Loon Lake Property Owners Association Water Quality Monitoring Program 2007-2024

Synthesis and Analysis of Water Quality Trends with Recommendations for Future Monitoring

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Final Report

May 26, 2025

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Introduction

This report is a synthesis of water quality data collected from 2007 through 2024 by members of the Loon Lake Property Owners Association (LLPOA). Water quality data was collected from a site named South Deep in the southern, deep basin of the lake. Following two meetings with LLPOA members who have monitored Loon Lake water quality, the following report objectives were developed.

1) Summarize sampling protocol over project period 2007-2024.
   a) Chemical variables, depths
   b) Physicochemical profiles
2) Test for trends in total phosphorus (TP), total nitrogen (TN) and chlorophyll *a* at various depths.
3) Test for trends in temperature, dissolved oxygen and relative thermal resistance to mixing (RTRM).
4) Make recommendations in sampling protocols to improve understanding of lake water quality.
5) Make recommendations for data management, analyses and reporting.

I have streamlined this report with the intent of efficiently presenting the data results and recommendations. I assume the LLPOA members who read this report already have the background, history and know the bathymetry of the lake. A thorough introduction of the lake basin, biota and management history is in the report of Moore et al. (2012).

Data Analysis Methods

1. *Database Build*

Sue Poe from LLPOA compiled the Hydrolab profile data and metadata into a spreadsheet database. The chemistry results from Spokane Tribe Tshimakain Creek laboratory were in electronic format but were in separate files from each sampling event. The chemistry data was compiled into a database. The two databases are now in a consistent format and electronic files will accompany this report draft report. The data covers 2007 to 2024, with most samples collected in June, August, and September. In 2024, data collection was limited to the month of September, with no profiling conducted. The databases follow the Tidyverse data structure in R (R Core Team, 2025). General database management and descriptive statistics were done with the R package, *dplyr* (Wickham et al. 2023). Most figures within this report were produced with ggplot2 (Wickham 2016). Trend analyses were done with the R package *EnvStats* (Millard 2023).

2. *Data Analysis Structure*

The LLPOA measured profile variables (temperature, dissolved oxygen, pH and conductivity) at consistent one meter depth intervals from surface to 21 meters, followed by 2 to 3 meter depth intervals to the lake bottom. This measurement granularity provided fine-scale data that supported the accurate delineation of the thermal stratification zones.

The LLPOA sampled from three depth zones (upper, mid and lower) of the lake at the South Deep site. Water was collected with a Van Dorn sampler at three depths within each depth zone. In the evaluation described below, each Van Dorn water collection at a specific depth is defined as a "grab". So, each LLPOA depth zone was comprised of three depths, with a “grab” at each depth. The three grabs were combined to make the “sample”. Equal volumes of water from each depth grab were composited by pouring into the sample bottle. The reason I broke out each discrete depth within a depth zone as a “grab” will become evident as I describe the results of the sampling evaluation below. The first LLPOA depth zone was the upper water column with sampling at 1, 3 and 5 meters. The second depth zone was the mid water column with sampling at 9, 12 and 15 meters. The third depth zone was the deep zone with sampling at 21, 24 and 27 meters. From first observations, the three depth zones were consistent with the lake's temperature structure when thermally stratified.

When a lake is thermally stratified, three zones exist. These zones are referred to as the epilimnion, metalimnion and hypolimnion (

Figure 1). The epilimnion is the upper, warm waters that are mixed by wind. The wind mixing in the epilimnion creates a consistent temperature profile and low RTRM values. Below the epilimnion is the metalimnion, a zone of rapid decreasing temperature with increasing depth (

Figure 1). The rapid change of temperature produces strong density gradients in the metalimnion. The strong density gradients resist wind mixing and can accumulate nutrients and algae. The hypolimnion is the cold, deep zone of the lake where the water is most dense. The hypolimnion is separated from the epilimnion by the metalimnion (

Figure 1). Comparing the depths of LLPOA's water chemistry samples with thermal stratification zones is crucial, as stratification affects lake processes, water quality, and ecology. Understanding the depths where grabs were taken in relation to the thermal stratification zones will aid in interpreting the water chemistry results.

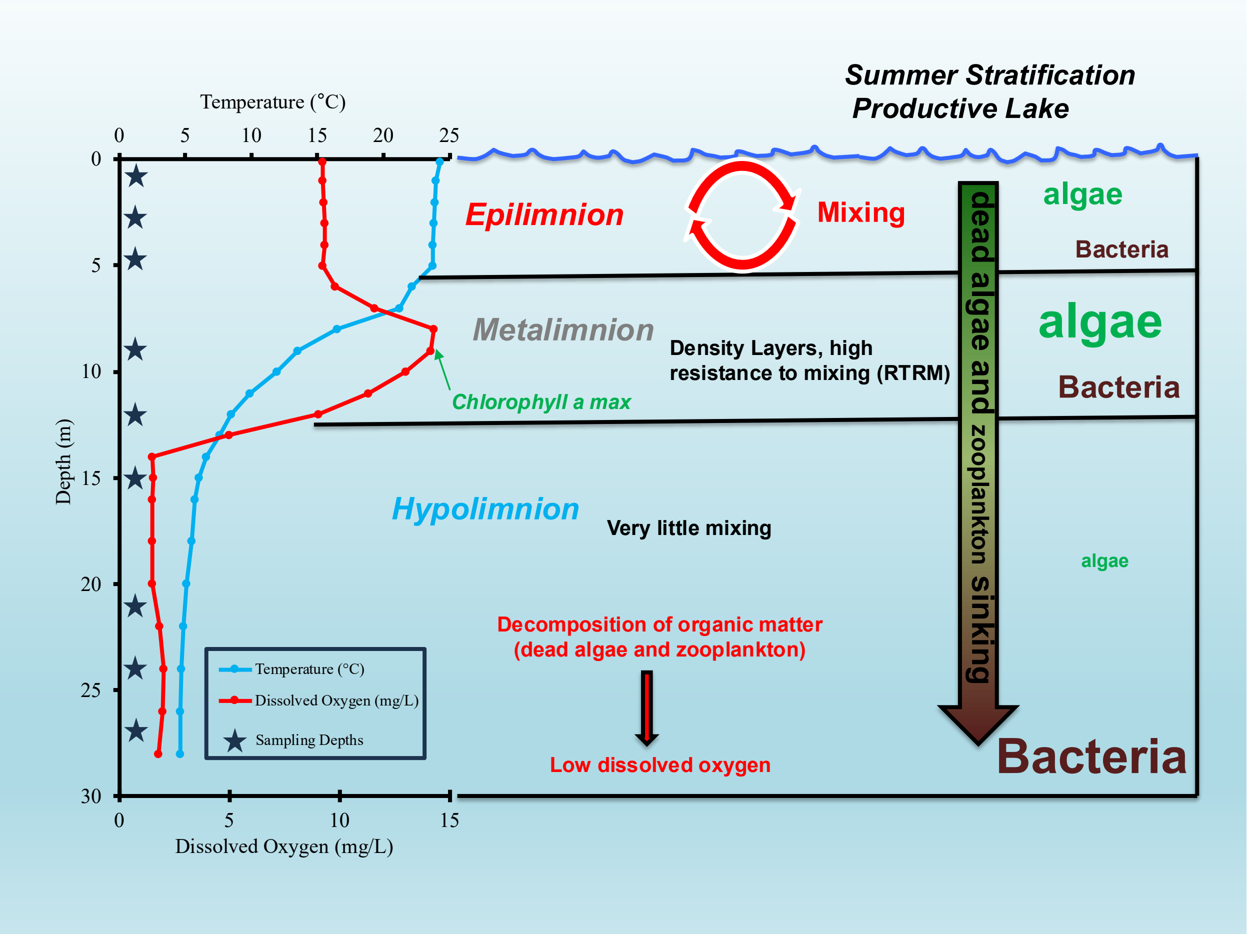


Figure 1. Conceptual diagram of Loon Lake water column with thermal stratification (epilimnion, metalimnion and hypolimnion), dissolved oxygen, and water column processes consistent with Loon Lake conditions in the summertime. Note: Stars are the sampling depths for water samples.

3. *Test Assumptions of Data Characteristics (normality, equal variances)*

After the databases were built and error checked, statistical tests for normality and equality of variances were used to characterize the data types and select the appropriate statistical tests Table 1. Non-parametric statistics were required as most of the data did not fit normal distributions with unequal variances for many variables.

4. *Statistical Differences Among Depth Zones*

A Kruskall-Wallis test determined if total phosphorus and total nitrogen concentrations differed among depth zones by month. The R package *rstatix* (Kassambara 2023) was used to do the Kruskall-Wallis test. The Dunn multiple comparisons test was used following a significant KrusKall-Wallis test result. The Dunn multiple comparison was used because there were three sample depths, and the test identified at which depths the concentrations were statistically different. The Dunn test was conducted using the R package *rstatix* (Kassambara 2023).

5. *Statistical Trend Analysis*

Temperature and dissolved oxygen from the epilimnion, metalimnion and hypolimnion for the months of June, August and September were evaluated for changes over the period from 2007-2023. The Kendall trend test was used to detect trends (Hirsch and Slack 1984, Kendall 1948). The Kendall trend analyses were done with the R package EnvStats (Millard 2023). In the results, I will report positive, negative or neutral slopes of the trend. If the value of the slope (+ or -) is large enough, then the slope is statistically significant. A statistically significant slope means there is a high probability the trend is real. The conclusion of a non-statistically significant Kendall test, but with a small negative or positive slope should be that the trend is not strong enough to rule out random chance in the data. Thus, confidence in a non-statistically significant trend (slope) is low.

Table 1. A summary and description of statistical tests used in this report.

Statistical Test	Variables	Type	Application
Shapiro-Wilks	Temp, D.O., TP, TN, Chla	Normality test	Test normal distribution of data.
Levene	Temp, D.O., TP, TN, Chla	Equal Variances test	Test for equal variances for a single variable among depth zones and months.
Kruskall-Wallis	Temp, D.O., TP, TN, Chla	Non-Parametric Analysis of Variance (ANOVA)	Test for differences of single variable among depth zones and months.
Dunn (multiple comparisons)	Temp, D.O., TP, TN, Chla	Non-Parametric Multiple comparisons	Given a significant Kruskall-Wallis result, test where differences in depth zone or months lie.
Kendall Trend	Temp, D.O., TP, TN, Chla	Non-Parametric Trend Analysis	Test for a trend over time for a variable at depth zone over the period of collection.

Results

1. Sampling Depth Evaluation

The temperature at depth from the profile database was used to evaluate if the three LLPOA-sampled depth zones overlapped with the three stratification zones. A density calculation was used to define the three stratification zones (epilimnion, metalimnion and hypolimnion). Differences in temperature-driven density between adjacent water layers were added into the relative thermal resistance to mixing (RTRM) equation (Kortmann 2015). The RTRM is a non-dimensional value, which quantifies stratification. This provided a numerical estimate to break out the three stratification depth zones, and compare to the depths that LLPOA sampled for water chemistry and chlorophyll *a*. Each sampling date was evaluated to determine if the sampling depths (grabs) for water samples fell within the three depth zones associated with thermal stratification.

From the sampling depth evaluation, the LLPOA sampling depths have effectively collected water chemistry from the epilimnion and hypolimnion of Loon Lake (*Table 2*.) Ninety six percent of sample dates from all three depths (1, 3, 5 meters) were within the epilimnion (*Table 2*). One hundred percent of sample dates from all three depths (21, 24, 27 meters) were within the Hypolimnion (*Table 2*). The mid-water grab depths (9, 12, 15 meters) did not effectively collect data from the metalimnion (*Table 2*). No sample date included all three depths within the metalimnion, and the 15 meter depth was never within the metalimnion. Only ten percent of the sample dates had two of the three grab depths within the metalimnion (*Table 2*). In most cases, the LLPOA mid-water samples were a mixture of deep metalimnion and upper hypolimnion zones. However, this does not make the mid-water samples useless as the depths were consistently sampled and can be statistically tested the same as the samples collected in the epilimnion and hypolimnion. Chemistry dynamics in the metalimnion are important to understand from a lake water quality, limnologic, and aquatic ecological aspect.

2. Temperature

The months of June, August, and September had the most temperature profiles from 2007 to 2023. The lake at the South Deep site was thermally stratified on every sampling date in June, August and September from 2007-2023 (Figure 2). On average the epilimnion warmed from 17.4 (°C) in June to 23.1 (°C) in August (Figure 2). The average temperature in the epilimnion in September over the period was 18.5 (°C), (Figure 2). Over the period, temperature in the hypolimnion changed little between months, ranging from 6.0 (°C) in June to 6.2 (°C) in September (Figure 2). Two samplings occurred outside of the June-September window. These sampling events were May 21, 2009 and October 12, 2024. On May 21, 2009, the lake was weakly stratified at 8 meters with a average epilimnion temperature of 13.0 (°C). On October 12, 2024, the lake was moderately stratified at 12 meters with an average epilimnion temperature of 14.8 (°C).

Table 2. Evaluation of LLPOA sampling depths compared to thermal stratification zones in Loon Lake.

LLPOA Sample Depths	Stratification Zone	Percent of LLPOA Van Dorn Grabs within Stratification Zone
1, 3, 5 meters	Epilimnion	96% of all dates had 1, 3, 5 meter grabs within the epilimnion. 100% of all dates had 1, 3 meter grabs within epilimnion.
9, 12, 15 meters	Metalimnion	0% of all dates had 9, 12, 15 meter grabs within metalimnion. 10% of all dates had 9, 12 meter grabs within metalimnion.
21, 24, 27 meters	Hypolimnion	100% of all dates had 21, 24, 27 meter grabs within the hypolimnion.

In June, average temperature in the epilimnion and metalimnion was cooler from 2007-2010 compared to recent years. Temperature in the hypolimnion in June has increased recently with a consistent increasing trend since 2018 (Figure 3). For the month of June, there is a weak positive slope (Kendall trend test) for the epilimnion, metalimnion and hypolimnion temperature (Table 3). This indicates a potential increasing temperature trend, but not statistically significant (Figure 3), (Table 3). Thermal stratification strength was estimated by summing all relative thermal resistance to mixing (RTRM) values in the metalimnion on each date. A higher RTRM value indicates stronger thermal stratification, and higher resistance to wind mixing. Although thermal stratification is generally weaker in June, the month had the largest range of RTRM values (44.1 to 194.9) of all months over the period (Figure 6). This may be explained by high air temperature variability and length of lake ice cover in the spring affecting lake-mixing duration prior to thermal stratification (Pilla and Williamson 2022). In June, the average maximum depth of the epilimnion is 5.5 meters and changes little throughout August (Table 4). In September, as the epilimnion cools, the stratification intensity in the metalimnion begins to weaken and the epilimnion expands and deepens to a average of 8.1 meters (Table 4).

Loon Lake is warmest in August. The warmest average epilimnion temperature from the 2007-2023 period was 25.7 (°C) on August 1, 2022 (Figure 4). Unlike June, August has a statistically significant positive slope for temperature in the epilimnion, metalimnion and hypolimnion (Table 3), (Figure 4). In August the epilimnion temperature is increasing 0.22 (°C) per year. The metalimnion is increasing 0.28 (°C) per year, and the hypolimnion is increasing 0.12 (°C) per year. This increasing temperature trend in summer is a global trend (Woolway et al. 2022). Loon Lake in August is strongly thermally stratified. The summed values in the metalimnion for each sample date range from (233.1 to 330.0), (Figure 6).

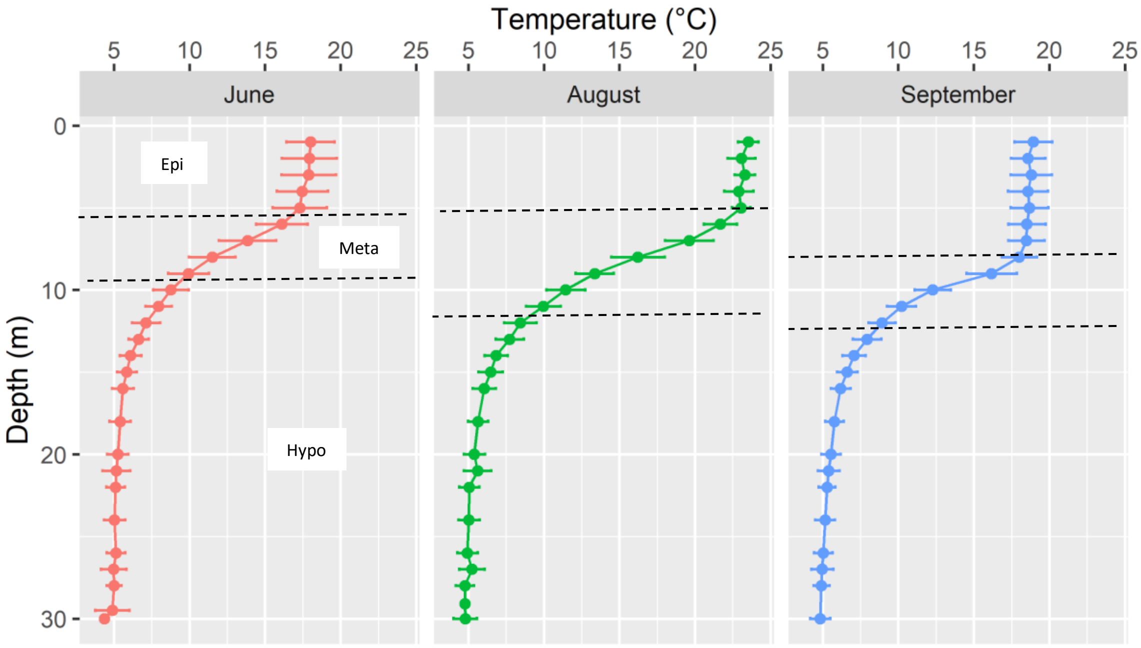


Figure 2. Mean (average) water column temperature for June, August and September from years 2007-2023. Horizontal error bars are one standard deviation from the mean. The dashed lines delineate the epilimnion (Epi), metalimnion (Meta) and hypolimnion (Hypo), with values from Table 3.

Table 3. Kendall trend test for mean (average) temperature in June, August and September in the epilimnion, metalimnion and hypolimnion, from 2007 through 2023. Note: P-values in bold are statistically significant at alpha level 0.05.

Depth	Variable	Month	# Years	tau	Slope	P-value
Epilimnion	Temperature	June	15	0.26	0.13	0.137
Metalimnion			15	0.30	0.13	0.198
Hypolimnion			15	0.25	0.08	0.228
Epilimnion	Temperature	August	12	0.58	0.22	**0.012**
Metalimnion			12	0.66	0.28	**0.003**
Hypolimnion			12	0.48	0.12	**0.034**
Epilimnion	Temperature	September	17	0.28	0.10	0.127
Metalimnion			17	0.15	0.05	0.434
Hypolimnion			17	0.24	0.06	0.202

Loon Lake cools in September but remains thermally stratified (Figure 5). Only two years throughout the period was the epilimnion above 20 (°C), (Figure 5). There is a weak positive slope (Kendall trend test) for the epilimnion, metalimnion and hypolimnion (Table 3). This indicates an increasing temperature trend. However, like June, not statistically significant (Figure 5), (Table 3). As Loon Lake begins to cool and denser water from the surface sinks, thermal stratification weakens as the metalimnion slowly erodes. Loon Lake in September remains moderately thermally stratified. The summed values in the metalimnion for each sample date range from (101.3 to 199.7), (Figure 6). In September, as the epilimnion cools, the stratification intensity in the metalimnion begins to weaken and the epilimnion expands and deepens to a average of 8.1 meters (Table 4). As the metalimnion erodes, it shrinks as it expands into the upper hypolimnion (Table 4).

After analyzing the temperature throughout the water column in June, August and September over the period of 2007-2023, there is evidence that the Lake is warming over time. All slopes of temperature trends are positive, and the temperature in the entire water column in August is statistically increasing. This warming trend in temperate lakes similar to Loon Lake is supported in the literature (Woolway et al. 2022, O'Reilly et al. 2015).

Table 4. The upper (shallow) and lower (deep) depths of the epilimnion, metalimnion and hypolimnion from profiles collected at the South Deep site from 2007-2023. The mean (average) ± 1 standard deviation is reported for each month.

		Epilimnion (m)		Metalimnion (m)		Hypolimnion (m)	
Month	#Years	Surface	Lower	Upper	Lower	Upper	Lower
June	15	0.1	5.5±1.0	6.7±1.1	8.5±1.2	9.7±1.5	28.0
July	6	0.1	5.3±0.6	6.3±0.6	9.3±1.2	10.3±1.2	28.0
August	12	0.1	5.2±0.7	6.3±0.8	10.8±1.0	12.0±1.3	28.0
September	17	0.1	8.1±0.7	9.2±0.8	10.9±0.6	12.1±0.8	28.0

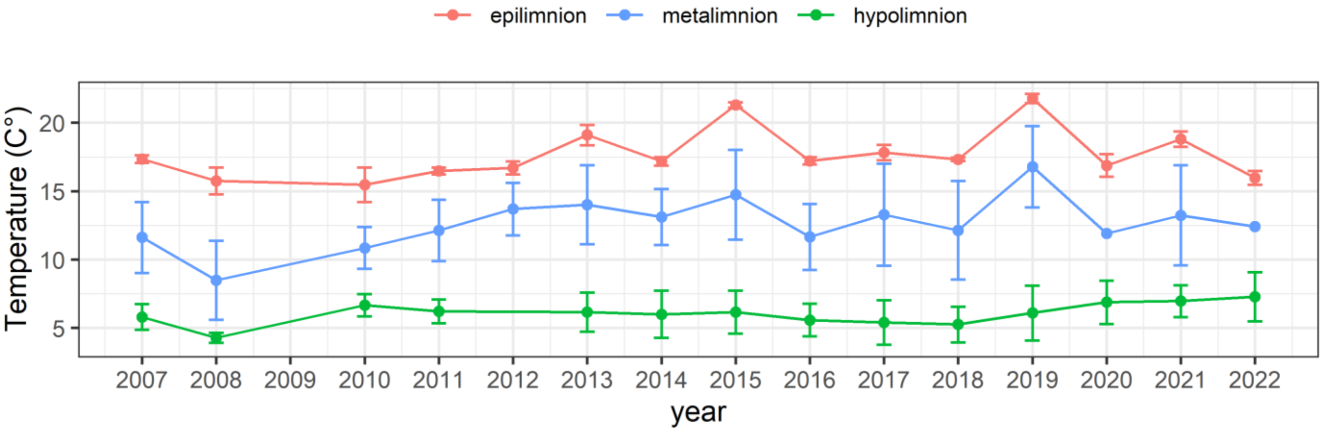


Figure 3. Temperature in the epilimnion, metalimnion and hypolimnion in June from 2007-2023 Note: gaps between years and error bars are one standard deviation from the mean.

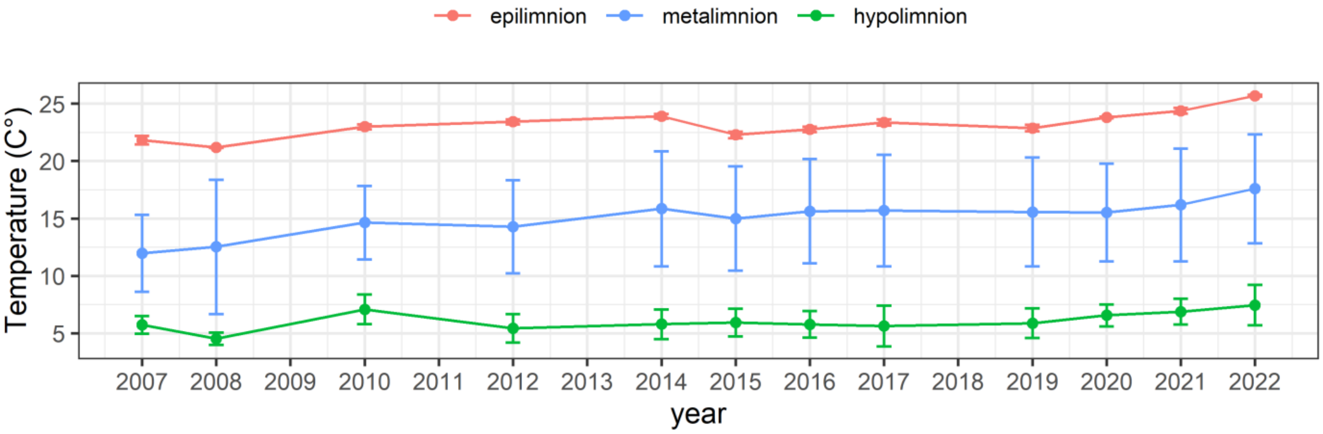


Figure 4. Temperature in the epilimnion, metalimnion and hypolimnion in August from 2007-2023. Note: gaps between years and error bars are one standard deviation from the mean.

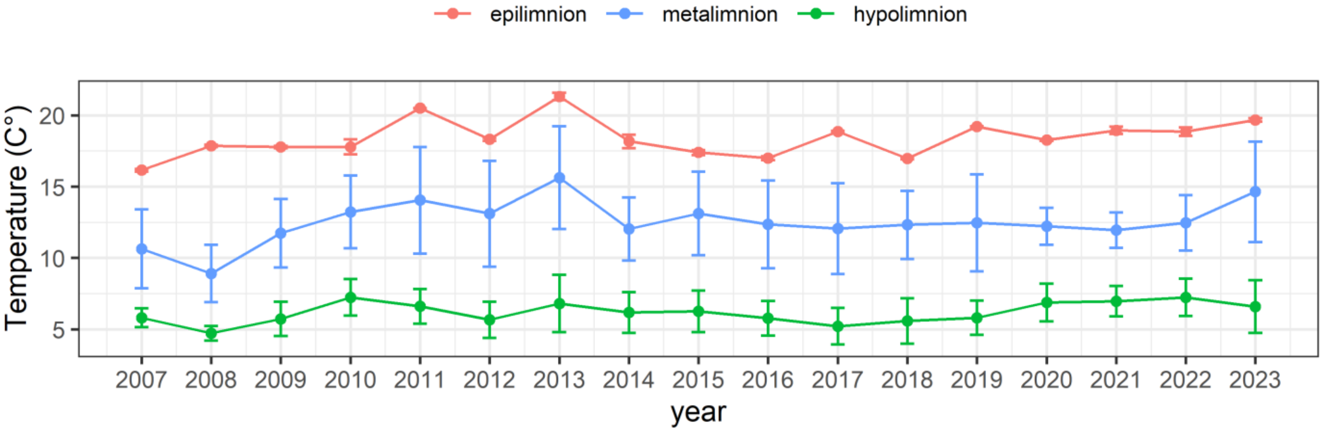


Figure 5. Temperature in the epilimnion, metalimnion and hypolimnion in September from 2007-2023 Note: gaps between years and error bars are one standard deviation from the mean.

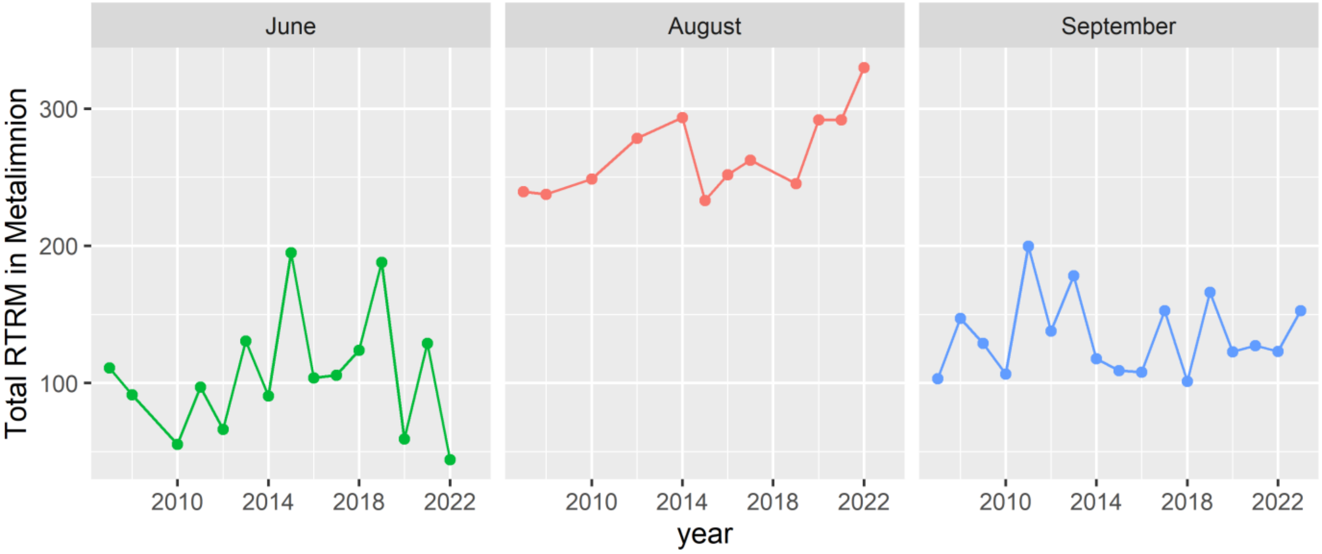


Figure 6. Relative thermal resistance to mixing (RTRM), summed across all depths from the metalimnion in June, August and September.

3. Dissolved Oxygen

The months of June, August, and September had the most Dissolved oxygen profiles from 2007 to 2023. The lake at the South Deep site was thermally stratified on every sampling date in June, August and September from 2007-2023. The dissolved oxygen analysis follows the same steps as the temperature analysis in the previous section of this report. The LLPOA measured profile variables at consistent one meter depth intervals from surface to 21 meters, followed by 2 to 3 meter depth intervals to the lake bottom. This provided fine-scale dissolved oxygen data at depth, which improves the understanding of Loon Lake water quality drivers and ecological processes.

During thermal stratification, dissolved oxygen was low in the hypolimnion, and high in the metalimnion (Figures 8-10). These conditions occurred every year in June through September (**Error! Reference source not found.**). The solubility of oxygen in water is temperature dependent. Oxygen solubility increases with lower water temperatures, and decreases in warmer water. Thus, the warm epilimnion should hold less oxygen than the cold hypolimnion. The metalimnion due the temperature gradient should have lower dissolved oxygen in the upper depth and higher dissolved oxygen in its lower depth. However, the above-mentioned oxygen conditions do not occur in Loon Lake, likely due to algae productivity, and the physical processes associated with the metalimnion (Wilkinson et al. 2015). Loon Lake has a significant metalimnetic oxygen maximum from June through September (**Error! Reference source not found.**). In addition, dissolved oxygen is significantly reduced in the hypolimnion by bacteria decomposing organic matter (much of which is dead algal cells) during thermally stratified periods (June through October).

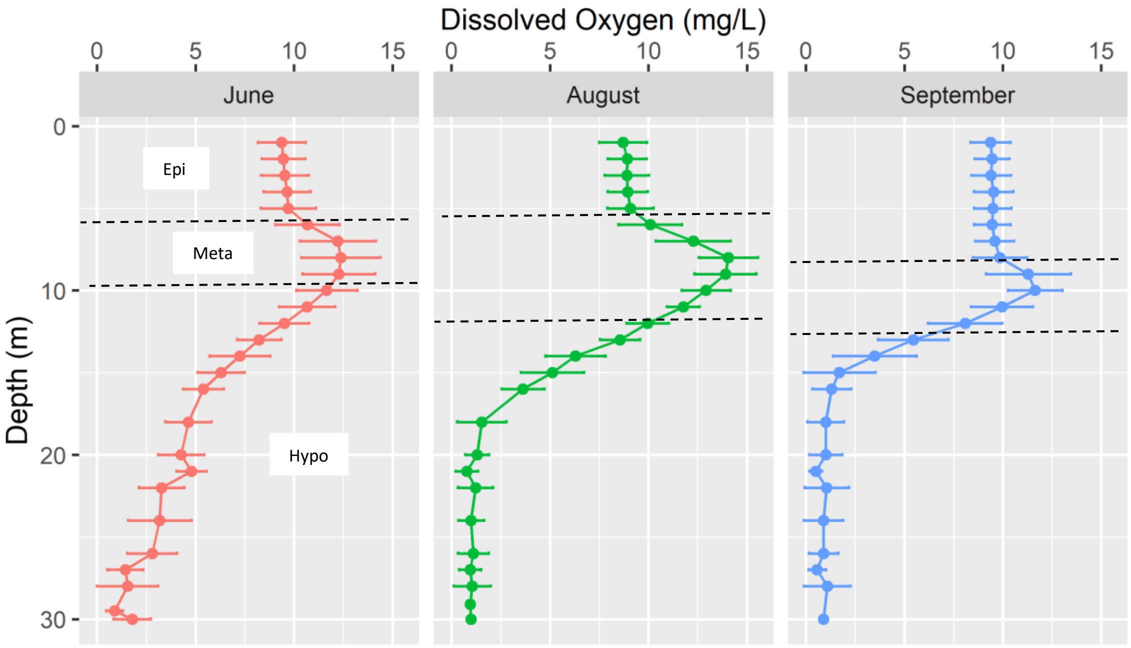
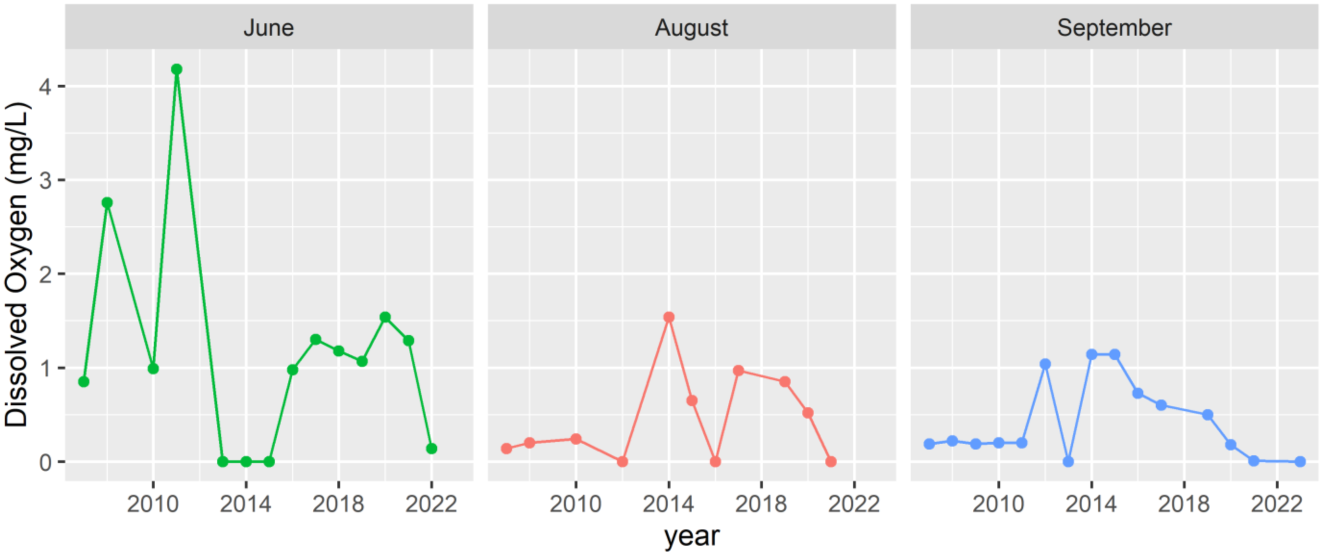


Figure 7. Mean (average) water column dissolved oxygen for June, August and September from years 2007-2023. Horizontal error bars are one standard deviation from the mean. The dashed lines delineate the epilimnion (Epi), metalimnion (Meta) and hypolimnion (Hypo), with values from Table 3.

The Kendall trends test revealed small positive and negative, slopes in the epilimnion and metalimnion for June, August and September (Table 5). However, none of the slopes were statistically significant for the epilimnion or metalimnion (Table 5). The hypolimnion had small positive slopes in June and September and a statistically significant positive slope in August (Table 5). Thus, dissolved oxygen is higher in the hypolimnion in the recent years compared to the beginning of the sampling in 2007 (Figure 9). One potential explanation for the increased dissolved oxygen in the hypolimnion in August may be from resupply of dissolved oxygen to the upper hypolimnion from the high dissolved oxygen concentrations in the metalimnion (Figure 7).



*Loon Lake in most years has an anoxic (no oxygen) zone in the deepest part of the hypolimnion at the sediment water interface (*Figure 12). This anoxia can happen in any month from June through September, and in some years e.g., June 2014, the sediment water interface was anoxic, then dissolved oxygen increased to >1 mg/L in August. The general trend remains that dissolved oxygen significantly decreases in the hypolimnion every year from June through September (Figure 11). Nearly every year the hypolimnion is anoxic (no oxygen) for a variable period during thermally stratified periods (Figure 12).

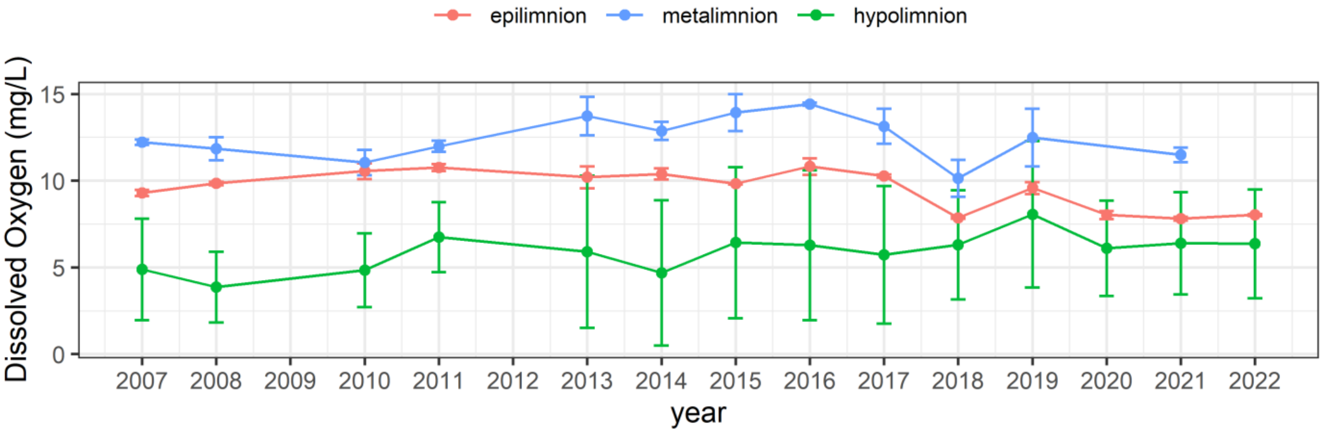


Figure 8. Dissolved oxygen in the epilimnion, metalimnion and hypolimnion in June from 2007-2023. Note: gaps between years and error bars are one standard deviation from the mean.

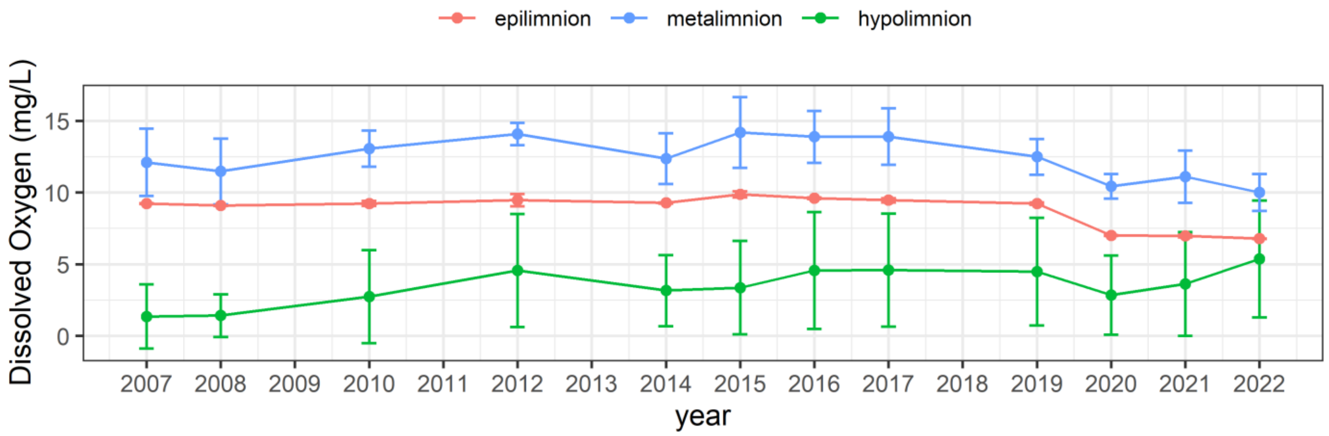


Figure 9. Dissolved oxygen in the epilimnion, metalimnion and hypolimnion in August from 2007-2023. Note: gaps between years and error bars are one standard deviation from the mean.

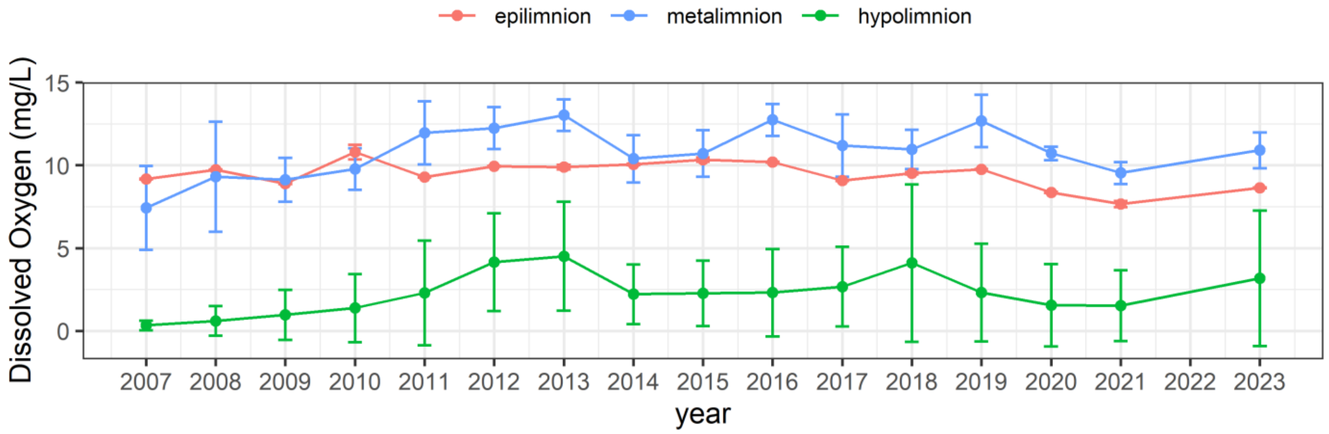


Figure 10. Dissolved oxygen in the epilimnion, metalimnion and hypolimnion in September from 2007-2023. Note: gaps between years and error bars are one standard deviation from the mean.

Table 5. Kendall trend test for mean dissolved oxygen in June, August and September in epilimnion, metalimnion and hypolimnion, from 2007 through 2023. Note: P-values in bold are statistically significant at alpha level 0.05.

Depth	Variable	Month	# Years	tau	Slope	P-value
Epilimnion	Dissolved Oxygen	June	15	-0.26	-0.12	0.200
Metalimnion			15	0.10	0.06	0.669
Hypolimnion			15	0.38	0.13	0.063
Epilimnion	Dissolved Oxygen	August	12	-0.27	-0.14	0.240
Metalimnion			12	-0.24	-0.13	0.304
Hypolimnion			12	0.55	0.20	**0.016**

Epilimnion	Dissolved Oxygen	September	16	-0.22	-0.07	0.260
Metalimnion			16	0.27	0.13	0.163
Hypolimnion			16	0.37	0.12	0.053

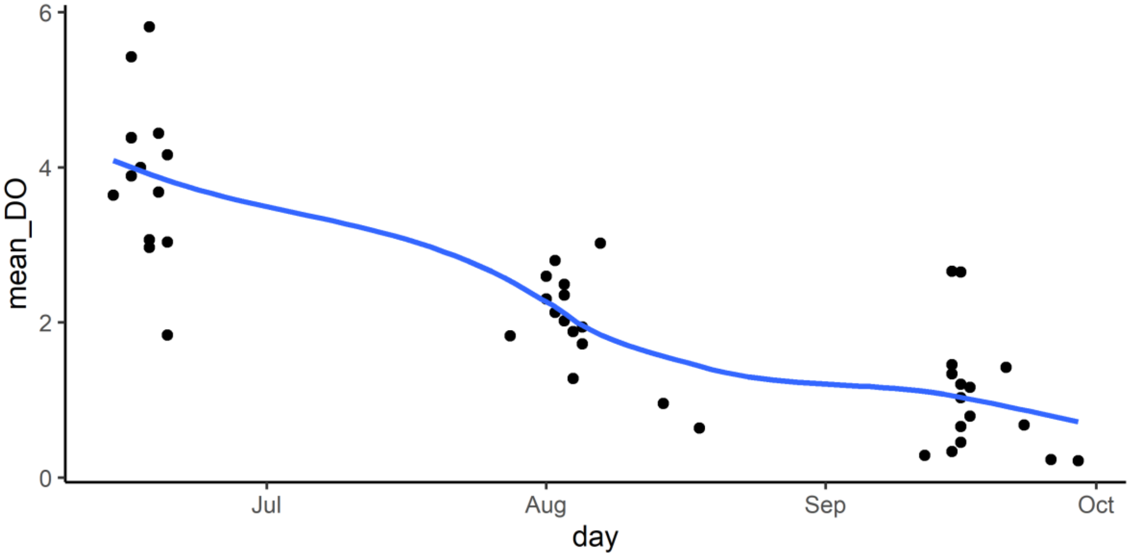


Figure 11. Mean (average) Dissolved oxygen in the hypolimnion (depths 15m to 28m) from June through September.

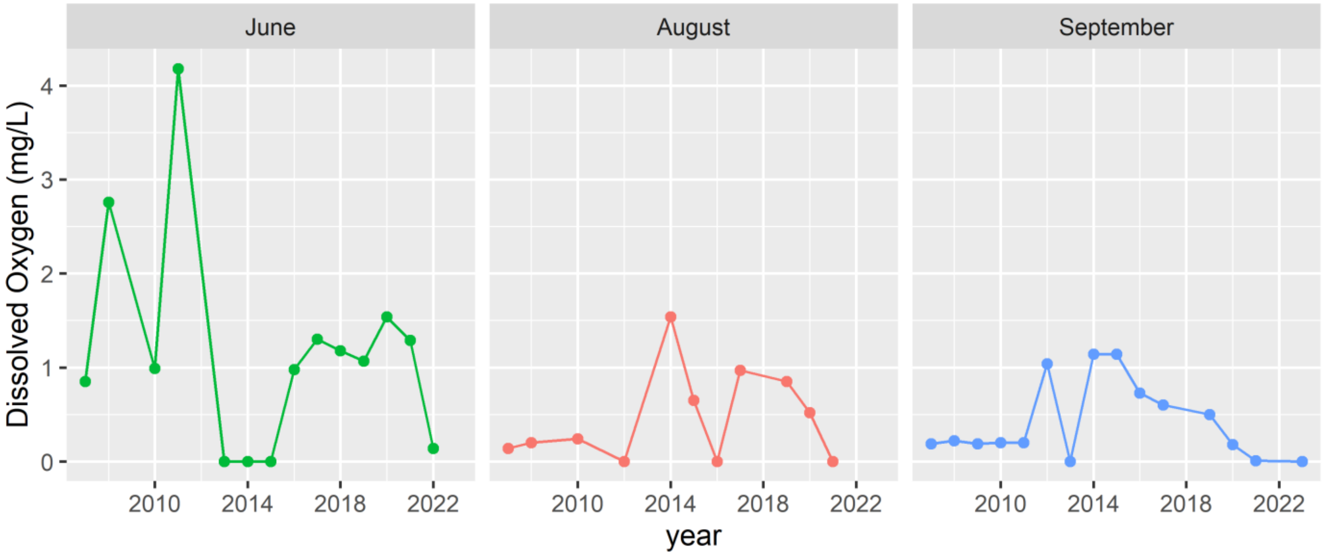


Figure 12. Minimum dissolved oxygen in the deep hypolimnion in June, August and September from 2007-2023.

4. Total Phosphorus

Three types of statistical results exist for total phosphorus in the three depth zones of the lake. The first is a Kruskall-Wallis test, which determined if total phosphorus concentrations differed among depth zones by month over the 2007-2023 period. Second, a Dunn multiple comparison test was used after a significant Kruskall-Wallis test, identifying at which depths the concentrations were statistically different. The third statistical test is the Kendall trend test, which tested for changes at the three depth zones over the period from 2007-2023.

Total phosphorus concentration consistently increases over the season in the hypolimnion (Figure 13). In June the total phosphorus concentration in the epilimnion was significantly lower than in the mid water column with sampling at 9, 12 and 15 meters (Table 6, Figure 14). In September total phosphorus concentration was significantly different among all three depth zones with the hypolimnion concentrations nearly 3X of those in the epilimnion, and 2X from those in the mid water column with sampling at 9, 12 and 15 meters (Table 7, Figure 15). The general trend of total phosphorus concentration from the epilimnion, mid water column with sampling at 9, 12 and 15 meters, and hypolimnion is a declining concentration from 2007 through the mid-2010s at all three depth zones (Figure 15). Following this decline, in the hypolimnion total phosphorus concentration began increasing from 2018 through 2023 (Figure 15). Despite a recent rise in total phosphorus, the overall decreasing trend in the hypolimnion remains unchanged.

Table 6. Kruskal-Wallis test for total phosphorus concentration differences among sampling depths for the months of June-September. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Variable	# Years	Kruskal-Wallis Chi-squared	P-value
June	Total Phosphorus	15	7.09	**0.029**
July		6	7.97	**0.019**
August		9	15.97	**<0.001**
September		18	38.02	**<0.00001**

Overall, there is a decrease in total phosphorus over the period of 2007-2023. For the month of June, there is a weak negative slope (Kendall trend test) for total phosphorus concentration at all sampling depths. This weak decreasing trend is not statistically significant (Table 8*Table 11*). In September, like June, the total phosphorus concentration at all sampling depths shows negative slopes. However, the negative slopes for the epilimnion and hypolimnion in September are statistically significant (Kendall trend test), (Table 8*Table 11*). Total phosphorus concentration in the epilimnion and hypolimnion in September is significantly lower now than when sampling started in 2007.

Table 7. Dunn multiple comparisons test for total phosphorus among sampling depths for the months of June-September. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Group1	Group2	Years	Dunns Statistic	Adjusted P-value
June	Epilimnion	Depths_9_12_15m	15	-2.53	**0.034**
	Depths_9_12_15m	Hypolimnion		-0.54	0.587
	Epilimnion	Hypolimnion		1.99	0.094
July	Epilimnion	Depths_9_12_15m	6	-2.15	0.064
	Depths_9_12_15m	Hypolimnion		0.52	0.606
	Epilimnion	Hypolimnion		2.66	**0.023**
August	Epilimnion	Depths_9_12_15m	9	-2.53	**0.023**

	Depths_9_12_15m	Hypolimnion		1.41	0.157
	Epilimnion	Hypolimnion		3.94	**<0.001**
September	Epilimnion	Depths_9_12_15m	18	-2.29	**0.022**
	Depths_9_12_15m	Hypolimnion		3.82	**<0.001**
	Epilimnion	Hypolimnion		6.10	**<0.0001**

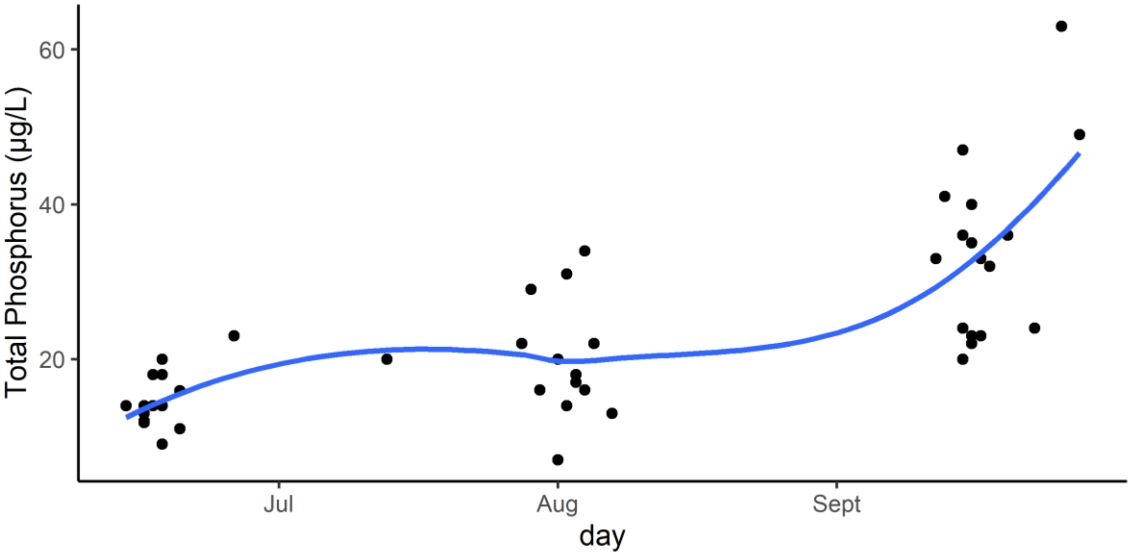


Figure 13. Total Phosphorus seasonal trend in hypolimnion from June through September (years 2007 through 2023). Note: curving line is the smoothed fit of the data.

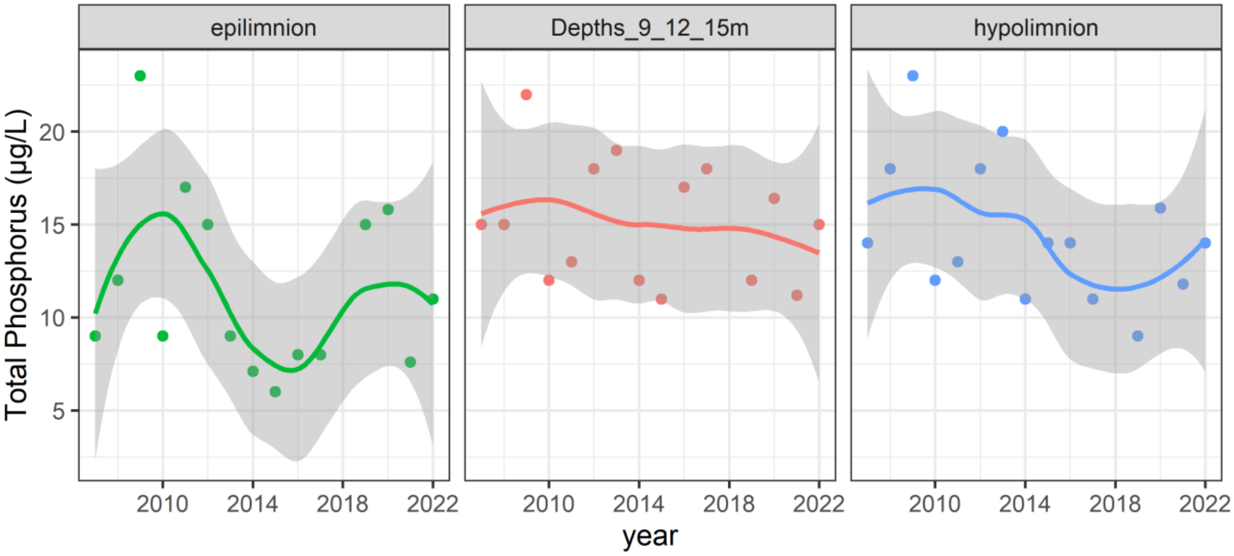


Figure 14. Total phosphorus concentrations from June among sampling depths (years 2007 through 2022). Note: curving lines are the smoothed fit of the data, and gray shading is the 95% confidence intervals for the smoothed fit.

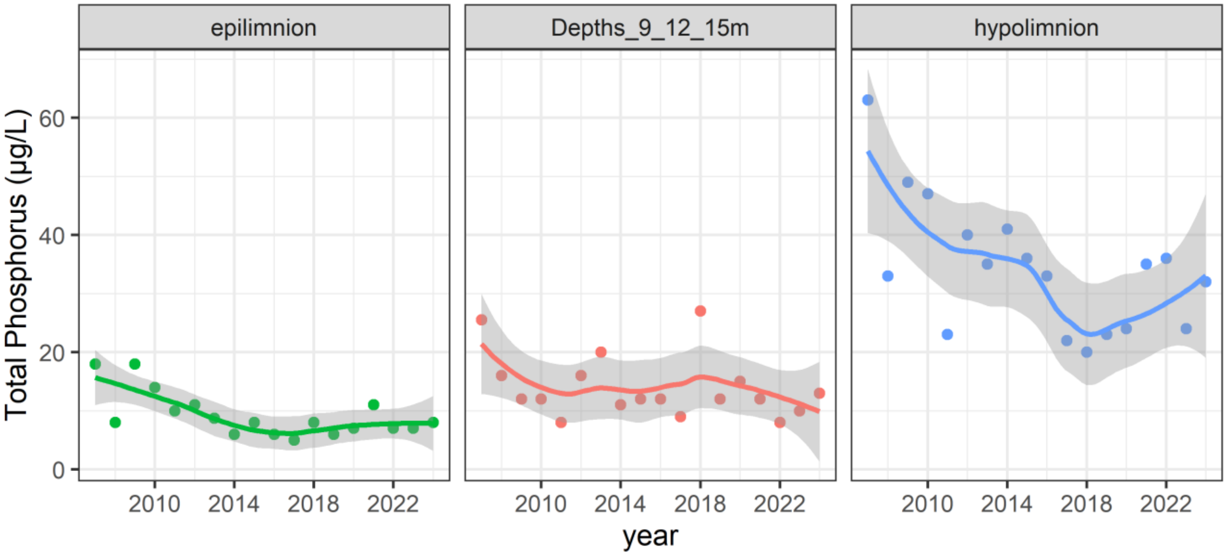


Figure 15. Total phosphorus concentrations from September among sampling depths (years 2007 through 2023). Note: curving lines are the smoothed fit of the data, and gray shading is the 95% confidence intervals for the smoothed fit.

Table 8. Kendall trend test for total phosphorus for samples collected in June and September from 2007 through 2023. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Depth	Variable	# Years	tau	Slope	P-value
June	Epilimnion	Total Phosphorus	15	-0.17	-0.13	0.396
	Depths 9_12_15m		15	-0.17	-0.20	0.396
	Hypolimnion		15	-0.26	-0.30	0.192
September	Epilimnion	Total Phosphorus	18	-0.39	-0.33	**0.026**
	Depths 9_12_15m		18	-0.20	-0.20	0.261
	Hypolimnion		18	-0.37	-1.22	**0.037**

5. *Total Nitrogen*

The three statistical tests run for total phosphorus concentrations were also used for total nitrogen concentrations. Total nitrogen concentration in June was similar throughout the period (2007-2023) at all three sampling depth zones (Figure 16, *Table 9*). Sample size was lower in July and August, and total nitrogen concentration was not different among the sampling depths (*Table 9*). In September total nitrogen concentration was significantly higher in the hypolimnion compared to the epilimnion (*Table 9*, Table 10). The general trend of total nitrogen concentration from the epilimnion and hypolimnion in September was a declining concentration from 2007 through the mid-2010s, followed by an upswing in concentration since 2018 (Figure 17). Total nitrogen in the mid-depth zone (depths 9, 12 and 15 meters) was more variable from year-to-year in September (Figure 17).

For the month of June, over the 2007-2023 period, there is a weak negative slope (Kendall trend test) for total nitrogen concentration at all sampling depths. This weak decreasing trend is not statistically significant. In September, like June, the total nitrogen concentration at all sampling depths shows negative slopes. The negative slopes for the epilimnion and hypolimnion in September are statistically significant (Kendall trend test), (*Table 11*). Total nitrogen concentration in the epilimnion and hypolimnion in September is statistically lower now than it was when sampling started in 2007.

Table 9. Kruskal-Wallis test for total nitrogen concentration differences among sampling depths for the months of June-September. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Variable	# Years	Kruskal-Wallis Chi-squared	P-value
June	Total Nitrogen	15	0.92	0.613
July		6	0.65	0.722
August		9	1.53	0.464
September		18	8.57	**0.014**

Table 10. Dunn multiple comparisons test for total phosphorus among sampling depths for the month of September. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Group1	Group2	Years	Dunn Statistic	Adjusted P-value
September	Epilimnion	Depths_9_12_15m	18	-0.76	0.499
	Depths_9_12_15m	Hypolimnion		2.03	0.084
	Epilimnion	Hypolimnion		2.83	**0.014**

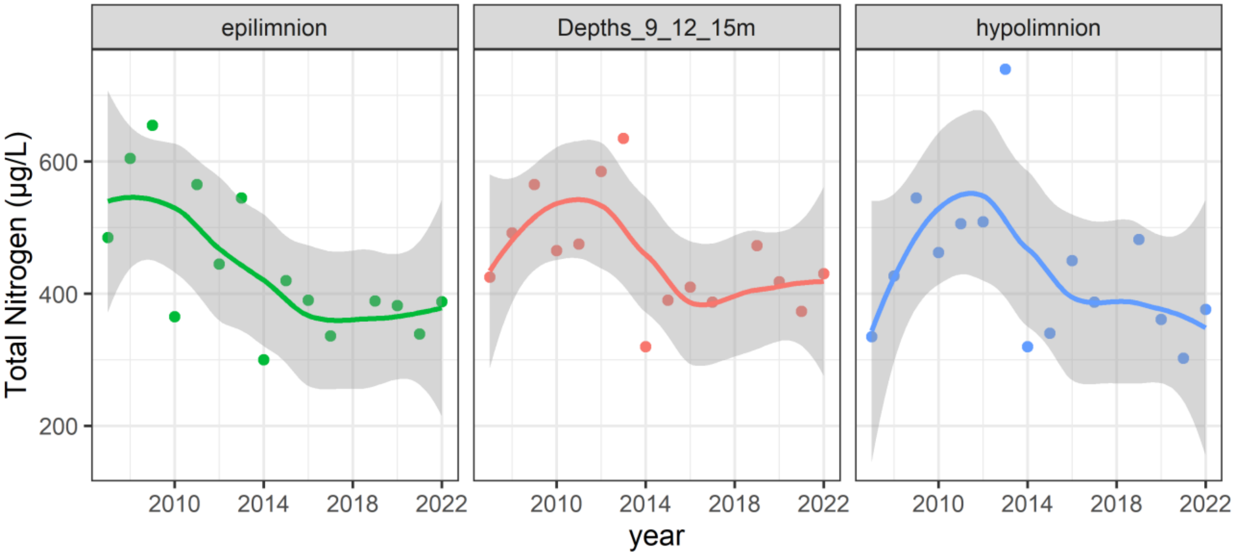


Figure 16. Total nitrogen concentrations from the month of June among sampling depths (years 2007 through 2023). Note: curving lines are the smoothed fit of the data, and gray shading is the 95% confidence intervals for the smoothed fit.

Table 11. Kendall trend test for total nitrogen for samples collected in June and September from 2007 through 2023. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Depth	Variable	# Years	tau	Slope	P-value
June	Epilimnion	Total Nitrogen	15	-0.20	-6.30	0.322
	Depths 9_12_15m		15	-0.26	-4.70	0.198
	Hypolimnion		15	-0.20	-6.30	0.322
September	Epilimnion	Total Nitrogen	18	-0.37	-7.00	**0.037**
	Depths 9_12_15m		18	-0.19	-4.75	0.302
	Hypolimnion		18	-0.35	-8.50	**0.049**

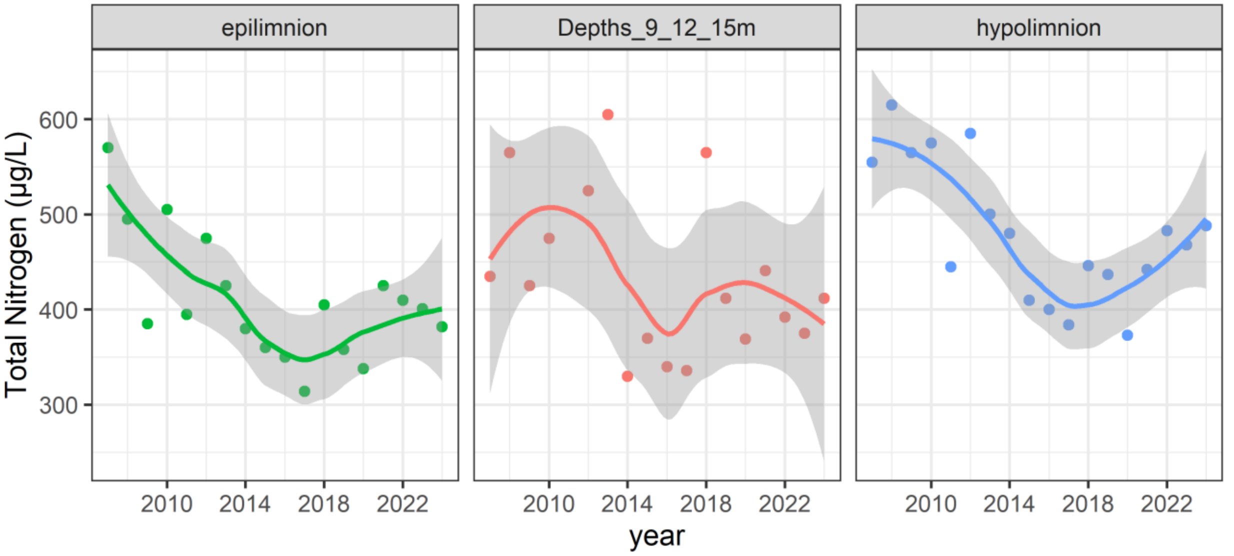


Figure 17. Total nitrogen concentrations from September among sampling depths (years 2007 through 2023). Note: curving lines are the smoothed fit of the data, and gray shading is the 95% confidence intervals for the smoothed fit.

6. Nitrogen:Phosphorus Ratio

The total nitrogen:total phosphorus ratio (N:P ratio) in the epilimnion is important because cyanobacteria (blue-green algae) have a higher likelihood of blooming and producing toxins when the N:P ratio is low. Some cyanobacteria e.g., *Aphanizomenon* spp. can use atmospheric nitrogen from the epilimnion and outcompete smaller green algae that do not produce toxins. Harris et al. (2014) reported an N:P ratio >50 reduced the amount of cyanotoxins, and an N:P ratio >75 significantly reduced biovolume of toxin-producing cyanobacteria in an eastern Oregon reservoir. Aside from 2008, the N:P ratio in Loon Lake in September was <50 until 2014 (Figure 18). In September there is a positive, but not statistically significant slope (Kendall trend test) for the N:P ratio (Table 12). Throughout the period from 2007-2024, there has not been a N:P ratio >75 which would significantly reduce the probability of cyanobacteria blooms.

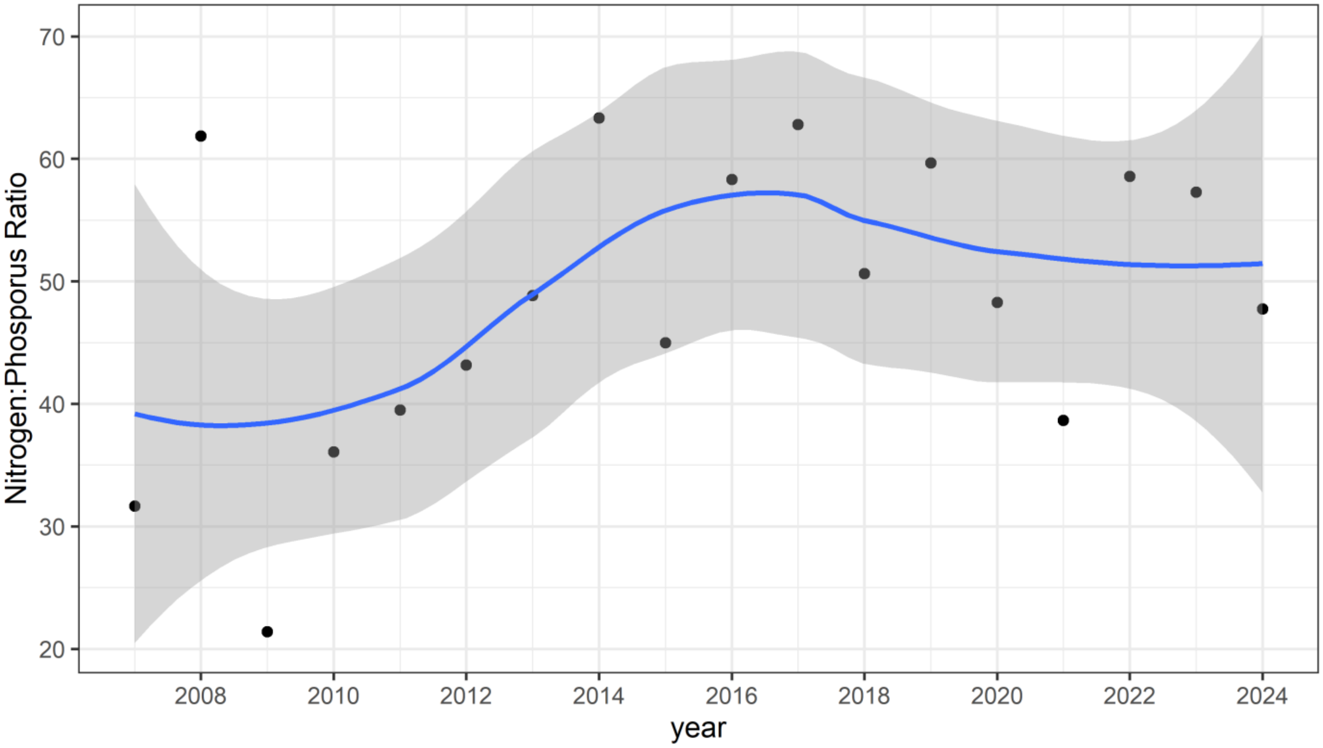


Figure 18. Nitrogen:phosphorus ratio from September in the epilimnion (years 2007 through 2023). Note: curving lines are the smoothed fit of the data, and gray shading is the 95% confidence intervals for the smoothed fit.

Table 12. Kendall trend test nitrogen:phosphorus ratio for samples collected in June and September from 2007 through 2023. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Depth	Variable	# Years	tau	Slope	P-value
June	Epilimnion	N:P Ratio	15	-0.18	-0.69	0.37

September	Epilimnion	N:P Ratio	18	0.25	1.24	0.15

7. *Chlorophyll a*

Chlorophyll a concentration in the epilimnion of Loon Lake is relatively low, with concentrations characteristic of oligotrophic, low productivity lakes. The maximum chlorophyll *a* concentration in the summer was 3.2 µg/L in July of 2018. Most other chlorophyll *a* concentrations from the period are below 2.0 µg/L in the epilimnion. In September, chlorophyll *a* is lower in recent years with a small negative slope, but not statistically significant (Table 13), (Figure 19). The epilimnion is the only depth zone sampled for chlorophyll a during the period of 2007-2024. As previously discussed Loon Lake has a metalimnetic maximum for dissolved oxygen and a likely driver of that maximum is increased algal production which would have higher chlorophyll a concentrations.

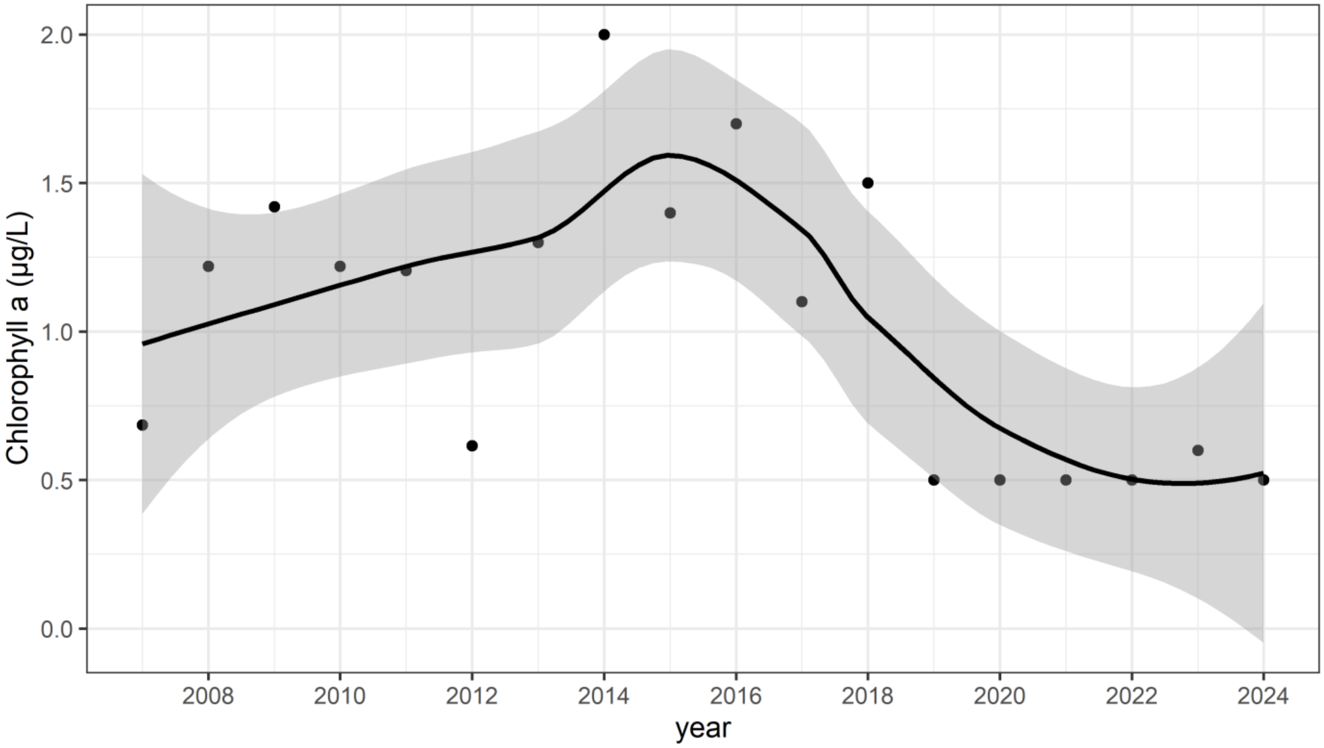


Figure 19. Chlorophyll a from September in the epilimnion (years 2007 through 2023). Note: curving lines are the smoothed fit of the data, and gray shading is the 95% confidence intervals for the smoothed fit.

Table 13. Kendall trend test for chlorophyll a for samples collected in June and September from 2007 through 2024. Note: P-values in bold are statistically significant at alpha level 0.05.

Month	Depth	Variable	# Years	tau	Slope	P-value
June	Epilimnion	Chlorophyll *a*	15	-0.20	-6.30	0.322

September	Epilimnion	Chlorophyll *a*	18	-0.327	-0.03	0.060

Discussion

To understand the results of this report and provide context, I will first discuss the key processes occurring in Loon Lake and how these results relate to them. Loon Lake, like other lakes in the temperate zone, thermally stratify in the summer. Thermal stratification produces distinct vertical zones in the lake where the upper water (epilimnion) is warm and well mixed with atmospheric oxygen. The mid layers of the lake develop steep temperature and density gradients (thermoclines), that “cap” the deepest part of the lake (hypolimnion), preventing the deeper, colder and denser water from mixing with the upper water. Aerobic bacteria in the hypolimnion decompose organic matter (mostly dead algae and zooplankton). As the bacteria decompose the organic matter, they use oxygen and produce CO2. Since the hypolimnion is isolated from the epilimnion, it does not get oxygen resupplied by the atmosphere, and oxygen concentration declines as the thermal stratification persists through the summer into the fall. When the sediment water interface of Loon Lake has oxygen, phosphorus is bound to iron and manganese oxyhydroxides. These chemical bonds store phosphorus in the sediment, and it is not available to the algae for growth. Phosphorus is an essential nutrient that regulates algae growth. When the hypolimnion of a lake becomes extremely low, or devoid of oxygen, phosphorus is released from the sediments and mixes in the water column in the fall when the lake is the same temperature throughout the water column (isothermal), and mixes from top to bottom. This phosphorus released from the sediments and mixed in the fall is available for algae growth in the spring.

Lake productivity and thermal stratification affect the amount of dissolved oxygen at the lake bottom. In more productive lakes, more algae and zooplankton are produced which supplies the hypolimnion with more organic matter. The higher amount of organic matter drives higher bacterial production with increased decomposition rates and increased oxygen consumption. This increase in lake productivity produces anoxia in the hypolimnion, which releases nutrients from the sediments into the water column (described above). This is essentially a degradation feedback loop where increased phosphorus feeds increased lake productivity that increases phosphorus release from the sediments, and amplifying lake productivity. This process is called “internal nutrient cycling” in lakes. Loon Lake has a high water residence time. It takes a long time for water to cycle in and out of the lake. Lakes with high water residence can be sensitive to internal nutrient cycling because of low inflow and flushing outflow. In other words, the phosphorus and nitrogen that accumulate in the hypolimnion over the summer and mix in the fall remain in the lake over the winter and are available to grow more algae the next season. An encouraging result for the Loon Lake is the significantly increasing trend in dissolved oxygen in the hypolimnion in August. This trend may be an indication that bacterial respiration in the upper hypolimnion is lower due to less lake productivity and less organic matter production. However, the increasing dissolved oxygen trend is for the entire hypolimnion, and the deepest waters in the lake are still anoxic (zero dissolved oxygen), or hypoxic (< 3 mg/L) dissolved oxygen.

As mentioned above, lake productivity is also an important driver for oxygen reduction in the hypolimnion. The two most important productivity variables collected in the LLPOA monitoring program are total phosphorus and chlorophyll *a*. In Loon Lake total phosphorus concentration in the hypolimnion significantly increases over the season from June through September. The increase in phosphorus concentration over the season is likely the product of the anoxic (no oxygen) sediment/water interface and liberation of phosphorus from the sediments. Higher lake productivity (more algae) increases the concentration of phosphorus in the sediments as the algae and the zooplankton the algae feed, die and sink to the sediments. Thus, more algae produce more phosphorus that binds to the sediments (described above), which equates to more phosphorus being liberated by the sediments under anoxic conditions. It is important to note that total phosphorus concentration is significantly lower now in the epilimnion and hypolimnion in September compared to the late 2000's when the LLPOA monitoring began. The current, lower phosphorus concentrations may be an indicator that internal phosphorus loading is decreasing.

The LLPOA monitoring samples 1, 3 and 5 meters of the upper water column for chlorophyll *a*. Chlorophyll *a* is a key indicator of lake productivity, and in Loon Lake is low. Higher chlorophyll *a* equates to increased lake productivity, which is correlated with low oxygen in the hypolimnion. The low chlorophyll *a* in the upper waters of Loon Lake contradicts the high oxygen demand in the hypolimnion of Loon Lake. However, the dissolved oxygen in the metalimnion (below the depths where chlorophyll *a* was collected) is higher than any other depth zone in Loon Lake. This metalimnetic dissolved oxygen maximum is likely driven by high algae densities and the physics associated with the density layers in the metalimnion (Wilkinson et al. 2015). Thus, Loon Lake is likely significantly more productive than what the historic sampling protocol has generated.

An important finding in this analysis is that Loon Lake is becoming warmer, and in late summer the entire water column is warmer than it was when the LLPOA monitoring started. The warming trend in Loon Lake is consistent with temperate lakes around the world (O'Rielly et al. 2015). Increasing lake temperature affects the dissolved oxygen concentrations throughout lakes by reducing dissolved oxygen solubility (Zhang et al. 2025). A warmer water column, especially in the hypolimnion increases the metabolic rate of aerobic bacteria which are decomposing the organic matter settling into the hypolimnion. The duration of thermal stratification is an important aspect of Loon Lake's temperature dynamics. Rising lake temperatures and earlier seasonal warming extend the period of thermal stratification, resulting in a decrease in dissolved oxygen levels in the hypolimnion (Woolway et al. 2022). The LLPOA data set for temperature does not have spring and late fall profiles which are needed to better estimate the duration of thermal stratification.

Conclusions

Loon Lake continues to have a significant anoxic/hypoxic deep hypolimnion, with seasonal decreasing dissolved oxygen and seasonal increasing total phosphorus, characteristics of water quality impairment from internal nutrient cycling. However, dissolved oxygen and total phosphorus concentrations in the hypolimnion are improved compared to the late 2000's. Continued water quality monitoring is imperative to determine if these improving conditions persist over time, and if the internal nutrient loading declines over time.

Recommendations

Water Column Profiles

1. Expand water column profiles (hydrolab) and Secchi disk depth from April through November (one meter intervals surface to bottom), (
2.
3. Table 14).
    a. Reason: Expanding the hydrolab profiles earlier and later will improve the estimation of:
        i. Duration of thermal stratification and lake warming/cooling characteristics.
        ii. Onset and duration of dissolved oxygen maximum in metalimnion.
        iii. Onset and duration of dissolved oxygen decline in hypolimnion.

4. Keep the South Deep site and add a new Northern Deep site for profiles (hydrolab) and Secchi disk depth from April through November (one meter intervals surface to bottom), (
5.
6. Table 14).
    a. Reason: estimate the spatial extent of water column variables.
        i. Thermal stratification depths and intensity
        ii. Hypolimnion dissolved oxygen
        iii. Metalimnetic dissolved oxygen maximum

Water chemistries

7. If the recommended increased effort in water profile (hydrolab) sampling squeezes time and budget, I would recommend discontinuing water sampling for total phosphorus, total nitrogen and chlorophyll *a* in June and July (
8.
9. Table 14).
    a. Reason: July has been inconsistently sampled throughout the period, and the small number of samples reduces the ability to statistically test for trends.

10. Sample water at the South Deep site in August and September for total phosphorus (TP), total nitrogen (TN) in epilimnion, metalimnion and hypolimnion. Sample water at the South Deep site in August and September for chlorophyll *a* in epilimnion and metalimnion (Table 14).
    a. Maintain Depths 1, 3 and 5 meters for epilimnion samples
    b. Maintain Depths 21, 24 and 27 for hypolimnion samples
    c. Discontinue the mid (9, 12 and 15 meter) sampling.
    d. Add a metalimnion depth zone, identified by the depths where temperature decreases at least 1 °C per one meter depth increase.

Quality Assurance Project Plan (QAPP)

11. Update the QAPP to reflect current sampling methodologies, sample handling and data management.

Databases

12. Update the water chemistry and profiles databases annually.

Reporting

13. Produce a lite annual lake status summary.
    a. Reason: A concise lake status summary report updating the trends analysis for the LLPOA members.
        i. A one or two page format updating the status of the lake compared to previous years.
        ii. Use the statistical methods from this synthesis report to update the trends in table format and use summary graphs of important water quality indicators.

Table 14. Proposed annual sampling schedule for Loon Lake based on recommendations in this report.

Sampling Method	Site	Depth Zone	April	May	June	July	Aug	Sept	Oct	Nov
Hydrolab Profiles[1]	South Deep	Surface to Bottom	X	X	X	X	X	X	X	X
Hydrolab Profiles[1]	North Deep	Surface to Bottom	X	X	X	X	X	X	X	X
TP, TN, Chlorophyll a	South Deep	Epilimnion[2]					X	X		
TP, TN, Chlorophyl a	South Deep	Metalimnion[3]					X	X		

TP, TN	South Deep	Hypolimnion[4]					X	X		

1. Sample entire water column from surface to bottom in one meter increments for temperature, pH, Dissolved oxygen, conductivity and Secchi disk depth.
2. Epilimnion depths, composite of 1, 3 and 5 meters.
3. Metalimnion depths, identified by the depths where temperature decreased at least 1 °C per one meter depth increase.(three depths to composite would be optimal).
4. Hypolimnion, composite of 21, 24 and 27 meters.

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