East Balsam Lake, Wisconsin - Limnological response to alum treatment: 2023 interim report

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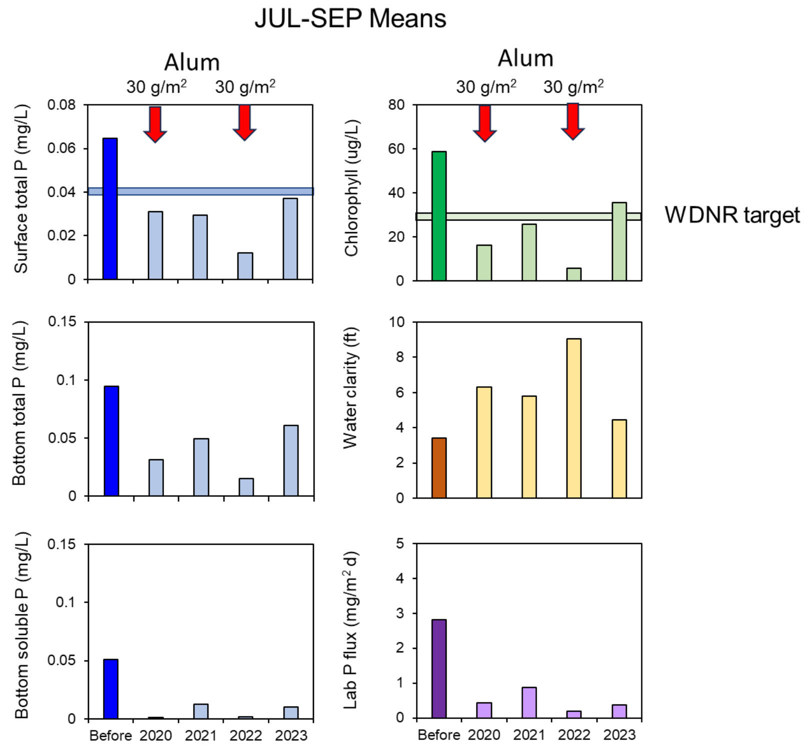
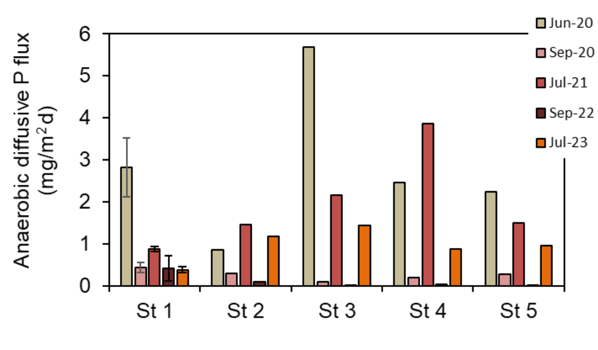
Executive summary



Changes in mean (JUL-SEP) limnological response variable in East Balsam Lake before and during the first two alum applications.

1. The summer of 2023 represented a nontreatment year for alum application to East Balsam Lake. Previously the lake had been treated with a 30 g/m^2 Al dose over 300 ac (i.e., > 10-ft depth contour) in 2020 and 2022. The next two alum treatments are scheduled for 2024 and 2026 at 20 g/m^2.
2. Unfortunately, mean summer limnological response variables rebounded (i.e., became impaired) during the nontreatment year 2023, resulting poorer WQ than in 2022. Because only 2 partial alum dose treatments have occurred so far, the Al floc concentration is not yet high enough to control all the internal P load originating from the sediment. Thus, during subsequent nontreatment years such as 2021 and 2023, some of the sediment phosphorus leaked through the saturated alum layer and into the water, becoming available for blue-green algal uptake, resulting in a bloom. As successive alum layers continue to be applied to the lake bottom through 2026, sediment internal phosphorus loading should be mitigated, resulting in much reduced blue-green algal growth and improved water clarity.
3. In July 2023, soluble P concentrations increased in the hypolimnetic bottom waters to 0.035 mg/L during a period of stratification and bottom anoxia. Although low relative to the



Variations in laboratory-derived sediment phosphorus flux at various stations in East Balsam Lake. P flux modestly rebounded (increased) during the nontreatment year 2023 because the alum floc became P saturated and lost binding capacity for P.

pretreatment period, laboratory-derived internal P loading from anoxic sediment in East Balsam Lake nevertheless increased during the 2023 nontreatment summer, coinciding with the July buildup of soluble P in the hypolimnion, indicating modest internal P loading. The increase in P flux in 2023 suggested the alum floc was probably saturated with P originating from the sediment and lost binding capacity.

4. Elevated hypolimnetic soluble P in July coincided with increases in chlorophyll concentration and bloom formation in August 2023. Chlorophyll increased to a peak 65 µg/L on 5 September.
5. Mean (July-September) surface total P increased to 0.037 mg/L (43% reduction over the pre-treatment average), mean bottom total P was 0.061 mg/L (36% reduction), and mean bottom SRP was 0.010 mg/L (80% reduction). Mean summer chlorophyll was 36 µg/L, well above the target goal of 27 µg/L. However, the overall mean summer chlorophyll in 2023 represented a 39% reduction compared to the pretreatment mean. Mean summer Secchi transparency was 4.42 ft, representing a 30% improvement over pretreatment conditions.
6. Aluminum-bound P concentrations in the upper 4-cm layer continued to remain elevated in 2023 compared to pretreatment concentrations, indicating P binding onto the Al floc layer.
7. Since alum did not appear to be detected outside the target treatment area (i.e., stations, 6, 7, and 8), I suggest these stations be moved into the application zone to better monitor the location and concentration of the alum during the 2024 and 2026 alum applications.
8. The third partial alum application of 20 g/m^2 is projected for 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 2023.

Methods

Lake monitoring

Station 1, located in the central, deepest area of the lake, was sampled biweekly between May and September 2023 (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 8 stations in East Balsam Lake in July 2023 (Fig. 1). Stations 1 through 5 coincided with those visited in 2015 (James 2015) and were located within the Al treatment zone. Stations 6, 7, and 8 were added in 2023 to assess possible post-application Al floc movement outside the treatment zone. Since East Balsam Lake is relatively large and shallow, wind-generated wave activity, turbulence, and resuspension could move and redistribute the Al floc, resulting in some concentration dilution. Al floc movement and redistribution has been documented in many other alum-treated lakes.

Vertical and spatial variations in sediment chemistry. Sediment cores collected at each station were sectioned at 2-cm intervals between 0 and 10 cm. All sediment core sections collected in the alum treatment zone were analyzed for moisture content, wet and dry bulk density, loss-on-ignition organic matter, loosely-bound P, iron-bound P, labile organic P, aluminum-bound P, and total aluminum (see *Analytical methods* below). Sections from stations 6, 7, and 8 were only analyzed for total aluminum.

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 located within the alum treatment zone (Fig. 1). One sediment core was collected at stations 2-5, while triplicate cores were collected at station 1, to monitor alum treatment effectiveness one year after the June 2022 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 ^{o}C for determination of moisture content, wet and dry bulk density, and burned at 550 ^{o}C 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).

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 at Amery exhibited peaks of 0.89 in on 25 June, 1.06 in on 3 July, 0.75 in on 23 July, a total of 1.54 in between 26-28 July, and 0.84 in on 14 August (Fig. 2). Monthly precipitation at Amery in 2023 was well below the long-term average in May, June, and August, and near average in July and September (Fig. 3).

East Balsam Lake stratified between mid-May and the end of June (Fig. 4). A cold front in early July coincided with water column mixing and nearly complete turnover. Stratified conditions re-established between mid-July and the end of September. Bottom anoxia developed during both stratified periods. In particular, bottom anoxia rapidly developed in May, which was early and unusual compared to other years. After complete water column mixing in early July, bottom anoxia again rapidly developed in conjunction with stratification and extended to the ~ 4.5-m depth in early August.

Bottom total P and SRP concentrations were relatively low during the Spring period of hypolimnetic anoxia (Fig. 5). However, both variables increased in concentration in August. The total P and SRP concentration maxima were 0.162 mg/L and 0.035 mg/L in early August, suggesting the occurrence of some internal P loading from anaerobic sediment. Concentrations exhibited a secondary peak of 0.070 mg TP/L and 0.017 mg SRP/L in early September. Surface total P exhibited a linear concentration increase between July and early September, coinciding with summer bottom anoxia and elevated hypolimnetic P (Fig. 6). The total P concentration maximum was 0.054 mg/L in early September. Chlorophyll increased in concentration between July and September, reflecting the similar surface total P trend (Fig. 7). This pattern suggested uptake and incorporation of P by cyanobacteria for growth, most likely derived from modest internal P loading in July. Chlorophyll concentrations peaked at 64 μg/L in early September. Secchi transparency declined in conjunction with the algal bloom to a minimum of 0.8 m (2.6 ft) in early September.

As in other years, 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 higher during the nontreatment year 2023 compared to alum application years (Fig. 10). Nevertheless, means were 36% and 80% lower compared to the pretreatment mean (Table 1 and Fig. 11). Mean summer surface total P and chlorophyll concentrations were also higher in 2023 at 0.037 mg/L and 35.6 μg/L, respectively. Improvement over pretreatment means was 43% and 39%, respectively (Table 1 and Fig. 11). Mean Secchi transparency was 30% improved in 2023 versus the pretreatment mean (Table 1 and Fig. 11).

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	2023	Percent improvement (Pre Al versus 2023)	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	0.037	43% reduction	< 0.040
		Mean bottom TP (mg/L)	0.085	0.104	0.095	0.032	0.050	0.015	0.061	36% reduction	< 0.050
		Mean bottom SRP (mg/L)	ND	0.051	0.051	0.001	0.013	0.001	0.010	80% reduction	< 0.050
		Mean chlorophyll (ug/L)	59.01	58.35	58.68	16.26	25.62	5.62	35.58	39% reduction	< 27
		Mean Secchi transparency (ft)	3.01	3.8	3.4	6.33	5.79	9.05	4.42	30% deeper	>10
Sediment	Station 1	Sediment diffusive P flux (mg/m^2 d)	ND	2.56	2.56	0.44	0.88	0.41	0.38	85% reduction	< 1.5

*Barr Engineering

Changes in sediment chemistry and anaerobic diffusive phosphorus flux

Within the designated alum treatment zone, Al concentrations were elevated in the upper 4-cm depth and declined to background concentrations deeper in the sediment profile (Fig. 12). The apparent Al floc layer (i.e., sediment containing the added alum) was 4-cm at all stations (Table

Table 2. Estimated thickness of the Al floc layer (i.e., sediment layer whjere Al concentrations were elevated compared to background concentrations, Al concentration in that layer, the percent recovery compared to the theoretical 60 g/m^2 added since 2020, the areal concentration of aluminum-bound P, and the Al:P binding ratio for various stations in East Balsam Lake.

Station	Al Floc depth	Al		Al-P	Al:P
	(cm)	(g/m2)	(%)	(g/m2)	
1	4	26.1	43.5	0.271	96.3
2	4	41.5	69.2	0.979	42.4
3	4	38.1	63.5	0.615	62.0
4	4	27.8	46.3	0.316	88.0
5	4	31.8	53.0	0.488	65.2

2). The area-based Al concentrations in the upper 4 cm were highest for stations 2 and 3. Surprisingly, the Al concentration was lowest in the middle, eastern, and southern portion of the alum application area (Table 2). These patterns suggested some post-application redistribution of the Al floc and concentration along the eastern and southern side of the application zone. Others have documented post-application Al floc movement (Egemose et al. 2013, Huser 2017, James and Bischoff 2020). At stations located outside the alum application area (i.e., stations 6, 7, and 8), Al concentrations were low throughout the sediment profile and reflected background Al. These patterns suggested that the alum was concentrated primarily in the designated application area and had not redistributed to other areas. The percent Al recovery (i.e., compared to the 60 g/m^2 theoretically added since 2020) ranged between 44% and 69%.

Al-bound P concentrations followed a similar pattern to that of Al, suggesting P binding onto the Al floc (Fig. 13). Concentrations were generally elevated in the upper 4-cm sediment layer and decreased to background concentrations below that sediment depth. Stations 1, 4, and 5 exhibited the lowest Al concentrations and correspondingly lowest Al-bound P concentrations (Fig. 14). Station 2 and 3 exhibited higher Al and Al-bound P concentrations. Similarly, area-based concentrations were greatest at stations 2 and 3 and lowest at stations 1, 4, and 5 (Table 2). The Al:P binding ratio was relatively high at all stations (Table 2) with Stations 1, 4, and 5 exhibiting the highest Al:P binding ratios (Table 2). Ratios should decline over time and with additional alum applications. Ideally, the long-term Al:P binding ratio should be < 20:1.

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. 15). 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. 15). By July 2021, the surface Al-bound P concentration maximum declined tremendously, again suggesting post-application movement of the Al floc from this region of the treatment zone (Fig. 15).

Laboratory-derived anaerobic P flux increased at most stations during the nontreatment year 2023 (Fig. 16). This trend was similar to patterns of rate increase during the nontreatment summer of 2021 and suggested that P binding within the Al floc layer was becoming saturated, allowing for some P diffusion into the water column. P concentration increases in the bottom waters in July and August were consistent with the rebound in laboratory P flux (Fig. 5). Diffusive P flux ranged between 0.4 mg/m^2 d and 1.4 mg/m^2 d (Fig. 16). With the exception of station 2, diffusive P flux was lower than pretreatment fluxes in 2023. Improvement ranged between 57% and 86%.

Changes in the concentrations of redox-P and Al-bound P in the surface sediment layer post alum treatment are shown in Figure 17. While Al-bound P concentrations have increased at all stations as a result of P binding onto the Al floc, greatest increases over time have occurred at Stations 2, 3, and 5 (Fig. 17).

Summary and recommendations

Internal P loading rebounded modestly during the nontreatment year 2023, resulting in an algal bloom. This lake response suggested that the currently applied alum (which is a partial dose), has probably become saturated with sediment P, resulting in some “leakage” or diffusion of additional P through the alum layer and into the water for algal uptake. This pattern can occur early in the alum treatment process and should diminish later as the full alum dose is applied to the sediment.

The alum application strategy for East Balsam Lake was to split the full dose (100 g/m^2) into smaller partial doses and spread applications out over a period of years. Splitting the alum application into lower doses is beneficial in improving the binding effectiveness of sediment P. When a lower concentration of alum is exposed to a high concentration of sediment P, its binding sites are more efficiently filled with phosphorus. However, a disadvantage of this application strategy is that the partial alum dose can become saturated with P and inefficient in completely controlling internal P loading during the early stages of treatment.

Sediment total Al (aluminum) results suggested that the Al floc layer was within the upper 4-cm of sediment in the treatment zone. The Al concentration was also not evenly distributed in this area, suggesting post-application movement of the precipitated Al either during application or afterward. This pattern is not unusual (Egemose et al. 2009, 2013; James & Bischoff 2020), particularly for a large basin such as East Balsam Lake, and can be caused by water movements during turnover periods. Area-based Al concentrations in the upper 4-cm sediment layer were greatest at stations 2 and 3, located along the western and northern perimeter of the treatment zone and lower in the center, eastern, and southern regions.

In addition, area-based Al concentrations were lower than the target 60 g/m^2 as of 2023. This pattern may be attributed to spreading and redistribution of the Al floc and possible mixing and incorporation into the sediment. Since the results suggested that the added Al is not leaving the intended application area (i.e., low Al found at stations 6, 7, and 8), I suggest that these particular stations be moved into the targeted application area to better quantify the location of the alum during the 2024 and 2026 treatments (Fig. 18).

The third partial alum application of 20 g/m^2 is projected for 2024. I recommend pursuing funding for and scheduling this application for 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 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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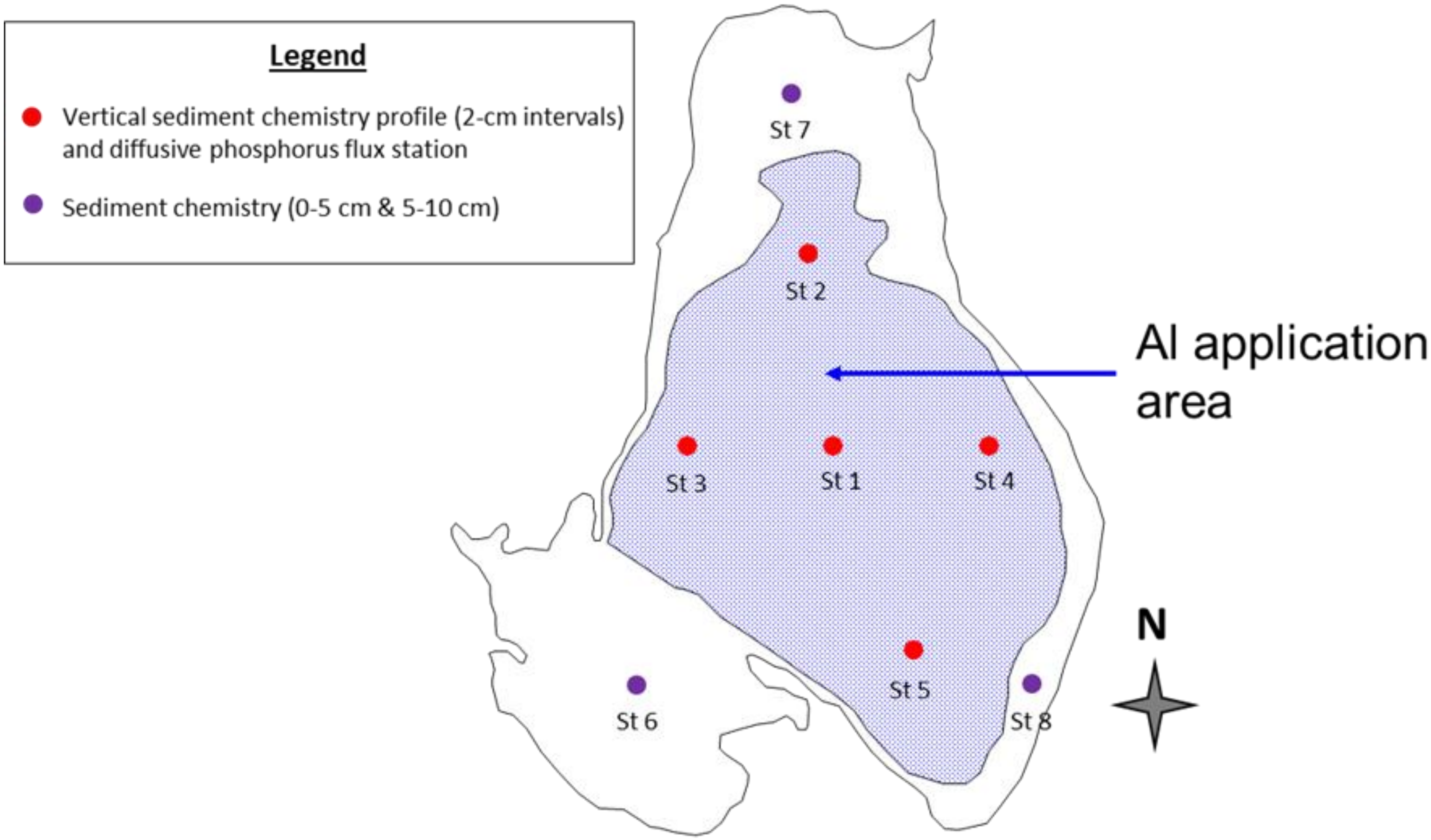


Figure 1. Sediment and water sampling stations.

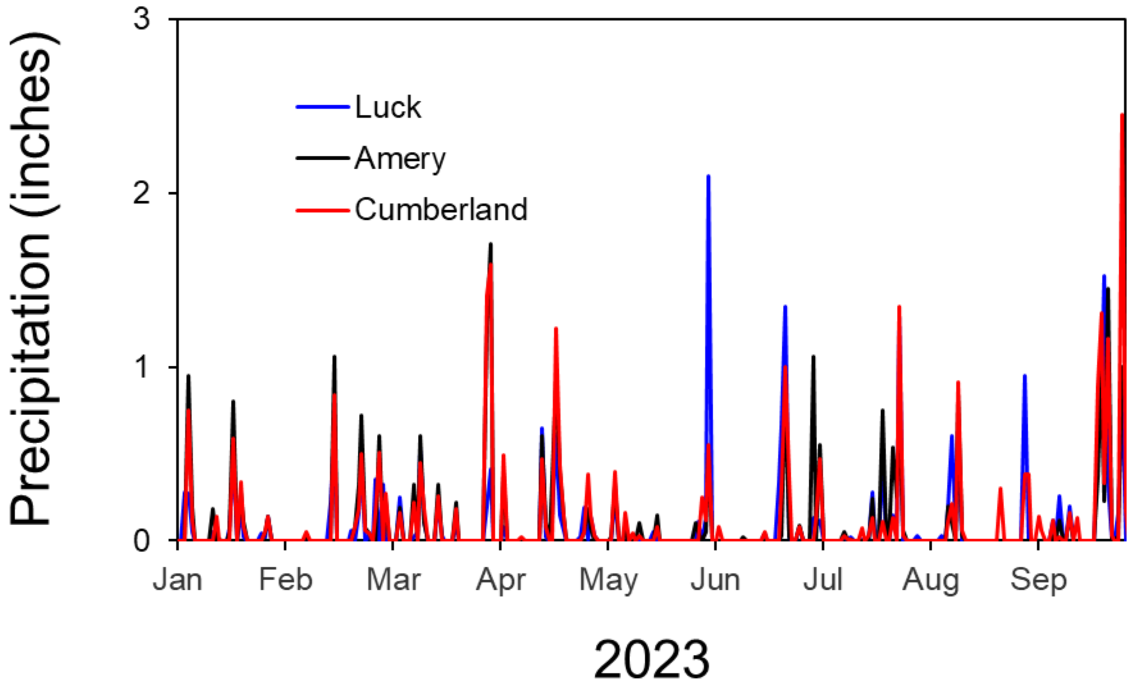


Figure 2. Variations in daily local precipitation measured at Amery, Cumberland, and Luck WI in 2023.

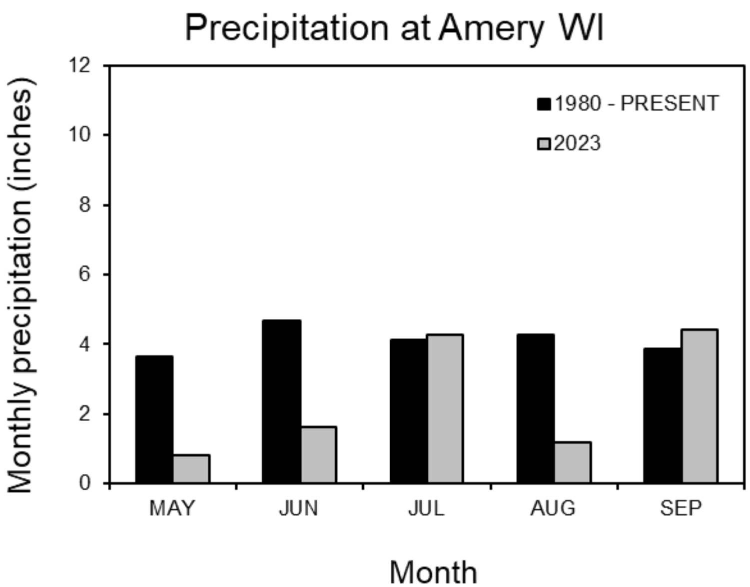


Figure 3. A comparison of average monthly precipitation (data from Amery WI).

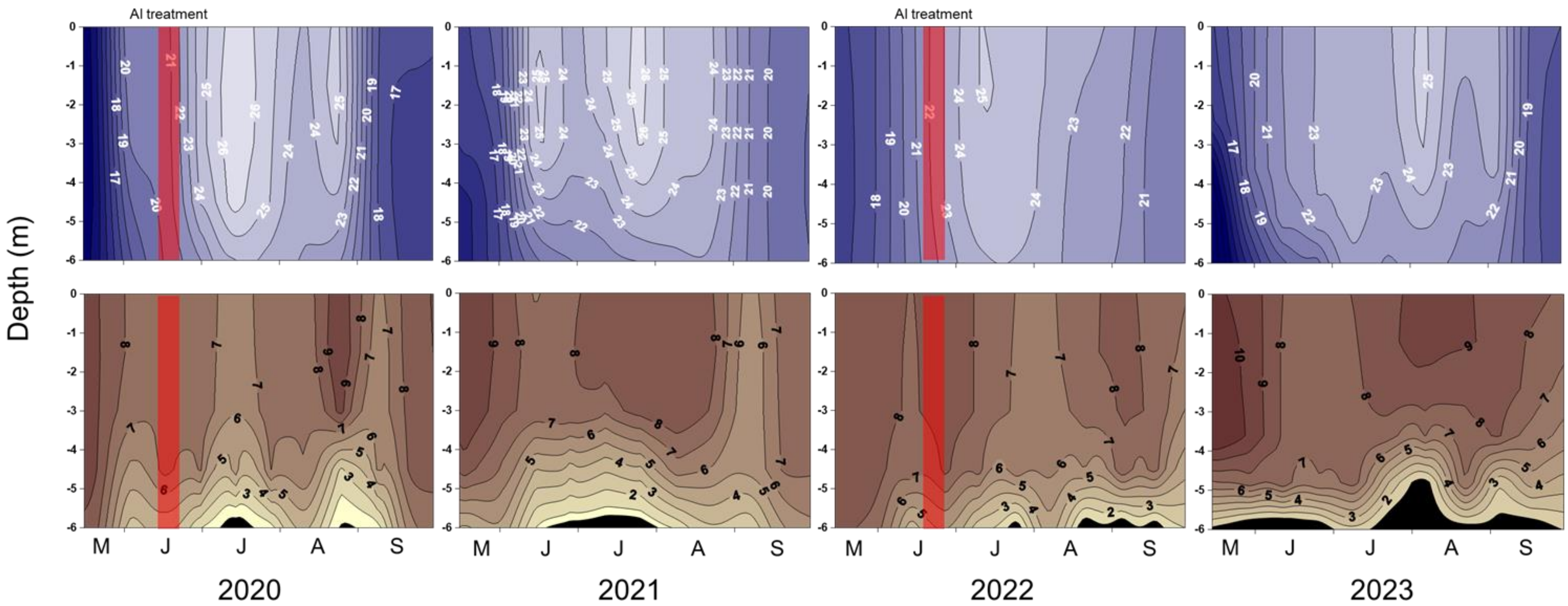


Figure 4. Seasonal and vertical variations in temperature (upper panel) and dissolved oxygen (lower panel) in 2020, 2021, 2022, and 2023.

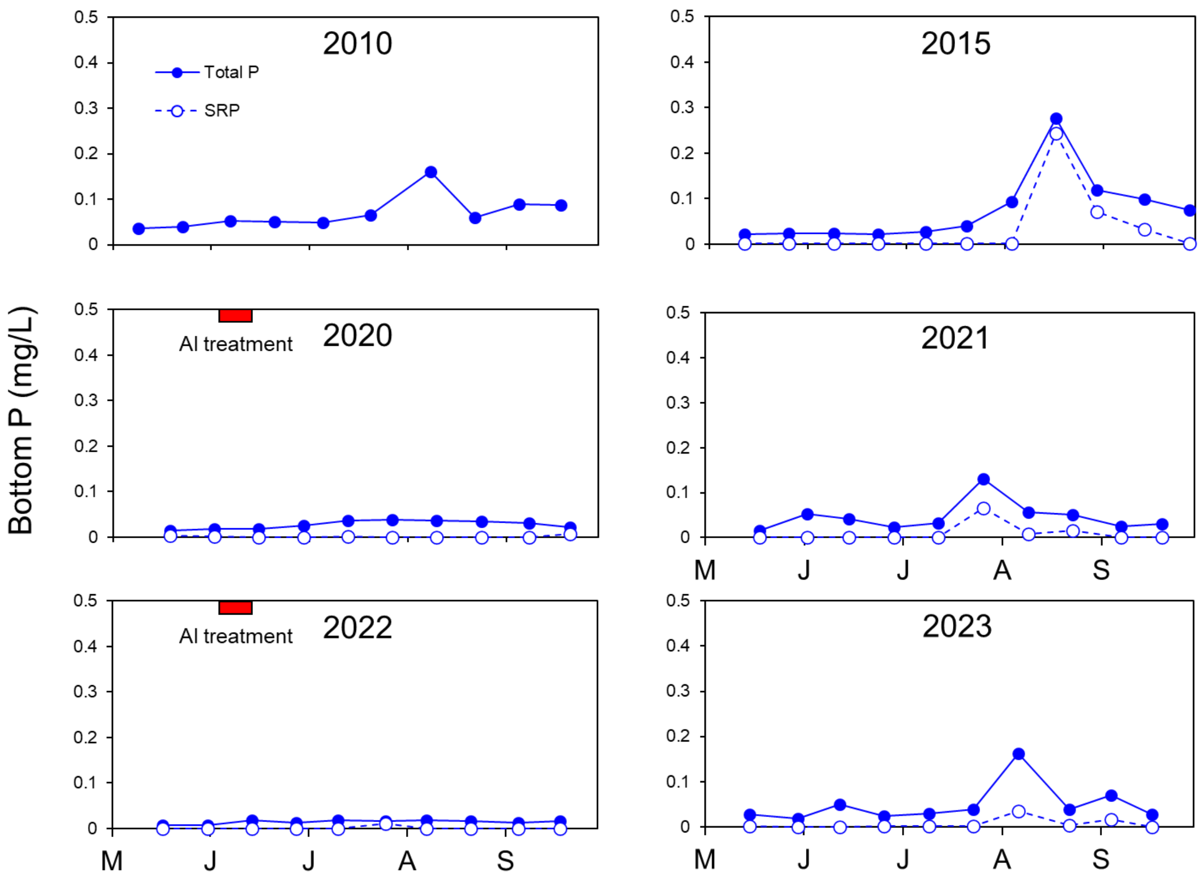


Figure 5. Seasonal variations in bottom (i.e., ~ 0.25 m above the sediment-water interface) total P, and bottom soluble reactive P (SRP) during pretreatment years 2010 and 2015, the first alum treatment year of 2020 (30 g Al/m^2), 2021, the second alum treatment year of 2022 (30 g Al/m^2), and 2023. The red horizontal bar denotes the period of alum applications.

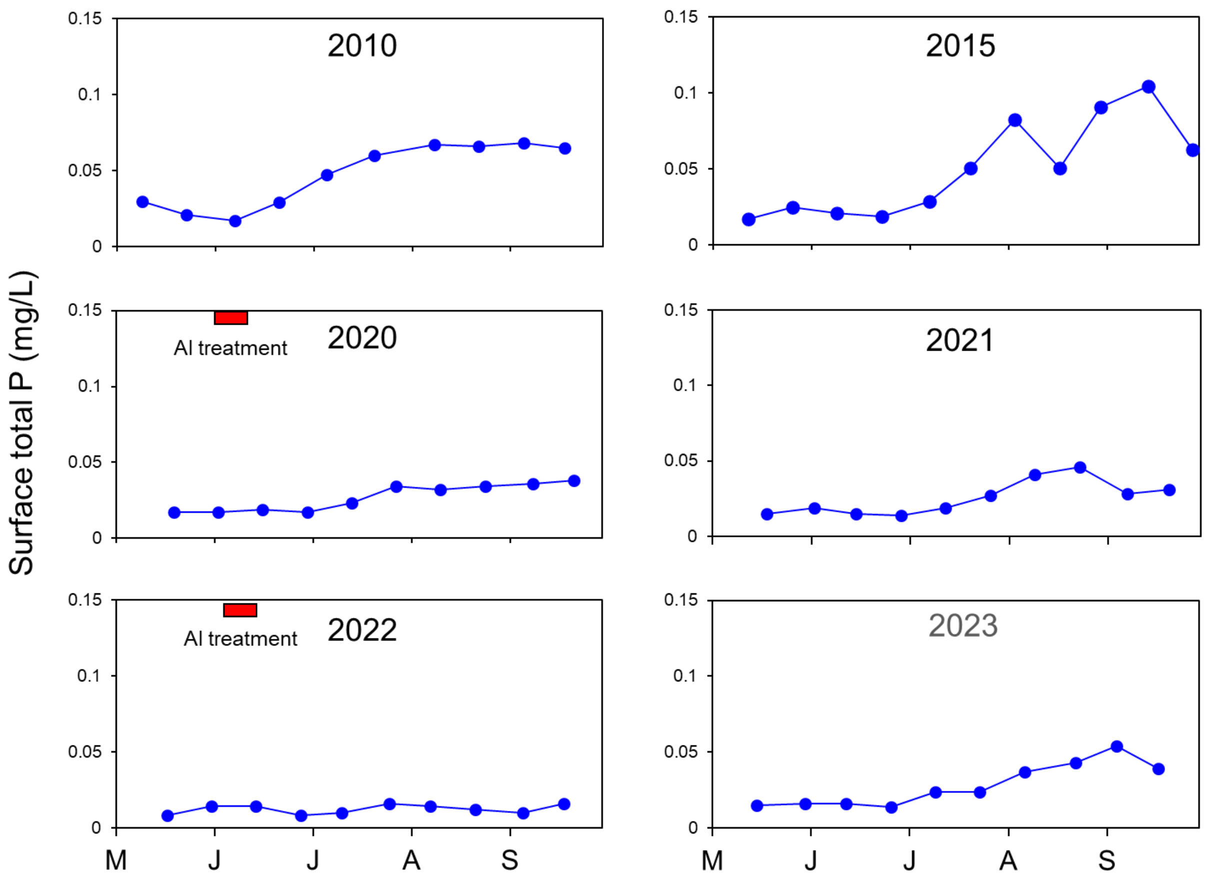


Figure 6. Seasonal variations in surface total P during pretreatment years (2010 and 2015), the first alum treatment year of 2020 (30 g Al/m^2), 2021, the second alum treatment year of 2022 (30 g Al/m^2), and 2023. The red horizontal bar denotes the period of alum applications.

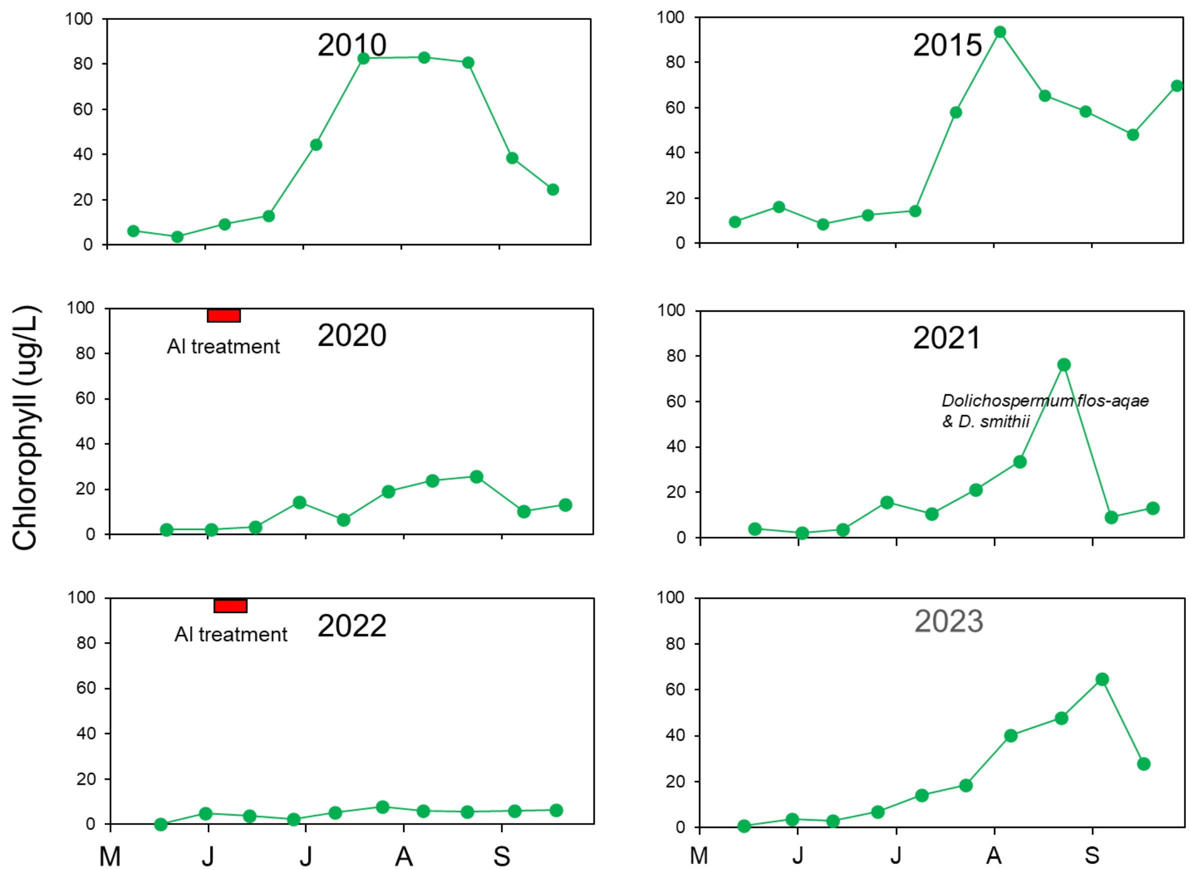


Figure 7. Seasonal variations in chlorophyll during pretreatment years (2010 and 2015), the first alum treatment year of 2020 (30 g Al/m^2), 2021, the second alum treatment year of 2022 (30 g Al/m^2), and 2023. The red horizontal bar denotes the period of alum applications.

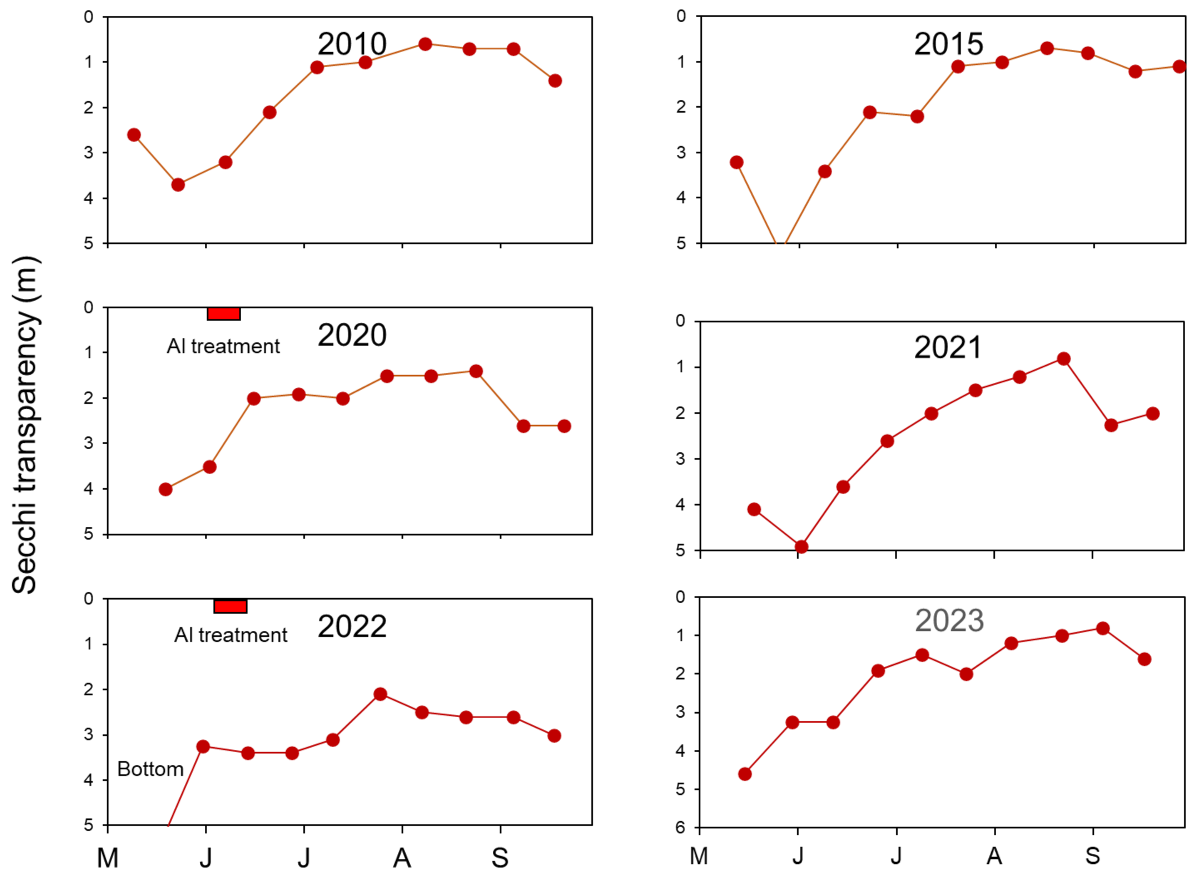


Figure 8. Seasonal variations in Secchi transparency during pretreatment years (2010 and 2015), the first alum treatment year of 2020 (30 g Al/m^2), 2021, the second alum treatment year of 2022 (30 g Al/m^2), and 2023. The red horizontal bar denotes the period of alum applications.

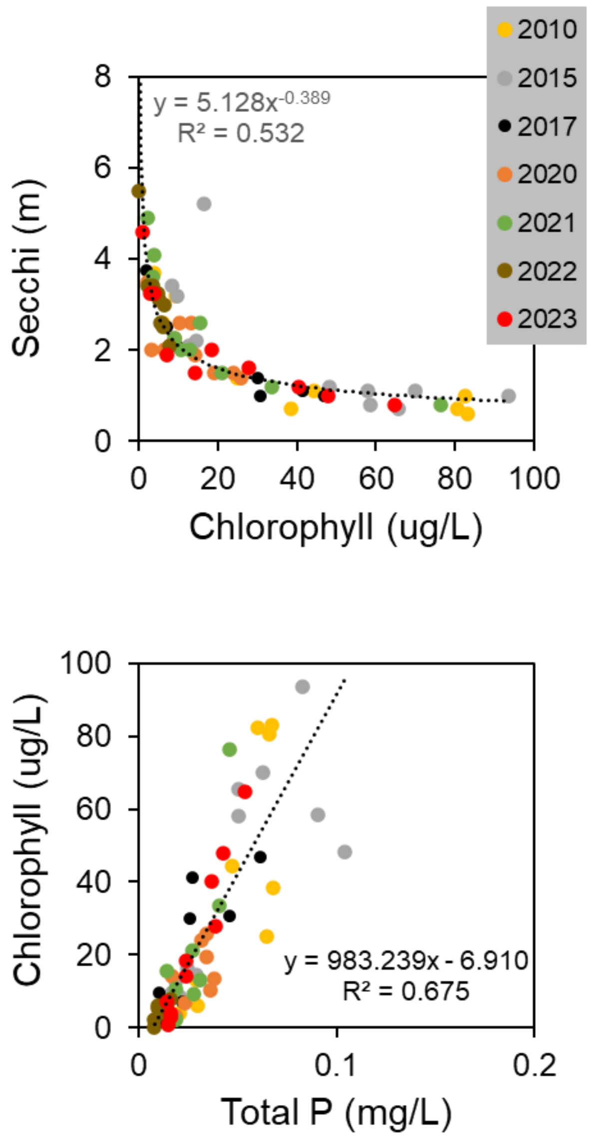
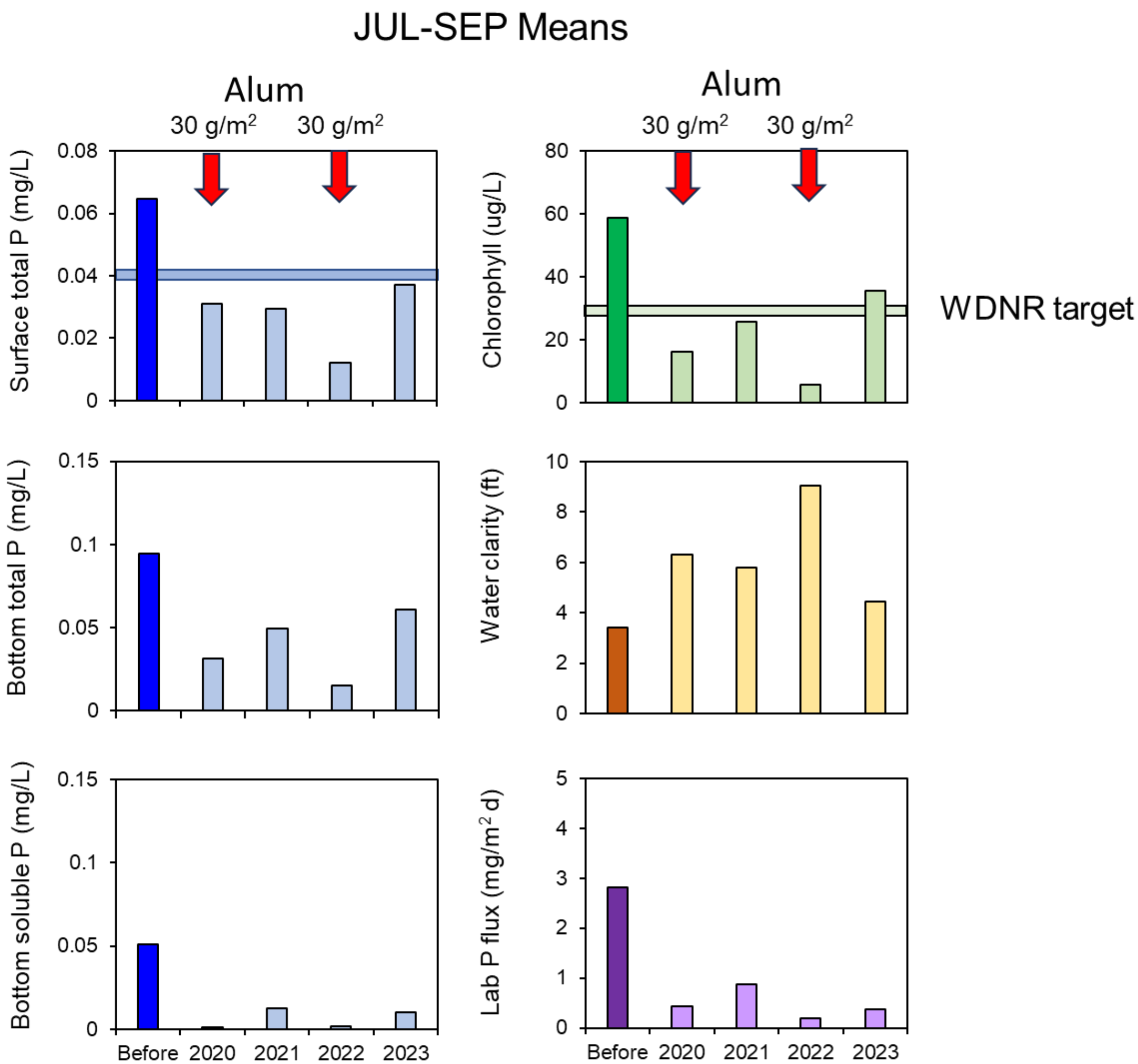


Figure 9. Relationships between Secchi transparency and chlorophyll (upper panel) and total phosphorus (P) versus chlorophyll (lower panel) during the pretreatment summers of 2010, 2015, 2017, and 2020-23 (post-treatment).

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 (2020-23) years.



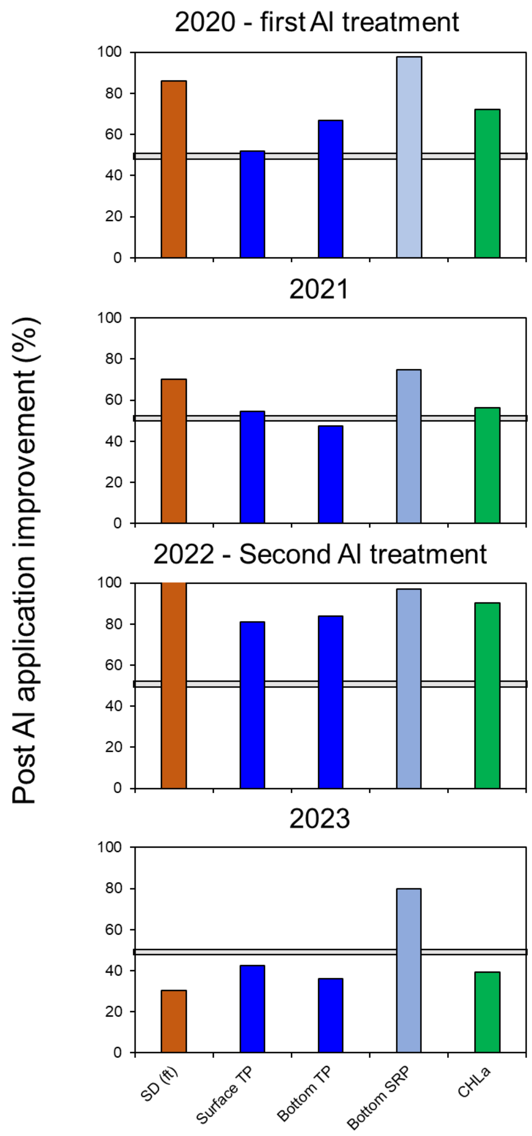


Figure 11. Post alum treatment improvement in WQ response variables in 2020-23.

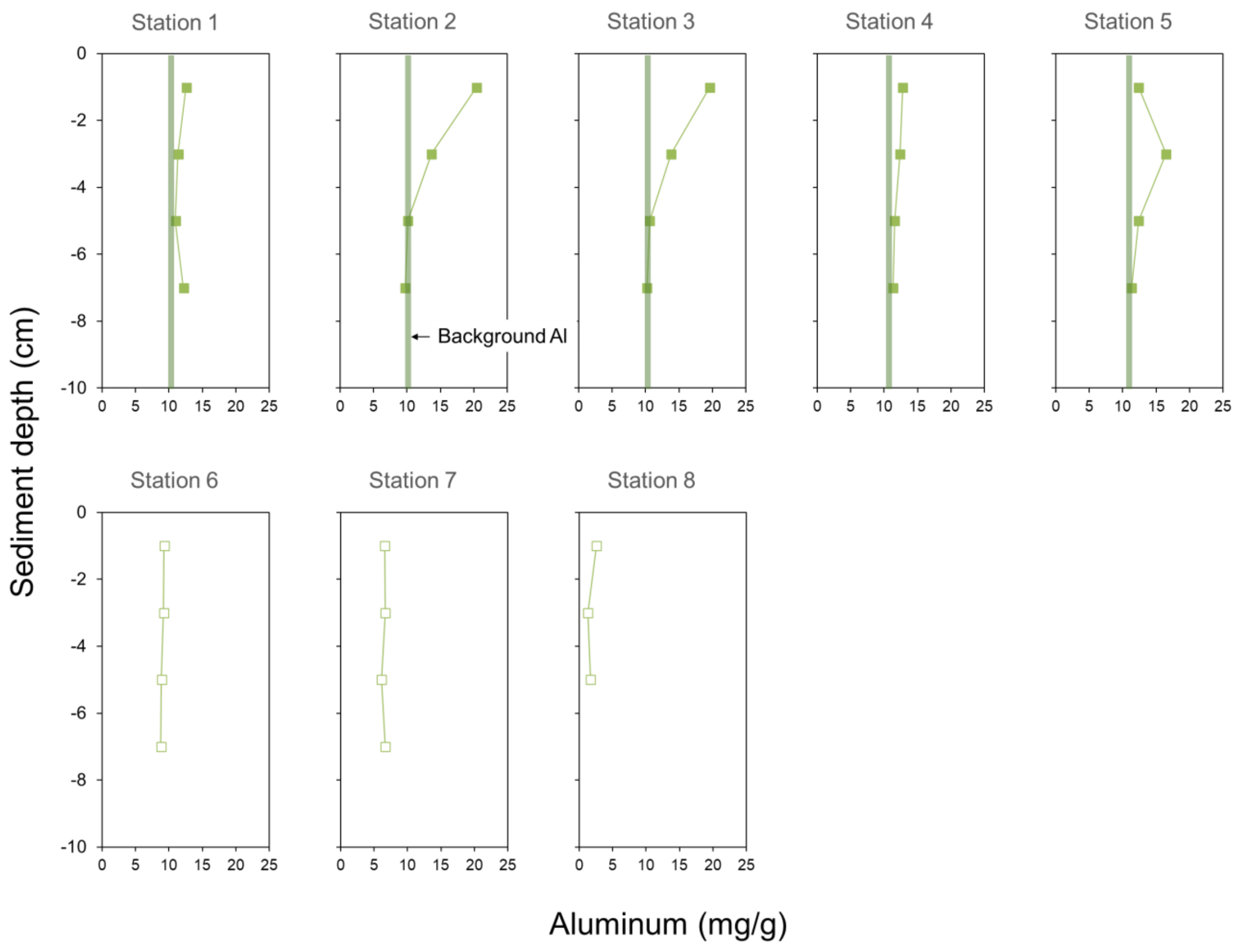


Figure 12. Vertical variations in sediment total aluminum. Station 1-5 were located within the alum application zone while stations 6-8 were located outside of this zone (see Figure 1).

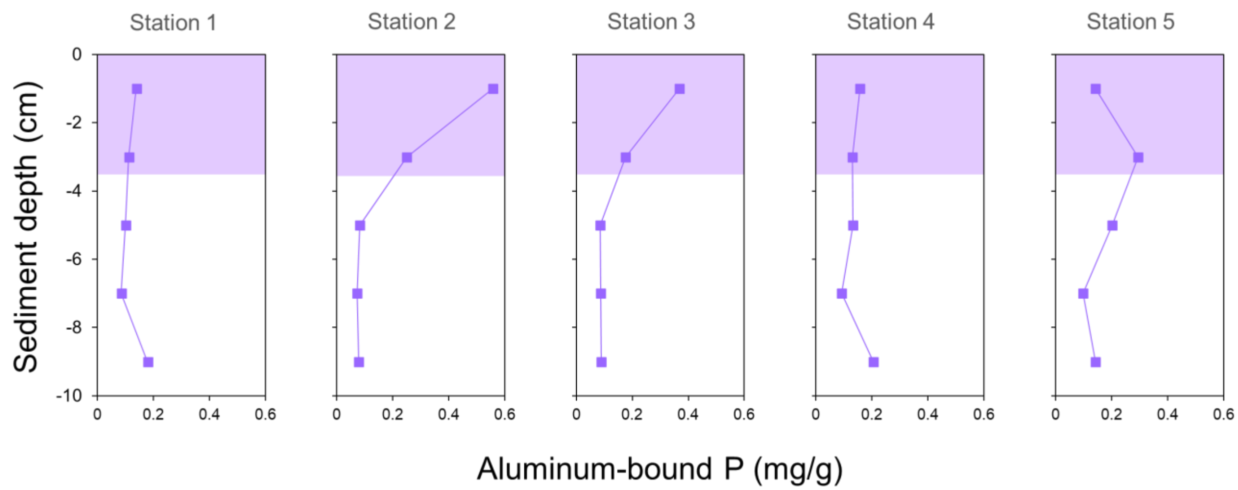


Figure 13. Vertical variations in sediment aluminum-bound P (i.e., P bound onto the Al floc). Purple shaded regions denote the probable location of the Al floc.

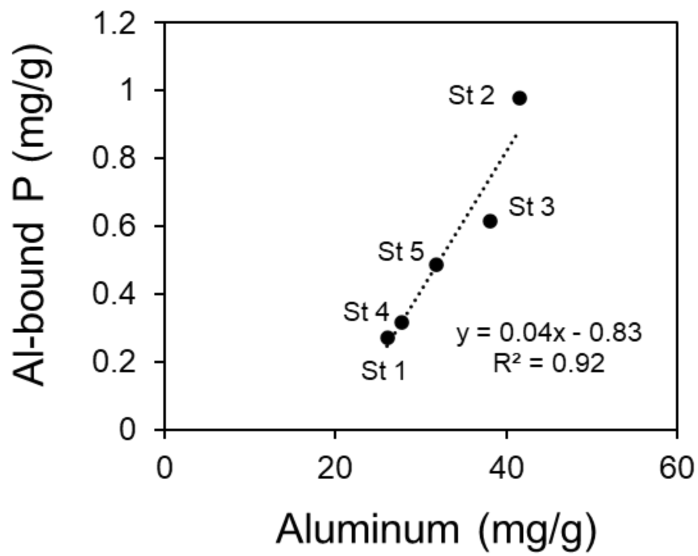


Figure 14. Regression relationships between aluminum and Al-bound P concentrations in the upper 4-cm section for various stations in East Balsam Lake.

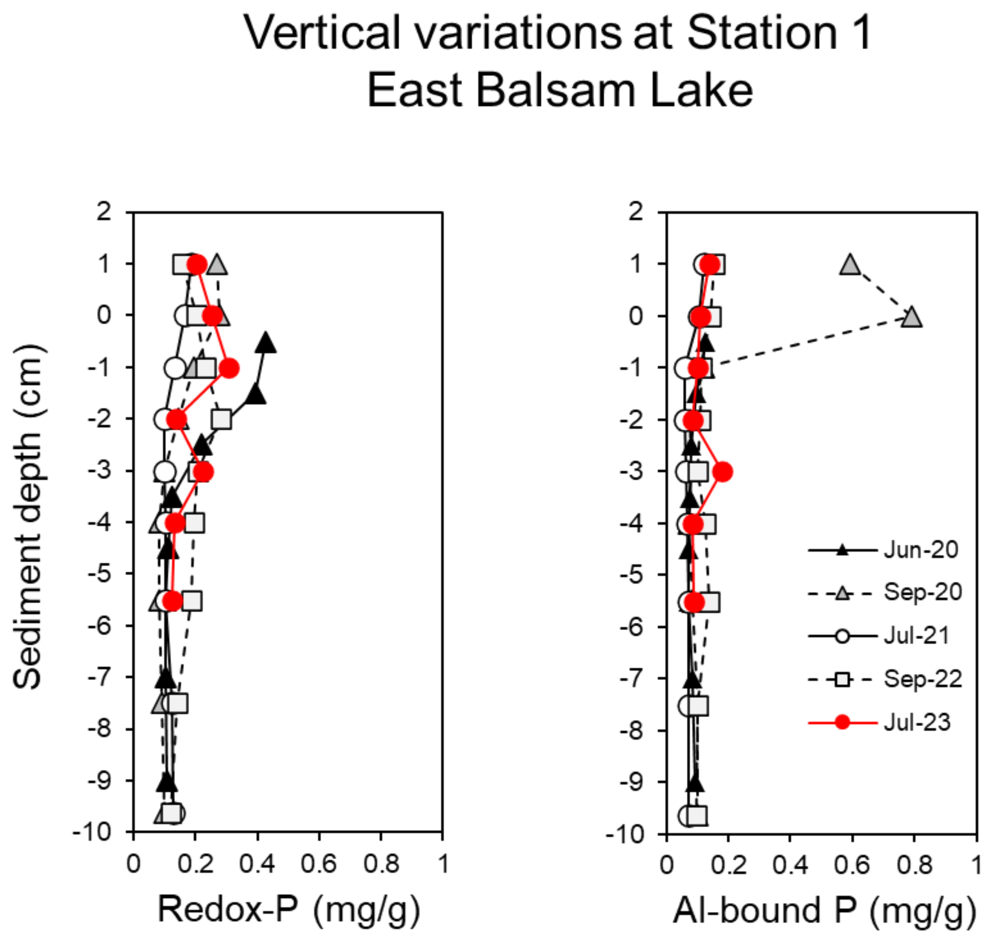


Figure 15. Vertical variations in sediment redox- (i.e., the sum of the loosely-bound P and iron-bound P sediment fractions) phosphorus (P) and aluminum (Al)-bound P concentrations for a sediment core collected from station 1 (Figure 1) in June 2020, September 2020, July 2021, September 2022, and July 2023. The sediment profile in June 2020 represents pre-treatment conditions while September 2020, July 2021, September 2022, and July 2023 represents post-alum treatment conditions.

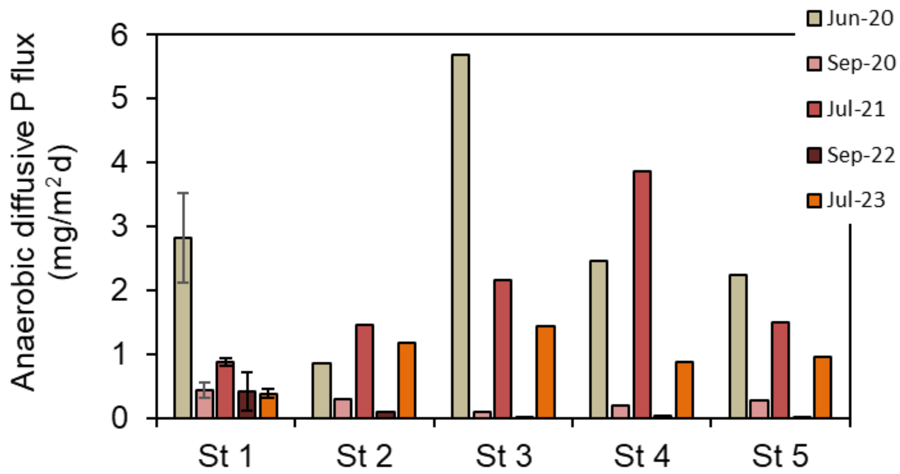


Figure 16. Mean anaerobic phosphorus (P) release rates at various stations before (i.e., June 2020) and after the alum applications. Horizontal lines represent ± 1 standard error.

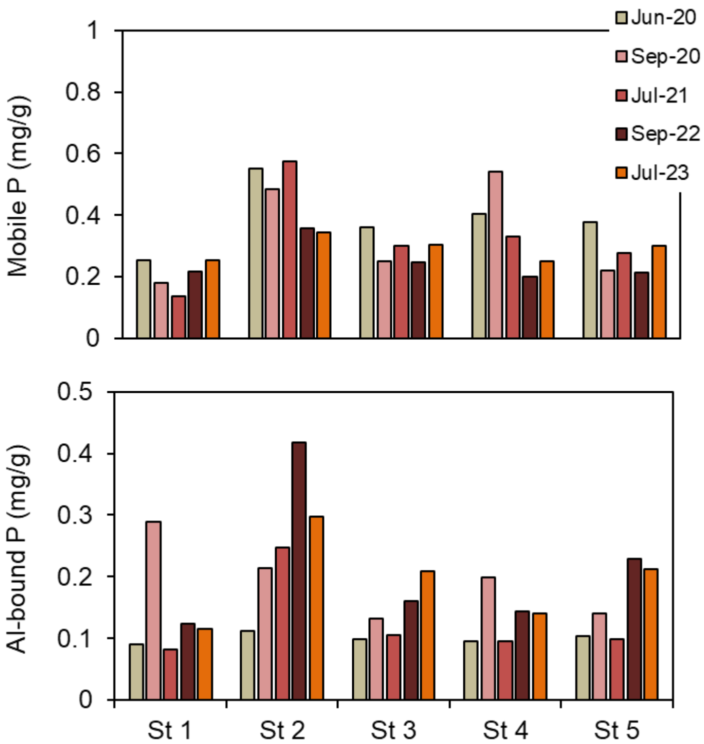


Figure 17. Changes in the concentration of redox-P (i.e., the sum of the loosely-bound and iron-bound P fractions, upper panel) and Al-bound P (lower panel) at various stations immediately before (June 2020) and after alum treatments.

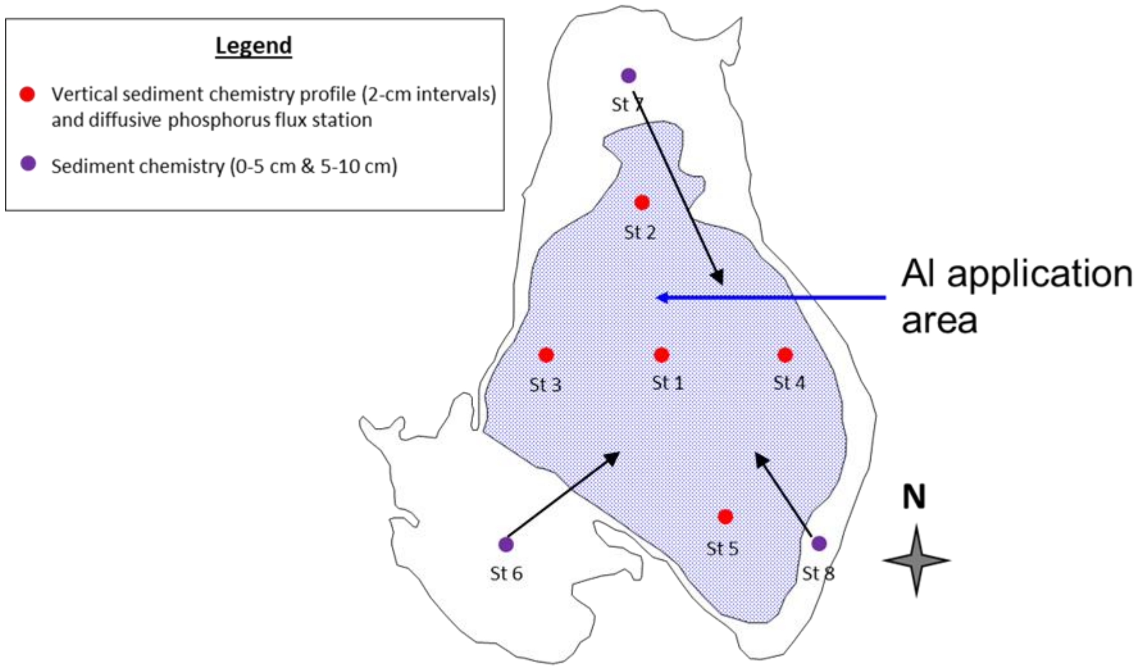


Figure 18. Suggested new locations for sediment stations 6, 7, and 8 to better monitor alum distribution during the 2024 and 2026 applications.