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PHOSPHORUS AND METAL CYCLING IN A DRINKING WATER SOURCE

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TRINITY COLLEGE

PHOSPHORUS AND METAL CYCLING IN A DRINKING WATER SOURCE

BY

AMANDA B. MODICA

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Phosphorus and Metal Cycling in a Drinking Water Source

BY

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Honors Thesis Committee

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Abstract

This project sought to investigate the cycling of phosphorus and metals in Lake Auburn, a drinking water source, specifically to analyze the impacts of an alum treatment on the lake for the purpose of decreasing concentrations of eutrophication-promoting phosphorus. The alum addition was performed in the summer of 2019 in two phases. Water samples were collected from the surface to the deepest point at five sites around the lake from February 2019 to November 2021. Data showed that the added alum slowly sank to the bottom of the lake. Total and dissolved metals data showed increased metals concentrations at sampling depths near the bottom of the lake under hypoxic conditions, as expected. For some sampling dates, corresponding increases in total phosphorus (TP) concentrations towards the bottom of the lake were also observed under low oxygen conditions. The trend was not the same for all sampling dates suggesting that external phosphorus loading may be the reason for larger TP concentrations closer to the surface in the water column. During the study, TP concentrations remained < 0.02 mg/L, even when the lake was exposed to hypoxic conditions.

Introduction

Phosphorus in Aquatic Systems

In bodies of fresh water such as lakes, rivers, and estuaries, anthropogenic eutrophication is of continued and increasing concern as it is associated with adverse effects on the freshwater ecosystem (Schindler et al. 2016; Huser and Pilgrim 2014). Eutrophication describes the presence of algal blooms and their related consequences, such as hypoxia and loss of biodiversity, on natural bodies of water as a result of the excessive enrichment of nutrients. The driving factors of eutrophication are thought to be associated with phosphorus (P) and nitrogen (N) (Huser & Pilgrim, 2014). Phosphorus is an essential element for plant growth, as well as various plant processes including, but not limited to, nucleic acid synthesis, respiration, photosynthesis, and glycolysis (Vance et al., 2003). However, P is often naturally found in a form that makes it unavailable for uptake by plants as it rapidly forms insoluble complexes with aluminum, iron, and other cations; thus, it is considered to be the primary limiting element for plant growth and development (Vance et al., 2003). While it is beneficial in small concentrations, anthropogenic inputs of P are thought to be a key influence in eutrophic outbreaks. Thus, P loading is often linked to excessive algal and cyanobacteria growth (i.e., algal blooms) and decay, and has negative impacts on water quality such as decreased sunlight and increased oxygen demand leading to hypoxic conditions. Large inputs of P into bodies of water are directly correlated with human population growth and the increased volumes of waste being produced as a result (Schindler et al., 2016). Similarly, greater human populations result in increased demand of land use for agricultural purposes, residential development, and the expansion of infrastructure. Aside from anthropogenic nutrient inputs, eutrophication is also accelerated by anthropogenic climate change (Seidel et al., 2021). Human-induced climate change has had such effects as increased global temperatures, thereby affecting the water column in many bodies of water (Seidel et al., 2021). Higher water temperatures are associated with consequences such as stratification, decline in dissolved oxygen, and acidification (Seidel et al., 2021; US Department of Commerce, n.d.).

Lakes can be classified into different trophic classes (Table 1) based on factors that affect the quality of water. Table 1 shows the trophic classes into their trophic state index (TSI), which condenses water quality parameters into a single numerical value for assessing the trophic state of a lake, as well as their associated levels of chlorophyll-a (Chla), total phosphorus (TP), and Secchi depth transparency (SD). These parameters are indicative of a lake's capability of supporting plant and animal life, which defines its level of productivity (Sheela et al., 2011). There are various methods for calculating TSI, one of which was outlined by the Florida Department of Environmental Protection (Paulic et al., 1996). The official Florida TSI Method calculates TSI based on the waterbody's limiting nutrient that controls plant growth, which is most often phosphorus in lakes. The method calculates separate component TSI values for the other parameters before averaging based on the limiting nutrient, allowing for the calculation of the overall TSI through empirical equations using natural logarithms.

Table 1. Criteria for classification of trophic status, as adapted from Sheela et al. (2011).

TSI	**Chla (µg/L)**	**TP (µg/L)**	**SD (m)**	**Trophic class**
< 30–40	0–2.6	0–12	> 8–4	Oligotrophic
40–50	2.6–7.3	12–24	4–2	Mesotrophic
50–70	7.3–56	24–96	2–0.5	Eutrophic
70–100+	56–155+	96–384+	0.5– < 0.25	Hypereutrophic

Generally speaking, oligotrophic lakes are associated with low productivity and are deep and transparent, with limited amounts of aquatic plant growth (Dodds et al., 1998). Lakes of this classification support cold water fish very well, effectively upholding adequate levels of dissolved oxygen in the cool water at the bottom of the lake (MiCorps, 2022). Eutrophic lakes, on the other hand, are considered to be highly productive, supporting an abundant amount of aquatic plant growth in the shallow and turbid lake environments (Government of New Brunswick, 2012). In deeper eutrophic lakes, the cool water at the bottom typically lacks dissolved oxygen and, therefore, these lakes can generally only support warm water fish (*Lake Water Quality*, n.d.). Mesotrophic lakes are those that fall between these two classifications and are associated with less extreme conditions (Government of New Brunswick, 2012), while hypereutrophic lakes exhibit extremely high productivity and are associated with unwanted algae and weed growth that can cause very limited visibility (Bogard et al., 2020).

External P Loading

External phosphorus loading occurs when P is carried by water through rivers or stream channels to lakes or reservoirs downstream in the watershed (Song et al., 2017). External P loading can occur via point sources, which are those discharged from any identifiable, singular source (e.g. pipe, drain, industry), or nonpoint sources, referring to those that are broadly distributed and disconnected (e.g. surface runoff, sediment erosion). Phosphorus is a vital nutrient used in agriculture, lawn fertilizers, and more. Contributing factors that affect external P loading include, but are not limited to, crop production, rainfall patterns, fertilizer application, septic system leaching, and combined stormwater/sewer overflows (Royer et al., 2006). Once P has entered the watershed, it undergoes an internal cycle within the ecological food web as it is utilized by aquatic plants and animals; however, its presence in high concentrations can also prompt excessive plant growth which can be harmful to ecosystem function. Sediments often contain high amounts of organic or particulate P, which can be released via decomposition processes. When there are excessive external P loads, inorganic P can also become adsorbed to sediment either chemically or via deposition, leading to an accumulation of P over time in the lake sediment (Song et al., 2017). A previous study found that up to 96% of total P input to the watersheds under study were a result of sources of external P loading (Song et al., 2017).

Metal Oxides in Lake Sediments as P Sink and Internal P Loading

Naturally-occurring minerals in lake sediment, such as aluminum (Al), manganese (Mn) and iron (Fe) oxides, can provide sorption sites for phosphorus (Slomp et al., 1996). These mineral oxides may, act as P sinks in lake sediment, effectively "trapping" P and decreasing free P concentrations in the water column. Facultative anaerobes can survive with or without oxygen, although they prefer aerobic conditions; under anoxic or near anoxic conditions, these microbes may use transition metals in minerals such as Mn and Fe as electron acceptors during respiration by reducing and dissolving them, thereby releasing P bound to them (Stieglmeier et al., 2009). Aluminum oxides, however, are not subject to these reductive dissolution processes that release bound P. The Environmental Protection Agency (EPA) has put forth guidelines for secondary drinking water standards limits of 50-200 μg Al /L, 300 μg Fe /L, and 50 μg Mn /L (US EPA, 2015b).

Internal phosphorus loading occurs from sources already within the water body, such as plants and animals that die and sink to the bottom, previous algal blooms that accumulate at the bottom, or P present in sediment. P-enriched sediment can cause problems in the water column over time as the sediment-bound P can be released. Low dissolved oxygen concentrations, for instance as a result of lake stratification, can create hypoxic conditions in the sediment, resulting in the release of chemically-bound P (Sulu-Gambari et al., 2018). Decomposition processes involve the breakdown of organic matter and result in inorganic and/or dissolved P being released into the water column as well (Song et al., 2017). In lakes that become eutrophic, internal P loading can become an even bigger source of P than external loading, particularly in watersheds that are well-protected.

It was determined by Kopáček et al. (2005) that the adsorption capacity of P in sediments was primarily associated with $Fe(OH)_3$ and $Al(OH)_3$. Thus, analysis of P, Al, and Fe concentrations in sediment can be an operational indicator of whether P would be released from lake sediment under hypolimnetic anoxic conditions (Kopáček et al., 2005). The results of their study revealed that internal P loading that occurred under anoxic conditions was associated with molar Al:Fe ratios < 3 and molar Al:Fe-bound P ratios < 25 (Kopáček et al., 2005).

Lake Stratification

Lake stratification results from density differences in the water column, which are typically a function of temperature and dissolved substances (Boehrer & Schultze, 2008). Thermal stratification may occur during the summer months if a lake is sufficiently deep, resulting in water near and at the surface being significantly warmer and less dense than deeper waters which can remain at near 4 °C. The formation of a thermocline occurs, which is a physical separation between the top and bottom layers due to differences in temperature and density. This stratification is associated with a marked decline in dissolved oxygen (DO) concentrations below it as a result of decomposition processes which exert an oxygen demand. If the oxygen demand is high and stratification persist for an extended period of time, the bottoem of the lake may become hypoxic, or even anoxic in extreme conditions.

Winter weather causes surface water temperatures to be coldest and the lake may freeze over, while the temperature of water beneath the surface remains relatively constant. Winter stratification of the lake is less likely to result in hypolimnetic hypoxic conditions as the oxygen demand in the winter tends to be much lower. Surface cooling can force the vertical circulation, or turnover, of water, thereby removing gradients of water properties. This typically occurs during autumn and spring when temperatures are less extreme, and the water is associated with more uniform concentrations of DO throughout the vertical water column as a result of the mixing.

Study Site

Lake Auburn is a natural lake and reservoir located in the Lake Auburn Watershed in Auburn, Maine, USA, which supplies drinking water to approximately 45,000 residents in the greater Lewiston-Auburn surrounding communities. The lake covers a total area of 2,260 acres (910 ha) and has a maximum depth of 118 feet, or approximately 36 meters (*Maine Dept of Inland Fisheries and Wildlife*, 1984). The lake is closed off to most recreational activities and most of the land surrounding the lake has been purchased by the water district over time (*Maine Dept of Inland Fisheries and Wildlife*, 1984), making the Lake Auburn Watershed highly protected with very few developed areas in the surrounding land (Figure 1). Its high water quality, cold and clear waters, low turbidity, and relatively low concentrations of nutrients make Lake Auburn a historically oligotrophic lake. Due to its watershed protection, Lake Auburn is one of only about 60 surface water sources in the United States permitted by the EPA to supply water without filtration. Thus, it is of utmost importance to monitor phosphorus in the lake to ensure the water quality is not diminished in order to maintain the EPA filtration waiver status.

However, in 2011 and 2012, excessive P concentrations caused the growth of algal blooms, which resulted in severely diminished water quality. If maintained, these conditions put the lake at risk for internal P loading, compromising public health and resulting in the inevitable withdrawal of the EPA filtration waiver (Amirbahman, n.d.). Record low dissolved oxygen content was observed at lower depths during this time as a result of the large algal blooms that accumulated and decomposed at the base of the lake, in addition to the fact that warm surface waters caused lake stratification which did not allow oxygen to be replenished at the bottom of the lake (*Lake Auburn*, n.d.). This resulted in the death of hundreds of fish in 2012, and the resulting water quality issue prompted the Lake Auburn Watershed Protection Commission to obtain a permit from the Maine Department of Environmental Protection (DEP) for permission to apply an algaecide to the lake in the future if necessary (*Alum Treatment Press Release – Lake Auburn Watershed Protection Commission*, 2019). According to previous research, Lake Auburn sediment exhibited molar Al:Fe ratios between 0.2 and 1.7 and molar Al:Fe-bound P ratios between 2.0 and 14.5, indicating a risk for internal P loading (Doolittle et al., 2018). Figure 2 shows historic average total phosphorus concentrations at the deepest sampling site of the lake.

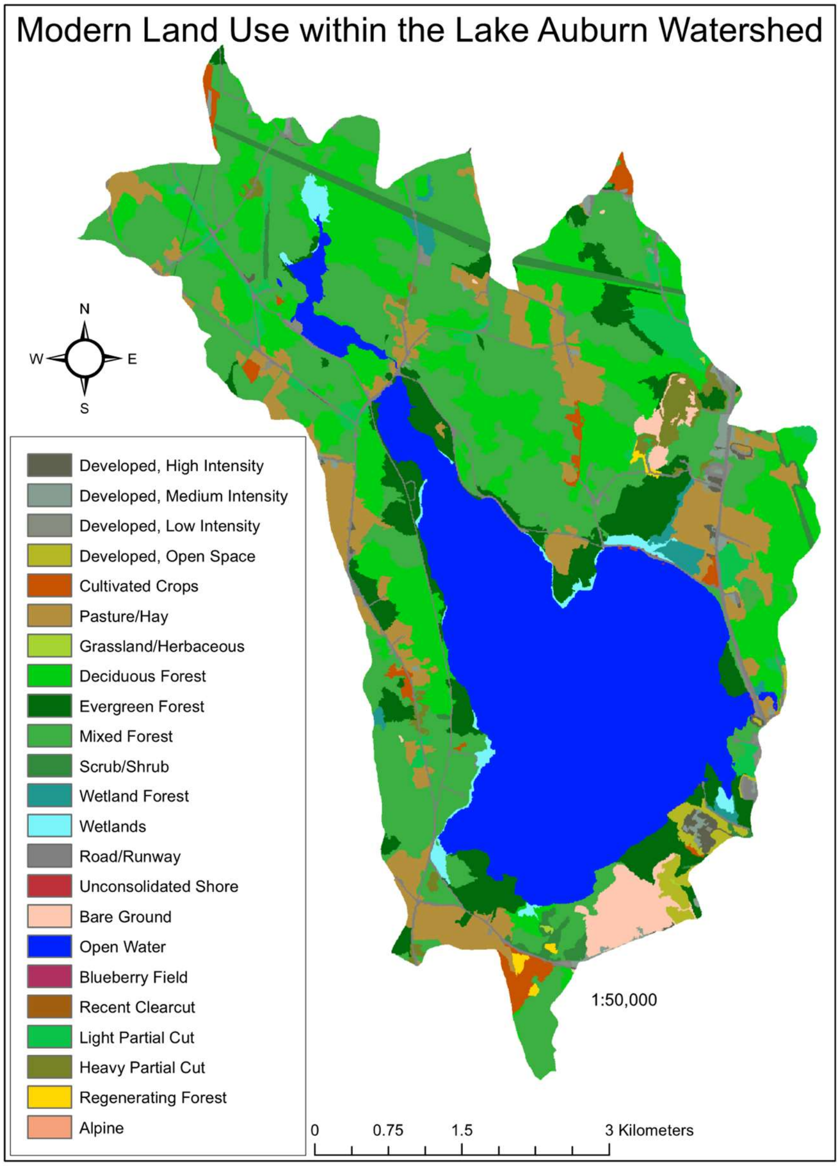

Figure 1. Land use map of areas surrounding Lake Auburn (Hilton 2016)

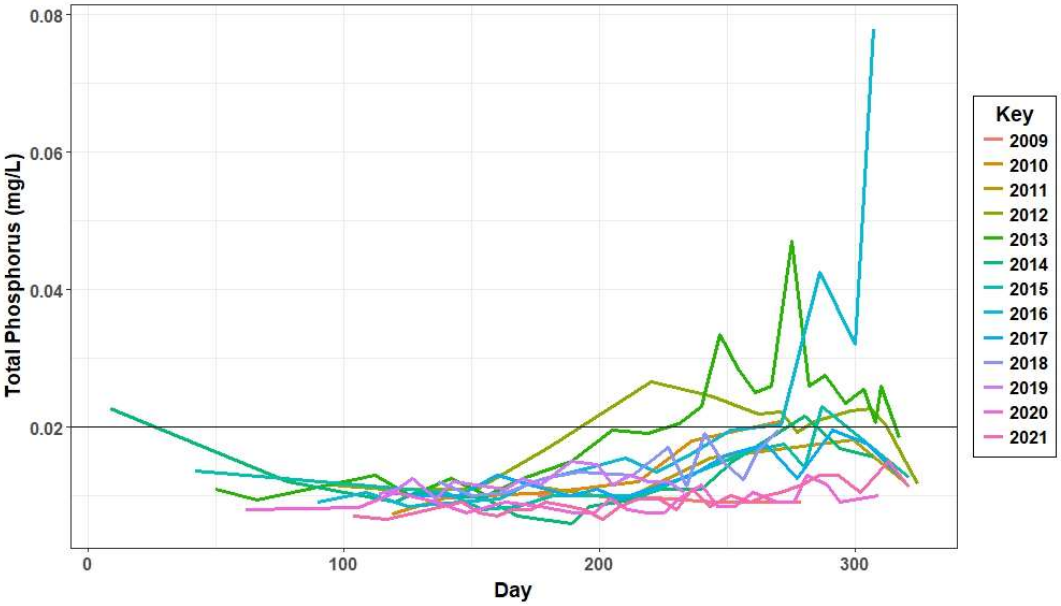

Figure 2. Average total phosphorus concentrations at the deepest sampling site.

In September of 2018, the algaecide was applied to combat more algal blooms that had formed, but customers supplied with drinking water from Lake Auburn complained about the resulting poor taste and odor. In December of 2018, Lake Auburn Watershed Protection Committee management staff met with consultants and state officials, who made a plan to perform an alum treatment on Lake Auburn in 2019 in order to improve drinking water quality and received a permit from the DEP in May 2019 to do so (*Alum Treatment Press Release – Lake Auburn Watershed Protection Commission*, 2019). Their goal was to facilitate the binding of free, algae-producing P to the alum, causing it to sink to the bottom of the lake. In addition, some of the P in lake sediments may also bind to the alum, avoiding its release into the water column. Aluminum sulfate ($Al_2(SO_4)_3$) and sodium aluminate ($NaAl(OH)_4$) were added to Lake Auburn in two phases, with the first involving a one-time dose of 2 mg/L over three-quarters of the lake between July 10th and August 2nd, 2019. The treatment was then halted to analyze data (Rice, 2019), and a second treatment was applied between October 3rd and October 23rd, 2019.

Materials and Methods

Sample Collection

Water samples were collected at five different sites located around Lake Auburn – sites 8, 12, 29, 30 and 32 – to ensure spatial representation of the water quality (Figure 3). At each site, a Kemmerer bottle was used to collect samples at the surface and then at every four meters until the bottom. An additional "core" water sample was taken from the surface to the top of the thermocline at each site. Samples were then transferred to 500 mL Teflon bottles. The temperature and dissolved oxygen concentrations were collected in one-meter increments from the surface to the bottom of each site using a YSI EXO2 Multiparameter Sonde. Fifteen milliliters of each sample were filtered on site using Pall Corporation 0.2 or 0.45 µm Acrodisc® Syringe Filters for dissolved metals. The remainder of the sample was acidified with concentrated sulfuric acid and stored at 4˚C. Metal and total phosphorus concentrations were analyzed for water samples at site 8 – the deepest sampling location – over the course of 12 sampling dates between 2019-2021 in order to investigate the impact of the alum treatment applied to Lake Auburn in the summer of 2019.

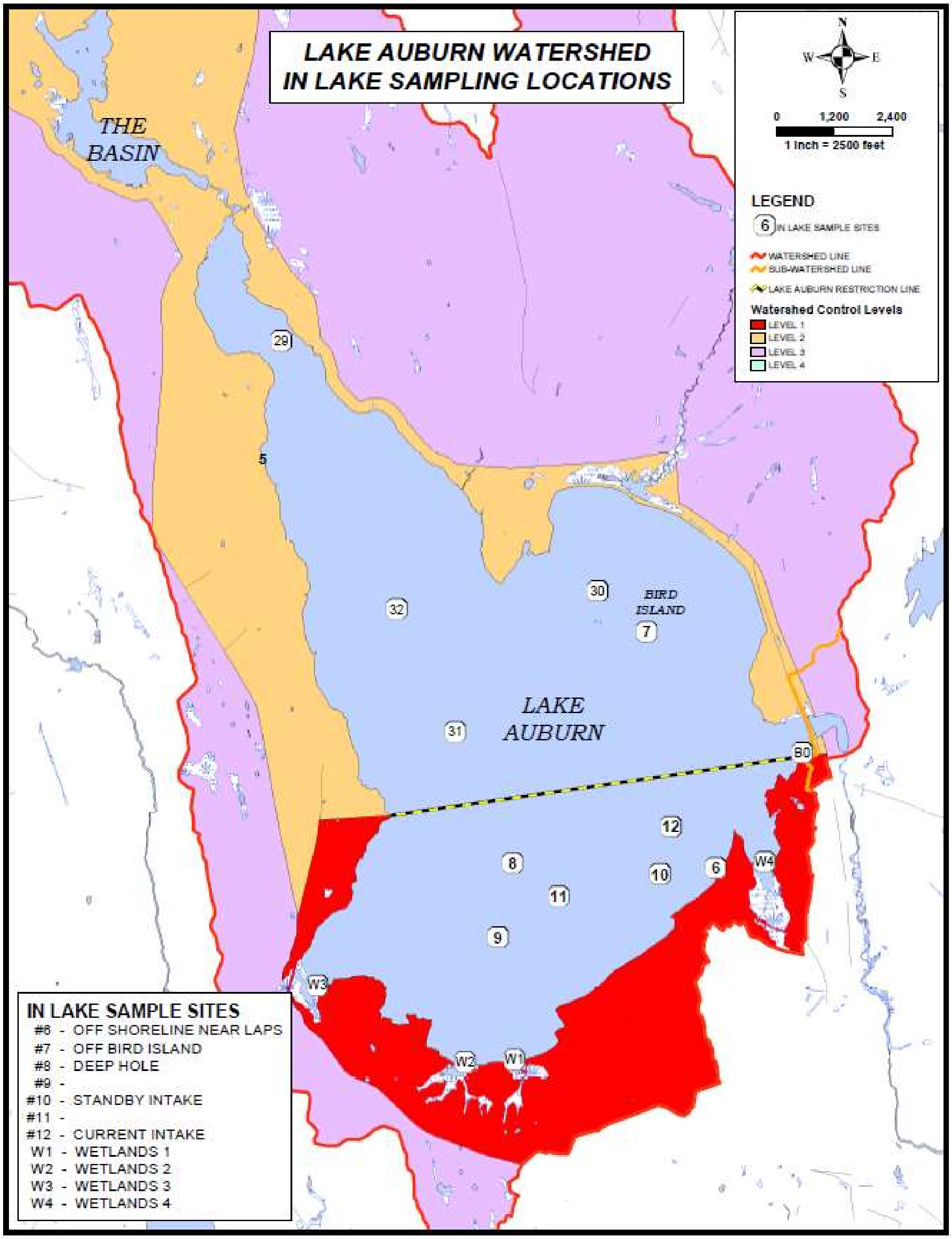

Figure 3. Lake Auburn sampling sites. Samples were collected at sites 8, 12, 29, 30 and 32.

Total Phosphorus Analysis

The total phosphorus concentration of each sample was measured following EPA Method 365.3 (O'Dell, 1993). Fifty milliliters of sample or standard were transferred to glass 125 mL

Erlenmeyer acid-washed flasks with caps; 1 mL of 11 N sulfuric acid and 0.4 g of ammonium persulfate were added and the samples were digested in a Fisherbrand™ SterilElite™ Tabletop Autoclave at 121°C for 30 minutes. Once cooled to room temperature, 4 mL of ammonium molybdate-antimony potassium tartrate solution and 2 mL of ascorbic acid solution were added to the samples. After 5 minutes, the absorbance at 650 nm was measured in a 10 cm cell using a Thermo Scientific GENESYS™ UV-Visible Light Spectrophotometer. The method detection limit was approximately 2 μg/L.

Metals Analysis

A portion of each sample was filtered in the field and acidified with 2% by volume trace metal grade nitric acid for dissolved metals analysis. Total metal concentrations of Mn, Al, and Fe were determined following Standard Method 3030 E. Nitric Acid Digestion (Baird et al., 2017). Ten milliliters of sample were transferred to digestion tubes and 0.5 mL of Fisher Scientific concentrated trace metal grade nitric acid was added; samples were then digested for 2.5 hours at 90˚C using an Environmental Express HotBlock®. Metal concentrations of filtered or digested samples were measured on a Perkin Elmer NexIon ICP-MS.

Results and Discussion

Analysis of the metal and phosphorus concentrations as related to temperature and dissolved oxygen concentrations on each sampling date elucidated trends of the cycling of phosphorus and metals within the vertical water column following the 2019 alum addition. The lake was stratified when the first alum addition was performed and a thermocline was present just above 10 m depth, as indicated by the rapid drop in temperature and DO content (Figure 3 d, e).

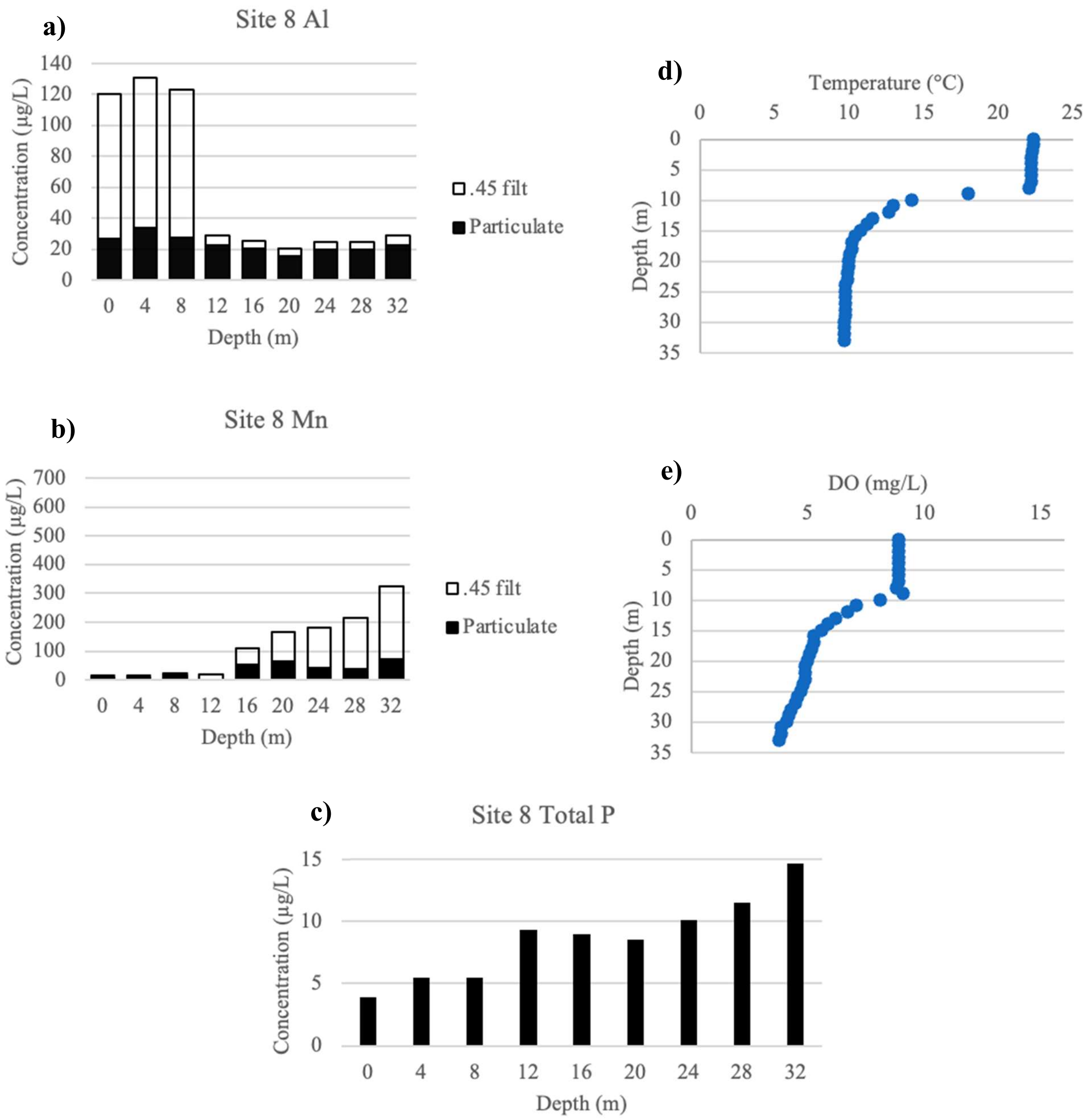

Figure 3. Site 8 data from September 3, 2019 sampling showing a) Al concentrations, b) Mn concentrations, c) TP concentrations, d) temperature of vertical water column, and e) dissolved oxygen concentrations throughout water column.

When DO levels are at or below 2-3 mg/L in the hypolimnion (US EPA, 2015a), the oxygen for microbial respiration is limited, which leads the microbes to use transition metals from metal oxides present in the lake sediment as electron acceptors (Nealson & Saffarini, 1994). This reductive dissolution process causes the metal oxide to be dissolved and the free transition metal to be released into the water. This also triggers the release of any P bound to the metal oxide, which is the cause for the increased concentrations of P at the bottom of the lake, below 20 m, for this sampling date. Mn and Al concentrations were below EPA water quality standards (introduced in section 1.3), while TP concentrations in the hypolimnion exceeded 12 µg/L, the limit for TP in oligotrophic lakes as outlined in Table 1.

In October 2019, DO content exhibited a further decrease, with hypoxic concerns below the thermocline (Figure 4 e). Although the second phase of the alum treatment was being performed at the time of this sampling – hence why Al concentrations are still highest above the thermocline – Al from the first treatment had time to form solid aluminum oxides that sink to the bottom of the lake, so Al concentrations throughout the vertical water column were more consistent compared to the previous month. Dissolved Mn was found in even higher concentrations below 12 m compared to the previous month (Figure 4 b), as were TP concentrations from 24 m and lower (Figure 4 e). These results suggest internal P loading due to the hypoxic conditions in the hypolimnion. However, even at these depths, P concentrations were below the limit for oligotrophic lakes (12 µg/L), and were considerably lower than they were in September 2019, suggesting that the alum addition successfully regulated P concentrations over the course of two months.

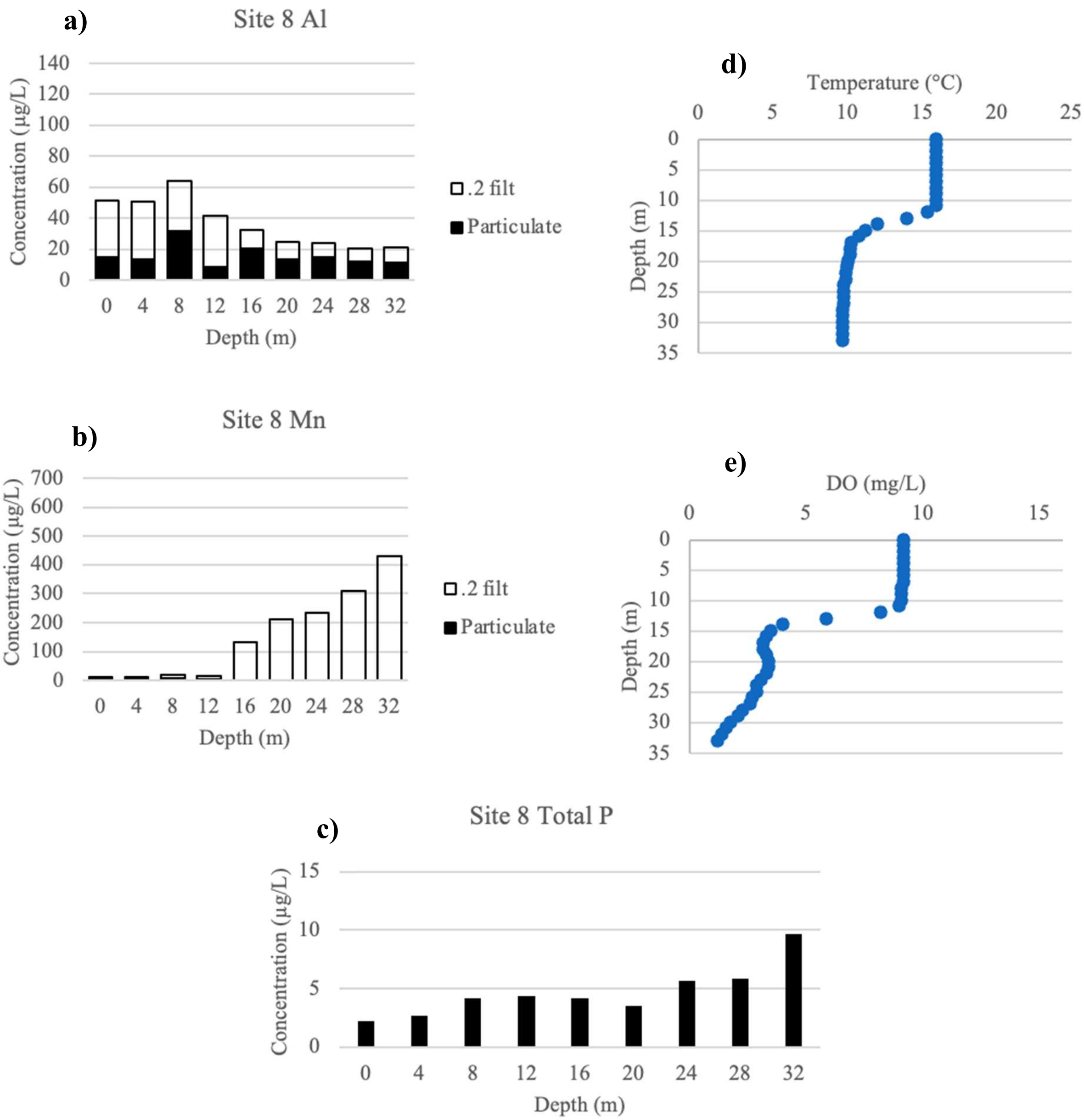

Figure 4. Site 8 data from October 8, 2019 sampling showing a) Al concentrations, b) Mn concentrations, c) TP concentrations, d) temperature of vertical water column, and e) dissolved oxygen concentrations throughout water column.

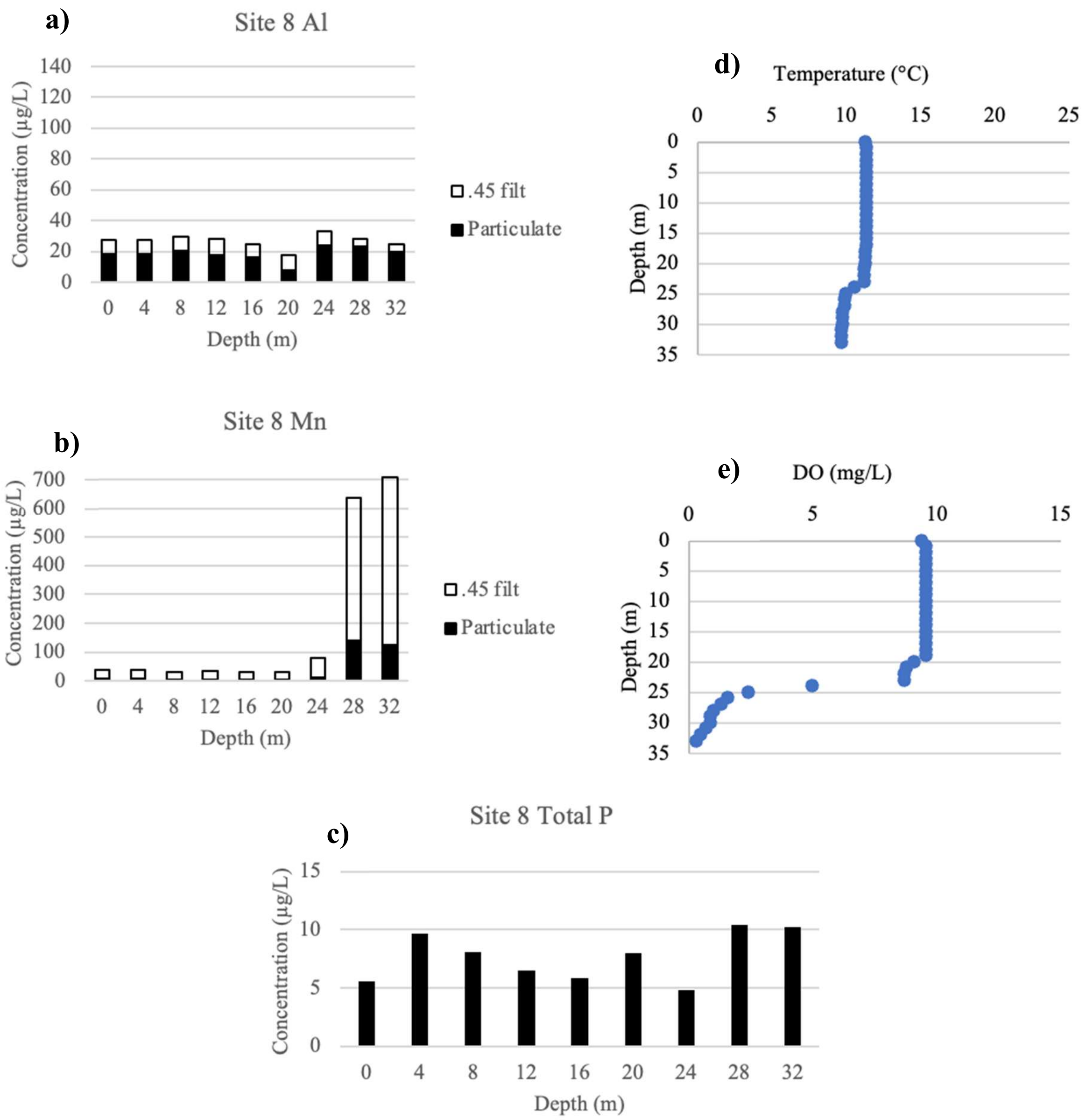

Figure 5. Site 8 data from November 7, 2019 sampling showing a) Al concentrations, b) Mn concentrations, c) TP concentrations, d) temperature of vertical water column, and e) dissolved oxygen concentrations throughout water column.

The November 7, 2019 sampling date was right before the lake turned over, so while temperature was relatively equalized throughout the vertical water column (Figure 5 d), DO levels were ~ 0.5 mg/L below 25 m (Figure 5 e). Thus, dissolved metal concentrations below 24 m were extremely high, with concentrations around 700 µg/L (Figure 5 b). The drastically increased concentrations of dissolved Mn below 24 m directly correlated with the near-zero levels of DO, indicating the use of transition metals as electron acceptors for microbial respiration due to low oxygen. There was no clear trend observed in TP concentrations throughout the vertical water column, and while concentrations remained below the water quality standard of 12 µg/L, there was an overall increase in TP compared to October 2019 data, which suggests potential external sources of P (Figure 5 e).

The March 2, 2020 sampling date occurred after the lake mixed and under ice, as indicated by the relatively equalized TP and metal concentrations (Figures 6 a, b, c). All reported concentrations were well below water quality standards. Winter temperatures caused the lake to be slightly colder at the surface than towards the bottom (Figure 6 d) and the water was very well oxygenated throughout the entire vertical water column (Figure 6 e), so there were no concerns for hypoxia. There were no more winter samples taken as the ice was not stable enough for sampling in the winter of 2021 or 2022.

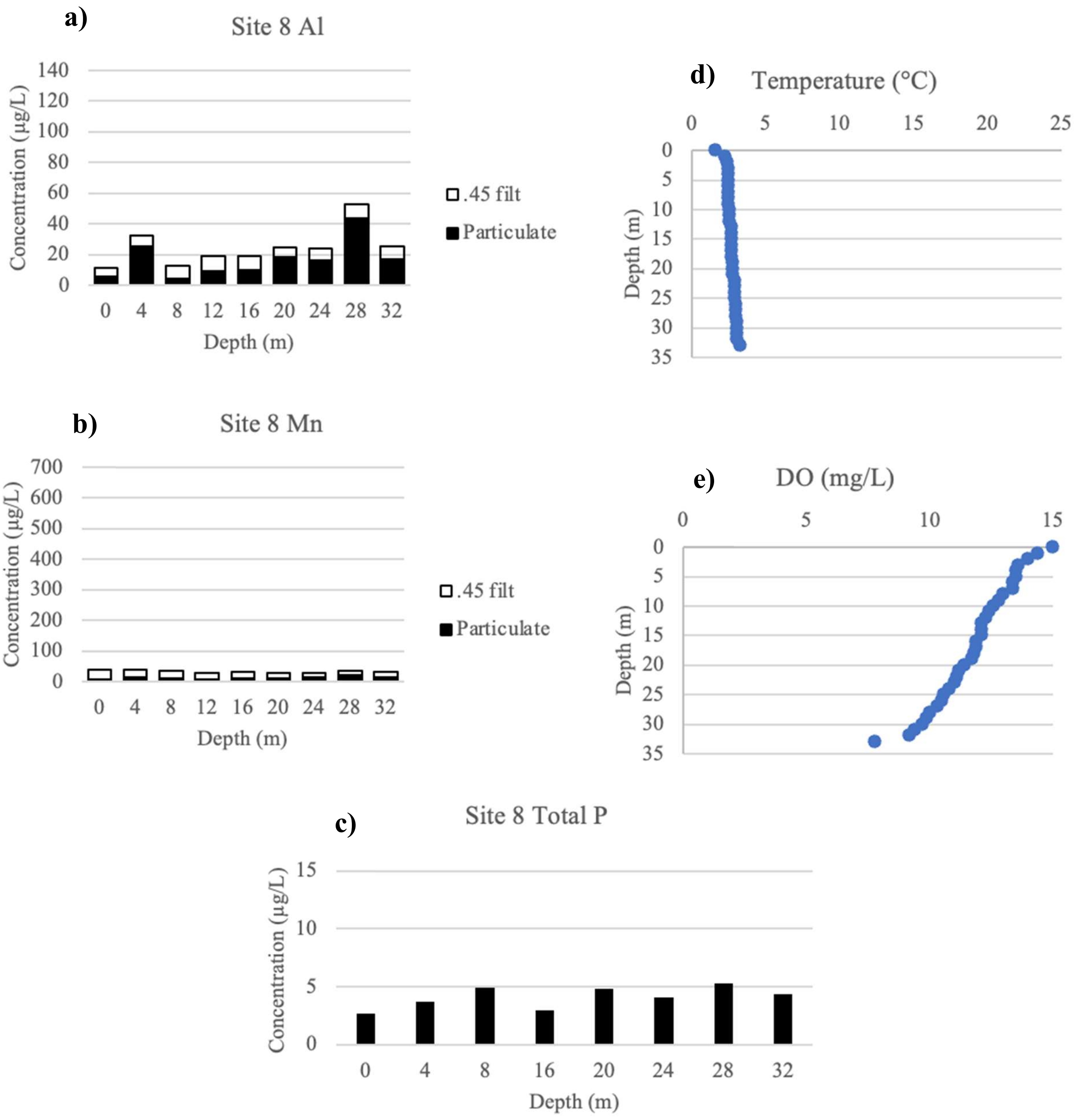

Figure 6. Site 8 data from March 2, 2020 sampling showing a) Al concentrations, b) Mn concentrations, c) TP concentrations, d) temperature of vertical water column, and e) dissolved oxygen concentrations throughout water column.

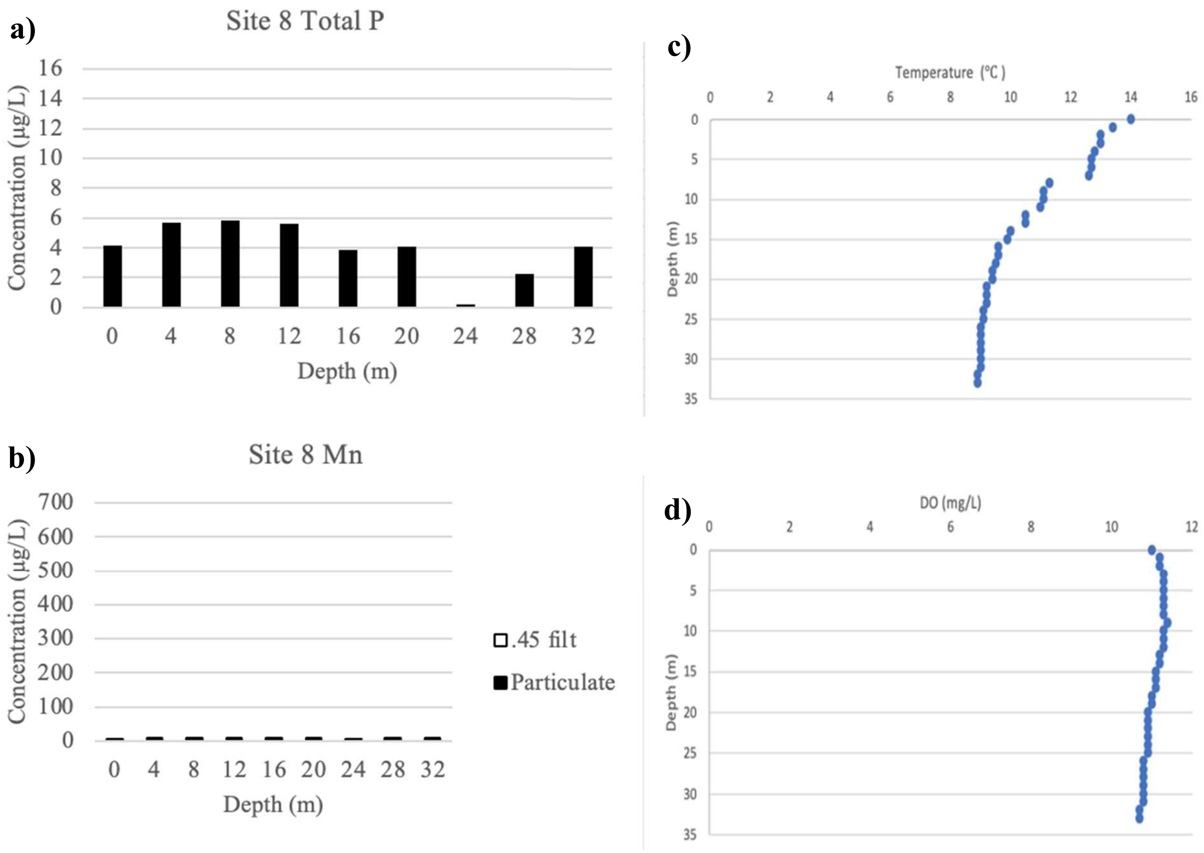

Figure 7. Site 8 data from May 17, 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

After the March 2, 2020 sampling, Al concentrations were below the detection limit and are no longer shown. In May 2021, the development of a thermocline can be observed (Figure 3 c), but the water column remained well oxygenated (Figure 3 d). For this reason, Mn concentrations were very low (Figure 7 b) and TP levels remained below 12 µg/L (Figure 7 a).

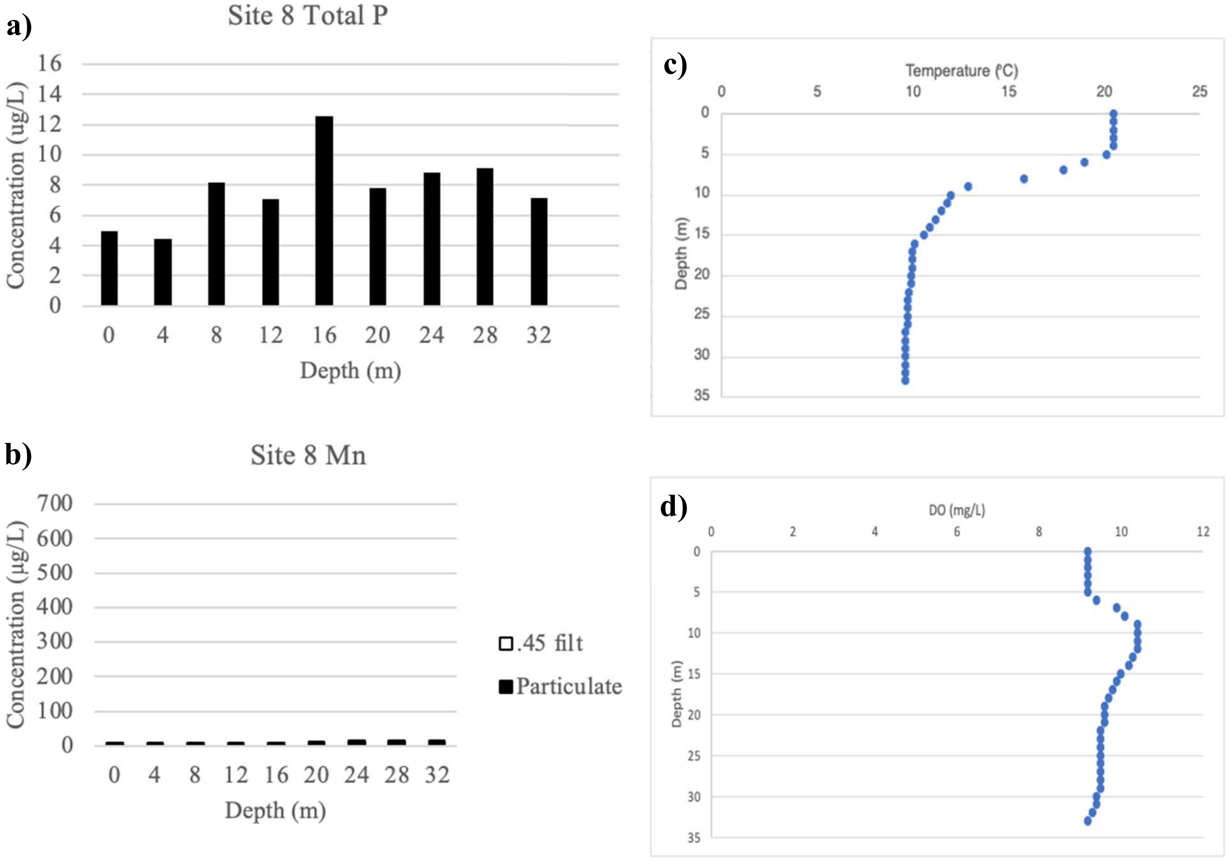

Figure 8. Site 8 data from June 15, 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

In June, temperature data indicated a thermocline right below 5 m (Figure 8 c), where this drastic decrease in temperature gave a slight increase in DO (Figure 8 d) given that cold water can hold more DO than warmer waters (*Dissolved Oxygen and Water | U.S. Geological Survey*, n.d.). However, oxygen content was not a concern as there were high concentrations throughout the vertical water column. While metal levels were nominal (Figure 8 b), TP concentrations were relatively high, particularly at 16 m where TP exceeded 12 µg/L (Figure 8 a). This may be explained by the presence of algae in the sample if it had moved down in the water column while not photosynthesizing, or perhaps indicative of potential sources of external P loading.

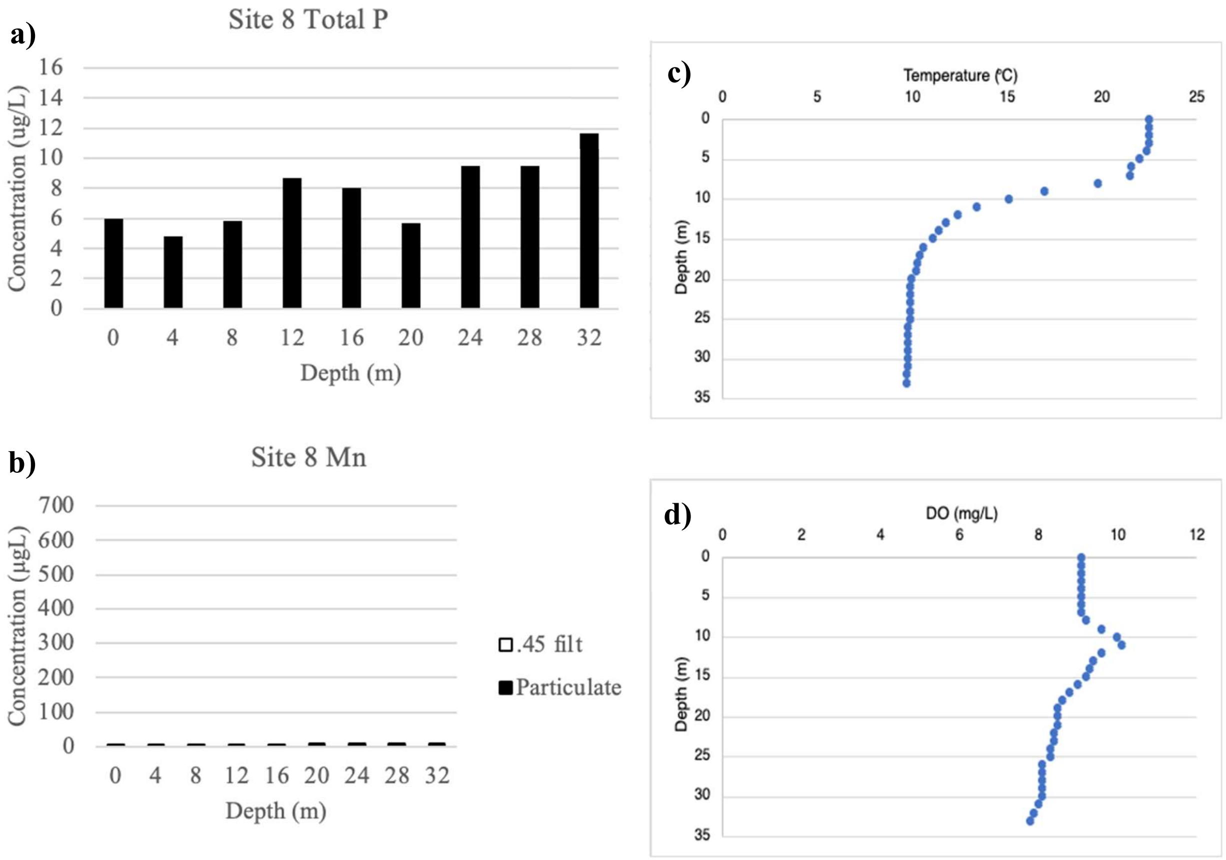

Figure 9. Site 8 data from July 13, 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

In July 2021, there continued to be an observed decrease in DO levels toward the bottom of the lake (Figure 9 d), but the lake remains well oxygenated throughout and above hypoxic levels of 2-3 mg/L. Metal concentrations remained very small and below EPA standards (Figure 9 b), while TP concentrations were elevated throughout and appeared to increase below 20 m (Figure 9 a). Despite this increase, TP concentrations remain below 12 µg/L and there is no indication of a concern for internal P loading as a result of hypoxic conditions, so this data likely suggests an external source of P.

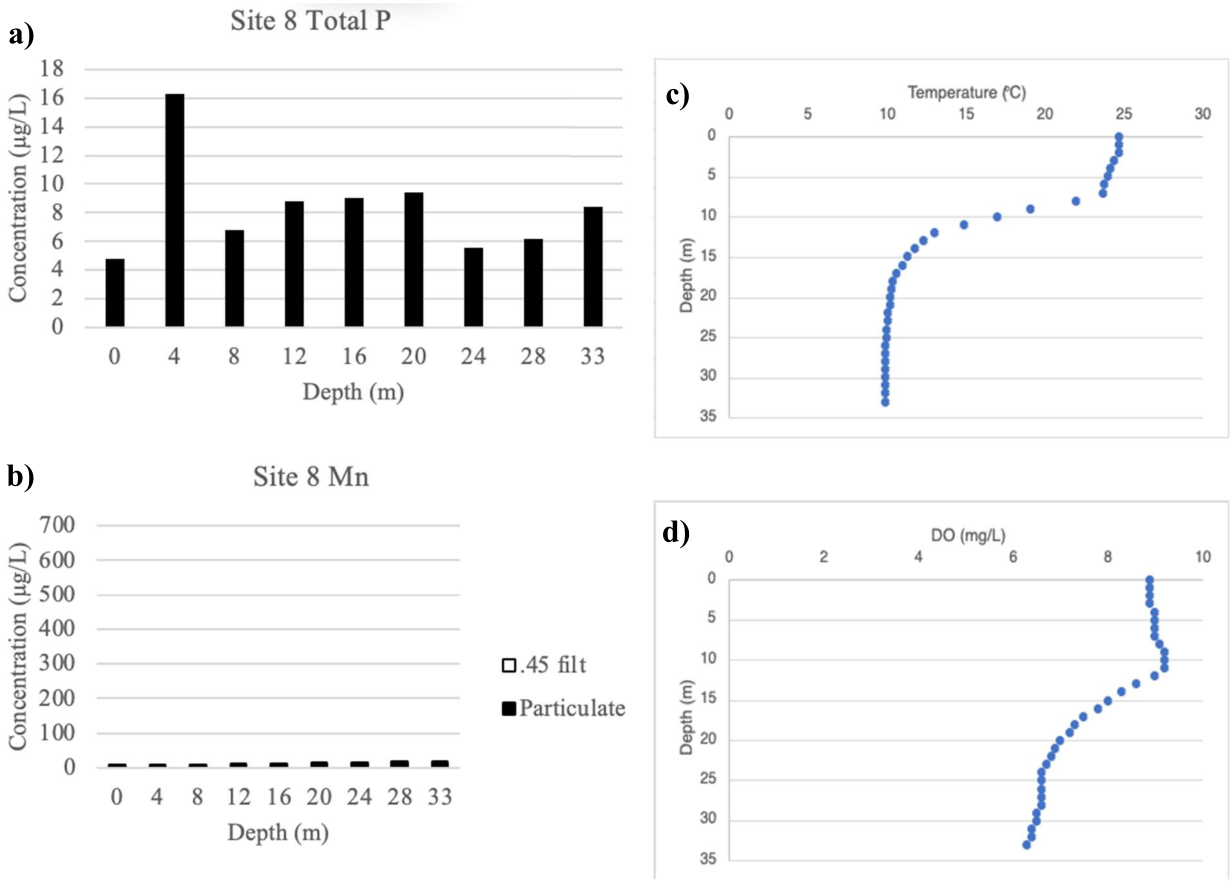

Figure 10. Site 8 data from August 13, 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

In August 2021, DO concentrations continued to decline as the depth increased (Figure 10 d), but remained above 6 mg/L. Metal concentrations remained low (Figure 10 b), and while TP concentrations are relatively low throughout (< 12 µg/L), TP is greatly elevated at 4 m with a concentration of approximately 16 µg/L, which can likely be attributed to algae caught in the water sample taken at 4 m (Figure 10 a).

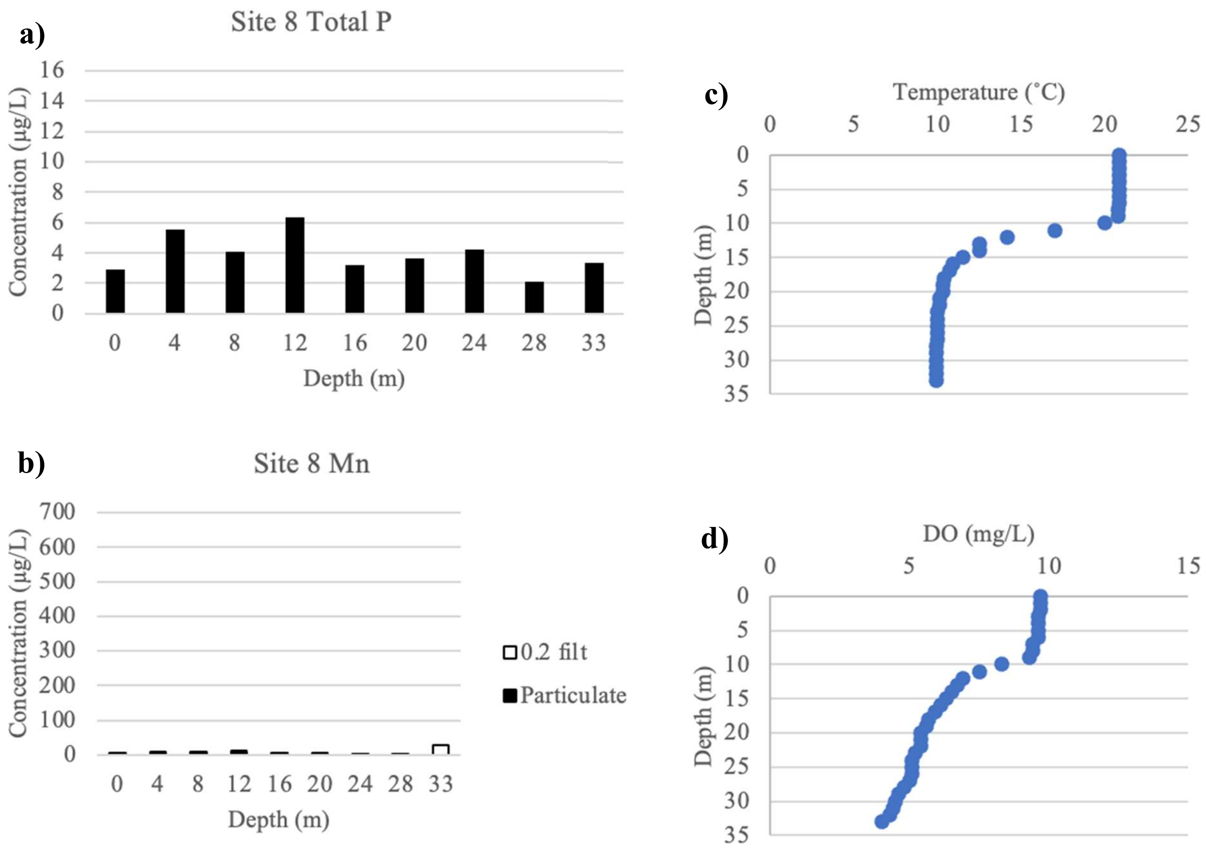

Figure 11. Site 8 data from September 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

September 2021 data demonstrated declining levels of DO, which began to reach levels of hypoxic concern (2 to 3 mg/L DO) at the bottom of the lake below approximately 20 m (Figure 11 d), while the thermocline continued to move deeper (Figure 11 c). Metal concentrations remained minute (Figure 11 b), and there was an observed decrease in overall TP content from August 2021, with TP below 12 µg/L at all depths, suggesting the adsorption of P to metal oxides in the sediment.

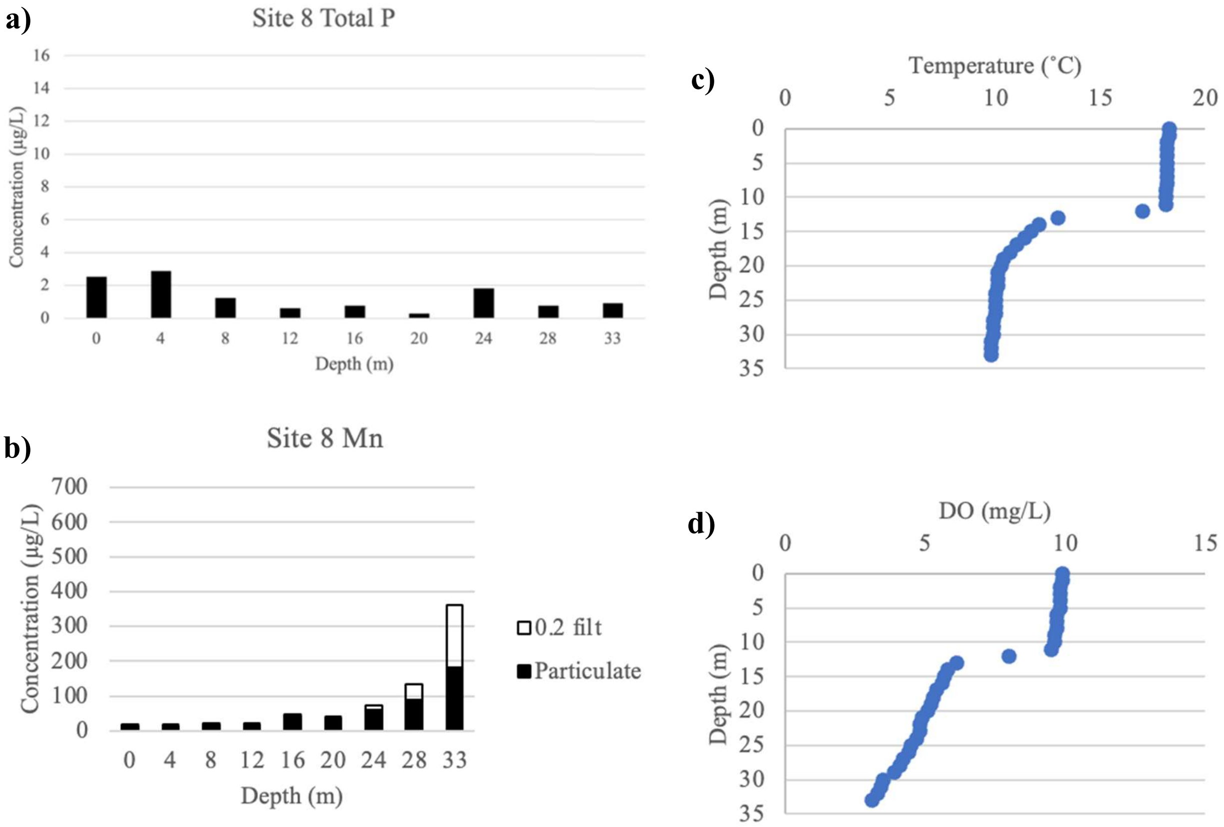

Figure 12. Site 8 data from October 8, 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

On October 8, 2021, metal concentrations began to increase for samples below 20 m (Figure 12 b), which can be attributed to the low concentrations of DO measured at these depths (Figure 12 d). Mn concentrations on this date were high below 20 m. TP concentrations were minimal throughout the vertical water column and well below the 12 µg/L limit for oligotrophic lakes (Figure 12 a)

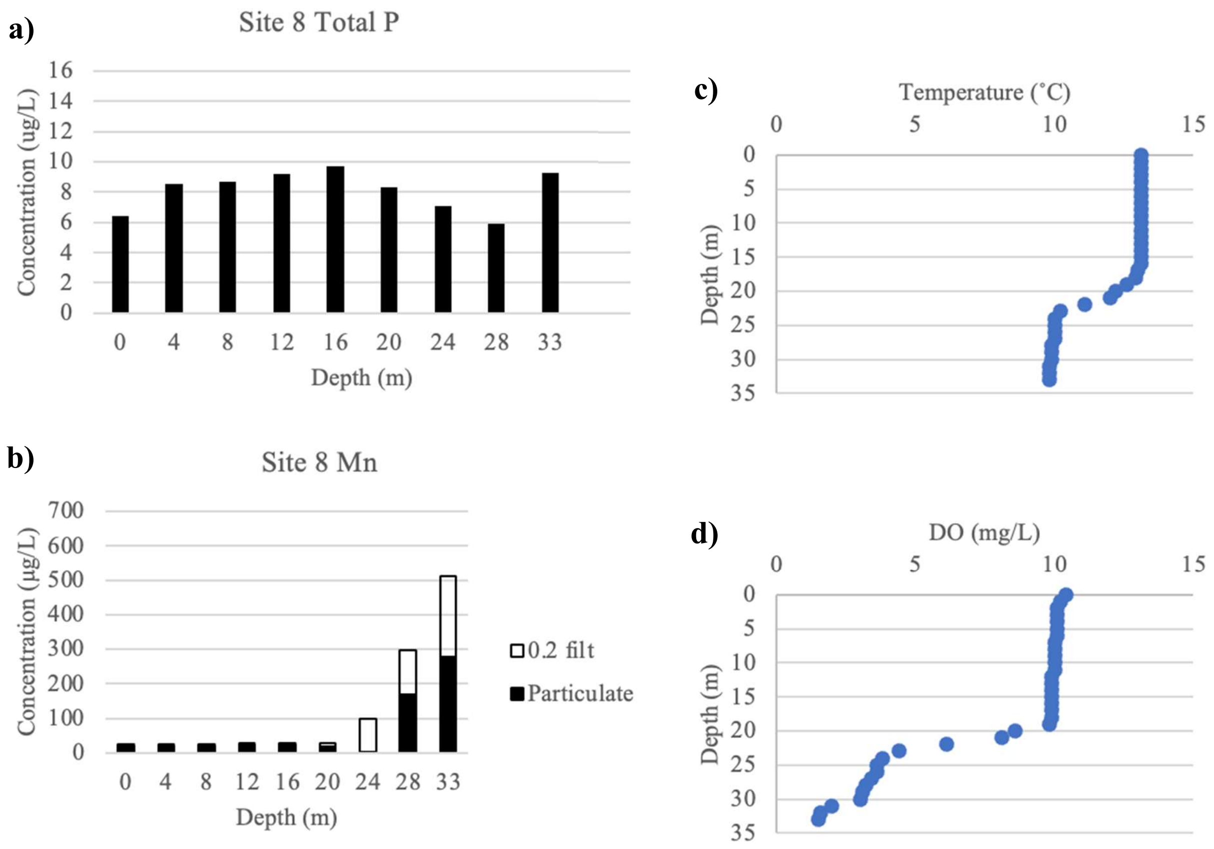

Figure 13. Site 8 data from October 29, 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

On October 29, 2021, there was a marked increase in TP concentrations from the previous sampling date earlier that month (Figure 13 a), which suggests internal P loading from the reductive dissolution of metal oxides in lake sediment by microbes, and/or as a result of external sources of P. The greatly elevated levels of dissolved Mn at depths below 20 m (Figure 13 b), as well as the near-zero levels of DO at these depths (Figure 13 d), both support the implication that reductive dissolution of metal oxides was occurring in the hypolimnion due to hypoxic conditions. Mn concentrations below 20 m were as high as approximately 500 µg/ L, and while TP levels increased overall from the previous sampling date, all concentrations remained below 12 µg/L.

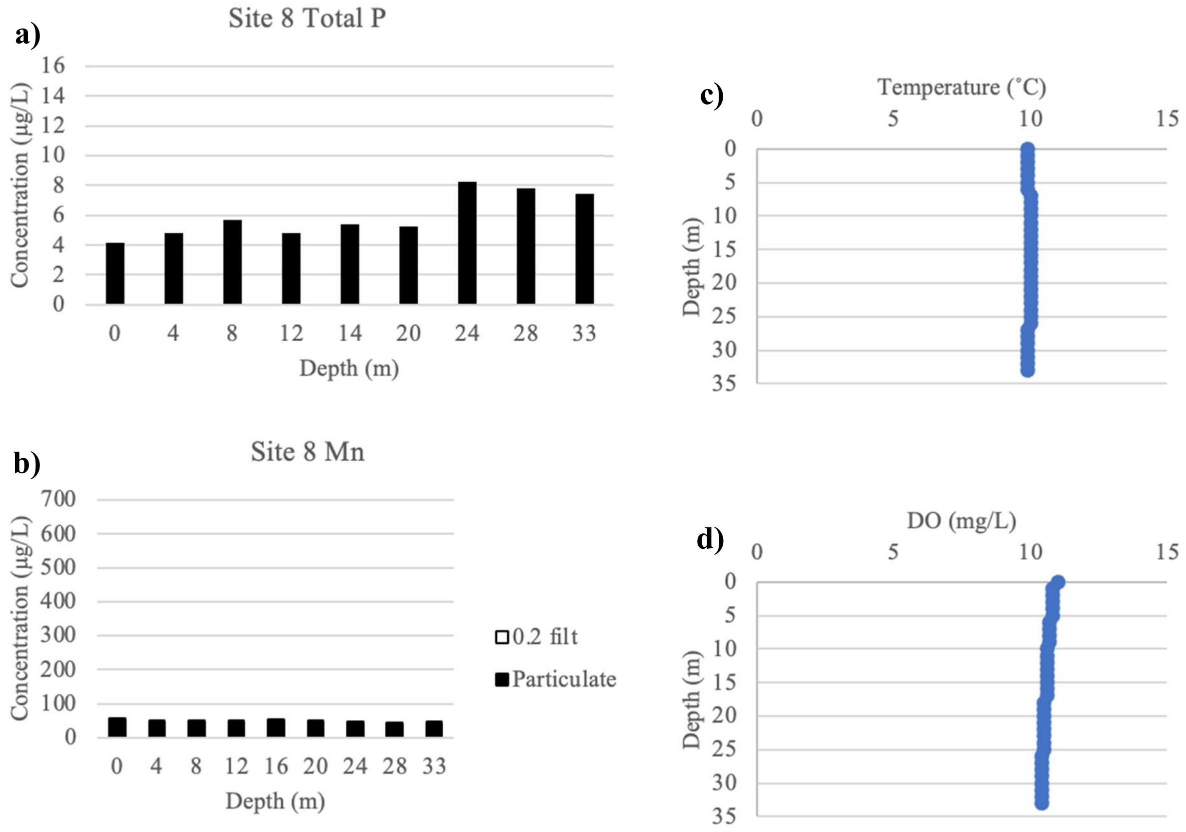

Figure 14. Site 8 data from November 2021 sampling showing a) TP concentrations, b) Mn concentrations, c) temperature of vertical water column, and d) dissolved oxygen concentrations throughout water column.

The final samples were taken in November 2021, shortly after the autumnal turnover of Lake Auburn. The internal mixing of the water equalized TP, DO, and metal levels, as well as the temperature throughout the vertical water column (Figure 14). Metal concentrations were below water quality standards, TP levels were maintained in the oligotrophic range, and the entire vertical water column was well oxygenated.

Conclusion

This study investigated the cycling of phosphorus and metals in Lake Auburn in order to assess the impact of an alum treatment on the water quality of a drinking water source. The alum addition applied in the summer of 2019 was successfully integrated into the lake within a few months following autumnal turnover, as evidenced by measurements of Al concentrations at various depths of the lake at its deepest site. Although the lake exhibited hypoxic conditions when during stratification, resulting in heightened metal concentrations and consequentially increased TP concentrations, this is a natural phenomenon that could not be mitigated by the alum addition, nor was it meant for that purpose. However, phosphorus levels following the alum treatment were rarely detected at concentrations that exceeded the limit for oligotrophic waters (< 12 µg/L), which was the primary goal for the addition. Instances when this concentration was exceeded occurred before the alum treatment was fully incorporated into the lake, as well as sporadically elevated levels on certain sampling dates, though these were few and far between and could likely be attributed to external P loading. Analysis of water samples for the rest of the study period not presented in this work will allow future researchers on this project to determine whether the alum treatment on Lake Auburn had its intended impact of lessening concentrations of algae-producing phosphorus in the water through its binding interactions with aluminum compounds.

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