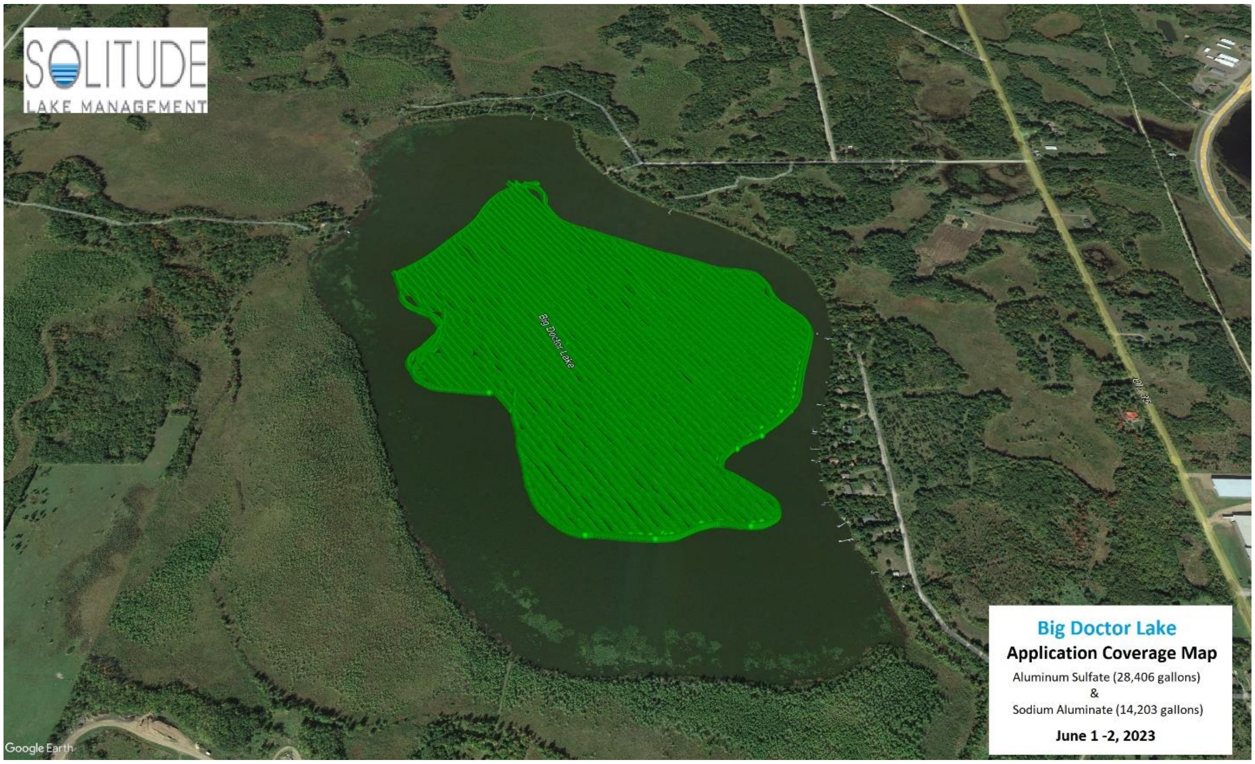
Big Doctor Lake Post-Rehabilitation Monitoring: 2023



Big Doctor Lake alum application 2023 – Solitude Lake management

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Objective

Multiple Al applications over a period of years are planned for Big Doctor Lake to control internal phosphorus loading. The overall recommended Al dose was 95 g Al/m^2 over the 7-ft depth contour (89 ac). The Al dose (as buffered alum to prevent pH declines) was split into 40 g/m^2 in 2023, 30 g/m^2 in 2025, and 25 g/m^2 in 2027. The first of the partial alum application occurred in early June 2023 (i.e., 28,406 gal aluminum sulfate and 14,203 gal sodium aluminate).

The objectives of this research were to monitor lake response and WQ trajectory during the alum application process. Specifically:

- Seasonal variations in limnological response variables (phosphorus, chlorophyll, Secchi transparency),
- laboratory-derived diffusive P flux at several locations in the application area, and
- changes in sediment aluminum and aluminum-bound P concentrations.

This interim report describes Big Doctor Lake limnological and sediment internal P loading response during the 2023 alum treatment.

Approach

In-lake monitoring

Water samples for limnological variables were collected at a station located in the central portion of the lake (i.e., St BDL-2; Fig. 1). Samples were collected biweekly between late May and the end of September 2023. An integrated sample was collected over the upper 2-m for analysis of total phosphorus and chlorophyll a. An additional discrete sample was collected within 0.25 m of the sediment surface for analysis of total and soluble reactive P. Secchi transparency and in situ measurements (temperature, dissolved oxygen, pH, and conductivity) were collected at 0.5-m intervals on each date.

Vertical variations in sediment characteristics

Sediment cores collected at BDL-1, -2, and -3 were sectioned at 2-cm intervals down to the 10-cm depth for analysis (Fig. 1). Sections from these stations were analyzed for:

Moisture content
Density
Loss-on-ignition organic matter
Loosely-bound P
Iron-bound P
Labile organic P
Aluminum-bound P
Total Al

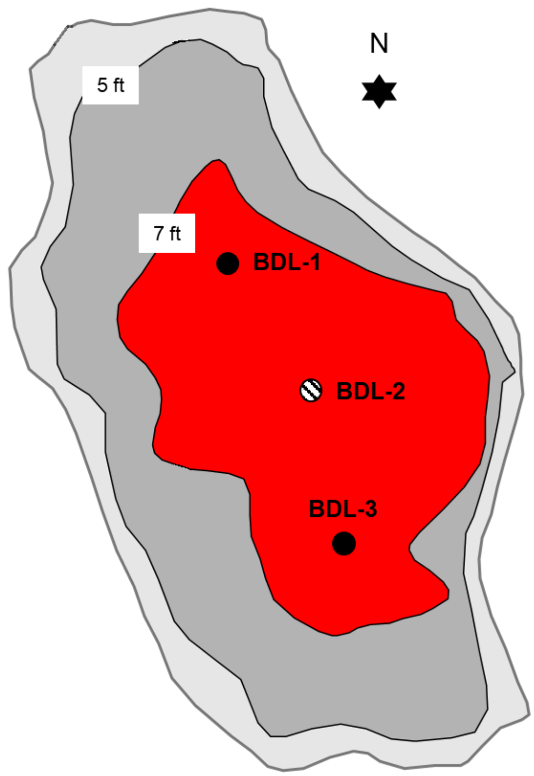

Figure 1. Station locations in Big Doctor Lake. BDL-2 represents the WQ and central sediment chemistry location. BDL-1 and BDL-3 represent lateral sediment chemistry stations in the proposal Al application area (denoted in red).

The loosely-bound (Boström 1984) and iron-bound (Nürnberg 1988) sediment P fractions are readily mobilized at the sediment-water interface as a result of eH (i.e., oxidizing and reducing conditions) and pH reactions (Mortimer 1971, Boström 1984). Labile organic sediment P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to SRP under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The aluminum-bound P fraction approximates the concentration of P that has been bound to the Al floc and sequestered from further input to the overlying water column via diffusive flux.

Laboratory-derived rates of phosphorus release from sediments under anaerobic conditions

Anaerobic phosphorus release rates were measured from intact sediment cores collected at the 3 stations in mid-August 2023 (~ 2.5 months after alum application). Three replicate intact sediment cores were collected at station BDL-2 and 1 core each at station BDL-1 and BDL-3 for evaluation of anaerobic diffusive P flux (Fig. 1). The sediment incubation systems were placed in a darkened environmental chamber and incubated at a constant temperature for 1-2 weeks. The incubation temperature was set at 20 C for all stations to simulated summer conditions. The oxidation-reduction environment in each system was controlled by gently bubbling nitrogen through an air stone placed just above the sediment surface to maintain anaerobic conditions.

Summary of Results

Total Al concentrations were greatest in the upper 2- to 4-cm sediment layer at each station (Fig. 2). In addition, total Al was highest in concentration (23.8 mg/g) at BDL-2, located in the center of the treatment zone, compared to lower surface Al concentrations of 14.0 mg/g and 12.5 mg/g at BDL-1 and BDL-3, respectively. Aluminum-bound P (i.e., P bound to the Al floc)

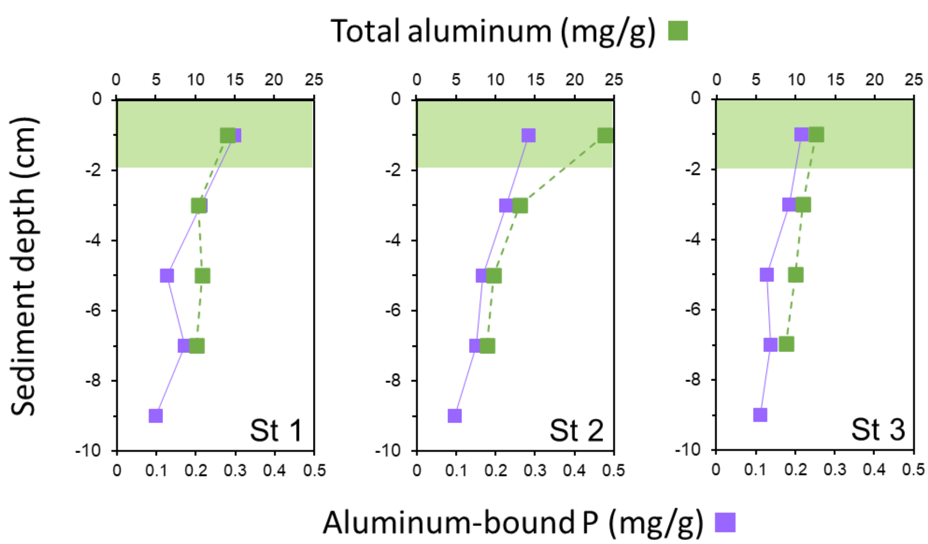

Figure 2. Variations in sediment total aluminum and aluminum-bound P as a function of sediment depth.

Table 1. Total sediment aluminum and aluminum-bound P concetrations in the upper 4-cm sediment layer at various stations in Big Doctor Lake in 2023 (~ 2.5 months after alum application).

Station	Sediment Depth (cm)	Al (g/m2)	Al-P (g/m2)	Al:P binding ratio
1	4	34.8	0.728	47.8
2	4	37.8	0.535	70.7
3	4	31.3	0.535	58.5

concentrations exhibited similar peaks in the surface sediment layer (Fig. 2). Integrated over the 4-cm sediment thickness, Al concentrations ranged between 31 g/m^2 and 38 g/m^2, near the application target of 40 g/m^2 (Table 1). Integrated aluminum-bound P concentrations were higher at BDL-1 versus the other stations (Table 1). The Al:P mass binding ratio was moderately high at 48:1 to 71:1. This pattern is not surprising or unexpected given only 2 months into the first alum application. Ratios should decline over time and with additional alum applications. Ideally, the long-term Al:P binding ratio should be < 20:1.

Laboratory-derived anaerobic diffusive P flux decreased substantially after the June 2023 alum treatment (Fig. 3). Before treatment in 2017, Anaerobic diffusive P flux was relatively high, ranging between 5.5 and 7.2 mg/m^2 d. In August 2023, rates were near zero, indicating nearly complete suppression of internal P loading from sediment in conjunction with the alum application. Improvement in 2023 ranged between 97% and 99%.

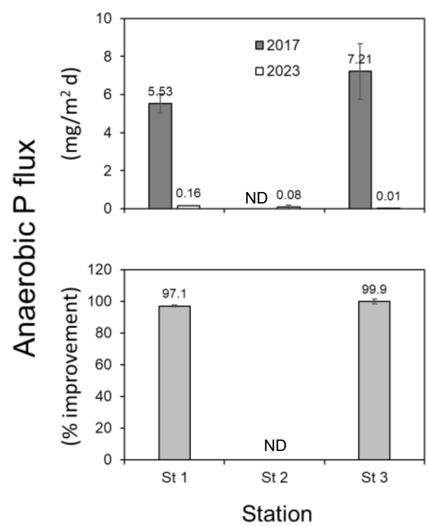

Figure 3. Anaerobic P flux at various stations before (i.e., 2017) and after (i.e., 2023) the first alum application. ND = no data collected at station 2 in 2017.

Daily precipitation patterns at Luck WI were very moderate between late April most of May 2023 (Fig. 4).

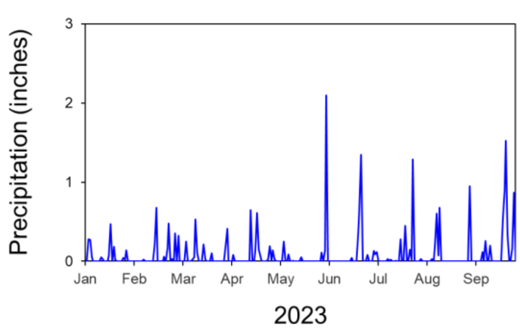

Figure 4. Seasonal variations in daily precipitation measured at Luck WI.

Although precipitation occurred, daily totals were generally less than 0.5 inches during this period. More substantial precipitation occurred in late May at ~ 2 in. With the exception of a 1.4 in storm in late June 2023, conditions were otherwise droughty between June and late July. A

1.3 in storm occurred in late July; however, August was relatively dry. Storms > 1 in occurred in early and late September.

Big Doctor Lake stratified briefly in mid- to late June after the alum application (Fig. 5). The water column completely mixed in in mid-July, then a second brief period of stratification developed in late July. Complete mixing and turnover occurred in early August, followed by another period of brief stratification. Bottom anoxia was not detected throughout the summer (Fig. 5). The lake bottom only became hypoxic (i.e., < 2 mg/L dissolved oxygen) during a brief period of stratification in late August.

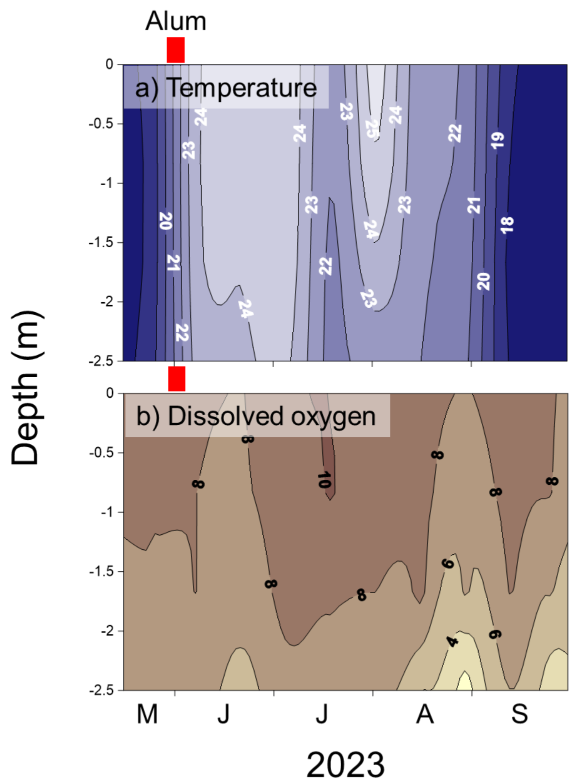

Figure 5. Contour plots of seasonal and vertical variations in water temperature (C, upper panel) and dissolved oxygen (mg/L, lower panel) in Big Doctor Lake.

Before the start of the alum application in early June 2023, surface total P and chlorophyll concentrations were relatively high in late May at 0.049 mg/L and 27.9 µg/L, respectively (Fig. 6). The Big Doctor Lake District reported the occurrence of a substantial fish kill under the ice in 2023. Fish decomposition may have contributed P for algal uptake and growth in the late spring spring. Algal cells may have also stored this P for later growth under optimal temperature conditions in early August. While surface total P remain relatively high in concentration throughout June and July (range = 0.046 mg/L to 0.049 mg/L), chlorophyll concentrations declined to a minimum of 14 µg/L in mid-June in conjunction with the alum treatment.

However, chlorophyll concentrations increased rapidly in early August to 94 µg/L (Fig. 6). This rapidly forming bloom developed concurrently with the period of warm surface temperatures and stratification. The bloom declined to a chlorophyll concentration of 34 µg/L in late August, then increased to a secondary peak in September of 61 µg/L. Interestingly, surface total P

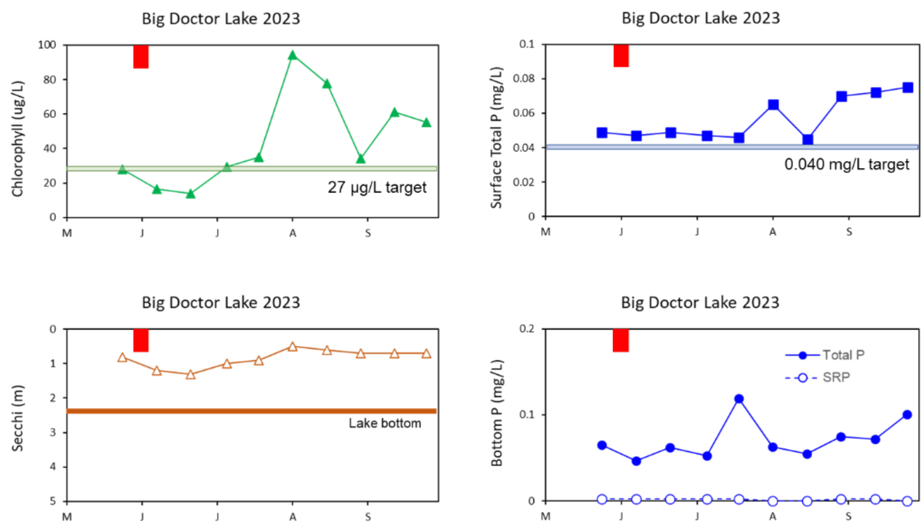

Figure 6. Seasonal variations in chlorophyll, surface and bottom P, and Secchi transparency in Big Doctor Lake in 2023. Red bars denote the period of alum application.

concentrations increased as well in September, suggesting incorporation of P into algal cells for growth. Perhaps cooler temperatures in September controlled the extent of growth as this bloom exhibited a lower chlorophyll concentration compared to the August bloom.

Bottom soluble P concentrations were below detection limits throughout the study period (Fig. 6), which coincided with low anaerobic diffusive P flux. Bottom total P exhibited a peak of 0.12 mg/L in mid-July. Since the lake bottom exhibited oxic conditions and sediment internal P loading was negligible, the peak in bottom total P may have been associated with algal biomass above the sediment-water interface. Bottom total P concentrations declined in mid-August, then increased linearly in September. Again, this P may have been associated with algal biomass rather than diffusive P flux from sediment.

Secchi transparency was relatively poor throughout the summer of 2023 (Fig. 6). Clarity improved temporarily to ~ 4 ft in June after the alum application. However, it rapidly declined to less than 2.5 ft during the algal bloom periods in August and September.

Unfortunately, although the 2023 alum treatment appeared to be very successful in suppressing anaerobic diffusive P flux from the sediment within the alum application zone, summer WQ improvement was negligible (Fig. 7 and Table 2). Mean summer (July-September) surface total P declined slightly from a pretreatment 0.085 mg/L to 0.060 mg/L in 2023 (29% improvement). However, the mean summer chlorophyll concentration was high in 2023 at 55 µg/L (only 8% improvement), compared to the pretreatment summer mean of 60 µg/L. Mean summer Secchi transparency was essentially unchanged in 2023 versus the pretreatment mean.

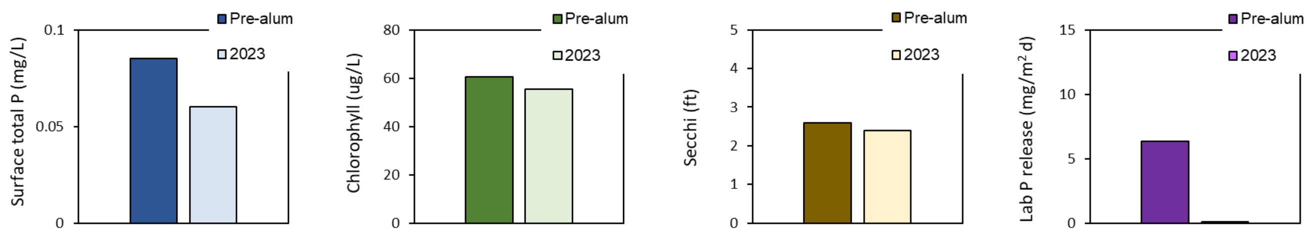

Figure 7. Mean summer (July-September) limnological response variables and laboratory-derived P release from anoxic sediment before and after the 2023 alum application to Big Doctor Lake.

Table 2. Summary of changes in lake water quality and laboratory-derived phosphorus release from sediment in Big Doctor Lake during the 2023 alum treatment year. Overall goals after completion of the treatment schedule are shown in the last column. Average pre Al (i.e., limnological conditions berfore the start of alum treatments) represents the mean of years 2012-2019.

Variable			**Average pre Al**	2023	Percent improvement (Pre Al versus 2023)	Goal after internal P loading control
Lake	Mean (Jul-Sep)	Mean surface TP (mg/L)	**0.085**	0.060	29% reduction	< 0.040
		Mean bottom TP (mg/L)		0.077		< 0.050
		Mean bottom SRP (mg/L)		ND		< 0.050
		Mean chlorophyll (ug/L)	**60.40**	55.3	8% reduction	< 27
		Mean Secchi transparency (ft)	**2.6**	2.40	No improvement	>10
Sediment	Station 1	Sediment diffusive P flux (mg/m^2 d)	**6.40**	0.08	99% reduction	< 1.5

Conclusions and recommendations

One of the surprising perplexities of the 2023 alum application summer was the lack of lake WQ response despite nearly complete suppression of anaerobic diffusive P flux in the application zone. Reasons for these discrepancies are not entirely known. The lack of lake WQ response may have been somehow related to the severe fish kill reported on the lake during the winter period. Fish decomposition probably occurred during the spring and early summer months, resulting in some recycling of P and potential uptake by cyanobacteria. Although summer algal blooms did not occur until late July, algal inocula residing in the water or sediment could have assimilated this P and stored it as cellular reserves for later growth during periods of optimal temperature conditions.

Another possibility could be that cyanobacteria inoculated the water from sediment areas outside the treatment zone (i.e., depths < 7 ft). For instance, certain cyanobacteria can reside in shallow sediments and assimilate P in excess of growth requirements until optimal temperature conditions develop (similar to the above argument). The population can then grow and develop blooms. Since Big Doctor Lake is relatively shallow throughout the basin, cyanobacteria could have also originated from the deeper treatment zone as well. If so, they probably had already built-up luxury cellular P stores before the treatment occurred that could be used for later growth despite alum suppression of diffusive P flux.

This pattern might result in a lagged lake response to treatment (i.e., lake WQ will improve in 2024). For example, during the first alum application year, Half Moon Lake (Eau Claire) exhibited a *Cylindospermopsis sp.* bloom and high chlorophyll in August. However, chlorophyll declined substantially during the next summer and *Cylindrospermopsis* disappeared. The hypothesis was that *Cylindrospermopsis* had already assimilated luxury stores of cellular P for bloom formation before the alum was applied in June. But, growth of this same genera became limited by P availability from the sediment the next year as a result of the previous year’s alum application.

Next years monitoring results will be critical in assessing the effectiveness of the alum treatment in controlling overall internal P loading and reducing algal blooms. For instance, lower chlorophyll concentrations and bloom frequency in 2024 might suggest that fish decomposition and luxury uptake of P by cyanobacteria before the June alum treatment was responsible for the poor WQ in 2023. Decisions regarding the need and effectiveness of future alum applications will become clearer after analysis of the 2024 summer season.

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