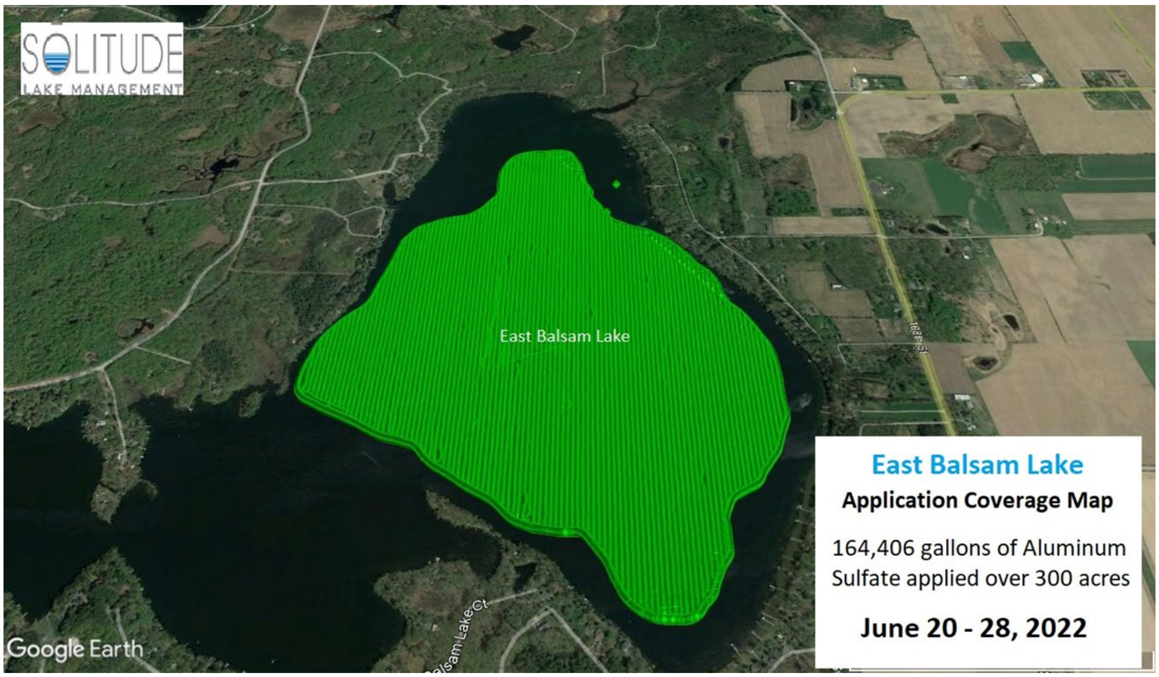
East Balsam Lake, Wisconsin - Limnological response to alum treatment: 2022 interim report

5 December 2022



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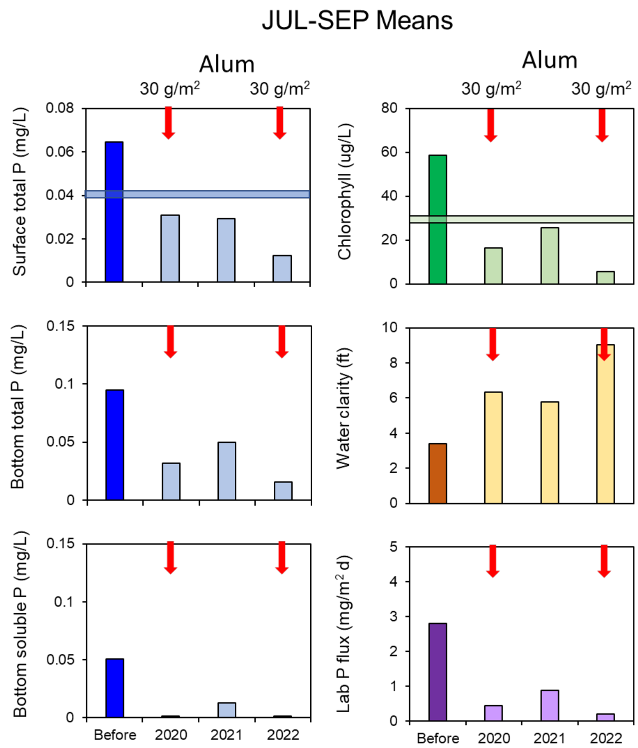
Executive summary



1. The second partial 30 g/m^2 alum application occurred between 20-28 June 2022.
2. Mean (July-September) surface total P declined tremendously to only 0.012 mg/L (81% reduction over the pre-treatment average), mean bottom total P and SRP were very low at 0.015 mg/L (84% reduction) and not detectable (>97% reduction), respectively, mean chlorophyll was only 5.62 µg/L (90% reduction), and mean Secchi transparency was 9.1 ft (166% improvement) in 2022.
3. Laboratory-derived diffusive P flux from sediment under anaerobic conditions at station 1 declined to only 0.2 mg/m^2 d in 2022, representing a 92% decline over pretreatment means (2.6 mg/m^2 d). Anaerobic diffusive P flux declined by 88% to 100% at the other stations.
4. Aluminum-bound P concentrations in the upper 5-cm layer increased at all stations after the second partial alum application in 2022. Concentration increases were greatest at stations 2 and 5 These patterns suggested the Al floc might have become resuspended and redistributed as a result of wind and wave activity along the N-S wind rose, resulting in dilution via spreading out and mixing into the sediment.
5. Redox-P concentrations (i.e., the mobile P fraction linked to internal P loading) in the upper 5-cm sediment layer remained lower than pretreatment concentrations.
6. The third partial alum application of 20 g/m^2 is projected for 2024. I recommend pursuing funding for and scheduling this application for late May or early June 2024.

Objective

East Balsam Lake, part of the Balsam Lake chain, is relatively shallow (6.4 m max depth, 2.9 m mean depth), expansive (550 ac surface area, Barr Engineering 2011), and polymictic (Osgood index = 1.2). The lake has exhibited high mean summer total phosphorus and chlorophyll concentrations of 0.065 mg/L and 58 µg/L, respectively, which exceeded WisCALM (2019) standards. James (2018) suggested that > 70% of the phosphorus (P) inputs to East Balsam Lake occur via internal P loading. An aluminum sulfate (alum) dosage of ~ 100 g/m^2 over 300 ac was estimated to control internal P loading to improve limnological water quality conditions (James 2018). The strategy is to split this dose into lower concentrations to be applied at 2-year intervals in order to maximize P binding efficiency onto the Al floc over time. The first partial Al application of 30 g/m^2 was applied to East Balsam Lake between 15-20 June 2020. The second 30 g/m^2 application was applied between 20-28 June 2022.

Post-treatment monitoring of water and sediment chemistry was initiated in 2020 to document the trajectory of water quality improvement during rehabilitation as part of a comprehensive adaptive management program aimed toward making informed decisions regarding adjusting alum application and dosage to meet future water quality goals. Post-treatment monitoring included field and laboratory research to document changes in 1) lake limnological response variables (total P, soluble reactive P, chlorophyll, Secchi transparency), 2) diffusive P flux from sediment under anaerobic conditions for stations located within and outside the treatment area, and 3) binding of P by the alum floc. Overall, lake water quality was predicted to respond to internal phosphorus loading reduction with lower total phosphorus and chlorophyll concentrations, lower bloom frequency of nuisance chlorophyll levels, and higher water transparency. The objectives of this interim report are to describe East Balsam Lake limnological and sediment internal P loading response in 2022.

Methods

Lake monitoring

Station 1, located in the central, deepest area of the lake, was sampled biweekly between May and September 2022 (Fig. 1). An integrated sample was collected over the upper 2-m for analysis of total P, soluble reactive P (SRP), and chlorophyll. An additional discrete sample was collected 0.5 m above the sediment surface for analysis of these same variables. Total P samples were predigested with potassium persulfate according to APHA (2011). Total and soluble reactive P (i.e., P available for uptake by algae) were analyzed colorimetrically using the ascorbic acid method (APHA 2011). Samples for viable chlorophyll (i.e., a surrogate measure of algal biomass) were filtered onto glass fiber filters (Gelman A/E; 2.0 μ nominal pore size) and extracted in 90% acetone before fluorometric determination (EPA 445.0). Secchi transparency and in situ measurements (temperature, dissolved oxygen, pH, and conductivity) were collected on each date using a YSI 6600 sonde (Yellow Springs Instruments) that was calibrated against dissolved oxygen Winkler titrations (APHA 2011) and known buffer solutions. Vertical in situ profiles were collected at 0.5-m to 1-m intervals.

Sediment chemistry

Sediment sampling stations. Sediment cores were collected at 5 stations (1, 2, 3, 4, and 5) in East Balsam Lake in September 2022 (Fig. 1). These station locations coincided with those visited in 2015 (James 2015). All stations were located within the Al treatment zone.

Vertical and spatial variations in sediment chemistry. A sediment core collected at station 1 was sectioned at 1-cm intervals between 0 and 6 cm and at 2-cm intervals below the 6-cm depth. Additional cores were collected at stations 2-5 for examination of sediment characteristics in the upper 5-cm layer. All sediment core slices were analyzed for moisture content, wet and dry bulk density, loss-on-ignition organic matter, loosely-bound P, iron-bound P, labile organic P, and aluminum-bound P (see *Analytical methods* below).

Laboratory-derived diffusive phosphorus flux from sediments under anaerobic conditions. Anaerobic diffusive P fluxes were measured from intact sediment cores collected at all sediment sampling stations shown in Figure 1. One sediment core was collected at stations 2-5, while triplicate cores were collected at station 1, to monitor alum treatment effectiveness after the June Al application. The sediment incubation systems were placed in a darkened environmental chamber and incubated at 20 C for up to 7 days. The incubation temperature was set to a standard temperature for all stations for comparative purposes. 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.

Water samples for SRP were collected from the center of each system using a 60-cc syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Rates of P release from the sediment (mg/m^2 d) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Analytical methods. A known volume of sediment was dried at 105 ºC for determination of moisture content, wet and dry bulk density, and burned at 550 ºC for determination of loss-on-ignition organic matter content (Avnimelech et al. 2001, Håkanson and Jansson 2002). Phosphorus fractionation was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), and sodium hydroxide-extractable P (i.e., aluminum-bound P). Additional sediment was dried to a constant weight, ground, and digested for analysis of total Al at Pace Analytical Laboratories (Minneapolis MN and Green Bay WI).

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that lead to desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of the loosely-bound and iron-bound P fraction represents redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions) and will be referred to as ***redox P***. Aluminum-bound P reflects P bound to the Al floc after aluminum sulfate application and its chemical transformation to aluminum hydroxide ($Al(OH)_3$).

Summary of Results

Lake limnological response

Local precipitation (measured at Amery and Luck WI) more than 1 inch occurred in early April, mid-June, and August (Fig. 2). Daily precipitation exceeded 2 inches at Luck WI in early April and at Amery WI in late August. Monthly precipitation at Amery in 2022 was below average in May, June July, and September, compared to the long-term average, suggesting draughty conditions (Fig. 3). In contrast, it was over 2X the long-term monthly average in August (Fig. 3).

East Balsam Lake weakly stratified in mid-June through September (Fig. 4). Bottom anoxia developed in late July and late August through mid-September. Periods of apparent mid-summer water column mixing occurred early July and early August that completely reoxygenated the bottom waters.

Total P and SRP concentrations in the bottom waters were very low throughout the summer period in conjunction with the June alum application (Fig. 5). Despite periods of hypolimnetic anoxia, total P remained below 0.02 mg/L and SRP was usually not analytically detectable. Surface total P concentrations were very low throughout the summer period, ranging between 0.008 mg/L and only 0.016 mg/L (Fig. 6). In addition, chlorophyll concentrations were less than 10 μg/L in conjunction with the 2022 alum application (Fig. 7). Secchi transparency exceeded 3 m (~ 10 ft) between May and early July and fluctuated between 2 and 3 m (~ 6.5 ft to 10 ft) between mid-July and the end of September (Fig. 8).

Strong linear relationships continued to exist between 2-m integrated surface total P and chlorophyll over pre- and post-treatment summer periods, indicating algal productivity was P-limited in East Balsam Lake and responded to negligible internal P loading after the second alum application (Fig. 9). Secchi transparency was also inversely related to 2-m integrated surface chlorophyll concentrations, suggesting that P-limited algal growth and reduction in biomass translated into greater summer water clarity in East Balsam Lake.

A comparison of mean summer (July-September) limnological response variables before (i.e., mean of 2010 and 2015) and after (i.e., 2020 and 2021) alum treatment is shown in Figure 10. Mean bottom concentrations of total P and SRP were very low in 2022 after the June 2022 alum application (Fig. 10), representing an 84% and 898% reduction over the pretreatment mean (Table 1 and Fig. 11). Mean summer surface total P and chlorophyll improvement also continued in 2022 as these variables declined by 82% and 90%, respectively (Table 1 and Fig. 11). Mean Secchi transparency was 166% improved in 2022 versus the pretreatment mean (Table 1 and Fig. 11). Overall, limnological response variable means currently exceeded target WQ goals as a result of the 2020 and 2022 alum treatment.

Table 1. Summary of changes in lake water quality and laboratory-derived phosphorus release from sediment in East Balsam Lake after the alum treatments in June 2020 and 2022. 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 2010 and 2015.

		Variable	2010*	2015	Average pre Al	2020	2021	2022	Percent improvement (Pre Al versus 2022)	Goal after internal P loading control
Lake	Mean (Jul-Sep)	Mean surface TP (mg/L)	0.062	0.067	**0.065**	0.031	0.029	0.012	82% reduction	< 0.040
		Mean bottom TP (mg/L)	0.085	0.104	**0.095**	0.032	0.050	0.015	84% reduction	< 0.050
		Mean bottom SRP (mg/L)	ND	0.051	**0.051**	0.001	0.013	0.001	98% reduction	< 0.050
		Mean chlorophyll (ug/L)	59.01	58.35	**58.68**	16.26	25.62	5.62	90% reduction	< 20
		Mean Secchi transparency (ft)	3.01	3.8	**3.4**	6.33	5.79	9.05	166% increase	>10
Sediment	Station 1	Sediment diffusive P flux (mg/m^2 d)	ND	2.56	**2.56**	0.44	0.88	0.2	92% reduction	< 1.5

*Barr Engineering

Changes in sediment chemistry and anaerobic diffusive phosphorus flux

Al-bound P concentrations in the surface (i.e., upper 5 cm) sediment increased at all stations in 2022 after the second alum application, suggesting continued binding of sediment P onto the Al floc layer (Fig. 12). Al-bound P functionally reflects the P that has been bound to the Al floc that was applied in 2020 and 2022. Concentrations were greatest at stations 2 and 5 versus the centrally-located station 1. They were also higher compared to stations 3 and 4, located on the eastern and western edges of the treatment zone (see Fig. 1). The spatial variability in Al-bound P concentration suggested the Al floc became redistributed along the north-south wind rose, perhaps via wind-generated water mixing and movement as a result of weather fronts moving in the N-S direction. Others have found that the Al floc can move after application particularly in shallow lakes or shallower regions within a lake (Egemose et al. 2009, 2013; Huser 2017; James and Bischoff 2019).

Changes in vertical patterns of Al-bound P at station 1 since the June 2020 and 2022 alum applications also suggested that the Al floc and associated bound P became redistributed and diluted (Fig. 13). Immediately after the 2020 alum application, a concentration peak of formed Al-bound P was observed in the upper 2-cm sediment layer (September 2020, Fig. 13). By July 2021, the surface Al-bound P concentration maximum declined tremendously (Fig. 13). This pattern was again verified by resampling the sediment at this station in September 2021 (not shown). However, Al-bound P concentrations have increased in the upper 10 cm sediment layer from 2021 to 2022, suggesting binding of P onto the Al floc layer (Fig. 14).

Redox-P (i.e., the P that is associated with internal P loading) has continued a trend of lower concentrations in the upper 5-cm sediment layer after the 2020 and 2022 alum application (Fig. 12 and 13). Lower redox-P has coincided with very low laboratory-derived anaerobic diffusive P fluxes in 2022 (Fig. 15). In particular, anaerobic diffusive P flux was nearly undetectable at stations 2, 3, 4, and 5 in September 2022, and less than 0.5 mg/m^2 d at station 1 after the second alum application (Fig. 15).

Summary and recommendations

Mean summer (July-September) limnological response variables were tremendously improved after the second partial alum application that occurred in June 2022. Mean summer surface total P and chlorophyll concentrations were only 0.012 mg/L and 5.6 µg/L, respectively, well below WisCALM WQ standards for shallow lake systems. Mean summer Secchi transparency was 166% improved in 2022 at 9.1 ft (2.75 m). Anaerobic diffusive P flux has declined by > 90%

suggesting effective control of internal P loading by the two partial alum applications.

The third partial alum application of 20 g/m^2 is projected for 2024. I recommend pursuing funding for and scheduling this application for late May or early June of 2024. The goals with these lower dose alum treatments are to 1) spread costs for alum out over a longer time period and into smaller cost increments and 2) increase overall Al binding efficiency and binding capacity by exposing lower Al doses to sediment and hypolimnetic P. Monitoring and adaptive management approaches are being used to assess water quality and sediment response in order to adjust application timing and Al dosage if necessary to meet goals and expectations. It will be important to examine the spatial distribution of the Al floc both in 2023 and 2024 to assess the possibility of further movement and redistribution. Al dosage and application areas will be reassessed based on these findings.

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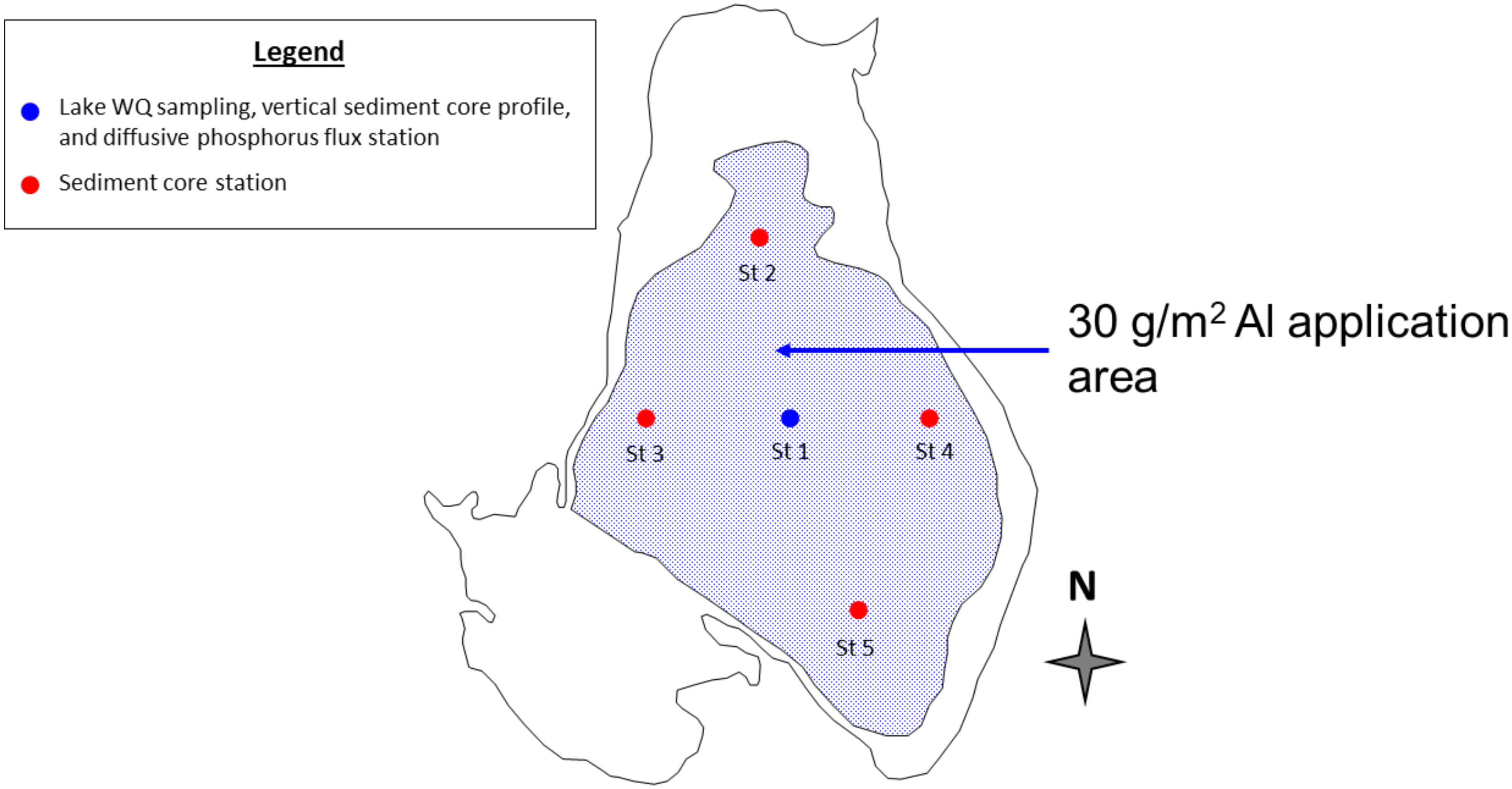


Figure 1. Sediment and water sampling stations.

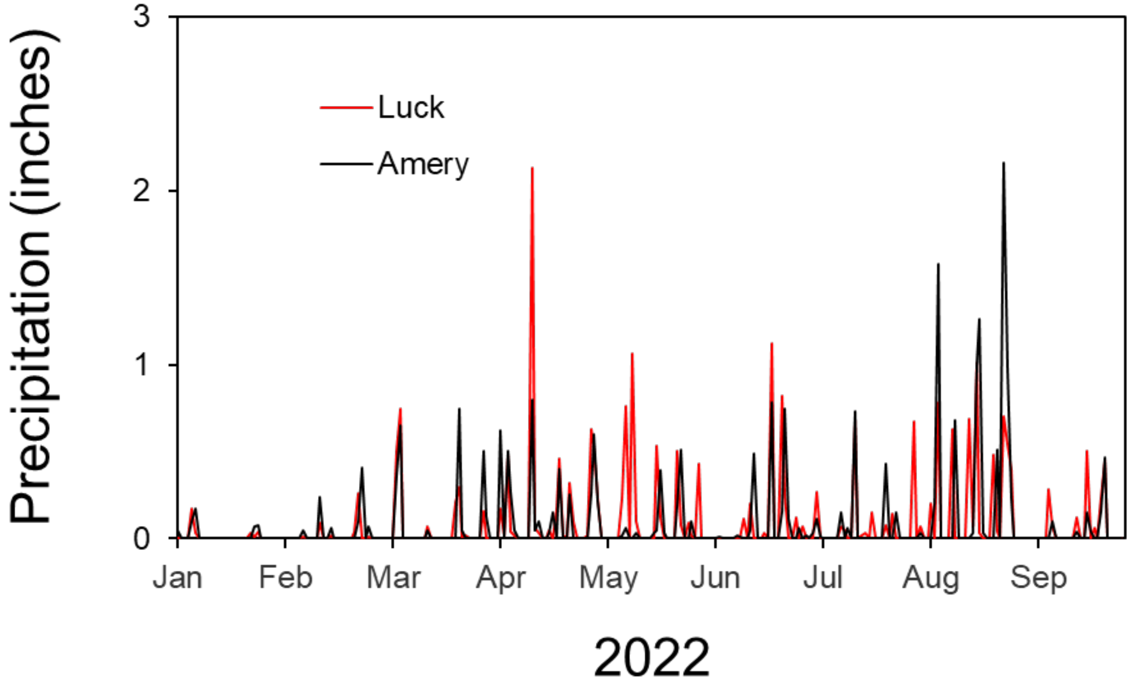


Figure 2. Variations in daily local precipitation measured at Amery and Luck WI in 2022.

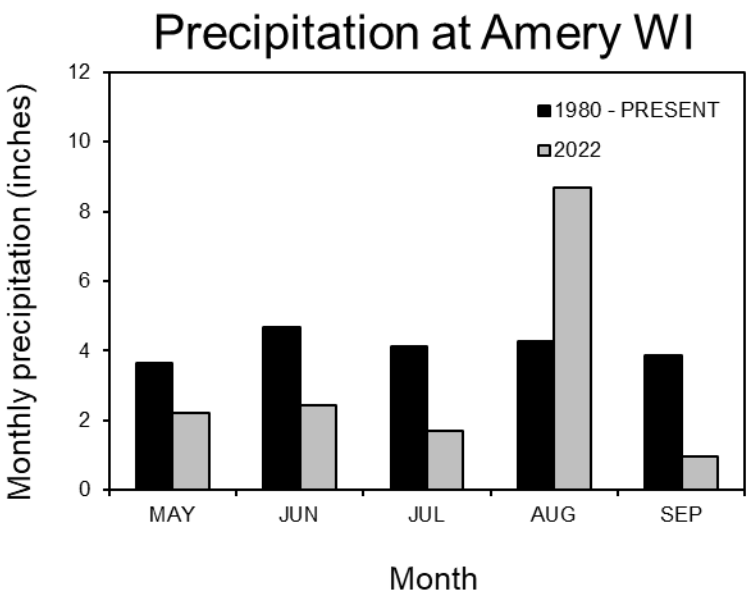


Figure 3. A comparison of average monthly precipitation (data from Amery WI).

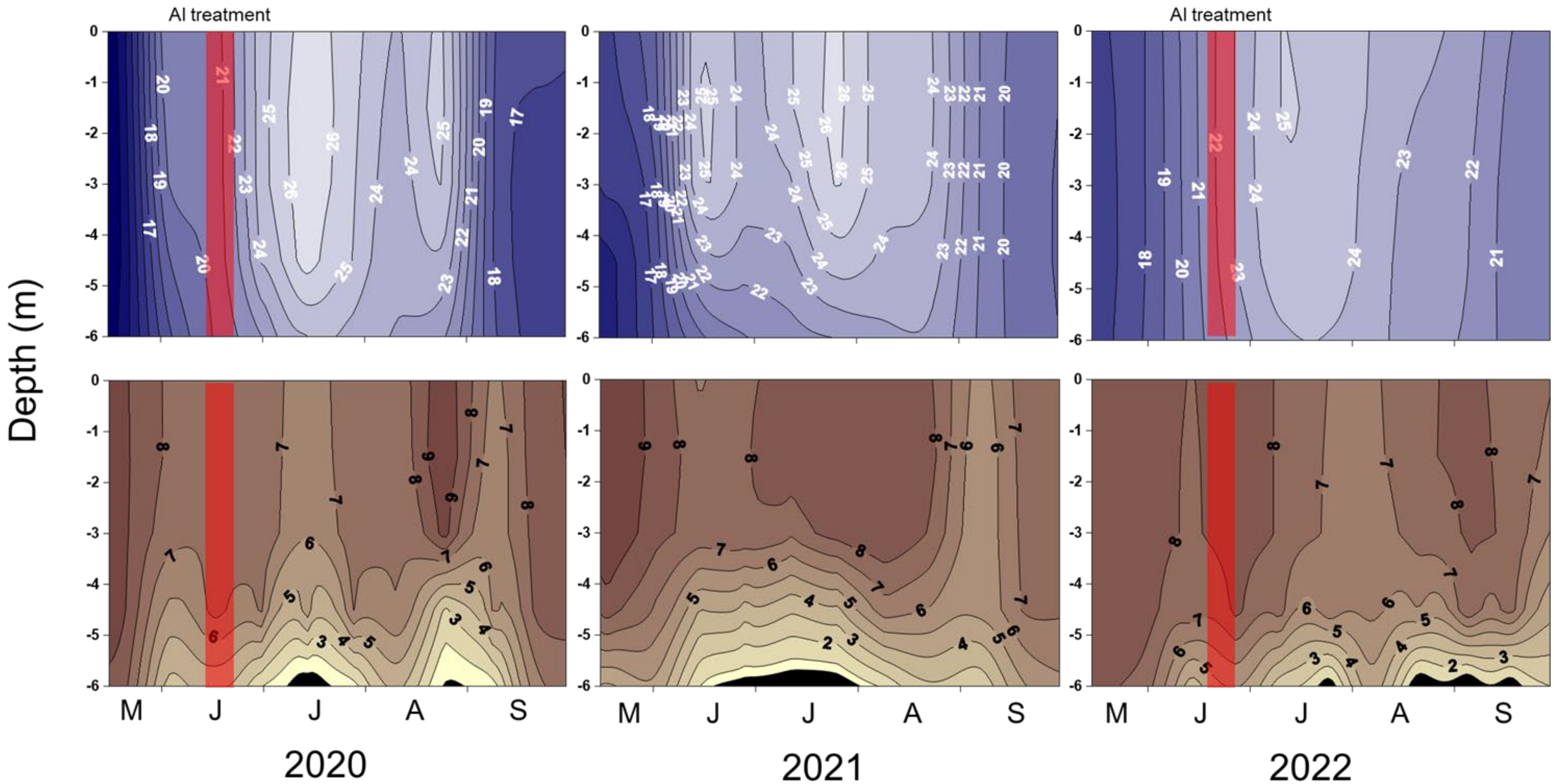


Figure 4. Seasonal and vertical variations in temperature (upper panel) and dissolved oxygen (lower panel) in 2020, 2021, and 2022.

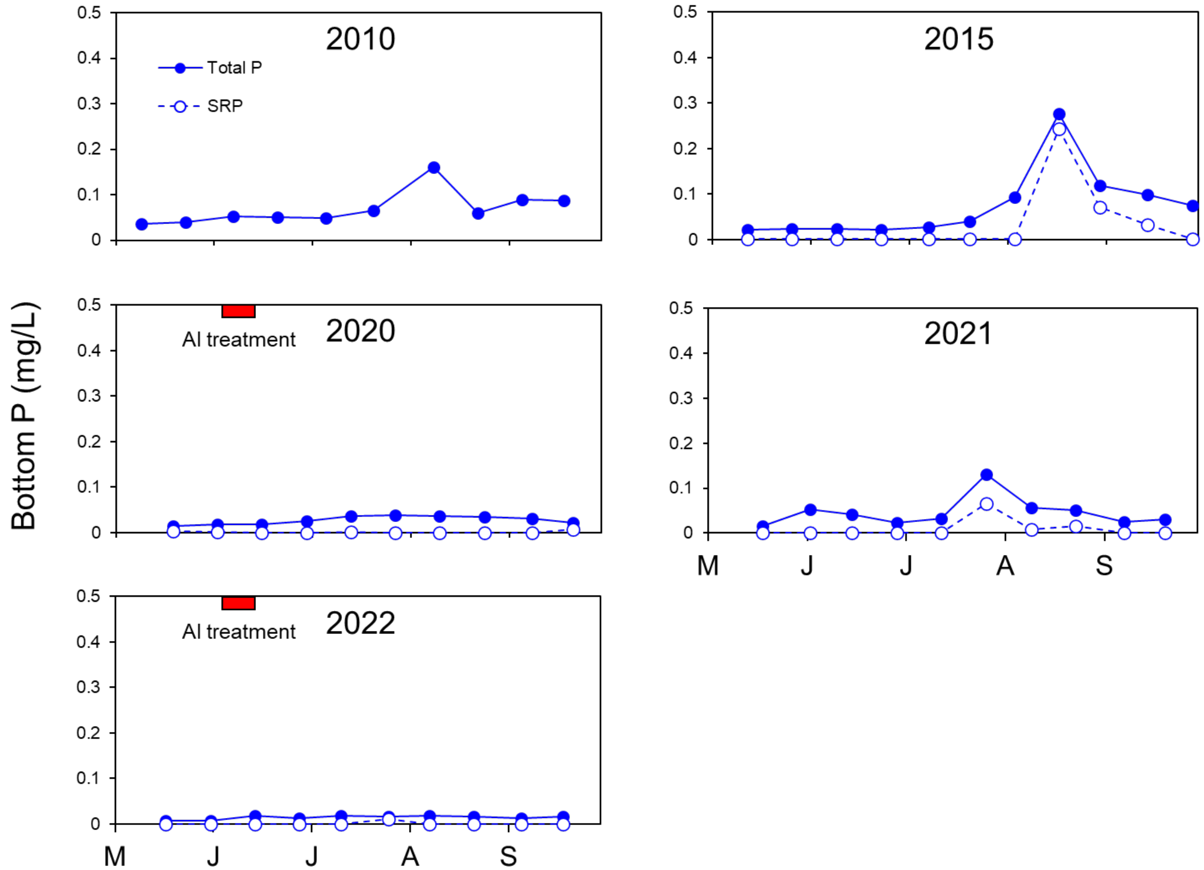


Figure 5. Seasonal variations in bottom (i.e., ~ 0.25 m above the sediment-water interface) total P, and bottom soluble reactive P (SRP) during pretreatment years 2010 and 2015, the first alum treatment year of 2020 (30 g Al/m^2), 2021, and the second alum treatment year of 2022 (30 g Al/m^2). The red horizontal bar denotes the period of alum applications.

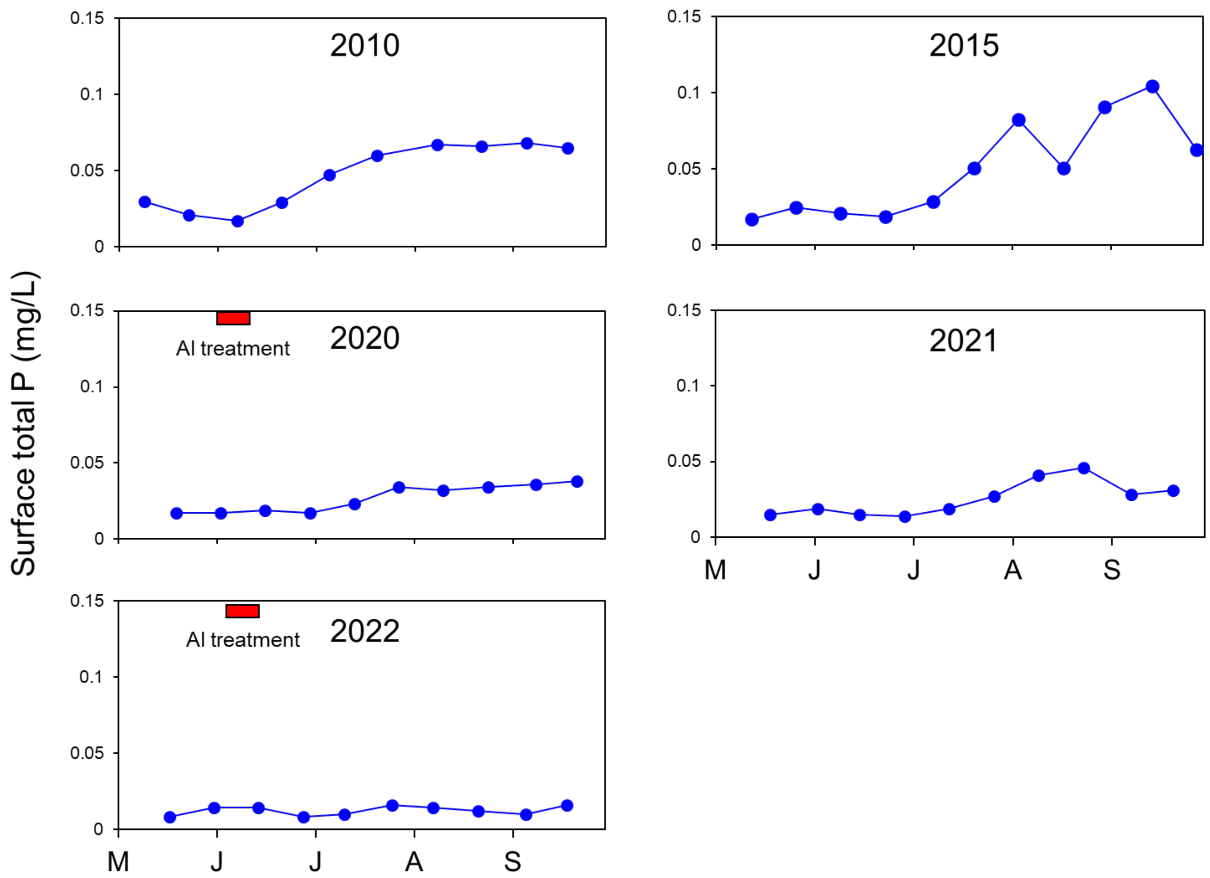


Figure 6. Seasonal variations in surface total P during pretreatment years (2010 and 2015), the first alum treatment year of 2020 (30 g Al/m^2), 2021, and the second alum treatment year of 2022 (30 g Al/m^2). The red horizontal bar denotes the period of alum applications.

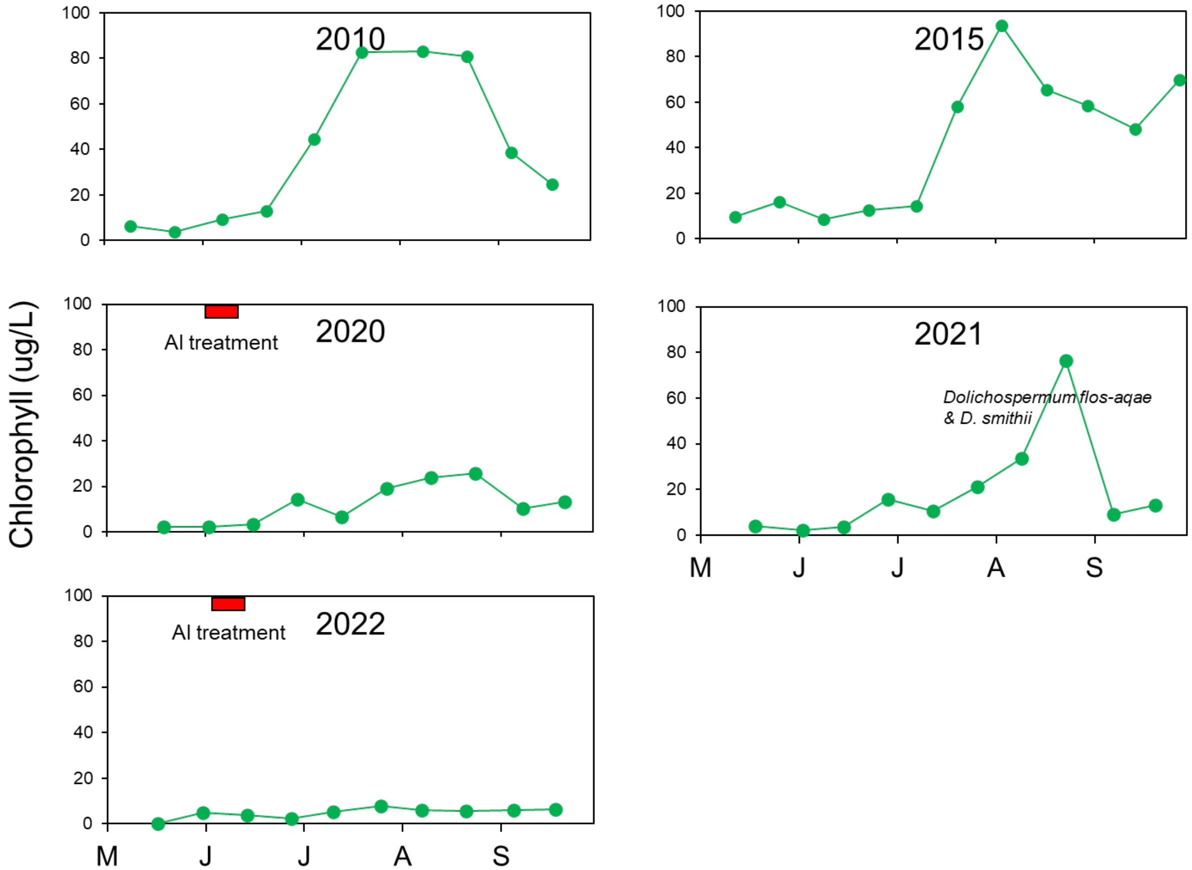


Figure 7. Seasonal variations in chlorophyll during pretreatment years (2010 and 2015), the first alum treatment year of 2020 (30 g Al/m^2), 2021, and the second alum treatment year of 2022 (30 g Al/m^2). The red horizontal bar denotes the period of alum applications.

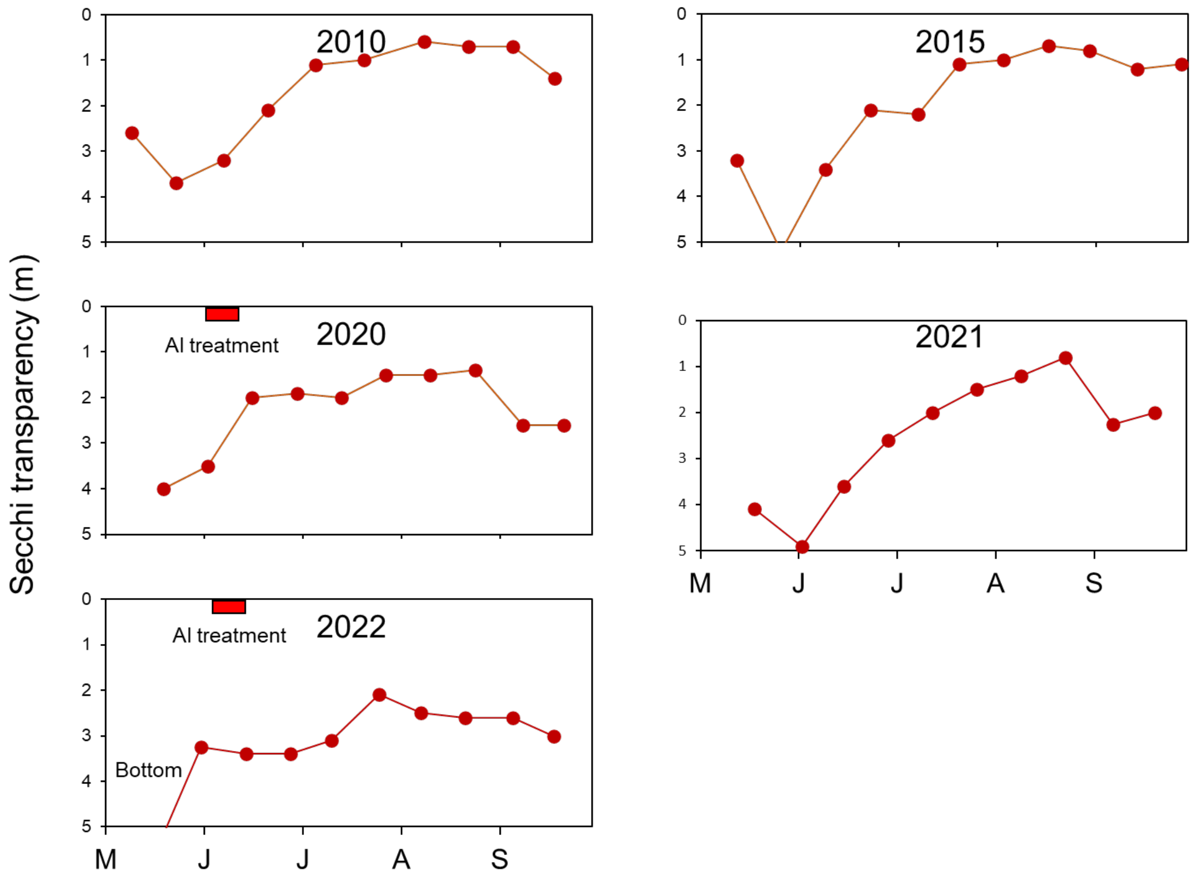


Figure 8. Seasonal variations in Secchi transparency during pretreatment years (2010 and 2015), the first alum treatment year of 2020 (30 g Al/m^2), 2021, and the second alum treatment year of 2022 (30 g Al/m^2). The red horizontal bar denotes the period of alum applications.

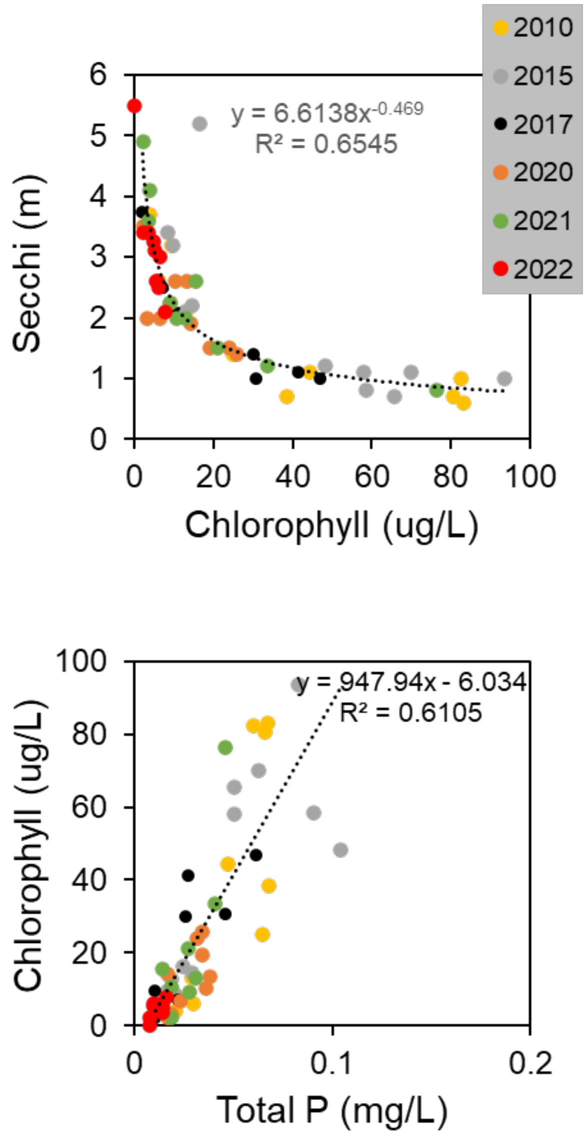
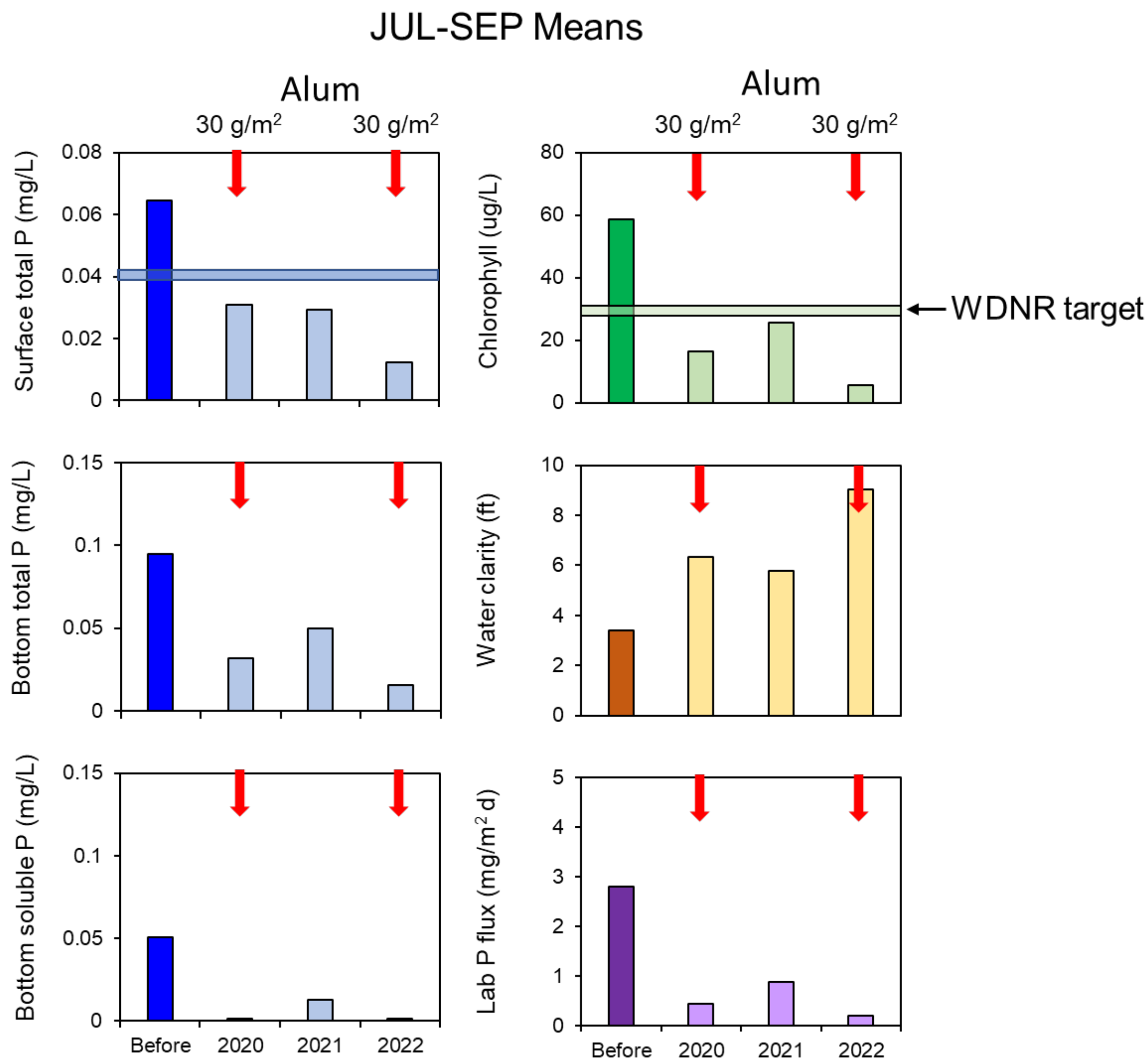


Figure 9. Relationships between Secchi transparency and chlorophyll (upper panel) and total phosphorus (P) versus chlorophyll (lower panel) during the pretreatment summers of 2010, 2015, 2017, and 2020-22 (post-treatment).

Figure 10. A comparison of mean summer (July-September) concentrations of surface and bottom total phosphorus (P) and soluble reactive P (SRP), chlorophyll, Secchi transparency, and mean laboratory-derived diffusive P flux from sediment (station 1) during pretreatment (mean of 2010 and 2015) and post alum treatment (2020-22) years.



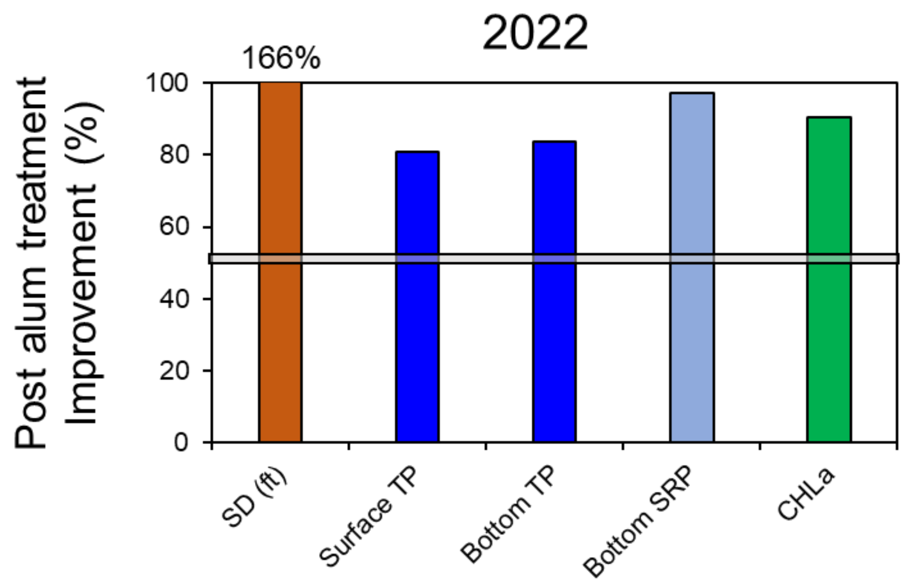


Figure 11. Post alum treatment improvement in WQ response variables in 2022.

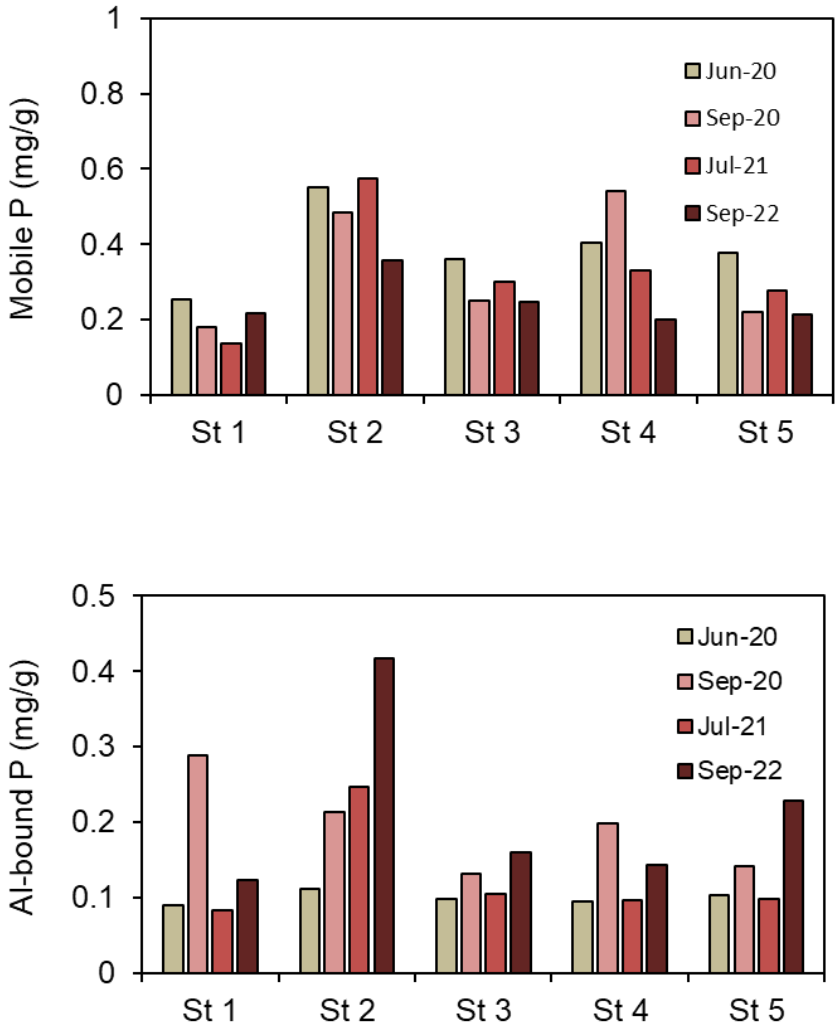


Figure 12. Changes in the concentration of redox-P (i.e., the sum of the loosely-bound and iron-bound P fractions, upper panel) and Al-bound P (lower panel) at various stations immediately before (June 2020) and after alum treatments in June of 2020 and 2022.

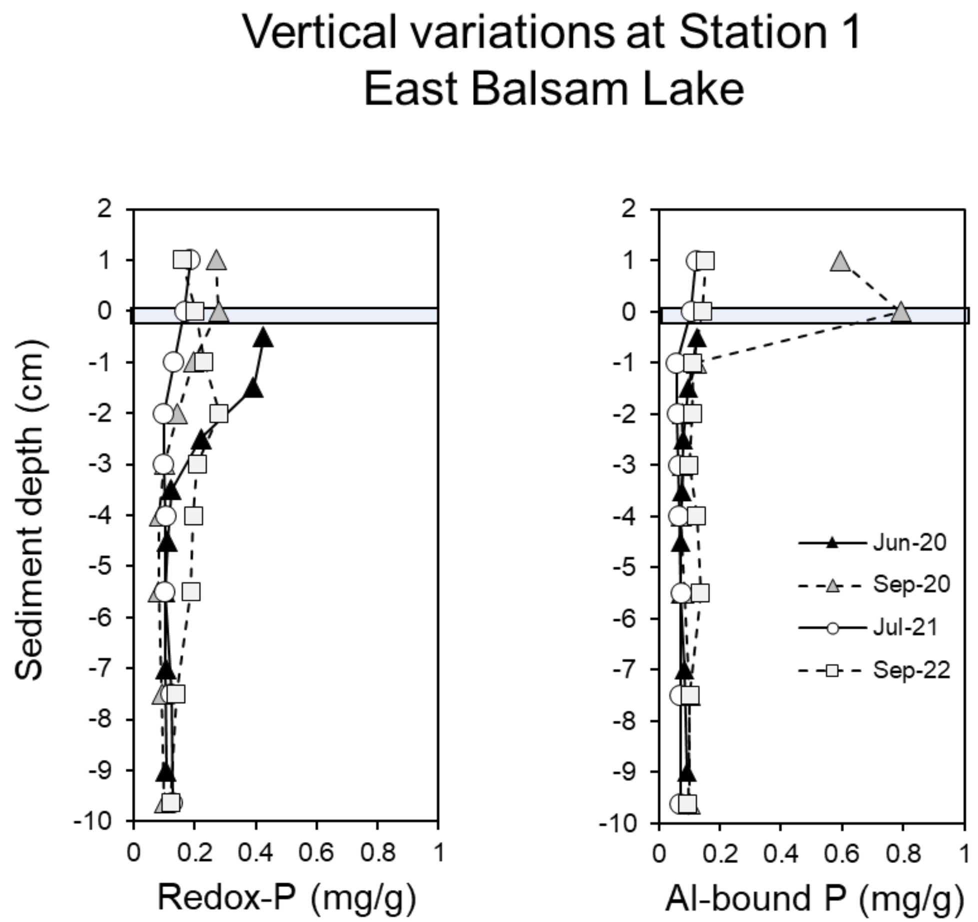
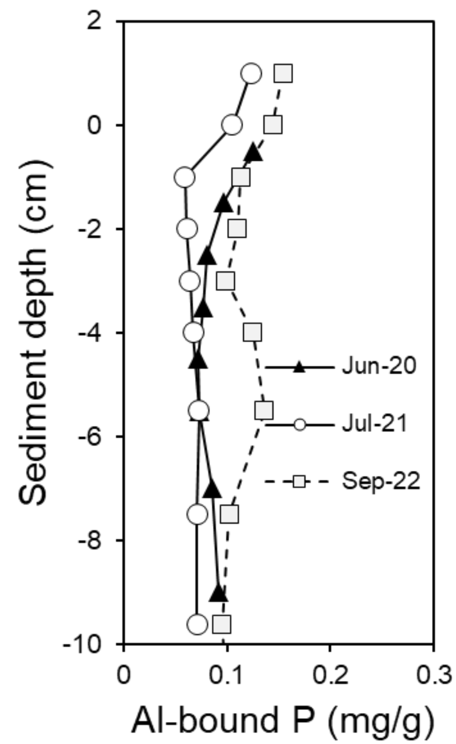


Figure 13. Vertical variations in sediment redox- (i.e., the sum of the loosely-bound P and iron-bound P sediment fractions) phosphorus (P) and aluminum (Al)-bound P concentrations for a sediment core collected from station 1 (Figure 1) in June 2020, September 2020, July 2021, and September 2022. The sediment profile in June 2020 represents pre-treatment conditions while September 2020, July 2021, and September 2022 represents post-alum treatment conditions. Alum applications occurred in 2020 and 2022 The light blue horizontal line denotes the original sediment surface before Al applications. The Al floc settled on top of this interface and represents a new layer.

Figure 14. A comparison of vertical variations in aluminum (Al)-bound P concentrations for a sediment core collected from station 1 (Figure 1) in June 2020, July 2021, and September 2022. The sediment profile in June 2020 represents pre-treatment conditions while July 2021 and September 2022 represents post-alum treatment conditions. Alum applications occurred in 2020 and 2022 The light blue horizontal line denotes the original sediment surface before Al applications. The Al floc settled on top of this interface and represents a new layer.



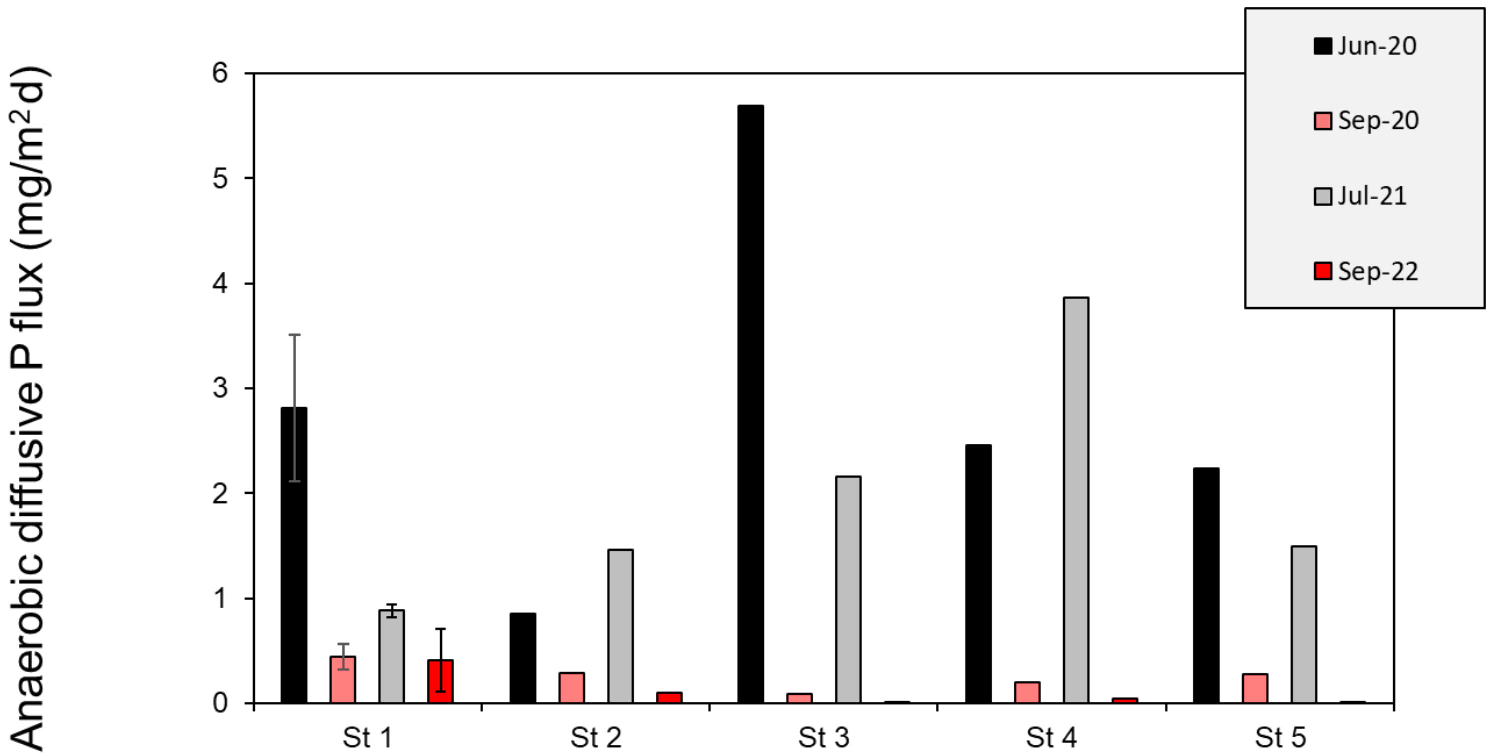


Figure 15. Mean anaerobic phosphorus (P) release rates at various stations before (i.e., June 2020) and after the alum applications in 2020 and 2022. Horizontal lines represent ± 1 standard error.

Supplemental Studies 2022: Limnological conditions near Rock Island

Summary

- This supplemental study addressed a concern that the embayment west of the Rock Island peninsula potentially needed alum treatments to reduced internal P loading and improve WQ conditions in this region of East Balsam Lake.
- Research in 2021 indicated that diffusive P flux from anaerobic sediment was very low in this west embayment area, suggesting internal P loading subsidies to cyanobacteria growth were probably minor.
- Limnological WQ conditions were very good (i.e., mesotrophic) in both the west embayment and the main east Balsam basin during the partial alum application of the main basin in 2022 (i.e., the west embayment was not treated with alum). Mean summer chlorophyll was only 8.3 μg/L and mean summer Secchi transparency exceeded 8 ft. Mean surface total P was only 0.017 mg/L. Bottom concentrations of total P and SRP were low despite the development of stratification and anoxia in late July.
- The results suggested that internal P loading was likely low to negligible in the west embayment and probably did not play a role in stimulating cyanobacteria blooms in 2021.
- The west embayment WQ is more likely connected to the main basin WQ via wind and water circulation rather than by localized internal P loading. I do not see a current need for supplemental alum application in the west embayment.

Objectives

The objectives of these supplemental studies were to examine WQ conditions in an untreated (i.e., no alum) area of East Balsam Lake located on the west side of the Rock Island peninsula. The goal of this research was to determine the need, if any, for expanding the alum application to this area of the lake.

Results synopsis

Figure S1. Location of station 6 in the embayment west of the Rock Island peninsula.

Station 6 was established in the bay west of the Rock Island peninsula (depth ~ 3.75 m) for limnological WQ and sediment sampling and analyses (Fig. S1). A sediment core was collected at station 6 in September 2021 for determination of diffusive P flux under anaerobic conditions and P fractions. In 2022, water samples were collected at biweekly intervals for determination of surface 2-m integrated total P and chlorophyll and bottom total P and SRP. In situ measurements of temperature, dissolved oxygen, pH, and conductivity were collected at 0.5-m intervals from the lake surface to the bottom. Secchi transparency was estimated using a 20-cm diameter black and white alternating disk.

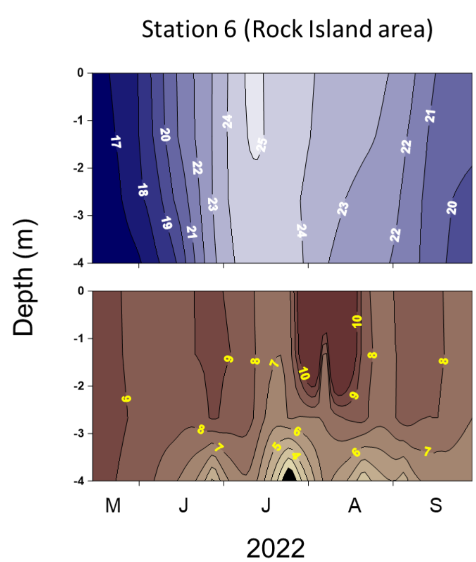


Figure S2. Contour plots of water temperature (upper) and dissolved oxygen (lower) at station 6 in 2022. Black area at the lake bottom in late July denotes a period of hypolimnetic anoxia.

The embayment area exhibited periods of weak stratification between mid-June and late August 2022 (Fig. S2). Bottom anoxia occurred briefly in late July. Bottom total P and SRP concentrations were low throughout the summer and did not exceed 0.05 mg/L (Fig. S3). Surface total P concentrations were also low and fluctuated between 0.008 mg/L and 0.024 mg/L throughout the summer. Chlorophyll concentrations did not exceed 12 µg/L and varied between 0.46 µg/L and 11.6 µg/L. Secchi transparency was relatively deep throughout the summer and ranged between 5.9 ft in late July and 12.3 ft in May.

In general, summer (JUL-SEP) limnological variables exhibited similar means for station 1 and 6 (Table S1). The mean summer surface total P concentration was well below the WisCALM standard of 0.04 mg/L at both stations. Mean summer chlorophyll concentrations were similar at

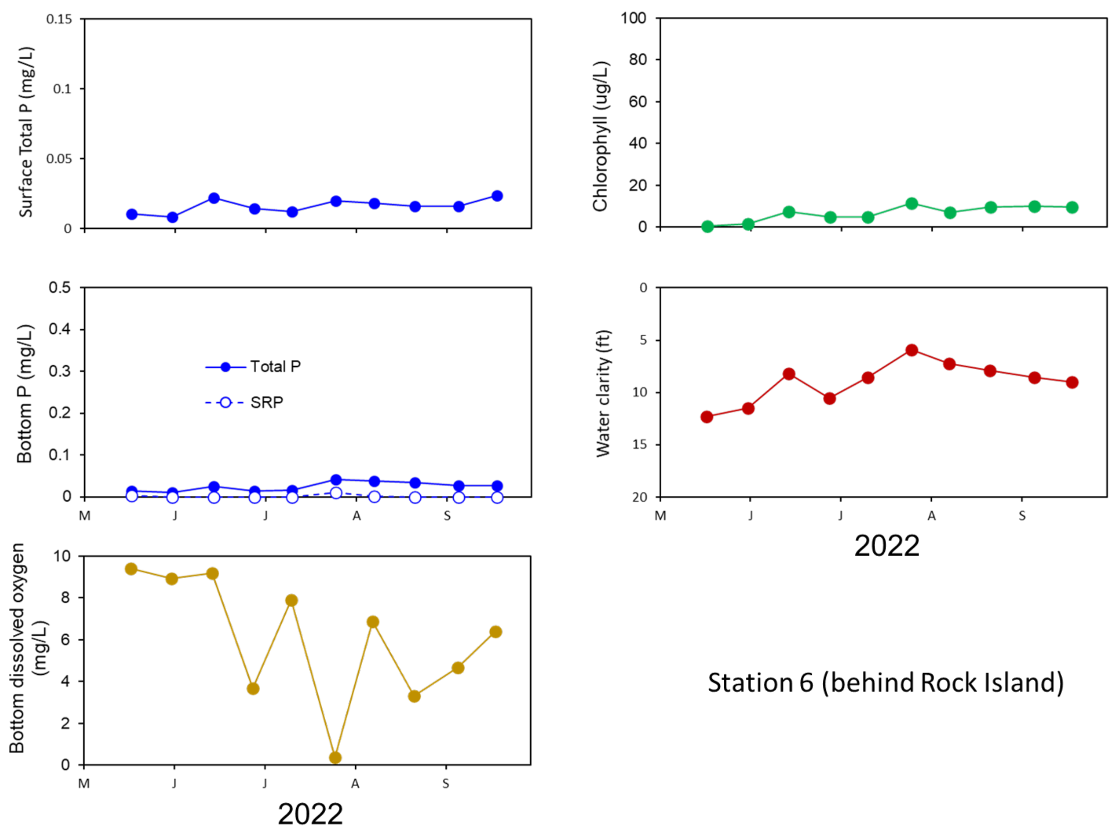


Figure S3. Seasonal variations in 2-m integrated total phosphorus (P), bottom P, bottom dissolved oxygen, 2-m integrated chlorophyll, and Secchi transparency at station 6 in 2022.

Table S1. Average (JUL-SEP) limnological response variables at station 1 and 6 in east Balsam Lake in 2022.							
Summer	Secchi transparency		Surface TP	Bottom TP	Bottom SRP	CHLa	P Flux
	(m)	(ft)	(mg/L)	(mg/L)	(mg/L)	(ug/L)	(mg/m^2 d)
			2022 (JUL-SEP average)				2021
St 1	2.76	9.05	0.012	0.015	0.001	5.62	0.9
St 6	2.51	8.23	0.017	0.028	0.002	8.34	0.7

both stations and below the WisCALM 20 μg/L standard bloom frequency. Summer mean Secchi transparency was similar between the 2 stations, exceeding 8 ft. Finally, sediment diffusive P flux under anaerobic conditions was relatively low at both stations as of 2021.