Water Quality Trends in North and South Lake Leelanau, 1990-2024

Maria Scarborough, Madison Moore, and M. Megan Woller-Skar, Ph.D
Department of Biology
GRAND VALLEY STATE UNIVERSITY, ALLENDALE, MI 49401

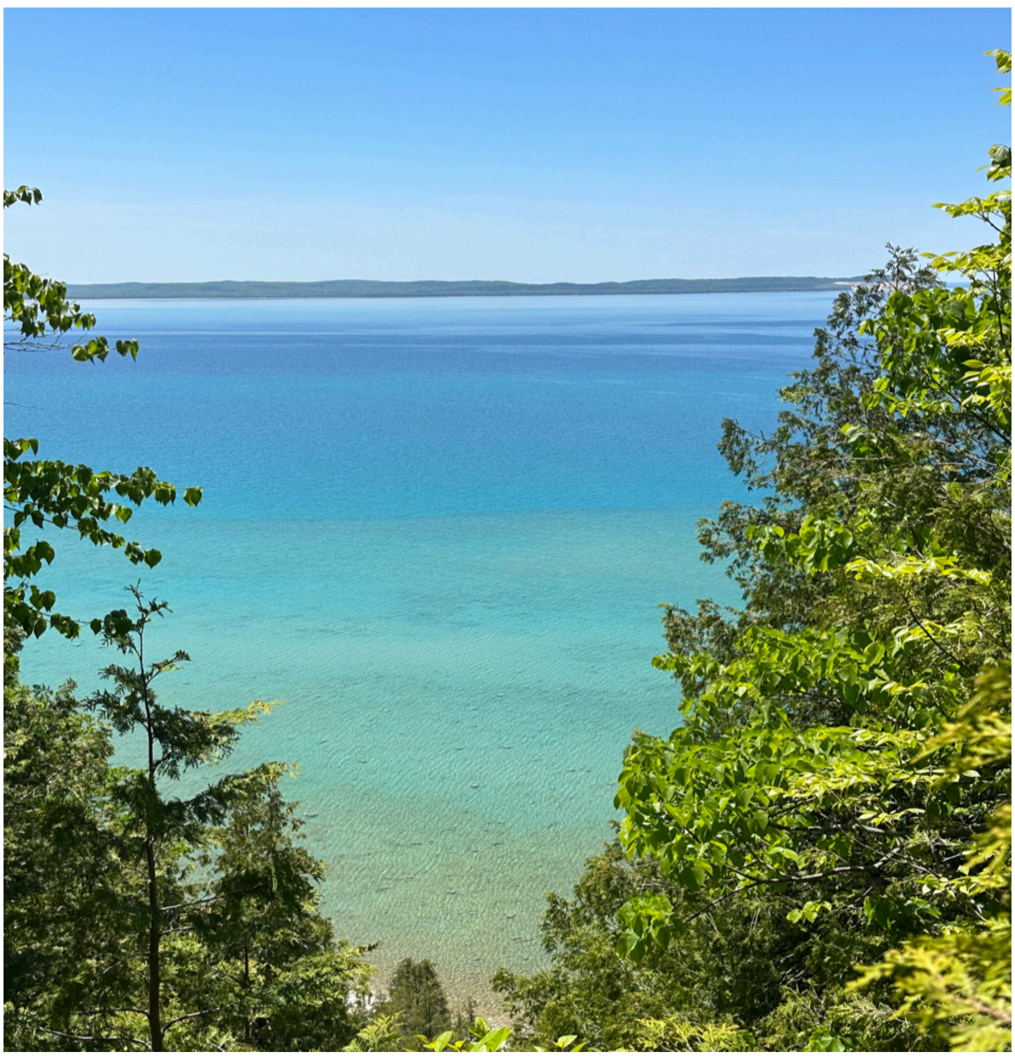

TABLE OF CONTENTS

OVERVIEW

Abstract

Water quality monitoring has been conducted in a standardized method in Leelanau County for the past 34 years. Throughout this time, a variety of organizations, individuals, and volunteers have contributed to a robust collection of data that helps tell the story of water quality trends in Leelanau Lakes. For this study, we focused our analyses on the deepest basins of North and South Lake Leelanau. We monitored trends in total phosphorus, NOx, temperature, ORP, conductivity, and dissolved oxygen. We compared trends in months May through October for both the surface layer and bottom layer of North and South Lake Leelanau.

Thermal stratification of both North and South Lake Leelanau has increased in duration, with the surface temperature of the warmest months increasing significantly over the last three decades. Total surface phosphorus has increased, while NOx has decreased. Increased temperature in the surface and at depth was supported by principal components analyses (PCA) in North and South Lake Leelanau. PCA also showed increased oxidative reductive potential. These changes highlight the effects that global temperature rise has had on northern oligotrophic lakes. The increase in available surface phosphorus coupled with a warmer and more persistent stratification can increase the likelihood and intensity of algal blooms. Therefore the need for consistent implementation of best management practices and a continued effort to reduce nutrient loading is essential to protect the health of Lake Leelanau as we continue to face the effects of climate change.

Site Summary

Lake Leelanau is a large (8,607-acre) oligotrophic lake located within Leelanau County, Michigan (Figure 1). The watershed drains an area of roughly 140 square miles (Hanchin et al. 2007) across three counties, and is notable for its clear blue lakes, natural lands, and its abundance of recreational opportunities. The lake itself is divided into two main basins separated by an approximately mile-long navigable channel known as “the narrows”. The two basins (though limnologically linked through shared surface water) are often considered to be independent lakes, particularly in ecological analyses. Despite their connection, the two basins will be referred to and analyzed separately throughout this report as: North Lake Leelanau (or NLL), and South Lake Leelanau (or SLL).

South Lake Leelanau is the larger of the two basins, with a surface area of 5,693 acres, an average depth of 25 feet (7.6 meters), and a maximum depth of 62 feet (20 meters) (U’ren et al. 2010). It has 25 miles of shoreline and a volume of 5,356 million cubic feet (Farber and Nielsen 2001). The primary source of surface water inflow (about 78%) to SLL is through the Solon Swamp, where Victoria Creek and Cedar Run Creek converge (U’ren et al. 2010). North Lake

Leelanau is smaller in surface area, though it contains roughly 98% the volume of SLL, due to its greater average depth. It is 2,419 acres with an average depth of 43 ft (13m) and a maximum depth of 120 ft (about 40m) (U'ren et al. 2010). It has 15 miles of shoreline and a volume of 5,260 million cubic feet (Farber and Nielsen 1998). The lake empties through the Leland River, on the west end of the lake, into Lake Michigan, and has an estimated retention time of 2.07 years (Northwest Michigan Regional Planning and Development Commission 1983).

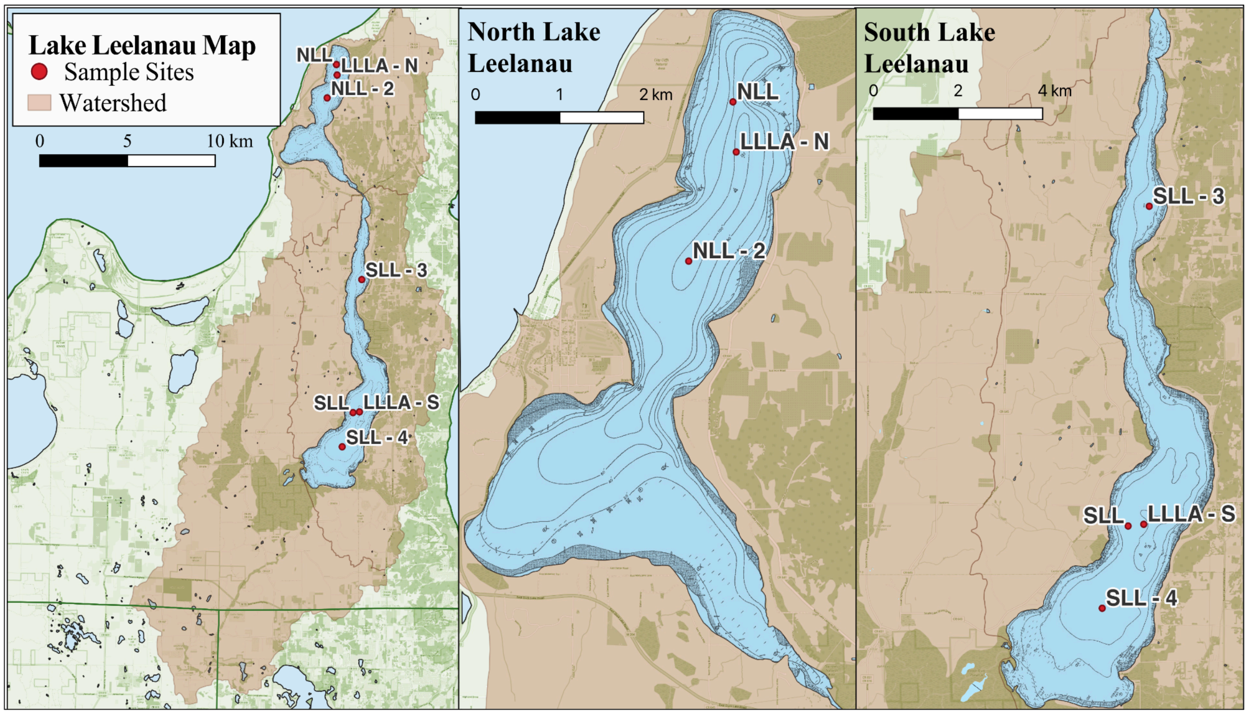

Figure 1. Sampling locations within the Lake Leelanau watershed. Red dots indicate sampling sites labeled with site abbreviations*. Inset maps provide detailed views of North Lake Leelanau and South Lake Leelanau. Depth contours from Michigan DNR inland lake maps (1948). *Site locations are approximate.

Since the initiation of the water quality monitoring program in 1990, thousands of data points have been collected across the major lakes in Leelanau County. In this report alone, we analyzed 11,496 samples from NLL and 9,336 samples from SLL (See Appendix Table A1). For analyses that required full-depth profiles (temperature) or a separation of surface and bottom samples, we used only data from the deepest part of each lake.

Project Goal

The goal of this report is to synthesize the data collected over the last 34 years into a meaningful interpretation of the status of water quality in Lake Leelanau. To the best of our ability, we have summarized our findings in the context of available information. However, the snapshot of data we get from a single sample on a single day can only tell us so much. The nutrients in lakes and the ecosystem dynamics are in constant motion, and relation to the system around them. While we can gain an understanding of general trends in the lake over time, the data presented here should be used as guidelines and not a finite sentence. Additionally, we have agency in our relationship to these natural resources and can use the trends we observe to initiate change. Although we cannot change the amount of precipitation or the global change in climate patterns, we can take small actions through policy, reductions in motorized boat usage, implementation of riparian buffers, reducing or eliminating use of fertilizers on lakeshore properties, and reducing development especially of impervious surfaces. Together we can be responsible stewards of our incredible natural resources and ensure that the work we do today benefits not only ourselves, but our future generations.

INTRODUCTION

Trophic Status

The trophic status of a lake provides a quick summary of water quality breaking lakes into categories ranging from high water quality (oligotrophic), medium water quality (mesotrophic), and poor water quality (eutrophic, Table 1). These categories are determined by specific parameters such as total phosphorus, secchi depth, and frequency of blue-green algal blooms; values for these parameters per trophic state were originally determined by Wetzel (2001). Keeping trophic states in mind can help lake managers such as the Lake Leelanau Lake Association maintain Lake Leelanau as an oligotrophic lake.

Table 1. Lake trophic states based on phosphorus, nitrogen, secchi depth, and presence of blue-green algal blooms as determined by Wetzel 2001.

	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus (ug/L)	8	26.7	84.4
Total Nitrogen (ug/L)	661	753	1875
Secchi Depth (m)	10	4.2	2.5
Blue-Green algae	lacking blooms	-	blooms common

Lake Stratification

Lakes in Michigan stratify, or form layers and completely turnover, or mix from top to bottom, twice a year (Figure 2). These lakes are stratified in summer and winter, and turnover in fall and spring. The top layer is the epilimnion, which we refer to as the “surface” and the bottom layer is the hypolimnion, which we refer to as the “bottom” or “deep” throughout this document (Figure 2).

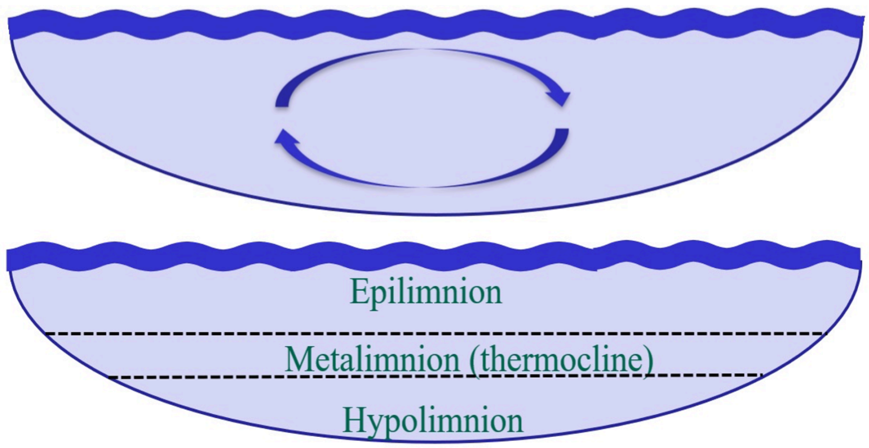

Figure 2. Cross section of a Michigan lake during turnover (top graphic) and stratification (bottom graphic) with layers.

When lakes stratify, the top and bottom are essentially completely separate habitats, with different concentrations of nutrients and temperatures. These different conditions often support different species of algae and fish. It is for this reason that samples are taken at different depths in summer, and why we focused our analyses at the surface and bottom of the lake from May - October.

Temperature

One of the greatest threats to lakes like ours is the global increase in air temperature due to climate change (Butcher et al. 2015; Edlund et al, 2017; Stetler et al. 2021). Warmer air temperatures can lead to stronger and more prolonged thermal stratification, beginning earlier and persisting later into the year. As average surface temperatures approach or exceed 25℃, conditions become more favorable for harmful algae, like cyanobacteria (Robarts & Zohary; 1978, Konopka & Brock, 1978), increasing the likelihood of blooms. Additionally, warmer surface temperatures later in the year can delay the onset and duration of the ice-covered period, limiting access to winter recreation, and impacting key ecological functions of an ice-covered lake.

Lakes that support cold water fish species are particularly vulnerable to warming. Certain species like walleye - a common game species in North and South Lake Leelanau - prefer temperatures between 10-22 ℃ (Christie & Regier 1988). As average water temperatures increase, the space that is habitable to species like this can be reduced, potentially threatening their ability to forage, reproduce, and survive through the winter. Therefore, monitoring and understanding long-term trends in lake thermal structure is essential in understanding the health of the overall ecosystem.

Nitrate / Nitrite (NOx)

In our study, we focused on two forms of dissolved inorganic nitrogen, which are often monitored when looking at water quality - nitrite and nitrate, or more simply, NOx. In NLL and SLL, we would expect NOx concentrations to be low, due to the limited nutrient input and high concentrations of dissolved oxygen that are typical of deep oligotrophic lakes. During stratification, we would expect surface NOx to decline over time as it is used up by phytoplankton and aquatic plants. In the bottom waters, NOx is more likely to be stable throughout the stratified period.

Total Phosphorus (TP)

Globally, phosphorus is a key driver of eutrophication of lakes and because of this, has been intensely studied over the last 5 decades. Even small increases can tip a lake toward algal blooms which can be both a nuisance and potentially harmful to human and animal health (Reinl et al., 2021). Because of its central role, phosphorus is routinely monitored to track water quality and assess the impacts of land use and climate change on ecosystem health. Sources of phosphorus include increased development - especially impervious surfaces, agriculture, septic systems, and eroded soils (Carpenter et al., 1998). In our lakes, surface phosphorus may increase early in the summer due to seasonal nutrient loading, then decline as plant and algal uptake (along with chlorophyll a) increase. In contrast, bottom phosphorus may likely remain stable, particularly during the stratified period if bottom waters remain well oxygenated.

METHODS

Site Description and Long-term Monitoring

Long term monitoring of North and South Lake Leelanau has been ongoing since 1990. Most of the data analyzed in this report were collected from the deepest parts of each lake (Appendix Table A1). These sites provide data from both the surface and bottom waters of NLL and SLL and allow us to monitor the trends in the stratified lakes. For more comprehensive site and long-term monitoring descriptions see Keilty & Woller 2002.

Statistical Analyses

For both NLL and SLL, the surface was defined as ≥ 0 meters and < 2 meters depth. In the deeper NLL, the deep/bottom was defined as ≥ 30 meters and < 34 meters depth for samples that had fine scale measurements (i.e. temperature). For samples with coarse resolution, we defined the bottom as ≥ 20 meters and < 30 meters depth. For the shallower SLL, the deep water was defined as ≥14 meters and < 17 meters depth for samples with finer scale (i.e. temperature), and ≥ 16 and ≤ 18 for those with broader scale samples.

For ease of visualization, data were often plotted by "decade". Because we have more than 30 years of data, the decades were defined as "the 1990s" (1990-2001), "the 2000s" (2002-2012), and "the 2010s" (2013-2024). Additionally, most data were filtered to "summer months" which we considered to be May/June through September/October. This range was chosen as the majority of samples were collected during these months, the lake is most likely thermally stratified, and the separation in concentrations between surface and bottom layers of the lake are the most distinct.

Long-term trends were identified using principal components analysis (PCA). This is a technique that specializes in summarizing complex data into the parameters of greatest importance, and allows visualization in 2-dimensional plots. We separated data by basin (NLL and SLL) and depth (surface and bottom) for analyses and reported the amount of data included in the plot to allow for assessment of confidence.

Before analyses, any point greater than 3 standard deviations from a given mean value was considered an outlier. Most outliers were removed, however, in cases when outliers were within the context of a full depth profile (e.g. temperature), values were checked against all data from the sample date and retained if they were either (a.) within the expected range of that date's values, or (b.) ecologically plausible due to large rain or wind events if historical weather data were available. All statistical analyses were conducted using R Statistical Software (R version 4.4.3; R Core Team 2025). Data that violated assumptions were transformed (usually log10, ln, or sqrt) and a confidence interval of 95 percent (alpha = 0.05) was used to define significance in all statistical tests.

Spatial Analyses

Often, water quality is impacted by fertilizer application and nutrient runoff, specifically nitrogen and phosphorus, with likely sources being runoff from agricultural and urban/developed cultivated lawns. Because of this interest in water quality, we conducted spatial analyses focused on the following land cover categories: agricultural, forested, bare land, developed, and water. Although forest, agriculture, and developed land are relatively easy to interpret, the category "open land" is a bit ambiguous. In this sense, open land can be interpreted and anything with low vegetation, such as fallow land, meadow, etc. Land cover data were raster files with 30m x 30m resolution accessed from GIS Michigan Open Data and USGS National Map Download Applications (https://www.usgs.gov/the-national-map-data-delivery/gis-data-download).

We had two objectives with spatial analyses: to quantify land cover in the Lake Leelanau watershed over time, and to locate sites in the watershed with both high slope and agricultural land cover in 2023. Because of the long 30 year period, we chose land cover in 5-year increments starting with 1993 to correspond to the beginning of the Leelanau Conservancy's water quality data collection and ending in 2023. By looking at changes in land cover from 1993 to 2023, we hoped to potentially identify locations within the Lake Leelanau watershed that could be related to changes in nitrogen and phosphorus within the lake. Since the threat of eutrophication is expected to increase with climate change, we wanted to find the overlap between high slopes and agriculture land cover. This overlap identifies areas in the watershed where rain gardens and landscaping for water quality could mitigate fertilizer runoff.

RESULTS

Temperature

North Lake Leelanau

Thermal profiles of NLL revealed warming trends across all months over the last three decades. In later decades, stratification begins earlier, in May rather than June, and persists into October with warmer temperatures (Figure 3). The average depth and temperature of the thermocline did not significantly change, though the presence of a thermocline in May and October were detected in later decades only, suggesting a shift in stratification intensity over time (Table 2).

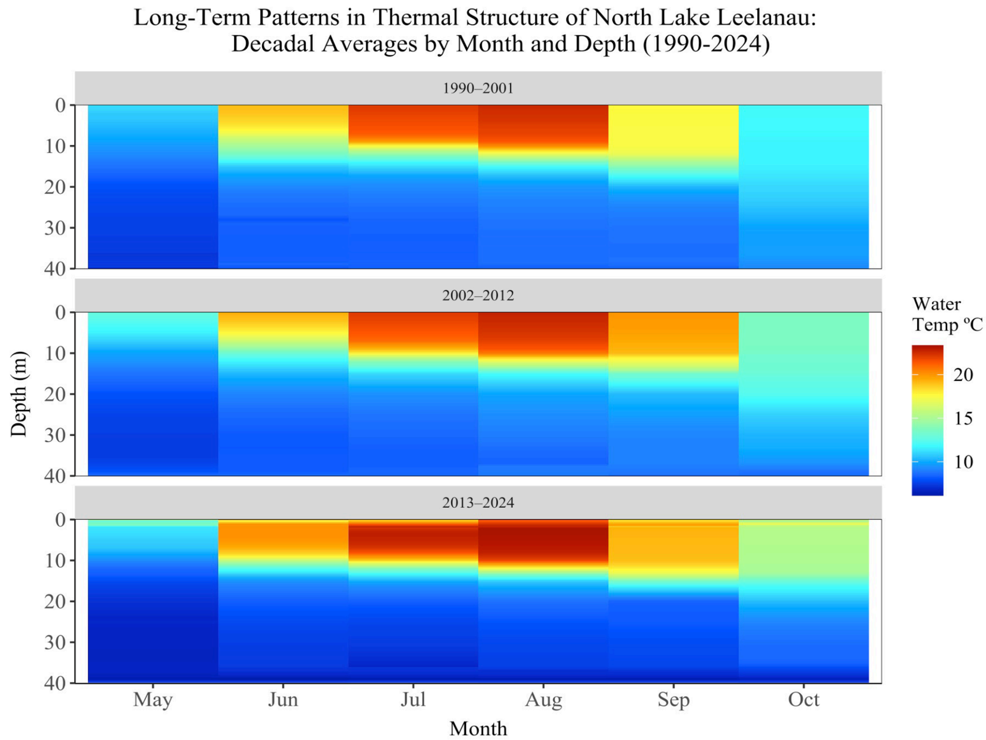

Figure 3. Thermal structure of North Lake Leelanau summarized by monthly depth averages across decades (1990-2024). Based on interpolated profiles from sampling dates with vertical coverage (≥ 30 m depth range, ≥ 5 depth layers). Total number of samples summarized n = 2,726 (n = 1428, 534, 764).

Average surface temperatures increased in all months except May. A linear regression analysis of temperature in summer months (June- September) suggests slight warming with an estimated average yearly temperature increase of 0.036 °C, though not significant ($p = 0.068$). The warmest month of the year, August, showed a significant increase in temperature ($p = 0.005$) with an estimated annual increase of 0.066°C (Figure 4). Additionally, a model of just the peak summer months, July and August, shows significant warming highlighting that while the variation between June and September is not significant, the warmest months are seeing significant increases in temperature.

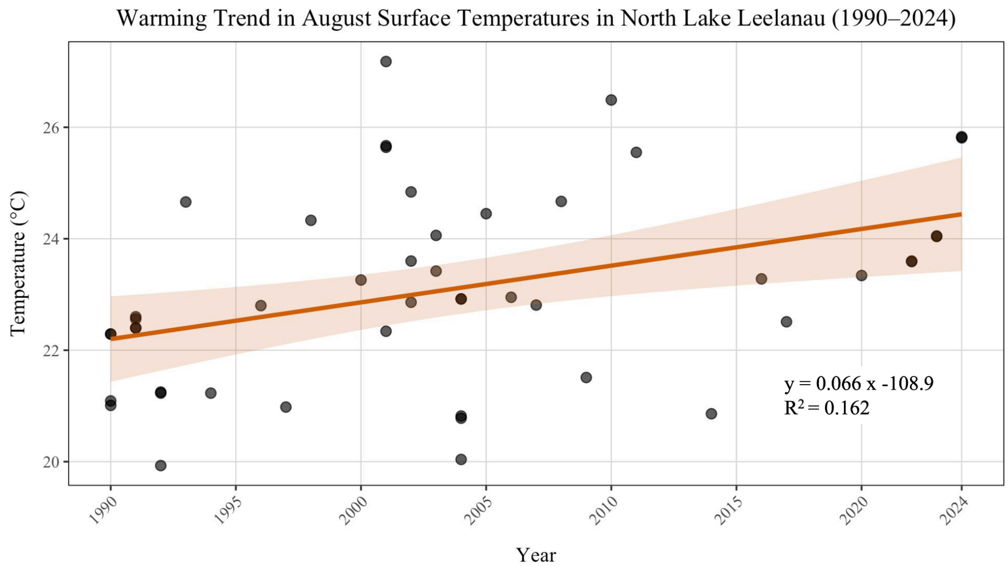

Figure 4. Long-term trends in August surface water temperature in North Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant warming trend of +0.066 ºC per year ($p = 0.005$), with both the slope and intercept statistically significant ($p < 0.001$). The model explains 16.2% of the variation in temperature ($R^2 = 0.162$), and assumptions of normality and heteroscedasticity were met.

In the bottom waters, the opposite seems to be true. A regression analysis of temperature trends in summer months (June – September) show a measurable and significant decrease in overall temperature at a rate of -0.033 °C per year (Figure 5). The model, slope, and intercept were all significant ($p < 0.001$), with 16.7% of the variation in temperature over time explained by the model ($R^2 = 0.1668$).

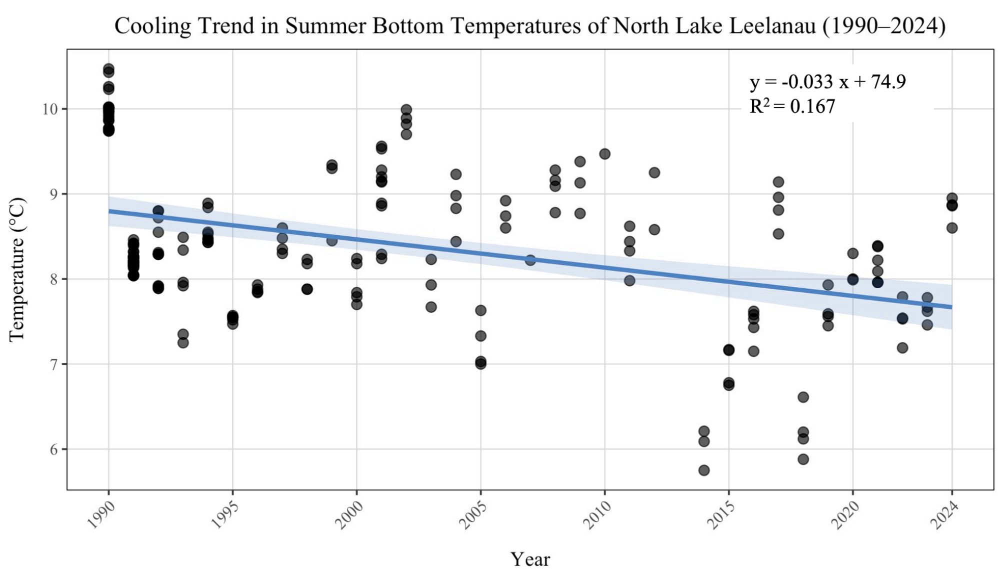

Figure 5. Long-term trends in summer bottom water temperature in North Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant cooling trend of -0.033 ºC annually ($p < 0.001$), with both the slope and intercept statistically significant ($p < 0.001$). The model explains 16.7% of the variation in temperature ($R^2 = 0.167$).

Table 2. Summary table including mean values, associated standard error (SE), and total number of samples (n), of the termocline depth in North (NLL) and South (SLL) Lake Leelanau by season and decade.

			May	Summer	September	October
NLL	1990-2000	mean ± SE	-	9.76 ± 0.63	14.75 ± 1.00	-
		n	-	25	8	-
NLL	2001-2012	mean ± SE	-	9.30 ± 0.53	14 ± 0	-
		n	-	24	2	-
NLL	2013-2024	mean ± SE	7.33 ± 1.67	10.34 ± 0.70	14.29 ± 0.18	14.38 ± 0.39
		n	3	21	7	2
SLL	1990-2000	mean ± SE	-	11.14 ± 0.66	13.50 ± 0.67	-
		n	-	21	6	-
SLL	2001-2012	mean ± SE	-	10.55 ± 0.67	13.75 ± 0.25	-
		n	-	22	4	-
SLL	2013-2024	mean ± SE	7.25 ± 5.3	10.62 ± 0.90	14.76 ± 0.32	14.85 ± 0.14
		n	4	17	9	2

South Lake Leelanau

In SLL, we see similar trends. Thermal profiles revealed warming trends across all months over the last three decades (Figure 6). In later decades, stratification begins earlier, in May rather than June, and persists into October with warmer temperatures. The average depth and temperature of the thermocline did not significantly change, though the presence of a thermocline in May and October were detected in later decades only, suggesting a shift in stratification intensity over time (Table 2).

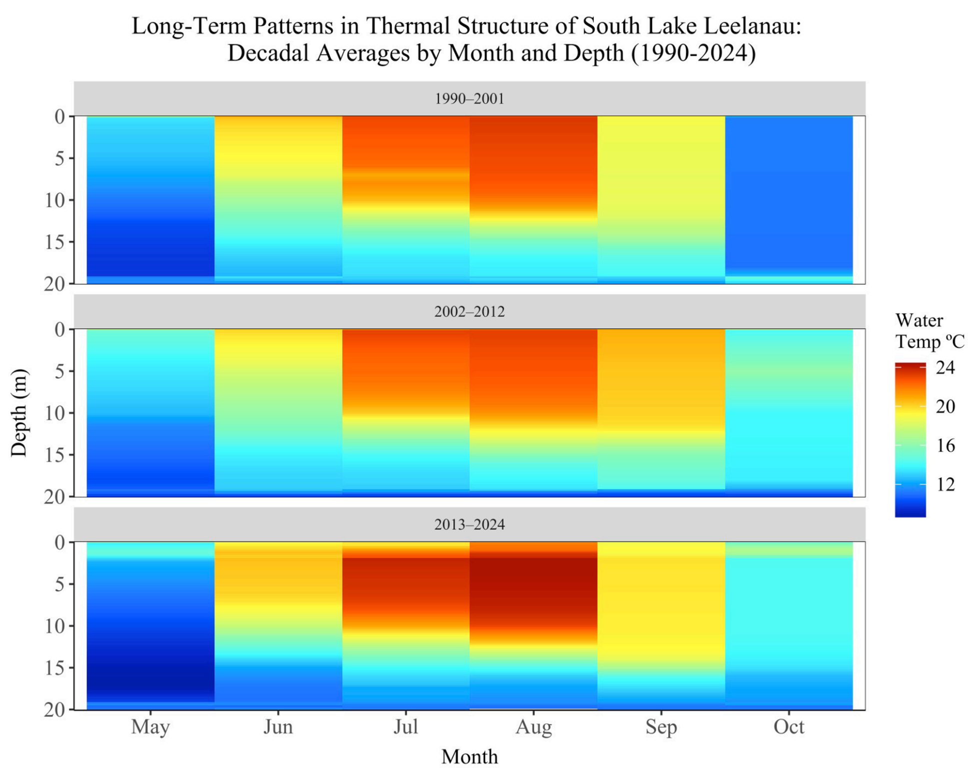

Figure 6. Thermal structure of South Lake Leelanau summarized by monthly depth averages across decades (1990-2024). Based on interpolated profiles from sampling dates with vertical coverage (≥ 15 m depth range, ≥ 5 depth layers). Total number of samples summarized n = 1930 (n = 784, 494, 652).

The average temperature of summer months is increasing over time, particularly in July and August. A simple linear regression of summer months (June - September) showed us a slight, but significant warming trend with model and slope significant ($p < 0.05$). This model explains only 2.7 % of the variation in temperature over time ($R^2 = 0.0269$), with warming estimated to be +0.036 °C per year (Figure 6).

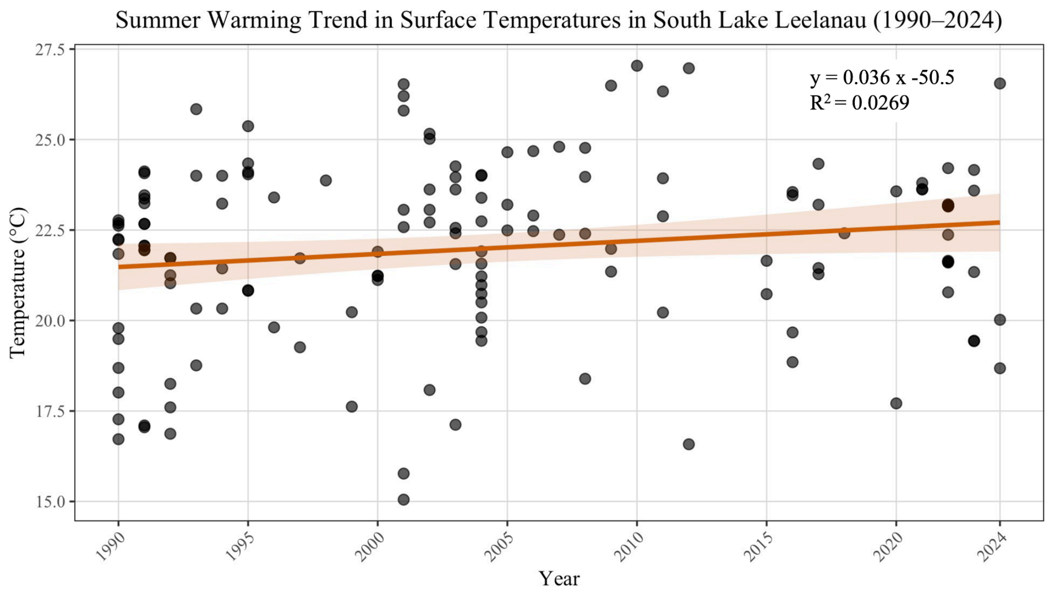

Figure 7. Long-term trends in summer surface water temperature in South Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant warming trend of +0.036 ºC per year ($p < 0.01$), with both the slope and intercept statistically significant ($p = 0.02$). The model explains 2.7% of the variation in temperature ($R^2 = 0.0269$).

For the deep waters of SLL, we observe a slight but significant decrease in temperature over time (Figure 7). The linear model explains 2.4 % of the observed variation in temperature over time. The estimated change in temperature of the bottom is -0.036 ºC, meaning the temperature of the water on the bottom is decreasing by 0.036 ºC per year.

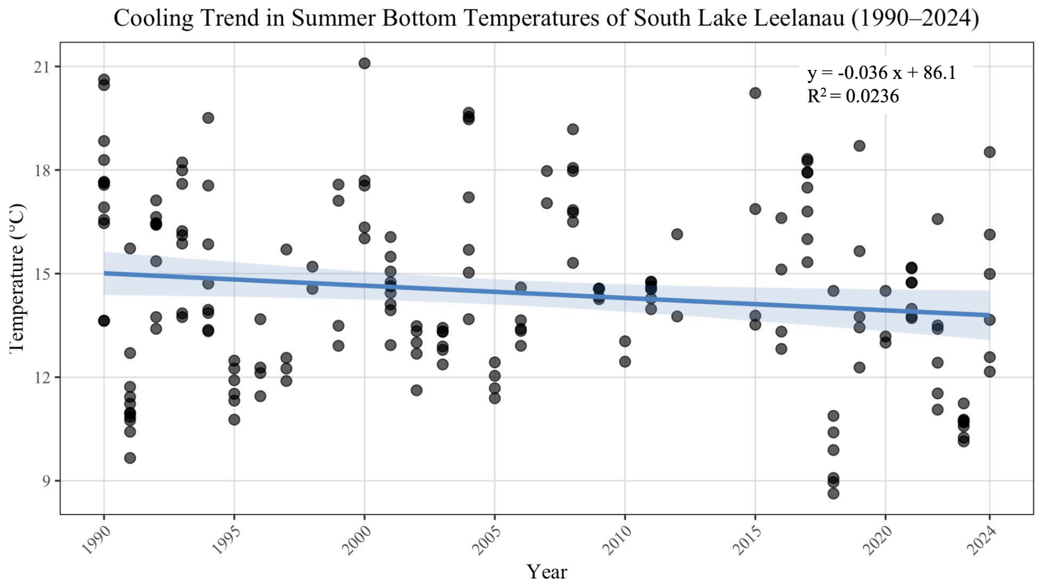

Figure 8. Long-term trends in summer bottom water temperature in South Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant cooling trend of -0.036 ºC per year ($p < 0.034$), with both the slope and intercept statistically significant ($p < 0.05$). The model explains 2.4% of the variation in temperature ($R^2 = 0.0236$).

Nitrate / Nitrite (NOx)

North Lake Leelanau

Average NOx concentrations in the surface waters of NLL have decreased over the last three decades, with the 2000s and 2010s being significantly lower than the 1990s (Figure 9). Figure 9 also shows a significant drop in NOx concentration in the deep waters from the 1990s to the 2000s, with the concentration stabilizing between the 2000s and 2010s. Additionally, we observe a decrease in the standard error and standard deviation, as well as a narrowing of the 95% confidence interval for both the surface and deep water, suggesting a reduction in variability of NOx over time (Table 3).

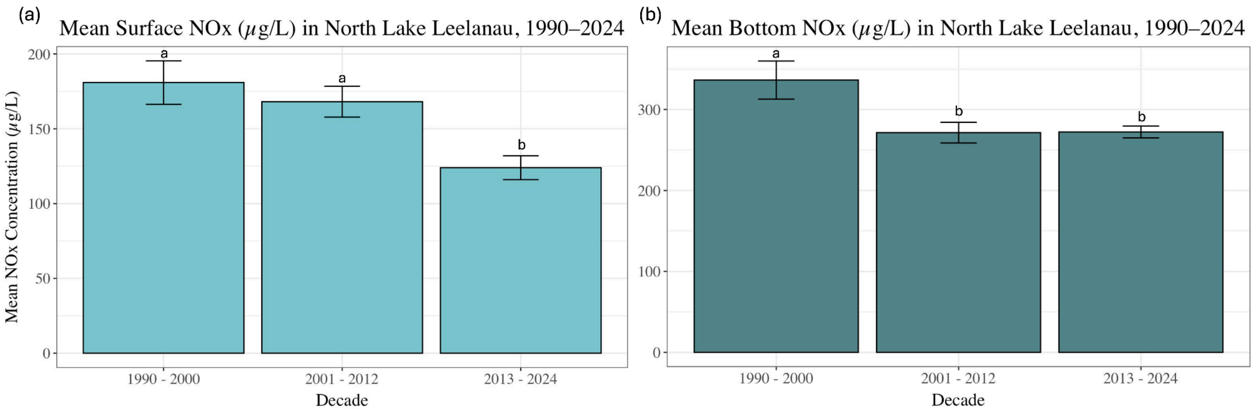

Figure 9. Mean summer NOx concentration (µg/L) in the (a) surface, and (b) bottom waters of North Lake Leelanau, summarized by decade (1990-2024). Error bars represent ± 1 standard error. Significant differences between decades are denoted by letters above each bar. Bars that share a letter are not significantly different; bars with different letters are significantly different (Tukey's HSD < 0.05).

Table 3. Summer NOx concentrations by decade in North Lake Leelanau (NLL), from the surface and bottom layers. Values measured include number of samples (n), mean NOx concentration (µg/L), standard deviation (SD), standard error (SE), and 95% confidence interval (CI).

Lake	Layer	Decade	n	mean	SD	SE	CI
NLL	surface	1990 - 2000	34	207.2	137.5	23.6	46.2
NLL	surface	2001 - 2012	55	168.1	76.5	10.3	20.2
NLL	surface	2013 - 2024	39	124.8	48.7	7.8	15.3
NLL	bottom	1990 - 2000	34	390.9	217.6	37.3	73.2
NLL	bottom	2001 - 2012	49	269.3	88.6	12.7	27.8
NLL	bottom	2013 - 2024	29	274.0	39.0	7.2	14.2

A simple linear regression of NOx concentrations in the surface water during summer months (June - September) showed a significant decrease in NOx concentration over time ($p < 0.001$), with the model explaining 14.9 percent of the variation ($R^2 = 0.149$, Figure 10). The estimated change in NOx concentration of surface waters in North Lake Leelanau is -3.01 µg/L per year.

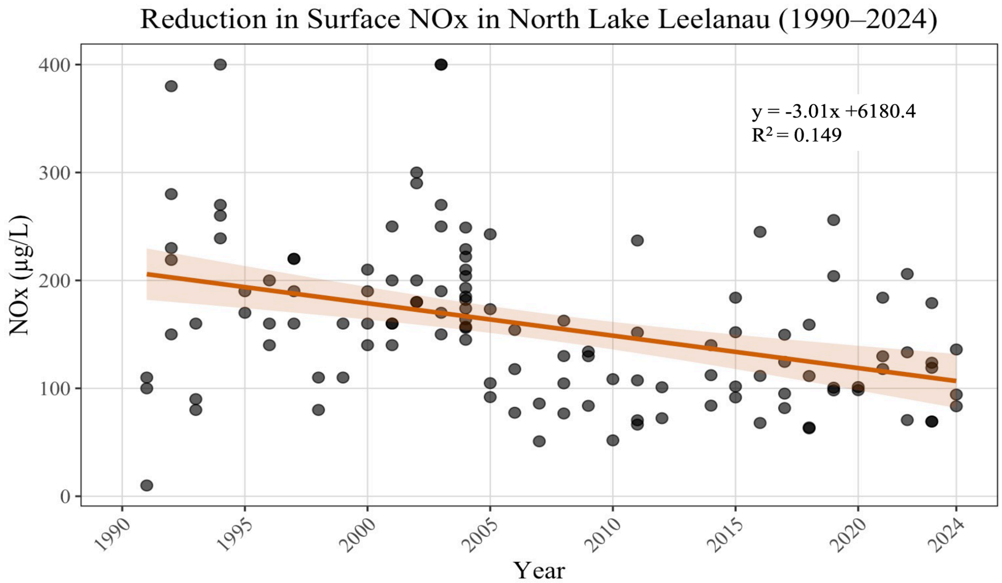

Figure 10. Long-term trend in summer surface NOx of North Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant decrease of -3.01 µg/L per year ($p < 0.001$), with both the slope and intercept statistically significant ($p < 0.001$). The model explains 14.9% of the variation in NOx over time ($R^2 = 0.149$).

This trend is consistent in bottom waters, with linear regression suggesting a significant decrease in NOx concentration over time ($p < 0.001$), with the model explaining 10.1 percent of the variation ($R^2 = 0.1005$, Figure 11). The estimated change in NOx concentration of the bottom waters is -3.11 µg/L per year.

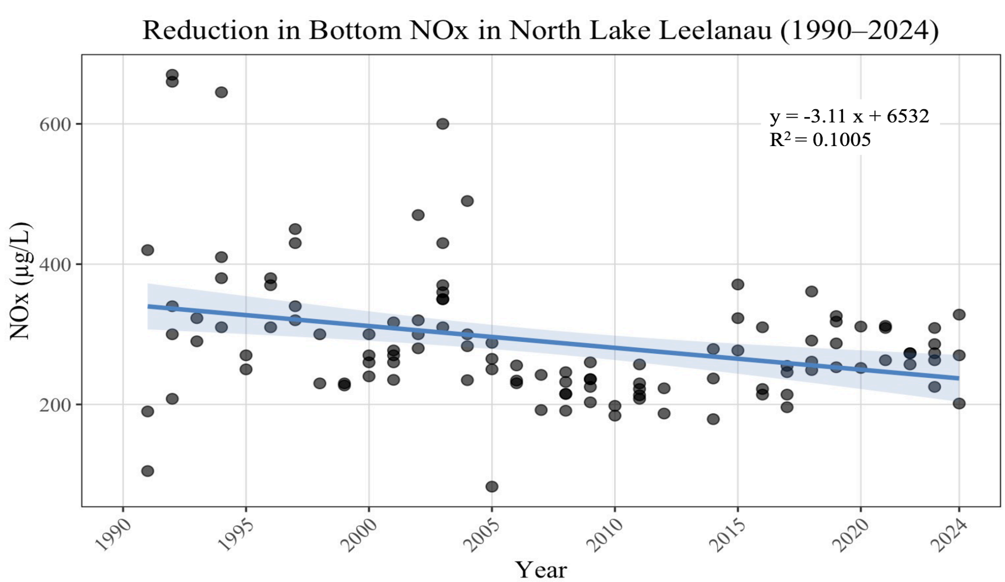

Figure 11. Long-term trend in summer bottom NOx of North Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant decrease of -3.11 µg/L per year ($p < 0.001$), with both the slope and intercept statistically significant ($p < 0.001$). The model explains 10.1% of the variation in temperature over time ($R^2 = 0.1005$).

Seasonal trends in NOx concentrations in the surface water of North Lake Leelanau show early season loading of NOx in all three decades, with concentrations dropping throughout the summer season (Figure 12).

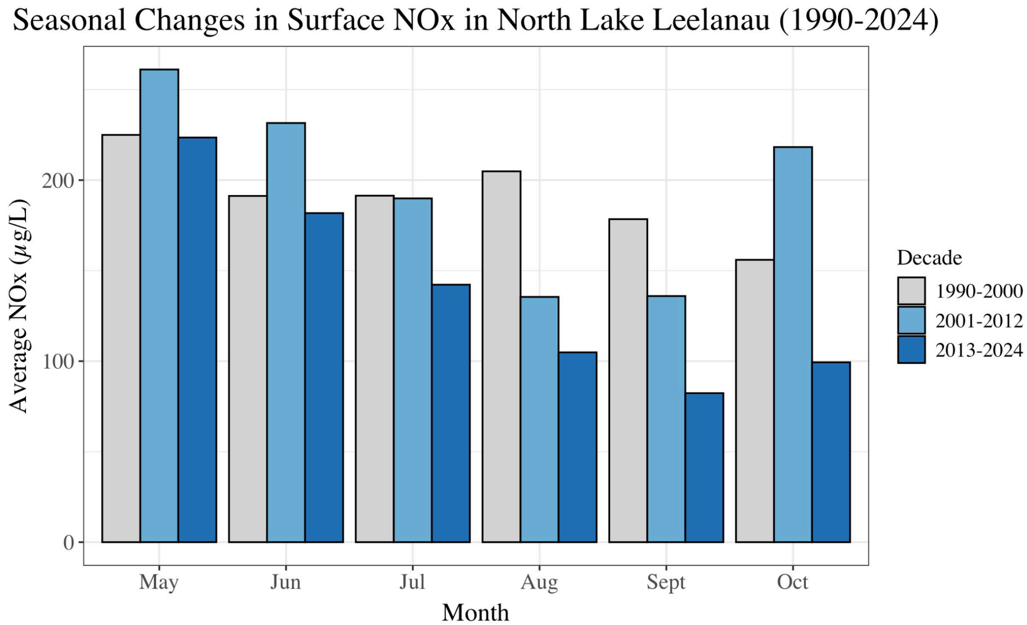

Figure 12. Average seasonal concentration of surface NOx (µg/L) in North Lake Leelanau over the last three decades.

South Lake Leelanau

Average NOx concentrations in the surface waters of South Lake Leelanau have decreased over the last three decades, with the 2010s being significantly lower than the 1990s and 2000s (Figure 13). Figure 13 also shows NOx concentrations in the bottom water remaining stable throughout the study period with no significant changes over time. Additionally, we observe a decrease in the standard error and standard deviation, as well as a narrowing of the 95% confidence interval for both the surface and deep water, suggesting a reduction in variability of NOx over time (Table 4).

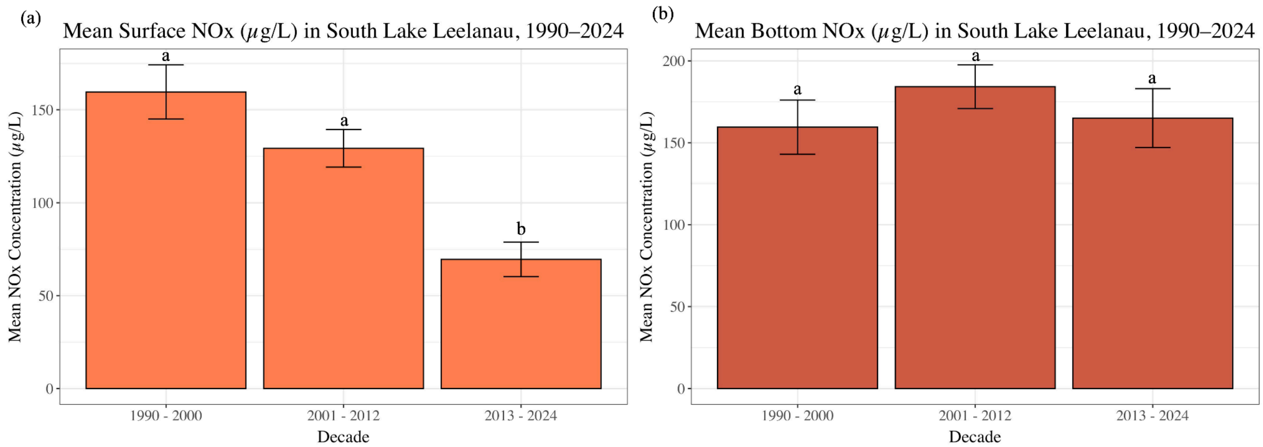

Figure 13. Mean summer NOx concentration (µg/L) in the (a) surface, and (b) bottom waters of South Lake Leelanau, summarized by decade (1990-2024). Error bars represent ± 1 standard error. Significant differences between decades are denoted by letters above each bar. Bars that share a letter are not significantly different; bars with different letters are significantly different (Tukey's HSD < 0.05, Dunn (Bonferroni method) <0.05).

Table 4. Summer NOx concentrations by decade in South Lake Leelanau (SLL), from the surface and bottom layers. Values measured include number of samples (n), mean NOx concentration (µg/L), standard deviation (SD), standard error (SE), and 95% confidence interval (CI).

Lake	Layer	Decade	n	mean	SD	SE	CI
SLL	surface	1990 - 2000	31	159.6	81.2	14.6	28.6
SLL	surface	2001 - 2012	54	129.3	74.3	10.1	19.8
SLL	surface	2013 - 2024	36	69.5	55.9	9.3	18.3
SLL	bottom	1990 - 2000	31	159.6	92.0	16.5	32.4
SLL	bottom	2001 - 2012	47	184.2	90.5	13.3	26.1
SLL	bottom	2013 - 2024	33	155.4	88.4	15.6	30.6

A simple linear regression of NOx concentrations in the surface water during summer months (June - September) showed a significant decrease in NOx concentration over time ($p < 0.001$), with the model explaining 24.9 percent of the variation ($R^2 = 0.149$, Figure 14). The estimated change in NOx concentration of surface waters in South Lake Leelanau is -4.08 µg/L per year.

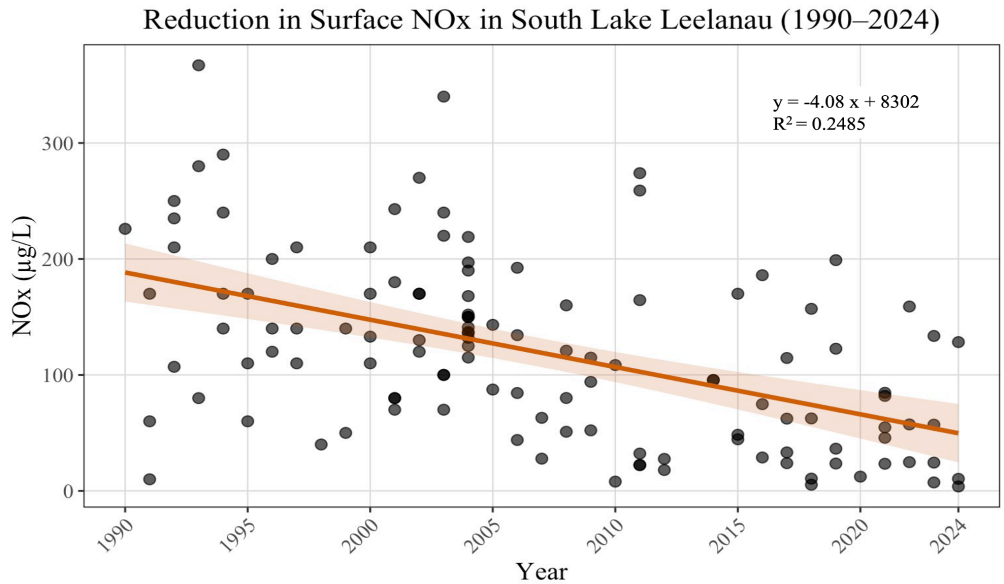

Figure 14. Long-term trends in summer surface NOx of South Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant decrease of -4.08 µg/L per year ($p < 0.001$), with both the slope and intercept statistically significant ($p < 0.001$). The model explains 24.9% of the variation in NOx over time ($R^2 = 0.2485$).

Seasonal trends in NOx concentrations in the surface water of SLL show early season loading of NOx in all three decades, with concentrations dropping throughout the summer season (Figure 15).

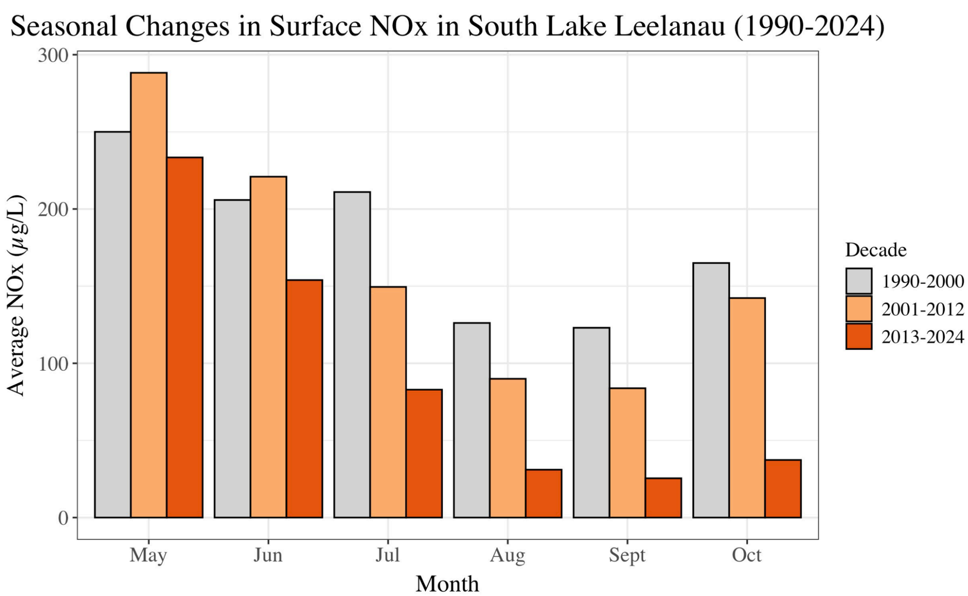

Figure 15. Average seasonal concentration of surface NOx (µg/L) in South Lake Leelanau over the last three decades.

Total Phosphorus (TP)

North Lake Leelanau

Total phosphorus (TP) concentrations in the surface water of NLL have increased significantly since the 1990s and 2000s ($p < 0.05$, Figure 16). In contrast, concentrations of TP in the bottom water have decreased significantly ($p < 0.05$, Figure 16). Average annual concentrations of total phosphorus in both the surface and bottom water of North Lake Leelanau fall within the threshold for oligotrophic lakes defined by Wetzel 2001 (Table 5).

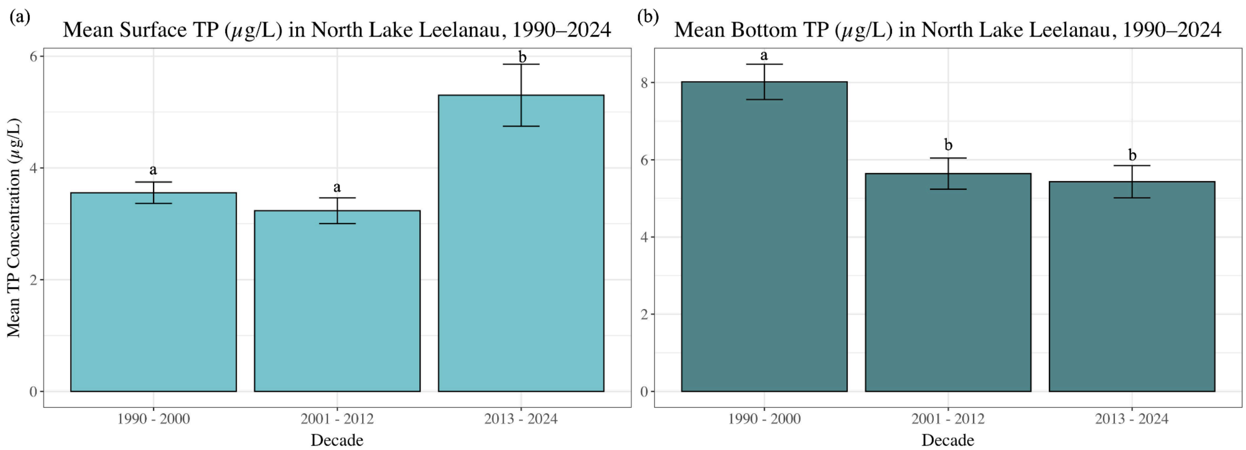

Figure 16. Mean summer total phosphorus (TP) concentrations (µg/L) for the (a) surface, and (b) bottom water of North Lake Leelanau by decade (1990-2024). Error bars represent ± 1 standard error. Differences among decades are indicated by letters above bars: bars sharing a letter are not significantly different, bars with different letters are (Tukey's HSD < 0.05).

Table 5. Summer TP concentrations by decade in North Lake Leelanau (NLL), from the surface and bottom layers. Values measured include number of samples (n), mean TP concentration (µg/L), standard deviation (SD), standard error (SE), and 95% confidence interval (CI).

Lake	Layer	Decade	n	mean	SD	SE	CI
NLL	surface	1990 - 2000	42	3.6	1.2	0.2	0.4
NLL	surface	2001 - 2012	54	3.0	1.0	0.1	0.3
NLL	surface	2013 - 2024	37	5.3	3.4	0.6	1.1
NLL	bottom	1990 - 2000	42	8.0	3.0	0.5	0.9
NLL	bottom	2001 - 2012	48	5.6	2.8	0.4	0.8
NLL	bottom	2013 - 2024	37	5.4	2.5	0.4	0.8

Simple linear regression revealed a significant increase in surface phosphorus from 1990 to 2024 ($p = 0.001$, Figure 17). To meet model assumptions for a simple linear regression, TP concentrations were ln transformed. Because of this, the slope is interpreted as the average annual percent change in TP rather than a change in total concentration. Therefore, the model predicts an average increase of approximately 1.3% total phosphorus per year. We see the opposite in the bottom water of North Lake Leelanau where the average annual change is decreasing by 1.3% (Figure 18).

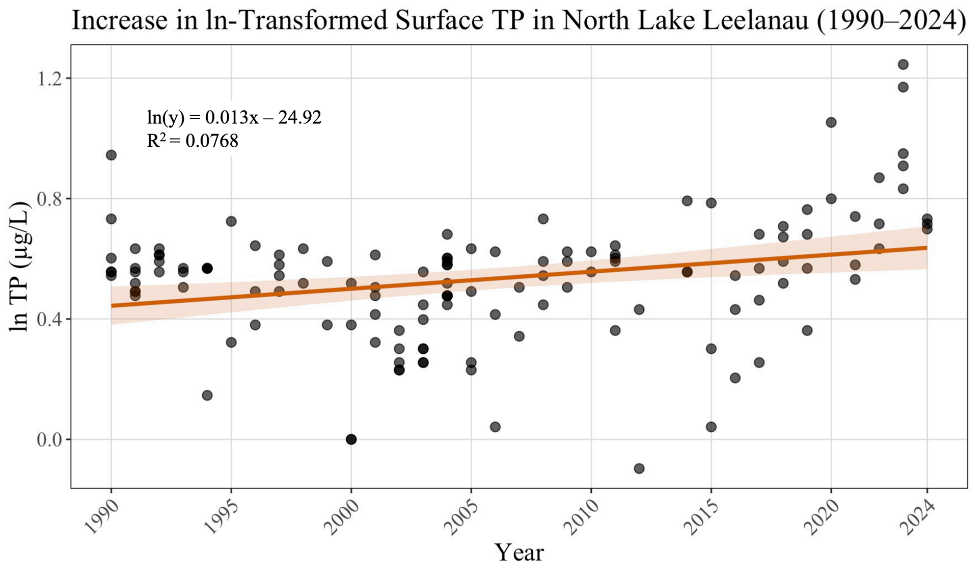

Figure 17. Long-term trends in ln-transformed summer surface total phosphorus (TP) of North Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant increase of 1.3% average TP per year ($p = 0.001$), with both the slope and intercept statistically significant ($p < 0.05$). The model explains 7.7% of the variation in NOx over time ($R^2 = 0.0768$). Data were ln-transformed to fit model assumptions.

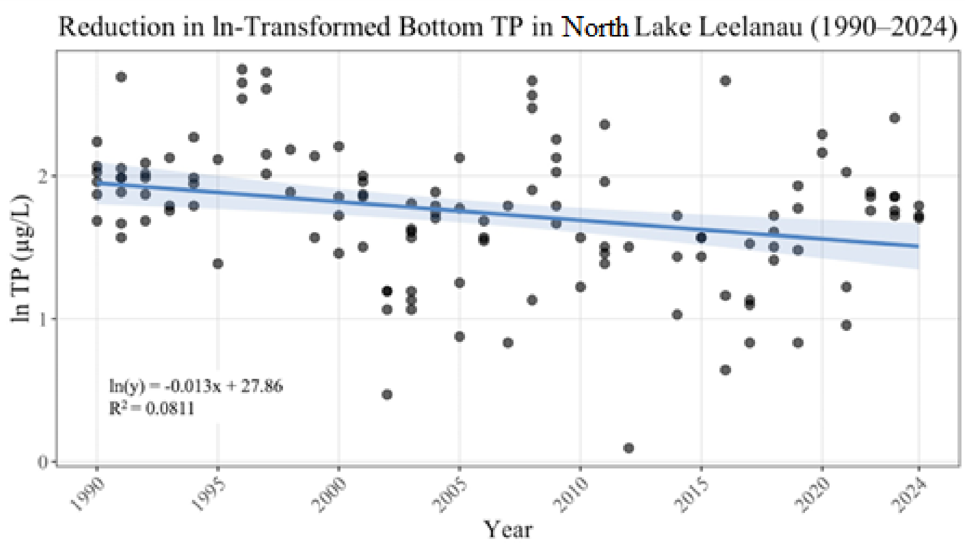

Figure 18. Long-term trends in ln-transformed summer bottom TP of North Lake Leelanau from 1990 to 2024. The linear regression model indicates a significant decrease of 1.3% average TP per year ($p = 0.001$), with both the slope and intercept statistically significant ($p < 0.05$). The model explains 8.1% of the variation in NOx over time ($R^2 = 0.0811$). Data were ln-transformed to fit model assumptions.

Finally, seasonal trends in total phosphorus across decades in the surface water show loading likely occurring earlier in the season and decreasing only slightly throughout the summer (Figure 19).

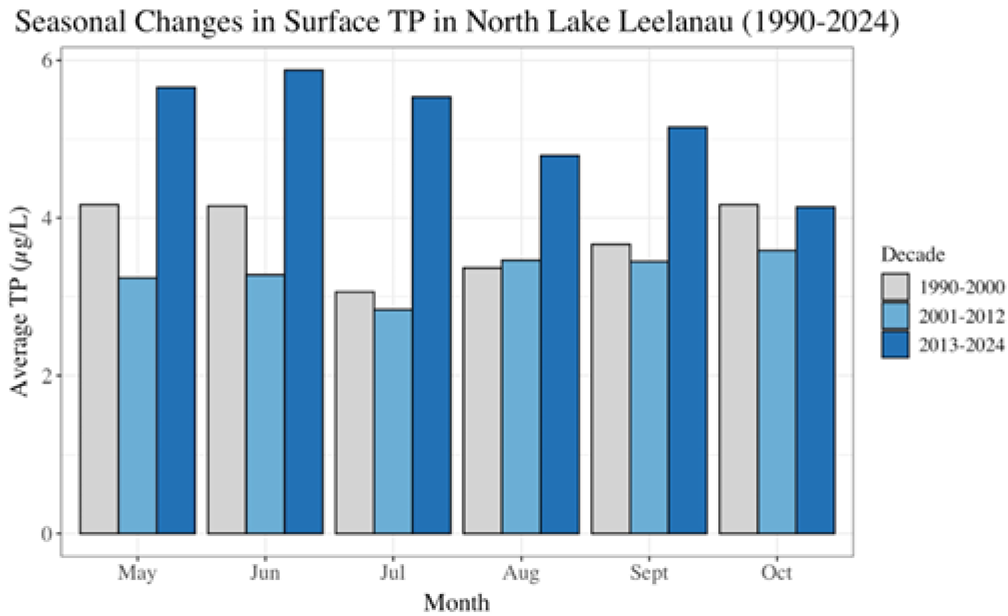

Figure 19. Average seasonal concentration of surface TP (µg/L) in North Lake Leelanau over the last three decades.

South Lake Leelanau

Total phosphorus (TP) concentrations in the surface water of SLL have increased slightly, but not significantly since the 1990s (Figure 20). In contrast, concentrations of TP in the bottom water decreased significantly from the 1990s to 2000s ($p < 0.05$) and have remained stable since (Figure 20). Average annual concentrations of total phosphorus in both the surface and bottom water of SLLfall within the threshold for oligotrophic lakes defined by Wetzel (2001, Table 6).

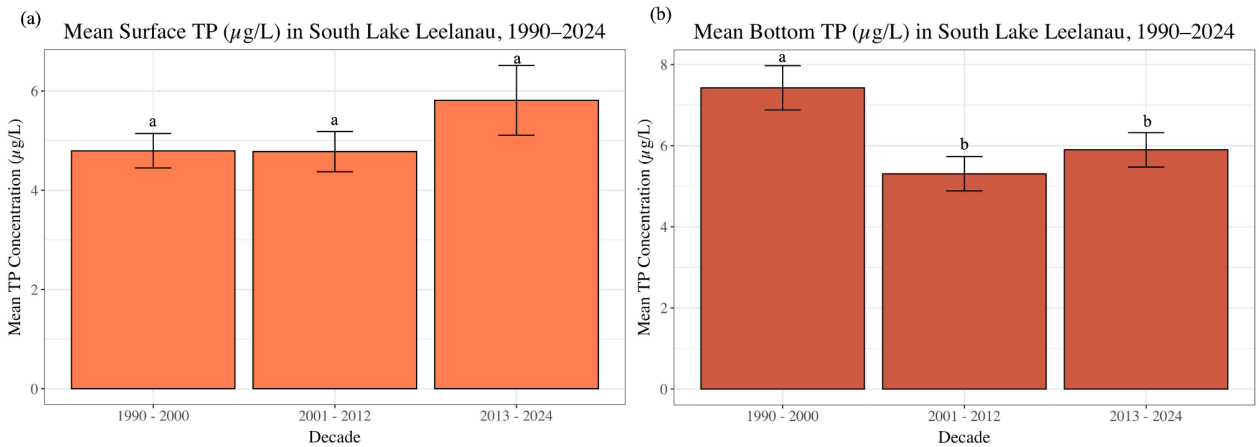

Figure 20. Mean summer total phosphorus concentrations (µg/L) for the (a) surface, and (b) bottom water of South Lake Leelanau (1990-2024). Error bars represent ± 1 standard error. Differences among decades are indicated by letters above bars: bars sharing a letter are not significantly different, bars with different letters are (Tukey's HSD < 0.05).

Table 6. Summer TP concentrations by decade in South Lake Leelanau (SLL), from the surface and bottom layers. Values measured include number of samples (n), mean TP concentration (µg/L), standard deviation (SD), standard error (SE), and 95% confidence interval (CI).

Lake	Layer	Decade	n	mean	SD	SE	CI
SLL	surface	1990 - 2000	39	4.8	2.2	0.3	0.7
SLL	surface	2001 - 2012	53	4.8	2.9	0.4	0.8
SLL	surface	2013 - 2024	37	5.8	4.3	0.7	1.4
SLL	bottom	1990 - 2000	39	7.4	3.4	0.5	1.1
SLL	bottom	2001 - 2012	46	5.3	2.9	0.4	0.8
SLL	bottom	2013 - 2024	32	5.9	2.4	0.4	0.8

Simple linear regression of total phosphorus concentration (µg/L) in the surface of SLL shows a slight but not significant increase of TP over time at a rate of 0.046 µg/L per year (Figure 21). In the bottom water of SLL simple linear regression shows a slight significant ($p = 0.034$) reduction of TP over time at a rate of -0.052 µg/L per year (Figure 22).

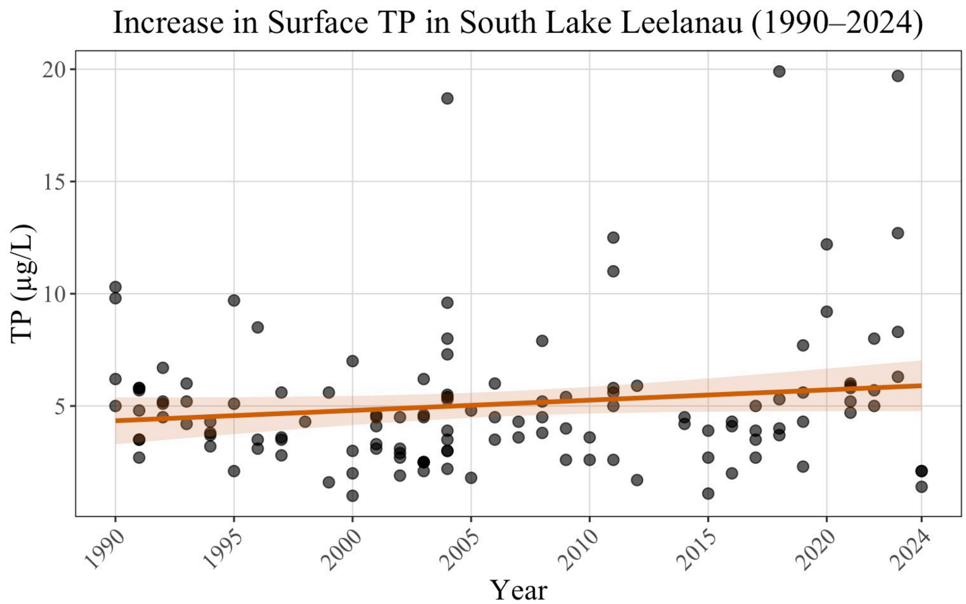

Figure 21. Long-term trends in summer surface TP of South Lake Leelanau from 1990 to 2024. The linear regression model indicates a slight but not significant increase of 0.046 µg/L per year ($p = 0.1003$). The model explains 2.1% of the variation in TP over time ($R^2 = 0.02112$).

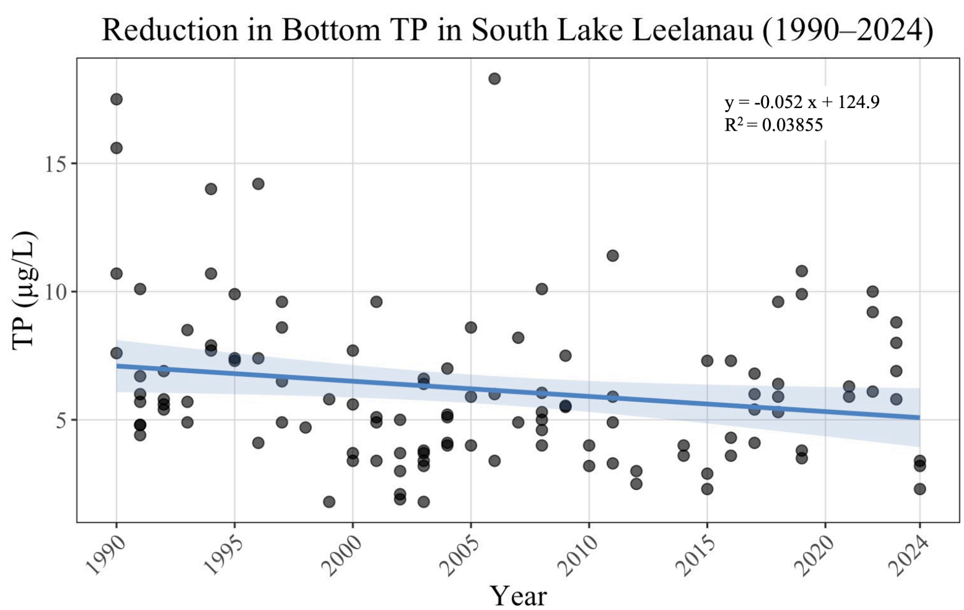

Figure 22. Long-term trends in summer bottom TP of South Lake Leelanau from 1990 to 2024. The linear regression model indicates a slight but significant decrease of -0.059 µg/L per year ($p = 0.034$), with both the slope and intercept statistically significant ($p < 0.05$). The model explains 3.9% of the variation in TP over time ($R^2 = 0.03855$).

Finally, seasonal trends in total phosphorus across decades in the surface water show loading likely occurring later in the season with a strong peak in September (Figure 23).

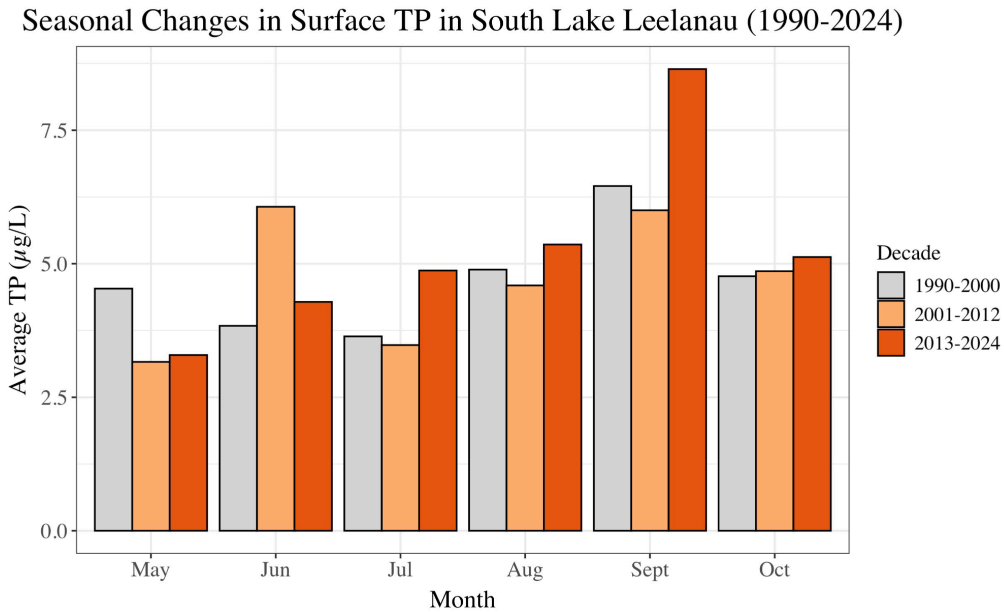

Figure 23. Average seasonal concentration of surface TP (µg/L) in South Lake Leelanau over the last three decades.

Long-term (PCA)

Before introducing the principal component analyses (PCA) figures for each basin, it is important to understand how to interpret PCA figures. Recall that the purpose of PCA is to try and understand complex datasets (30+ years, with multiple parameters) and summarize findings into 2-dimensional figures. To determine the value of the figure in summarizing the data, we rely on the percentage of data represented by the figure. More data is typically better (higher percentage) but we are summarizing a lot of information, so we expect some loss. For these figures, values above 55% are considered good and worth interpretation. Next refer to the vectors in each plot. Each parameter has a vector connecting the label such as “Wtemp.C” to the graph origin (0, 0) on the plot. Longer vectors are more important than shorter vectors, shorter vectors are less important. For the ellipses for each arbitrary time period (1990-2001, 2002-2013, 2014-2024), imagine they are being stretched in the direction of the parameter vector that is more important. The ellipses provide a visualization for each time period with vectors determining the shape of the ellipse. Finally, note that pH is included in some PCA figures and not others. This is because the pH value often included outliers and missing values.

North Lake Leelanau

Long-term trends in the surface water of NLL are well explained by PCA with almost 79% of the data represented in the 2-dimensional plot (Figure 24). The amount of information retained in this plot is exceptional considering the data were collected over 34 years. The findings are not unexpected, as oxidative reductive potential (ORP) and conductivity, along with dissolved oxygen and water temperature are negatively correlated (vectors are pointed away from each other). The ellipses move starting with early to later years towards higher temperatures and greater ORP.

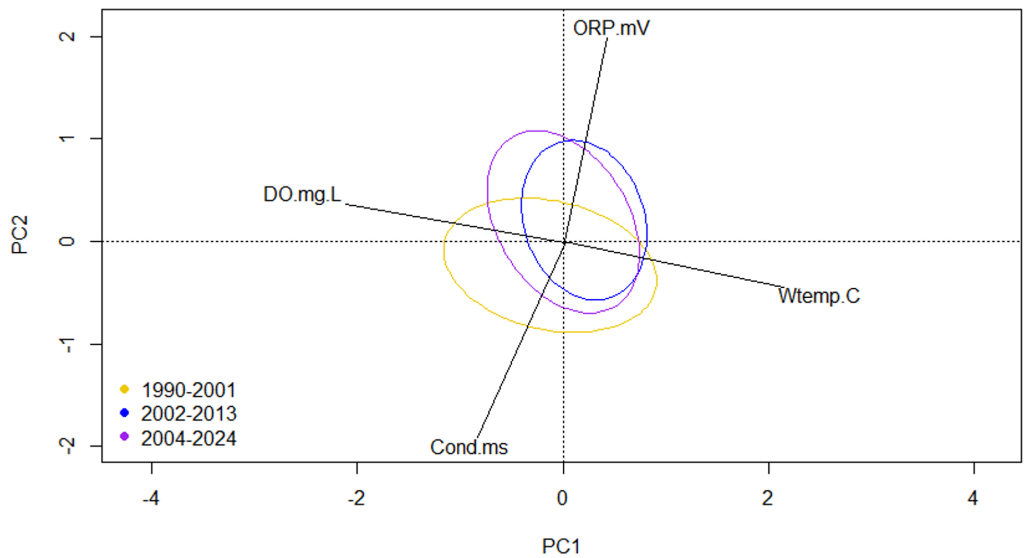

Figure 24. Principal component analyses of NLL surface water with 78.9% of the data explained in a correlation biplot. Eigenvectors are oxidative reduction potential in mV (ORP.mV), water temperature in Celsius (Wtemp.C), conductivity in microsiemens (Cond.ms), and dissolved oxygen in mg/L (DO.mg.L). Time periods are represented by ellipses indicative of 95% confidence interval of the standard error of the centroid for data collected during this time.

The PCA biplot for the bottom water in NLL represented 58% of the data (Figure 25), with conductivity and water temperature negatively correlated to ORP. Dissolved oxygen was tightly correlated to pH, as were ORP and water temperature (very small angles between vectors). Surprisingly, water temperature was uncorrelated (at a right angle) to dissolved oxygen. Moreover, dissolved oxygen and pH were completely uncorrelated to ORP and water temperature. The ellipses indicate early years had greater conductivity, middle years slightly warmer temperatures and greater ORP, and most recent years with greater temperatures, ORP, and perhaps greater pH.

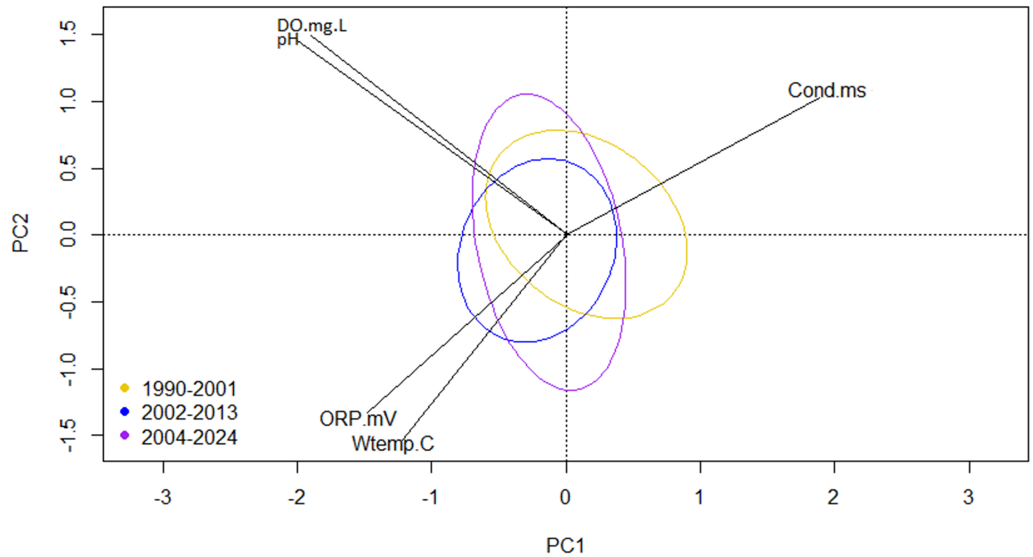

Figure 25. Principal component analyses of NLL bottom water with 57.6% of the data explained in a correlation biplot. Eigenvectors are oxidative reduction potential in mV (ORP.mV), water temperature in Celsius (Wtemp.C), conductivity in microsiemens (Cond.ms), pH, and dissolved oxygen in mg/L (DO.mg.L). Time periods are represented by ellipses indicative of 95% confidence interval of the standard error of the centroid for data collected during this time.

South Lake Leelanau

Similar to the surface water for NLL, PCA findings for surface SLL were well represented in the 2-D biplot, with 60% of the data retained (Figure 26). Both ORP and conductivity along with water temperature and dissolved oxygen were weakly negatively correlated. The ellipse indicates the data in the most recent decade has greater variance (larger ellipse relative to others) than previous decades. This is particularly true with respect to water temperature and dissolved oxygen (the ellipse is stretched mainly along these vectors).

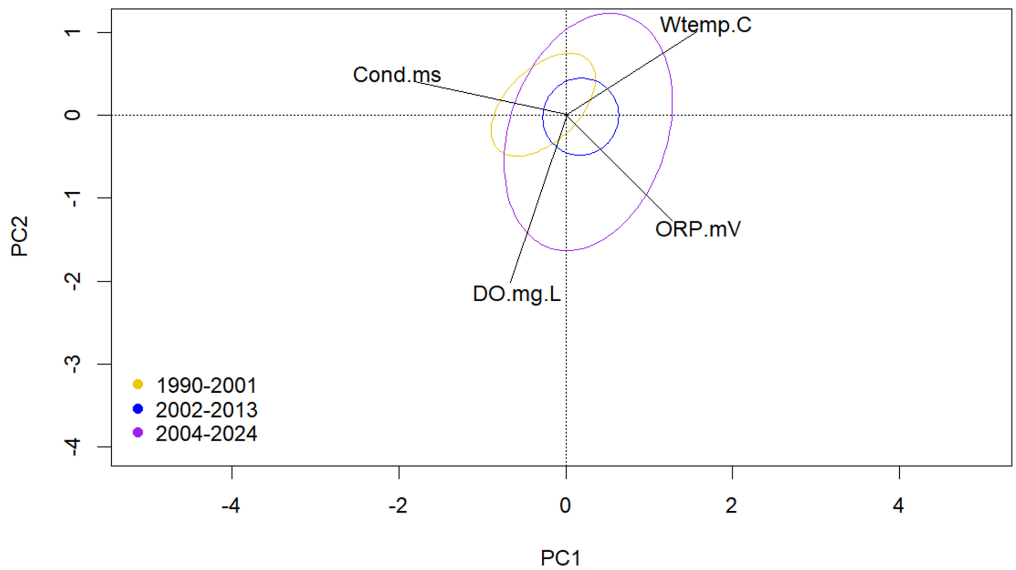

Figure 26. Principal component analyses of SLL surface water with 60.7% of the data explained in a correlation biplot. Eigenvectors are oxidative reduction potential in mV (ORP.mV), water temperature in Celsius (Wtemp.C), conductivity in microsiemens (Cond.ms), and dissolved oxygen in mg/L (DO.mg.L). Time periods are represented by ellipses indicative of 95% confidence interval of the standard error of the centroid for data collected during this time.

The final PCA biplot for SLL bottom water retained approximately 66% of the original data Figure 27). The relationships among the vectors varied slightly from other PCA plots. Surprisingly, water temperature was slightly uncorrelated to dissolved oxygen and ORP decreased in recent decades. Bottom depths in SLL were more acidic, with greater conductivity, and lower dissolved oxygen. Lastly, water temperature was weakly negatively correlated with conductivity.

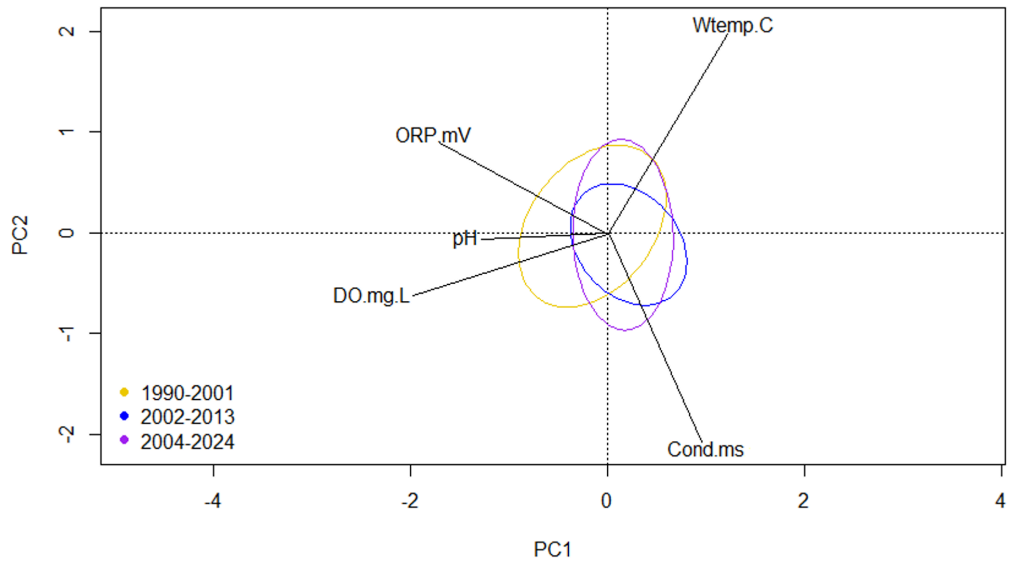

Figure 27. Principal component analyses of SLL bottom water with 65.6% of the data explained in a correlation biplot. Eigenvectors are oxidative reduction potential in mV (ORP.mV), water temperature in Celsius (Wtemp.C), conductivity in microsiemens (Cond.ms), pH, and dissolved oxygen in mg/L (DO.mg.L). Time periods are represented by ellipses indicative of 95% confidence interval of the standard error of the centroid for data collected during this time.

Spatial Analyses

Very little land cover change occurred in the Lake Leelanau Watershed from 1993-2023 (Table 7). Small changes occurred in agriculture (decrease from 20% - 18%) and developed land (increase from 8% - 10%). Since the watershed is large, the maps are difficult to interpret in this document (Figure 28). As such, high quality digital images have been shared with the Lake Leelanau Lake Association, to facilitate review.

Table 7. Percentage of land use/land cover category (forest, agriculture, developed, and open land) as determined from GIS Michigan Open Data and USGS National Map in the Lake Leelanau Watershed from 1993 to 2023. Note that this table does not include water.

Year	Forested	Agriculture	Developed	Open Land
1993	50%	20%	8%	21%
1998	51%	18%	8%	23%
2003	51%	18%	9%	23%
2008	50%	18%	9%	22%
2013	50%	19%	9%	22%
2018	50%	18%	9%	22%
2023	50%	18%	10%	22%

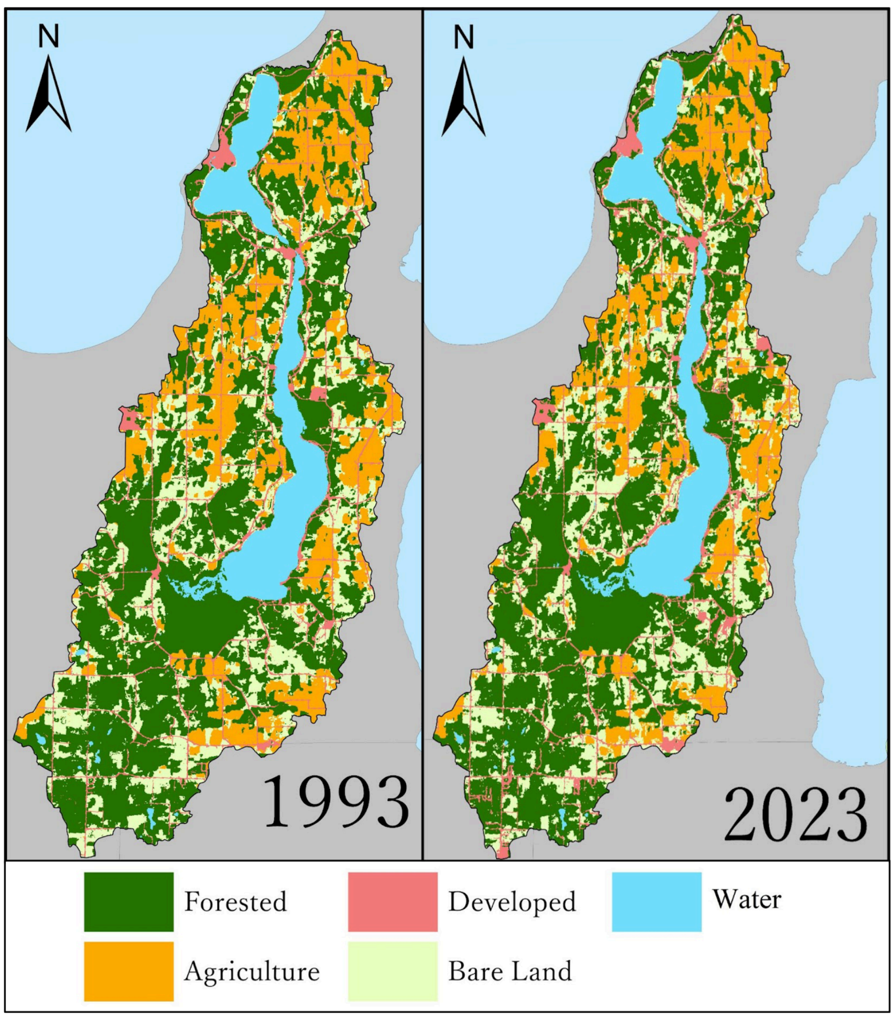

Figure 28. Land cover determined by data from USGS GIS data (https://www.usgs.gov/the-national-map-data-delivery/gis-data-download) for 1993 and 2023 in the Lake Leelanau Watershed.

Slope and flow of entering tributaries in the Lake Leelanau Watershed in 2023 are represented in Figure 29. In addition to fertilizer runoff from lakefront property and other areas in the watershed, fertilizer applied to agriculture is likely to runoff slopes, enter tributaries and impact nutrient levels in Lake Leelanau. There are a number of caveats that must be considered as one interprets this map. Agricultural land use is determined by spatial data downloaded from USGS. It is not ground-truthed and therefore the land may no longer be managed for active agriculture, the land may not use any fertilizer, and/or managers may use very little fertilizer. Darker blue points in Figure 29, indicate locations where tributaries with high flow enter Lake Leelanau. These points and their subwatersheds (essentially upstream of these locations) can be used to focus runoff mitigation efforts.

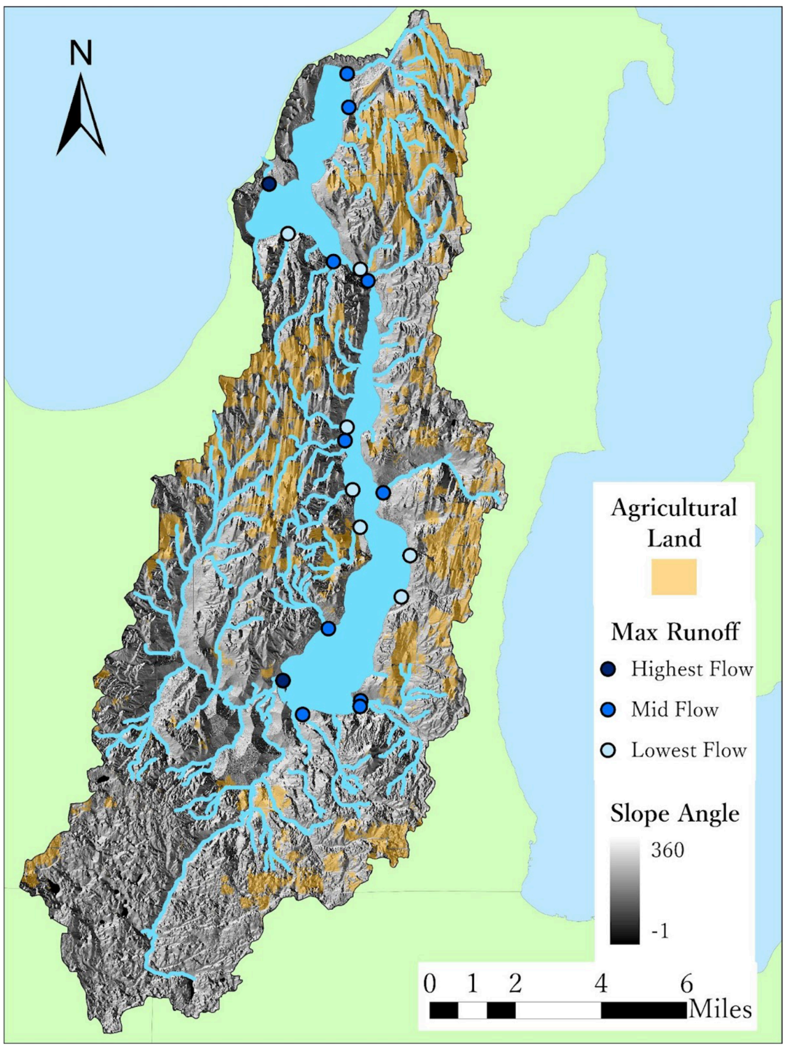

Figure 29. Slope, tributary flow, and agricultural land cover determined using ArcGIS with data from USGS (https://www.usgs.gov/the-national-map=data-delivery/gis-data-download) for 2023 in the Lake Leelanau Watershed. Note: only tributaries with medium - high flow are included for runoff.

DISCUSSION

Temperature

Thermal profiles from both North and South Lake Leelanau show clear evidence of warming over the last 30 years. In the most recent decade (2013-2024), stratification began earlier, in May rather than June, and persisted later, into October rather than September, highlighting a shift in stratification intensity. Although the average depth and temperature-at-depth of the thermocline has not changed significantly, surface temperatures show a warming trend, particularly in peak summer months, July and August. August surface temperatures in NLL are estimated to increase by 0.066 ºC per year, while summer (Jun-Aug) temperatures in SLL are estimated to increase by 0.036 ºC per year. Additionally, summer surface temperatures, particularly in shallower South Lake Leelanau are more frequently approaching summer temperatures of 25 ºC (Appendix Figure A1; A2), increasing the likelihood for nuisance and harmful algal blooms.

Although we observe significant cooling in the deep water of both lakes, this is not necessarily unexpected. Recent research suggests that increasing thermal stratification - driven by rising surface temperatures, reduced wind speed, and weaker mixing - can lead to cooler bottom water temperatures (Magee & Wu 2017). As stratification strengthens, the transfer of heat to deeper lake layers is limited, leading to thermal isolation and overall lower bottom temperatures, potentially impacting the lakes ecological functions, and habitat suitability for sensitive taxa.

Nitrate/ Nitrite (NOx)

NOx concentrations in the surface waters of both North and South Lake Leelanau have declined significantly over the last 30 years, particularly in the last decade. In NLL, concentrations of NOx in the deep water also dropped significantly in the last decade, while SLL's deep water remained relatively stable. In both lakes, the narrowing of confidence intervals and reduced variability in NOx concentrations over time suggest that conditions have become more stable and water quality has improved. Much of the decline can be attributed to decreased atmospheric deposition of nitrogen in the last 20 years, a function of the Clean Air Act. Seasonal influx of NOx are consistent in both lakes with concentrations peaking in the spring and tapering off through the summer and fall. This spring peak could be linked to early season fertilizer application from agricultural and/or lakefront property. Continued and increased monitoring, particularly in high flow areas would be necessary to fully understand seasonal trends.

Total Phosphorus (TP)

Total phosphorus (TP) concentrations in the surface water of both North and South Lake Leelanau have increased over the last 30 years. North Lake Leelanau has experienced a significant increase in TP concentration over time, particularly in the most recent decade, with a modeled average annual increase of 1.3% per year. South Lake Leelanau has also experienced an increase in TP concentration over time, though not significant. Conversely, the concentration of TP in the bottom water of both lakes has decreased significantly over the last 30 years, potentially highlighting the effects that a more intense thermal stratification has on limiting vertical mixing and available deep water dissolved oxygen. Average TP concentrations in both lakes remain within the oligotrophic range, however, even small increases in TP are worth noting as elevated phosphorus levels, especially when combined with rising surface temperatures, can enhance the growth of algae and aquatic plants, potentially leading to nuisance and harmful algal blooms. Seasonal trends show surface TP peaking earlier in the spring in NLL and later in the season in SLL. The early loading in NLL could reflect early season fertilizer application from agricultural and/or lakefront property, while the later season peak in South lake is potentially tied to septic system use throughout the summer. Continued monitoring and seasonal analyses are recommended to further understand these trends.

Long-term (PCA)

Principal component analyses (PCA) confirmed higher temperature in surface water in both NLL and SLL in recent years. Surface water was also increasing in ORP in both lakes, and in bottom water of NLL at that same time. Often, greater ORP is positively correlated with dissolved oxygen and indicates high water quality. Although dissolved oxygen was weakly correlated with ORP in SLL, these parameters were uncorrelated in NLL. Decreasing ORP in the deep water of SLL is not cause for concern. Even clean lakes may have lower ORP at depth as the accumulation of sediment and organic materials at depth results in more bacteria which consume oxygen. New research suggests that decreasing ORP can be related to eutrophication and blue-green algal blooms (Zhang et al., 2024). Conditions in Lake Leelanau are very good news and the Lake Association may elect to increase measurements of ORP in an attempt to monitor the shift towards eutrophication expected with climate change.

Spatial Analyses

Very little change in land use in the Lake Leelanau Watershed has occurred in the last 30 years. Agricultural land use decreased in area from 20% - 18% (1993-2023), suggesting that fertilizer application to agricultural land may not be the main driver of nutrient inputs into NLL and SLL. Dark blue points in Figure 29 highlight areas where we suggest runoff mitigation efforts (aside from the outflow at the Leland River). More specifically, **if private landowners are amenable**, areas along Houdek Creek on NLL and Victoria Creek on SLL could be buffered with rain gardens and landscaping for water quality (Popa, 2022). This work should be coupled with continued efforts by the LLLA to work with lakefront property owners to minimize fertilizer runoff from developed land.

Summary and Recommendations

In summary, both North and South Lake Leelanau are very clean lakes and have remained that way for the last 34 years! This is great news and a testament to the commitment of the LLLA to the lake. Surface water in both NLL and SLL is warming and likely will continue to do so. The lake is stratifying earlier in the spring and remaining so, later into the fall. In the recent decade, total phosphorus is increasing at the surface (significantly so in NLL). The likely cause of this increase is fertilizer runoff from developed land, especially lakefront properties, and agriculture, along with leaking septic systems. Nitrate/nitrate is decreasing in NLL and at the surface in SLL (stable in SLL deep water). The projections for climate change are continued warming and greater likelihood for blue-green algal blooms (even with low nitrogen and phosphorus).

Warmer surface water, especially greater than 25 ºC, favors blue-green algae. The evidence indicates that the lakes are warming and remaining stratified for longer periods. In addition, total phosphorus is increasing in surface water. Both of these changes create better environments for blue-green algal blooms. Since it is very difficult to change the temperature of water, we suggest the LLLA focus on fertilizer runoff mitigation to decrease the likelihood of blooms. The LLLA is poised with the expertise needed for landscaping for water quality on lakefront properties as well as on private land (**with landowner consent**) in subwatersheds with high development and/or active agriculture.

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Farber, H. A., & Nielsen, W. H. (2001). *Carrying capacity of South Lake Leelanau* [Unpublished report]. Lake Leelanau Lake Association. https://dspace.nmc.edu/.../47f3cad3-8f9f-45eb-90d6-088675b7dc93/content

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APPENDIX

Table A1. Summary of total number of samples analyzed for each water quality metric at each sampling location between 1990 and 2024.

Smapling Location	Nitrogen Nitrate (NOx)	Dissolved Oxygen (DO)	Total Phosphorus (TP)	Chlorophyll-a (Chl.a)	Temperature (Temp)	Conductivity (Cond)
NLL	19	-	19	17	-	-
NLL - 1	628	3163	691	143	3249	3061
NLL - 2	137	23	179	-	23	-
NLL - other	72	-	72	-	-	-
Total	856	3186	961	160	3272	3061
SLL	15	-	15	5	-	-
SLL - 1	-	-	-	63	-	-
SLL - 2	-	-	-	134	-	-
SLL - 3	212	-	248	-	-	733
SLL - 4	137	-	154	-	-	-
SLL - 5	461	2145	508	-	2252	2135
SLL - other	52	-	52	15	-	-
Total	877	2145	977	217	2252	2868

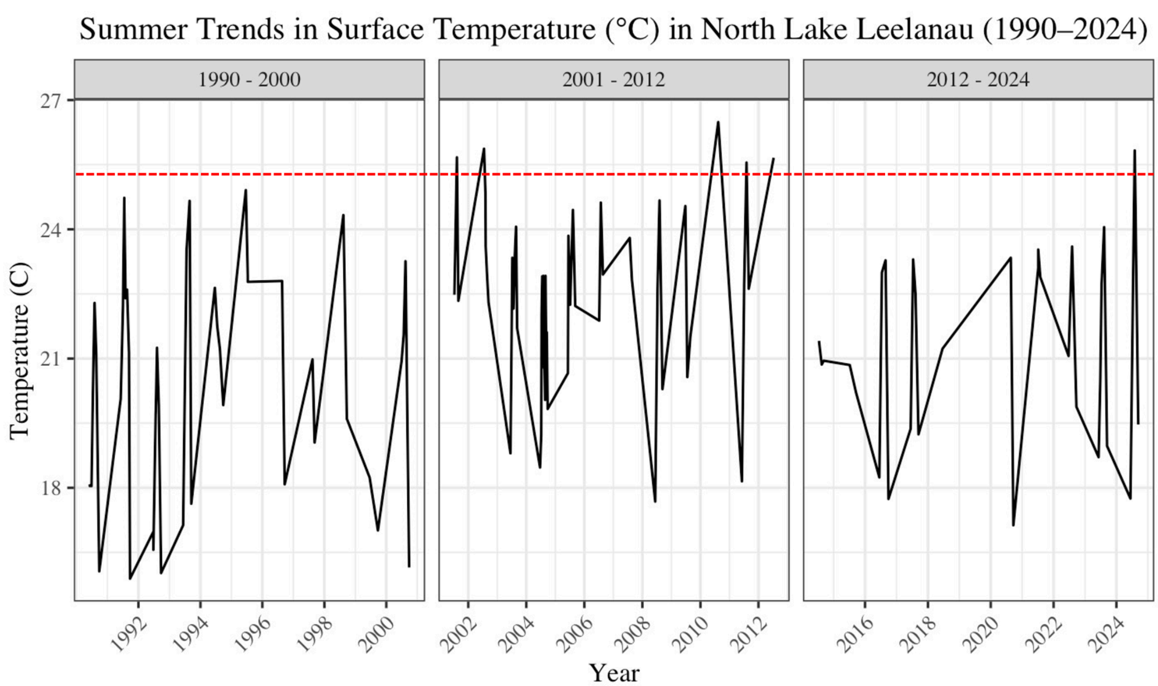

Figure A1. Summer (Jun-Aug) surface temperature (ºC) in North Lake Leelanau from 1990-2024. Red dashed line marks 25ºC threshold for ideal cyanobacterial growth.

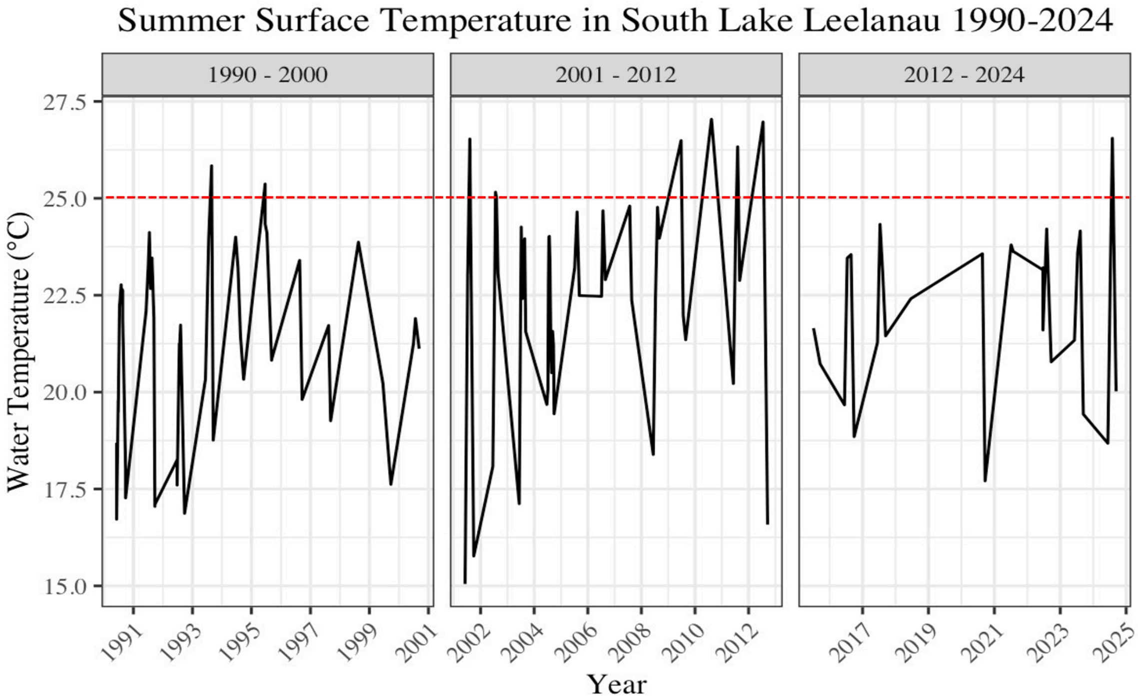

Figure A2. Summer (Jun-Aug) surface temperature (ºC) in North Lake Leelanau from 1990-2024. Red dashed line marks 25ºC threshold for ideal cyanobacterial growth.