A Watershed Based Approach: Pinpointing Phosphorus and Chloride Inputs in an Oligotrophic Lake. Pleasant Lake, New London, NH

Quinn Aldrich, Nick Baer, Samantha Carus, David Lutz, Steven Williamson (Alphabetical)

Environmental Science Program, Colby-Sawyer College

Abstract

This report builds upon research conducted by the Colby-Sawyer College Community-Based Project class during the 2023-2024 academic year to identify areas of concern for nutrients and contaminants within the Pleasant Lake watershed. Phosphorus and chloride variability throughout the watershed was examined from data collected from September to August. An analysis of historical data revealed in-lake approaching the phosphorus threshold for oligotrophic lakes of 8 ug/L (NHDES, n.d). Several tributary sites within the watershed were found to exhibit phosphorus concentrations consistently exceeding the oligotrophic lake threshold. Analysis of land use within the watershed and water chemistry parameters revealed high phosphorus loading from both anthropogenic and natural sources. A significant relationship between storm sampling and the several water quality parameters was determined, such as phosphorus, chloride, and turbidity. The study highlights the importance of distinguishing between storm and non-storm sample conditions, which emphasizes the need for continuous monitoring to track nutrient and mineral input throughout the year. This study works towards gaining a comprehensive understanding of tributary conditions by capturing summer storm events and their impact on chloride and phosphorus concentrations. Summer nutrient dynamics were found to behave differently than what was observed in fall and winter. This year-round data can be used to inform the development of targeted strategies to mitigate cyanobacteria blooms and improve overall watershed management. Key findings of this year long dataset and analysis are summarized in this report.

Objectives

This study aims to analyze yearlong dynamics within the Pleasant Lake watershed by assessing the concentration and loading of nutrients and pollutants from tributaries. Examining loading, which is calculated using nutrient or mineral concentration and discharge measurements, identified tributaries of concern for the lake's water quality. Prioritizing routine baseflow and storm event sampling provided insight to the impact on total phosphorus, chloride, pH, turbidity, apparent color, and conductivity. Data collection during summer storm events contributed to a comprehensive yearlong dataset of Pleasant Lake, as well as highlighted the importance of summer storms on nutrient loading. Summer tributary data was compared to summer VLAP data to detect significant differences between in-lake sampling near inlets and stream sampling. Lastly, to better understand sources of nutrients and pollutants, headwater samples were collected and analyzed for significant differences compared to routine tributary sites. The overall objective of this report is to serve as a foundation for the development of a watershed-based management plan for the Pleasant Lake Community.

Background

An ongoing concern of freshwater systems is eutrophication, which can be defined as the natural process of nutrient and sediment accumulation in a body of water. Eutrophication can be accelerated due to anthropogenic, or human, activity and development within a watershed. A key concern regarding eutrophication is the presence of excessive plant and algal growth that often leads to the occurrence of potentially toxic cyanobacteria blooms (Smil, 2000). Cyanobacteria blooms introduce can introduce toxins that pose health risks to aquatic organisms alter ecosystems and pose human health risks. Potential human health impacts include respiratory distress/reaction, muscle weakness, bodily irritation, organ damage, and increased uptake of carcinogens (Zhang, et al., 2022). The cyanotoxins produced by cyanobacteria can cause negative health effects in aquatic and terrestrial organisms. Additionally, harmful toxins in cyanobacteria impacts biodiversity, native plants, and native fish species (Zhang, et al., 2022).

There have been growing concerns regarding the impact of these blooms due to an increases of cyanobacteria blooms across New Hampshire. New Hampshire has experienced more advisories issued for lakes in 2023 than any previous year, issuing 69 advisories in 49 lakes (NHDES, 2023). Pleasant Lake had cyanobacteria blooms, predominantly Dolichospermum, on June 24, 2022, and June 23, 2023, resulting in two alerts for the waterbody (NHDES, 2023). The NHDES has no formal cell counts in their records for Pleasant Lake, as the 2022 bloom was sampled after the material had begun to degrade and the 2023 bloom was never sampled. However, NHDES issues waterbody-wide warnings (advisories) when the cell count exceeds 70,000 cells/mL. Alerts are a step-down from an official advisory. The Pleasant Lake 2022 sample had a toxicity of 0.99 PPB of microcystins. To protect public health, the United States Environmental Protection Agency (US EPA) has recommended recreational standards for microcystin concentrations of < 8 PPB (US EPA, 2019). However, it is important to note that a bloom's toxicity level and toxins produced vary over its duration due to environmental factors (Sivonen, 2009). Mitigating the effects of eutrophication and cyanobacteria blooms requires monitoring of key nutrients, particularly phosphorus.

Phosphorus (P) is a major limiting macronutrient in aquatic systems as it controls the growth of aquatic plants and algae. While P is essential for biological development and reproduction, excess phosphorus leads to excessive biological growth, often leading too cyanobacteria blooms (US EPA, 2023_a). Additionally, excess phosphorus can lead to the depletion of dissolved oxygen levels and cause harm to aquatic species. Terrestrial sources of anthropogenic phosphorus entering aquatic systems include fertilizers, improperly managed sewage-related discharge, and lake-bottom sediments containing legacy phosphorus (Smil, 2000). Several studies have investigated the influence that human development, particularly impervious surfaces, in a watershed has on water quality. According to the EPA (2018), surface runoff doubles and continues to increase once the landcover of a watershed reaches 10-20% impervious surface. A publication by the New Hampshire Estuaries Project (2007) stated that sensitive aquatic species can still be impacted with land cover consisting of less than 10% impervious surface. The influence of human development and impervious surfaces within the boundaries of the Pleasant Lake Watershed will be further explored throughout this study.

Increased nutrient loading from precipitation events pose a threat to the New England region, as storms are more frequent, and temperatures rise. Shrestha et al. examined the transport of Phosphorus during precipitation events in minimally developed watersheds. Storm events produced high Phosphorus concentrations in forested catchments. During storms, total phosphorus (TP) was introduced through dissolved particulate matter. The study found that the peak total phosphorus was proportional to the runoff ratio, showing the impact of precipitation amount, intensity, and antecedent moisture impacted P transport (Shrestha et al. 2020). Lou et al. found total phosphorus loading was highest when the storm's maximum rainfall intensity or duration was also highest (2009). Considering precipitation high-intensity loading, this study will examine the role of stormflow.

Internal phosphorus loading from lake sediment contributes to cyanobacteria blooms in oligotrophic lakes (Bormans et al, 2016). Past phosphorus inputs are sequestered in the lakes which can be made labile in the water. Historical phosphorus inputs include historical land use and agricultural practices. As phosphorus can enter freshwater systems in a variety of ways, this project examines possible sources of phosphorus inputs from tributaries during baseflow and storm samples. Furthermore, headwater sampling of key sites will show differences in phosphorus concentrations between tributary headwaters and regular sampling locations.

Chloride is another pollutant of concern, as rising concentrations can significantly impact freshwater ecosystems. Chloride enters the environment as sodium, calcium, and magnesium chloride, or salts (Hong, 2023). Chloride concentrations in freshwater systems are increasing as a result of road and de-icing salt application. According to New Hampshire Lakes, chloride levels in New Hampshire freshwater bodies are around 100 times higher today than 50 years ago or before road salt application was implemented. Additionally, Chloride is not effectively removed from the environment by vegetation or natural processes, so nearly all chloride applied as road salt will eventually end up in nearby surface waters (NHDES, n.d). The EPA has designated the concentration of chloride that is considered toxic to aquatic organisms at 230 mg/L, however sensitive species are affected at lower concentrations. Due to the integral role of plankton communities in freshwater systems, monitoring areas with consistently elevated chloride levels is a major focus of this project.

Methods

I. Site Description

Pleasant Lake is a deep, cold-water, oligotrophic lake in New London, New Hampshire, covering 606-acres at average surface elevation of 805 feet (NHDES, 2019). The eastern shore is home to the small village of Elkins, a historically settled area. The town of New London was home to 4,416 residents as of 2018, with many being seasonal residents. However, the Pleasant Lake watershed, approximately 7,488 acres in size (NHDES, 2019), remains largely undeveloped despite an increasing population and desirability for tourism in the area. Utilizing ArcGIS and satellite imagery technology, the Pleasant Lake watershed was determined to consist of approximately 96% undeveloped land, with a percentage around 99% consisting of permeable surface.

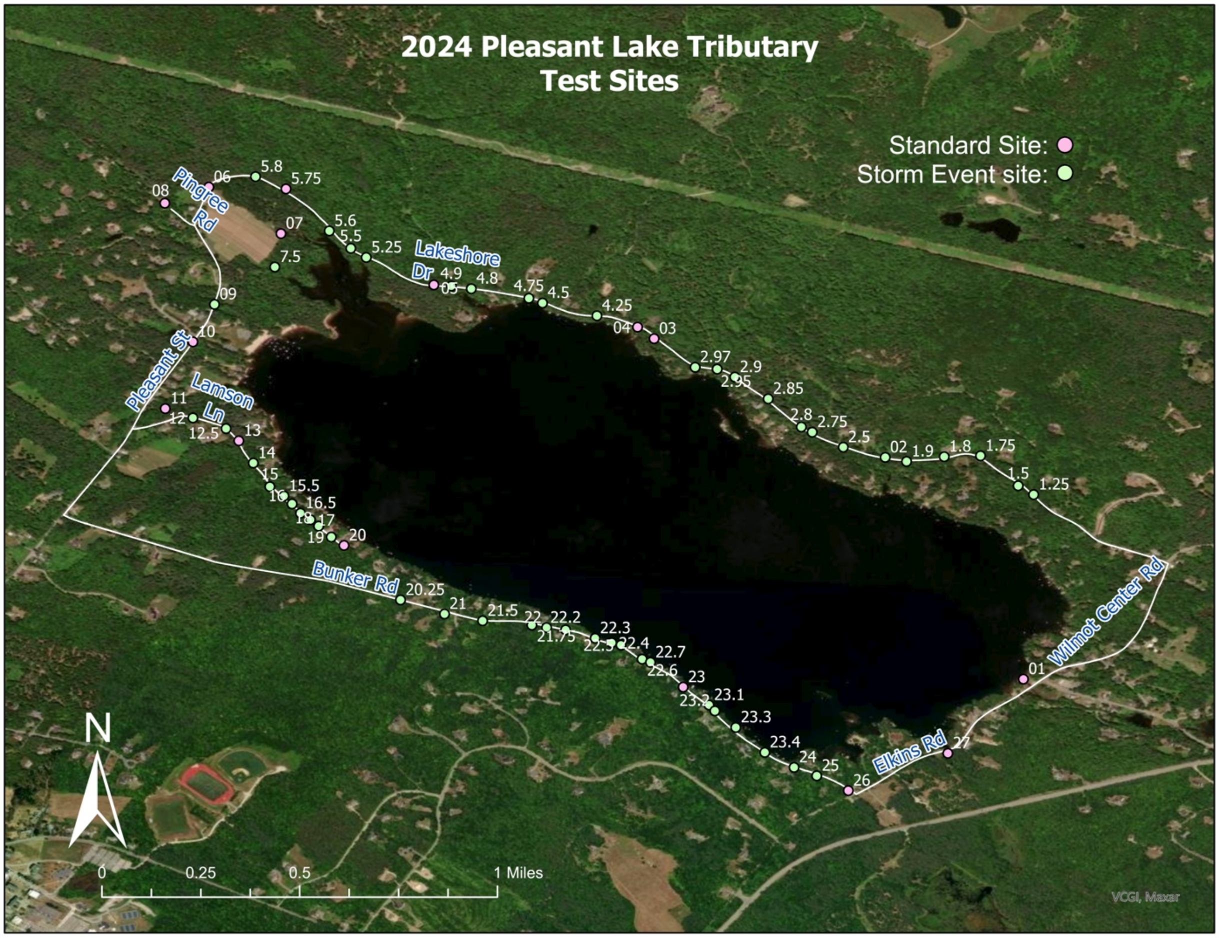
II. Sampling Procedure

a. VLAP Data

The Volunteer Lake Assessment Program (VLAP) is a water quality testing organization run through the New Hampshire Department of Environmental Services (NHDES). The VLAP has been routinely sampling Pleasant Lake in the summer since 1979. An extensive historical database of in-lake water quality parameters exists in the VLAP database, which is available to the public. Historical VLAP data provided a foundation for our extended sampling and research into the dynamics of the Pleasant Lake Watershed. An analysis of this data revealed decreasing visibility at the deep spot and increasing concentrations of chloride. In recent years, volunteers have sampled 10 in-lake sites, including areas where tributaries, such as White and Red Brook, enter the lake. Since in-lake sampling reflects mixed stream and lake conditions, this study incorporated tributary sampling to identify specific nutrient and mineral sources.

b. Fall 2023/Spring 2024 Sampling

Increased water sampling efforts began in Fall 2023 as part of a third-year community-based research course at Colby-Sawyer College. Ten Environmental Science and Studies students collaborated with the Pleasant Lake Protective Association (PLPA) and the Town of New London to monitor tributaries within the watershed. Sampling was conducted bi-weekly to twice weekly, depending on weather and precipitation events. A total of 62 sites were identified (**Map 1**), categorized as 17 Standard Sites and 45 Storm Event Sites. Between September 2023 and April 2024, 22 sampling days were conducted, resulting in 750 water samples collected.

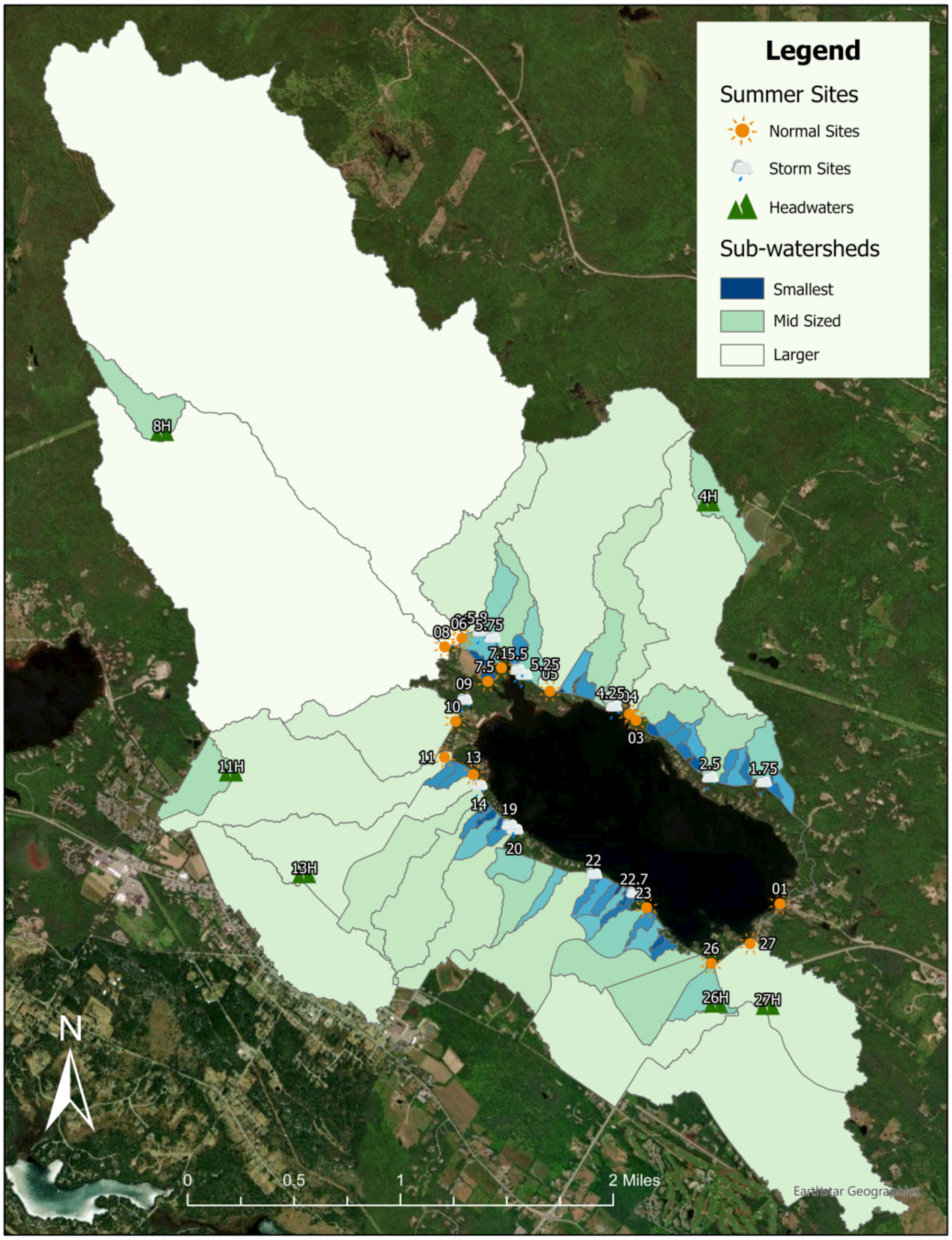


Map 1: Storm Event and Baseflow sampling sites that were sampled during Fall 2023 and Spring 2024 by the Colby-Sawyer College Community-Based Research Class are shown on the map. 62 sites were identified around Pleasant Lake.

c. Summer 2024 Sampling

To build a comprehensive, yearlong dataset, sampling occurred twice weekly from June-August 2024. Water samples were collected for baseflow and storm events, with storm sampling events occurring following precipitation events. Due to a dry summer, several tributaries active during spring snowmelt were dry and not sampled.

Headwater sampling was an additional analysis to pinpoint potential phosphorus and chloride sources within a sub watershed during summer sampling. Additional sampling targeted headwater sites to pinpoint potential phosphorus sources within sub-watersheds. Sub-watershed analysis in ArcGIS identified accessible headwater sites, leading to targeted sampling at Sites 4, 8, 11, 13, 26, and 27. **Map 2** displays the summer sampling and headwater sites. Between June and August 2024, 504 samples were taken, with 3,528 individual parameters run. This included 402 baseflow samples and 99 storm samples collected.



Map 2: Storm and Baseflow sites for summer sampling, as well as new headwater sites are shown within the Pleasant Lake watershed. Fewer sites around the lake were sampled due to reduced flow and dry conditions during the summer.

d. Sediment Core Collection

Several sediment cores were collected from various locations within the lake adjacent to their corresponding tributary sites for a potential future analysis of legacy phosphorus. Samples were taken using a sediment core tube from a pontoon boat at multiple sites, including the area where the tributary enters the lake at Turtle Cove, Site 4, Site 10, White Brook, Red Brook, Site 26, and the Fire Pond. After collection, samples were frozen for preservation.

III. Laboratory Procedure

a. Water Quality Parameters

Water samples were analyzed for pH, conductivity, color, chloride, and turbidity within 24 hours of collection. All standard operating protocols were adapted from the NHDES VLAP, and samples were run in a state certified lab. To ensure accuracy and reliability, quality checks and assurances were implemented including calibration and replicate samples. Between each sample, cuvettes were triple rinsed with deionized water and seasoned with a small amount of the sample. After every 10th sample, a standard and replicate were analyzed to ensure the machines were properly calibrated.

b. Total Phosphorus Analysis

Phosphorus concentrations were determined using a potassium persulfate solution to digest all forms of phosphate in the samples to orthophosphate. 4 mL of potassium persulfate was added to 25 mL of each water sample. The flasks were placed in an autoclave at 121 degrees Celsius for 45 minutes. After cooling, an ammonium molybdate color reagent was added to the flasks. Phosphorus absorbency was then measured using a Genesys 30 spectrometer at a wavelength of 880 nm. This study adhered to lab procedures and the New Hampshire State's standard procedure which included creating a standard curve to calculate concentration from absorbance values. Quality checks involved using known concentrations as well as a spiked blank. Additionally, replicate samples were analyzed every ten samples to confirm the replicate fell within 0.004 mg/L of the sample.

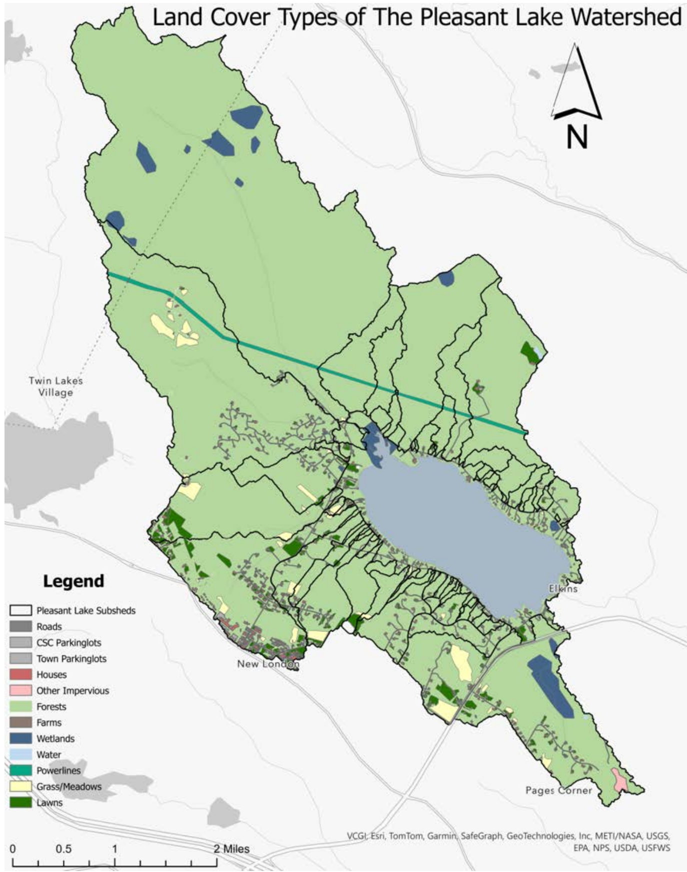
IV. Statistical Analysis

a. Sub watershed Delineation

Esri's ArcGIS Pro was used to generate boundaries of each sub-watershed using a digital elevation model of the Pleasant Lake Watershed. Using digital elevation models (DEMs) from the United States Geological Service (USGS), points on the surface were selected that corresponded to sampling sites. The ArcGIS hydrology toolbox was used for flow direction and flow accumulation. Areas of concern were manually changed using the split and merge functions on ArcGIS.

b. Land Use and Salt Application Maps

V. Land cover and roads were digitized using ArcGIS to understand the land use and development within the watershed. 2024 ESRI world satellite imagery of watershed was digitized by creating new feature classes of land use types and merged with the subwatershed map. These maps quantified human development and impervious surface cover using these feature classes.



Map 3 3: This map illustrates land use within the Pleasant Lake watershed. Land cover types were assigned based on interpretation of high-resolution satellite imagery and Google Earth on ArcGIS.

a. Using the digitized landcover map, the percentage housing cover of land within each subwatershed was calculated. These percentages were then related to phosphorus concentrations observed in each tributary throughout the yearlong study. A statistically significant positive relationship between the two variables was found, with a p-value of 0.0041. This suggests that increases in housing coverage are significantly associated with higher total phosphorus concentrations. Although the model explains only 5.5% of the variability in phosphorus concentrations, it suggests that additional factors may also influence water quality.

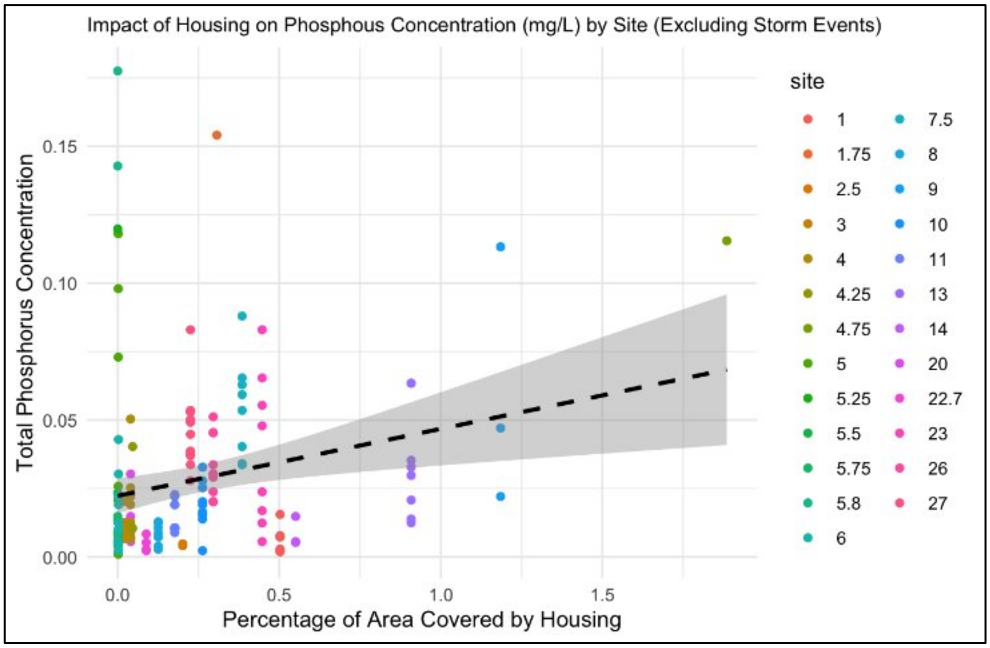
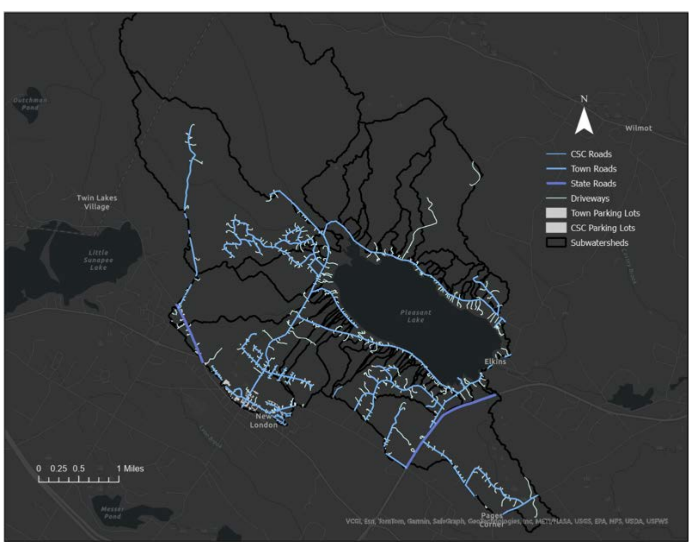


Figure 1 4: A linear regression analysis assessed the relationship between the percentage of area covered by housing and average phosphorus concentrations by sites. The analysis indicated a significant positive association, with a p-value of 0.0041.

VI. All pavement surfaces, such as state roads, town roads, driveways, and parking lots were digitized in the Pleasant Lake watershed. Using digitized maps of roads within the watershed, the state road salt application total in tons was calculated. This was based on standard New Hampshire Department of Transportation (NHDOT) application rates in tons/mi/year and town road rates were calculated through communication with the New London Department of Public Works.



Map 45: Road and other pavement types were digitized in the Pleasant Lake watershed.

Results:

I. VLAP Preliminary Data

Historical VLAP data was analyzed to provide a foundation for further research and analysis. In-lake measurements and parameters taken by the VLAP were of high importance when looking at past trends in the Lake. Temperature and dissolved oxygen profiles taken at the deep spot of the lake can reveal potential problems within a lake system, such as anoxic conditions and potential release of sediment-bound phosphorus. **Figure 2** reveals dissolved oxygen concentrations at the deep spot reaching anoxic levels, more frequently at depths below 25m. After 2018, measurements for depths below 25m were no longer taken. Reimplementing this practice of continuing to the ~30m depth of the lake is of utmost importance in understanding the conditions that may release sediment-bound phosphorus into the water column.

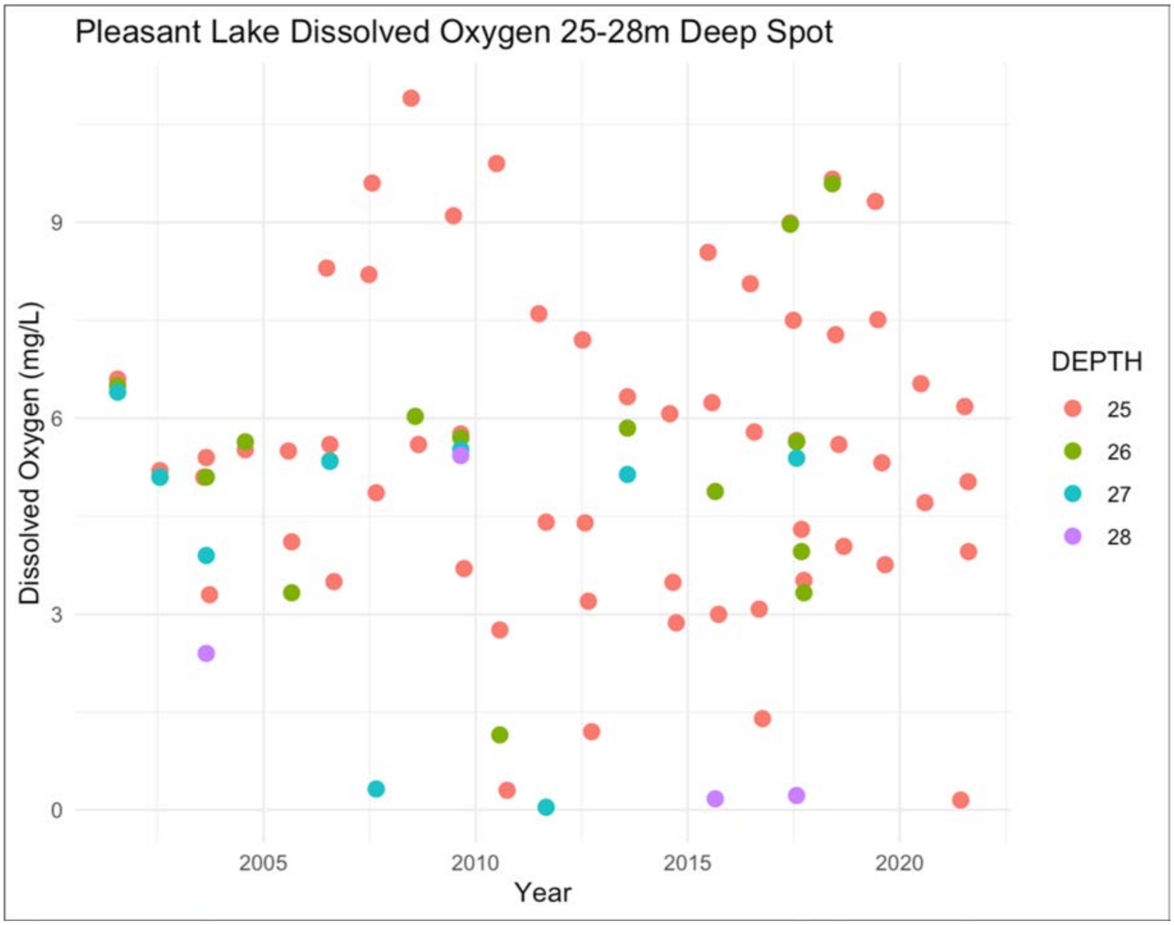


Figure 1: Dissolved oxygen concentrations from the Pleasant Lake Deep Spot site at 25-28m are shown. Beginning in 2007, the bottom of the lake has occasionally experienced anoxic conditions

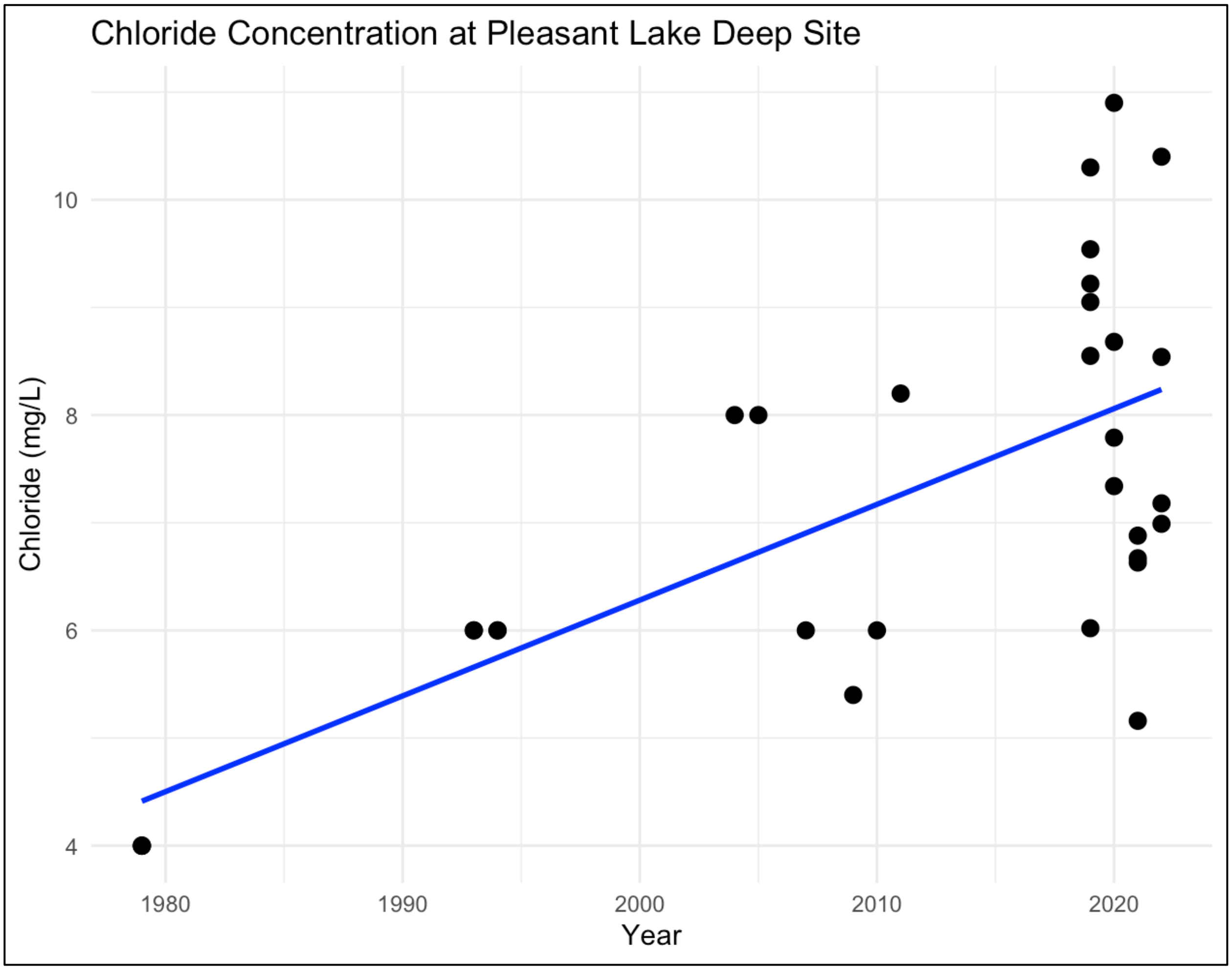


Figure 2: Chloride concentrations at the Pleasant Lake deep site are shown from historical VLAP samples.

Analysis of historical VLAP data also revealed an increase in chloride concentrations at the Pleasant Lake deep site, as seen in **Figure 3**. This increase gave reason for continued chloride monitoring in the tributaries to determine key sites that are bringing chloride into the system.

II. In-Lake vs Tributary Analysis

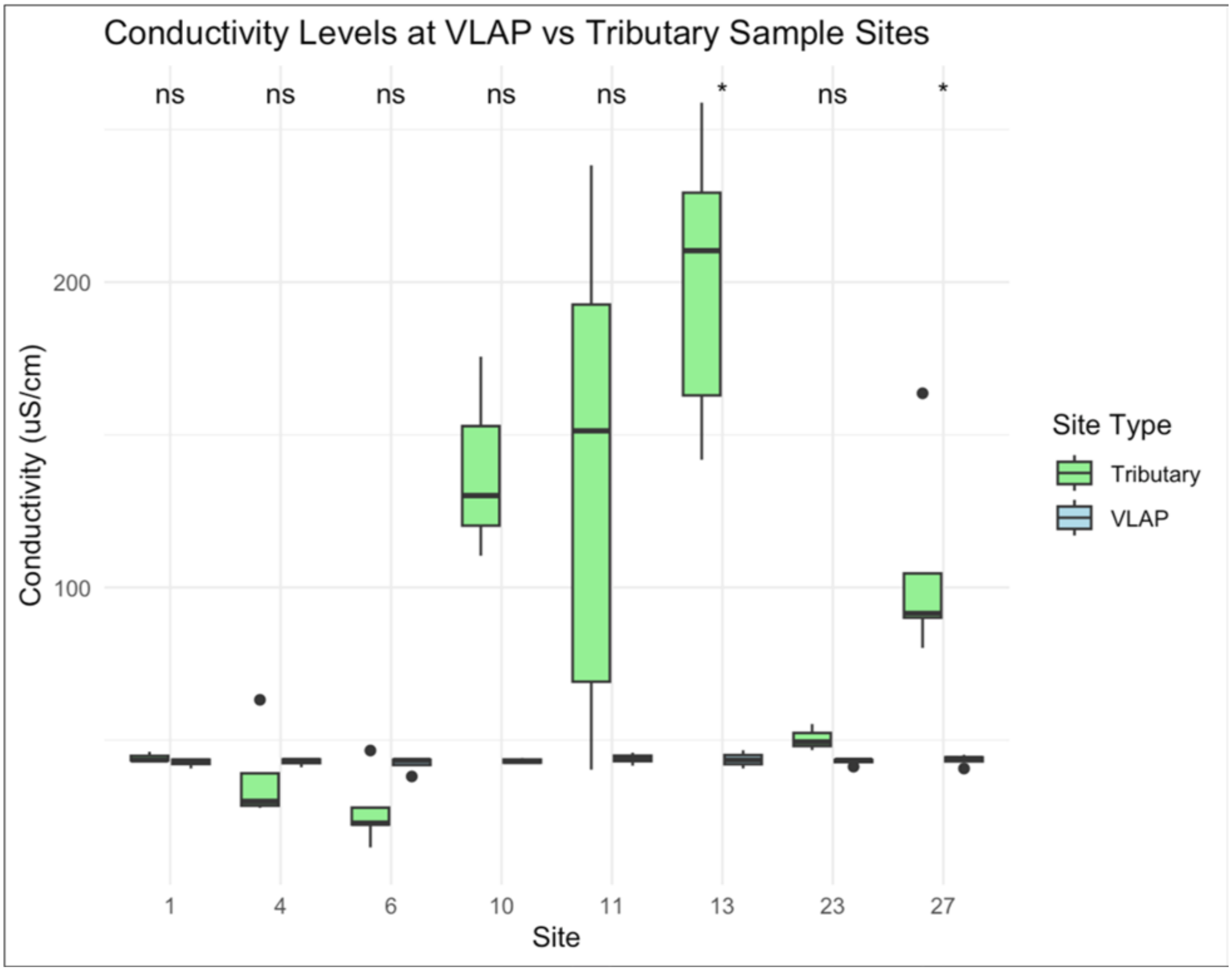


Figure 3: Conductivity values for tributary sampling sites and their corresponding in-lake VLAP sampling sites are shown. Wilcox test significance between groups p values: ns = no significance. 0.05 0.01** 0.001*** <0.001*****

A cornerstone of this project was building upon the effort of the VLAP sampling at Pleasant Lake, which focuses on monitoring in-lake sites for long-term changes in trends. An area that the VLAP effort lacks in is consistent input or tributary monitoring, that specifically examines what is entering the lake from specific sources. Corresponding tributary sites were assigned to existing VLAP sites for a paired analysis to determine whether the values measured in-lake significantly differed from tributaries.

A comparison of conductivity values in micro-siemens per centimeter (uS/cm) in **Figure 4**, of in-lake VLAP sites and tributary sites revealed greater variation of levels within and between sites in tributaries. Two sites, 13 and 27, have statistically significant differences in conductivity levels between in-lake and tributary when using a Wilcox test. Other sites did not show statistically significant differences, likely due to the small sample size of 3, which was limited due to the VLAP summer sampling schedule.

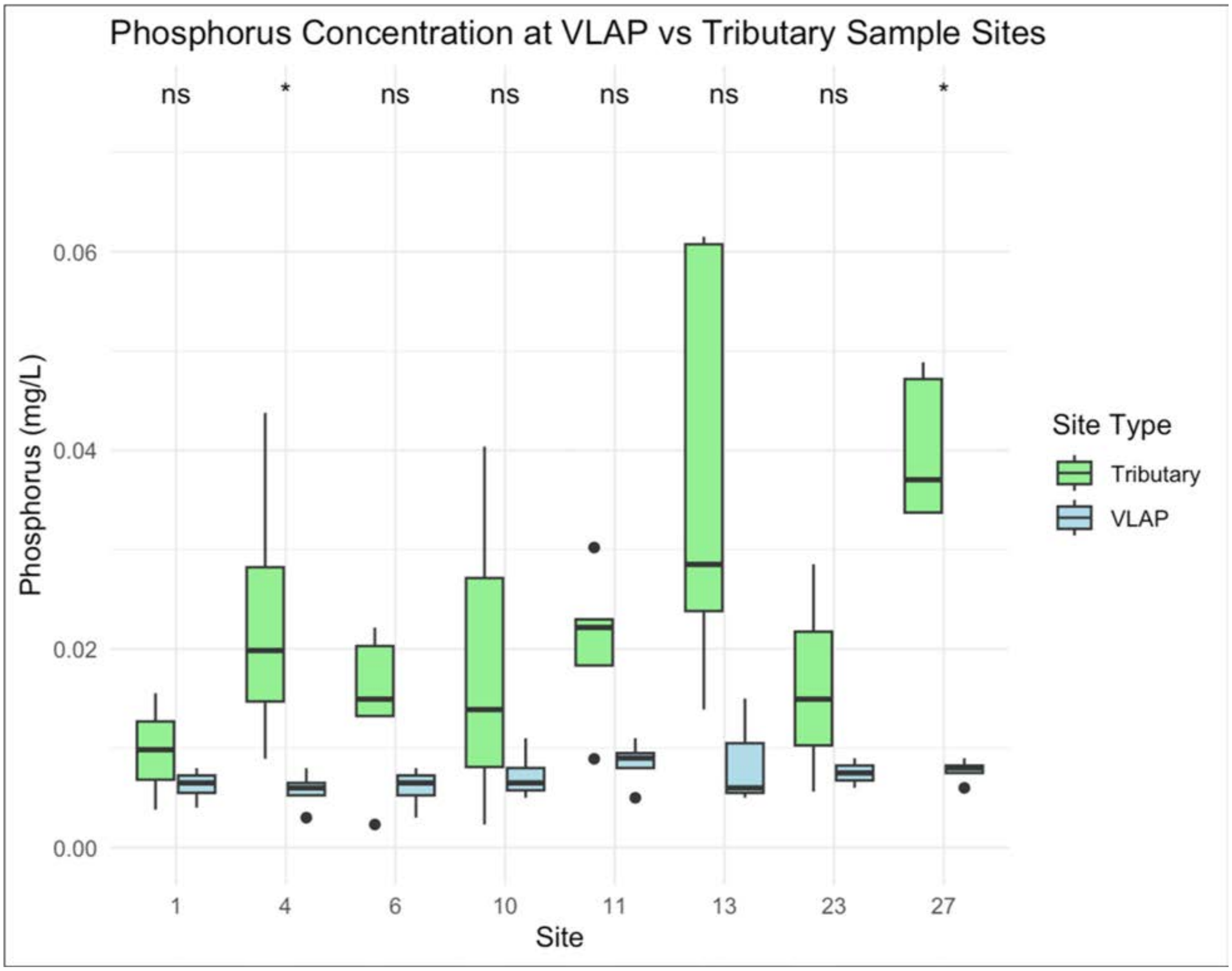


Figure 4: Phosphorus concentrations for tributary sample sites and their corresponding in-lake VLAP sampling sites are shown. Wilcox test significance between groups p values: ns = no significance. 0.05 0.01** 0.001*** <0.001*****

Like the conductivity analysis, a comparison of phosphorus concentrations in milligrams per liter (mg/L) in **Figure 5**, of in-lake VLAP sites and tributary sites revealed greater variation of levels within and between sites in tributaries. Two sites, 4 and 27, have statistically significant differences in phosphorus levels between in-lake and tributary when using a Wilcox test. Other sites did not show statistically significant differences, likely due to the small sample size of 3, which was limited due to the VLAP summer sampling schedule. These analyses highlight the importance of tributary sampling to understanding inputs from a watershed.

III. Storm and Seasonal Differences

A focus of the Community-based research study was quantifying the impact of storm or precipitation events on phosphorus loading within the watershed. The fall into early-spring study found significant differences between storm and baseflow events for phosphorus loading in grams per day (g/day) entering the system through tributaries. At the conclusion of the summer study, and thus yearlong data collection process, a full seasonal analysis was conducted and is displayed in **Figure 6.** With additional spring sampling, as well as summer sampling data, only fall data revealed a significant difference between storm and baseflow phosphorus loading. This data may be helpful in targeting times of the year to implement stormwater management practices and ensure they are functioning properly.

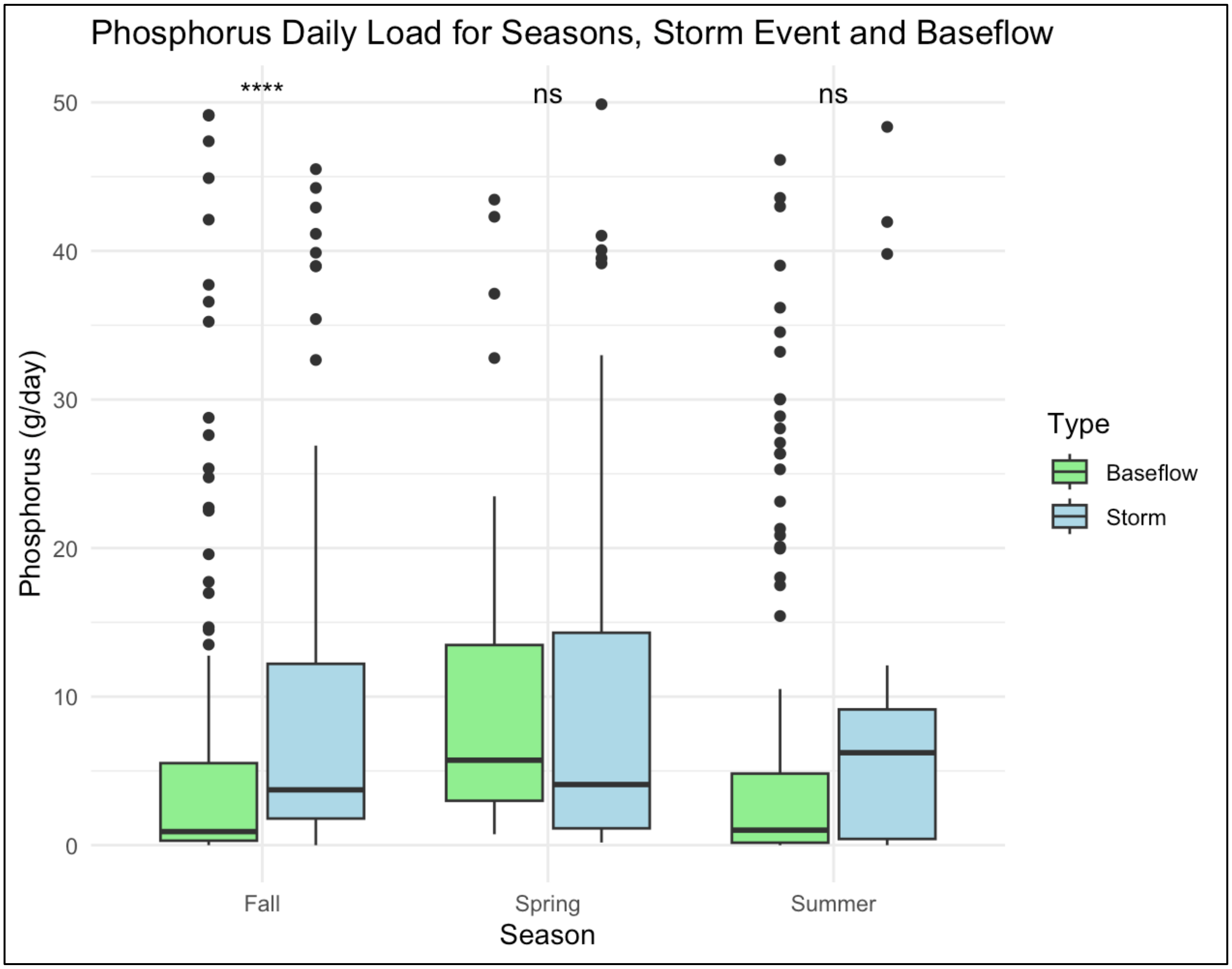


Figure 6: Phosphorus daily load (g/day) for tributary sample sites . Wilcox test significance between groups p values: ns = no significance. 0.05 0.01** 0.001*** <0.001*****

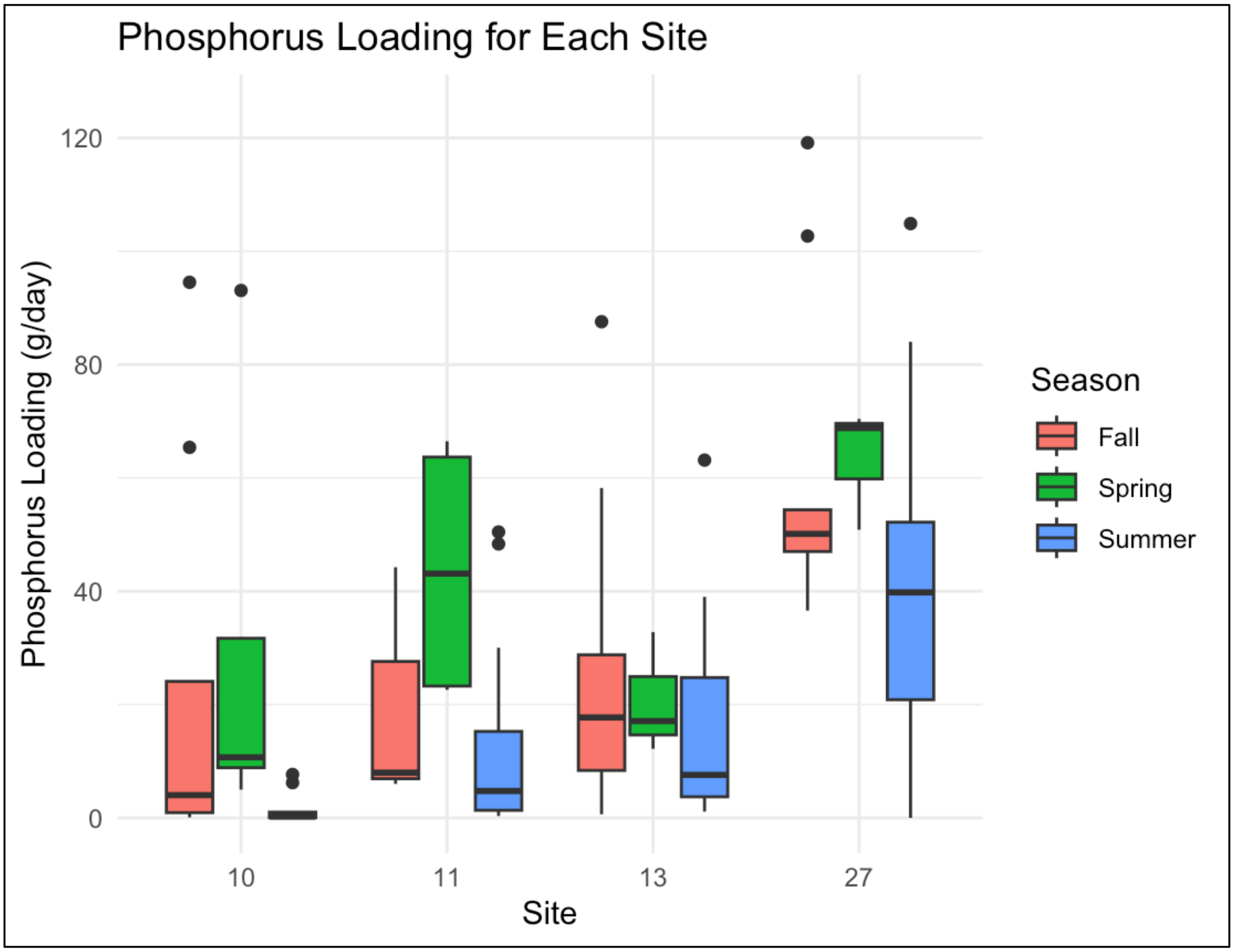


Figure 7: Phosphorus daily load (g/day) for tributary sample sites across fall, spring and summer across key sites.

An analysis of average phosphorus loading (g/day) across seasons in the yearlong dataset is shown in **Figure 7**. The data reveals that spring snowmelt often contributes the highest daily phosphorus load of the seasons. This seasonal peak likely results from snowmelt, which can increase runoff and erosion, mobilizing sediment-bound phosphorus. A study by Liu et al. (2023) found that spring snowmelt accounted for 74.5% of annual runoff and 81.2% of phosphorus losses in their study watershed. While the difference between spring and other seasons in this study was not as dramatic, it underscores the significant role of spring flushes in phosphorus dynamics.

IV. Headwater Analysis

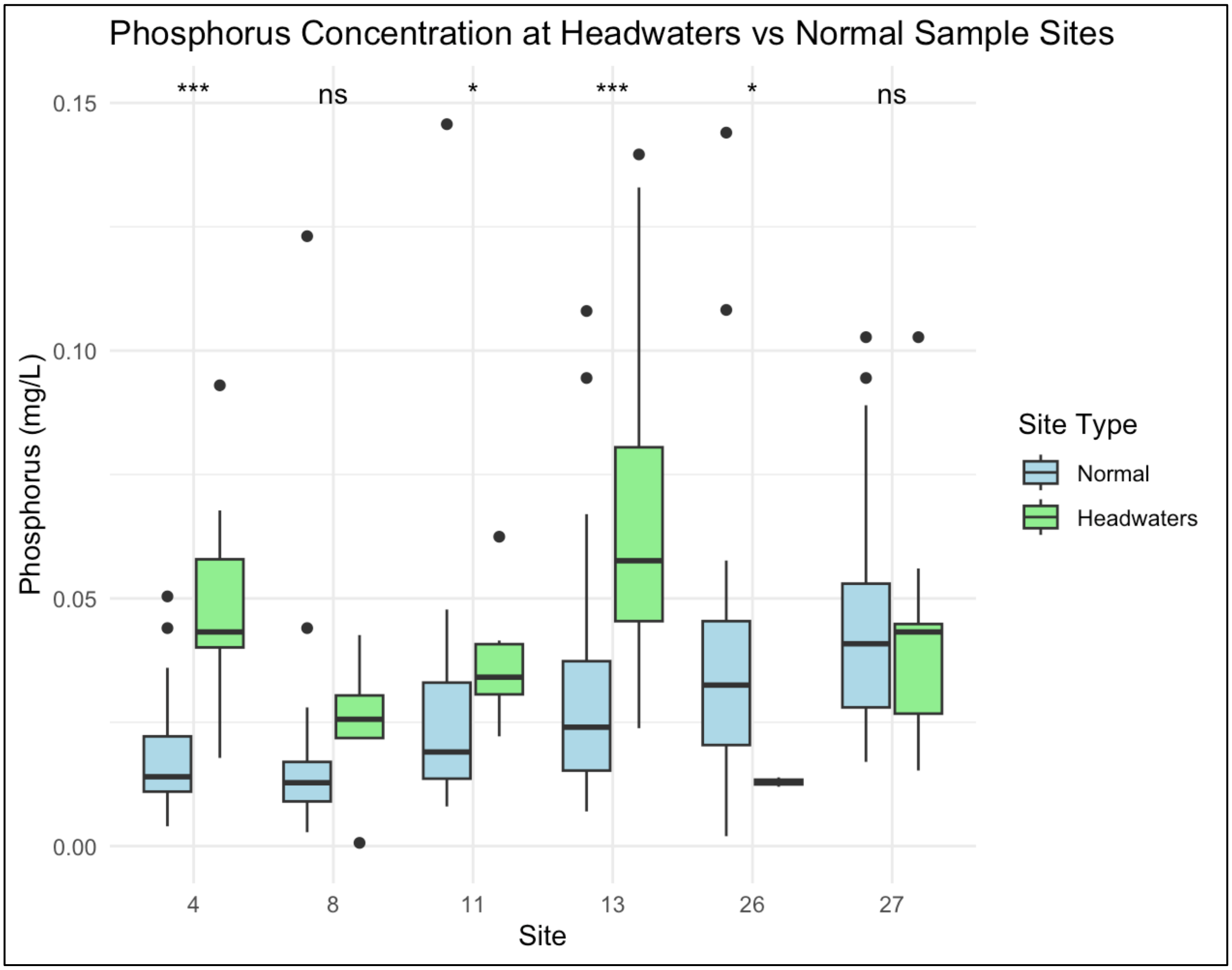


Figure 8: Phosphorus concentrations at tributary headwaters and their corresponding routine sampling site are shown. Wilcox test significance between groups p values: ns = no significance. 0.05 0.01** 0.001*** <0.001*****

The headwaters of key tributaries were identified for targeted analysis to determine whether they were viable for bracket sampling. Comparing headwater sites and normal tributaries would determine whether there were inputs of nutrients or other minerals as the stream approaches the lake. **Figure 8 displays** phosphorus concentrations (mg/L) for headwater and normal sampling sites on each tributary. Phosphorus concentrations were generally higher at headwater sites, which is to be expected, as most are wetland-fed streams whose sources accumulate nutrients. Notably, headwater samples from sites 4, 11, and 13 showed significantly higher phosphorus levels compared to their respective normal samples, as confirmed by a Wilcoxon test. These elevated levels may be attributed to the proximity of wetlands, which are naturally rich in organic matter and phosphorus. In contrast, normal samples at Site 26 show significantly higher phosphorus concentrations than headwater samples. This anomaly may indicate the presence of downstream contributions, such as runoff from developed areas or impervious surfaces, leading to the increase of phosphorus.

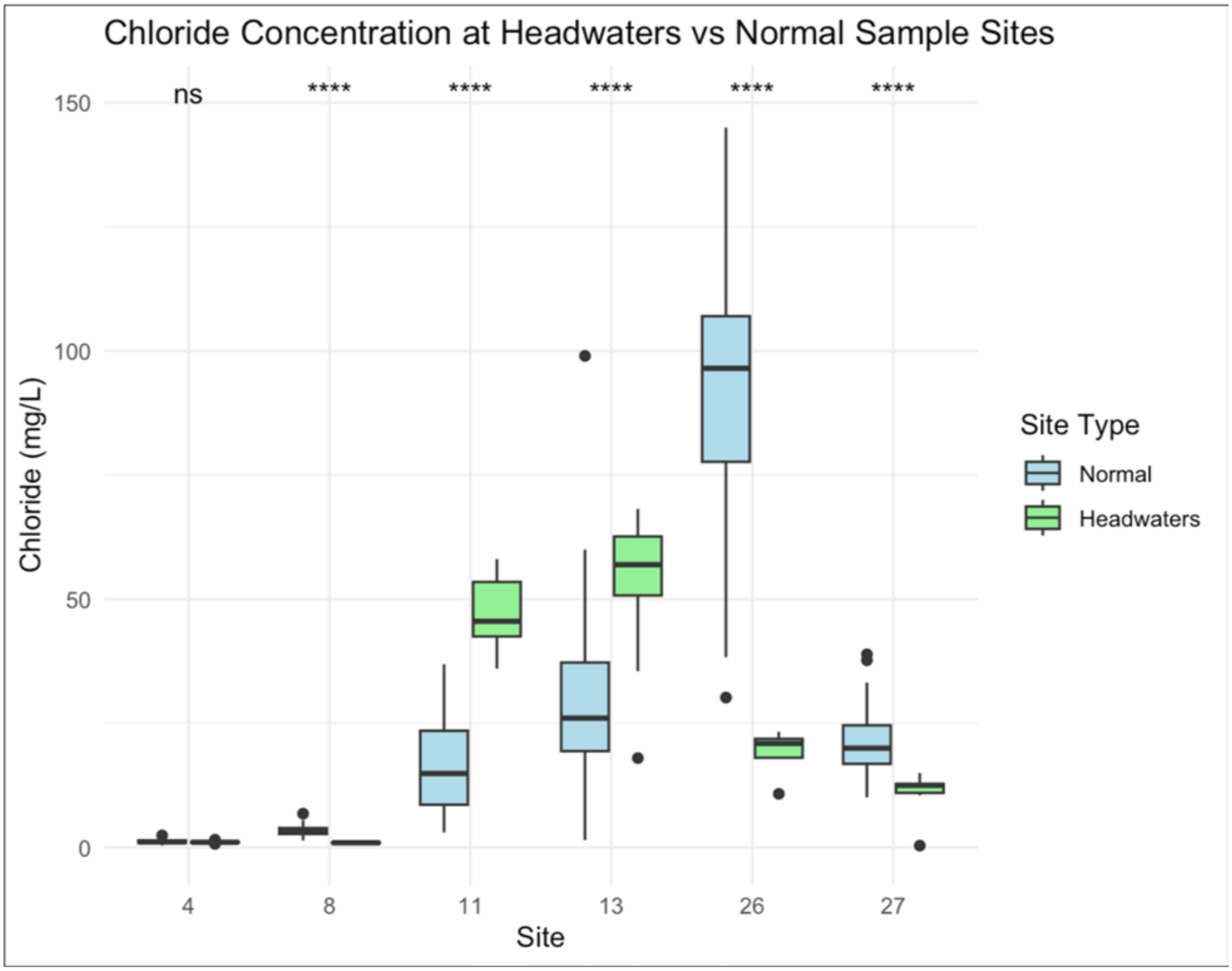


Figure 9: Chloride concentrations for tributary headwaters and their corresponding routine sampling sites are shown. Wilcox test significance between groups p values: ns = no significance. 0.05 0.01** 0.001*** <0.001*****

In addition to phosphorus concentrations, an analysis between normal and headwater chloride levels was conducted for select sites, as seen in **Figure 9**. Site 11 and 13 headwaters had significantly higher chloride concentrations than normal samples. Site 26 had significantly higher chloride concentrations at its normal site, potentially due to salt application on the state roads between the headwater site and the tributary site. Site 26 had consistently elevated chloride concentrations.

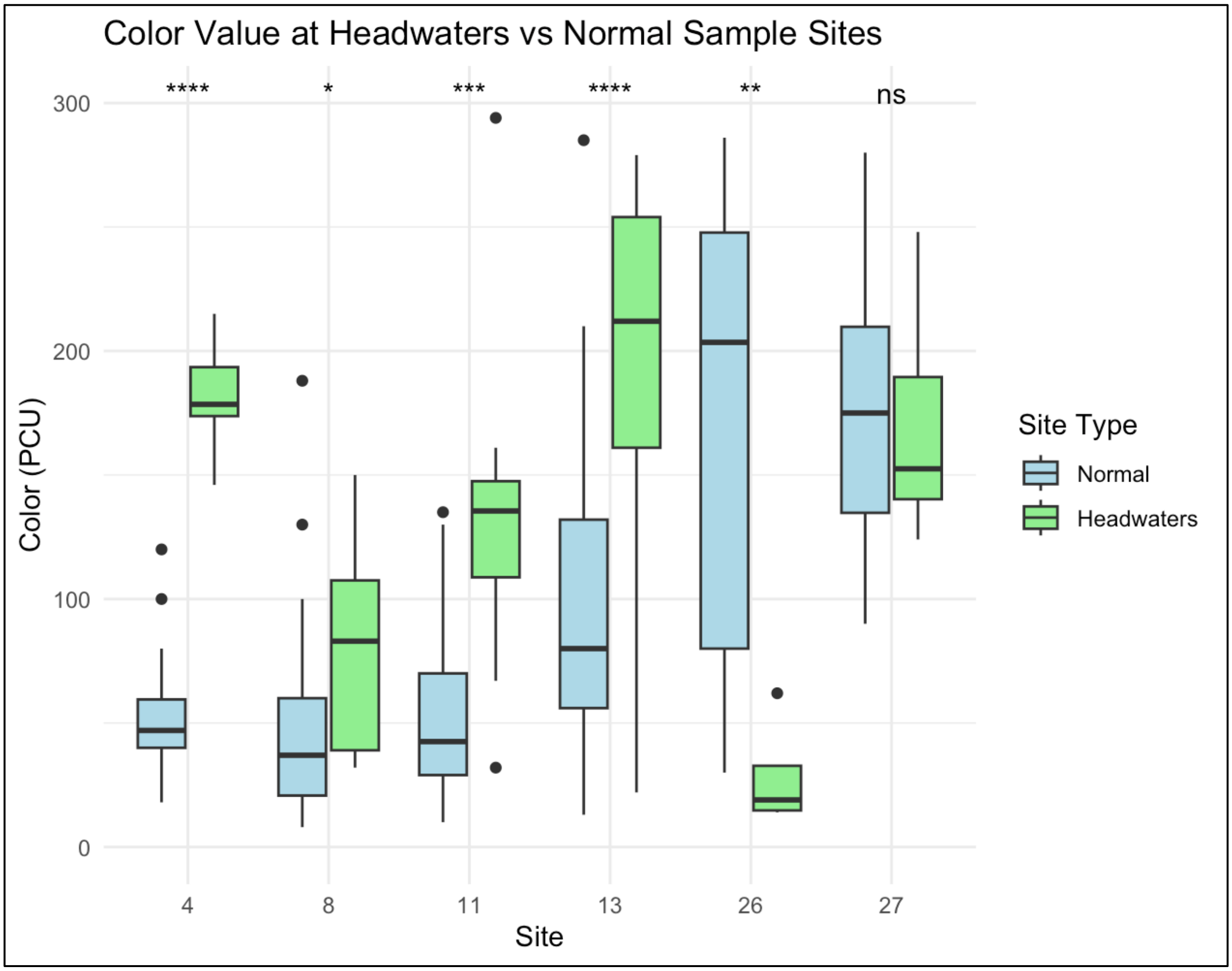


Figure 10: Color values for tributary headwaters and their corresponding routine sampling sites are shown. Wilcox test significance between groups p values: ns = no significance. 0.05 0.01** 0.001*** <0.001*****

Figure 10 shows a color comparsion between headwater and normal sample sites. Headwater samples from 488 Lakeshore drive (Site 4) White Brook (Site 11), and Little Brook (Site 13) and Site 26 had higher color values. These headwater sites are primarily wetland-fed or standing water, where organic matter and tannins impact the color of the water.

V. Summer Storm Events

Summer precipitation and storm events significantly increased both phosphorus concentration and loading. **Figure 11** displays phosphorus concentration data collected before and after a particular summer storm. Phosphorus loading increased following the heavy precipitation, about 0.4 inches of rain per hour, across all sites. For example, phosphorus levels increased from 30 µg/L to 91 µg/L at Great Brook and from 13 µg/L to 123 µg/L at Little Brook. The most substantial increase was observed at Fire Pond, where phosphorus rose from 83 µg/L to 198 µg/L after a storm event. This is supported by previous studies, as several precipitation events can account for nearly half of annual phosphorous loading (Biagi et al. 2022). These results highlight the strong influence of precipitation events, particularly summer thunderstorms, on nutrient dynamics and the potential for storm-driven phosphorus pulses impact on water quality.

Site	Before Storm	After Storm
Great Brook	30 ug/L	91 ug/L
Little Brook	13 ug/L	123 ug/L
White Brook	23 ug/L	146 ug/L
Red Brook	35 ug/L	108 ug/L
Bunker/Elkins	45 ug/L	168 ug/L
Fire Pond	83 ug/L	198 ug/L

Figure 11: Table displaying phosphorus loading of top contributing site before and after major precipitation on June 20th

Conclusion and Next Steps

Tributary sampling provides a more accurate and descriptive reflection of water entering Pleasant Lake compared to in-lake sampling near tributary mouths. **Figure 4 and Figure 5** illustrate that both phosphorus concentrations and conductivity levels have greater variation within and between tributary sites. This discrepancy is largely due to dilution effects within the lake. The speed at which stream water mixes with lake water is not consistent or well-understood, but a study by Ward et al (2022) found that stream water temperature influences how it mixes into lake water. While mixing dynamics within Pleasant Lake are likely unique to its morphology, the tributary vs. in-lake analysis supports the idea that mixing occurs too quickly for in-lake samples to be representative of watershed inputs.

Assessing watershed, or external inputs into Pleasant Lake, is not the only important factor in understanding nutrients. To enhance the understanding of in-lake dynamics, dissolved oxygen levels should be measured beyond 25 feet at the lake's deepest point. This parameter is essential for detecting hypoxic conditions, which can trigger the release of sediment-bound phosphorus and contribute to algal blooms. **Figure 2** displays the historical VLAP data taken at the deep site for dissolved oxygen, showing values below 25m stopping. The deep spot of a lake is where anoxic conditions are most likely to occur, as the zone becomes devoid of light, photosynthetic activity, and mixing during the summer months. A sediment core at this deep site was taken by a fellow CSC student for analysis in a Capstone Project. Results of aluminum, iron, and phosphorus ratio analyses will help inform the potential for internal phosphorus loading from this reactive sediment layer at the deep site.

Yearlong monitoring identified sites of high priority for continued monitoring and the potential implementation of stormwater management strategies by the Pleasant Lake Protective Association. Site 26, at the intersection of Elkins and Bunker, showed significantly higher chloride concentrations than any other site in the watershed, across the entire yearlong dataset.

Sampling of this site at its headwaters revealed lower concentrations than what was seen at the routine site, confirming that downstream chloride and phosphorus spikes likely originate from activities such as residential development and state road maintenance that are prevalent in that subwatershed. Site 27 revealed consistently elevated phosphorus concentrations, likely due to stagnant water conditions, organic matter accumulation, and its historical use as a fish-rearing pond. Additionally, Great Brook exhibited the highest phosphorus loading, mainly due to high discharge and natural phosphorus contributions from the surrounding forested area.

Overall, housing development and land cover influenced phosphorus concentrations. The digitized land cover type map of the Pleasant Lake watershed revealed low human development and impervious surface cover. Despite the watershed's relatively low development percentage, anthropogenic phosphorus sources were measurable through housing coverage. A statistically significant relationship between percent housing cover and phosphorus concentrations was found. In particular, White and Red Brook were identified as significant phosphorus contributors, and their watersheds had a high percentage of housing land cover. Despite only 0.47% of the watershed is impervious surfaces, it still has a relationship with phosphorus concentrations. For context, according to the EPA, once a watershed is 10–20% impervious, surface runoff doubles and continues to increase. 15% impervious surface cover is considered a threshold and beyond this there's a notable increase in phosphorus loading. All Pleasant Lake's subwatersheds this "threshold" of 15% impervious, however it still impacts phosphorus concentrations. As the watershed continues to develop, education of phosphorus mitigation best practices are essential as well.

Monitoring over the course of a year highlighted key seasonal drivers of phosphorus and chloride loading, particularly spring snowmelt and summer storm events. During spring snowmelt, large volumes of water move through the watershed, increasing phosphorus transport. During summer storm events, phosphorus loading rises due to sediment transport and higher discharge rates.

Several existing initiatives by the Lake Sunapee Protective Association (LSPA) can serve as models for mitigation efforts. These include rain gardens, such as the one implemented at Bucklin Beach on Little Lake Sunapee, that help slow runoff and improve infiltration. Further stormwater management, such as the implementation of swales and gravel pits, at road intersections, particularly at the Bunker/Elkins intersection, would significantly improve efforts to reduce runoff impacts from paved surfaces. In addition to this, the Sunapee Swirler has been installed along the shores of nearby Lake Sunapee, in efforts to reduce sediment entry and increased phosphorus into the lake. The Sunapee Swirler has a simple design, as seen in **Figure 12**, that is affordable for small town budgets and requires no special maintenance (LSPA, 2020). These devices could be utilized by the PLPA in areas before water enters the lake through culverts, to help reduce sediment-bound phosphorus.

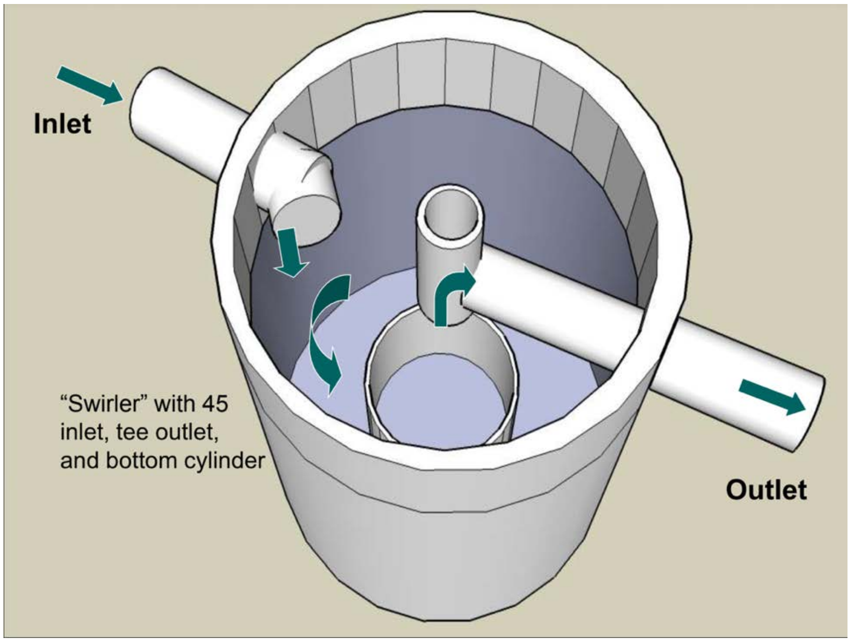


Figure 12: Diagram of the Sunapee Swirler and its components for sediment catchment (LSPA, 2020).

In addition to local examples, there are also state-led programs with the mission of educating landowners of best management practices for their properties. The NH Lakes organization runs a free and voluntary program called LakeSmart, where homeowners can have their property evaluated and certified that it is being properly managed to protect water quality and habitats. Property owners can fill out an online survey describing their property and receive tips and recommendations to implement in order to make their property lake friendly. The NHDES also offers a free program to residential and small commercial properties called Soak Up the Rain, that provides ways to manage stormwater runoff. Exploring either of these programs would be a positive way for residents and businesses within the Pleasant Lake Watershed to reduce their individual impact on the lake.

Finally, a salt minimization plan to reduce road salt application rates of state-maintained could benefit the watershed. Results of analyses conducted on salt application practices and chloride concentrations revealed that state-maintained roads are likely the greatest contributors of chloride into the Pleasant Lake Watershed. Sites 26, 13, and 27, Bunker/Elkins, Red Brook, and the Fire Pond respectively, had the highest chloride concentrations, as well has had State Routes 11 and 114 within their watershed boundaries. The salt application rate of the state was found to be 17 times that of the town, at 17.2 tons/mile/year compared to 1 ton/mile/year. Action can be taken by the Town of New London and PLPA to lower the salt application rate on state roads within the watershed boundaries. Other lakes and ponds in New Hampshire, and even rivers, have implemented salt minimization plans to reduce increasing chloride levels due to excessive road salt application. The NHDES provides information for the creation and implementation of Salt Minimization Plans, and once implemented the New Hampshire Department of Transportation (NHDOT) will be required to follow the plan. More information on this process is located on the NHDES website and is linked in the references of this paper (NHDES, 2020). A successful pilot road salt reduction program exists on the Interstate 89 bridge between New Hampshire and Vermont, crossing the Connecticut River (NHDOT, 2014). The program utilizes monitoring software that automatically detects conditions and applies appropriate de-icing treatment. The Town of New London and PLPA could work toward a Salt Minimization or Reduction plan with the NHDES or EPA as a way to effectively reduce chloride inputs into Pleasant Lake. A balance between ecological concerns and road safety would have to be met but implementing more mindful practices throughout the entire watershed would help to address rising chloride levels.

Overall, continued involvement and education are imperative, including the ongoing promotion of best management practices. Continuing to monitor conditions in the Pleasant Lake Watershed will help inform future management initiatives, potential grant opportunities, and preserve the quality of the lake for years to come.

Appendix:

I. VLAP

Graphs included in this section are for those interested in further understanding the history of Pleasant Lake's water quality through visual trends observed in parameters such as dissolved oxygen, visibility, and phosphorus. All data used in the figures below were collected through the VLAP and accessed via their public database.

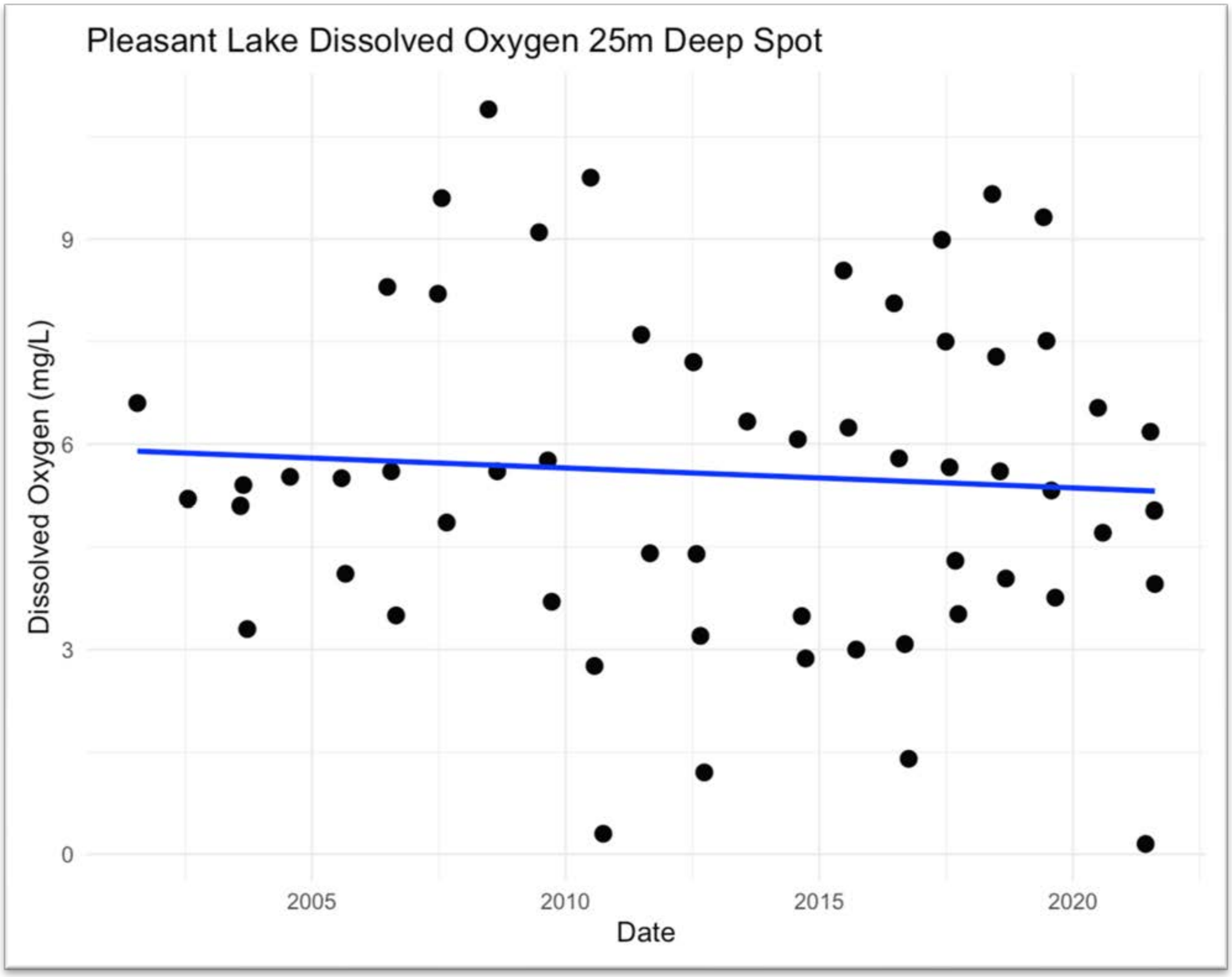


Figure 5: The dissolved oxygen concentrations from 2001-2022 at a depth of 25 meters at the Deep Spot site at Pleasant Lake are shown. A stable, but slightly declining trend is observed. Concentrations occasionally reach anoxic levels at this depth, beginning in 2011.

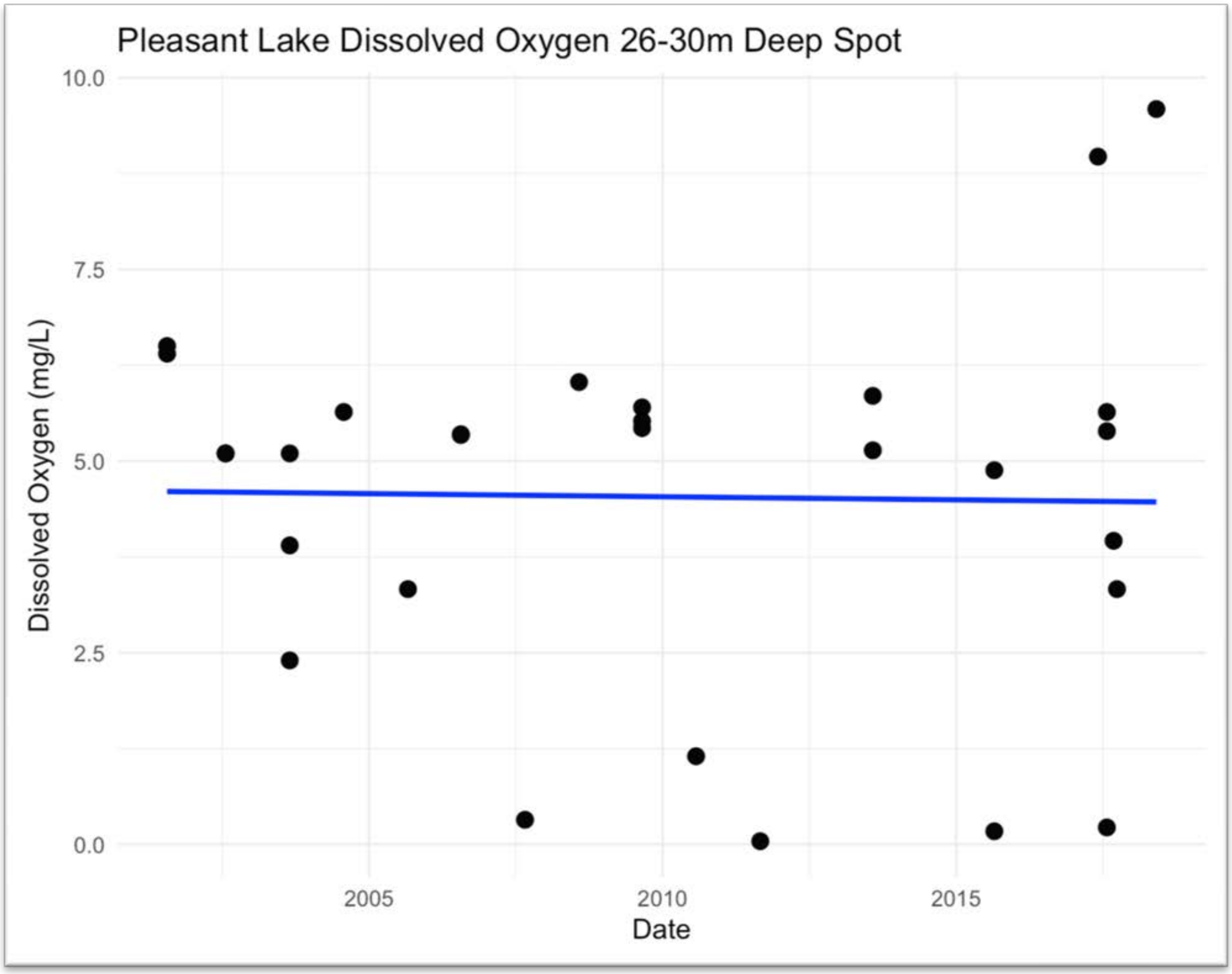


Figure 6: The dissolved oxygen concentrations from 2001-2018 at a depth of 26-30 meters at the Deep Spot site at Pleasant Lake are shown. Measurements below 25m were no longer taken after 2018. Dissolved oxygen levels occasionally reach anoxic conditions beginning in 2007 and continuing until these depths were no longer sampled.

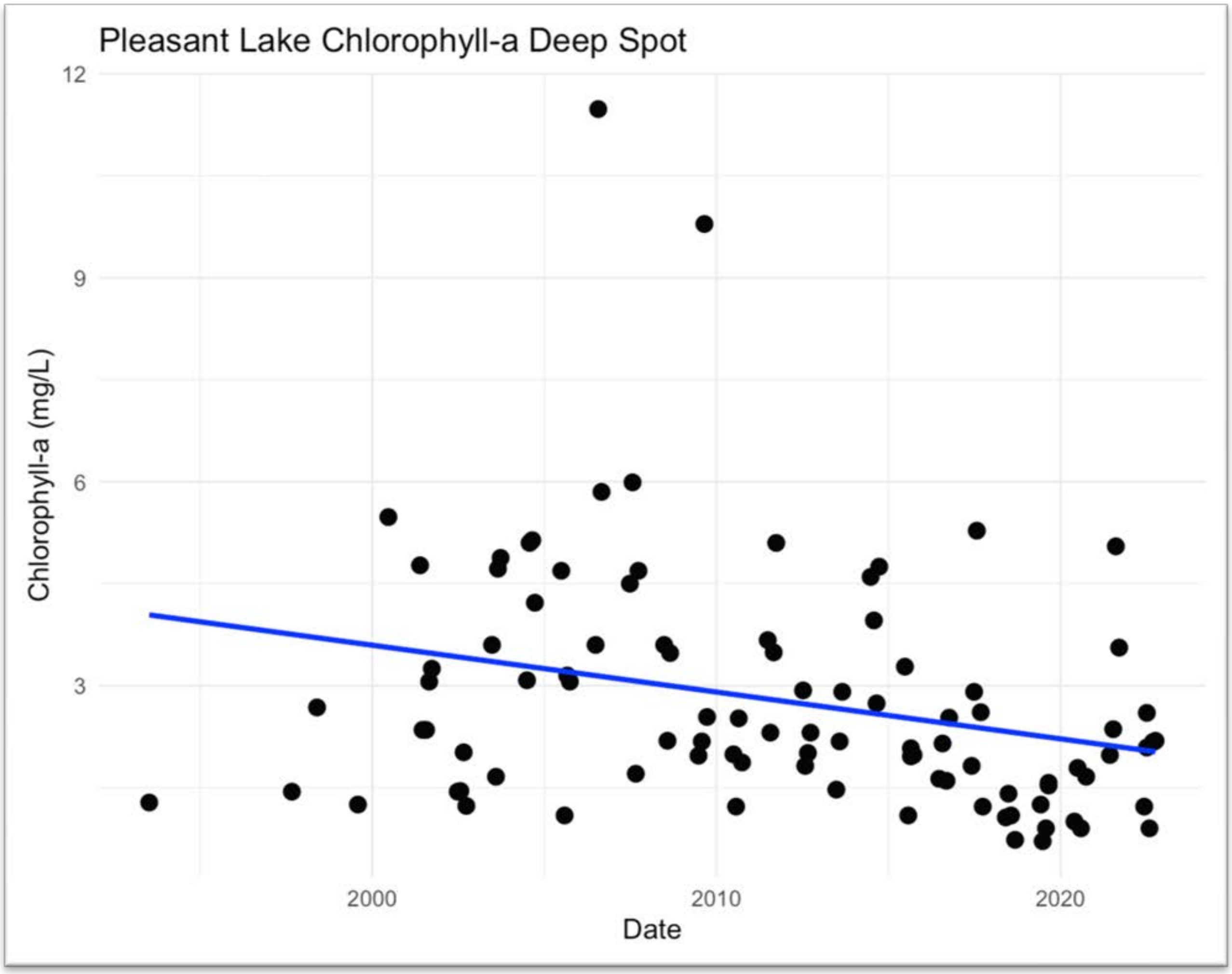


Figure 7: Concentrations of chlorophyll-a at the Pleasant Lake Deep Spot site from 1993 to 2022 are shown. Levels show a slight decreasing trend.

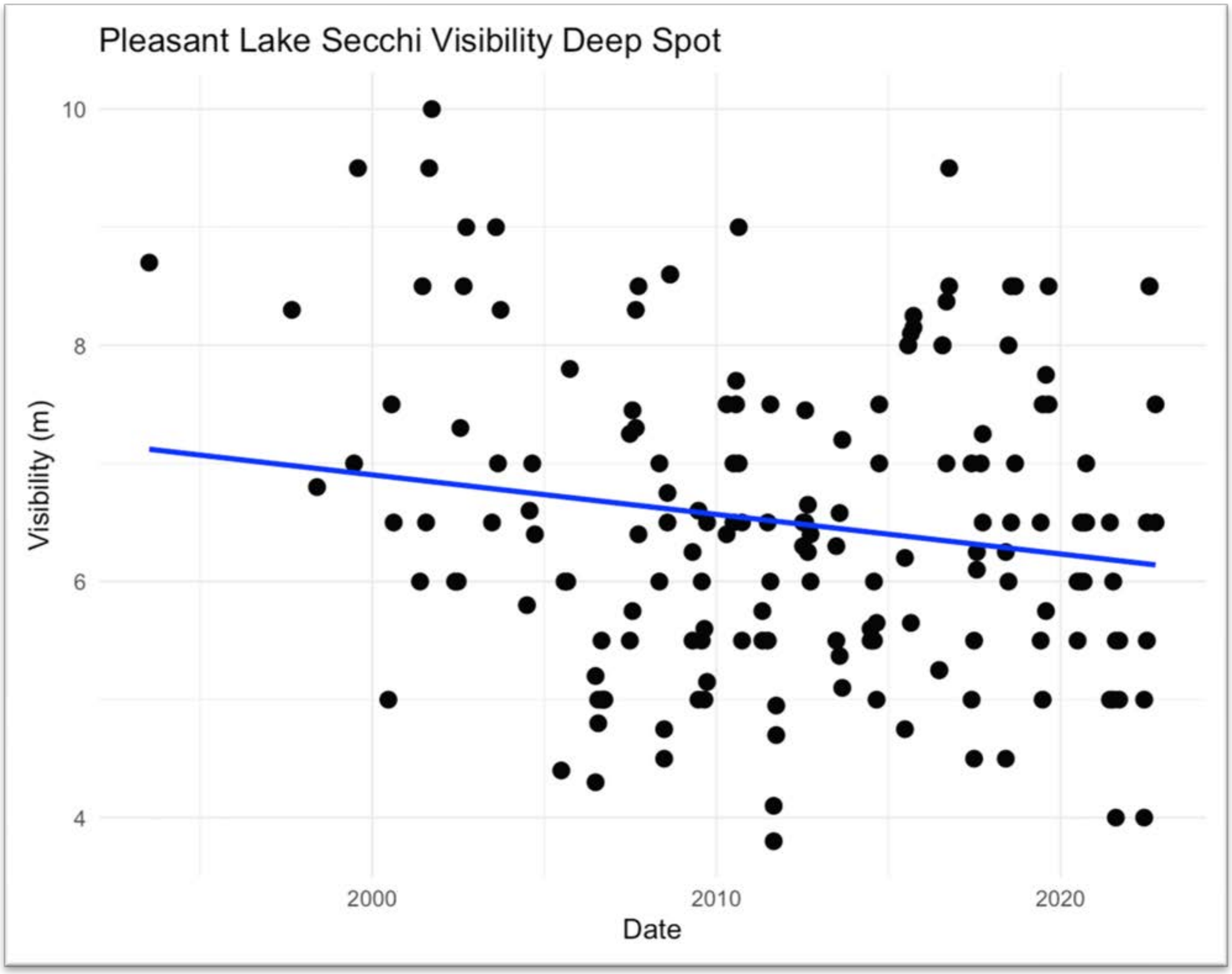


Figure 81: The depth at which a secchi disk is visible at the Deep Spot site at Pleasant Lake is shown, from 1992-2022. The data shows a gradually decreasing trend in visibility.

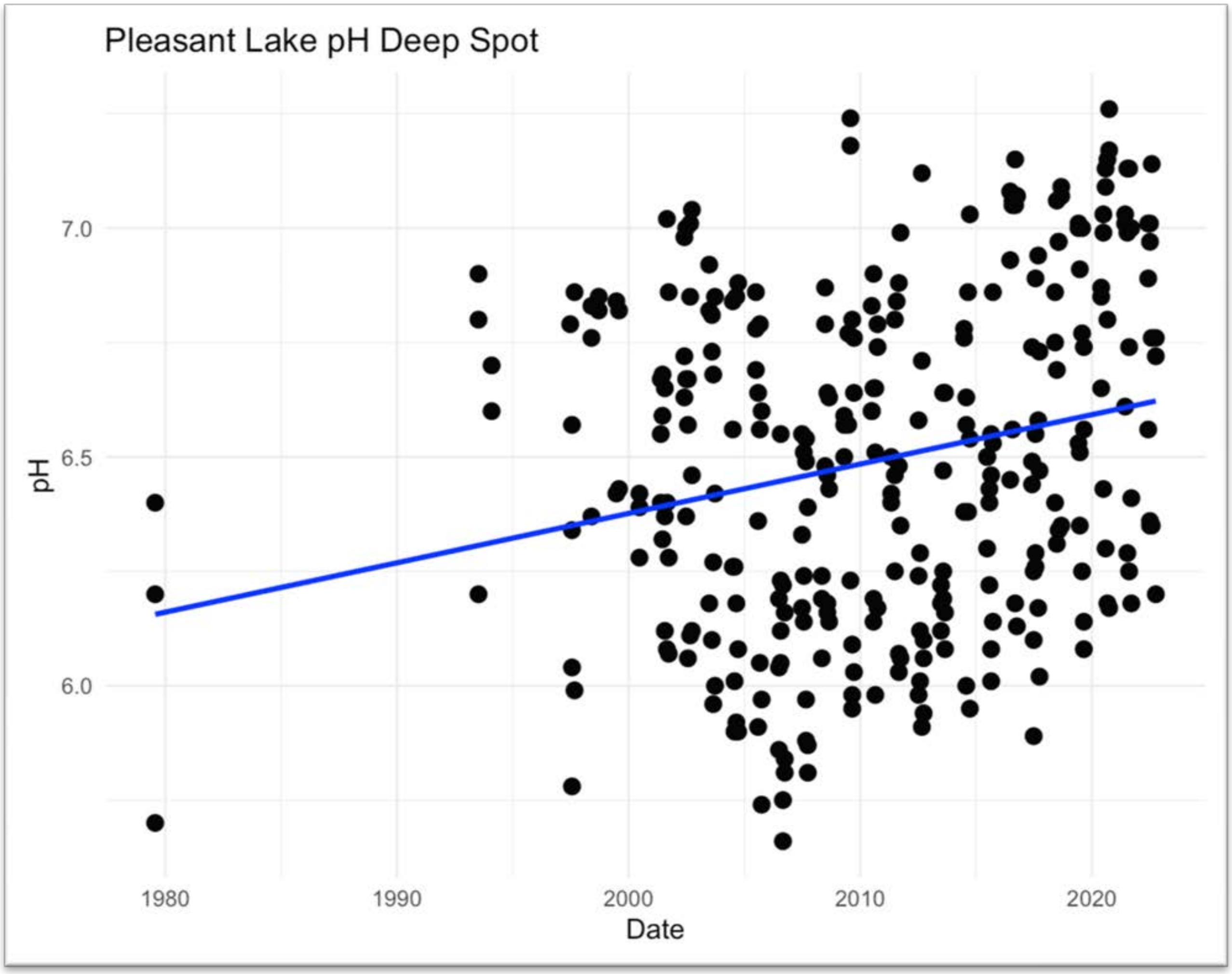


Figure 9: The pH values at the Deep Spot site at Pleasant Lake are shown, from 1979 to 2022. The data shows a rising trend in pH, indicating recovery from acid rain.

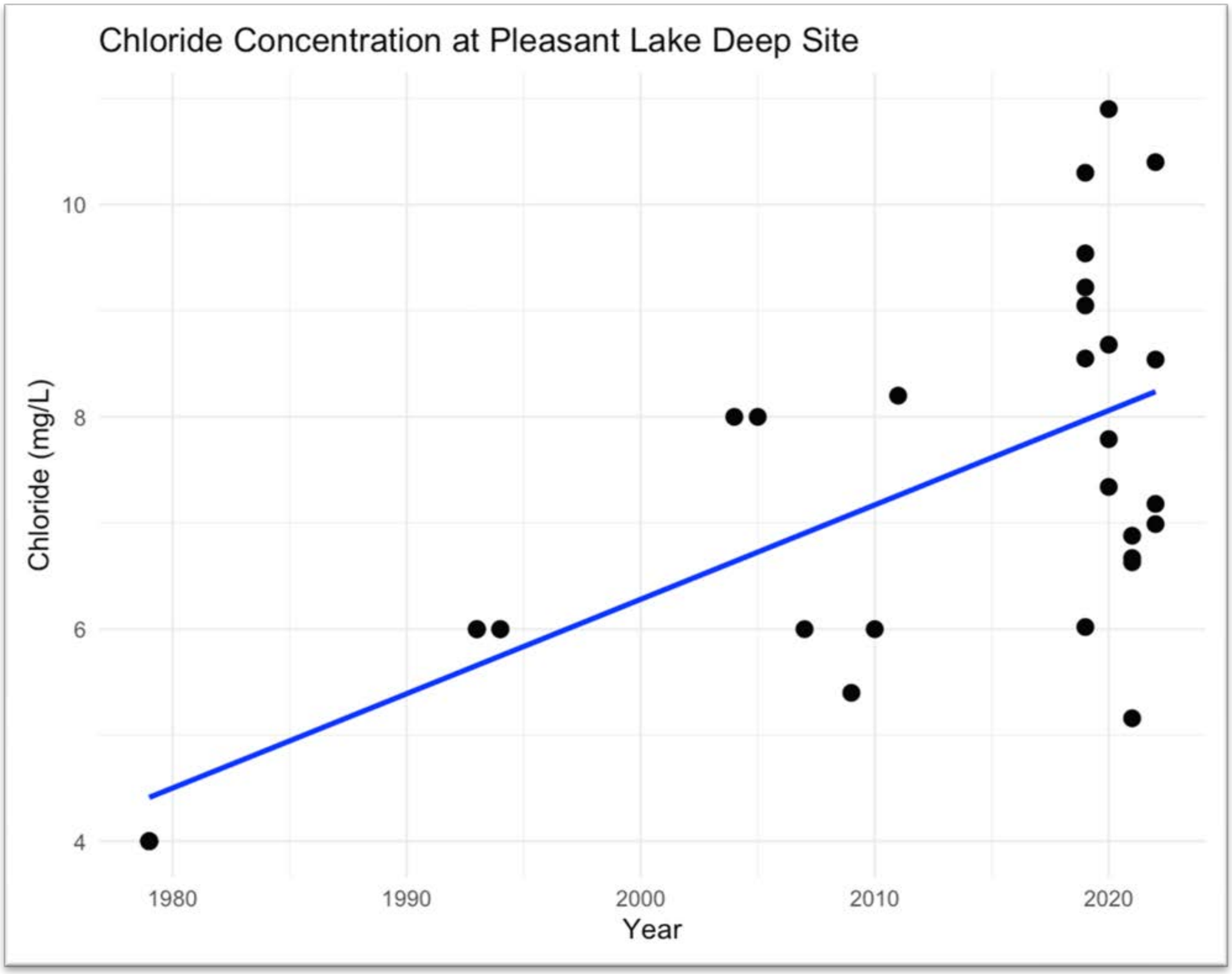


Figure 110: Concentrations of chloride at the Pleasant Lake Deep Spot site are shown, from 1979-2022. Though points are limited, an increasing trend is observed.

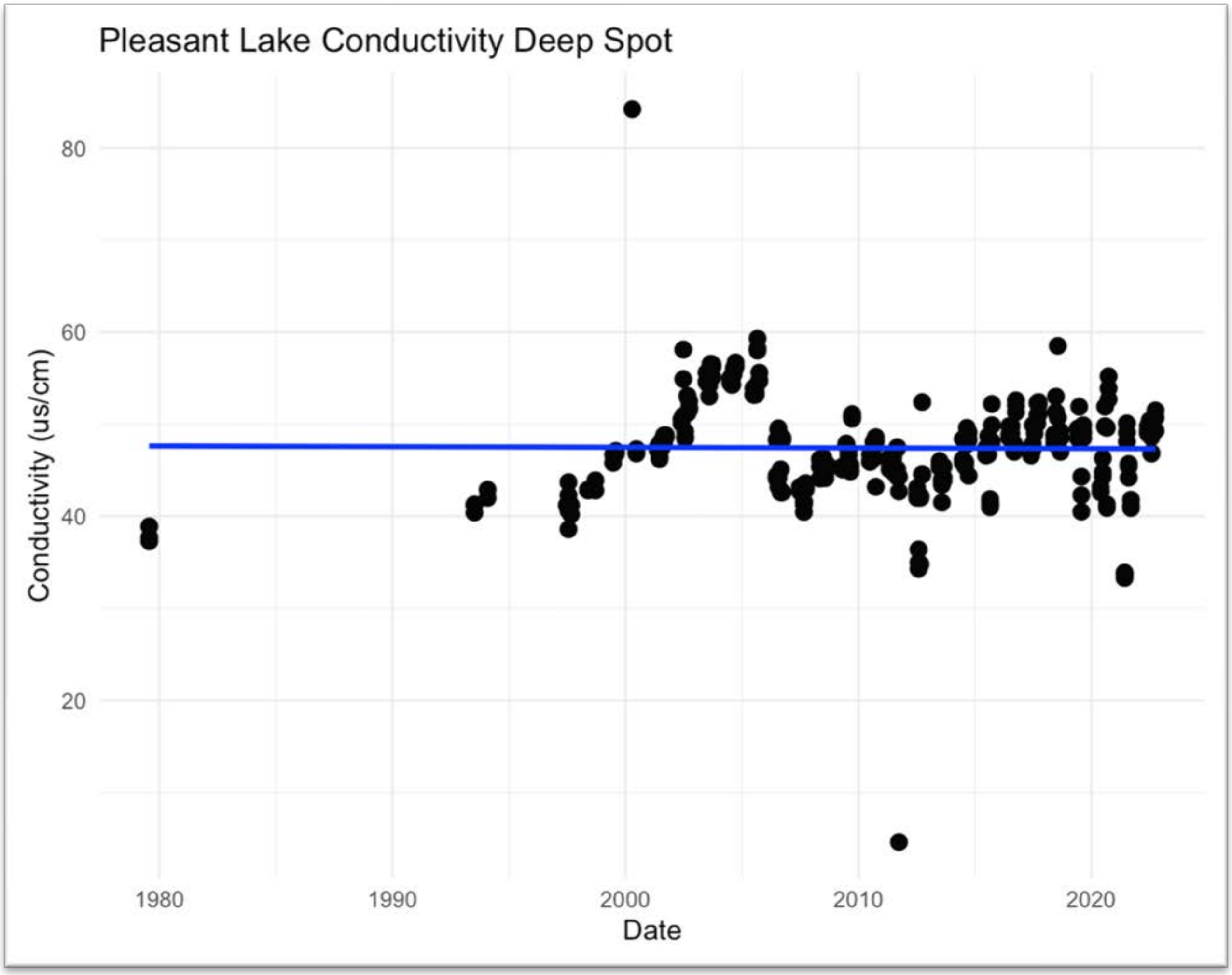


Figure 114: Conductivity levels at the Pleasant Lake Deep Spot site have been remaining relatively stable from 1979-2022.

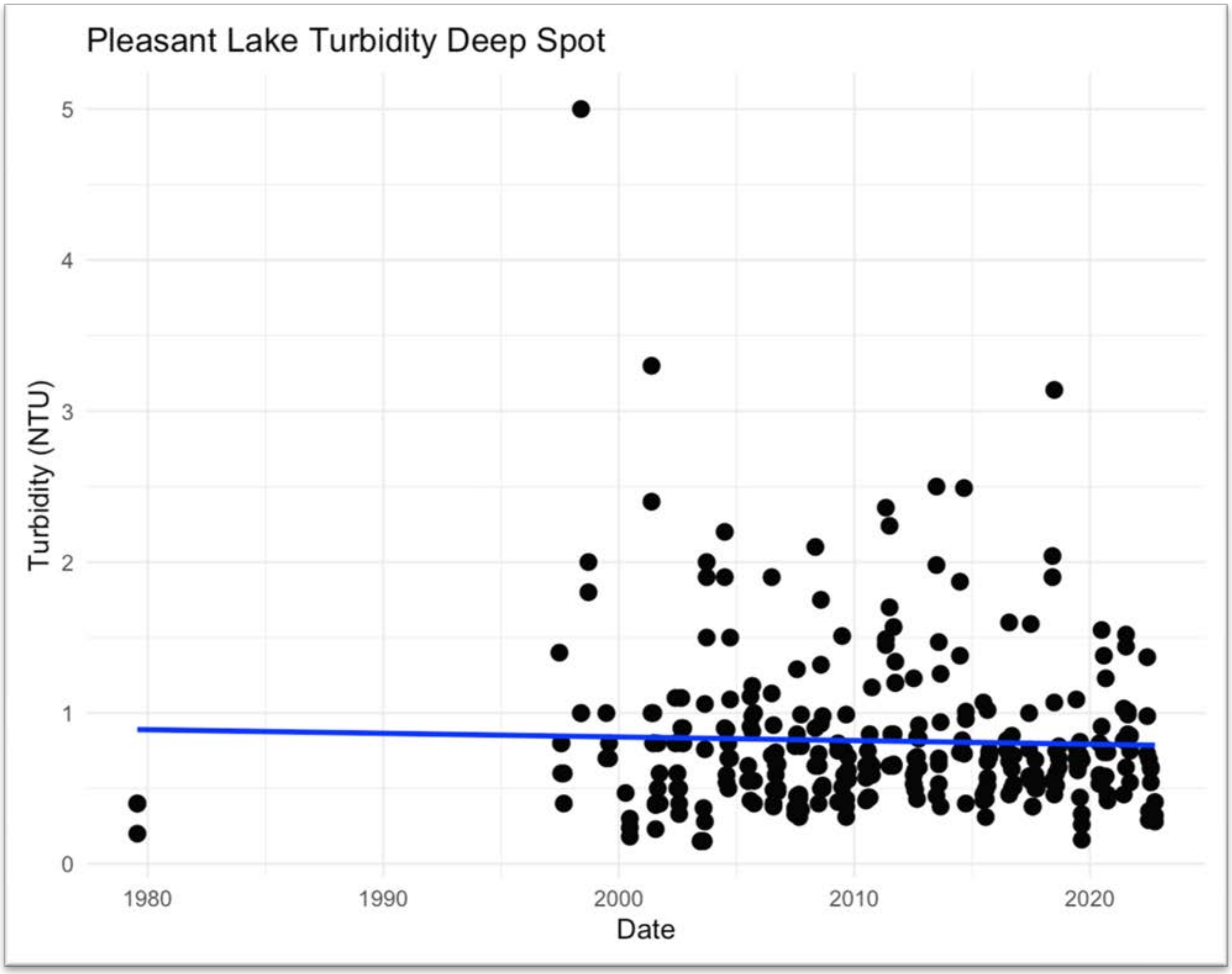


Figure 125: Turbidity levels at the Pleasant Lake Deep Spot site have been remaining relatively stable from 1979-2022.

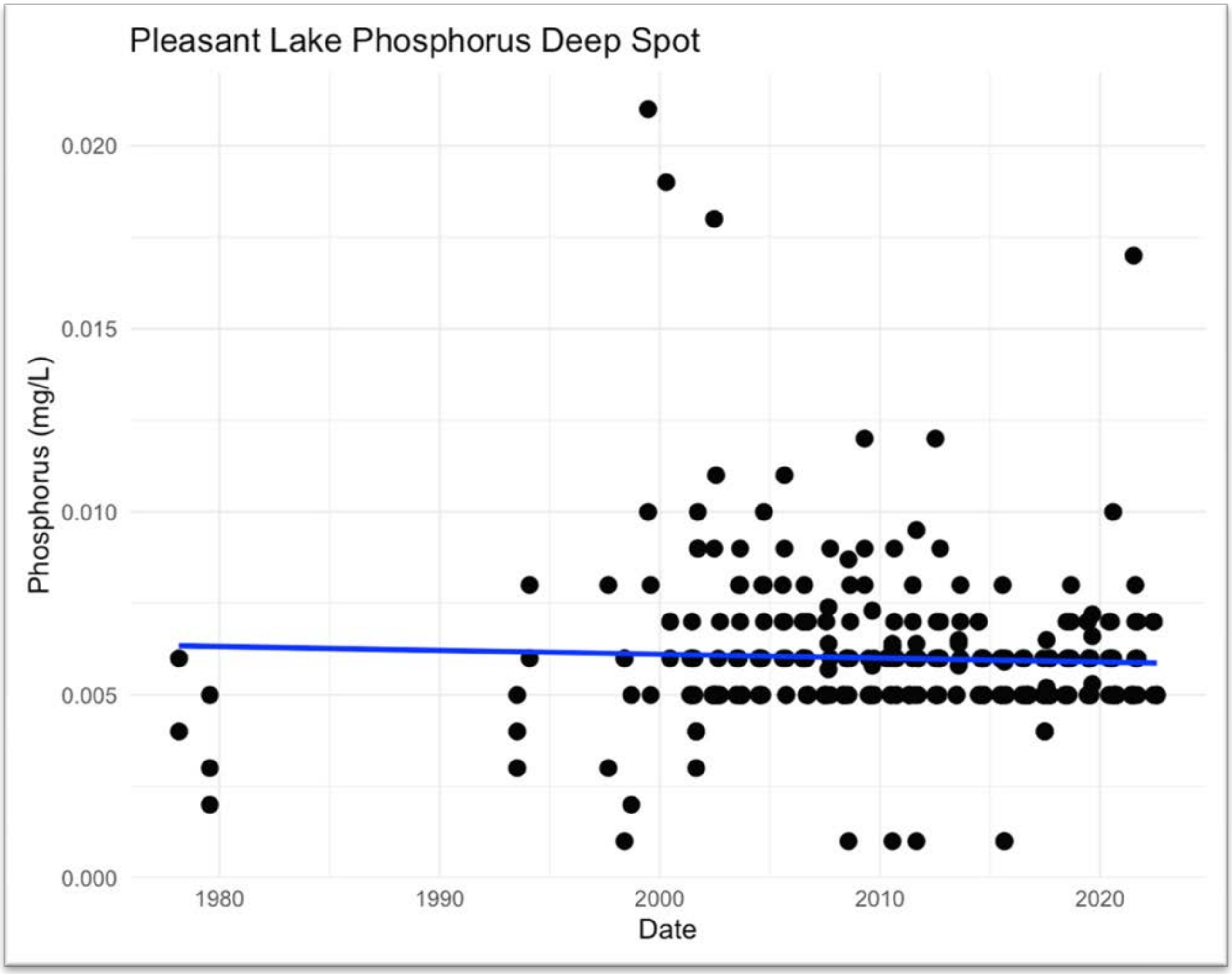


Figure 136: Phosphorus levels at the Pleasant Lake Deep Spot site have been remaining relatively stable from 1979-2022.

References

Bormans, M., Marsalek, B. & Jancula, D. (2016). Controlling internal phosphorus loading in lakes by physical methods to reduce cyanobacterial blooms: a review. *Aquatic Ecology, 50* (3), 407-422. https://doi.org/10.1007/s10452-015-9564-x

Hong Y, Zhu Z, Liao W, Yan Z, Feng C, Xu D. (2023). Freshwater Water-Quality Criteria for Chloride and Guidance for the Revision of the Water-Quality Standard in China. *International Journal of Environmental Research and Public Health.* 20(4): 2875. Doi: 10.3390/ijerph20042875.

Luo, H., Luo, L., Huang, G., Liu, P., Li, J., Hu, S., Wang, F., Xu, R., & Huang, X (2009). Total pollution effect of urban surface runoff. *Journal of Environmental Sciences*, *21*(9). https://doi.org/10.1016/S1001-0742(08)62402-X

Liu, Y., & Yang, W. (2023). Runoff, sediment, organic carbon, and nutrient loads from a Canadian prairie micro-watershed under climate variability and land management practices. *Environmental Monitoring and Assessment*, 195(3), 1-19. https://doi.org/10.1007/s10661-023-11913-3

LSPA. (2020). 2020 Lake Sunapee Watershed Management Plan. LSPA. https://www.lakesunapee.org/2020-wmp#:~:text=LSPA%20updated%20its%20existing%202008,Use%20Regulation%2C%20Zoning%20and%20Ordinances.

New Hampshire Estuaries Project. (2007). The Impacts of Impervious Surfaces on Water Resources. PREP Reports & Publications. 236. https://scholars.unh.edu/prep/236

NHDES. (2019). Volunteer Lake Assessment Program Individual Lake Reports, Pleasant Lake, New London, New Hampshire. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/2019-pleasant-newlondon.pdf

NHDES. (2020). Attachment A: Development of a Salt Minimization Plan. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/wmb-26.pdf

NHDES (n.d) *Road Salt Reduction.* Accessed From https://www.des.nh.gov/land/roads/road-salt-reduction

NHDOT. (2014). Evaluation of an Automated Bridge Anti-Icing System. NHDOT Research Record. https://mm.nh.gov/files/uploads/dot/remote-docs/nhdot-research-13733g-2014-report.pdf

Shrestha, A., Green, M.B., Boyer, J.N. et al. Effects of Storm Events on Phosphorus Concentrations in a Forested New England Stream. Water Air Soil Pollution 231, 376 (2020). https://doi.org/10.1007/s11270-020-04738-0

Smil, V. (2000). Phosphorus in the Environment: Natural Flows and Human Interferences. *Annual Review of Energy & the Environment*, *25*(1), 53. https://doi.org/10.1146.annurev.energy.25.1.53

USEPA. (2018). Percent of Stream and Shoreline with 15% or More Impervious Cover within 30 Meters. EnviroAtlas Factsheet. https://enviroatlas.epa.gov/enviroatlas/DataFactSheets/pdf/ESN/Percstreamw15percentimperviousin30meters.pdf

US EPA. (2023$_a$). Indicators: Phosphorus. US EPA. https://www.epa.gov/national-aquatic-resource-surveys/indicators-phosphorus

Zhang, W.; Liu, J.; Xiao, Y.; Zhang, Y.; Yu, Y.; Zheng, Z.; Liu, Y.; Li, Q. The Impact of Cyanobacteria Blooms on the Aquatic Environment and Human Health. Toxins 2022, 14, 658. https://doi.org/10.3390/toxins14100658

Ward, N.K., Brentrup, J.A., Richardson, D.C. *et al.* Dynamics of the stream–lake transitional zone affect littoral lake metabolism. *Aquat Sci* **84**, 31 (2022). https://doi.org/10.1007/s00027-022-00854-7