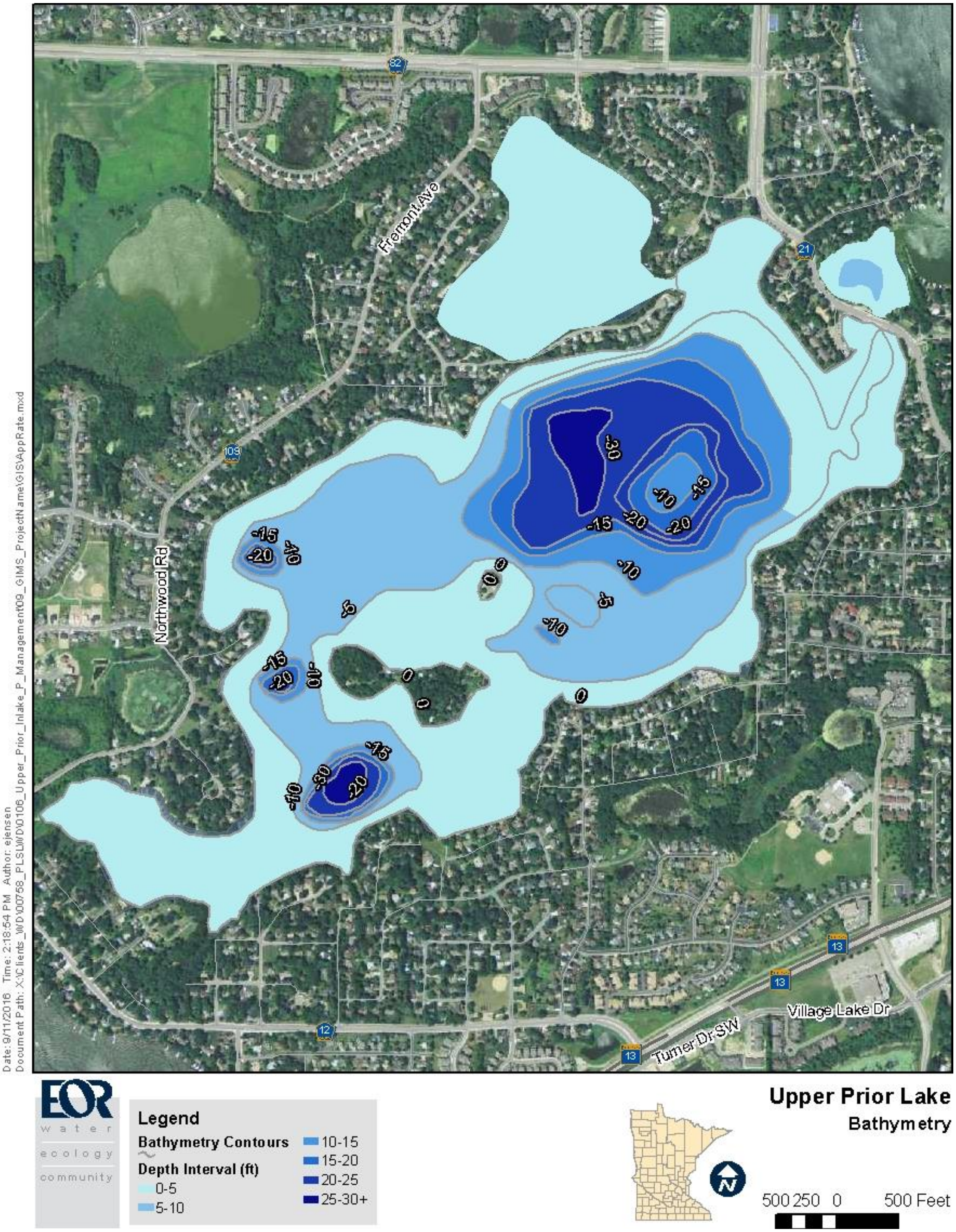

Figure 1. Upper Prior Lake Bathymetry

2 Phosphorus Cycling Management

2.1 Sediment Coring Analysis & Results

Twelve sediment cores were taken by St. Croix Watershed Research Station staff on May 10, 2016. Core locations were distributed to get a picture of sediment P at representative depths, both shallow and deep. Each core section was analyzed by the St. Croix Watershed Research Station for sediment total phosphorus and phosphorus fractions including the refractory forms of Mineral-bound P, Recalcitrant Organic-P, and Al-bound P and the labile or readily exchangeable forms of Fe-bound P, Labile Organic-P, and Loosely-bound P associated with internal loading. Estimates of Releasable Phosphorus (RP; the fraction that is readily available for algal growth) were determined by taking the sum of the Fe-bound P, loosely-bound P, and Labile Organic-P concentrations. Sediment cores were sectioned in 2-cm increments to a sediment depth of 10 cm. Statistical analyses were performed to identify the presence/absence of statistically significant trends in RP content based on sediment depth within the sediment core (0-2 cm, 2-4 cm, and 4-6 cm), and also the depth of the lake at the point where the sample was taken.

2.2 Mapping Releasable Phosphorus & Treatment Zones

A weight of evidence approach (Figure 2) was employed to map alum dosing rates and treatment zones. The final alum dosing map (Figure 7) is based on lake bathymetry, sediment core RP content, bottom hardness measurements collected from the 2015 Aquatic Vegetation Density Mapping-BioBase report (Mielke and Rockney, 2016), and lake sediment characteristics from the 2008 curly-leaf and Eurasian watermilfoil growth potential Report (McComas, 2008).

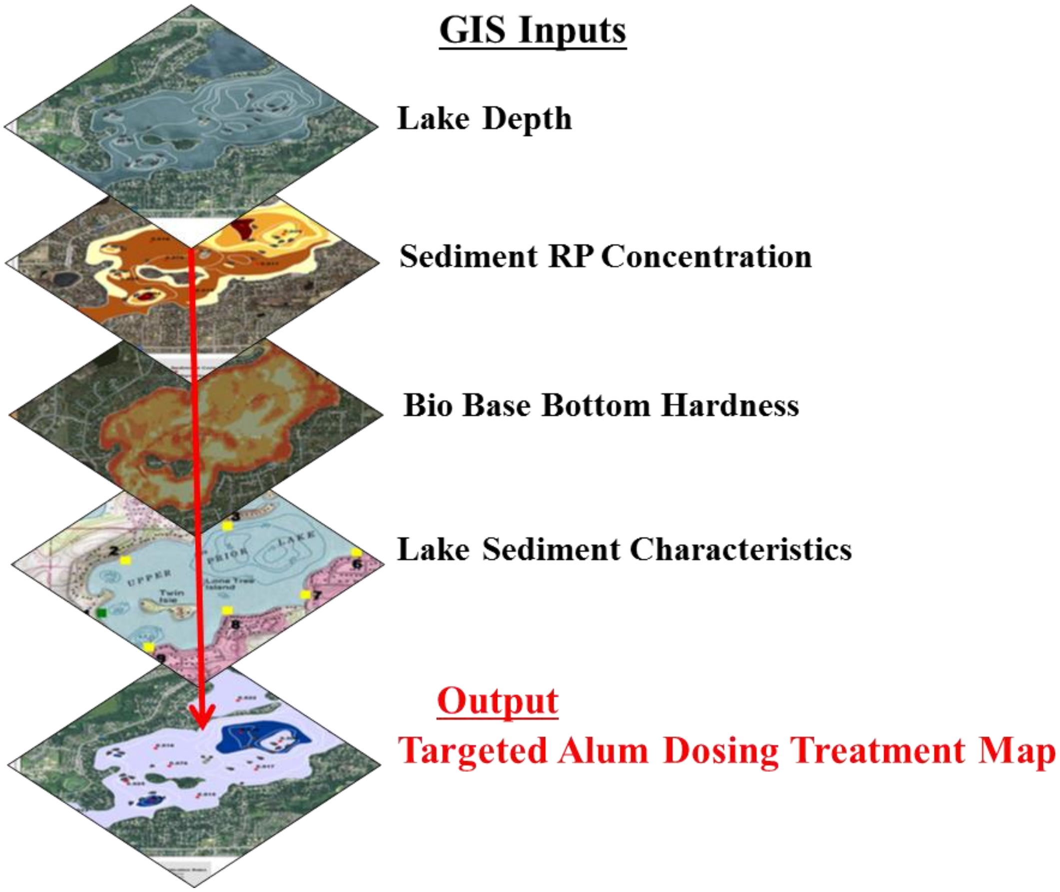

Figure 2. GIS inputs (weight of evidence) used to develop targeted alum dosing treatment plan.

2.2.1.1 Sediment Core Depth RP Concentration

The concentration of RP decreases with increasing depth within the sediment core, statistically significant differences are present between RP concentrations in the top 2 centimeters (0-2cm) of the sediment column in comparison with the RP concentration from 4-6 centimeters (Figure 3). There was not a statistically significant difference between observed RP concentrations in the top 2 centimeters (0-2cm) in comparison with the RP concentration from 2-4 centimeters. Overall, it can be seen that releasable P concentrations are more concentrated in the top 6 centimeters of sediment column. Alum dosing rates were adjusted accordingly to target only the amount of phosphorus present within the top 6 centimeters of the water column.

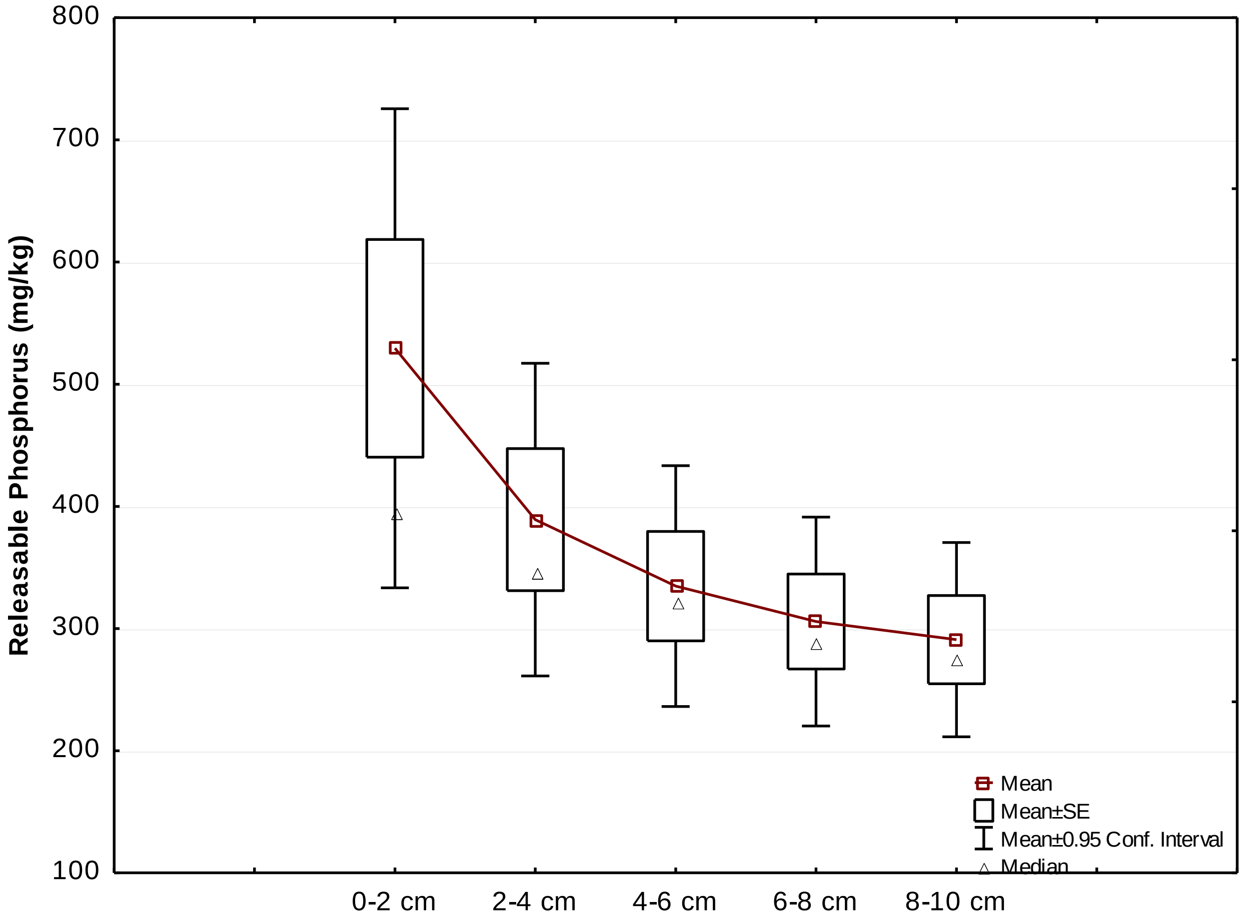

Figure 3. Releasable phosphorus (RP) concentration by sediment core depth showing highest RP concentrations in the first 6 cm of cores.

2.2.1.2 Sediment Core Depth RP Concentration with Lake Depth

In addition to differences in RP concentration within the sediment core, there are statistically significant differences (increasing trend) in RP concentrations with depth. The most significant differences in sediment RP content occur at depths greater than 25 feet (Figure 4). This trend of increasing RP concentration with depth justifies ensuring all deep zones within the lake receive alum treatment.

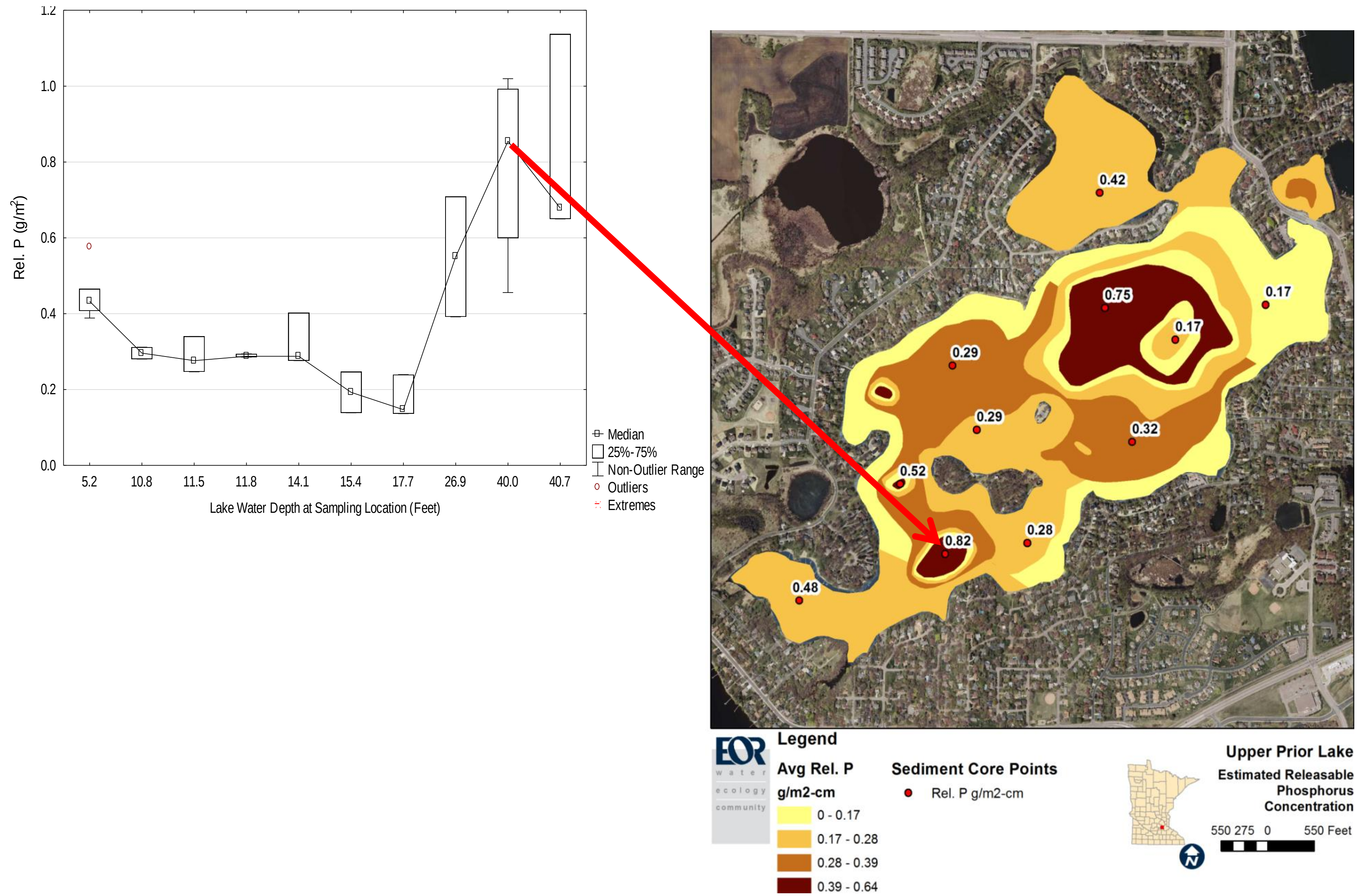

Figure 4. Releasable phosphorus (Rel. P) content within the first six centimeters of the sediment core increases significantly in the portions of the lake that are greater than 25 feet.

2.2.1.3 Bottom Hardness

A comparison of bottom hardness from the 2015 Aquatic Vegetation Density Mapping- BioBase report suggested that both of the shallow sediment samples (less than 10 feet deep) collected from shallow bays (Mud Bay and the Boat Ramp Bay west of Twin Isle) were soft mucky soils. These sediments are not representative of the "hard" band of sandier sediment, also at shallower depths, that was mapped around the edge of the lake. The sediment core collected from site 10 had the lowest observed RP content (0.17 g/m^2-cm). This core was collected from a location with a similar hardness rating observed in the hard band of sandier sediment that was mapped around the edge of the lake (Figure 5). Alum dosing rates were reduced accordingly based on the bottom hardness findings.

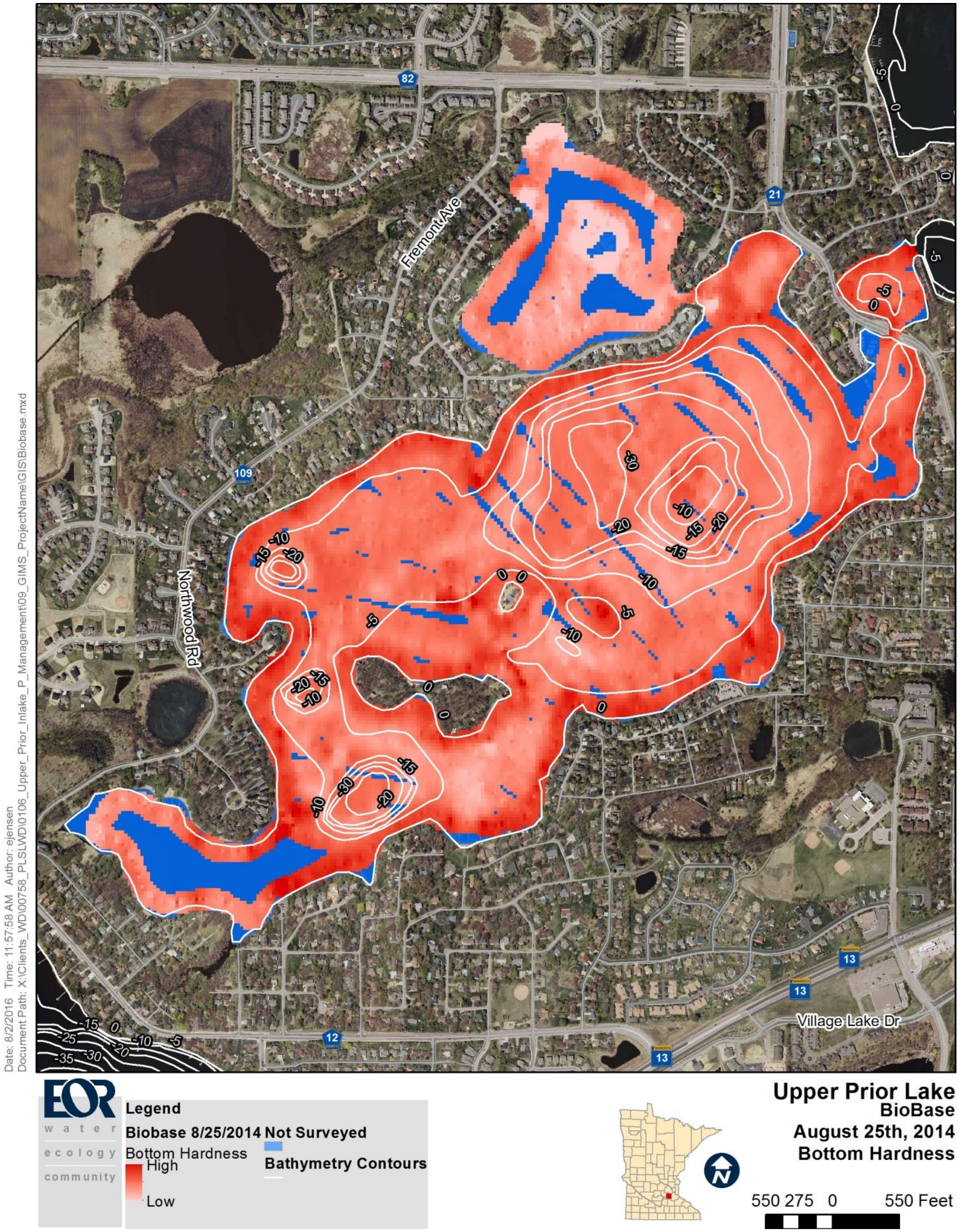

Figure 5. 2014 Upper Prior Lake BioBase Bottom Hardness Estimates

2.2.1.4 Lake Sediment Organic Matter Characteristics

It is important to note that anaerobic release of P from sediment, while important, is not the only mechanism for P release in lakes. Organic matter content of sediments appears to also be a factor in potential for phosphorus release, as well correlated with vegetation trends. Blue Water Science developed estimates of curly-leaf pondweed and Eurasian watermilfoil growth potential based on lake sediment characteristics for Upper Prior Lake in 2008 (Figure 6). Previous research has found that curly-leaf pondweed growth is most dense in lake sediments with a high percentage of organic matter (>20%). Sediment samples collected from the two shallow bays (Mud Bay and the Boat Ramp Bay west of Twin Isle) of Prior Lake contained black-brown-gray organic rich mud underlain by peat (organic). Both of the sediment samples collected from these highly organic sediments had elevated concentrations of releasable phosphorus.

Therefore, this reinforces the findings of bottom hardness for targeting some shallower areas for alum treatment. Unlike other shallow areas that are typically more sandy and have lower RP values, some additional shallow areas were included as areas that needed to be treated. In these shallow areas, alum treatments will help to reduce the portion of the internal loading that is caused by organics decay, as well as wind and wave action, by promoting a clear-water, aquatic plant dominated state in which the aquatic plants help to stabilize and minimize disturbance to sediments.

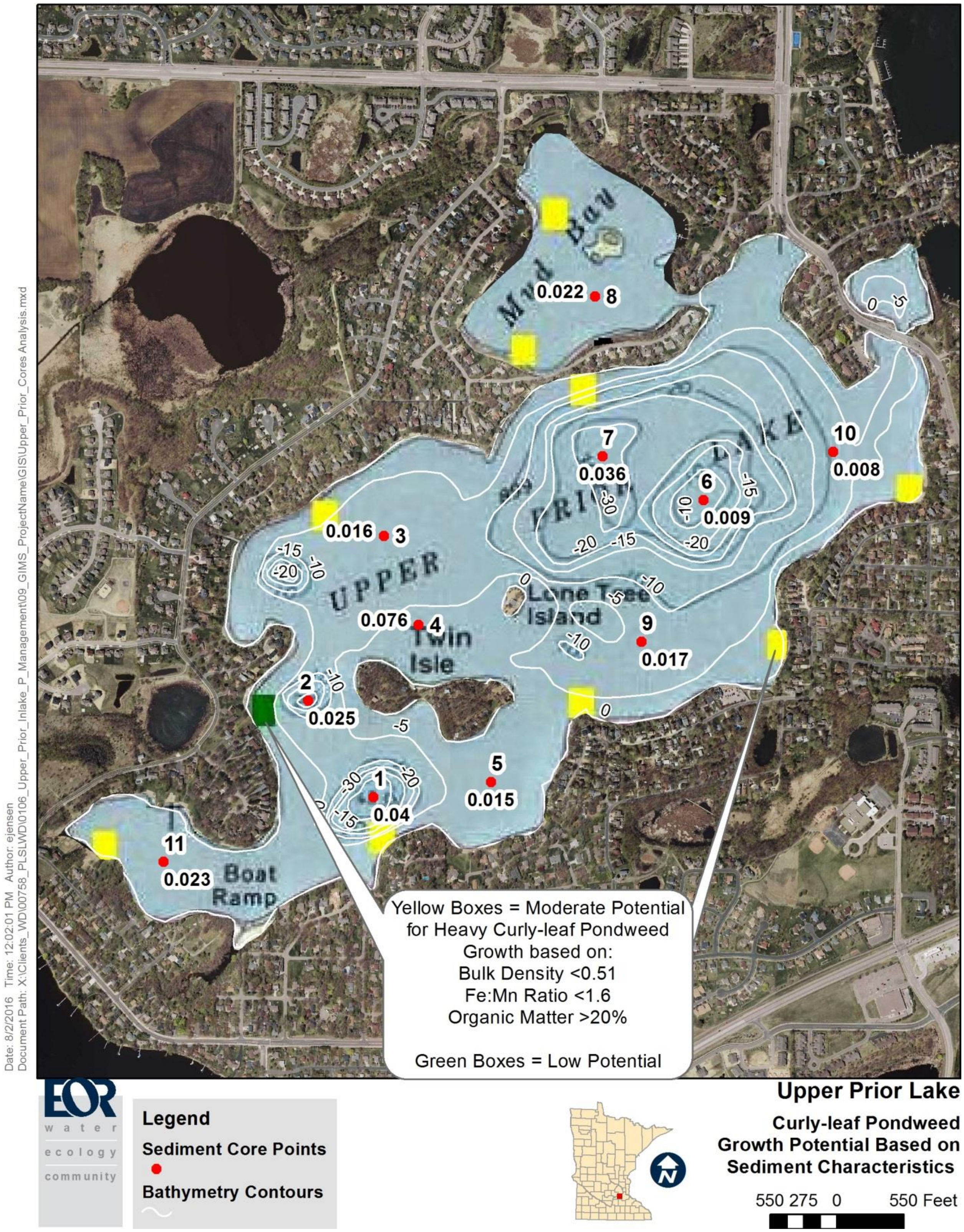

Figure 6. Blue Water Science Lake Sediment Characteristics. Yellow Squares indicate sediments conducive to supporting moderately dense stands of curly-leaf pondweed growth while green squares indicate areas supporting low density stands of curly-leaf pondweed.

2.2.2 Alum Dosing Recommendations

The weight of evidence approach provided the background information needed to clearly identify two distinct treatment zones with different concentrations in observed RP content (Figure 7). Treatment zone 1 has a total surface area of 230 acres and represents the shallower depths of the lake with moderate RP concentrations. Treatment zone 2 has a total surface area of 43 acres and represents areas with depths greater than 20 feet. The depth weighted average RP concentrations in the top six centimeters of the sediment column of Zones 1 and 2 are 0.32 and 0.74 g/m^2-cm.

Treatment of the phosphorus content within the top six centimeters of the sediment column within treatment zone 1 (230 acres) using an alum to phosphorus binding ratio of 115:1 requires the application of 384,000 gallons of alum at an average alum dosing rate of 1,670 gallons per acre. Treatment zone 2 (43 acres) uses an alum to phosphorus binding ratio of 55:1 and requires the application of 78,000 gallons of alum at an average alum dosing rate of 1,800 gallons per acre (462,000 gallons total). The alum to phosphorus binding ratios were based on the work of James and Bischoff (2015) which uses concentrations of redox-P (the iron-bound plus loose-bound fractions of P) to calculate this ratio. The higher ratio in the shallower Treatment zone 1 reflects the lower redox-P concentrations in comparisons to the deeper Treatment zone 2.

The cost for the alum dosing application materials and labor is estimated to be $812,928 based on an average cost of $1.76 per gallon of alum applied (Personal Communication, John Holz-HAB Aquatic Solutions). This does not include administration, design, permitting, or other management costs. The total dose will likely be split into two applications to address future contributions from the breakdown of labile organic phosphorus. Splitting the application into two doses also alleviates the need for a sodium aluminate buffer used to ameliorate pH changes. Additional monitoring following the first dose is recommended to determine the effectiveness of the first treatment and if dosing adjustments is required for the second treatment. Labile organic phosphorus consists of organic matter that is not strongly attached to sediment that will be broken down over time and eventually become bioavailable to algae. Labile organic phosphorus accounted for an average of 43% of the RP being targeted; controlling this source of phosphorus represents a commitment to extending the life expectancy of the alum treatment.

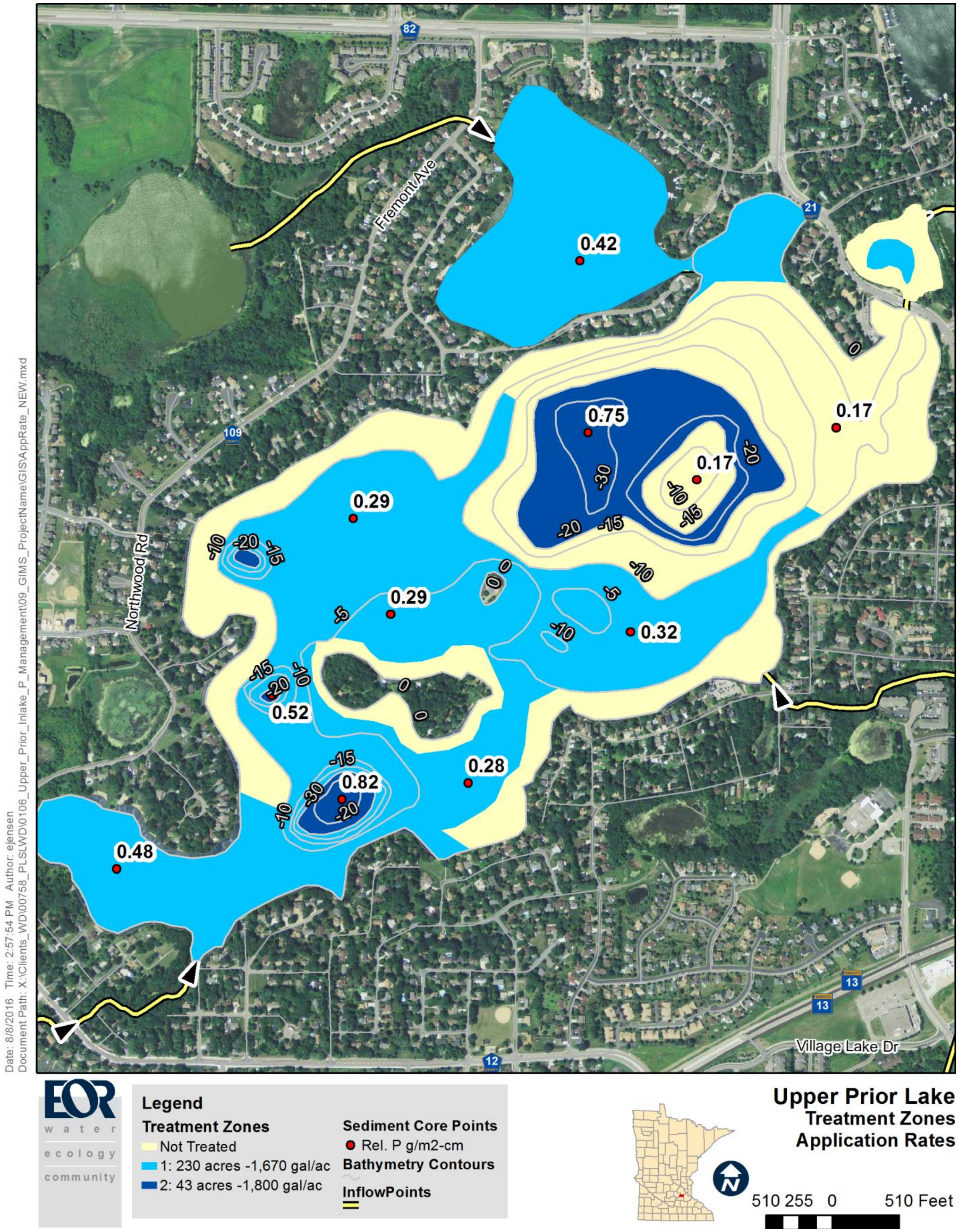

Figure 7. Upper Prior Lake Alum Dosing Rates and Treatment Zones

3 Phosphorus Cycling Management Alternatives (Not Recommended)

3.1 Hypolimnetic Aeration

The hypolimniom is the deeper portion of a lake where the water is stagnant and essentially uniform temperature. In this zone the water down near the sediment can become oxygen deprived as accumulated organic matter is broken down by microorganisms. And in these modified conditions, the natural ability of sediments to bind with phosphorus is altered and the phosphorus is released to the water column becoming available in the lake to algae. Hypolimnetic aeration is a phosphorus cycling control technique whereby phosphorus (P) rich anoxic sediments in the hypolimnion are oxygenated with a mechanical aeration system preventing an anaerobic condition that leads to release of P.

Hypolimnetic aeration has been proven successful in reducing contributions of phosphorus from lake sediments with sufficiently high iron to phosphorus concentrations such as Vadnais Lake which serves as a municipal drinking water source for the City of St. Paul. In many lakes, additions of iron are required to supplement hypolimnetic aeration to sufficiently bind phosphorus present within the sediment pool. Studies conducted in Vadnais Lake and the nature of lake sediment phosphorus release indicate that continued hypolimnetic aeration will be required to prevent internal phosphorus loading in perpetuity due to the large reservoir of labile phosphorus that accumulates in the sediment (Weiss et. al., 1996). The St. Paul Water Utility estimates the total capital cost of two conventional aerators installed in Vadnais Lake at $400,000 (approximately $620,000 in 2016 dollars), while operation and maintenance costs were approximately $37,000-$47,000 (approximately $57,000-$72,000 in 2016 dollars) per year (Weiss et. al., 1996).

In Upper Prior Lake, a portion of the internal loading from lake sediments is due to the shallow nature of the lake from physical mixing due to wind and wave action as well as from carp disturbance. A more sustainable approach relies on the conversion of Upper Prior Lake to a clear-water, aquatic plant dominated state following the removal of carp and addition of alum. Hypolimnetic aerators would need to be run in perpetuity to control releases of labile phosphorus within the hypolimnion which would also likely require the addition of iron to maintain high levels of iron in the lake sediment. At 428 acres, Upper Prior Lake is similar in size to East (394 acres) and West Vadnais Lakes (216 acres) which together comprise an area of 610 acres. The morphometry of Upper Prior Lake is such that at least two aerators would be required for Upper Prior Lake to maintain sufficient oxygen concentrations in the two deeper portions of the lake that are isolated from each other by the shallower littoral area that encompasses the center of the lake.

Unlike aeration, the alum plan presented permanently binds a mass of releasable P equal to ten years of internal loading. While hypolimnetic aeration may have similar or less upfront costs in comparison to alum, the continued annual operation and maintenance cost of $57,000-$72,000 (2016-dollars) are an expense that would be incurred in perpetuity as these systems are only effective so long as the aeration units are running. Over a 10 year period, the operational costs of the aeration system could add another $650,000 or more.

The concentration of P in Upper Prior Lake changes dramatically throughout the season as a result of contributions from internal sources. A really strong, clear-water phase during the spring can mask peaks in poor water quality that occur during the middle of the summer as indicated by this graph from 2015. Implementation of an aeration system that only reduces phosphorus from the deepest portions of the lake may fail to reduce these peaks in water quality given the large littoral area (85% of lake less than 15 feet deep). It is therefore very possible that we would not achieve the 60 ug/L in-lake P goal through implementing an aeration system.

3.2 Sediment Dredging

Analysis of lake sediment RP concentrations identified high RP levels in multiple locations dispersed throughout the lake. Excavation of nutrient rich sediment via dredging represents a practicable opportunity in environments where high concentrations of RP are relegated to confined areas. However, given the distribution of high RP concentration at multiple locations, the costs and practicality of dredging quickly become impracticable. Furthermore, dredging one bay will not have a perceptible change on the lake in terms of a recognized reduction in in-lake phosphorus concentrations. A targeted alum treatment allows for the most cost effective and overarching control of sediments with a high RP content and has the additional benefit of stripping the water column of phosphorus during application.

Nevertheless, as part of the analysis in this report, costs were estimated for a dredging operation to reduce RP to a similar extent as the proposed alum treatment. As previously noted, observed releasable phosphorus concentrations in Upper Prior Lake are significantly higher in the upper 6 centimeters of the sediment. A hydraulic dredging operation planned for Fountain Lake (Albert Lea, MN) found a similar difference in releasable phosphorus content with increasing sediment core depth. In Fountain Lake, substantially higher concentrations of releasable phosphorus were documented in the top 4 inches of the sediment profile. Hydraulic dredging (suction pumping) can be one of the most cost effective methods for removing large volumes of sediment from lakes. While sediment excavation via hydraulic dredging does not necessarily happen at a centimeter by centimeter level of precision, a harvesting operation targeted at removing the top 10 centimeters (4 inches) of the sediment profile would ensure that the most nutrient rich layers of sediment were sufficiently removed.

Costs for hydraulic dredging can be variable depending on the situation. It can be broken down into two fundamental groups: 1) the costs for doing the dredging and 2) the costs for dewatering and disposal of the excavated sediment. In hydraulic dredging, proximity to rural lands where sediment can be land applied, and access to the land, are large cost variables. Costs for dredging are based on the volume of material removed and the cost per cubic yard (CY) of material removed. A review of recent projects with costs for sediment excavation found a range of costs from $4/CY to $57/CY (Barr, 2014). Feasibility studies conducted on regional lakes in close proximity to the Twin Cities metropolitan area listed costs of $11/CY for Library Lake (Cumberland, Wisconsin) and $4/CY for Kohlman Lake (Maplewood, Minnesota).

Costs for conveyance, disposal, and dewatering of excavated sediment are extremely dependent on the location of the dewatering site relative to the lake, the dewatering system used, and the sediment disposal site. Initial capital costs for a conveyance and disposal system for Fountain Lake were estimated to be between $75,000 and $125,000 with additional costs of $1.5 for each CY of sediment removed from the lake. Dewatering costs can also vary considerably with a cost of $25/CY representing an average baseline cost. Additional costs include land acquisition costs for the disposal of the excavated material (Table 2). Disposal of the excavated material can have beneficial re-use applications as topsoil or other natural habitats; however, significant soil testing must be completed in accordance with procedures in the MPCA guidance document, "Managing Dredge Materials in the State of Minnesota."

Table 2. High and low cost estimates associated with sediment dredging in Upper Prior Lake

Cost Estimate	Total Area Targeted (Acres)	Volume Excavated (CY)	Excavation cost/CY	Excavation Costs	Dewatering	Conveyance and Disposal Costs	Land Acquisition	Total cost
High	273	150,000	11	$1,600,000	$3,800,000	$350,000	$100,000	$5,900,000
Low	273	150,000	4	$600,000	$3,600,000	$300,000	$50,000	$4,600,000

4 Carp Management

EOR's recommendations for carp management are consistent with management activities currently planned as part of the District's ongoing carp management plan (2013) using grant and matching dollars for activities through June 2018. As such, the following sections are meant to serve as background for understanding the results of efforts undertaken thus far in Upper Prior as well as the current research and best practices for carp management gleaned from local and regional studies.

4.1 Common Carp Background

Common carp (*Cyprinus carpio*) are known to uproot aquatic vegetation and stir lake sediments, thereby reducing the density of aquatic vegetation, increasing turbidity, and releasing nutrients back into the water column. The increase in nutrients can lead to algal blooms that decrease water clarity, further reducing the aquatic vegetation community. Research at the University of Minnesota has indicated that carp densities of 100 lb/acre or more can have a significant impact on the native vegetation community, and that a density of 30 lb/acre may be a more appropriate target for lake management (Bajer, Sullivan, & Sorensen, 2009). In addition, high concentrations of carp have been shown to cause significant water quality issues in lake environments.

4.1.1 Population Assessment

A total of 61 carp have been marked in Prior Lake with a combination of either a right pelvic, right pectoral, or radio tags as of June 14th, 2016. The 61 carp tagged to date represents a fairly small sample size. Estimates from mark-recapture studies can contain some statistical bias, especially when the number of recaptured individuals is small (Bernard and Hansen, 1992). An electrofishing survey is planned for September from which a preliminary population estimate will be calculated. Fish sampled during this time will also be marked and released. An additional open water seine will be performed in late fall to evaluate the viability of targeted locations for carp removal through a below the ice seine. Because of the limited number of individuals that have been captured to date, a second mark-recapture survey is recommended to provide a more accurate reflection of the carp population. An electrofishing survey conducted in September of 2014 estimated carp abundance at 306.5 lb/acre for Spring Lake and 236 lb/acre for Arctic Lake. Given the direct hydrologic connection between Spring Lake and Arctic Lake, there is reason to believe that carp densities in Upper Prior Lake also exceed the 100 lb/acre threshold.

4.1.2 Spawning Habitat Assessment

Common carp prefer to spawn in shallow, weedy bays of lakes with silty substrate and/or connected wetlands with submergent vegetation or inundated terrestrial vegetation at water depths less than 0.5 meters (approximately 2 feet). Marginal spawning occurs in water up to 1.8 meters (6 feet) deep (McCrimmon 1968). Large, shallow lakes or lakes with large shallow bays provide optimum in-lake spawning grounds for carp. Research conducted in Australia in 2008 found that carp are positively rheotactic which is another way of stating that carp tend to concentrate in large masses in areas with flowing water such as lake inflow and outflow points; especially during the spawning season. Telemetry data has suggested that while carp overwinter in deep lakes that don't winterkill, they tend to travel to winter-kill prone shallow lakes and wetlands to spawn. This behavior presumably takes advantage of a lack of predators in the shallow lakes and wetlands due to winterkill of predatory species such as bluegill (*Lepomis machrochirus*) (Bajer and Sorenson, 2010). An aerial photo collected at the Linn Lake outlet to South Center Lake in Chisago County, Minnesota in 2014 provides a critical demonstration of the potential role of connected inflow points in terms of their capacity to attract carp (Figure 8). Figure 9 highlights the location of the eight radio-tagged carp that appeared to be using the west end of Upper Prior, near the connecting channel with Spring Lake as their main spawning area in comparison with lake depth and proximity to inflow points and connected wetlands. Radio tagged carp were also found in Mud Bay in mid-spring and may have been attracted to the flowing water near the access channel to Arctic Lake through the Fremont Avenue culvert. Table 3 highlights the percent of the total lake area suitable as carp spawning habitat. The telemetry data collected to date provides additional evidence to suggest that shallow bays in close proximity to inflow/outflow points from connected wetlands/lakes represent potentially suitable locations for capturing carp during the spring spawning season.

Table 3. Percentage of lake area within preferred spawning depths (based on DNR bathymetry-not reflecting water level fluctuations).

Lake Name	0-5 ft.* (Preferred)	5-10 ft.* (Marginal)	>10 feet
Upper Prior	55%	21%	24%

Figure 8. Congregation of carp at Linn Lake Outlet in 2014.

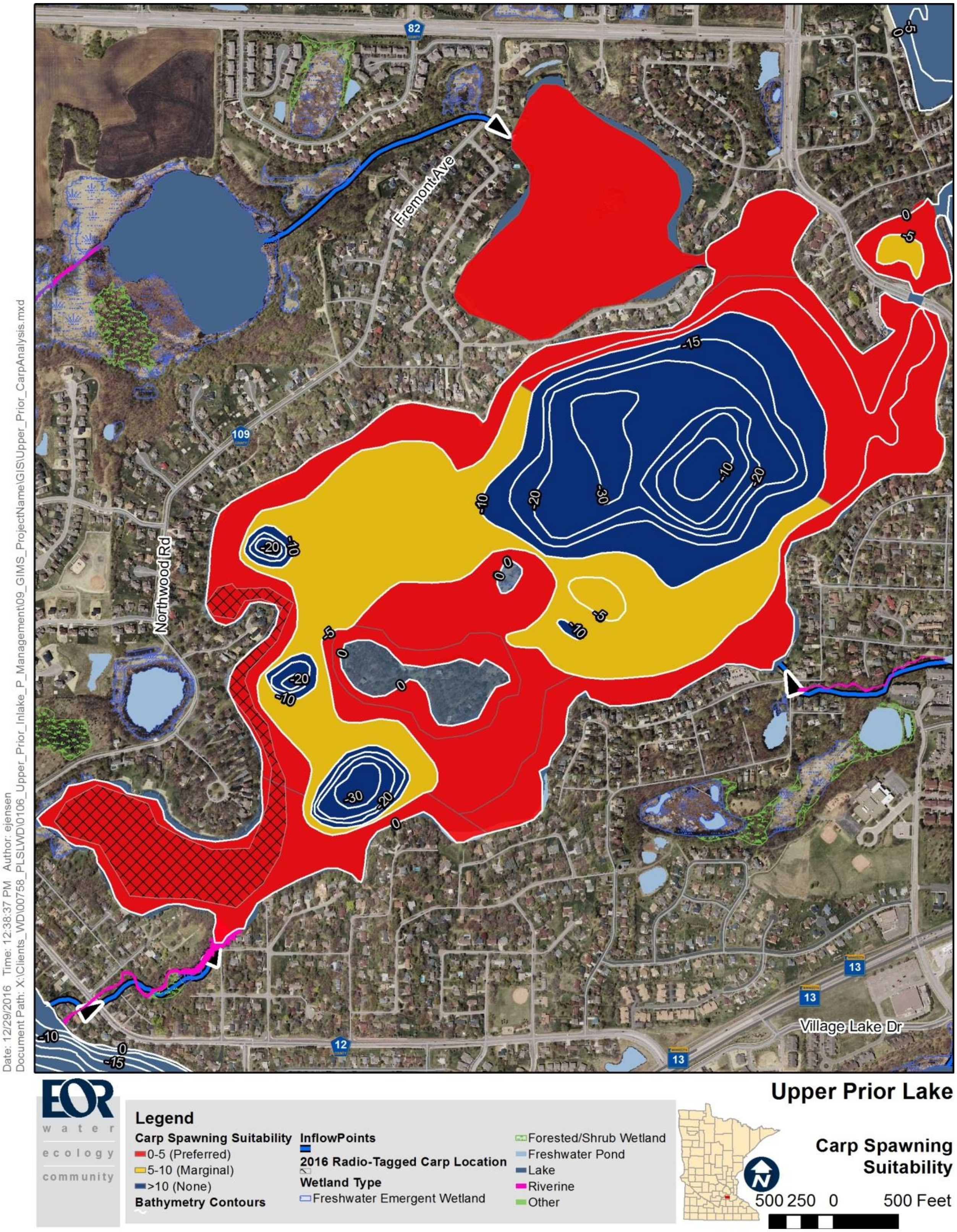

Figure 9. Comparison of radio-tagged carp location from open water surveys conducted in 2016 (WSB, 2016) with lake bathymetry and proximity to inflow points.

4.1.3 Overwintering Habitat Assessment

In the winter, common carp congregate in large aggregations that can be tracked using radio telemetry (Lechelt and Bajer, 2016). Strategic carp seining efforts conducted under the ice have demonstrated removal rates that have exceeded 80% of the adult population (Bajer et al., 2014). To date, the radio tagged carp within Prior Lake have not been surveyed to determine winter locations. Commercial fishermen have been solicited to assist with carp capture and removal and have expressed interest in conducting a harvesting operation in Prior Lake. The location of carp winter aggregation points will be passed onto commercial fisherman as this information becomes available following data collection in 2016.

4.1.3.1 Bait and Net

A study conducted on the Riley Chain of Lakes (Eden Prairie) by the University of Minnesota found that common carp can be trained to congregate on baited locations within 10 days (Bajer et al., 2010). Fifty percent of the carp population within the study lake congregated at the baited site within four days, and 61% by the 10th night. Interestingly, the carp only visited the bait at night, suggesting that any seining activities would need to take place during the night or early morning. When combined with winter telemetry data collection, baiting may provide an added means for increasing the efficacy of proposed winter seining operations.

4.1.4 Carp Migration Barrier and Harvesting Timeline

The 2004 Sustainable Water Quality Management Plan for Upper Prior Lake recommended an initial target carp population equivalent to the 100 lb/acre threshold. Additional research conducted since 2004 has suggested that a carp population with a density equivalent to 100 lb/acre may still be too high; with 30 lb/acre being a more sustainable target in terms of maintaining a resilient aquatic plant community (Bajer, Sullivan, & Sorensen, 2009). While carp populations have not officially been determined for Upper Prior Lake, it is likely that the population far exceeds this 30 lb/acre threshold based on carp population estimates in Spring Lake and Arctic Lake. The 30 lb/acre threshold ideally should be achieved prior to conducting the alum treatment.

Winter seining operations conducted on the Riley Chain of Lakes demonstrated the potential effectiveness of winter seining operations with over 80% of adult carp removed from each of the three lakes targeted (Bajer et al., 2010). Despite the potential effectiveness of these seining operations, methods for controlling future carp recruitment must remain a top priority given that a single female carp can carry over 1 million eggs. Juvenile carp grow fast and can quickly reach sizes that prohibit control by native piscivores (fish that consume other fish). The explosive population growth of this species can quickly negate dollars spent towards harvesting efforts.

Recent research has found that bluegills (*Lepomis machrochirus*) are capable of completely suppressing carp recruitment so long as sufficient concentrations of oxygen exist to prevent winterkill in connected bays and wetlands. Therefore, the number one priority in controlling future common carp recruitment is identifying hydrologically connected bays, wetlands, and shallow riverine marshes prone to winterkill (Bajer et al., 2014). Figure 9 shows the potential locations of these areas. A survey identifying additional hydrologically connected wetlands, ponds or other basins subject to winterkill is recommended to identify additional areas where migration barriers may be needed such as the wetland complexes adjacent to Northwood Road near the west end of the lake.

5 Aquatic Vegetation Management

5.1 Background

Aquatic plants compete with phytoplankton (algae) for available nutrients in the water column. This competitive interaction reduces the abundance of phytoplankton and therefore promotes an ecologically preferred clear-water state. In lakes like Upper Prior with a large littoral area (area of lake less than 15 feet deep), research has found that 40% plant area coverage (percent of total lake bottom with plant growth) promotes optimum water clarity (Canfield and Hoyer, 1992). An August, 2015 point intercept survey estimated plant area coverage at 33 acres (7.7% of surface area) in Upper Prior Lake. Only three native submergent plant species including coontail (*Ceratophyllum demersum*), Canadian waterweed (*Elodea canadensis)*, and sago pondweed (*Potamogeton pectinatus*) have been observed over the course of multiple aquatic plant surveys conducted on Upper Prior Lake since 2005. In contrast, estimated plant area coverage for Lower Prior Lake was between 41 and 44% from 2013-2015 (Mielke and Rockney, 2016) All three species (coontail, Canadian waterweed, and sago pondweed) are tolerant to poor water quality. The distribution of native species in Upper Prior Lake exhibits patchy growth to a depth of four to six feet with limited growth occurring past six feet due to water clarity.

Despite these findings, paleo sediment core data collected by the University of St. Thomas indicate biological changes have occurred in Upper Prior Lake in the past two centuries due to increases in nutrient export to the lake and deepening of the lake. Analysis of sediment cores documented a distinct shift from predominantly benthic species of diatoms associated with aquatic plant growth to planktonic diatoms associated with an increasingly eutrophic, algal - dominated waterbody. This observed change in diatom species suggests Upper Prior Lake was historically in a clear-water, macrophyte-dominated state prior to the increase in nutrient export to the lake.

Surveys conducted by the DNR first identified curly leaf pondweed in Spring Lake as early as 1982; it was considered rare at that time. It is not known when curly-leaf pondweed was first established in Upper Prior; however it is likely that it has been in Upper Prior since the 1980's. By 2005, a vegetation survey identified curly-leaf pondweed at 95 percent of sampled locations with Eurasian water milfoil being found at 75 percent of sampled locations (MPCA, 2011). In lakes dominated by curly-leaf, in-lake nutrient concentrations may start off near or below ecoregion standards while curly-leaf is growing during the spring/early summer. As curly-leaf begins to senesce in mid-June, phosphorus concentrations in the water column often increase dramatically leading to algae blooms and a shift from a clear-water, macrophtye dominated state to a turbid water state dominated by algae that prohibits the growth of native aquatic plants.

Recent concerns over blooms of filamentous algae have been raised following the accumulation of mats of filamentous algae in wind-blown bays of the lake in 2016. Filamentous algae growth is a symptomatic expression of a lake that has excessive nutrients (primarily phosphorus). Filamentous algae begin growing on the bottom of the lake or on submergent aquatic plants. Gas bubbles become trapped underneath the filamentous algae which cause mats of the algae to float to the surface. While filamentous algae growth is best controlled through reductions in external and internal nutrient loading, there are means of extracting the filamentous algae to minimize interference with recreational activities. Implementation of modified fish nets with a mesh size of ¼ inch or greater (up to 1.5 inches) have been used with varying degrees of success in other Minnesota Lakes. Larger mesh sizes are recommended if filamentous algae are the sole target species (Personal Communication, Steve McComas), while smaller mesh sizes are beneficial if duckweed is also problematic. Problems in controlling filamentous algae using nets include 1) it is a labor intensive process as filamentous algae is very dense by nature, therefore a net full of filamentous algae can be very heavy and 2) filamentous algae growth will continue along the bottom after initial removal efforts and may float to the top soon after nets are deployed.

5.1.1 Current Aquatic Plant Management

Since 2005, curly-leaf pondweed has been the primary focus with targeted herbicide applications conducted in 2013 (23 acres), 2014 (29.3 acres), and 2015 (21.5 acres). While herbicides have been successful in reducing the density of curly-leaf pondweed within the treated areas, curly-leaf continues to be found within treated areas in subsequent years. For example, in 2016, curly-leaf pondweed was sampled in many of the same locations where it had previously been identified, including several areas that were treated in 2015. A total of 18.5 acres were treated in 2016.

5.1.2 Future Management

5.1.2.1 Half Moon Lake- Case Study

Increases in water clarity following a reduction in internal loading following carp removal and/or alum dosing will result in an increase in the abundance and distribution of submergent aquatic plants in Upper Prior Lake; especially curly-leaf pondweed and Eurasian watermilfoil. As an example, an alum treatment conducted on Half Moon Lake (Maximum Depth of 13.2 feet) in Eau Clair, Wisconsin increased the percentage of the lake area that could support aquatic plants from 36% of the lake area to 100% (James, 2013). The limiting factor in controlling submergent plant growth in Half Moon Lake was light attenuation (reduction in light) by algae. Light attenuation can be measured using a radiometer that measures the Photosynthetically Active Radiation (PAR) levels in the lake with increasing depth. Secchi disk measurements can be used as a surrogate means of estimating PAR levels. In Half Moon Lake, secchi disk depths increased by 345% (1.1 to 3.8 meters) following a reduction in internal loading (James, 2013). In Upper Prior Lake, the mean secchi disk depth from 2005-2015 was 1.59 m; a 345% increase in secchi disk depth equates to a depth of 5.5 meters (18 feet). Based on this finding, it is likely that curly-leaf pondweed will expand its distribution to depths of 15 feet which is near the maximum depth at which curly-leaf is typically found.

5.1.2.2 Herbicide Evaluation

A critical component in maintaining the long-term ecological health of Upper Prior Lake relies on re-establishing a more balanced aquatic plant community comprised of native aquatic plants that can perpetuate the clear-water, aquatic plant dominated state throughout the growing season. Early-season herbicide applications targeted at reducing curly-leaf pondweed and Eurasian watermilfoil abundance will be required to reduce the canopy shading effect that these species have on native plants.

Common herbicides used to control curly-leaf pondweed and Eurasian watermilfoil in lakes include Diquat (Reward), Endothall (Aquathol), 2, 4-D (Navigate) and Fluridone (Sonar); each of these compounds has been certified for use in aquatic environments by the EPA (Table 4). Of these compounds, Endothall is best suited for control of curly-leaf pondweed in Upper Prior Lake because it is a fast-acting (12-36 hours), contact herbicide that can be used to be selective for curly-leaf if applied in the spring (Madsen, 2000). Timing of application (water temperatures between 50 and 60^0 F) is critical because Endothall is a broad- spectrum (non-selective) herbicide. Application of Endothall early in the growing season prior to native plant emergence may allow for control of curly-leaf pondweed with reduced impacts to native plants. While contact herbicides are fast acting, they may not have a sustained effect because they often are only effective on the portion of the plant above the water surface and in many cases do not kill the roots or rhizomes from which new plant growth can be generated (Gettys et. al, 2009).

Fluridone and 2, 4-D are systemic herbicides, systemic herbicides are slow acting; however, application of systemic herbicides typically results in the complete mortality of the entire plant including the portions of the plant that are below the sediment surface (McComas, 2003). Of these systemic herbicides, 2, 4-D is best suited for control of Eurasian watermilfoil in Upper Prior Lake because it is selective to broad-leaf species; especially Eurasian watermilfoil. 2, 4-D does not affect narrow leaf pondweeds such as sago pondweed or Canadian waterweed (native species found in the lake) or other pondweeds such as white-stemmed pondweed (*Potamogeton praelongus*) which was found in Lower Prior Lake and which may be present in the seed bank of Upper Prior Lake sediments. Research conducted on a combined early-season application of both Endothall and 2, 4-D has demonstrated simultaneous control of both curly-leaf pondweed and Eurasian watermilfoil. Research demonstrated that the combination of these herbicides resulted in an increased efficiency (due to use of Endothall) and complete control (2, 4-D) of both species within three weeks (Madsen, et. al, 2010). The combined application of both systemic and contact herbicides offers a promising solution for long-term control of both curly-leaf pondweed and Eurasian watermilfoil in Upper Prior Lake.

Table 4. Herbicide Treatment Options (Modified from Madsen 2000)

Treatment	Advantages	Disadvantages	Applicability to Upper Prior Lake	Applicability Ranking
Diquat	• Very rapid action • Contact herbicide	• Likely needs to be repeated annually • Senescing Plant Material • Does not kill the roots • Broad spectrum (kills other plants)	• Can be used effectively in lakes with heavy wave action • Acts in 5-7 days • More often to control floating-leaf plants. • Senescing plants could cause D.O. Flux	Moderate
Endothall	• Rapid action • Contact herbicide • Inhibits turion formation	• Likely needs to be repeated annually • Senescing Plant Material • May not kill the roots • Broad spectrum (kills other plants)	• Acts in 7-14 days • Proven effective on curly-leaf • Senescing plant material could cause D.O. Flux	High
Fluridone	• Highly effective, low dosage required • Systemic	• Very long contact period required • Kills the entire plant including roots • Broad spectrum (kills other plants)	• Not good for moving water, too long of a contact period • Proven effective on curly-leaf	Low
2, 4-D	• Does not harm native pondweeds • Inexpensive • Systemic	• No control of curly-leaf pondweed • Can take up to 6 weeks to see full effects	• Can be used effectively to target Eurasian watermilfoil while avoiding impacts to native pondweeds	High

5.1.3 Vegetation Management Costs

Approximately 85% (363 acres) of Upper Prior Lake is less than 15 feet deep. Currently, the DNR limits herbicide treatments to a maximum of 15 percent of the littoral zone of the lake (area less than 15 feet deep). Therefore, the maximum allowable treatment area in a given year is equivalent to an area of 54.5 acres. Figure 10 displays the existing distribution and abundance of curly-leaf pondweed and Eurasian watermilfoil based on data collected by Blue Water Science in 2015 and 2016. While curly-leaf pondweed and Eurasian watermilfoil may spread to a depth of 15 feet following an increase in water clarity, recent improvements in water clarity in Spring Lake following alum treatments suggest that nuisance levels of curly-leaf pondweed or Eurasian watermilfoil did not exceed a depth of 10 feet (Personal Communication, Steve McComas).

Approximately 76% (328 acres) of Upper Prior Lake is less than 10 feet deep; 15 percent of this area is 49.2 acres. Herbicide treatment costs range from $290 to $550 per acre (McComas, 2011); therefore costs for treating the entire 49.2 acre area are estimated to cost between $14,268 and $27,060. While initial aquatic plant management costs may exceed existing costs, surveys of aquatic vegetation conducted in other Minnesota lakes following alum treatments have demonstrated a reduction in plant area coverage and density following an initial burst of aquatic plant growth; therefore, costs should decrease with time (Personal Communication, Steve McComas).

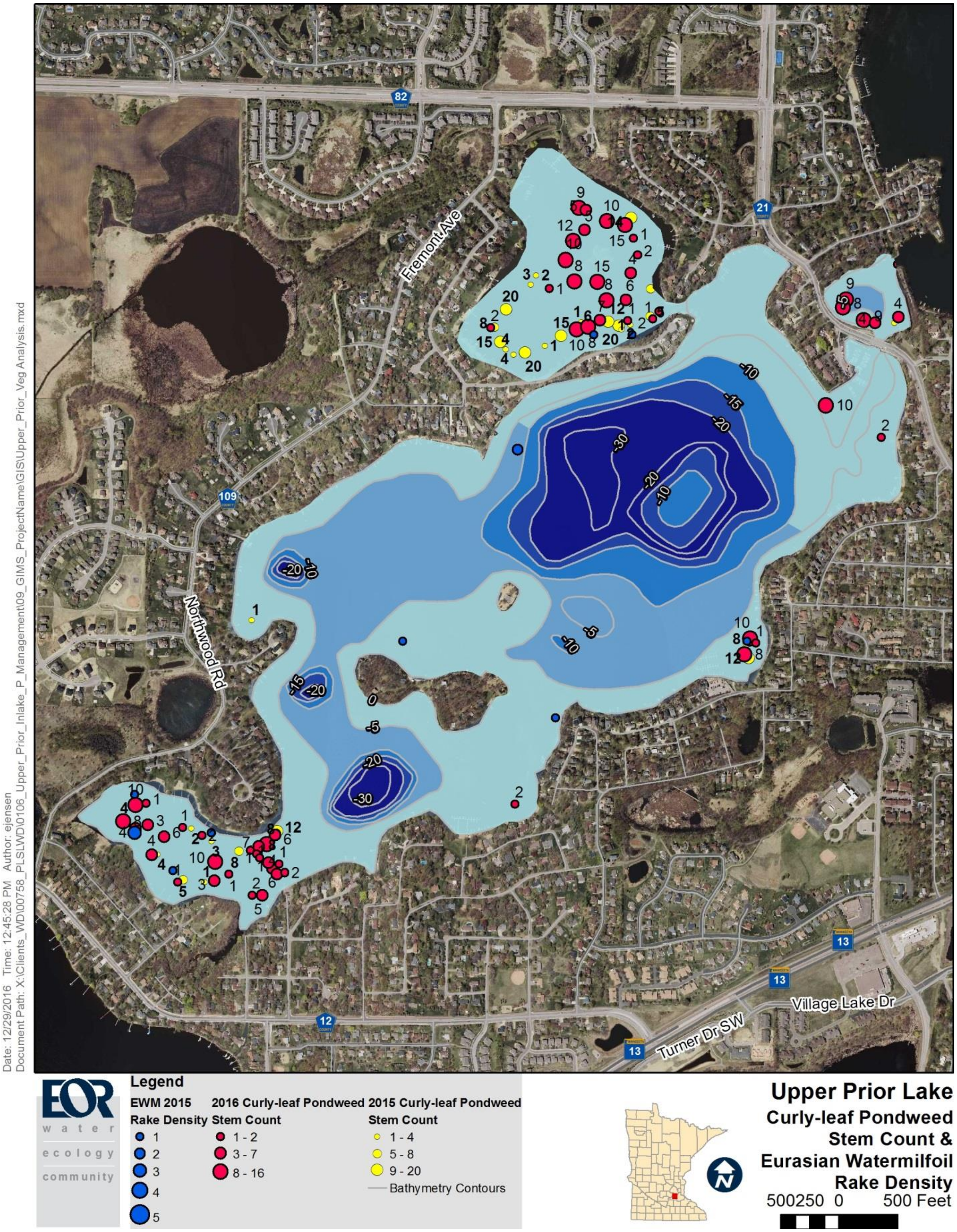

Figure 10. Distribution and density of Eurasian watermilfoil (EWM) and curly-leaf pondweed based on 2015 and 2016 aquatic plant surveys.

5.1.4 Ancillary Benefits

Promoting the clear-water, aquatic plant dominated state in Upper Prior Lake promotes an environment that is conducive to maintaining quality gamefish populations. Most gamefish species including sunfish, largemouth bass, northern pike, and muskellunge rely on submergent plant cover for both food and shelter. Predatory species such as northern pike can help to provide top-down control over rough species; thereby promoting the clear-water state. Plant area coverage between 10% and 60% (depending on the morphometry of the lake) is associated with optimum gamefish health (Valley et al., 2004).

6 Summary of Findings

Improving the water quality of Upper Prior Lake will require both management of anoxic P release in the lake sediment, in addition to re-establishing submerged vegetation throughout more of the shallow depths to maintain a clear water state and protect lake sediments from disturbance via wave and wind action. An analysis of 12 lake sediment cores revealed high P sediments in both shallow and deep areas of the lake from which a targeted alum treatment map was developed. Data collected from carp surveys conducted on Spring Lake and Artic Lake suggest that carp management will also be needed to increase the effectiveness and longevity of the alum treatment and re-establishment of aquatic vegetation as carp can disturb the alum floc layer and negatively impact aquatic vegetation growth. Last, management of invasive species including curly-leaf pondweed and Eurasian watermilfoil will be required to allow native plants to grow and perpetuate the clear water state.

6.1 Recommended Management Approach

We identified the following combined approach of three management activities to be the most practical and cost-effective way to address internal phosphorus loading to Upper Prior Lake:

1. Alum (in-lake): Alum treatment of lake areas with the high sediment P concentrations
2. Carp Management – Harvest and Exclusion: Reduction of common carp population through harvest and elimination of migration from adjacent waterbodies
3. Vegetation Management – Herbicide of invasives: Management of invasive plant species through targeted herbicide applications to allow natives to establish in shallow areas

6.1.1 Goal Statement

The goal behind the implementation of the proposed management activities is to achieve all of the internal load reductions identified by the Upper Prior Lake TMDL, allowing Upper Prior Lake to meet an average summer time surface water P concentration of 60 ug/L. Rather than focusing on a targeted hypolimnion P concentration, the focus should be on reducing the sediment phosphorus release rate as deemed necessary following carp management. It is likely that at least some alum treatment will be required given the significant differences in sediment releasable phosphorus content that occurs in the portions of the lake that are deeper than 25 feet. This trend of increasing RP concentration with depth and history of increased summer time phosphorus concentrations justifies ensuring all deep zones within the lake receive alum treatment even after carp management because these areas will continue to contribute to the internal load even if carp are controlled.

These activities should follow a chronological progression whereby carp numbers are first reduced (through harvest) and stabilized (by eliminating migration to the lake using fish barriers). Carp management will be undertaken as per the current PLSLWD funded program which includes harvest and electro-fishing surveys of carp to allow radio- and PIT (passive integrated transponder) tagging to determine Upper Prior population numbers and distribution as well as the extent of migration to and from adjacent waterbodies. As a result of tagging activities, installation of one or more barriers is expected to be necessary (in addition to the barrier already installed at Arctic Lake). One potential barrier location is the channel that connects Spring and

Upper Prior Lakes. Reducing the carp population is an important step to reduce disturbance of the layer of alum-treated bottom sediment that can result in decreased alum effectiveness as well as foster re-establishment of native vegetation that carp often impede. Further, a large carp population can, in and of itself, contribute to internal P loading by disturbing bottom sediments. Once carp population is under control, water quality will be re-evaluated to see if an Alum Treatment is necessary. If deemed necessary, the lake will be treated with two or more alum doses to bind releasable P in the lake-bottom sediments. Once releasable P in the water column has been reduced and lake clarity improves, the density and distribution of emergent vegetation will increase. Because Upper Prior Lake already has significant populations of two undesirable invasive species, curly leaf pondweed and Eurasian watermilfoil, it is very likely that these species will proliferate and dominate in a clearer water environment created by the alum treatment. As a result, on-going management of these invasive species with herbicide treatments will be necessary.

The management activities of the treatment plan with associated timing and costs are presented in Table 5 below. Adoption of the in-lake management plan would be expected to achieve all of the internal load reductions identified by the Upper Prior Lake TMDL. The Spring Lake alum treatment achieved the upstream lake load reductions identified by the TMDL. In combination, these two projects should achieve the 60 ug/L in-lake phosphorus goal for Upper Prior Lake. It is also important to note that these proposed activities are meant to be conservative estimates of the cost and effort to achieve Upper Prior Lake phosphorus goals; as these management activities are undertaken iteratively, an adaptive management approach may allow us to forego some proposed activities/costs.

Table 5. Recommended Management Plan Activities

	2017		**2018**		**2019**	**2020**	**2021**
Management Activity	**Winter**	**Spring**	**Winter**	**Spring**			
Carp harvests[1]	**$4,000***		**$4,000***				
Electrofishing survey with radio and/or PIT tagging to evaluate carp population and migration		**$7,250[2]***		**$4,000[3]***			
Design/Install carp migration barriers[4]				**$4,000***	**$4,000***		
Alum treatments[5]				**$420,000**		**$420,000**	
Invasive plant management[6]		**$25,000**		**$25,000**	**$25,000**	**$25,000**	**$25,000**
Total	**$4,000**	**$32,250**	**$4,000**	**$453,000**	**$29,000**	**$445,000**	**$25,000**
						Grand Total	**$992,250**

* Covered by existing grant funding and budgeted matching dollars; costs as per PLSLWD 2013 Carp Management Plan except where noted

1 Two winter seining harvests: $4,000 each

2 Setup and operation of PIT tagging antennae and data collection equipment; assumes $12,425 cost in fall 2016 for electro-fishing and tagging activities. Costs as per WSB Aug. 22, 2016 memo plus $2,000 assumed District staff time.

3 Electro-fishing carp survey for updated population assessment

4 Assumes installation of up to two additional barriers based on carp migration analysis: $4,000 each

5 Two alum doses (273 acres at 231,000 gallons each): $420,000 each. Based on same cost per gallon ($1.76) and no buffering solution as Spring Lake alum application.

6 Assumes 15% of vegetated acres (Up to 54.5 acres) treated per year: $25,000 each

7 References

Bajer, P. G., Sullivan, G., & Sorensen, P. W. 2009. Effects of a rapidly increasing population of common carp on vegetative cover and waterfowl in a recently restored Midwestern shallow lake. Hydrobiologia, 632(1), pp. 235-245.

Bajer PG, Sorensen PW. 2010. Recruitment and abundance of an invasive fish, the common carp, is driven by its propensity to invade and reproduce in basins that experience winter-time hypoxia in interconnected lakes. Bio. Invasions 12:1101-1112

Bajer PG, Headrick, M., Miller, B., and Sorensen PW. 2014. Development and implementation of a sustainable strategy to control common carp in Riley Creek Chain of Lakes.

Barr Engineering. 2014. Draft Preliminary Engineering Report: Fountain Lake Restoration Prepared For Shell Rock River Watershed District.

Bernard, D. R., and P. A. Hansen. 1992. Markrecapture experiments to estimate the abundance of fish. Alaska Department of Fish and Game, Special Publication No. 92-4, Anchorage.

Canfield DE Jr, Hoyer MV. 1992. Aquatic macrophytes and their relation to the limnology of Florida lakes. Bureau of Aquatic Plant Management, Florida Department of Natural Resources, Tallahassee, Florida, 32303.

Gettys, L. A., W. T. Haller, and M. Bellaud 2009. Biology and control of aquatic plants: a best management practices handbook. Aquatic Ecosystem Restoration Foundation, Marietta, GA. 210 pages

Heiskary, S. 1996. Lake sediment contaminant levels in Minnesota. Minnesota Pollution Control Agency, Water Quality Division, St. Paul, MN. 45 pp.

James, W. F. & J. M. Bischoff. 2015. Relationships between redoxsensitive phosphorus concentrations in sediment and the aluminum:phosphorus binding ratio, Lake and Reservoir Management, 31:4, 339-346.

James, W. F. 2013. Limnological, Sediment, and Aquatic Macrophyte Biomass Characteristics in Half Moon Lake, Eau Claire, Wisconsin, 2013

Lechelt, J.D. & Bajer P.G. Modeling the potential for managing invasive common carp in temperate lakes by targeting their winter aggregations Biol. Invasions 18: 831.

Madsen J.D. 2000. The advantages and disadvantages of aquatic plant management techniques: Part II. Mechanical and physical management methods. LakeLine 20: 22-34.

Madsen, J. D., R. M. Wersal, K. D. Getsinger, and J. G. Skogerboe. 2010. Combinations of endothall with 2,4-D and triclopyr for Eurasian watermilfoil control. APCRP Technical Notes Collection. ERDC/TN APCRP-CC-14. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

McCrimmon, H. R. 1968. Carp in Canada. Fish Resource Board Canadian Bulletin 165. 93 pp.

McComas, S. 2008. Curlyleaf and Eurasian Watermilfoil Growth Potential Based on Lake Sediment Characteristics for Fish, Spring, Upper Prior, and Lower Prior Lakes, Scott County, Minnesota. Prepared for Prior Lake – Spring Lake Watershed District.

McComas, S. 2011. Literature Review on Controlling Aquatic Invasive Vegetation with Aquatic Herbicides Compared to Other Control Methods: Effectiveness, Impacts, and Costs. Prepared for Minnehaha Creek Watershed District.

Mielke, S and Rockney, J. 2016. Aquatic Vegetation Density Mapping – BioBase 2015 Report. Prepared for Prior Lake – Spring Lake Watershed District.

MPCA. 2011. Spring Lake- Upper Prior Lake Nutrient TMDL. Prepared for Prior Lake- Spring Lake Watershed District.

Valley, R.D., T.K. Cross and P. Radomski. 2004. The role of submersed aquatic vegetation as habitat for fish in Minnesota lakes, including the implications of non-native plant invasions and their management. Minnesota Department of Natural Resources Spec. Pub. 160. St. Paul, MN 55155. 25 pp.

Weiss, P. T.Gulliver, J.S., & M. J. Semmens. 1996. Hypolimnetic Aeration with Hollow Fiber Membranes, Lake and Reservoir Management, 12:4, 468-476

8 Appendix A: Upper Prior Lake Sediment Phosphorus Survey Results

Table 5. Concentrations of total phosphorus and phosphorus fractions from Upper Prior Lake, Minnesota.

Upper Prior Lake			Total-P	Ex-P	BD-P	NaOH-P	Persulfate-P	Persulfate minus NaOH	HCl-P	TP minus sum of fractions
	(cm)		*Total P*	*Loosely Bound*	*Iron Bound*	*Aluminum Bound*		*Labile Organic*	*Mineral Bound*	*Recalcitrant Organics*
Cr #	Top	Base	mg P/g	mg P/g	mg P/g	mg P/g	mg P/g	mg P/g	mg P/g	mg P/g
Core 1	0	2	1.831	0.056	0.721	0.066	0.372	0.306	0.195	0.487
Core 1	2	4	1.339	0.025	0.387	0.049	0.256	0.207	0.221	0.449
Core 1	4	6	1.462	0.022	0.426	0.090	0.288	0.198	0.199	0.527
Core 1	6	8	1.326	0.044	0.414	0.095	0.192	0.097	0.214	0.461
Core 1	8	10	1.251	0.024	0.330	0.041	0.189	0.148	0.260	0.449
Core 2	0	2	1.618	0.021	0.431	0.049	0.272	0.223	0.232	0.663
Core 2	2	4	1.143	0.011	0.238	0.034	0.210	0.177	0.248	0.436
Core 2	4	6	1.054	0.010	0.209	0.033	0.187	0.154	0.265	0.384
Core 2	6	8	1.031	0.021	0.162	0.026	0.165	0.139	0.270	0.413
Core 2	8	10	1.056	0.025	0.162	0.026	0.167	0.141	0.270	0.431
Core 3	0	2	1.049	0.034	0.103	0.024	0.166	0.143	0.266	0.480
Core 3	2	4	1.032	0.032	0.096	0.023	0.170	0.146	0.286	0.449
Core 3	4	6	0.998	0.030	0.088	0.023	0.177	0.154	0.258	0.445
Core 3	6	8	1.035	0.031	0.079	0.023	0.167	0.144	0.289	0.468
Core 3	8	10	1.046	0.032	0.077	0.022	0.164	0.142	0.277	0.497
Core 4	0	2	1.196	0.044	0.128	0.024	0.176	0.152	0.273	0.575
Core 4	2	4	0.998	0.038	0.081	0.022	0.166	0.144	0.276	0.437
Core 4	4	6	0.989	0.037	0.069	0.019	0.148	0.129	0.268	0.467
Core 4	6	8	1.005	0.035	0.068	0.020	0.156	0.136	0.269	0.477
Core 4	8	10	0.921	0.036	0.060	0.020	0.144	0.124	0.275	0.406
Core 5	0	2	1.000	0.029	0.097	0.027	0.198	0.171	0.259	0.417
Core 5	2	4	0.934	0.029	0.083	0.028	0.183	0.155	0.475	0.163
Core 5	4	6	0.965	0.027	0.067	0.027	0.178	0.151	0.262	0.430
Core 5	6	8	0.868	0.029	0.064	0.026	0.171	0.145	0.261	0.343
Core 5	8	10	0.872	0.029	0.059	0.027	0.163	0.136	0.282	0.338
Core 6	0	2	0.850	0.044	0.106	0.007	0.086	0.078	0.248	0.366
Core 6	2	4	0.613	0.035	0.056	0.001	0.050	0.049	0.235	0.236
Core 6	4	6	0.596	0.038	0.047	0.001	0.047	0.045	0.241	0.223
Core 6	6	8	0.540	0.037	0.043	0.003	0.040	0.037	0.302	0.118
Core 6	8	10	0.790	0.035	0.043	0.001	0.037	0.036	0.269	0.406
Core 7A	0	2	2.074	0.055	0.595	0.069	0.390	0.321	0.189	0.845
Core 7A	2	4	1.546	0.035	0.441	0.064	0.296	0.232	0.190	0.584
Core 7A	4	6	1.420	0.038	0.370	0.224	0.249	0.026	0.176	0.587
Core 7A	6	8	1.233	0.028	0.306	0.041	0.205	0.164	0.218	0.477
Core 7A	8	10	1.191	0.042	0.243	0.035	0.190	0.156	0.221	0.493
Core 7B	0	2	2.074	0.050	0.562	0.071	0.379	0.308	0.194	0.888
Core 7B	2	4	1.630	0.037	0.417	0.066	0.319	0.253	0.184	0.672
Core 7B	4	6	1.463	0.028	0.388	0.155	0.274	0.119	0.174	0.599
Core 7B	6	8	1.363	0.035	0.358	0.219	0.226	0.006	0.186	0.558
Core 7B	8	10	1.199	0.039	0.255	0.036	0.191	0.155	0.214	0.500
Core 8	0	2	1.015	0.006	0.182	0.048	0.267	0.219	0.132	0.428
Core 8	2	4	0.974	0.003	0.188	0.050	0.276	0.226	0.135	0.372
Core 8	4	6	0.966	0.003	0.161	0.050	0.274	0.224	0.140	0.388
Core 8	6	8	0.900	0.001	0.140	0.047	0.268	0.221	0.136	0.354
Core 8	8	10	0.897	0.001	0.124	0.083	0.265	0.182	0.125	0.381
Core 9	0	2	1.292	0.040	0.167	0.034	0.210	0.176	0.328	0.547
Core 9	2	4	1.111	0.032	0.096	0.026	0.171	0.146	0.290	0.522
Core 9	4	6	1.697	0.031	0.086	0.023	0.169	0.146	0.282	1.129
Core 9	6	8	1.138	0.032	0.085	0.023	0.171	0.148	0.322	0.528
Core 9	8	10	1.022	0.031	0.084	0.024	0.170	0.146	0.305	0.433
Core 10	0	2	0.920	0.035	0.125	0.014	0.089	0.075	0.355	0.317
Core 10	2	4	0.733	0.024	0.063	0.010	0.055	0.045	0.356	0.235
Core 10	4	6	0.685	0.020	0.061	0.009	0.053	0.045	0.400	0.150
Core 10	6	8	0.641	0.018	0.051	0.008	0.047	0.039	0.362	0.163
Core 10	8	10	0.656	0.019	0.051	0.010	0.043	0.033	0.471	0.072
Core 11	0	2	1.317	0.014	0.285	0.063	0.314	0.251	0.223	0.481
Core 11	2	4	1.135	0.008	0.210	0.053	0.278	0.225	0.191	0.449
Core 11	4	6	1.014	0.007	0.179	0.051	0.235	0.184	0.191	0.402
Core 11	6	8	0.874	0.005	0.152	0.048	0.203	0.155	0.201	0.313
Core 11	8	10	0.828	0.005	0.147	0.046	0.186	0.139	0.197	0.294

*Sediment survey conducted by Mark B. Edlund of the St. Croix Watershed Research Station and Science Museum of Minnesota on behalf of the Spring Lake Prior Lake Watershed District.