ST. ANTHONY
FALLS LABORATORY

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Golden Lake Phosphorus Release and Alum Dosing Feasibility Study

Technical Memorandum

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1 Introduction and Purpose

Golden Lake is located in the City of Circle Pines in the Rice Creek Watershed District (RCWD) in southern Anoka County, MN. The Golden Lake Watershed is a sub-watershed of the Upper Mississippi Watershed. The lake (total surface area = 0.23 km^2 or 57.2 ac) is relatively shallow, with a maximum depth of 7.3 m (24 ft), mean depth of 2.4 m (8 ft), and 90% littoral area. The 27-km^2 (6566-ac) drainage area to Golden Lake is primarily rural and agricultural, and contributes flow to the lake through the Anoka County Ditch 53-62. The lake flows into Rice Creek just downstream of the Lino Lakes Chain of Lakes.

The trophic status of Golden Lake is eutrophic to hypereutrophic due to the high total phosphorus (TP) and chlorophyll-*a* concentrations. Golden Lake was placed on the State of Minnesota's 303(d) Impaired Waters list in 2002 for being impaired for aquatic recreation due to excess nutrients. The Total Maximum Daily Load (TMDL) study for the lake estimated a total phosphorus load of 208 kg/yr (458 lb/yr) to the lake relative to the 2004 conditions (MPCA 2009) (Figure 1). The contribution from internal phosphorus loading, due to the release of phosphorus (P) from sediments under anoxia, and possibly due to factors such as vertical mixing by wind, presence of rough fish and phosphorus release from decaying curlyleaf pondweed, was estimated to be 112 kg/yr (260 lb/yr), which is 57% of the total phosphorus load to the lake. To achieve in-lake water quality goal of 60 µg/L TP (per the MN Eutrophication Standards for shallow lakes in the North Central Hardwood Forests ecoregion), a TMDL goal of 120 kg/yr (264 lb/yr) was set and it requires a reduction of 106 kg/yr (232 lb/yr) in the total phosphorus load for 2004 conditions, and a projected reduction of 158 kg/yr (348 lb/yr) for 2020 conditions (MPCA 2009). The total internal load requires 86% reduction to meet the TMDL goal.

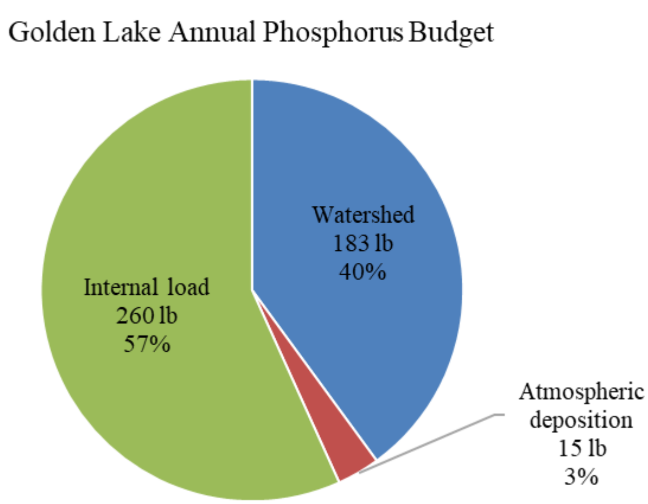

Figure 1. Golden Lake annual phosphorus budget based on 2004 load conditions in the TMDL study (data from MPCA 2009).

The purpose of this study is to estimate the existing annual internal phosphorus load in Golden Lake, and evaluate the feasibility and benefits of alum treatment for internal load reduction. Sediment cores were collected from Golden Lake to measure the sediment phosphorus release rates. The lake water chemistry (2011-2019 data from RCWD) were used with the laboratory phosphorus release study to estimate the internal phosphorus load in Golden Lake and compare it with the TMDL study. The lake sediment chemistry was analyzed to design an appropriate alum dose for binding the biologically-available phosphorus forms in the sediments that can contribute to internal loading in the lake. Recommendations on alum treatment and treatment cost estimates were also developed.

2 Methods

2.1 Laboratory Phosphorus Release Study

Ten sediment cores were collected from Golden Lake in June 2019 (Figure 2 and Figure 3). Using a surface corer with piston and drive rods, intact sediment cores with overlying water were collected into polycarbonate liner tubes (70 mm O.D.). Five cores were collected from water depths shallower than 3.1 m (10 ft) and the remaining five cores were collected from deeper areas. Two cores were collected from the deepest part of the lake (stations 8 and 9 in Figure 3). In situ dissolved oxygen (DO) and temperature profiles taken on the day of sediment coring indicated that the lake was stratified at ~2 m (6.6 ft) depth; the DO level dropped from 6 mg/L at 2 m depth to ~2 mg/L at 3 m depth, and further to < 0.5 mg/L at 4 m depth.

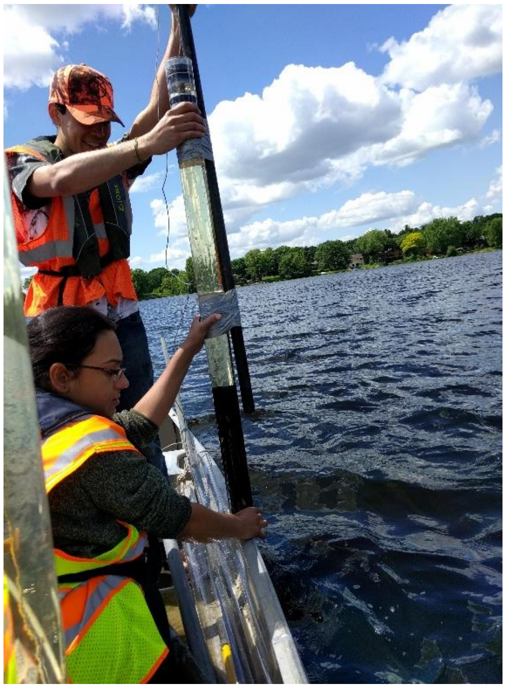

Figure 2. Sediment core collection at Golden Lake in June 2019.

Figure 3. Map showing the locations of ten sediment coring stations in Golden Lake. Coring stations 1, 2, 3, 4, 7 were located in depths below 3.1 m (10 ft). Coring stations 5, 6, 8, 9, 10 were located in depths greater than 3.1 m (10 ft).

The ten sediment cores were set up at 20 °C at the St. Anthony Falls Laboratory (SAFL) for the phosphorus release study (Figure 4). The incubation temperature variation was 20.4 ± 0.15 °C during the study. First, the water columns above the sediments were drained, filtered to remove particulates (using a 1.2 µm GF filter) and then carefully refilled into the columns without disturbing the sediments. Porous air stones attached to vinyl tubing were placed ~8 cm (~3 inch) above the sediment surface to gently mix the water column without agitating the sediments.

Figure 4. Golden Lake sediment cores set up for phosphorus release study at SAFL.

The phosphorus release study was divided into three phases. In the first phase, the water columns were aerated to simulate oxic condition (> 9 mg/L DO). Next, aeration was turned off to measure the rate of decrease in DO concentration in the water under an unmixed state. The Michaelis-Menten kinetic model was fit to the DO data to obtain a measure of the sediment oxygen demand (SOD) (Michaelis and Menton 1913):

$$S = \frac{S_{max}[C_{O2}]}{K_M + [C_{O2}]} \qquad (1)$$

where S is the substrate consumption rate, S_{max} is the maximum dissolved oxygen consumption rate, C_{O2} is the substrate (oxygen) concentration, and K_M is the half-consumption concentration. A constant K_M of 1.4 mg/L was used for all cores based upon a regression of 60 sediment types in Walker and Snodgrass (1986). It is assumed that all DO reduction is due to the microbial oxygen demand of the sediments, so K_M represents the surface of the sediments.

In the third phase, anoxic condition (DO < 1 mg/L) was simulated by bubbling the water columns with ultrapure nitrogen gas. The ortho-phosphate (soluble reactive phosphorus or SRP) concentrations in the water columns were periodically measured throughout the experiment. Water samples were drawn from approximately the center of the mixed water column and immediately filtered through 0.45 µm membrane syringe filters. For the second (aeration-off) phase, an average phosphate concentration was determined based on four water samples collected across the total water column depth to account for the concentration gradient that can develop under unmixed condition. Phosphate (SRP) analysis was performed in a Lachat QuikChem 8000 series FIA autoanalyzer (detection limit = 0.010 mg P/L) using the ascorbic acid method (Standard Methods 4500 P-G, APHA/AWWA/WPCF 1995). The change in phosphate mass [concentration (mg/L) × water column volume (L)] divided by the respective experimental duration (days) and the sediment surface area (same as the core liner area, m^2) yielded the phosphate release rate (mg/m^2/day) for each phase. The water volume withdrawn during each sampling exercise was accounted for during the water column volume calculations.

2.2 Sediment Phosphorus Analysis

After the completion of the phosphorus (P) release study, the sediments were analyzed for different types of P fractions contained in the total sedimentary P pool (Table 1). The sediment chemistry analysis provides concentrations of biologically-available P fractions (i.e., the loosely-bound and iron-bound P (together termed redox-P), and the labile organic-P), that contribute to internal phosphorus loading, and are typically targeted for chemical treatment of sediments using alum.

Table 1. Sediment phosphorus (P) fractions measured in the Golden Lake sediments using the sequential phosphorus extraction method. Descriptions of the phosphorus fractions and their biological-availability are also included.

Sediment P fraction	Description	Biological availability and mobility conditions	Extractant for sequential extraction method
Loosely-bound P	Porewater-soluble and adsorbed to calcium carbonate	Biologically available; released under oxic and anoxic conditions	1 M ammonium chloride
Iron-bound P (Fe-P)	Adsorbed to iron oxyhydroxides	Biologically available; released under anoxic conditions	0.11 M sodium bicarbonate and 0.1 M sodium dithionite
Labile organic-P	Organic P that can be mineralized by bacteria to soluble P	Biologically available; released under oxic and anoxic conditions	Persulfate digestion of NaOH extract
Aluminum-bound P (Al-P)	P bound to amorphous aluminum hydroxide	Biologically unavailable; released under high pH conditions	0.1 M sodium hydroxide
Mineral-bound P	Calcite- and apatite-bound P	Biologically unavailable; released under low pH conditions	2 N hydrochloric acid
Residual organic-P	Presumed organic and refractory	Biologically unavailable	30% hydrogen peroxide and 2 N HCl

Five sediment cores that were collected from the shallow locations (stations 1, 2) and deeper locations (stations 5, 8, 9) were analyzed for the sediment P fractions. The sediments were extruded into sections of 2-cm layers over the upper 10-cm depth and into 5-cm layer over the 10-15 cm depth of the core. Concentrations of the sediment P fractions were determined in following the sequential extraction method using extractants summarized in Table 1 (method adapted from Psenner and Puckso 1988 and SCWRS 2010). The labile organic-P fraction was determined by subtracting the aluminum-bound P from the nonreactive NaOH-extractable P (Al-P + labile organic-P determined by persulfate digestion of NaOH extract). The extracts from each step were centrifuged at 3500 RPM for 10 minutes and analyzed for SRP concentrations in a Lachat autoanalyzer. The extracts from the iron-bound P analysis step were bubbled with oxygen for 20 minutes before SRP analysis. Water content analysis (drying at 105 °C) and organic matter content analysis (loss on ignition at 550 °C) were also performed on each sediment sample from the cores. The sediment bulk density was calculated using the water content and fixed density for organic matter content (Engstrom 2005).

2.3 Alum Dosing Calculation

The basis of alum dosing is to primarily target the highly-mobile redox-P fraction (loosely-bound P + iron-bound P) in the sediments and convert it to the immobile aluminum-bound P which is not sensitive to changes in DO conditions. Organic P is converted into phosphate through microbial degradation and mineralization (Jensen and Andersen 1992), with an estimated half-life on the order of 0.8 to 13 years (de Vicente et al. 2008, James 2011). While some alum dosing methods are based upon the redox-P mass (Rydin and Welch 1998, Pilgrim et al. 2011, Huser and Pilgrim 2014, James and Bischoff 2015), other applications have included the slowly-releasable labile organic-P fraction in the alum dose estimate (Reitzel et al. 2005, de Vicente et al. 2008, NALMS alum workshop 2019). A wide range of doses have been applied using Al:P ratio varying from 10:1 to >100:1, where Al:P represents the ratio of aluminum applied to the aluminum-bound phosphorus formed (Rydin and Welch 1998, de Vicente et al. 2008, Huser and Pilgrim 2014, James and Bischoff 2015). While one lake-wide alum application devised for redox-P and labile organic-P was successful at a low Al:P ratio of 4:1 (Reitzel et al. 2005), a Al:P ratio of 8.8 has been suggested for the labile organic-P fraction in Danish lake studies (NALMS alum workshop 2019). de Vicente et al. (2008) recommend using a minimum of 10:1 Al:P ratio to reduce the biologically-available sediment P (i.e., loosely-bound-P + iron-bound P + labile organic-P), since there is evidence of potential decrease in the phosphorus-binding efficiency of alum due to the crystallization of amorphous aluminum hydroxide floc after application.

In this study, the sum of redox-P mass and labile organic-P mass was considered as the available phosphorus to be treated by alum addition (see results section for justification). The amount of aluminum sulfate ($Al_2(SO_4)_3$; expressed as Al) to capture the available-P (mg P/g dry sediment) was determined using (Osgood et al. 2017):

$$Available - P\ \left(\frac{g}{m^2}\right) = Available - P\ \left(\frac{mg}{g}\right) \times bulk\ density\left(\frac{g}{cm^3}\right) \times total\ solids\ \% \times sediment\ treatment\ depth\ (cm) \times unit\ conversion\ factor \qquad (2)$$

$$Al\ \left(\frac{g}{m^2}\right) = Available - P\ \left(\frac{g}{m^2}\right) \times Al\!:\!P \qquad (3)$$

The sediment depth for phosphorus inactivation by alum was determined based on the vertical profile of available-P in the upper 15 cm sediments. The unit conversion factor is 10 [10^4 (cm^2/m^2) × 10^{-3} (g/mg)]. The Al:P ratio was assumed based on literature review since the Al-P binding efficiency in the Golden Lake sediments was not directly evaluated in the laboratory.

2.4 Golden Lake Water Quality Data

The dissolved oxygen and temperature profiles collected at the deepest location in the lake, and the surface and hypolimnetic TP concentrations in Golden Lake from 2011 to 2019 (Appendix A) were used for the internal load estimation and alum dose calculation.

3 Results of Laboratory Study

3.1 Sediment Phosphorus Release Rates

In the first phase of oxic incubation, phosphate concentrations remained very low in the aerated water columns in the ten cores (Figure 5), suggesting phosphate release did not occur from the sediments under oxic conditions. An increase in phosphate mass was observed in one core. The mineralization and mobilization of labile organic phosphorus in the sediments into phosphate form can occur under oxic conditions (Jensen and Andersen 1992). The mean oxic release rate was 0.661 mg/m^2/day (± 1.38 Std. Dev.) for the ten columns.

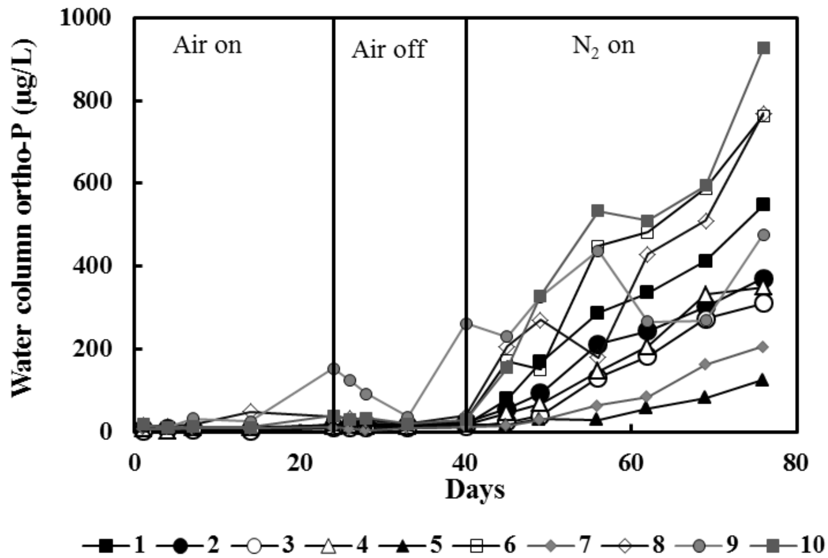

Figure 5. Phosphate (ortho-P) release measured from the Golden Lake sediment cores at 20 °C in the laboratory. The three phases of the phosphorus release study are separated by solid lines. First, the water columns were oxic by aeration (air on). Then, aeration was switched off and the water columns were under quiescent condition (air off). In the last phase, the water columns were anoxic by nitrogen gas bubbling (N_2 on).

After aeration was switched off, the water columns were under quiescent conditions. The initial DO concentration of ~9.8mg/L in the water columns decreased due the sediment oxygen demand, and the DO reached below 1 mg/L in most columns after 8 to 11 days (Figure 6). The sediment oxygen demand varied from 0.839 to 1.84 g/m^2/day in the ten columns, with a mean S_{max} of 1.57 g/m^2/day (± 0.493 Std. Dev.). It is likely that a concomitant phosphate release was mostly not observed because the water columns did not turn fully anoxic until the end of the 15-day air-off phase (Figure 5).

Once anoxic condition was established by nitrogen gas bubbling, the water column phosphate concentrations gradually increased due to sediment phosphorus release over the 30-day anoxic period (Figure 5). The anoxic phosphate release rates varied from 2.41 to 17.6 mg/m^2/day for the ten cores, with a mean anoxic release rate of 7.64 mg/m^2/day (± 4.98 Std. Dev.). The mean release rate is in the range observed for other mesotrophic and eutrophic lakes (Nürnberg 1988, Jensen and Andersen 1992, Pilgrim et al. 2007). The mean anoxic phosphate release rate was 10.1 mg/m^2/day (± 6.29 Std. Dev.) for cores from the deeper areas (> 3.1 m or 10 ft), and 5.19 mg/m^2/day (± 1.09 Std. Dev.) for cores collected from the shallow areas (> 3.1 m or 10 ft).

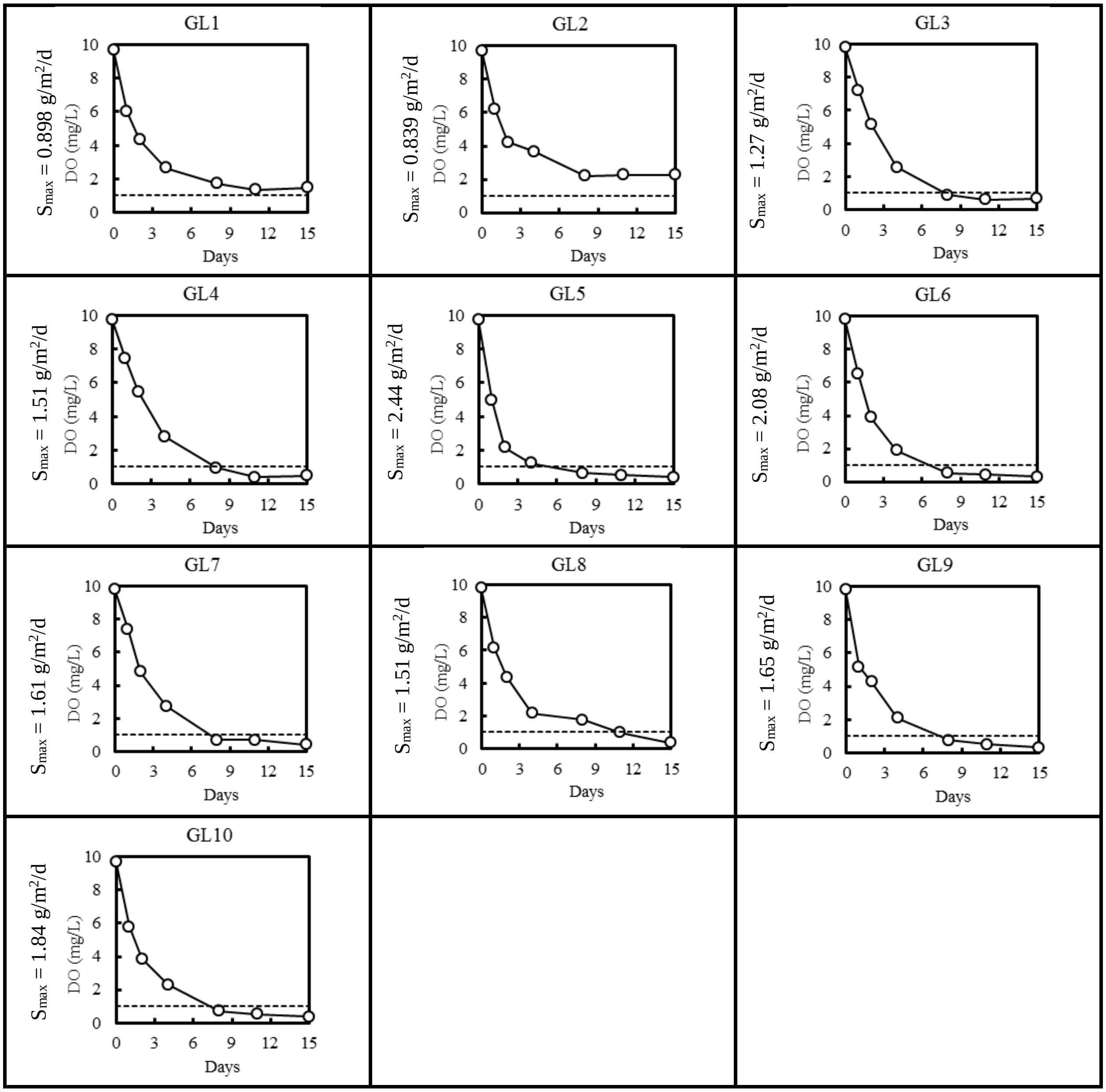

Figure 6. Dissolved oxygen (DO) concentrations measured in the unmixed water columns of the Golden Lake sediment cores during the air-off phase of the phosphorus release study in the laboratory. DO concentrations were measured ~8 cm over the sediment surface. The 1 mg/L DO level is shown for reference. The calculated S_{max} is also included for the ten cores.

3.2 Sediment Phosphorus Characterization

The analysis of five sediment cores collected from the shallower areas (stations 1 and 2) and deeper areas (stations 5, 8 and 9) of Golden Lake provided the spatial distribution of sediment phosphorus concentrations and physical characteristics of the lake sediments (Table 2).

Table 2. Sediment characteristics and phosphorus fractions in the Golden Lake sediments. The phosphorus fractionation results provided are on dry weight basis.

Sediment Core ID	Depth interval (cm)	% Moist -ure	% Organic	Bulk density (g/cm^3)	Sediment Phosphorus Fractions					
					Redox-P (Loose- + Fe-P)	Al-P	Ca-P	Labile Org-P	Residual -P	Total P
					mg P/g dry weight sediment					
1	0-2	96%	42%	1.019	0.207	0.155	0.187	0.528	0.079	1.155
	2-4	94%	40%	1.030	0.090	0.124	0.189	0.409	0.070	0.881
	4-5	94%	40%	1.031	0.061	0.119	0.208	0.378	0.163	0.930
	5-7	93%	38%	1.038	0.058	0.107	0.219	0.301	0.142	0.828
	7-10	91%	35%	1.048	0.051	0.110	0.217	0.270	0.132	0.780
	10-15	90%	32%	1.058	0.052	0.103	0.207	0.193	0.034	0.588
2	0-2	91%	29%	1.049	0.076	0.072	0.356	0.216	0.061	0.780
	2-4	89%	29%	1.066	0.065	0.071	0.235	0.177	0.087	0.636
	4-6	89%	29%	1.066	0.047	0.075	0.226	0.166	0.048	0.562
	6-8	88%	28%	1.070	0.034	0.062	0.237	0.131	0.082	0.546
	8-10	88%	29%	1.073	0.042	0.059	0.287	0.121	0.031	0.540
	10-15	87%	28%	1.075	0.032	0.046	0.250	0.091	0.075	0.494
5	0-2	97%	48%	1.013	0.596	0.397	0.139	0.649	0.125	1.907
	2-4	95%	44%	1.023	0.223	0.262	0.183	0.563	0.129	1.360
	4-6	94%	42%	1.029	0.120	0.184	0.214	0.432	0.087	1.037
	6-8	94%	42%	1.032	0.103	0.148	0.214	0.385	0.075	0.925
	8-10	93%	40%	1.034	0.160	0.162	0.206	0.373	0.145	1.045
	10-15	92%	41%	1.042	0.136	0.105	0.262	0.382	0.072	0.957
8	0-2	97%	45%	1.014	0.611	0.562	0.110	0.635	0.114	2.033
	2-4	93%	44%	1.028	0.561	0.328	0.076	0.407	0.071	1.443
	4-6	96%	45%	1.021	0.444	0.332	0.125	0.494	0.119	1.514
	6-8	96%	43%	1.023	0.242	0.193	0.117	0.466	0.150	1.168
	8-10	95%	40%	1.027	0.205	0.269	0.178	0.377	0.046	1.075
	10-15	93%	40%	1.036	0.299	0.659	0.219	0.594	0.060	1.832
9	0-2	98%	45%	1.011	0.887	0.893	0.153	0.964	0.068	2.966
	2-4	96%	43%	1.017	0.839	1.061	0.175	1.405	0.044	3.524
	4-6	96%	43%	1.021	0.914	1.147	0.198	1.552	0.041	3.852
	6-8	96%	44%	1.021	0.973	0.863	0.175	0.915	0.059	2.986
	8-10	95%	40%	1.028	0.747	0.834	0.366	0.849	0.138	2.933
	10-15	93%	40%	1.035	0.687	0.899	0.340	1.372	0.050	3.348

The moisture content in the upper 15-cm sediments ranged from 87 to 98%, with high moisture content in the upper layers that decreased with increasing sediment depth. The average sediment organic matter content varied 28 to 45% in the ten cores, with average concentrations of 43% in the deeper sediments (cores# 5, 8, 9) and 33% in the relatively shallower sediments (cores# 1, 2). Lower moisture content and higher dry bulk density were measured in sediment cores 1 and 2 than in the deeper sediment cores.

Spatial variability was observed in the concentrations of P fractions in the lake sediments (Figure 7 and Table 2). The loosely-bound P was generally low (< 0.03 mg P/g) in the sediments. The iron-bound P concentrations were low in the upper 15 cm of the shallow cores (0.062 mg P/g average) and much higher in the deeper cores (0.475 mg P/g average). The deepest sediments (core# 9 collected at 7.3-m or 24-ft contour) contained the highest iron-bound P concentrations (0.824 mg P/g average) compared to other coring stations. Labile organic-P concentrations were also high in the deeper sediments, and in fact constituted the major fraction of the total sediment phosphorus. High labile organic-P levels have been observed in other shallow lakes and can contribute internal load in some lakes (James 2011). Labile organic-P thus presents an additional source of internal load in Golden Lake. Overall, redox-P (loosely-bound P + iron-bound P) and labile organic-P concentrations were higher in the deeper sediments than the shallow sediments in the lake. Since summertime anoxia is prevalent in the deeper parts of the lake, the bioavailable P (redox-P + labile organic-P) in these sediments is important for generating internal load. The vertical profiles of the P concentrations indicated generally higher concentrations in the surficial sediments, which can be important for internal loading in eutrophic systems (Carey and Rydin 2011). Concentration peaks for redox-P and labile organic-P were found to be in the 0-6 cm depth in shallow sediments and in the 0-8 cm depth in the deeper sediments (Figure 7).

Aluminum-bound P was highest in core# 9 (7.3-m contour) and lowest in core #2 (between 1.5-m and 3.1-m contour). Mineral-bound P concentrations were relatively higher in the shallow sediments than the deeper sediment cores. The average total phosphorus composition in the shallow sediment cores was 9% redox-P, 13% Al-P, 35% Ca-P, 32% labile organic-P and 12% residual-P. The deeper sediment cores contained 23% redox-P, 24% Al-P, 12% Ca-P, 36% labile organic-P and 6% residual-P, on average. When considering only the biologically-available P, the shallow sediments contained 22% redox-P and 78% labile organic-P, and the deeper sediments contained 38% redox-P and 62% labile organic-P in the upper 15 cm sediments.

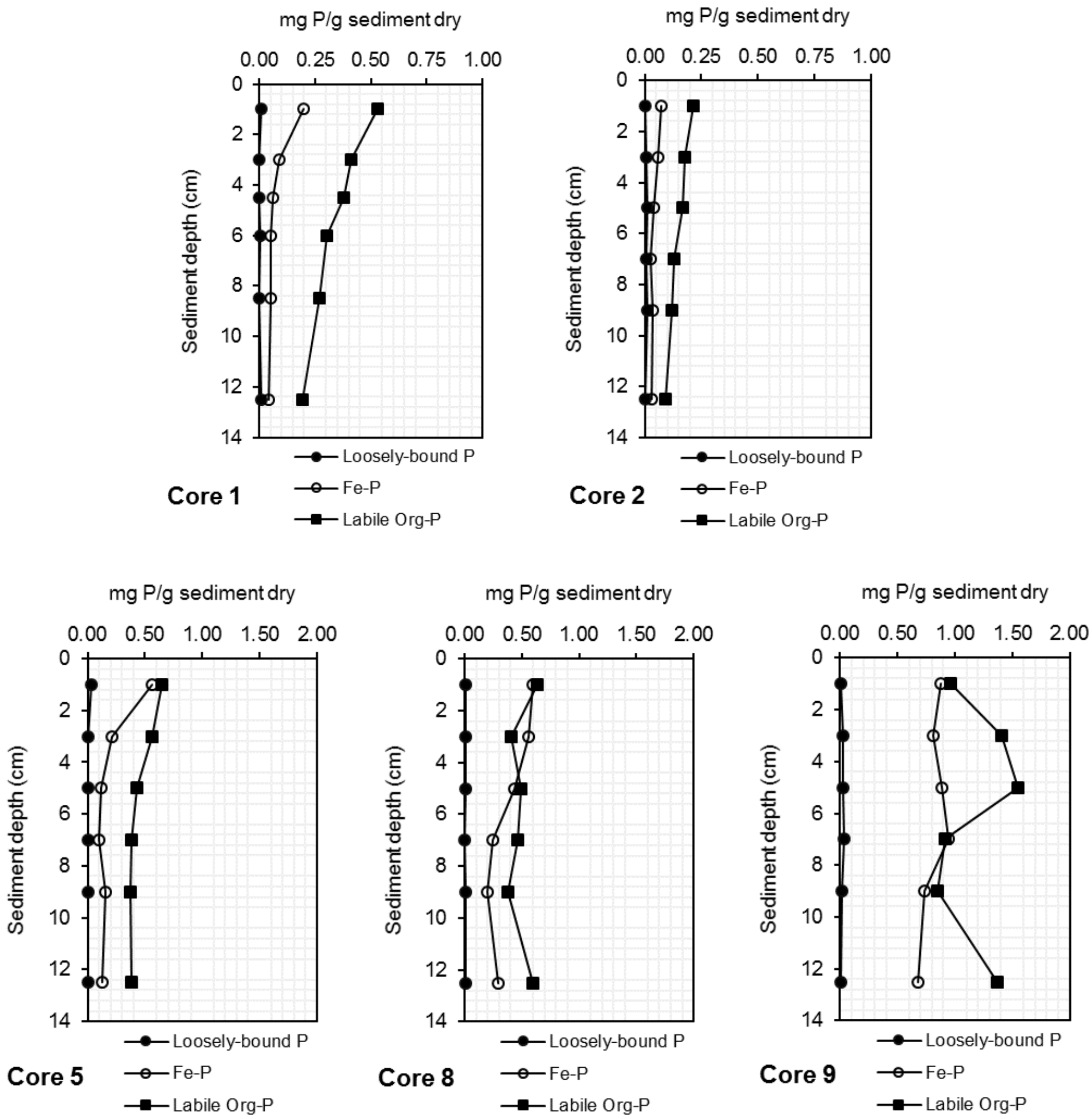

Figure 7. Vertical profiles of loosely-bound P, iron-bound P (Fe-P) and labile organic-P in five sediment cores collected from Golden Lake. Phosphorus fractions are expressed on a dry sediment weight basis. The sediment depth 0 cm represents the sediment-water interface. Concentrations are plotted in the mid-point of a given sediment depth interval (for example, concentration for 0-2 cm depth is plotted at 1 cm). Coring stations 1 and 2 were located in water depths below 3.1 m (10 ft). Coring stations 5, 8 and 9 were located in water depths greater than 3.1 m (10 ft). Coring station 9 was located in the deepest areas of the lake (7.3-m or 24-ft contour).

4 Findings and Interpretations

4.1 Estimate of Internal Phosphorus Load

The long-term DO and temperature data for Golden Lake indicated that the DO concentration dropped below 1 mg/L at depths between 1.6 m (6 ft) and 5.3 m (18 ft) during the growing season (May to September) (2011-2019 monitoring data; Appendix A). Literature models estimate the summer mixed layer depth or thermocline depth between 3.9 m and 4.4 m (~13 to 14 ft) for the surface area and maximum water depth of Golden Lake (Gorham and Dyce 1989; Fee et al. 1996). The change in depth of anoxia from the beginning to the end of summer means the area of lake under anoxia and thus the internal load contribution varies over the summer period. Therefore, monthly estimates of internal load in Golden Lake were calculated.

The in situ temperature conditions in the lake were established by calculating an area-weighted average temperature below the depth of anoxia. This was done because microbial activity in the sediments is dependent on temperature, and can influence the rate and magnitude of P release and thus internal loading (Holden and Armstrong 1980, Jensen and Andersen 1992, Nürnberg 2009). Since the sediment cores were not incubated at the in situ temperature in the laboratory, a temperature correction was applied to the anoxic P release rate measured at 20 °C to obtain the P release rate expected under the in situ temperature using Equation 4:

$$k_{T°\mathrm{C}} = k_{20°\mathrm{C}} \times \theta^{(T-20)} \tag{4}$$

where, k is the P release rate at a given temperature (T °C), and θ is the Arrhenius temperature coefficient. A $\theta = 1.15$ was used based on the average θ for 10 lakes that ranged from 1.06 to 1.23 (1.15 mean ± 0.066 std. dev.) in several lake sediment incubation studies (Lee et al. 1977, Holden and Armstrong 1980, Jensen and Andersen 1992, Natarajan et al. 2017).

Nürnberg (1995) has suggested a similar temperature correction method following the Q_{10} rule of Van Holst to account for the variability in internal load due to the influence of summer mixed layer water temperature on the P release rates and the releasing area (or anoxic factor). Literature values of Q_{10} for lake sediment P release rate range from 1.4 to 7.7 (Jensen and Andersen 1992), which corresponds to Arrhenius temperature coefficient θ values of 1.09 to 1.23.

Table 3 provides the estimated monthly internal load from the anoxic area in Golden Lake based on the phosphorus release rate adjusted for the water temperature in the anoxic zone. The internal load is expected to be lowest in May (1.4 kg or 3.0 lb) and highest in July (28 kg or 61 lb), yielding an estimated total internal load of 71 kg/yr (158 lb/yr) during the May to September period. It is assumed that the internal load generated during the warmer months represents the annual internal load in the lake.

Table 3. Internal phosphorus (P) load estimate for Golden Lake. The anoxic P release rates were corrected for average temperature in the estimated anoxic area in the lake.

Month	Estimated depth of anoxia (m)	Approximate anoxic area (km^2)	Average water temperature (°C)	Expected anoxic P release rate ($mg/m^2/day$)	Estimated internal P load (kg)	Estimated internal P load (lb)
May	5.33	0.022	10.5	1.99	1.37	3.02
June	3.18	0.070	13.8	4.02	8.43	18.6
July	2.63	0.148	16.7	6.06	27.8	61.4
August	2.54	0.148	16.7	6.06	26.9	59.4
September	3.91	0.070	13.8	3.16	6.84	15.1
				Total internal load =	**71.4**	**158**

The 2009 TMDL study estimated the internal load in Golden Lake to be 112 kg/yr (260 lb/yr) (MPCA 2009). Since the BATHTUB model for the lake was calibrated by adjusting the internal load to match observed in-lake conditions, the results of the BATHTUB model are subject to the uncertainties of external load estimates. The current internal load estimate of 71 kg/yr (158 lb/yr) is based on DO profiles and measured sediment P release rates that were adjusted to the summer mixed layer water temperature, and is therefore believed to be more representative of the lake conditions. If a temperature correction is not applied, the internal load estimate will be 117 kg/yr (258 lb/yr).

The TMDL study calls for reducing the internal load to 16 kg/yr (36 lb/yr) to achieve the TMDL goal for Golden Lake. This means, about 77% reduction in the estimated annual internal load of 71 kg/yr is required to meet the TMDL goal. A proper alum addition will reduce the internal phosphorus load to almost zero.

4.2 Alum Dose Calculation

In the Golden Lake sediments, the biologically-available P (redox-P + labile organic-P) was moderately high, with labile organic-P constituting the major fraction of available-P (22% redox-P and 78% labile organic-P in shallow sediments, and 38% redox-P and 62% labile organic-P in the deeper sediments). Therefore, the total mass of redox-P and labile organic-P was considered for the alum dosing calculation, assuming a Al:P ratio of 20:1. The 20:1 Al:P ratio is appropriate, considering the inclusion of the labile organic-P mass that degrades into phosphate only at a slow rate and the possibility that aging alum may lose its binding efficiency after application (de Vicente et al. 2008). Vertical profiles indicated that the highest concentration of redox-P and labile organic-P was attained within the upper 8 cm depth (Figure 7), therefore the available P in the 0-10 cm depth was considered for the alum dose. Several alum application studies have targeted phosphorus in the top 4 to 10 cm sediments for inactivation by alum (Rydin and Welch 1999, James and Barko 2003). In the absence of lake alkalinity data, a buffered alum dose with sodium aluminate (Na_2AlO_2) as buffer was devised for pH management during the alum addition.

Table 4 provides the alum dose calculated for Golden Lake. The historic DO profile data indicate a mean depth of anoxia at 3.1 m in the lake during June to September. Therefore, two alum doses were developed for the deeper (> 3.1 m or 10 ft) and shallow areas (< 3.1 m) based on the lake's contour data. It is strongly recommended that areas deeper than 3.1 m in Golden Lake be treated with an alum dose of 123 g Al/m^2; this area is ~69,806 m^2 (17.3 ac) and represents 30% of the total lake surface area.

The shallow sediments are expected to be generally oxygenated and have a low potential to release P under such conditions. However, DO levels in shallow lakes can exhibit relatively large diurnal variation due to photosynthesis and respiration, especially in littoral areas covered with dense aquatic vegetation and algae, that cause periods of local anoxia leading to P release (James et al. 1996, Hoverson 2008). The shallow area (< 3.1 m depth) in Golden Lake is 0.16 km^2 or 39.5 ac, which is almost 69% of the total lake surface area, and can be considered for a one-time alum treatment at an application rate of 65 g Al/m^2.

It is recommended to complete the alum application in early spring or late fall. If the treatment is carried out during the summer months, an additional amount of 13 gal Al/ac is needed to capture the phosphorus mass in the entire lake water column.

Based on research suggesting decreased binding efficiency of aging alum floc (de Vicente et al. 2008), the total alum dose is often divided into multiple applications to improve alum performance and longevity, and to modify future doses depending on the success of the first dose (James 2011, Huser and Pilgrim 2014). The 123 g Al/m^2 for the deeper area can be applied as a single dose, or divided into two applications. It is recommended to assess the lake water quality condition including the sediment chemistry before future alum treatments are done.

Table 4. Estimate of alum dose for inactivating available-P in the Golden Lake sediments. Dosing is provided for the deeper and shallow sediments, and for water column P removal.

Alum dose for deeper sediments: Depth > 3.1 m or 10 ft; Treatment area = 69,806 m^2 or 17.3 ac			
Redox-P	mg/g	0.508	Average concentration in the upper 10 cm (cores# 5, 8 and 9)
Labile organic-P	mg/g	0.698	Average concentration in the upper 10 cm (cores# 5, 8 and 9)
Available-P	mg/g	1.21	Redox-P + Organic-P
Treatment depth	cm	10	Based on vertical profile of available-P
Bulk density	g/cm^3	1.02	Average for upper 10 cm
Total solids	%	5	Average for upper 10 cm
Available-P	g/m^2	6.17	Available-P × bulk density × total solids × treatment depth × 10 (Equation 2)
Al:P ratio		20	Assumption
Al dose	**g Al/m^2**	**123**	Available-P × Al:P (Equation 3)
Al dose	**gal Al/acre**	**2269**	g Al/m^2 × 0.22 kg Al/gal × unit conversion factor
Alum dose for shallow sediments: Depth < 3.1 m or 10 ft; Treatment area = 159,915 m^2 or 39.5 ac			
Redox-P	mg/g	0.073	Average concentration in the upper 10 cm (cores# 1, 2)
Labile organic-P	mg/g	0.270	Average concentration in the upper 10 cm (cores# 1, 2)
Available-P	mg/g	0.343	Redox-P + Organic-P
Treatment depth	cm	10	Based on vertical profile of available-P
Bulk density	g/cm^3	1.05	Average for upper 10 cm
Total solids	%	9	Average for upper 10 cm
Available-P	g/m^2	3.24	Available-P × bulk density × total solids × treatment depth × 10 (Equation 2)
Al:P ratio		20	Assumption
Al dose	**g Al/m^2**	**64.7**	Available-P × Al:P (Equation 3)
Al dose	**gal Al/acre**	**1191**	g Al/m^2 × 0.22 kg Al/gal × unit conversion factor
Alum dose for water column phosphorus: Entire lake; Treatment area = 231,480 m^2 or 57.2 ac			
Epilimnion TP	mg/L	0.058	10-year mean TP (2008-2018) in Golden Lake
Lake volume	m^3	564,934	
Al:P		3:1	
Water column dose	kg Al	99	Epilimnion TP × Lake volume × Al:P
Water column dose	gal Al	449	0.22 kg Al/gal
Water column dose	**gal Al/ac**	**7.86**	Total lake area = 57.2 ac

4.3 Estimated Cost and Benefit of Alum Treatment

The cost of alum treatment can vary depending on the form of alum used (wet or dry), dosage requirements, area treated, equipment mobilization, and labor (MPCA 2004). The material cost of alum can also vary year to year. To develop the cost estimate, it was assumed that liquid alum costs $2.10/gallon and sodium aluminate costs $5.60/gallon.). The estimated treatment cost (applied material cost + 10% contingency cost) is $92,833 for the deeper area of the lake (> 3.1 m or 10 ft), and $111,580 for the shallower area (< 3.1 m) (Table 5). The cost estimate does not include mobilization, engineering, and project management costs. If the alum treatment is performed in summer instead of early Spring or late Fall, an additional $1066 will be required for the water column phosphorus stripping.

Table 5. Cost estimate for alum application in the proposed treatment areas in Golden Lake. The cost estimate does not include mobilization and project management costs.

	Al dose g Al/m^2	Buffered alum quantity		Applied material cost	Material cost + 10% contingency cost
		Alum (gal)	Sodium aluminate (gal)		
Treatment area > 3.1 m or 10 ft depth (69,806 m^2 or 17.3 ac)	123	17,223	8612	$84,393	$92,833
Treatment area < 3.1 m or 10 ft depth (159,915 m^2 or 39.5 ac)	64.7	20,701	10,351	$101,436	$111,580
Water column dose	0.072	198	99	$969	$1066
Total cost (material cost + contingency cost) =					**$205,478**

The cost estimate also excludes additional costs that will be involved for preparation of bid documents, contract execution, monitoring before, during and after treatments, interpretation of data to determine benefit of treatment and establish second treatment dosage rate, mobilization and demobilization for the treatments, managing public access during treatment, public meetings and input from City council and residents, grant application and administration costs, development of memos/reports and follow up meetings that will be needed to meet grant agency and local information requirements, etc. An estimate of these costs based on other lake alum treatment projects is summarized in Appendix B for reference.

At least 85% reduction in sediment phosphorus release has been observed with alum dosing, although other factors such as high external load can impact the overall reduction in lake phosphorus levels (NALMS alum workshop 2019). The impact of external phosphorus load on the overall lake water quality and alum efficiency was, however, not considered in this study.

5 Summary and Recommendations

In Golden Lake, the anoxic sediment phosphorus release rates were high at 10.1 $mg/m^2/day$ in the deep portion of the lake and moderate at 5.2 $mg/m^2/day$ in the shallow sediments, producing a mean release rate of 7.64 $mg/m^2/day$ for the whole lake. The sediment phosphorus fractionation analysis revealed moderately high concentrations of redox-P and labile organic-P fractions in the deeper sediments that present a potential source of internal load to the lake. Labile organic-P constituted the major fraction of the biologically-available P as well as total sedimentary P, and is expected to contribute a slow flux of phosphorus from the sediments.

The historic DO and temperature profiles in the lake indicated that anoxia (DO < 1 mg/L) was present in areas under 5.3 m depth in May but extended to areas of 2.5 m depth in August. To account for the changes in the depth of anoxia and water temperature, monthly estimates of internal load were developed for the summer period using temperature-corrected phosphorus release rates. The internal load in Golden Lake is estimated to be 71 kg/yr (158 lb/yr) under the in situ temperature conditions.

To reduce the internal load by capturing the biologically-available phosphorus (redox-P + labile organic-P) in the sediments, an alum dose of 123 g Al/m^2 is recommended for the deeper portions of the lake (> 3.1 m depth). The estimated cost for alum application (excluding mobilization) is $92,833. The recommended alum dose may be applied as a single dose over the proposed treatment area, or split into two doses since all the biologically-available phosphorus, especially the labile organic-P, will not be available to bind with the applied alum. The treatment of shallow areas of the lake (< 3.1 m depth) will cost $111,580 at a dosage rate of 65 g Al/m^2. Future alum doses must be determined based on the improvements in lake water quality and the sediment chemistry after the first alum application.

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Appendices

Appendix A: Golden Lake Water Quality Monitoring Data for 2008 to 2019 (data obtained from the Rice Creek Watershed District)

Table A- 1. Golden Lake dissolved oxygen (DO) and temperature (Temp) profiles data from 2008 to 2018. The DNR Lake ID for Golden Lake is 20045.

Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)
2011				2012				2013				2014			
6/16/2011	0.50	20.13	8.27	6/5/2012	0.50	23.00	13.40	6/3/2013	0.50	20.17	11.88	5/28/2014	0.50	21.90	8.38
6/16/2011	1.50	19.91	7.46	6/5/2012	1.00	20.42	7.20	6/3/2013	1.50	18.57	8.29	5/28/2014	1.00	21.26	6.69
6/16/2011	2.00	19.52	5.10	6/5/2012	1.50	18.84	0.76	6/3/2013	2.00	17.66	6.3	5/28/2014	2.00	14.62	4.09
6/16/2011	2.50	17.67	0.25	6/5/2012	2.00	17.83	0.20	6/3/2013	2.50	15.49	0.95	5/28/2014	3.00	12.02	3.50
6/16/2011	3.00	15.54	0.48	6/5/2012	3.00	15.77	0.14	6/3/2013	3.50	11.27	1.4	5/28/2014	4.00	10.27	1.75
6/16/2011	3.50	13.24	0.68	6/5/2012	4.00	13.27	0.02	6/3/2013	4.50	7.62	0.16	5/28/2014	5.00	8.88	0.45
6/16/2011	4.00	11.27	0.20	6/5/2012	4.50	12.24	0.00	6/3/2013	5.50	6.63	0.11	5/28/2014	6.00	8.23	0.20
6/16/2011	4.50	10.10	0.03	6/5/2012	5.00	11.85	0.01					5/28/2014	7.00	7.30	0.13
6/16/2011	5.00	9.51	-0.06	6/5/2012	6.00	10.97	-0.02	7/2/2013	0.50	26.37	9.56				
6/16/2011	5.50	9.08	-0.10	6/5/2012	7.00	10.57	-0.03	7/2/2013	1.50	23.83	4.65	6/11/2014	0.50	23.03	8.46
6/16/2011	6.00	8.77	-0.11					7/2/2013	2.00	22.13	0.81	6/11/2014	1.00	22.43	4.00
6/16/2011	6.50	8.50	-0.10	6/19/2012	0.25	22.66	8.15	7/2/2013	2.50	18.73	0.30	6/11/2014	2.00	18.05	0.24
6/16/2011	7.00	8.25	-0.13	6/19/2012	0.50	22.65	7.33	7/2/2013	3.00	14.73	0.99				
				6/19/2012	1.00	21.30	3.15	7/2/2013	3.50	12.78	0.30	6/25/2014	0.50	23.14	3.05
7/26/2011	0.50	26.00	4.35	6/19/2012	2.00	19.63	0.30	7/2/2013	4.50	9.41	0.12	6/25/2014	1.00	22.88	2.76
7/26/2011	1.00	25.26	3.11	6/19/2012	3.00	17.40	0.13	7/2/2013	5.50	8.22	0.07	6/25/2014	1.50	22.37	0.33
7/26/2011	1.50	24.47	0.33	6/19/2012	4.00	14.15	0.08					6/25/2014	2.00	19.90	0.27
7/26/2011	2.00	22.80	0.13	6/19/2012	5.00	12.54	0.03	7/22/2013	0.50	25.81	6.93	6/25/2014	3.00	15.40	0.17
7/26/2011	3.00	17.90	0.04	6/19/2012	6.00	11.32	0.01	7/22/2013	1.50	25.63	6.43	6/25/2014	4.00	10.85	0.16
7/26/2011	4.00	13.44	-0.05	6/19/2012	6.50	10.88	0.01	7/22/2013	2.00	25.35	1.50	6/25/2014	5.00	9.21	0.09
7/26/2011	5.00	11.30	-0.07					7/22/2013	2.50	21.31	0.45	6/25/2014	6.00	8.71	0.07
7/26/2011	6.00	10.62	-0.12	7/2/2012	0.50	29.11	7.83	7/22/2013	3.00	18.32	0.22	6/25/2014	6.50	8.48	0.06
7/26/2011	7.00	9.90	-0.13	7/2/2012	1.00	28.24	4.1	7/22/2013	4.00	11.77	0.15	6/25/2014	7.00	8.43	0.06
				7/2/2012	1.50	26.15	2.05	7/22/2013	5.00	9.61	0.13				
8/12/2011	0.50	23.85	11.46	7/2/2012	2.00	23.43	0.25					7/9/2014	0.50	24.32	4.38
8/12/2011	1.00	23.30	2.12	7/2/2012	3.00	17.65	0.17	8/1/2013	0.50	23.74	9.61	7/9/2014	1.00	22.86	3.97
8/12/2011	1.50	22.57	0.60	7/2/2012	4.00	14.45	0.07	8/1/2013	1.50	21.68	5.8	7/9/2014	1.50	22.54	3.32
8/12/2011	2.00	22.20	0.11	7/2/2012	5.00	12.63	0.03	8/1/2013	2.00	20.81	1.71	7/9/2014	2.00	21.62	1.44

Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)
8/12/2011	3.00	17.75	0.05	7/2/2012	6.00	11.58	0.05	8/1/2013	3.00	19.04	0.31	7/9/2014	2.50	18.74	0.20
8/12/2011	4.00	13.50	-0.04					8/1/2013	4.00	12.32	0.18	7/9/2014	3.00	15.84	0.14
8/12/2011	5.00	11.62	-0.09	7/19/2012	0.50	26.69	3.2	8/1/2013	5.00	10.20	0.12	7/9/2014	4.00	11.36	0.09
8/12/2011	6.00	10.74	-0.02	7/19/2012	1.00	26.53	2.37	8/1/2013	6.00	8.39	0.12	7/9/2014	5.00	9.39	0.07
				7/19/2012	1.50	26.47	2.4	8/1/2013	6.50	7.94	0.08	7/9/2014	6.00	8.93	0.06
9/8/2011	0.50	21.02	9.09	7/19/2012	2.00	26.08	0.9					7/9/2014	7.00	8.57	0.06
9/8/2011	1.00	20.31	4.64	7/19/2012	3.00	19.10	0.16	8/12/2013	0.50	24.63	8.07	7/9/2014	7.50	8.44	0.05
9/8/2011	2.00	20.02	1.83	7/19/2012	4.00	14.88	0.08	8/12/2013	1.50	24.01	5.02	7/9/2014	8.00	8.32	0.07
9/8/2011	3.00	18.78	0.13	7/19/2012	5.00	12.99	0.12	8/12/2013	2.00	22.46	1.17				
9/8/2011	4.00	14.12	0.11	7/19/2012	6.00	12.03	0.06	8/12/2013	2.50	20.79	0.73	7/23/2014	0.50	25.52	8.03
9/8/2011	5.00	12.16	0.01	7/19/2012	7.00	11.43	0.08	8/12/2013	3.50	15.87	0.33	7/23/2014	1.00	25.31	6.84
9/8/2011	6.00	11.25	-0.03					8/12/2013	4.50	11.39	0.19	7/23/2014	2.00	21.75	0.25
9/8/2011	6.50	10.75	-0.06	8/2/2012	0.25	28.65	9.61	8/12/2013	5.50	9.31	0.14	7/23/2014	3.00	16.60	0.19
				8/2/2012	0.50	27.87	9.85					7/23/2014	4.00	11.98	0.11
9/28/2011	0.50	15.95	6.30	8/2/2012	1.00	27.35	9.96	9/11/2013	0.50	23.45	7.19	7/23/2014	5.00	9.97	0.09
9/28/2011	1.00	15.41	5.75	8/2/2012	1.50	27.16	6.44	9/11/2013	1.00	23.44	7.20	7/23/2014	6.00	9.07	0.07
9/28/2011	2.00	15.20	3.38	8/2/2012	2.00	26.24	0.33	9/11/2013	1.50	23.41	6.78	7/23/2014	6.50	8.78	0.07
9/28/2011	3.00	14.72	1.65	8/2/2012	3.00	20.30	0.19	9/11/2013	2.00	23.36	5.89	7/23/2014	7.00	8.56	0.06
9/28/2011	4.00	14.37	0.40	8/2/2012	4.00	14.90	0.12	9/11/2013	2.50	23.16	0.65				
9/28/2011	5.00	13.40	0.14	8/2/2012	5.00	13.27	0.10	9/11/2013	3.00	20.92	0.27	8/6/2014	0.50	24.81	7.57
9/28/2011	6.00	11.47	0.05	8/2/2012	6.00	11.90	0.06	9/11/2013	4.00	14.13	0.19	8/6/2014	1.00	24.5	2.06
9/28/2011	6.50	10.88	0.00	8/2/2012	6.50	11.69	0.08	9/11/2013	5.00	10.63	0.22	8/6/2014	1.50	24.02	0.24
9/28/2011	7.00	10.55	0.00					9/11/2013	6.50	9.62	0.14	8/6/2014	2.00	22.03	0.19
9/28/2011	7.50	10.37	-0.01	9/14/2012	0.50	19.55	8.17	9/11/2013	7.00	8.99	0.12	8/6/2014	3.00	16.46	0.16
				9/14/2012	1.00	19.37	6.72	9/11/2013	7.50	8.61	0.11	8/6/2014	4.00	12.52	0.10
2015				9/14/2012	1.50	19.19	5.19					8/6/2014	5.00	10.28	0.17
5/20/2015	0.50	15.55	10.53	9/14/2012	2.00	19.07	5.45	**2017**				8/6/2014	6.00	9.40	0.09
5/20/2015	1.50	15.36	10.50	9/14/2012	3.00	18.94	4.00	5/19/2017	0.50	15.94	8.18	8/6/2014	7.00	8.76	0.06
5/20/2015	2.50	14.59	9.40	9/14/2012	4.00	18.73	0.21	5/19/2017	1.50	15.88	7.95	8/6/2014	7.50	8.62	0.06
5/20/2015	3.50	14.07	7.74	9/14/2012	5.00	15.10	0.13	5/19/2017	2.50	13.94	6.10				
5/20/2015	4.50	12.60	0.56	9/14/2012	6.00	13.15	0.09	5/19/2017	3.50	10.41	4.61	9/3/2014	0.50	22.59	6.86
5/20/2015	5.50	10.41	0.35	9/14/2012	7.00	12.17	0.09	5/19/2017	4.50	9.40	3.78	9/3/2014	1.00	22.48	6.75
5/20/2015	6.00	9.92	0.27					5/19/2017	5.50	8.45	0.49	9/3/2014	1.50	22.36	6.35
5/20/2015	6.50	9.59	0.24	9/26/2012	0.50	16.48	8.95	5/19/2017	6.50	7.68	0.11	9/3/2014	2.00	22.04	2.16
5/20/2015	7.00	9.41	0.25	9/26/2012	1.00	15.08	7.34					9/3/2014	2.50	21.32	0.30
5/20/2015	7.50	9.32	0.22	9/26/2012	1.50	14.90	6.28	6/1/2017	0.50	17.08	9.09	9/3/2014	3.00	18.86	0.22
				9/26/2012	2.00	14.77	5.07	6/1/2017	1.50	16.39	7.67	9/3/2014	4.00	13.46	0.18
6/5/2015	0.50	20.15	10.01	9/26/2012	3.00	14.71	4.40	6/1/2017	2.50	14.84	4.20	9/3/2014	5.00	11.08	0.15
6/5/2015	1.00	20.01	9.48	9/26/2012	4.00	14.65	2.83	6/1/2017	3.00	12.38	2.87	9/3/2014	6.00	9.55	0.14

Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)
6/5/2015	2.00	19.09	8.14	9/26/2012	5.00	14.61	3.08	6/1/2017	3.50	10.93	2.51	9/3/2014	7.00	8.86	0.11
6/5/2015	3.00	16.56	4.85					6/1/2017	4.50	9.81	0.37	9/3/2014	7.50	8.71	0.10
6/5/2015	3.50	15.05	2.99	**2016**				6/1/2017	5.50	8.90	0.14				
6/5/2015	4.00	13.95	0.66	5/5/2016	0.50	16.46	12.70	6/1/2017	6.50	7.87	0.08	9/17/2014	0.50	16.89	10.74
6/5/2015	5.00	11.64	0.37	5/5/2016	1.50	16.06	12.67	6/1/2017	7.50	6.77	0.07	9/17/2014	1.00	16.78	10.06
6/5/2015	6.00	10.42	0.30	5/5/2016	2.50	13.33	10.54					9/17/2014	1.50	16.35	8.61
6/5/2015	7.00	9.45	0.22	5/5/2016	3.50	10.83	6.65	6/15/2017	0.50	24.42	7.24	9/17/2014	2.00	16.01	7.49
6/5/2015	7.50	9.23	0.20	5/5/2016	4.50	9.50	2.86	6/15/2017	1.50	24.31	7.17	9/17/2014	2.50	15.85	6.75
				5/5/2016	5.50	8.20	1.24	6/15/2017	2.00	23.40	0.36	9/17/2014	3.00	15.66	5.66
6/18/2015	0.50	22.9	8.02	5/5/2016	6.50	7.56	0.78	6/15/2017	2.50	16.06	0.18	9/17/2014	3.50	15.30	3.24
6/18/2015	1.00	22.63	7.86	5/5/2016	7.00	7.32	0.52	6/15/2017	3.50	11.63	0.14	9/17/2014	4.00	14.79	0.32
6/18/2015	1.50	22.34	7.56					6/15/2017	4.50	10.48	0.11	9/17/2014	5.00	11.24	0.29
6/18/2015	2.00	22.07	4.81	5/18/2016	0.50	16.3	12.71	6/15/2017	5.50	9.57	0.10	9/17/2014	6.00	10.06	0.20
6/18/2015	2.50	20.35	0.52	5/18/2016	1.50	14.66	10.83	6/15/2017	6.50	8.51	0.08	9/17/2014	7.00	9.15	0.16
6/18/2015	3.00	17.49	0.57	5/18/2016	2.50	12.93	8.56					9/17/2014	7.50	8.96	0.20
6/18/2015	4.00	14.13	0.26	5/18/2016	3.50	11.85	6.62	6/27/2017	0.50	20.7	10.17				
6/18/2015	5.00	11.95	0.21	5/18/2016	4.50	10.94	2.38	6/27/2017	1.50	20.19	8.97	**2018**			
6/18/2015	6.00	10.78	0.18	5/18/2016	5.50	9.56	0.45	6/27/2017	2.50	18.79	4.10	6/1/2018	0.40	25.05	8.44
6/18/2015	7.00	9.76	0.17	5/18/2016	6.50	8.15	0.38	6/27/2017	3.50	13.87	0.29	6/1/2018	1.33	23.61	7.74
6/18/2015	8.00	9.35	0.14	5/18/2016	7.00	7.85	0.34	6/27/2017	4.50	11.00	0.16	6/1/2018	2.37	16.90	4.22
				5/18/2016	7.50	7.54	0.32	6/27/2017	5.50	9.81	0.14	6/1/2018	3.38	9.32	2.32
7/2/2015	0.50	25.46	8.84					6/27/2017	6.50	8.78	0.13	6/1/2018	4.41	7.61	0.42
7/2/2015	1.00	24.23	8.27	6/1/2016	0.50	20.77	7.82	6/27/2017	7.00	8.42	0.11	6/1/2018	5.44	6.26	0.13
7/2/2015	1.50	24.05	8.52	6/1/2016	1.50	20.76	7.79					6/1/2018	5.82	5.81	0.11
7/2/2015	2.00	23.58	1.79	6/1/2016	2.50	16.15	4.66	7/13/2017	0.50	24.67	6.88				
7/2/2015	2.50	22.19	0.30	6/1/2016	3.50	12.59	3.08	7/13/2017	1.50	24.67	6.81	6/12/2018	0.39	21.73	9.25
7/2/2015	3.00	18.97	0.26	6/1/2016	4.50	11.04	0.36	7/13/2017	2.50	21.03	0.48	6/12/2018	1.62	21.04	8.97
7/2/2015	4.00	15.10	0.23	6/1/2016	5.50	10.15	0.34	7/13/2017	3.50	14.33	0.24	6/12/2018	2.51	16.60	3.72
7/2/2015	5.00	12.40	0.20	6/1/2016	6.00	9.46	0.29	7/13/2017	4.50	12.26	0.24	6/12/2018	3.68	9.77	1.21
7/2/2015	6.00	11.18	0.18					7/13/2017	5.50	10.62	0.16	6/12/2018	4.70	7.86	0.27
7/2/2015	7.00	10.03	0.18	6/17/2016	0.50	23.33	9.14	7/13/2017	6.50	9.77	0.15	6/12/2018	6.05	5.64	0.20
				6/17/2016	1.50	22.76	7.80					6/12/2018	7.25	5.04	0.19
7/15/2015	0.50	25.7	8.62	6/17/2016	2.50	19.96	4.02	9/12/2017	0.23	21.63	8.90				
7/15/2015	1.00	25.31	8.15	6/17/2016	3.50	14.95	1.21	9/12/2017	0.77	19.96	8.08	7/13/2018	0.34	26.585	7.44
7/15/2015	1.50	24.90	4.37	6/17/2016	4.50	11.82	0.33	9/12/2017	1.37	19.60	7.80	7/13/2018	1.77	25.664	5.41
7/15/2015	2.00	24.17	1.43	6/17/2016	5.50	10.52	0.29	9/12/2017	2.10	19.16	6.21	7/13/2018	2.52	20.93	1.73
7/15/2015	2.50	23.33	0.32	6/17/2016	6.50	9.35	0.28	9/12/2017	3.10	18.58	3.51	7/13/2018	3.23	15.33	1.45
7/15/2015	3.00	20.09	0.27					9/12/2017	4.25	16.57	0.05	7/13/2018	4.09	13.12	0.26
7/15/2015	4.00	15.55	0.21	6/29/2016	0.50	25.82	11.26	9/12/2017	5.24	12.98	0.00	7/13/2018	4.85	10.42	0.18

Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)
7/15/2015	5.00	13.05	0.19	6/29/2016	1.50	24.12	6.87	9/12/2017	6.52	9.89	0.00	7/13/2018	5.60	8.03	0.16
7/15/2015	6.00	11.69	0.17	6/29/2016	2.50	22.67	0.47	9/12/2017	7.16	9.37	0.00	7/13/2018	6.50	6.54	0.16
7/15/2015	7.00	10.58	0.15	6/29/2016	3.50	15.61	0.38								
7/15/2015	7.50	10.40	0.14	6/29/2016	4.50	12.30	0.34	9/28/2017	0.30	19.33	5.35	7/24/2018	0.50	25.76	9.35
				6/29/2016	5.50	11.05	0.31	9/28/2017	1.30	19.3	5.32	7/24/2018	1.00	25.7	9.34
9/2/2015	0.50	24.17	11.61	6/29/2016	6.50	9.33	0.30	9/28/2017	2.30	19.20	5.47	7/24/2018	1.50	25.58	9.27
9/2/2015	1.00	24.16	11.13	6/29/2016	7.00	9.00	0.28	9/28/2017	3.30	19.09	5.14	7/24/2018	2.00	24.10	5.52
9/2/2015	1.50	22.23	5.52	6/29/2016	7.50	8.85	0.27	9/28/2017	3.80	18.92	1.38	7/24/2018	2.50	21.60	1.06
9/2/2015	2.00	20.91	0.28					9/28/2017	4.30	18.32	0.14	7/24/2018	3.00	17.60	0.42
9/2/2015	3.00	18.95	0.20	7/15/2016	0.50	23.64	6.73	9/28/2017	5.30	14.86	0.06	7/24/2018	4.00	14.66	0.22
9/2/2015	4.00	18.35	0.17	7/15/2016	1.50	22.97	6.08	9/28/2017	6.30	11.39	0.01	7/24/2018	5.00	10.47	0.20
9/2/2015	5.00	16.43	0.13	7/15/2016	2.50	22.52	2.23					7/24/2018	6.00	7.82	0.20
9/2/2015	6.00	13.96	0.09	7/15/2016	3.50	16.50	0.46					7/24/2018	7.00	6.16	0.19
9/2/2015	6.50	12.21	0.07	7/15/2016	4.50	12.98	0.33								
				7/15/2016	5.50	11.74	0.31					8/8/2018	0.30	25.305	9.37
9/16/2015	0.50	21.84	7.78	7/15/2016	6.50	10.07	0.30					8/8/2018	1.34	23.718	7.34
9/16/2015	1.00	21.57	7.37	7/15/2016	7.50	9.52	0.30					8/8/2018	2.10	22.78	4.81
9/16/2015	1.50	21.25	6.89									8/8/2018	2.30	21.98	1.33
9/16/2015	2.00	21.21	5.97	7/29/2016	0.50	25.19	7.53					8/8/2018	2.61	21.36	0.65
9/16/2015	2.50	20.61	4.08	7/29/2016	1.50	24.76	7.44					8/8/2018	3.14	18.47	0.20
9/16/2015	3.00	19.87	1.43	7/29/2016	2.50	24.36	0.40					8/8/2018	4.04	15.63	0.16
9/16/2015	4.00	18.77	0.29	7/29/2016	3.50	18.60	0.35					8/8/2018	5.13	11.29	0.16
9/16/2015	5.00	16.62	0.21	7/29/2016	4.50	14.55	0.33					8/8/2018	6.12	8.31	0.15
9/16/2015	6.00	13.95	0.14	7/29/2016	5.50	12.70	0.30					8/8/2018	7.01	6.95	0.15
9/16/2015	6.50	12.58	0.13	7/29/2016	6.50	10.78	0.29								
				7/29/2016	7.00	10.15	0.29					8/23/2018	0.34	23.72	7.24
2019												8/23/2018	1.40	23.64	7.18
5/15/2019	0.40	18.56	14.66	8/9/2016	0.50	25.8	6.70					8/23/2018	2.28	23.33	6.96
5/15/2019	1.00	16.76	13.30	8/9/2016	1.00	25.75	6.59					8/23/2018	2.74	22.01	0.88
5/15/2019	2.00	12.50	10.95	8/9/2016	1.50	25.73	6.55					8/23/2018	3.67	18.11	0.22
5/15/2019	3.00	10.03	4.86	8/9/2016	2.00	25.43	1.58					8/23/2018	4.65	13.87	0.20
5/15/2019	4.00	9.21	2.90	8/9/2016	2.50	24.15	0.36					8/23/2018	5.54	10.57	0.18
5/15/2019	5.00	6.88	0.42	8/9/2016	3.50	19.44	0.32								
5/15/2019	6.00	4.80	0.37	8/9/2016	4.50	15.00	0.30					9/18/2018	0.50	22.53	7.28
5/15/2019	7.00	3.86	0.34	8/9/2016	5.50	13.18	0.29					9/18/2018	1.50	22.52	7.16
5/15/2019	7.50	3.81	0.33	8/9/2016	6.60	11.62	0.29					9/18/2018	2.00	22.42	6.46
				8/9/2016	7.00	10.73	0.28					9/18/2018	2.50	21.84	1.72
6/3/2019	0.50	19.96	9.78									9/18/2018	3.50	19.75	0.30
6/3/2019	1.00	19.78	9.86	8/26/2016	0.50	22.72	8.36					9/18/2018	4.50	16.47	0.22

Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)
6/3/2019	1.50	17.62	7.85	8/26/2016	1.50	22.04	6.90					9/18/2018	5.50	11.85	0.20
6/3/2019	2.00	15.53	7.11	8/26/2016	2.00	21.93	5.19					9/18/2018	6.50	8.99	0.19
6/3/2019	2.50	13.73	5.45	8/26/2016	2.50	21.63	4.36					9/18/2018	7.25	8.20	0.18
6/3/2019	3.00	12.70	4.39	8/26/2016	3.00	21.14	1.33								
6/3/2019	4.00	11.90	3.42	8/26/2016	4.00	18.77	0.39								
6/3/2019	5.00	9.02	0.35	8/26/2016	5.00	14.83	0.33								
6/3/2019	6.00	5.73	0.29	8/26/2016	6.00	12.70	0.29								
6/3/2019	7.00	4.52	0.28	8/26/2016	7.00	11.28	0.28								
6/3/2019	7.50	4.34	0.28												
				9/7/2016	0.50	22.32	6.16								
6/17/2019	0.75	22.23	9.19	9/7/2016	1.50	22.05	4.11								
6/17/2019	1.50	21.04	8.49	9/7/2016	2.50	21.16	2.06								
6/17/2019	2.50	16.50	4.51	9/7/2016	3.00	20.66	0.37								
6/17/2019	3.50	12.58	1.53	9/7/2016	3.50	20.36	0.43								
6/17/2019	4.50	10.56	0.36	9/7/2016	4.00	19.49	0.34								
6/17/2019	5.50	7.75	0.30	9/7/2016	5.00	15.81	0.35								
6/17/2019	6.50	5.23	0.28	9/7/2016	6.00	13.67	0.32								
6/17/2019	7.00	4.88	0.28												
6/17/2019	7.50	4.81	0.26	9/26/2016	0.50	17.68	4.52								
				9/26/2016	1.50	17.7	4.40								
7/8/2019	0.40	26.85	9.23	9/26/2016	2.50	17.69	4.37								
7/8/2019	1.00	26.02	8.65	9/26/2016	3.50	17.68	4.39								
7/8/2019	2.00	22.85	5.94	9/26/2016	4.50	17.66	3.99								
7/8/2019	3.00	16.11	0.93	9/26/2016	5.50	16.98	0.53								
7/8/2019	4.00	13.55	0.29	9/26/2016	6.50	13.21	0.41								
7/8/2019	5.00	9.62	0.28	9/26/2016	7.50	12.18	0.37								
7/8/2019	6.00	7.14	0.26												
7/8/2019	7.00	5.72	0.26												
7/8/2019	7.50	5.39	0.26												
7/24/2019	0.50	26.1	8.73												
7/24/2019	1.50	24.92	7.84												
7/24/2019	2.00	23.90	4.41												
7/24/2019	2.50	20.50	1.25												
7/24/2019	3.50	16.17	0.35												
7/24/2019	4.50	13.00	0.28												
7/24/2019	5.50	9.52	0.24												
7/24/2019	6.50	7.05	0.25												
7/24/2019	7.50	6.19	0.25												

Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)	Date	Depth (m)	Temp (°C)	DO (mg/L)
8/6/2019	0.30	26.8	8.38												
8/6/2019	1.00	25.9	8.24												
8/6/2019	2.00	23.55	2.99												
8/6/2019	3.00	18.61	0.29												
8/6/2019	4.00	16.41	0.26												
8/6/2019	5.00	11.62	0.26												
8/6/2019	6.00	8.74	0.25												
8/6/2019	7.00	6.81	0.25												
8/6/2019	7.50	6.62	0.24												
8/20/2019	0.35	24.27	8.57												
8/20/2019	1.00	23.85	8.85												
8/20/2019	1.50	23.69	8.74												
8/20/2019	2.00	22.70	4.64												
8/20/2019	2.50	20.70	0.45												
8/20/2019	3.00	19.47	0.26												
8/20/2019	4.00	17.58	0.22												
8/20/2019	5.00	14.34	0.22												
8/20/2019	6.00	9.05	0.22												
8/20/2019	7.00	8.20	0.22												
8/20/2019	8.00	6.79	0.23												
9/10/2019	0.35	18.83	6.11												
9/10/2019	1.20	18.71	5.68												
9/10/2019	2.22	18.58	5.43												
9/10/2019	3.28	18.56	5.11												
9/10/2019	4.32	18.02	2.65												
9/10/2019	5.11	14.74	0.28												
9/10/2019	6.10	10.54	0.26												
9/10/2019	6.75	8.49	0.25												

Table A- 2. Golden Lake phosphorus water quality data from 2008 to 2018. The DNR Lake ID for Golden Lake is 20045.

Date	TP-Surface (mg/L)	Date	TP-Surface (mg/L)	Date	TP-Surface (mg/L)	Date	TP-Surface (mg/L)
2008	0.0490	6/1/2011	0.0750	6/25/2014	0.1215	8/26/2016	0.0595
2008	0.0510	6/16/2011	0.0950	7/9/2014	0.1489	9/7/2016	0.0482
2008	0.0350	7/26/2011	0.1550	7/23/2014	0.1126	9/26/2016	0.0662
2008	0.0750	8/12/2011	0.1030	8/6/2014	0.0682	5/19/2017	0.0300
2008	0.0800	9/8/2011	0.0720	9/3/2014	0.0756	6/1/2017	0.0391
2008	0.0380	9/28/2011	0.1220	9/17/2014	0.0627	6/15/2017	0.0562
2009	0.0280	5/23/2012	0.0630	5/20/2015	0.0471	6/27/2017	0.0469
2009	0.0300	6/5/2012	0.0720	6/5/2015	0.0352	7/13/2017	0.0418
2009	0.0350	6/19/2012	0.0830	6/18/2015	0.0331	8/8/2017	0.0402
2009	0.0430	7/2/2012	0.0560	7/2/2015	0.0396	8/22/2017	0.0519
2009	0.0460	7/19/2012	0.0770	7/15/2015	0.0314	9/12/2017	0.0365
2009	0.0440	8/2/2012	0.0490	7/31/2015	0.0799	9/28/2017	0.0432
2009	0.0610	8/14/2012	0.0460	8/17/2015	0.0539	6/1/2018	0.0223
2009	0.0670	9/14/2012	0.0990	9/2/2015	0.0672	6/12/2018	0.0230
2009	0.0400	9/26/2012	0.1300	9/16/2015	0.0641	6/27/2018	0.0234
2009	0.1150	6/3/2013	0.1348	5/5/2016	0.0259	7/13/2018	0.0230
2010	0.0300	7/2/2013	0.0597	5/18/2016	0.0259	7/24/2018	0.0270
2010	0.0340	7/22/2013	0.0614	6/1/2016	0.0188	8/8/2018	0.0234
2010	0.0410	8/1/2013	0.0540	6/17/2016	0.0307	8/23/2018	0.0248
2010	0.0390	8/12/2013	0.0434	6/29/2016	0.0356	9/18/2018	0.0502
2010	0.0850	9/11/2013	0.0460	7/15/2016	0.0450		
2010	0.1130	5/28/2014	0.0570	7/29/2016	0.0524		
2010	0.0830	6/11/2014	0.0894	8/9/2016	0.0418		

Appendix B: Summary of estimated alum treatment costs based on other lake treatment projects.

	Item	Explanation	[1]Osgood 2006	[2]Barr 2012	[3]ENSR 2016	[4]Herrera 2018	[5]Wenck 2018
	CONTRACTOR COST						
1	Material application (excludes mobilization)	Applied material cost- $1.10 to $2.10/gal for alum; $2.75 to $5.60/gal for sodium aluminate buffer					
2	Submittals/ mobilization/ demobilization	40% of materials cost OR ~$6000/day for labor and equipment. Mobilization cost varies based on site conditions.					
3	Tax	% of (material + application + mobilization costs)					
4	Contingency	10-20% of contractor cost					
	CONSULTANT COST						
5	Planning	Alum treatment dosing plan preparation. Cost is variable.					
6	Bidding, permitting, and specification development	Prepare bidding document, bidding, selection of contractor		$10,000			$15,000
7	Administration, public relations, meetings			$6,000			
8	Treatment oversight and monitoring	Cost can be quite variable based on the scale of operation. Jar tests (pH testing) and water quality monitoring are conducted 1 day before, on the day of, 2 days after, and 2 weeks after the alum application. Random locations in the treatment zones are to be monitored. Additional costs for lab analysis. Contractor may include lake pH monitoring in the total application cost. Consultants are present to oversee the entire operation and conduct tests in the lake.		$10,000	$30,000	$31,000	$15,000
9	Post-treatment monitoring and report	1 season May to October, 1 sample/month, 1 surface sample and 1 bottom sample at the deep station, sediment coring and P fraction analysis are recommended. Written report on alum effectiveness based on data above.	$5000 + staff				$20,000
10	Future alum treatment plan adjustments	Adjust alum application rates based on results of the first dose. Account for inflation.					

[1]Lake Mitchell/Firesteel Creek Water Quality Improvement Project. 2006. Final Progress Report on the 2003-2005 Alum Demonstration Project, Prepared by Osgood Consulting.
[2]Spring Lake Sediment Core Analysis, Alum Dose Determination and Application. 2012. Prepared for Prior Lake – Spring Lake Watershed District by Barr Engineering.
[3]Cedar Lake Aquatic Ecosystem Restoration Feasibility Study, Cedar Lake, IN, Alum Treatment Analysis. 2016. Prepared for the US Army Core of Engineers by ENSR/AECOM.
[4]Hear Lake Treatment Plan. 2018. Prepared for Anacortes Parks and Recreation by Herrera Environmental Consultants, Inc.
[5]Ann Lake Internal Load Feasibility Study. 2018. Prepared for Kanabec SWCD, Ann Lake Watershed Alliance and MPCA by Wenck Associates, Inc.