The Spatiotemporal Variation of Sediment Characteristics and Nutrient Deposition in Two Coosa River Reservoirs

by

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Abstract

Reservoirs create biogeochemical hotspots along river systems by trapping sediments and nutrients from their river watersheds. This study aims to understand sediment transport and nutrient deposition through time and space for two Coosa River reservoirs, Lay Lake and Weiss Lake. Lay Lake was built in 1914 and has historically suffered from poor water quality and eutrophication; Weiss Lake was built in 1961 and lies on the border of Alabama and Georgia receiving inputs from NW Georgia. Paleolimnological and sediment analytical techniques were applied to surface sediments and sediment cores to accomplish two primary objectives: 1) examine Lay Lake for aging reservoir storage and the impacts of upstream dam construction, as well as to characterize algal and cyanobacteria responses to material inputs over time, and 2) identify drivers of material delivery and spatial deposition for key nutrients (C, N, P) and heavy metals (As, Pb, Zn) for both Weiss Lake and Lay Lake. Cores and surface sediment samples were collected and analyzed for bulk density, organic matter, photosynthetic pigments, nutrients and heavy metals. Cores were dated using key differences between reservoir and riverine sediments, as well as the BACON model in R. Results reveal Lay Lake has been relatively eutrophic since its creation in 1914, and has maintained a relatively diverse phytoplankton community through time. While change linked to age was not evident, a change in 1964 due to upstream dam construction did occur causing decreased flows and alterations to deposition. Although, this change did not alter phytoplankton community structure. Weiss Lake and Lay Lake also appeared to be distributing materials differently according to individual reservoir characteristics and patterns in land use, hydrology, and material inputs. Results emphasize the complexity and heterogeneity of reservoirs and long-term eutrophication, and suggest that management for hydroelectric reservoirs should be focused on individual needs of each system.

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List of Abbreviations

ADEM	Alabama Department of Environmental Management
ANOVA	Analysis of Variance
As	Arsenic
BD	Bulk Density
C:N	Carbon-Nitrogen Ratio
N	Nitrogen
N:P	Nitrogen-Phosphorus Ratio
OC	Organic Carbon
OM	Organic Matter
P	Phosphorus
Pb	Lead
PCA	Principal Component Analysis
Zn	Zinc

Chapter 1: A Review on Reservoirs and Reservoir Sedimentation

Reservoirs Characteristics

Reservoirs are complex human-made freshwater systems typically created by damming river systems and flooding river valleys. When compared to natural lake systems, reservoirs have complex morphology and a narrower basin than lakes (Hayes et al., 2017). They also have a more complex perimeter with little to no littoral zone due to steep shorelines caused by the inundated floodplains (Hayes et al., 2017). The flooding of river valleys creates ample branches and coves causing reservoirs to be dendritic. Typical reservoir systems have the dam and hydropower generator in a central location downstream, while other reservoirs differ in this morphology and construction with diversion canals and spillways that are not directly near the powerhouse. The diversion and separation of flows from a single direction complicates the hydrology and mixing of these systems making them differ in many physical and biochemical ways from a reservoir with simple morphology.

Reservoirs are generally divided into three zones related to their physical, chemical, and biological characteristics (Fig. 1.1) (Wetzel, 2001; Thornton et al., 1980). The first zone, the riverine zone, is farthest from the dam and at the head of the reservoir. This first zone is defined by high flows, high turbidity, and increased influx of nutrients. Primary productivity is low in this zone as sunlight cannot penetrate through the water column and high flows confound phytoplankton growth. The second zone is the transition zone where water flows downstream from the riverine zone and the velocity and turbidity decreases increasing sedimentation. This decrease in turbidity allows sunlight to penetrate past the surface promoting primary productivity in the transition zone. The final zone closest to the dam has a more stable water column and increased sedimentation but can have less primary productivity as nutrients are less available.

This final zone is considered the lacustrine zone, and is defined by lentic characteristics and deeper water depths. The boundaries between the zones can be influenced by multiple reservoir characteristics such as retention time, thermal stratification, morphometry, and mixing which causes differing zonation across individual reservoir systems (Thornton et al., 1980; Soares et al., 2012).

Operation and Management

Reservoirs are often categorized by their size and targeted management (Poff and Hart 2002; Thornton et al., 1980). Specifically, classification for reservoir management falls under two strategies: storage and run-of-river. The storage operation stores and releases water periodically according to energy needs and variations in local and seasonal rainfall. Storage reservoirs tend to hold large amounts of water but allow detailed control over when water is released from the dam. Run-of-river operation constantly releases water causing only small variations in reservoir water level overtime. As a result, reservoirs under this operation release roughly the same amount of water as they receive (Poff and Hart, 2002; Bilotta et al., 2016). Even so, run-of-river operations still impose negative anthropogenic impacts on river ecosystems by fragmenting habitats, changing flows and water temperatures, and increasing sedimentation in the river (Anderson et al., 2014).

Reservoirs are much younger than natural lakes and generally have a set period of operation, but many reservoirs have outlasted their original life expectancy leaving many outdated dams serving alternative purposes or even failing (Shuman, 1995). Little is known about the physical, chemical, and ecological impacts of aging reservoirs on river systems, especially with dams that are over a century old. Reservoirs can be owned and operated by individuals, private and public organizations, as well as the governmental agencies, but state dam safety programs have jurisdiction over most dams in the U.S. (Dams 101, 2021). Alabama specifically has more than 2000 dams, but it is the only state without a dam safety program to oversee maintenance of the dams and management of the reservoirs (Dam Safety, 2021). Therefore, little is known on the quality of private owned reservoirs in Alabama as they are less documented, surveyed, and maintained compared to government-owned systems.

Reservoir Sedimentation, Landscape Alterations, and Eutrophication

Sedimentation behind dams is a primary concern for long term reservoir management as it limits water storage capacity and alters biogeochemical processes in benthic areas (Thornton et al., 1980). Specifically, reservoirs have trapped 26 % of the world's sediment, 12 % of the world's phosphorus (P), and more than 30% of all nitrogen (N) and silica (Si) retention (Syvitski et al., 2005; Maavara et al., 2015; Harrison et al., 2009, 2012). Reservoirs have high sedimentation rates and an affinity for clay and silt that yields an increase in fine sediment after dam construction (Van Metre et al., 1997; Foster et al., 2011). Trapping of sediment can be severe in some regions where large-scale impoundments receive materials from large or altered watersheds. For example, large river systems such as the Colorado and Nile Rivers trap a majority of incoming sediment loads because of reservoir construction and flow diversion (Vörösmarty et al., 2003).

Reservoirs have large catchment to surface area ratios causing reservoirs to be sentinels of physical, chemical, and biological materials entering from the watershed (Thornton et al., 1980; Harrison et al., 2009). Sediments behind dams can accumulate materials from both terrestrial and aquatic environments and are impacted by many anthropogenic controls including agriculture, deforestation, industrial activity, mining, and urbanization (Syvitski et al., 2005). Reservoir sediments affected by urbanization have documented increases in nutrients (C, N, P), organic matter (DOC), as well as heavy metals (Zn, As, Pb) from increased water runoff from metropolitan areas (Canuel et al., 2009; Tremblay et al., 2001; Rosen & Van Metre, 2010). Likewise, reservoirs and reservoir sediments can be extremely influenced by industry in the surrounding landscape as industrial processes can produce pollutants that range between heavy metals, coal ash, and polychlorinated biphenyls (PCB). These industrial contaminants can be stored in sediments for decades and cause reservoir drinking water and sediments to become toxic and unsafe if not monitored adequately (Callender & Rice, 2000; Rose, 2015; Urbaniak et al., 2008). Additionally, agriculture can impact reservoir water and sediment quality as fertilizer run-off is a main component of excess nutrients in aquatic ecosystems (Schelske et al., 2005; Waters et al., 2015).

Large sediment and nutrient loads from river watersheds input nutrients necessary for algal growth. However, low water retention times from dam management can cause a flushing effect decreasing algal growth (Jones and Elliot, 2007). Reservoirs are generally constructed in areas where natural lakes are few, which for many regions places reservoirs in warmer regions making surface temperatures warmer and conditions more favorable for growth of cyanobacteria and other algae (Wetzel, 2001). Eutrophication and hyper-eutrophication of reservoirs is a management concern as increased primary producer abundance can decrease diversity, alter biological communities, and cause anoxia in aquatic ecosystems (Paerl and Huisman, 2009). In addition to the danger of algal blooms, cyanobacteria can produce toxins capable of harming humans and higher trophic level biota (Sukenik et al., 2015).

Significance and Paleolimnology

There have been few studies that aim to identify and understand alterations to environmental quality as sediments age behind dams. Some studies have revealed P retention is favored over N in human impacted systems (Yan et al., 2016) while others have revealed land use is a strong controlling factor over N removal within lentic systems (Harrison et al., 2009). Nutrient cycling in reservoirs is complex as P has no gaseous component to its biogeochemistry causing it to be highly correlated to the geology, whereas N contains gaseous components to its biogeochemistry allowing it to escape aquatic systems as N2 or other gases. The anthropogenic influences on nutrient stoichiometric ratios cause numerous ecological alterations in reservoirs at the microbial level as well as at higher trophic levels.

While reservoirs are monitored for targeted water quality parameters many of the long-term alterations to reservoirs as they age can be missed. One way to establish long term data sets integrating allochthonous and autochthonous processes in aquatic systems is through the collection of sediment cores and the application of paleolimnological techniques. Paleolimnology is a multidisciplinary approach to aquatic ecosystem history where biological, chemical, and physical measurements are used to infer environmental changes through time. Although paleolimnological studies have traditionally focused on natural lake systems, many sediment studies have been successful in investigating nutrient loading, sedimentation, storage of elements, eutrophication, and reservoir ontogeny in reservoirs (Maavara et al., 2015; Waters et al., 2015; Filstrup et al., 2010; Bradbury and Van Metre, 1997; Winston et al., 2014). Application of paleolimnological techniques on deposited reservoir sediments provide data representing the entire ecological and physical history of the reservoir (Foster et al., 2011). By gathering sediment cores from reservoirs, anthropogenic impacts to water quality can be assessed over long timescales so that management for these impacts may be more efficient and applicable.

Study Site

This project applied paleolimnological and sediment analysis to 2 reservoirs, Weiss Lake and Lay Lake, along the Coosa River. The Coosa River is one of Alabama's most important rivers having a watershed that extends outside of Alabama, and a channel that flows through a large portion of the state and includes six hydroelectric reservoirs (Table 1, Fig. 1.2). The Coosa River's headwaters start in Rome, Georgia and flow 26 km west where it crosses the Georgia-Alabama border. The Coosa River is part of the Alabama-Coosa-Tallapoosa (ACT) river basin which neighbors the Apalachicola-Chattahoochee-Flint (ACF) river basin of Georgia. This relationship between river basins is important as it places the Coosa River in a position of being a potential part of transboundary water conflicts between Alabama, Florida, and Georgia (Couch et al., 1996).

Weiss Lake and Lay Lake are both privately owned by Alabama Power and were created for hydropower, water supply, as well as recreation. Weiss Lake is the initial reservoir on the river and is the only storage reservoir. It is a shallow impoundment with an unusual morphology in that water is diverted in two directions once it enters the reservoir-- towards the hydroelectric generator through a diversion canal, or towards Dead River. Weiss Lake's unusual morphology and hydrology make it an interesting candidate for understanding sediment transport, nutrient deposition, cove processes, and the importance of inputs from tributaries for reservoirs that are considered "non-traditional".

Lay Lake was the first reservoir built on the Coosa in 1914 and has had multiple reservoirs built around it over the last century with Lay dam itself being modified in 1967. Although Lay Lake is a smaller impoundment, it has played a large role in trapping materials from the Coosa River as it borders multiple counties and has existed along the Coosa River for over 100 years. Lay Lake has had multiple water quality issues with excessive nutrients and eutrophication– therefore, understanding historical and current water quality conditions for Lay Lake is extremely important. The watershed of the Coosa River has changed slowly over time becoming more urban and industrial at the headwaters. Understanding the role that the surrounding landscape has played on sediment transport, nutrient deposition, and water quality overtime will be vital for setting future reservoir management plans.

Objectives

The primary objectives of this study are 1) characterize variations in nutrient deposition, phytoplankton abundance, and community structure through time in Lay Lake as it pertains to aging reservoir storage and the impacts of upstream dam construction, 2) identify drivers of material delivery and spatial deposition for key nutrients (C, N, P) and heavy metals (As, Pb, Zn) in surface sediments in Lay Lake and Weiss Lake and 3) connect depositional hot spots with point and nonpoint sources. These objectives will be investigated by collecting sediment cores and surface sediment samples from Lay and Weiss Lakes and analyzing nutrients, metals, organic matter, and photosynthetic pigments.

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Tables

Characteristics	**Weiss**	Neely Henry	Logan Martin	**Lay**	Mitchell	Jordan
Date of Impoundment	1961	1966	1964	1914	1923	1928
Length (km)	83.7	124.9	78.1	77.6	22.5	29.6
Area (km^2)	122.2	45.3	61.8	48.6	23.7	27.5
Drainage Area (km^2)	13,657	17,094	19,943	23,535	25,452	26,327
Avg. Depth (m)	3.2	3.3	5.5	6.8	8.9	10.6
Retention (days)	18	6	11	9	5	7
Operation	storage	run-of-river	run-of-river	run-of-river	run-of-river	run-of-river

Table 1. Dam statistics for all 6 hydroelectric reservoirs along the Coosa River. Reservoirs in bold are particularly of interest, Weiss Lake and Lay Lake.

Figures

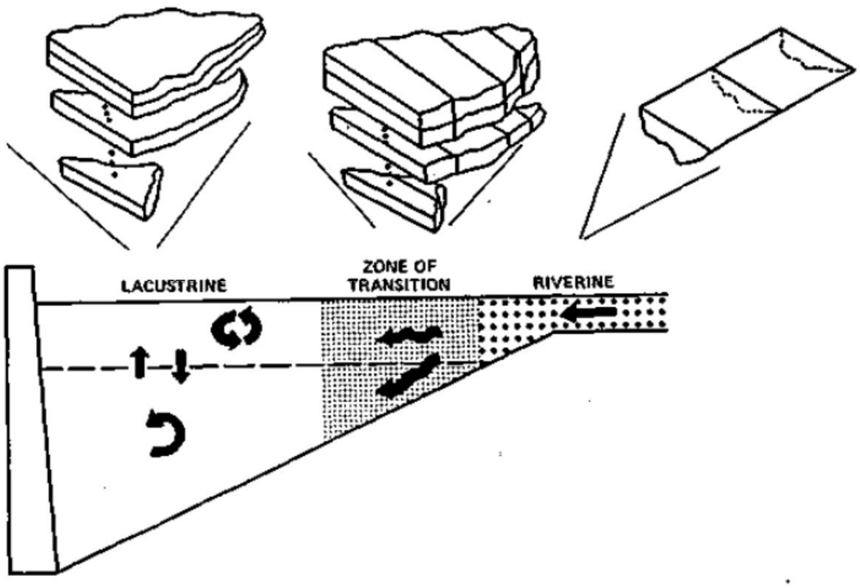

Figure 1.1. Reservoir gradational zones: riverine, transitional, and lacustrine. Figure taken from Thornton et al., 1980

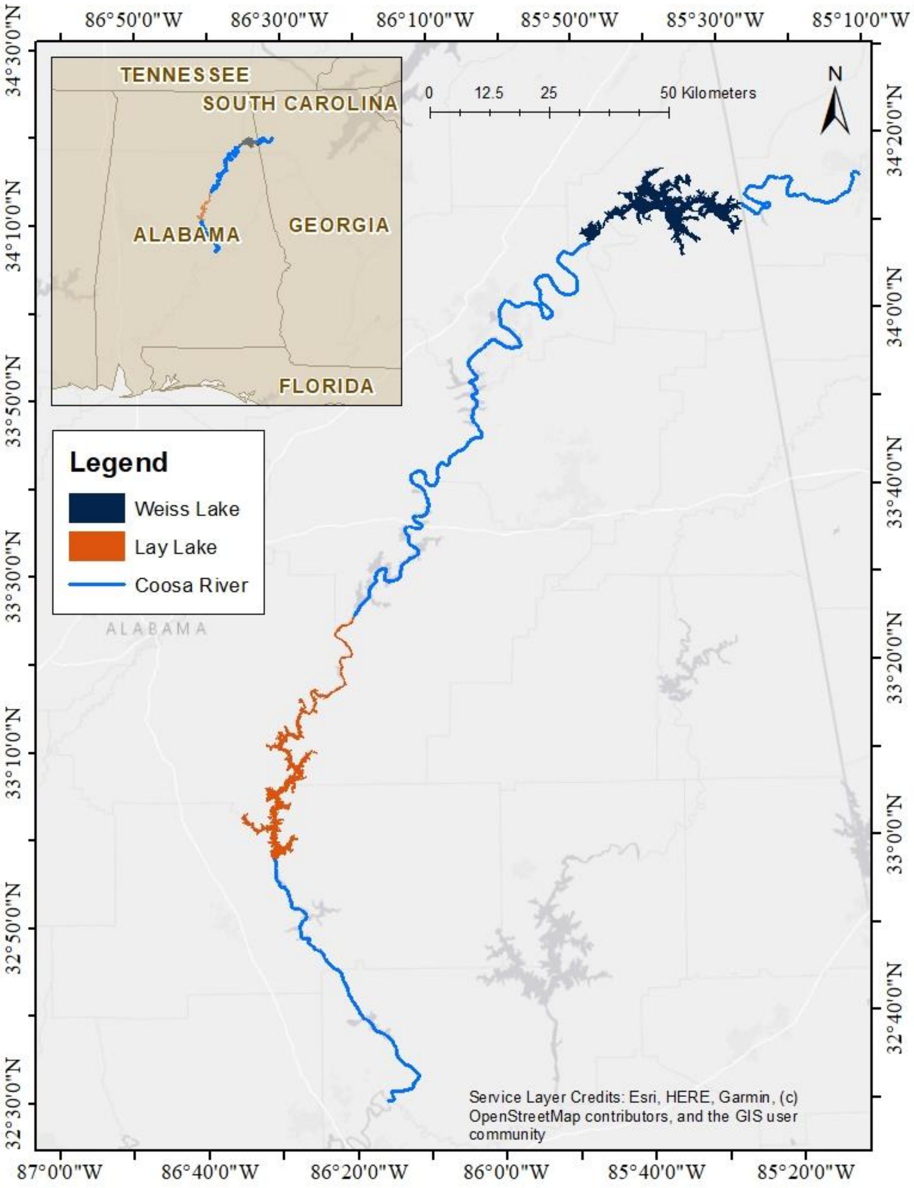

Figure 1.2. Map of the Coosa River, as well as the two reservoirs of interest. Weiss Lake is depicted in navy, and Lay Lake is depicted in orange.

Chapter 2: Paleolimnologically inferred long-term eutrophication of a Coosa River, Alabama reservoir

Abstract: Reservoirs are developing eutrophic conditions on a global scale due to anthropogenic activities that accelerate the loading of sediments and nutrients into river systems. One way to investigate long term trophic change in reservoirs is to utilize the sediment record behind dams that archive detailed records of past water quality trends. Here, paleolimnological tools were applied on a sediment core collected from Lay Lake, AL, USA, which is the oldest reservoir in the Coosa River Basin. Sediment samples were analyzed for organic matter, nutrients, and photosynthetic pigments to answer three objectives, 1) to characterize variations in phytoplankton abundance and phytoplankton community structure through time, 2) to determine if primary producer changes were linked to reservoir age, and 3) to identify drivers of plankton ecology in the system. Pigment data revealed Lay Lake has been relatively eutrophic since its foundation with oscillations in phytoplankton abundance happening periodically over the past century. Pigments revealed a diverse phytoplankton community that moved in concert with one another, but nutrient and statistical analyses reveal phytoplankton groups may not have responded in unison to the same triggers. While change did occur to the phytoplankton community, a trend associated with age did not occur. However, USGS stream gauge data showed a substantial decrease in flows entering the reservoir after 1964 linked to the building of upstream reservoirs. Statistical analysis revealed differences between pigments and nutrients pre-1964 to post-1964. Whereas a eutrophic state was established in Lay Lake prior to 1964, the construction of upstream reservoirs appears to have magnified the reservoir’s eutrophication. Lay Lake demonstrates the complexity of managing reservoir water quality for single targets and the need for further study of reservoir trophic state development through time.

Introduction

The damming of rivers creates novel aquatic ecosystems that integrate lentic and lotic characteristics (Wetzel, 2001). Riverine movement of sediments and nutrients are altered by dams that capture materials from terrestrial inputs and aquatic processes. The human domination of our landscape has increased sediment loading into rivers, therefore increasing the amount of fine sediment behind dams and creating biogeochemical hotspots (Syvitski et al., 2005). Specifically, urban, agricultural and industrial processes have altered rates of nutrient (C, N, P) inputs and nutrient cycling and thus accelerated eutrophication of freshwater systems on a global scale (Smith, 2003). Anthropogenic eutrophication has become the catalyst for changes in ecological community structure and the deterioration of water quality (Smith and Schindler, 2009). Hydrological changes created by dams further exacerbate eutrophic conditions by lengthening retention times and increasing surface temperatures (Paerl and Huisman 2008; Jones and Elliott, 2007). These increased retention times and changes in thermal structure increase the longevity of algal blooms as blooms can start earlier and persist longer (Jones and Elliot, 2007).

Many studies have shown that climatic processes can act in concert with anthropogenic impacts increasing primary productivity, thus altering trophic states and water quality (Paerl and Huisman, 2008; Jöhnk et al., 2008). Repeated and long-term monitoring efforts are crucial, but most datasets do not extend past ten to twenty years. One way to investigate and reconstruct historical environments in reservoirs is to utilize the sediment record and paleolimnological techniques (Smol, 2008). Reservoir sediments have been shown to provide detailed environmental archives spanning the existence of the dam, which is over 50 years for most reservoirs. Paleolimnological studies can record nutrient and water quality data well beyond monitoring efforts (Waters et al., 2015, Halac et al., 2020; Van Metre et al., 1997).

Paleolimnological proxies have provided reliable information on past trophic status, reservoir succession, sedimentary processes, and historical trends in water quality and land use (Waters et al., 2015; Van Metre et al., 1997; Canuel et al., 2009; Bradbury and Van Metre, 1997).

To reconstruct historic primary producer abundance and community structure, the measurement of photosynthetic pigments such as chlorophylls and carotenoids has proven to be a useful diagnostic tool (Leavitt and Hodgson, 2001). Phytoplankton (diatoms, cyanobacteria, other algae) are responsive to environmental change and can be valuable indicators of temporal ecosystem change that respond to alterations of watershed land use and nutrient inputs (Bradbury and Van Metre, 1997; Waters et al., 2015; Waters et al., 2010). Here, I measured photosynthetic pigments and nutrients (C, N, P) on a sediment core collected from an aging reservoir (>100 years old) to answer three objectives: 1) to characterize variations in phytoplankton abundance and phytoplankton community structure through time, 2) to determine if primary producer changes were linked to reservoir age, and 3) to identify additional drivers of plankton ecology in the system.

Methods

Study site: *The Coosa River and Lay Lake*

The Coosa River begins in NW Georgia, flows through much of Alabama, and combines with other rivers to end in the Mobile Bay area. The Coosa River contains six hydroelectric reservoirs that are maintained privately by Alabama Power and are all 55 years old or older with the oldest reservoir, Lay Lake, being 107 years old. Lay Lake is a smaller 48.5 km^2 impoundment with other reservoirs upstream and downstream. Lay Lake is a run-of-river reservoir with forested watershed and has had constant water quality issues with eutrophication. In 1973 Lay Lake was classified as eutrophic, nutrient rich and highly productive with phytoplankton assemblages dominated by pollution-associated genera (US EPA, 1976). In recent years Lay Lake was declared impaired by the Alabama Department of Environmental Management for excessive organic material and nutrient inputs (ADEM, 2008). Benefits and uses of Lay Lake include hydropower, water supply, recreation and wildlife habitat.

Field and Laboratory Methods

A 91-centimeter sediment core was collected from Lay Lake using a gravity coring rig known for retrieving undisturbed sediments in deeper waters (Smol, 2008). The core location was in close proximity to the dam where high sedimentation is known to occur based on bathymetric maps and multiple test cores collected throughout the reservoir (Fig. 2.1). The core was sectioned into 2-centimeter sections and analyzed for bulk density, percent organic matter, freeze dried, then ground with mortar and pestle. Bulk density (BD) was calculated by removing and weighing a 1 cm^3 aliquot of wet sediment and subsequently drying the aliquot for 24 hours in a 60ºC oven and re-weighing and expressed as g dry cm^{-3} wet. Organic matter (OM) content was assessed by burning dry sediment in a muffle furnace at 550°C for 3 hours following Håkanson & Jansson (1983) and calculated as loss on ignition.

The dry sediment samples were analyzed for photosynthetic pigments through the use of a Shimadzu high performance liquid chromatography machine (HPLC). Pigments were extracted using a mixture of acetone, methanol, and water and allowed to digest 16–24 hours in a freezer following the methods of Leavitt and Hodgson (2001). Following extraction, samples were centrifuged and filtered to remove particulate matter, and placed into the HPLC autosampler. Specific pigments were identified through comparison of retention times and spectra comparison to known standards (DHI, Denmark). Final pigment concentrations were expressed as nmol pigment per g organic matter (g org^{-1}). Organic carbon (OC) and nitrogen (N) were measured using a Costech Elemental Combustion C/N analyzer with an attached auto-sampler. Prior to analysis, samples were acidified for 12 hours in HCl vapor to remove inorganic carbon. Phosphorus (P) and other elements were measured using Induced Coupled Plasma (ICP) following nitric acid digestion for 90 minutes in a heated block (EPA 6010B .).

Dating methods

Core sections were dated using multiple characteristics that distinguish reservoir sediments from pre-reservoir sediments. Physically, reservoir sediments were distinctive from pre-reservoir sediments as they were typically dark, rich in organic matter, and had higher percentages of fine-grained sediments, such as clay (Van Metre et al., 1997). Additionally, reservoir sediments had higher concentrations of lacustrine photopigments that increased after dam construction allowing the time of infill to be distinguishable from other areas in the core (Leavitt and Hodgson, 2001; Paerl et al., 2003). Once the date of dam construction was determined, specific dates for each section of the core were calculated using the BACON package in R. BACON is a Bayesian statistics model used explicitly for age-depth modeling. The date of dam construction and the date of core collection were used in the BACON analysis and the statistical package assigned dates for each core section.

Statistical methods

Hydrological data was gathered through the USGS National Water Dashboard website, and historic precipitation data was gathered from Drought.gov. Based on flow alterations in 1964, sediment core data were divided into two groups: dam construction to 1964 (1914-1964 AD) and 1964 to present (1964-2019 AD). To determine significant changes in sediment composition linked to flow change, two-tailed t-tests and box plots were used. Percentile outlier tests were performed by setting the percentiles to 1 and 99 in R. This was done to screen for the top present day (0-2 cm) sample that was much fresher than historic samples. Principal component analysis (PCA) was also used to ordinate samples from the two groups and to determine percent of variance between phytoplankton groups and key paleolimnological variables.

Results

Lithology and chronology

The Lay Lake sediment core was 91 centimeters long and contained two relatively homogenous areas with lighter brown sediments from 91 to 70 cm and darker sediments from 70 cm to the top of the core. BD slightly decreased above 70 centimeters, while photopigment and nutrient concentrations increased. Therefore, 70 centimeters was identified as the depth of dam construction and assigned the date of 1914 BCE. The BACON model calculated specific dates for each section of the core by allocating 70 centimeters as 1914, and 0 centimeters as 2019 (Fig. 2.2).

Organic proxies and nutrients

Most organic proxies oscillated throughout the core and seemed to lack any large stratigraphic shifts (Fig. 2.3). BD was relatively consistent throughout the core, averaging 0.33 g cm^{-3} (±0.06). A small change occurred around 1965 when BD began to slightly decline eventually reaching 0.16 g cm^{-3} in 2019. OM also showed little changed and averaged 11% (±1.06) throughout the core but dropped to 9.7% in 1965 with one spike to 15% in 1995. Organic proxies and nutrients oscillated during similar time periods. Specifically, OM, OC, N, and P decreased strongly in 1965, as well as during the period between 1989 and 1995. After 1995, OM decreased, while OC, N, and P largely increased.

Throughout the core OC and N were low in concentration but moved in concert, sporadically oscillating within tight intervals (Fig. 2.3). OC averaged 3.2% (±0.29), while N averaged 0.29% (±0.036). Both OC and N reached maximum levels in 2019 at 3.8% and 0.4%, respectively. P also oscillated throughout the core, but in a more asynchronistic pattern to other nutrients. P averaged 1.3 mg g^{-1} (± 0.15) and reached background levels of 1.14 mg g^{-1} in 1965. In 1977 P peaked at 1.61 mg g^{-1}, but later hit its minimum value of 1.06 mg g^{-1} in 1992.

C:N and N:P ratios also reflected nutrient fluctuations in Lay Lake, and continued to oscillate throughout the sediment record (Fig. 2.3). Average values of C:N and N:P were 12.9 (± 0.53) and 4.9 (± 0.59), respectively. C:N tended to follow the trends set by other nutrients, but N:P was slightly different. The highest C:N value of 13.9 occurred in 1965, but C:N values dropped quickly afterwards and stayed low until 1989. During 1989-1992 C:N increased to 13.7, but quickly began to decrease and eventually reached the lowest value of 10.96 in 2019. N:P ratios also fluctuated, but slightly increased between 1914 and 2019. N:P spiked in 1956 and 1989, and hit its maximum value of 6.3 in 2019.

Sedimentary photosynthetic pigments

All pigment concentrations oscillated similar to nutrient stratigraphy lacking distinct stratigraphic shifts, but increases in pigment concentrations occurred around 1965 and the early 1990s (Fig. 2.4). Following 1965, pigments significantly increased. This phytoplankton growth lasted for 25 years, until 1989 when abundance dropped and stayed low until 1995. Following 1995, pigment concentrations continuously increased until present day 2019.

Chlorophyll-a and chlorophyll-b concentrations were the most constant throughout the core, but greatly increased between 1995-2019 (Fig. 2.4). Average chlorophyll concentrations were 23.3 nmol g org^{-1} (±31.4) for chlorophyll-a, while chlorophyll-b averaged 14 (±8.8).

Degradation pigments, such as pheophytin-a and pyropheophorbide-a, oscillated in a similar pattern experiencing increases after 1965 and 1995. Average concentrations for pheophytin-a and pyropheophorbide-a were 161.5 (±40) and 35.5 (± 7.3), respectively. Beta-carotene, alloxanthin, and diatoxanthin favored each-other in core profiles. All 3 of these pigments increased after 1995 and reached their maximum concentration in 2019. Diatoxanthin specifically was much higher in 2019 than any other year and reached a maximum value of 161.3 nmol g org^{-1}. Previously to 2019, Diatoxanthin's average concentration was 52.5 nmol g org^{-1} (±14.7). Alloxanthin averaged a concentration of 71.5 (± 22.4) , and was the only pigment to continuously increase over time (Fig. 2.4). Beta-carotene averaged 47.4 nmol g org^{-1} (±16).

Cyanobacterial pigments were the most dynamic photopigments and fluctuated throughout the core (Fig. 2.4). Canthaxanthin peaked in 2019 at 280 nmol g org^{-1}, excluding 2019 the average had been 59.3 (±16). The canthaxanthin top sample appeared to be fresh and masked the sample concentrations below it. Some of the following analyses will remove this sample given its lack of historical context (Fig. 2.4, Fig 2.5). Lutein + zeaxanthin had a much higher abundance than canthaxanthin with an average concentration of 267 nmol g org^{-1} (±64.3) (Fig. 2.4). Lutein + zeaxanthin represent isomer pigments that cannot be differentiated through our methods. Lutein represents chlorophytes, whereas zeaxanthin represents cyanobacteria (Leavitt and Hodgson, 2001) (Table 2.1).

Statistical analyses

USGS stream gauge data revealed historical daily discharge at the upper part of Lay Lake (Fig. 2.1, Fig. 2.6). The gauge recorded an average of 14,000 cfs from 1914 until 1964. Post-1964 flows drastically decreased hitting minimum values near 500 cfs in some years, but in 1979 the gauge stopped recording discharge. T-tests revealed all photopigments and nutrients--

excluding C:N, P, K, and Fe-- to be significantly different ($p < 0.05$) before and after 1964 (Table 2.2). Box plots also illustrated these relationships where OC, N, and N:P values were much higher post-1964, C:N values were slightly lower, and P values were roughly the same (Fig. 2.7).

Percentile outlier tests did not find any potential outliers that existed between all samples. Nevertheless, chlorophyll-a: pheophytin-a values revealed the top sample to be much fresher in photopigments than the rest of the core (Fig. 2.8). Pheophytin-a is a degradation product of chlorophyll, thus high chlorophyll-a: pheophytin-a values represent less degraded material (Leavitt and Hodgson, 2001). As a result, PCA did not contain the present-day sample as it skewed the historic ordinances between nutrients and pigments.

PCA identified environmental variables with similar activity. PC1 and PC2 represented 77.0% and 10.3% of the data set's variance, respectively (Fig. 2.9). All photopigments ordinated positively along PC1 but varied in ordination along PC2. Nutrients (OC, N, P) ordinated in the same cluster, positively along PC1 but negatively along PC2. Chlorophylls and total fluorescence ordinated in a neutral relationship to nutrients, while diatoxanthin and beta-carotene ordinated more closely to nutrients. Cyanobacterial and degradation pigments ordinated between chlorophylls and diatoxanthin.

Discussion

Based on pigment concentrations, phytoplankton abundance in Lay Lake was extremely high and diverse throughout the existence of the reservoir, but pigment concentrations do suggest oscillations of abundance. A change in primary production linked to the aging of the reservoir was not evident as traditional succession did not occur. Long term eutrophication of Lay Lake is complex and seems to be driven by a multitude of drivers.

Primary Producers in Lay Lake through time

Over the past century, Lay Lake has seen consistent eutrophic conditions with minor decreases in productivity during specific periods. Photosynthetic pigments reveal a diverse community structure between chlorophytes, cryptophytes, diatoms, and cyanobacteria with the groups moving in concert with one another throughout the core stratigraphy (Fig. 2.4). Fluctuations of canthaxanthin and lutein + zeaxanthin were the most extensive suggesting cyanobacteria to be the group with the greatest dynamic temporal change in Lay Lake. In contrast, fluctuations of chlorophylls and total fluorescence were the least extensive suggesting chlorophytes may have a constant abundance through time than any other phytoplankton group. The high presence of cyanobacteria along with other phytoplankton assemblages is unique as eutrophication often results in a reduction of species diversity with cyanobacteria becoming the dominant primary producer group (Dokulil and Teubner, 2000). In addition, C:N maintained values around 12.9 throughout the core suggesting aquatic producers to be the primary source of organic matter deposited in the lake (Fig. 2.3). Given that Lay Lake exists in a primarily forested watershed, this is surprising and further supports a continuous high amount of phytoplankton productivity in the system. High concentrations of pigments and C:N ratios reveal Lay Lake has been relatively eutrophic since damming in 1914.

Identifying drivers of eutrophication through time

Phytoplankton growth and eutrophication are typically associated with N and P additions due to excess runoff from the landscape (Smith, 2003). Studies have shown that dams are trapping 12% of the world’s P and favor the retention of P over N (Bosh and Allan, 2008;

Maavara et al., 2015; Grantz et al., 2014). This is an important aspect of reservoir biogeochemical processes that ultimately decreases stoichiometric N:P ratios and causes a cascade of biogeochemical changes in reservoirs. Lay Lake has experienced small increases in P loading and storage throughout its existences, but a continual increase in P loading similar to other reservoir systems, has not occurred. N:P has also slightly increased since damming in 1914, suggesting increases in N:P appear to have greater influence from changes in N loading.

PCA revealed OC, N, and P to be generally ordinated with most photopigments suggesting at least a slight relationship to nutrients for most phytoplankton groups (Fig. 2.9). Pigments associated with diatoms ordinated the closest with nutrients in the PCA (Fig. 2.9). Diatoms have high nutrient uptake rates, as well as high growth rates making them successful competitors in high nutrient periods (Litchman, 2007). Chlorophylls and total fluorescence did not ordinate with any nutrients suggesting additional drivers of groups that are associated with these pigments, such as chlorophytes. Pigments associated with cryptophytes and cyanobacteria ordinated more closely with nutrients than chlorophytes suggesting a slight relationship with nutrients. P ordinated the least with all photopigments suggesting P is playing a smaller role on productivity than OC and N. The PCA emphasizes nutrients are impacting phytoplankton communities individually, but are possibly not the primary driver of phytoplankton fluctuations or long-term eutrophication.

Landscapes surrounding aquatic systems are typically sources for excess nutrients either through wastewater, erosion, fertilizer use, or other anthropogenic activities. Lay Lake's watershed is unique in that it has not been directly affected by urbanization or mass agriculture as many other aquatic systems have. The watershed is currently 80% forested, 13% agriculture, and 2% urban (ADEM, 2008). The high forest presence labels this watershed as low impacts since forested systems are known for buffering nutrients and mitigating erosion along river systems (Klapproth and Johnson, 2009). Burford et al. (2007) revealed the proportion of forest cover in the watershed is significantly correlated with algal cell concentrations, suggesting that a shift from 100% to 50% forest has had a substantial effect on water quality. The high amount of forest surrounding Lay Lake suggests long term water quality is being affected by material inputs from upstream sources rather than the local watershed where sampling occurred. Likewise, the consistent C:N values well below terrestrial signals (~20 and above) suggest that terrestrial materials are not the primary constituent of deposited organic matter (Fig. 2.3).

Hydrology is an additional driver of eutrophication that has received less study despite hydroelectric reservoirs containing variable flow dynamics. Many phytoplankton blooms are sensitive to mixing regimes and flushing rates as water discharge affects water temperatures, turbidity and the availability of nutrients in the water column (Paerl and Huisman, 2008; Elliot, 2010). The increase in retention time caused by dam construction can be related to high phytoplankton biomass and can promote earlier and longer blooms (Jones and Elliot, 2007). Phytoplankton in Lay Lake responded to a shift in hydrology with the building of 3 upstream dams in the 1960s. Specifically, the creation of Logan Martin Lake in 1964 extremely diminished flows into Lay Lake and can be seen as one of the many drivers of algal increases during this time period (Fig. 2.6). The decrease in discharge from Logan Martin Dam into Lay Lake would have created stagnant water columns, decreased turbidity, and increased light penetration into the photic zone causing warmer surface temperatures. These changes from upstream dam building would have promoted photosynthesis and phytoplankton blooms, as seen post-1964 (Fig. 2.4).

The construction of the dam in 1964 also impacted nutrient dynamics. P deposition increased following dam construction. Previous research on similar reservoir system showed a different outcome with P collecting in upstream reservoirs following construction (Webster et al. 2021). As a result, P inputs in Lay Lake may be local or internally fed through legacy P. This is corroborated by the erratic pattern P maintained before and after the addition of Logan Martin Lake and how P loading into Lay Lake did not decrease long-term after the building of 3 upstream dams in the 1960s. Furthermore, the change in hydrology created by Logan Martin dam seemed to have affected the cycling of N in Lay Lake with increases in N deposition following dam construction (Table 2.2). Hydrology and retention time have affected in-lake N concentrations in other studies by promoting the cycling of N in reservoirs either through the removal of N by burial in accumulated sediments or by gaseous emissions to the atmosphere (Akbarzadeh et al., 2019; Finlay et al., 2013).

Of the 3 macronutrients, N was the most ordinated with photopigments revealing N limitation may be playing a role in phytoplankton fluctuations or processes impacting N biogeochemistry are the same for phytoplankton abundance. A report from 1976 documents the limitation of phytoplankton growth in Lay Lake by available N, and characterizes P loading from non-point sources as “uncontrollable” (US EPA, 1976). The historic limitation of phytoplankton by N may have been exacerbated by changes in hydrology over time, as this report also documents the mean hydraulic retention time in 1976 was 14 days. The current retention time for Lay Lake is 9 days (ADEM, 2008) demonstrating a change in management since the 1976 study. In conglomeration, reservoir creation upstream played a role in the lake's ecological and geochemical history as it suppressed large amounts of water from flowing downstream and ultimately changed biogeochemical processes.

The increased algal production associated with the flow changes in 1964 did not persist until the time of core collection. Algal biomass decreased in 1989 due to an unknown cause and stayed low until 1995. According to historic drought data from the surrounding area, a dramatic shift occurred between 1989 and 1990 going from an exceptional drought period to an exceptional wet period (Fig. 2.10). Specifically, a flood from February of 1990 killed 2 people in the upper parts of the Coosa River, and may have played a role in the transition of phytoplankton abundance (Rogers, 2003). However, no other drought or wet periods were in accordance with significant phytoplankton shifts, therefore this disturbance may only have played a minor role. Nevertheless, the transition documented in the early 1990s catapulted Lay Lake into present day conditions consisting of extremely high phytoplankton production.

Novel stability and existence

The lack of succession seen in Lay Lake's sediment record is surprising as it has been documented that reservoirs often pass through a sequence of changes in aquatic primary production and composition following impoundment (Rodhe, 1964; Ostrofsky and Duthie, 1978; Thornton et al., 1990). Alterations to reservoir processes can include an initial increase of phytoplankton production in the first phase depending on the amount of newly available nutrients from flooded terrestrial material and the extent of water level changes (Chamberlain, 1972; Kimmel et al., 1990). Within the second phase, algal production may decrease as new nutrient sources decline, which eventually leads to a trophic re-equilibrium phase. Lay Lake failed to exhibit any of these phases over time, only recording slight oscillations in material delivery and storage since 1914. This stability is especially unique as Lay Lake has existed for over a century. Other studies have been conducted on century old reservoirs but with different objectives and in different climates. Fontana et al. (2014) studied the eutrophication of a tropical reservoir largely affected by population growth in the watershed using geochemistry and diatom assemblages, but did not utilize photopigments. Bradbury and Van Metre (1997) studied the land use and water quality of a reservoir built in 1912 that was later largely affected by urbanization and population boom, but was not surrounded by intense forestry. Halac et al. (2020) studied the eutrophication history of a sub-tropical reservoir built in 1881, but the reservoir had a water residence time comparable to a natural lake (219 days). This makes it difficult to characterize and compare century old impoundments as the small amount of literature available varies widely in context. For Lay Lake, the lack of physical, chemical, and biological change over the past century is unique, and suggests that management of aging reservoirs could be directed by local conditions.

Management implications

Eutrophication is a threat to aquatic biodiversity and water quality that remains poorly understood, especially in hydroelectric reservoirs. Researchers and river managers may benefit from more holistic approaches to eutrophication management that take internal nutrient controls and biogeochemical alterations into account, such as legacy P. The landscape plays a large role in water quality, and studies have shown combined terrestrial freshwater planning to be extremely beneficial to freshwater ecosystems (Leal et al., 2020). Managed hydrology schemes are also severely impacting river systems, and the long-term impacts of pulsed water flows on aquatic species needs to be understood and accounted for moving forward. The creation of impoundments alone creates immense multifaceted impacts to river systems. Specifically, the building of dams on the Coosa River has caused the greatest modern extinction event in North America pushing 36 species into extinction (Southeastern Freshwater Extinction Crisis, 2021).

This study of Lay Lake demonstrates the need for further research on aging reservoirs to manage and predict changes through time. Not every reservoir system operates similarly and finding the culprit of eutrophication in Lay Lake will be necessary if it continues to be used as a drinking water reservoir. Water gauge studies are needed to understand flow dynamics and their impacts on phytoplankton communities, especially considering Lay Lake is a run-of-river reservoir that releases water constantly throughout the year. Nevertheless, the oscillating signals between phytoplankton groups and nutrient inputs is promising and reveals Lay Lake's water quality may be able to reach recovery at some point in the future. Photosynthetic pigments are a unique and suitable answer to understand water quality changes through time, especially in aquatic systems. Further utilizing these key paleoenvironmental proxies will aid government and scientific agencies nationwide as management projections are being established.

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Tables

Pigment	Abbreviation	Phytoplankton Indicator
Total Fluorescence	Total	Total Primary Productivity
Chlorophyll-a	Chl-a	Total Primary Productivity
Chlorophyll-b	Chl-b	Chlorophytes
Pheophytin-a	Pheo-a	Total Primary Productivity
Pyropheophorbide-a	Pyro	Total Primary Productivity
Beta-carotene	B-car	Total Primary Productivity
Alloxanthin	Allo	Cryptophytes
Diatoxanthin	Diato	Diatoms
Canthaxanthin	Canth	Cyanobacteria
Zeaxanthin	Zea	Cyanobacteria
Lutein	Lut	Chlorophytes

Table 2.1. List of abbreviations and phytoplankton indicators for photosynthetic pigments

Variable	*p* -value
C:N	0.09
K	0.67
Fe	0.29
P	0.18
Canth	0.018
Chl-a	0.016
Chl-a:Pheo-a	0.018
Diato	0.024
N	0.017
N:P	0.013
OC	0.018
Al	0.002
Chl-b	0.002
Lut+Zea	0.002
Mg	0.007
OM	0.001
Pyro	0.005
Total	0.001
B-car	0.0007
Allo	<0.0001
Ca	<0.0001
Pheo-a	<0.0001

Table 2.2. Results from two-tailed t-tests between pre-1964 and post-1964 sediment groups. Variables considered nonsignificant between groups are bolded and have a *p*-value > 0.05.

Figures

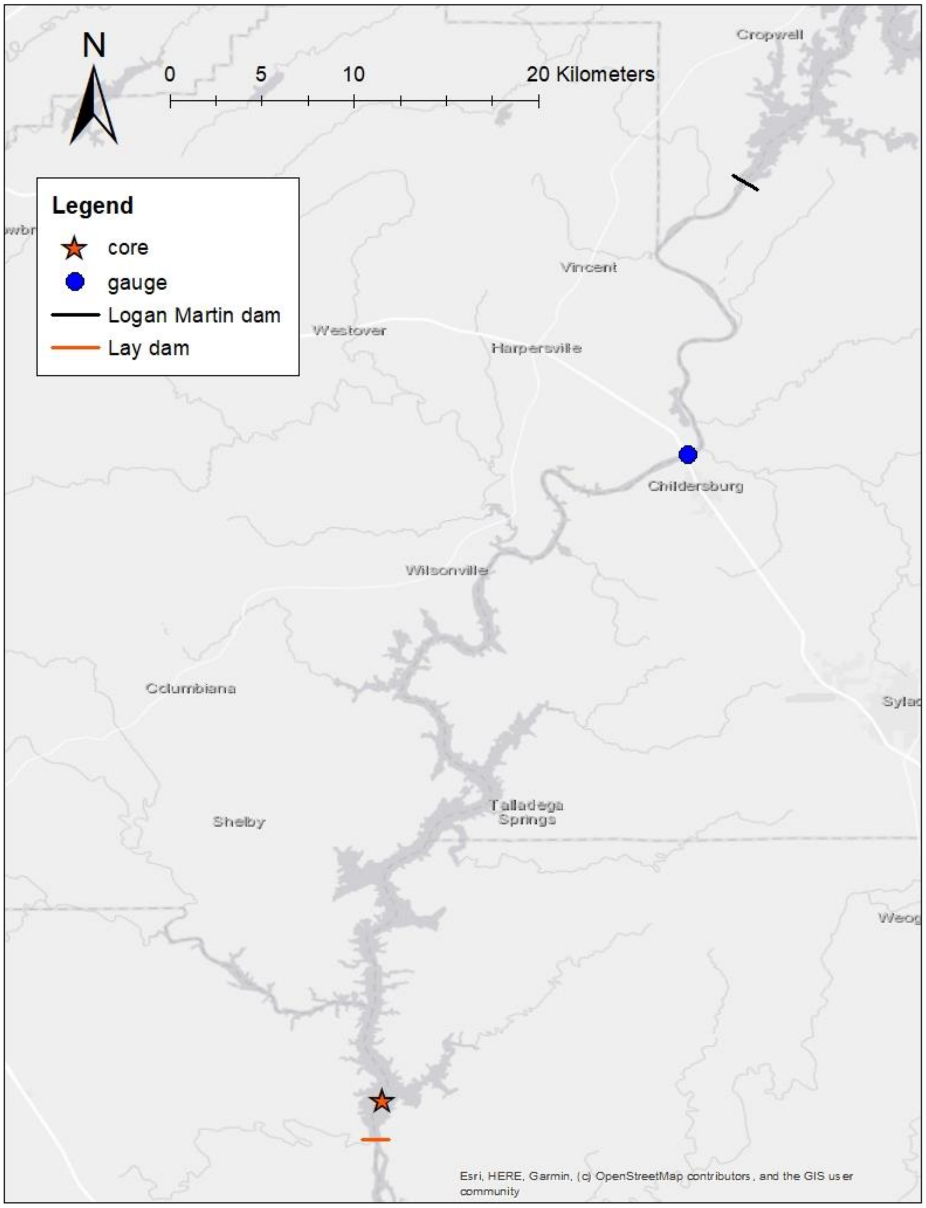

Figure 2.1. Locations of the Lay Lake sediment core designated by the orange star, and the USGS gauge designated by a blue circle.

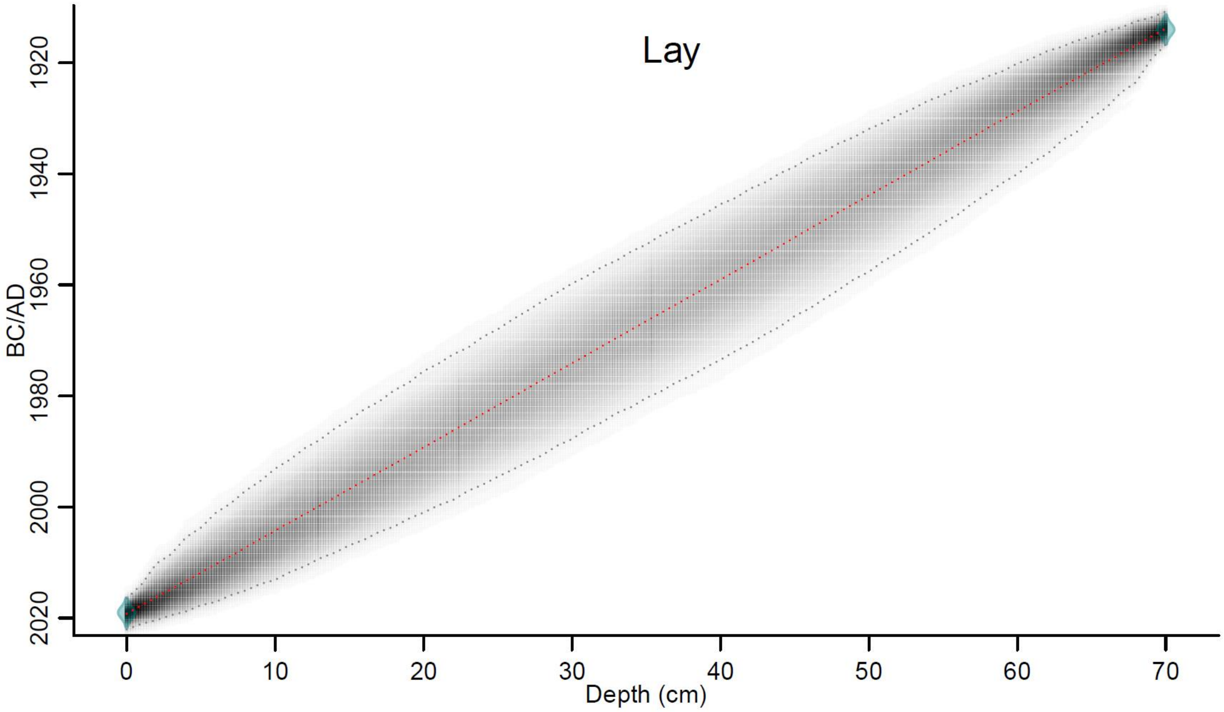

Figure 2.2. Depth vs. Age plot of the Lay Lake sediment core. Dates were calculated using the BACON model in R.

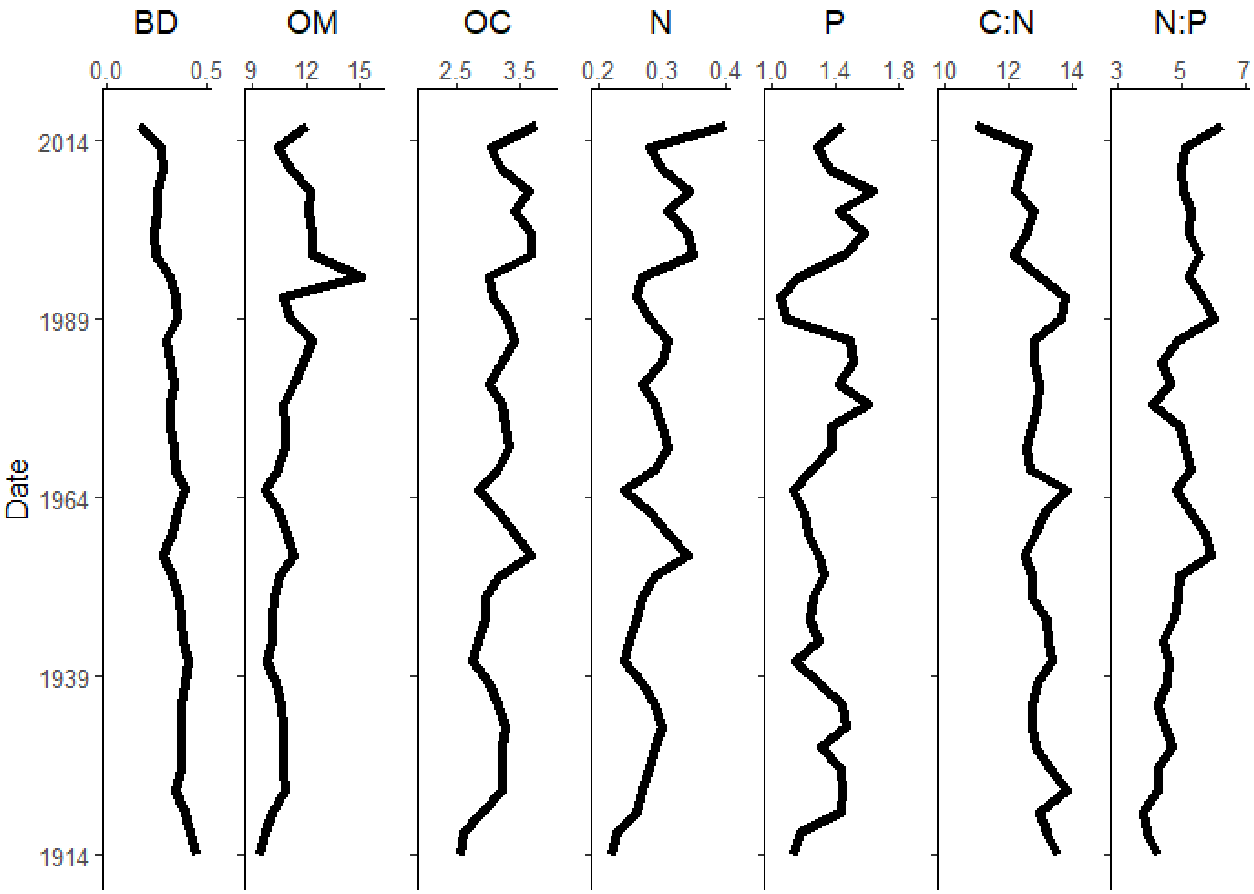

Figure 2.3. Core profiles for organic proxies and nutrients throughout the Lay Lake sediment core. Bulk density (BD) is reported in g cm^{-3}. Organic matter (OM), organic carbon (OC), and nitrogen (N) are reported in %. Phosphorus (P) is reported in mg g^{-1}. C:N and N:P are molar ratios.

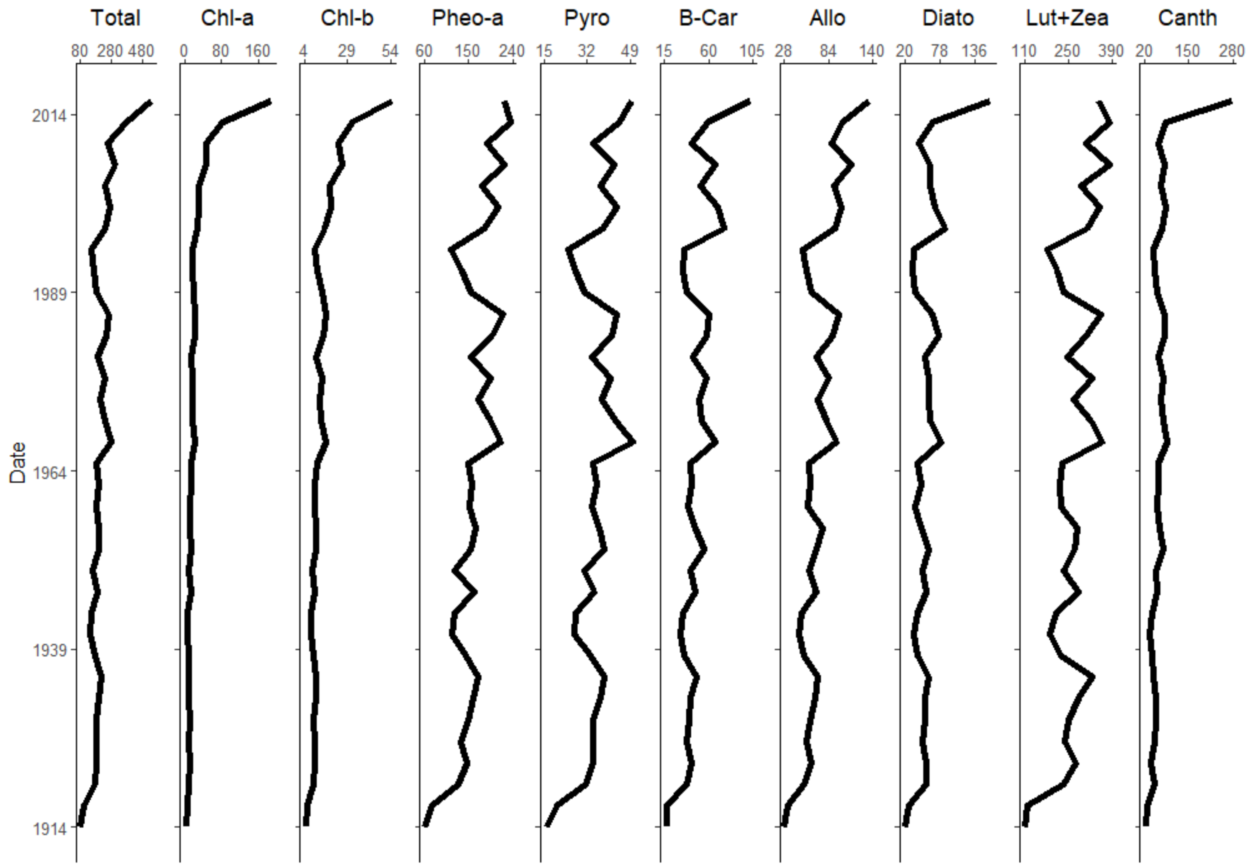

Figure 2.4. Core profiles of photosynthetic pigments through time. Pigments are reported in nmol g org^{-1}.

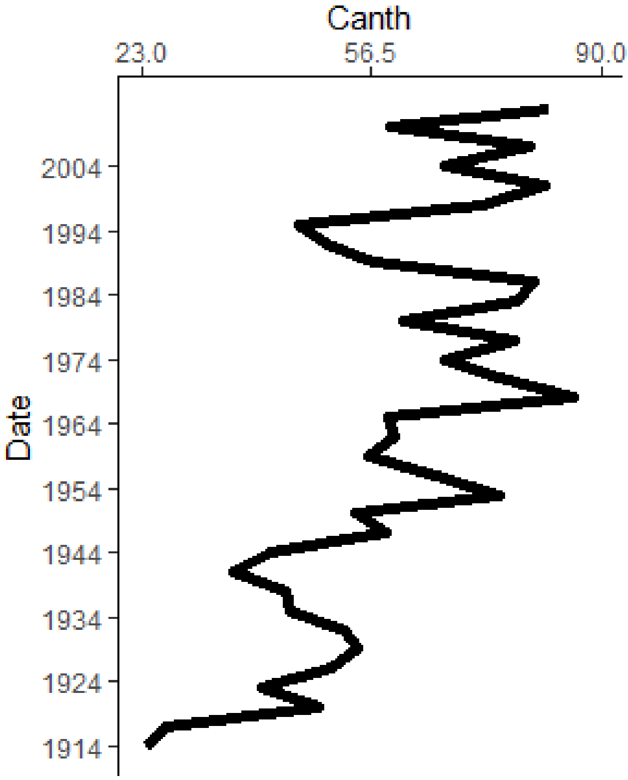

Figure 2.5. Core profile of canthaxanthin through time. This profile excludes the top most sample (2016-2019) to reveal stratigraphic changes. Canthaxanthin is reported as nmol g org^{-1}.

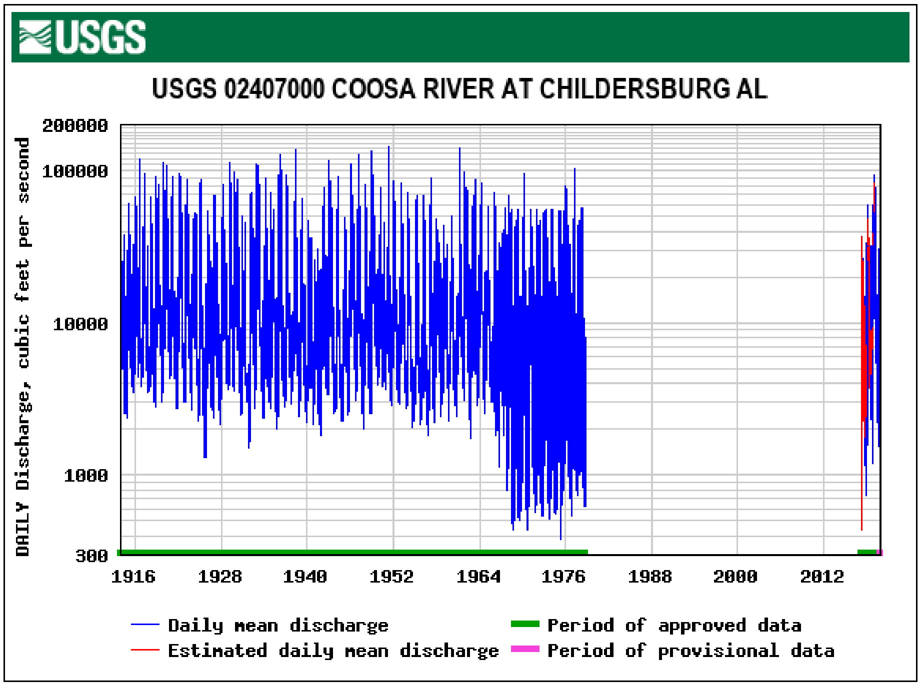

Figure 2.6. Figure by the United States Geological Survey (USGS) revealing daily average discharge downstream of Logan Martin Dam and into Lay Lake. Decrease in discharge is evident in 1964. Discharge is reported in cfs.

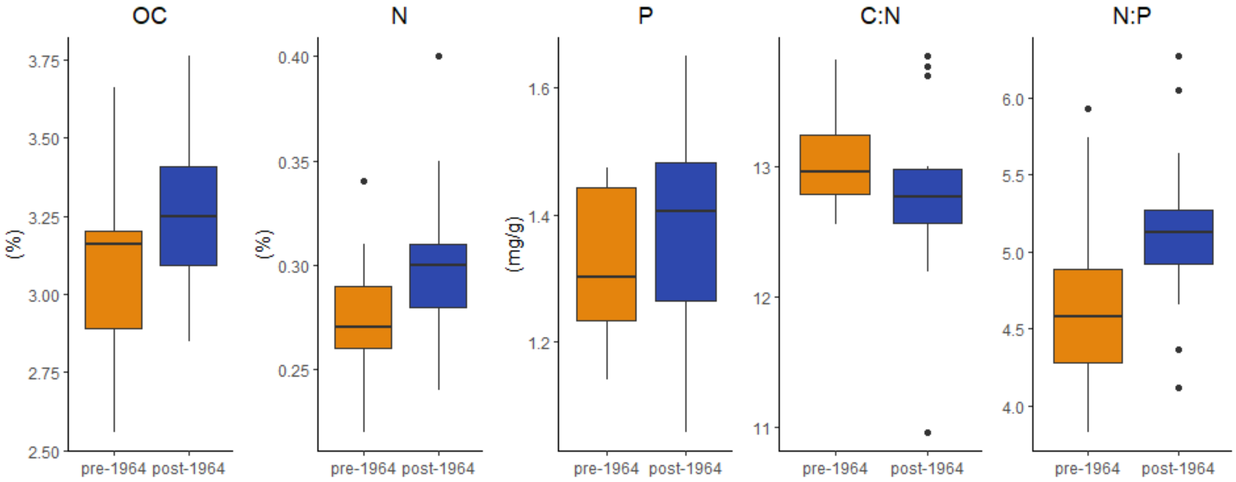

Figure 2.7. Box plots revealing changes in organic proxies before and after 1964. Pre-1964 is designated by orange boxes. Post-1964 is designated by blue boxes.

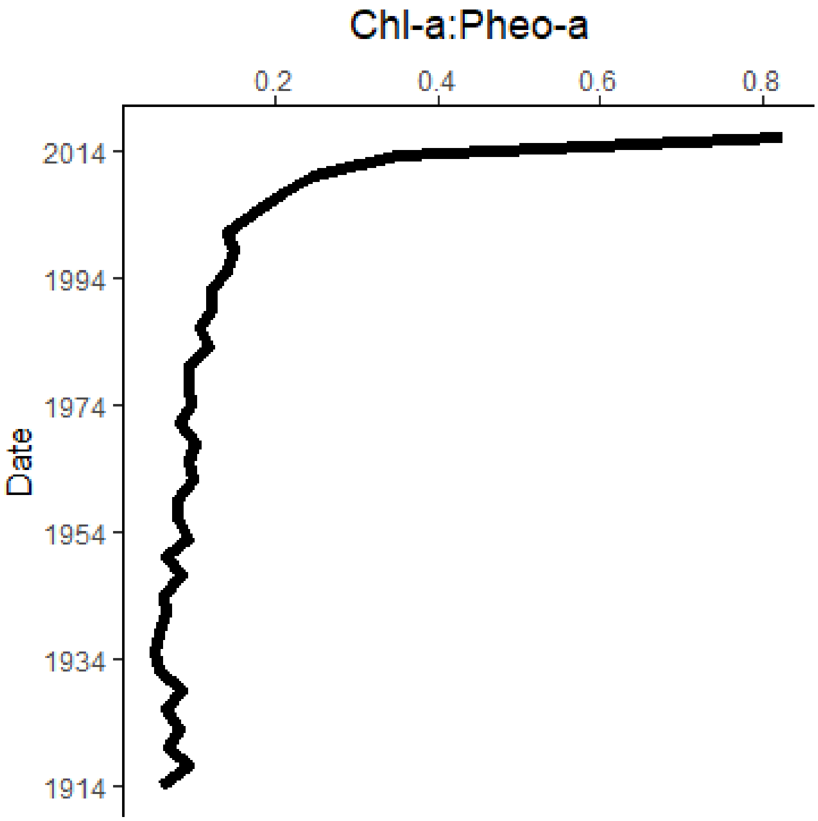

Figure 2.8. Core profile of chlorophyll-a: pheophytin-a overtime. Higher chl-a: pheo-a values represent fresher chlorophyll, whereas lower values represent more degraded chlorophyll.

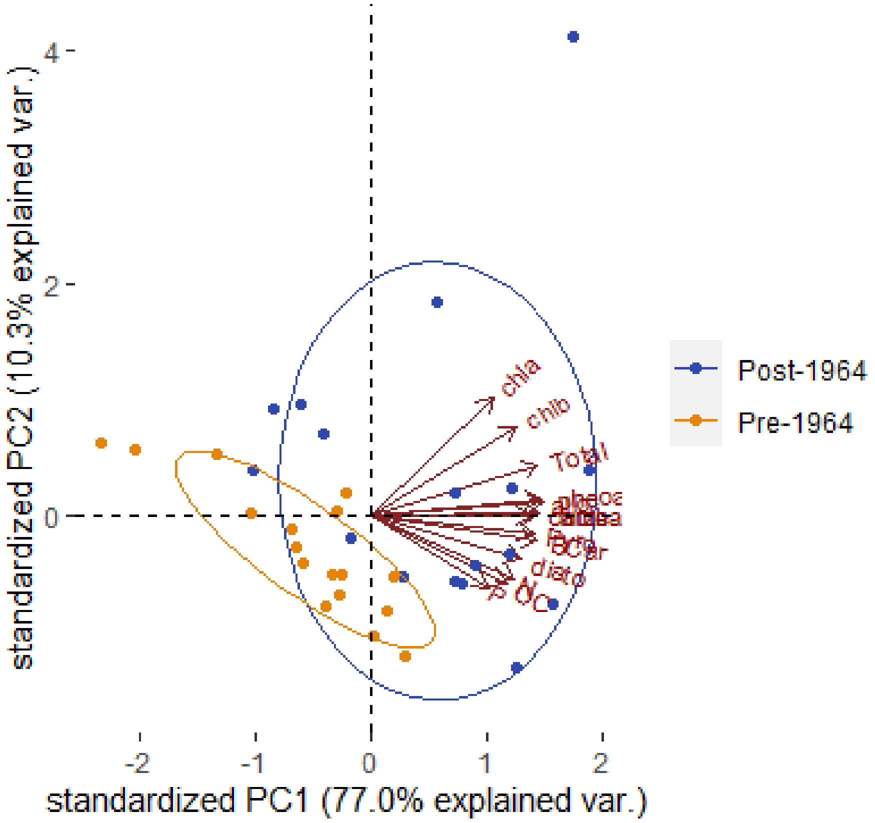

Figure 2.9. Principal component analysis (PCA) of photosynthetic pigments and nutrients (OC, N, P) spanning 1914-2016. Top sample was taken out for historical accuracy. Orange samples are dated pre-1964, whereas blue samples are dated post-1964. Ellipses represent one standard deviation.

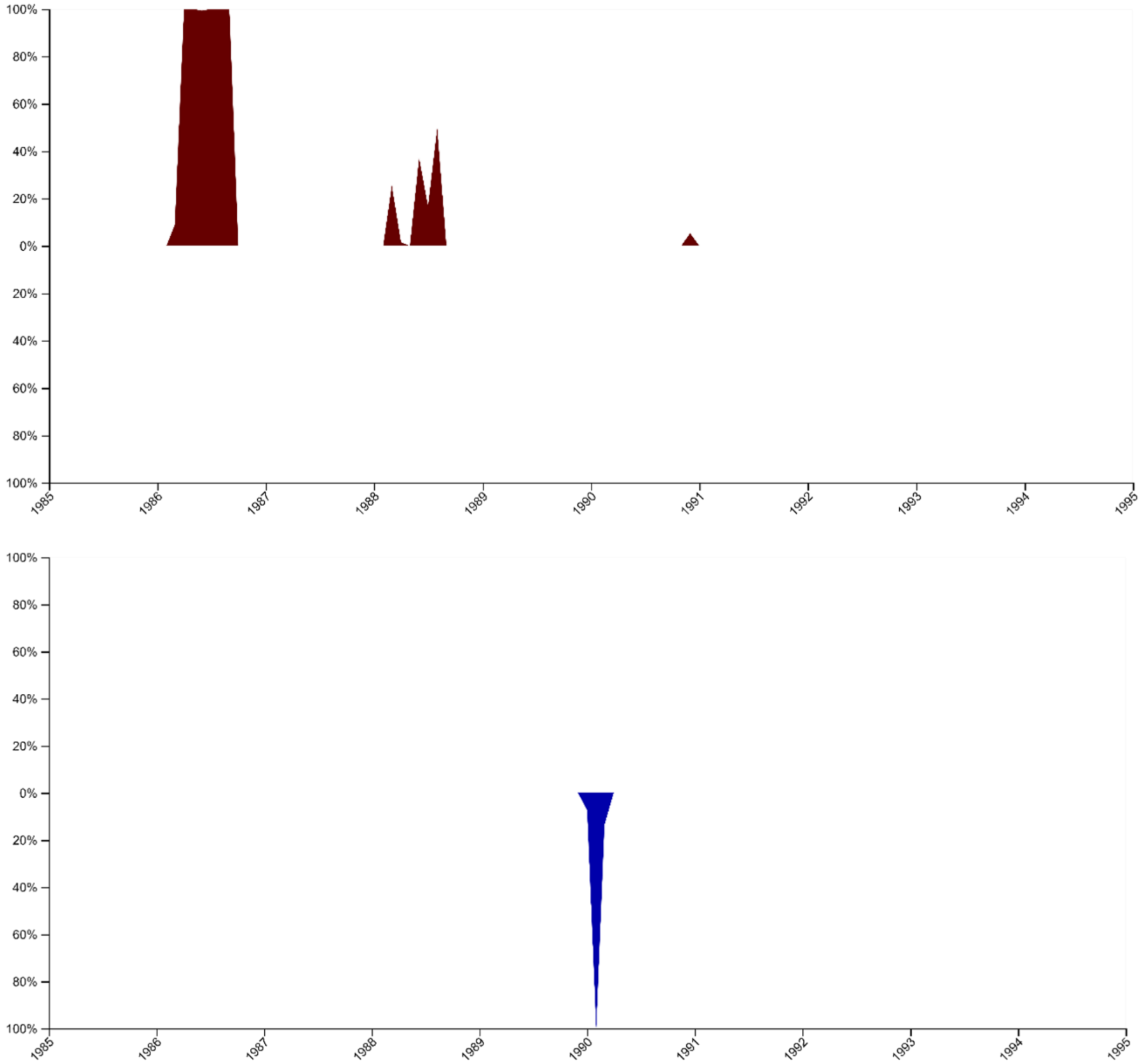

Figure 2.10. Historical droughts and wet periods spanning 1985-1995 for Shelby County, AL. Maroon uptick represents exceptional drought that has the capability of causing lake volumes to be extremely low. Blue downtick represents exceptional wet periods such as flooding. Information and figure from Drought.gov.

Chapter 3: Understanding Spatial Variation of Surface Sediments in Two Unique Reservoir Systems, Weiss Lake and Lay Lake

Abstract

Reservoirs have increasingly trapped large loads of sediments behind dams from their river watersheds. These sediments hold onto important macronutrients such as organic carbon (OC), nitrogen (N), and phosphorus (P), but also heavy metals such as lead (Pb), zinc (Zn), and arsenic (As). Multiple mechanisms have been described as regulating the distribution of sediments in reservoirs, but different reservoir types (large vs. small, sinuous vs. linear, etc.) have received less consideration. In this study, I investigated the mechanisms that influence the spatial distribution of sediments in two reservoirs with different morphologies, age, and management, Weiss Lake and Lay Lake on the Coosa River, AL, USA. Objectives were to 1) identify drivers of material delivery and deposition for key nutrients (OC, N, P) and heavy metals (As, Pb, Zn), and 2) connect depositional hot spots with material sources and local ecosystem health. I collected 86 surface sediment samples between the two reservoirs using a PONAR grab sampler and measured each sample for total concentrations of each element. Samples were grouped and analyzed according to hydrology, reservoir zonation, water depth, location in the reservoir, and differences in watershed land cover. Both reservoirs revealed a complex system that involved multiple different parameters controlling the distribution of surface sediments and material deposition. In both reservoirs, nutrients seemed to be locally sourced through land use and distributed through hydrologic pathways, while metals mainly originated from upstream sources carried downstream by the river channel. Results reveal the dynamic nature of reservoirs and the need for individual reservoir-based management when considering sedimentary processes.

Introduction

The creation of impoundments along rivers establishes unique biogeochemical hotspots that are novel in their retention and storage of sediments, nutrients, and heavy metals (Syvitski et al., 2005; Mavaara et al., 2015; Vörösmarty et al., 2003). These material inputs to reservoirs have increased with alterations in anthropogenic landscapes such as increased urbanization, industry, and agriculture (Syvitski et al., 2005; Calendar and Rice, 2000). These sediments can serve as diagnostic indicators of reservoir health and pose threats to ecosystem biota and reservoir productivity if not managed successfully (Schleiss et al., 2016).

Sediment characteristics of reservoirs are often associated with catchment dynamics and sediment delivery processes, which can be altered by dams (Collins et al., 2010; Schleiss et al., 2016). Because rivers typically carry sediment particles with a wide range of sizes depending on flow velocity, turbulence, and sediment inputs, sediments can reveal important information on the catchment and reservoir relationship (Schleiss et al., 2016). These processes play important roles in internal lake biogeochemical processes critical to aquatic and general ecology (Wetzel 2001). The entrapment of sediment behind dams is also consequential as nutrients and heavy metals are often constituents of depositional materials. Introduction of large-scale nutrient (OC, N, P) additions to water reservoirs can decrease water quality and increase anthropogenic eutrophication, while decreasing downstream nutrient budgets (Smith, 2003; Vörösmarty et al., 2003). The addition of heavy metals (Pb, Zn, As) through sediments has also been extremely concerning as toxic substances trapped in sediments constitute a geohealth hazard (Warren, 1981).

Spatial sediment surveys in reservoirs thus far have typically been aimed at locating point source pollution for heavy metals, understanding the effects of land use on the basin, or characterizing biogeochemical gradational zones (Frascareli et al., 2018; Torregroza-Espinosa et al., 2018; Calendar and Rice, 2000; Zorzal-Almeida et al., 2018). Because of the common morphometry and design between reservoirs, most studies utilize a general longitudinal sampling pattern as water moves downstream towards the dam. This sampling regime assumes coarser sediments deposit in the turbid high velocity upstream regions of the reservoir known as the "riverine" zone, and fine sediments reach the lake-like dam pool area, known as the "lacustrine" zone. A transition zone exists between the riverine and lacustrine zones depending on physicochemical parameters in the water column (Thornton et al., 1980; Wetzel, 2001; Schleiss et al., 2016). These zones are also assumed to drive primary productivity as they are defined by turbidity, energy, mixing, and light limitations (Thornton et al., 1980). Nevertheless, not all reservoirs fit this simplistic design, and sedimentation and material distribution has shown to be a complex and multifaceted process.

Prior research demonstrates the dynamic nature of nutrient biogeochemistry in reservoirs. Burford et al. (2007) and Qin et al. (2020) showed water volume and depth have measurable effects on the type of algal blooms in reservoirs as these factors control nutrient suspension in the water column. Whitmore et al. (1996) showed highly variable sediment distribution in shallow lakes that can be stressed by wind. Jones et al. (2008) showed hydrology must be considered when setting nutrient criteria in reservoirs, as criteria based on reservoirs with long retention time cannot accurately be applied to rapidly flushed systems. Wetzel (2001) explained high order streams to be the main input of water in dendritic reservoirs allowing high precipitation-based erosion. Tarela and Menéndez (1999) showed that evolution of reservoir bottoms depends strongly on the geometry of the reservoir and the sediment size. Syvitski et al. (2019) revealed water temperature variations impact rivers that transport a majority of fine sediment, typical of most large rivers. These processes and mechanisms may respond differently according to size and shape of the reservoir, climate, geography and geology, as well as hydrology. Therefore, further understanding of these processes controlling sediment, nutrient, and metal distribution is needed for reservoir management decisions impacting economic and societal safety.

Recognizing the complexity of spatial and temporal sedimentation dynamics in reservoirs, this research utilized surface sediments from 2 reservoirs of varying characteristics on the Coosa River system in Alabama, USA. Eighty six surface sediment samples were collected between the two systems and analyzed for bulk density, organic matter, nutrients, and heavy metals. The objectives of this research were to 1) identify drivers of material delivery and deposition for key nutrients (OC, N, P) and heavy metals (As, Pb, Zn), and 2) connect depositional hot spots with point and nonpoint sources, as well as infer local ecosystem health.

Methods

Study site: *The Coosa River, Weiss Lake and Lay Lake*

The Coosa River begins in Rome, Georgia, USA where the Etowah and Oostanaula Rivers converge, and flows west eventually meeting Weiss Lake's headwaters (Fig. 3.1). Weiss Lake lies in the Valley and Ridge physiographic province and drains 13,657 km^2 most of which is in NW, Georgia (Table 3). Weiss Lake is the first and largest hydroelectric reservoir on the Coosa River with a surface area of 122.2 km^2. Weiss Lake is the only storage reservoir on the Coosa River and was created by Alabama Power in 1961 to have both a spillway and hydroelectric powerhouse that are approximately 6 km apart. This separation created a unique finger-like morphology and two different pools of water that are connected by a diversion canal. Weiss Lake is used for hydropower, recreation, irrigation, drinking water, and flood control and has suffered from multiple water quality issues (eutrophication) stemming from increased urban sprawl, as well as erosion and sedimentation from construction, forestry, and agricultural activities. Septic systems along the shoreline of Weiss Lake are periodically defective increasing nutrient and organic loading (ADEM, 2004).

In contrast, Lay Lake is the oldest reservoir on the Coosa River and was built by Alabama Power in 1914 (Table 3). Lay Lake is approximately 185 km south of Weiss Lake and also lies in the Valley and Ridge physiographic province. Lay Lake is a narrow, linear, run-of-river reservoir and has a surface area of 48.6 km^2. Lay Lake is deeper than Weiss Lake with an average depth of 6.7 m, and is surrounded by 3 upstream (including Weiss Lake) and 2 downstream reservoirs. Lay Lake provides hydropower, water supply, recreation and wildlife habitat and has constantly been labeled as impaired for excessive organic material, nutrient inputs, and eutrophication.

Field and Laboratory Methods

Eighty six surface sediment samples were taken with a PONAR grab sampler to characterize and represent depositional processes occurring throughout Weiss and Lay Lake. Sample sites were evenly spaced across the reservoir to represent a whole-reservoir spatial sampling but avoided shorelines to ensure accuracy and to prevent collecting sediment that were not indicative of the entire system. The surface sediment samples were analyzed for bulk density, and percent organic matter (OM). Bulk density (BD) was calculated by removing and weighing a 1 cm^3 aliquot of wet sediment and subsequently drying the aliquot for 24 hours in a 60ºC oven and re-weighing. Bulk density was expressed as g dry cm^{-3} wet. The remaining sample was freeze-dried. Dry sediment samples were then ground to a fine powder with mortar and pestle and used for the remaining analyses. Organic matter content was assessed by burning dry sediment in a muffle furnace at 550°C for 3 hours and calculating percent loss-on-ignition following Håkanson & Jansson (1983). Organic carbon (OC) and nitrogen (N) were analyzed using a Costech Elemental Combustion C/N analyzer with an attached auto-sampler. Prior to analysis, samples were acidified for 12 hours in HCl vapor to remove inorganic carbon. Phosphorus (P) and other elements such as lead (Pb), Zinc (Zn), and Arsenic (As) were measured using Induced Coupled Plasma (ICP) following nitric acid digestion for 90 minutes in a heated block (EPA 6010B). Nutrients such as OC, N, and P were chosen as key sedimentary variables for this study linked to trophic status and the heavy metals, Pb, Zn, and As, were chosen to represent anthropogenic activity in the area, such as urban sprawl, industry, and agricultural practices.

Spatial methods

Spatial analysis was conducted using ArcMap 10.7.1. Heat maps were created by manually adjusting symbology on point data to characterize changes in concentration for selected parameters (OC, N, P, Pb, Zn, As). The USGS National Map Data website was utilized to characterize the perennial and artificial path of water from the National Hydrography dataset. DataBasin.org provided watershed (HUC 8) and sub-watershed (HUC 10-12) shapefiles from the Watershed Boundary Dataset (WBD), as well as a GAP Land Cover data set for Alabama and Georgia. The WBD is a comprehensive aggregated collection of hydrologic unit data consistent with the national criteria for delineation and resolution, while the USGS GAP Land Cover Data Set includes detailed vegetation and land use patterns for the continental United States (2014).

The Near tool within the Proximity toolset in ArcMap was utilized to calculate distances between the samples and the perennial river channel. Sub-watersheds surrounding Weiss Lake were then chosen based on proximity and direct influence on the basin. The northern and southern sides of Weiss Lake were categorized using a polygon drawing feature in ArcMap and tracing selected sub-watersheds. The GAP Land use data was clipped to the corresponding shapefiles using the data management tool “Clip Raster” in ArcMap. This allowed for a comparison to local land use trends between the northern and southern sub-watersheds of Weiss Lake using corresponding count data.

Statistical methods

To determine significant changes in sediment composition linked to multiple sedimentation mechanisms, samples were split into groupings based on gradational zones, barriers within the lakes, proximity to the river channel center, and water depth. Multiple statistical analyses were used including two-tailed t-tests, analysis of variance (ANOVA), and post-hoc tests. To graphically depict the division between groups, box plots were created in R using measured sedimentary data and their quartiles. Scatterplots were created using proximity to the river channel or depth as the independent variable, and measured sedimentary variables as the dependent variable. R^2 values were then determined based on the linear correlation of the data.

Results

Lay Lake’s surface sediment samples were variable in organic matter and bulk density (Fig. 3.2). Samples in the channel were low to moderate in OM averaging 8.8 % (±3.4), but increased to 17% near the dam. Samples in coves had an average OM concentration of 8.6 % (± 0.3), and an average BD of 0.4 g cm^{-3} (± 0.3). The average BD for the channel was roughly 0.44 g cm^{-3} (± 0.3), revealing sediments to be relatively unconsolidated throughout the reservoir.

Although, the southern-most cove near the dam had sandy samples with higher BD near 1.32 g cm^{-3} (Fig. 3.2).

Organic carbon and N percentages were low throughout Lay Lake averaging 3 % (± 1.2) and 0.26 % (±0.11), respectively. The main channel samples contained a gradient of nutrient concentrations, increasing in concentration near the dam (Fig. 3.3, Fig. 3.4). Cove samples were variable in nutrient concentrations, but generally small cove samples contained higher amounts of OC and N. P averaged 0.81 mg g^{-1} (± 0.32) throughout the reservoir, following the trend of other nutrients (Fig. 3.4). C:N averaged 14.8 (± 5), where N:P averaged 6.9 (± 2.3) (Fig. 3.5). N:P was generally higher in coves than in the main channel. Heavy metal concentrations in surface sediments showed greater heterogeneity than nutrient concentrations (Fig. 3.6, Fig. 3.7). Zn concentrations were very low throughout the reservoir averaging 0.04 mg g^{-1} (± 0.028) and did not accumulate in any spatial pattern. Pb averaged 0.03 mg g^{-1} (± 0.017), but was higher in samples associated with the channel and dam pool (Fig. 3.7). As averaged 0.008 mg g^{-1} (± 0.0025) and was generally the highest near the dam and bottleneck regions. Although the trends seen in As were similar to Pb's, As was more spatially variable.

Weiss Lake's surface sediment samples demonstrated depositional heterogeneity for organic matter and bulk density (Fig. 3.8). Samples from the eastern basin of the lake were typically higher in OM concentrations, but the reservoir as a whole averaged 5.6 % (± 2.92) (Fig. 3.8). BD for the entire reservoir averaged 0.72 g cm^{-3} (± 0.36) (Fig. 3.8). Samples near the spillway had the highest BD, which was related to granule to pebble sized rocks in the benthos and the lack of OM in this area (Fig. 3.8). The terminal basin near the powerhouse was generally a mixture of materials, lacking any certain trend.

Nutrient concentrations in Weiss Lake were generally lower than in Lay Lake. OC values averaged 1.44 % (± 0.85) , while N values averaged 0.11 % (± 0.072). OC and N showed no spatial pattern throughout the reservoir. P averaged 0.52 mg g^{-1} (± 0.28) and was highest near the river channel and dam. OC, N, and P were all very low in the northern coves and in the channel leading towards the spillway (Fig. 3.9, Fig. 3.10). C:N averaged 17.8 (± 14.2) and was lowest in concentration near the dam pool (Fig. 3.11). C:N of coves typically ranged from 12-15, but the main basin C:N values were between 15-20. N:P averaged 4.96 (± 2.68) with the highest values in coves (Fig. 3.11). Metals followed similar trends to P with the exception of Zn (Fig. 3.12, Fig. 3.13). Zn averaged 0.06 mg g^{-1} (± 0.033) and was only high in samples near the river channel (Fig. 3.12). Pb averaged 0.02 mg g^{-1} (± 0.0096), while As averaged 0.005 mg g^{-1} (± 0.003) throughout the reservoir.

To assess Lay Lake's reservoir longitudinal zonation, samples were objectively separated based on reservoir morphometric characteristics (Fig. 3.14). ANOVA and Tukey's post-hoc tests revealed P to be significantly different ($p = 0.007$) between the northern (riverine) and terminal (lacustrine) zones. Statistical analysis also revealed N:P to be significantly different ($p = 0.04$) between the central (transitional) and terminal (lacustrine) zones, but no other variables were different between groups. N was initially considered significantly different by ANOVA ($p = 0.04$), but post-hoc tests revealed N had a *p*-value of 0.07 and 0.06 between the northern and central groups and the northern and terminal groups, respectively. Based on box plot data, the terminal zone had the highest P concentrations, but the lowest N:P values (Fig. 3.15).

Weiss Lake's complex morphology and hydrology complicated the conventional zones defined by Thornton et al. (1980), therefore samples were split into 3 zones based on bridge segmentations (Fig. 3.16). ANOVA analysis revealed OC and Zn were significantly different between the central and terminal basins. Tukey's post-hoc test revealed both OC and Zn were significantly different between the eastern and central basins alone, having *p*-values of 0.03 and 0.02, respectively. Box plot data revealed both variables had higher values in the eastern basin (Fig. 3.17).

To analyze the impacts of the historic river channel, samples were divided into 2 groups based on proximity to the channel and were labeled 'channel' samples or 'non-channel' samples. Given that Lay Lake is extremely linear and narrow, a set distance from the channel was not used to group sediment samples in Lay Lake. Channel samples were directly in the channel, whereas non-channel samples only included cove areas. Two tailed t-tests revealed that only N:P ($p = 0.004$) and Pb ($p = 0.0004$) were significantly different between groups. Pb was higher in channel samples, while N:P was higher in non-channel samples (Fig. 3.18, Fig. 3.19). For most variables measured, non-channel samples located in coves demonstrated the greatest heterogeneity as shown in a larger spread in box plots.

In Weiss Lake, samples were divided based on proximity to the historic river channel. Channel samples were designated based on being within 1000 m of the channel center, and samples beyond 1000 m were considered non-channel samples. One sample (SS-29) was 1050 m from the channel and was designated as channel-associated as it had direct relation to a meander in the channel. The samples in the terminal basin were not used in this analysis, as they had no relation to the perennial river channel that exits out of Weiss Lake at the spillway. Two-tailed t-tests revealed that Zn ($p = 0.005$) and N:P ($p = 0.016$) were significantly different between groups. Zn was higher in channel samples, while N:P was higher in non-channel samples (Fig. 3.20, Fig. 3.21). P was also higher in the channel samples but was not considered significantly different between groups ($p = 0.068$) (Fig. 3.20).

Further channel analysis divided the Weiss channel samples into 2 groups where the ‘inner’ channel consisted of 0-500 m from the channel, and ‘outer’ channel consisted samples located 500-1000 m from the channel. ANOVA analysis revealed Zn, N:P, and P were significantly different between groups. Tukey’s post-hoc revealed Zn to be significantly different between the outer and non-channel samples ($p = 0.002$), N:P to be different between the inner and non-channel samples ($p = 0.02$), but P to be different between multiple groups. Specifically, P was different between the inner and outer groups ($p = 0.04$) but was extremely different between the outer and non-channel groups ($p = 0.008$). Box and scatter plots illustrated the relationships between the 3 groups where the outer channel consistently contained the highest concentration of all variables (Fig. 3.22). This differed for N:P which showed a positive relationship with increasing distance from the channel (Fig. 3.23, Fig. 3.24); C:N values were constant across groups (Fig. 3.23).

In Lay Lake, most variables had little to no relationship with water depth as most R^2 values were close to 0.0, but P and Pb exhibited weak positive linear relationships (Fig. 3.25). P had an R^2 of 0.35, while Pb has a slightly higher R^2 of 0.36. Pb seemed to exhibit 2 clusters of samples on the plot that may not be indicative of a true relationship to water depth. Therefore, depth scatterplots were then characterized by their proximity to channel (Fig. 3.26). This revealed higher Pb concentrations in the channel samples, whereas lower Pb concentrations were in the non-channel samples. In Weiss Lake, all variables had little to no relationship with water depth given that the average depth of 3.2 m was consistent across the lake and most R^2 values were close to 0.0 (Fig. 3.27).

The application of probable effect concentrations created by MacDonald et al. (2000) deemed the majority of Lay Lake to be under probable effects concentration (PEC). All Zn concentrations were under 0.121 mg g^{-1}, the threshold effects concentration (TEC) for Zn in sediments (Fig. 3.29). Most As samples were under the TEC of 0.01 mg g^{-1} , but some were slightly above it never passing the PEC of 0.033 mg g^{-1} (Fig. 3.29). Pb was most commonly between the TEC (0.0358 mg g^{-1}) and the PEC (0.128 mg g^{-1}) (Fig. 3.30). The application of probable effect concentrations on Weiss Lake deemed the majority of the lake below TEC for toxic heavy metals. Only one sample (SS-42) was above the Zn PEC, and this sample had a concentration of 1.06 mg g^{-1} (Fig. 3.31). Another sample (SS-16) was above the TEC for As and Pb, and contained a concentration of 0.023 mg g^{-1} and 0.043 mg g^{-1}, respectively (Fig. 3.32).

Discussion

The surface sediment survey of Lay Lake and Weiss Lake identified different patterns of material deposition as well as drivers of sedimentation. Lay Lake, which represents a longitudinally centered reservoir was strongly influenced by linear river channel hydrology that flushed inputs towards the dam pool, but did not seem to be strongly influenced by a forested watershed. Weiss Lake, a more heterogeneous morphometric basin, was influenced by river channel hydrology as well, but the large surface area and sinuous pattern of the channel allowed large amounts of material to be primarily deposited in the outer reaches of the channel in contrast to heavy deposition near the dam. Coves in Weiss Lake were strongly influenced by changes in local land use as Weiss Lake’s watershed was more diverse than Lay Lake’s.

Lay Lake and Weiss Lake possess multiple differences in reservoir morphometry and management, but data revealed both were impacted by a multitude of drivers. Sedimentation was not strongly influenced by traditional ideologies such as reservoir zonation or water depth. Nevertheless, these two drivers are important to reservoir sedimentation as they can determine changes in energy and biogeochemical processes such as turbidity, mixing, and primary productivity (Thornton et al., 1980; Whitmore et al., 1996). Patterns in land use were also different between reservoirs, but were not always directly proportional to material inputs, especially in Lay Lake. Land use is a unique driver as it can determine the type and rate of material input into aquatic systems (Waters et al., 2015; Zorzal-Almeida et al., 2018). Additionally, hydrology is a strong driver of sedimentation that is often under looked. The anthropogenic management of water in reservoirs alters velocity, flushing rates, nutrient availability, and influx of materials (Jones et al., 2008; Schleiss et al., 2016). In this study, the hydrology of the river channel appears to be the main driver of sedimentation

Material Input and Land Use

Sediment nutrient concentrations in Lay Lake followed a pattern expected from reservoirs with simplistic basin morphometry, where a majority of materials were concentrated in the portion of the lake near the dam pool. The main channel area was generally higher in material concentrations than coves, meaning upstream areas may be the primary source of sedimentary materials. Zn is the only variable that did not display this trend as it was more sporadic across the reservoir (Fig. 3.6). Low concentrations of Zn are common in Alabama soil samples, therefore the small sporadic concentrations of Zn seen in Lay Lake may be through local non-point sources such as erosion from homesteads (Senwo and Tazisong, 2004). Pb was unique with high concentrations in the channel and in the dam pool (Fig. 3.7, Fig. 3.26). Pb is a toxic heavy metal that can originate from anthropogenic activity, including metallurgy and coal-combustion (Warren et al., 1981). The E.C. Gaston Steam Plant sits on the banks of northern Lay Lake and is a coal-fired power plant that has frequently polluted groundwater with toxic metals above federal advisory levels (Ash Tracker, 2021). The Gaston Steam Plant could be serving as a point source for Pb, as well as As, in Lay Lake.

Lay Lake's cove areas were typically lower in metal concentrations, but varied in terms of nutrient levels. Small coves consisted of higher OC and N, but varied in source material from the input of terrestrial organic matter such as leaves (C:N >20), or from input of algal biomass (C:N <12) that is more likely to form in stagnant waters (Meyers, 1994). Lay Lake does not contain macrophytes leading to inferences that a C:N ratio between 12 and 20 is a mixture of recalcitrant and labile organic matter. The main channel reflects this mixture, but with a higher algal presence near the dam possibly due to higher nutrient delivery or algal abundance in this region. Larger and open coves contained the lowest concentrations for nutrients and metals. Coves attached to large tributaries varied in sediment deposition, but some contained high P concentrations. As was also moderate in these regions and mimicked depositional patterns similar to P; therefore, As and P could be traveling in unison in these areas (Boyd, 2015). Overall, OC, N, P, and As revealed a mixture of point and nonpoint sources for these variables, while Pb and Zn are expected to be from upstream and local sources, respectively.

The variability of P concentrations in Lay Lake is attributed to a variety of sources that include upstream point sources, as well as local land-use driven nonpoint sources through wastewater or fertilizer use. During sample collection at Lay Lake, a prescribed fire area was noticed along the banks suggesting that management of the pine forests in Lay Lake's watershed could be a nonpoint source for nutrient pollution as seen in other forestry and prescribed fire studies (Waters et al., 2019; Coates et al., 2019). Lay Lake's watershed consists of 80% forestry, 13% agriculture, and 2% urban areas where the majority of urban and agricultural lands remain in the northern part of the watershed (ADEM, 2008). Forested systems are known to act as buffers against erosion and nutrient pollution, but our results revealed high P concentrations (upwards of 1.5 mg g^{-1}) in the channel, as well as in some coves (Klapproth and Johnson, 2009).

Weiss Lake's watershed consists of 54% forestry, 36% agriculture, and 10% urban lands with smaller amounts of wetlands and barren areas (US EPA Region 4, 2008). Surface sediments from Weiss Lake correspond to the mixed watershed that relies largely on riverine inputs, as the sediments are variable throughout the basin but are generally higher with proximity to the channel. Specifically, Zn and P concentrations were high in samples that were close to the main channel revealing these elements may be brought into Weiss Lake from upstream (Fig. 3.22). This is expected as the Coosa River forms in Rome, Georgia-- a highly urban and industrialized area consisting of coal-fired power plants, carpet manufacturers, and pulp mills that have the capability of emitting toxic heavy metals such as Zn (Warren, 1981; Callendar and Rice, 2000). Variables such as OC, N, As, and Pb revealed a combination of point and nonpoint sources.

Northern cove samples were low in concentrations of all variables measured, while the southern coves were typically higher. By dividing landscape areas into smaller watersheds that directly touched Weiss Lake, the land use data revealed the northern watershed had 13% more forestry and 12% less agriculture than the southern watershed (Fig. 3.28). This difference in land use could explain the lower amounts of materials on the northern side of the lake, and increased concentrations for the southern side. The impact of land use on spatial sedimentary trends are corroborated by high terrestrial C:N values in the northern coves indicative of forest inputs, and lower C:N values in the southern coves suggesting a greater influence from phytoplankton (Fig. 3.11). Terrestrial organic matter seems to be the primary source of organic matter input as C:N ratios for most of Weiss Lake since most C:N values are between 15-20. This suggests that the channel is carrying a substantial amount of terrestrial material.

Mechanisms for Material Distribution: Reservoir Zonation

Comparisons of the 3 reservoir zones on Lay Lake did not reveal biogeochemical differences as expected. Out of the 6 variables measured, P was significantly different between the terminal (lacustrine) zone and the northern (riverine) zone, while N:P was significantly different between the central (transitional) and terminal (lacustrine) zones. The lack of differences between groups reveal that decreases in flow are not driving material deposition in Lay Lake. Phosphorus could show some response, but the hydrological and physical changes in the three zones does not appear to be the primary driver of sediment processes.

Comparisons of the 3 reservoir zones on Weiss Lake was atypical as Weiss Lake is a morphologically-complex reservoir that is characterized by bridge segmentations. Therefore, samples in Weiss Lake were grouped into 3 “sub-basins" rather than zones. This analysis did not reveal the basins to be as biogeochemically unique as expected. Only 2 of the measured variables (OC and Zn) were significantly different between basins (central and eastern basins). OC and Zn were both higher in the eastern basin revealing these variables may be trapped behind the land bridge as they enter the reservoir from Georgia, but other variables were not affected by this bridge segmentation.

Mechanisms for Material Distribution: River Channel Hydrology

In narrow and linear reservoirs like Lay Lake, turbidity currents are the main mechanism of sedimentation (Oehy, 2003). Therefore, the river channel was hypothesized as playing a strong part in Lay Lake’s sediment distribution. However, when sediment samples were split into 2 groups corresponding to proximity to the river channel (channel vs. non-channel) only 2 variables in Lay Lake were significantly different, Pb and N:P. Reservoirs have been known to shift N:P ratios as P becomes trapped behind dams and N decreases with faster water residence times and escapes through denitrification (Akbarzadeh et al., 2019; Maavara et al., 2015). N:P was higher in non-channel samples indicating higher N deposition in cove areas, decreased P deposition, or both (Fig. 3.5). Similar patterns with N:P were also seen in the 3 zones analysis where N:P decreased in the terminal zone due to increasing P storage near the dam.

Pb was different in depositional pattern when compared to N:P. Pb is a heavy metal that is not essential for life, can be acutely toxic, and is relatively immobile in the environment (Cullen and McAlister, 2017). Pb was much higher in the channel than non-channel areas indicating it is being controlled by riverine processes possibly due to upstream inputs (Fig. 3.7). The river channel does not appear to be directly causing the spatial distribution of the other parameters, possibly because of internal cove processes or the differences in biogeochemistry between elements. Nonetheless, hydrology seems to be important in the cycling of key macronutrients, such as N and P in Lay Lake.

In Weiss Lake, the meandering river channel appears to be the primary driver of sediment distribution and deposition with a few cove samples deviating from this trend. T-tests revealed Zn ($p = 0.0045$) and N:P ($p = 0.016$) to be significantly different between samples that were river channel-associated (<1000 m to center of the river channel) and samples that were not associated with the river channel. N:P was highest in non-channel samples, while Zn was higher in channel samples (Fig. 3.21, Fig. 3.20). This trend was also seen in Lay Lake, but with Pb instead of Zn. Like Pb, Zn also results from industrial processes, such as metal manufacturing industries or electric utilities (Warren, 1981).

Because Weiss Lake is very large, the channel was further analyzed and samples were broken into 3 groups based on proximity to the channel center (inner channel: 0-500m, outer-channel: 500-1000m, non-channel: >1000m). Box plots, scatter plots, and ANOVAs revealed a that samples in the outer-channel region had the highest concentration of material (Fig. 3.22, Fig. 3.23). This mechanism may exist in Weiss Lake because of the relatively large surface area and sinuosity of the channel. The outer channel is most likely where water is losing energy and as a result is likely to be depositing the most materials carried by the channel. This relationship between distance to the channel and concentration is believed to be the primary driver of material deposition as the trend was consistent for all variables used.

Outer channel samples in Weiss Lake represented the most variability and can be attributed to differences between coves in the basin. ANOVA and post-hoc tests revealed Zn and P were significantly different between the outer and non-channel samples, N:P was significantly different between inner and non-channel samples, while P was also different between inner-outer channel samples. Therefore, the distribution of P in Weiss Lake is heavily reliant on hydrology and the mechanism occurring on the outer channel region.

Mechanisms for Material Distribution: Water Depth

Water depth was also examined as a mechanism for the spatial distribution of sediments due to the stability of deeper areas in reservoirs, as well as the slowing of flows in these pool environments. In Lay Lake, scatterplots revealed water depth only played a minor role in sediment distribution as P and Pb were the only two variables to trend upwards with increasing water depth (Fig. 3.25). P storage is often controlled by redox potential and oxygen concentrations that can change with increasing water depth allowing this mechanism to be a reliable predictor for P distribution (Pearsall and Mortimer, 1939).

In contrast, Pb displayed two clusters of concentrations on the scatter plot that P did not. Upon further analysis, Pb revealed a stronger relationship to the river channel than to water depth as the highest Pb concentrations grouped with channel samples on the depth plot, and the lower

Pb concentrations grouped with non-channel samples on the depth plot (Fig. 3.26). These clusters and relationship to the channel reveal depth is most likely not a driver of Pb deposition in Lay Lake. Depth in Weiss Lake was also considered to be a mechanism for spatial distribution, but the average depth in Weiss Lake is consistently around 3.2 m and did not appear to drive deposition (Fig. 3.27).

Material Hot Spots and Ecosystem Health

Areas in Lay Lake with the highest concentrations tended to be near the dam pool or near the “bottleneck” region in the middle of the reservoir. The bottleneck is where the lake diameter significantly decreases to a single point and can occur in many reservoir systems. High deposition in this zone could be attributed to the change in flows and increased depths allowing suspended particles to deposit in the stable benthic area. Threshold effect concentrations (TEC) are limits below which harmful effects are unlikely to be observed for benthic organisms, while probable effects concentrations (PEC) are considered thresholds above which harmful effects are highly likely to be observed (MacDonald et al., 2000). In Lay Lake, all heavy metals were below the PEC suggesting that surface sediment was safe as a whole, but some specific samples were above the TEC for As and Pb (Fig. 3.29, Fig. 3.30). Sedimentary Pb concentrations were above the TEC in the river channel, while As was only above the TEC near the dam and bottleneck regions. Some benthic organisms in Lay Lake may suffer from the elevated concentrations of Pb in the top sediments, but the toxicity is not considered to be ecologically dangerous.

Depositional hot spots in Weiss Lake were primarily near the channel or in specific coves on the southern side of the lake, but 41 of 42 surface sediment samples were below the TEC for the As, Pb, and Zn. One sample on the eastern side of the reservoir was above the PEC for Zn concentrations and can be considered a potential hotspot for Zn (Fig. 3.31). One sample in the central part of Weiss Lake was above TEC for both As and Pb (Fig. 3.32). This location was the only area where mud was non-existent, and small reddish-brown rocks were collected instead. These rocks were extremely high in Fe and other metals and can be considered possible iron concretions. This corresponds to the geology of the region as it includes the Red Mountain Formation, known for thin hematitic beds (Holmes, 2015). Iron oxides, such as hematite, have been known to absorb heavy metals from water (Dave and Chopda, 2014).

Management Implications

Many studies have supported the need for new reservoir management plans. Waters et al. (2015) demonstrated the need to consider both land use and river regulation in sediment transport models, as well as in management decisions. Suen and Eheart (2006) explained how flow management strategies need to incorporate flow magnitude, duration, frequency, timing, and predictability in contrast to ecological baseline flows that target only some parts of the aquatic ecosystem. The data presented here for Weiss Lake suggests that hydrology and the placement of the historic riverine channel needs to be considered as a primary depositional mechanism for reservoirs containing historic meandering channels. Many water management plans in the 21st century are based on data from the first half of the 20th century and do not take into account the complexity of reservoir systems (Belin, 2018). This includes the Army Corp of Engineers that has Water Control Plans and Manuals based on precipitation and water data from the decades preceding construction of each dam (Belin, 2018). The prediction of sedimentation is essential to improve reservoir management, and will only become more applicable with adaptive and individual reservoir plans. The traditional ideas of reservoir management have not been extremely successful in mitigating water quality issues, especially in Alabama where a majority of reservoirs are eutrophic.

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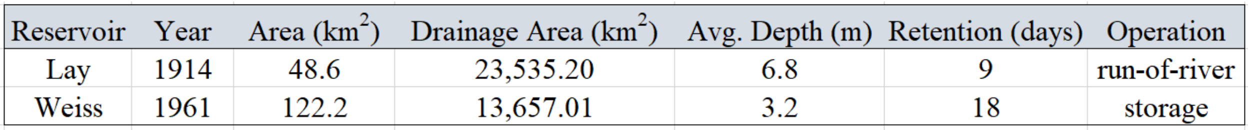
Tables



Reservoir	Year	Area (km^2)	Drainage Area (km^2)	Avg. Depth (m)	Retention (days)	Operation
Lay	1914	48.6	23,535.20	6.8	9	run-of-river
Weiss	1961	122.2	13,657.01	3.2	18	storage

Table 3. Reservoir statistics for Lay and Weiss Lakes, data from Alabama Department of Environmental Management.

Figures

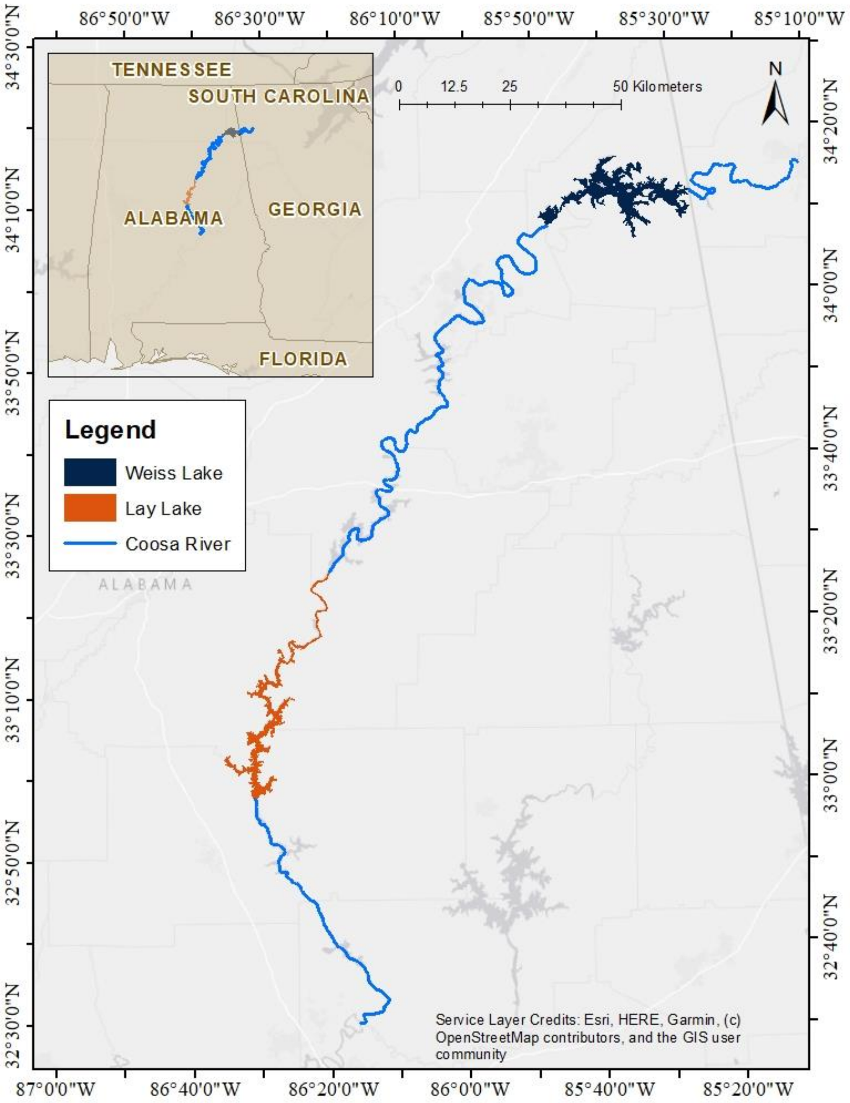


Figure 3.1. Overview of the Coosa River, as well as Weiss Lake depicted in navy and Lay Lake depicted in orange.

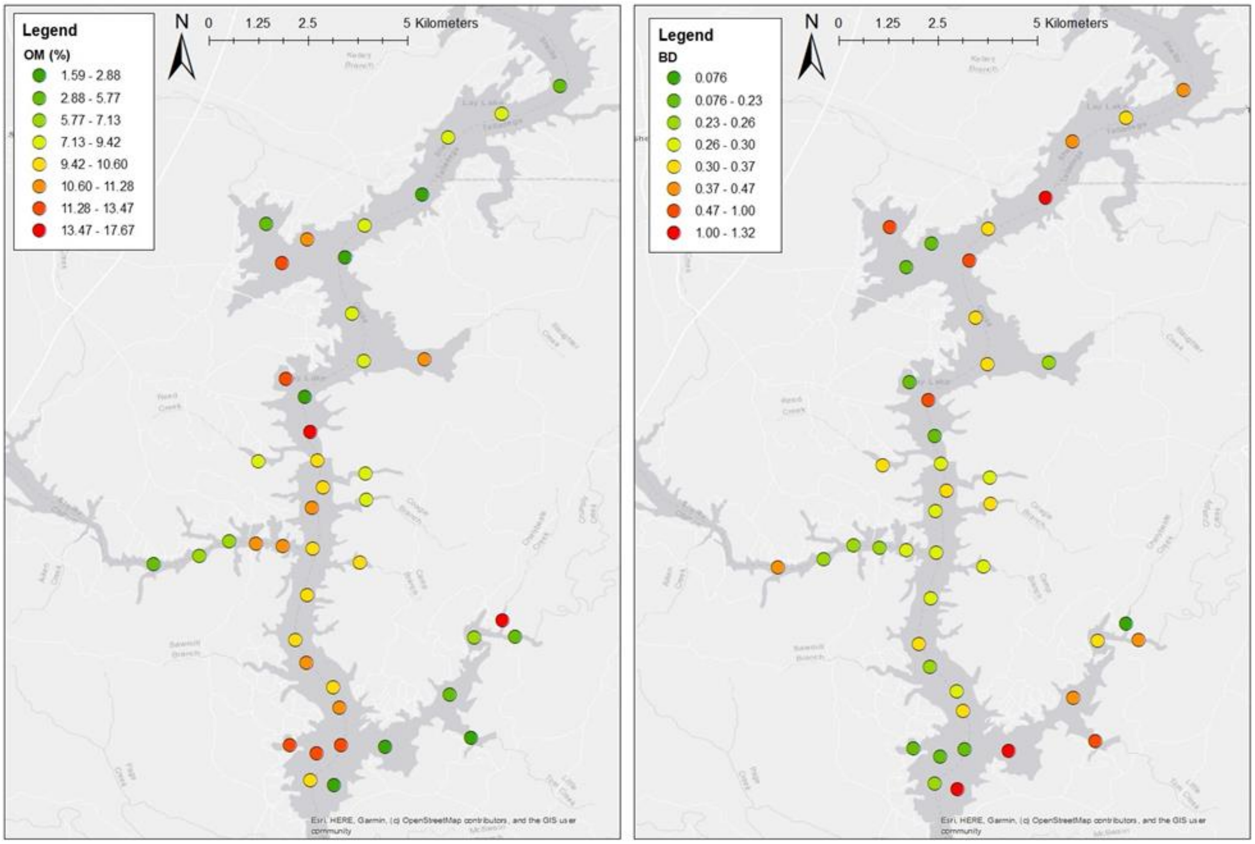


Figure 3.2. Heat maps of OM (left) and BD (right) in sediment samples throughout Lay Lake. OM is reported in percent, while BD is reported in g cm^{-3}.

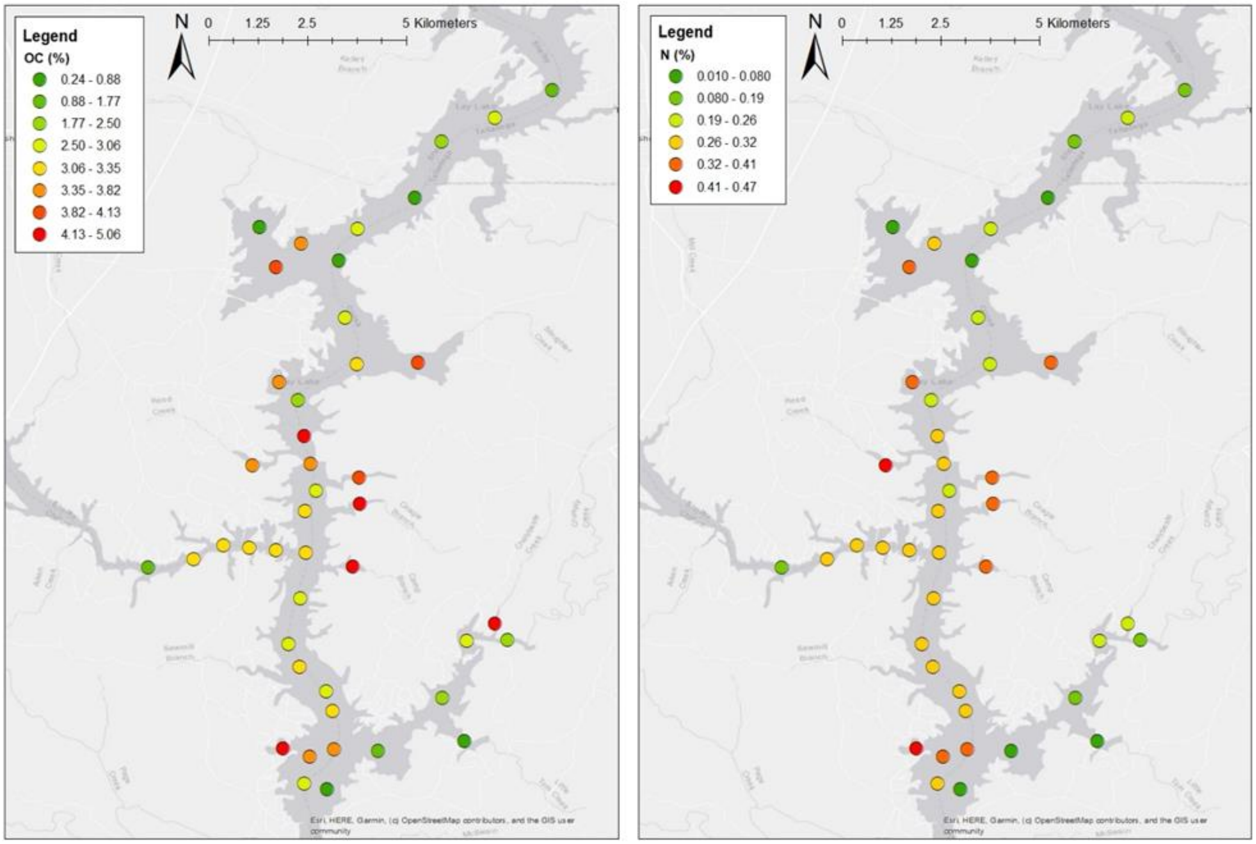


Figure 3.3. Heat maps of OC (left) and N (right) in sediment samples throughout Lay Lake. Values are reported in percent.

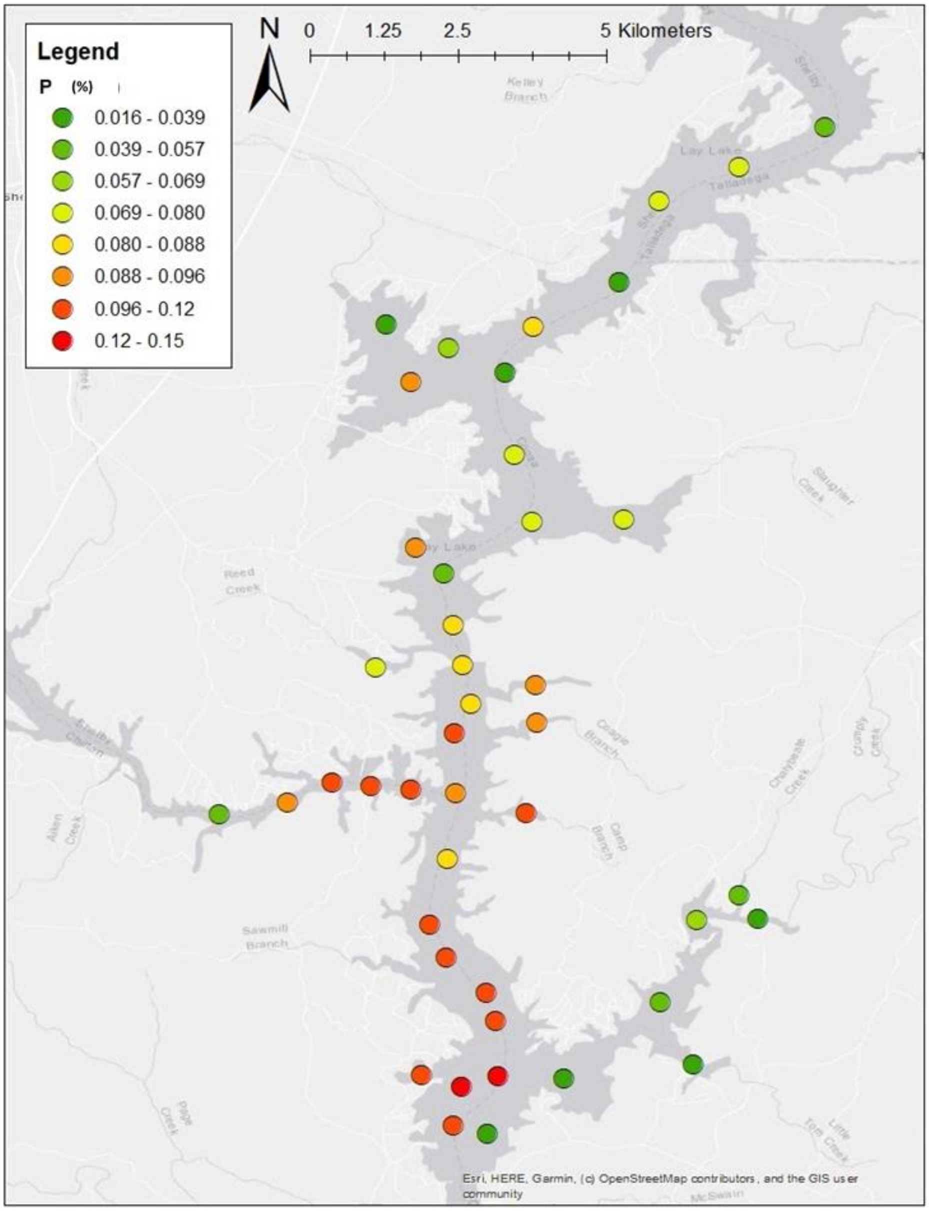


Figure 3.4. Heat map of phosphorus (P) in sediment samples throughout Lay Lake. Values are reported in percent.

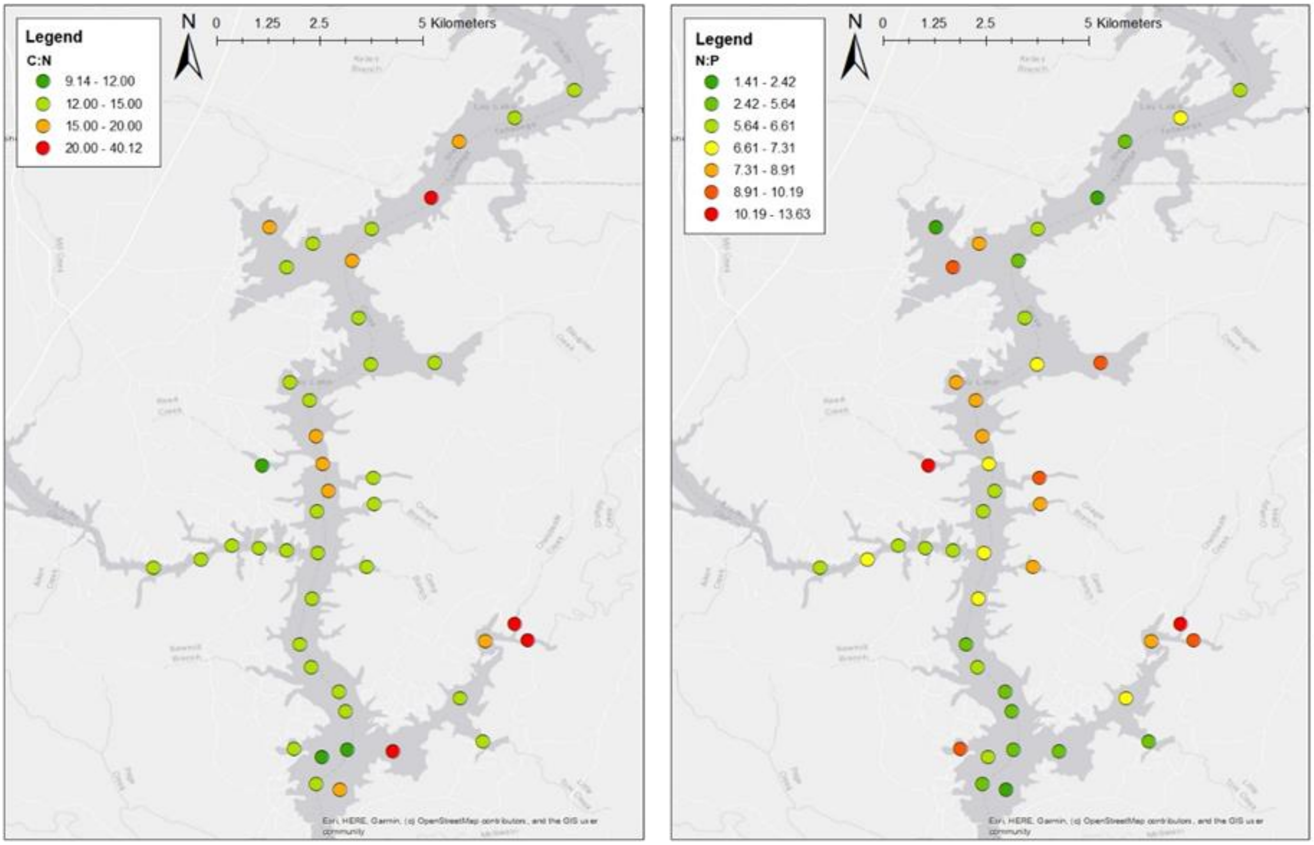


Figure 3.5. Heat maps of C:N (left) and N:P (right) in sediment samples throughout Lay Lake. C:N and N:P are molar ratios.

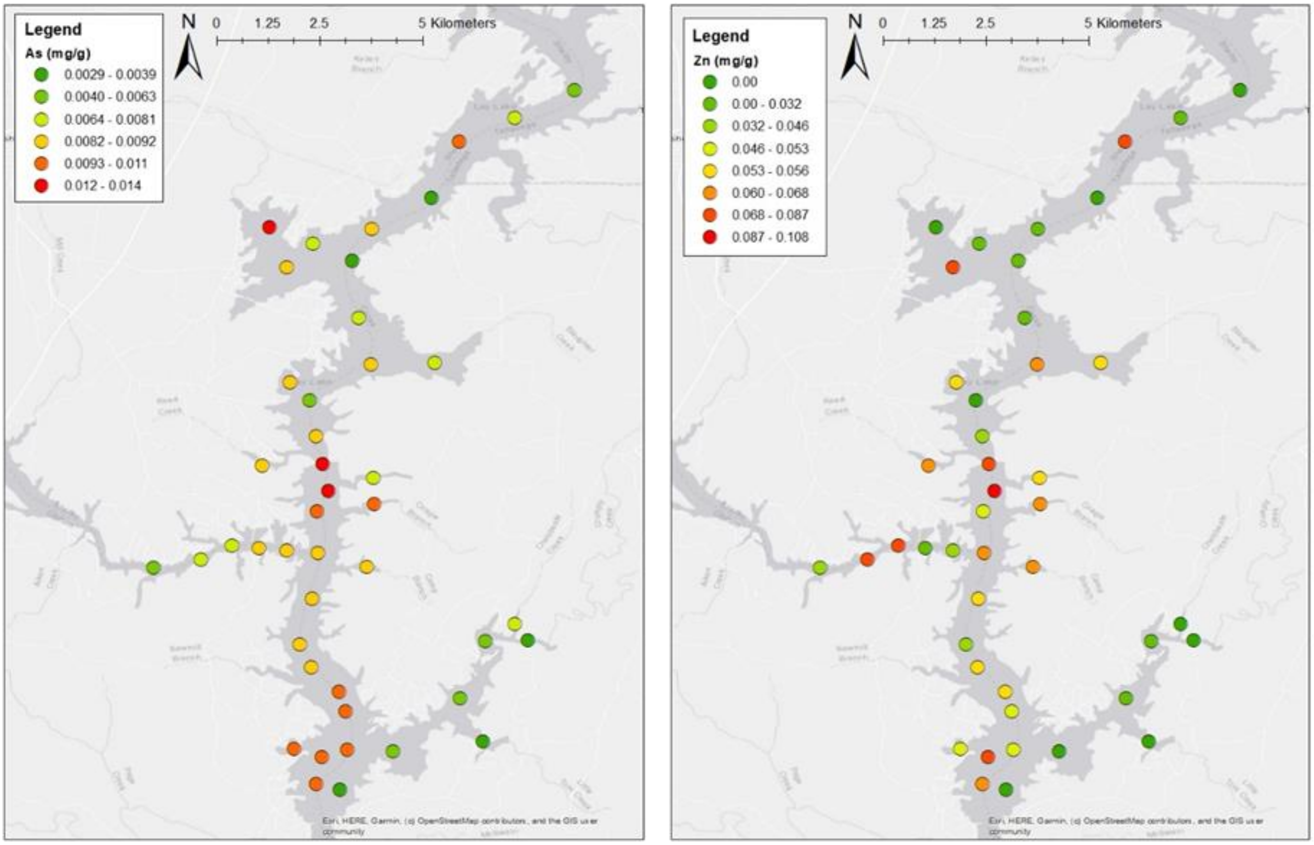


Figure 3.6. Heat maps of As (left) and Zn (right) in sediment samples throughout Lay Lake. Values are reported in mg g^{-1}.

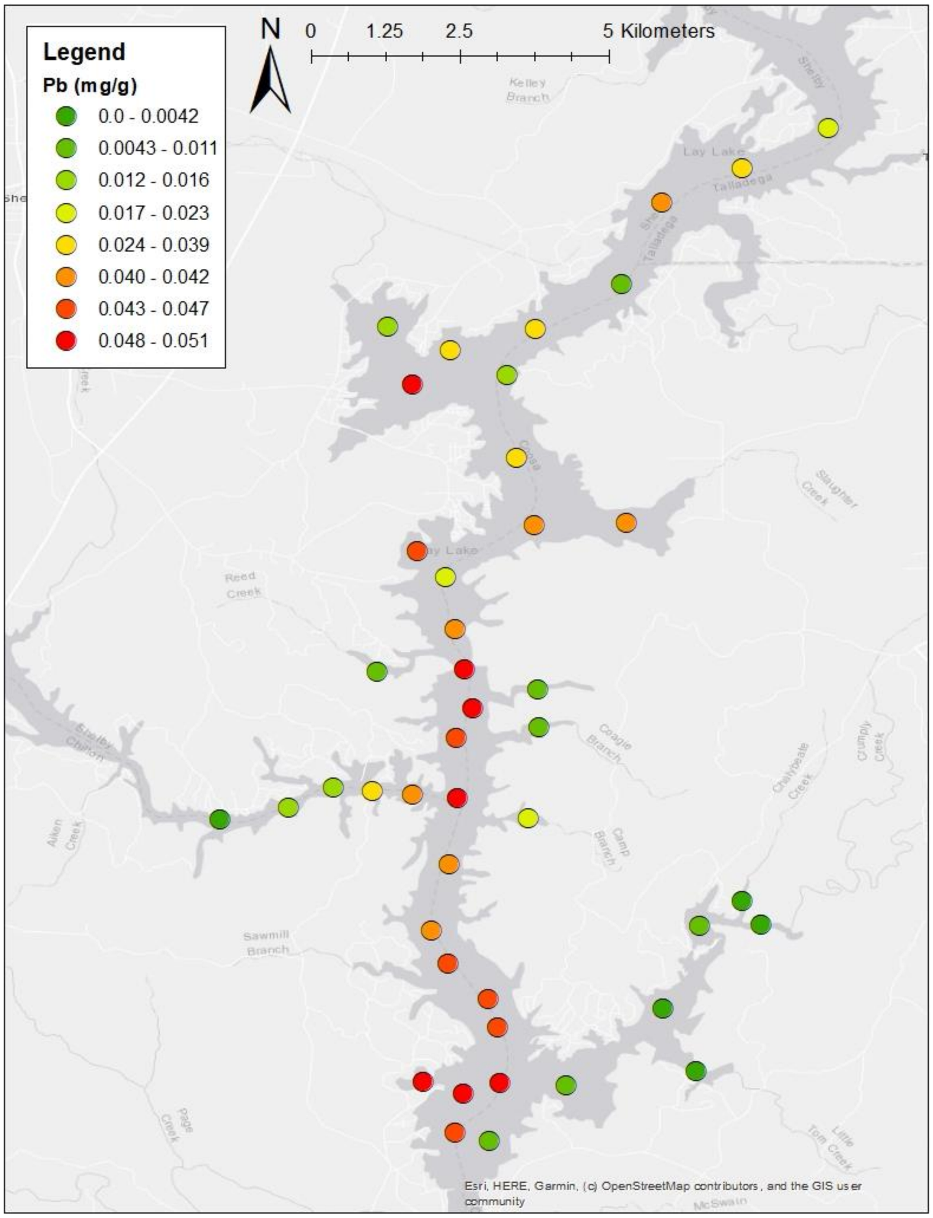


Figure 3.7. Heat map of lead (Pb) in sediment samples throughout Lay Lake. Values are reported in mg g^{-1}.

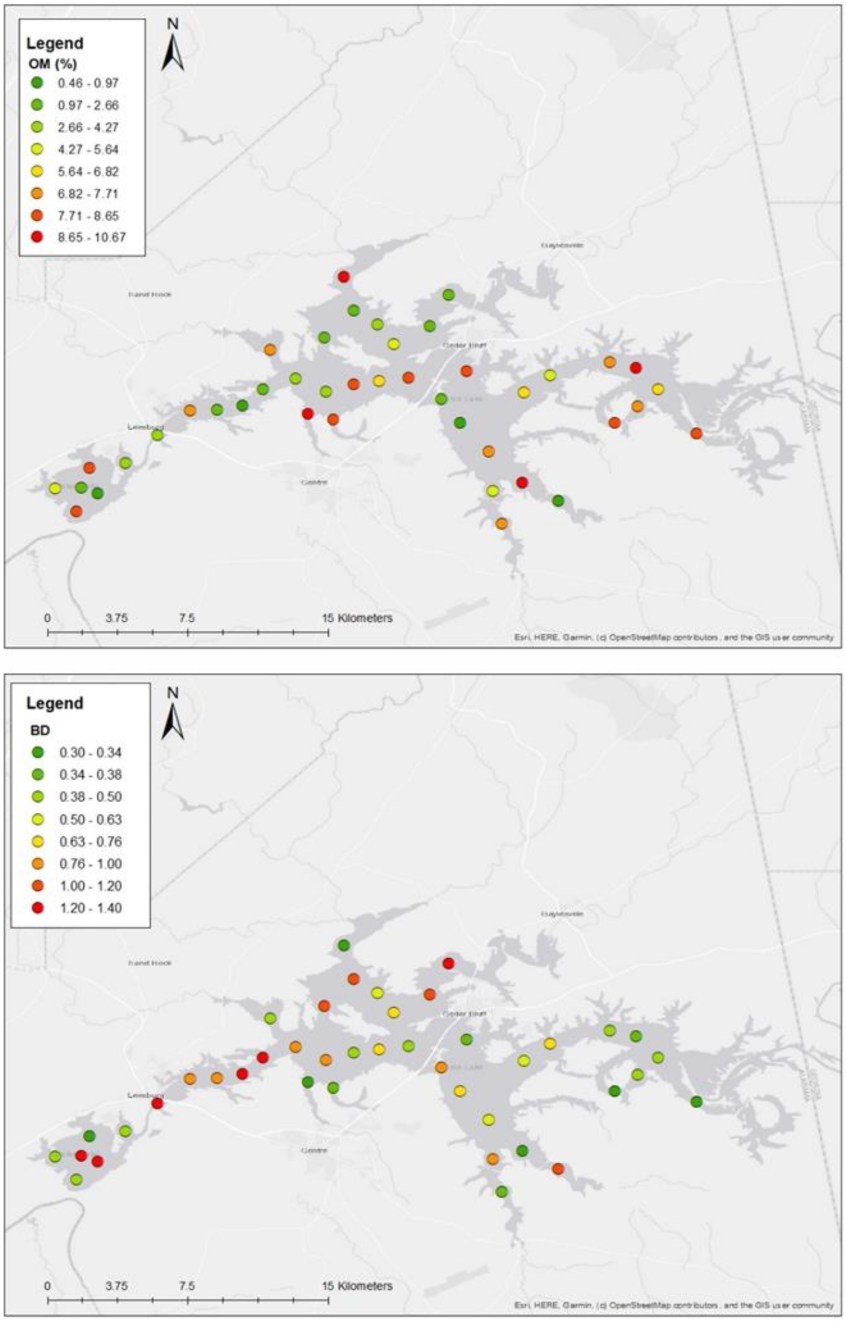


Figure 3.8. Heat maps of OM (top) and BD (bottom) in sediment samples throughout Weiss Lake. OM is reported in percent. BD is reported in g cm^{-3}.

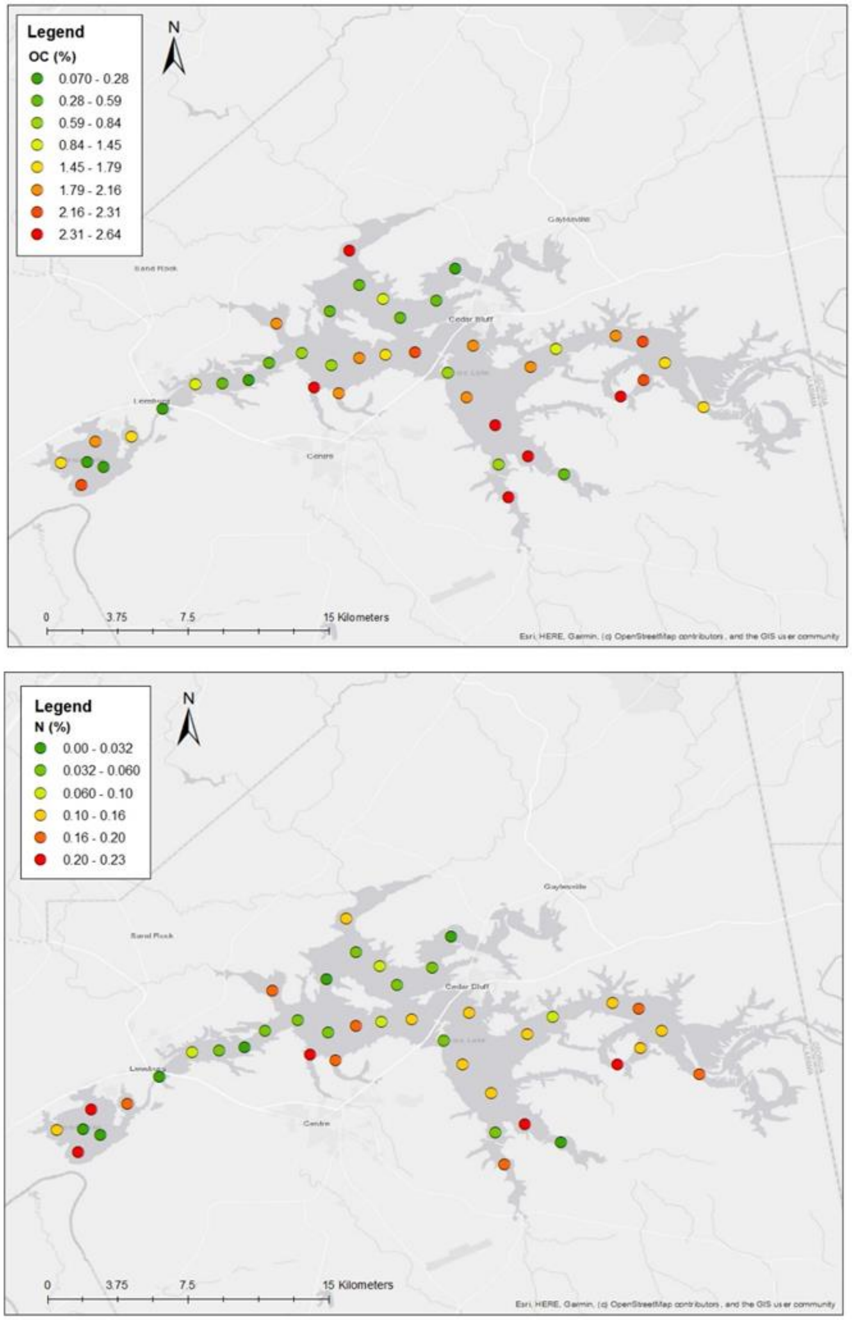


Figure 3.9. Heat maps of OC (top) and N (bottom) in sediment samples throughout Weiss Lake. Values are reported in percent.

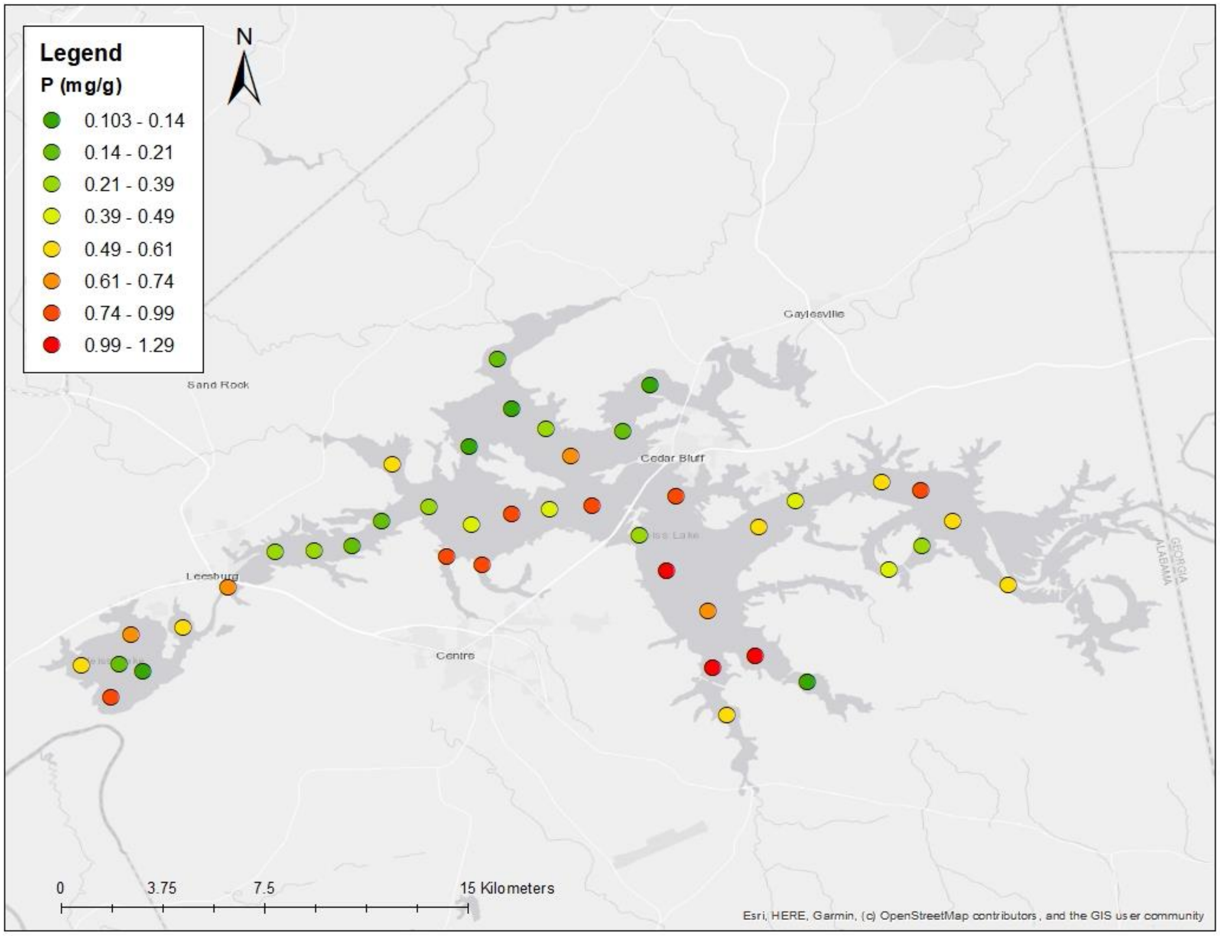
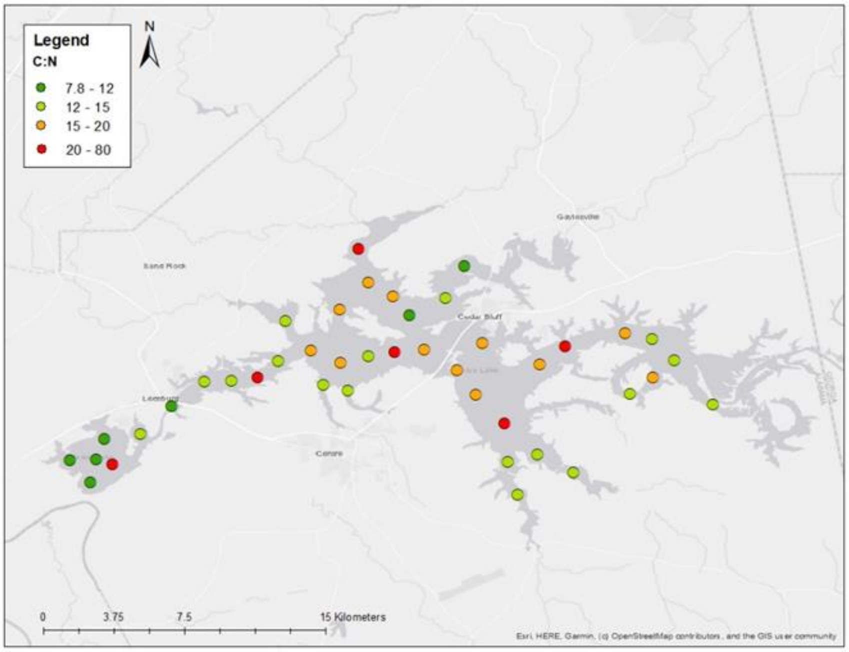


Figure 3.10. Heat map of phosphorus (P) in sediment samples throughout Weiss Lake. Values are reported in mg g^{-1}.



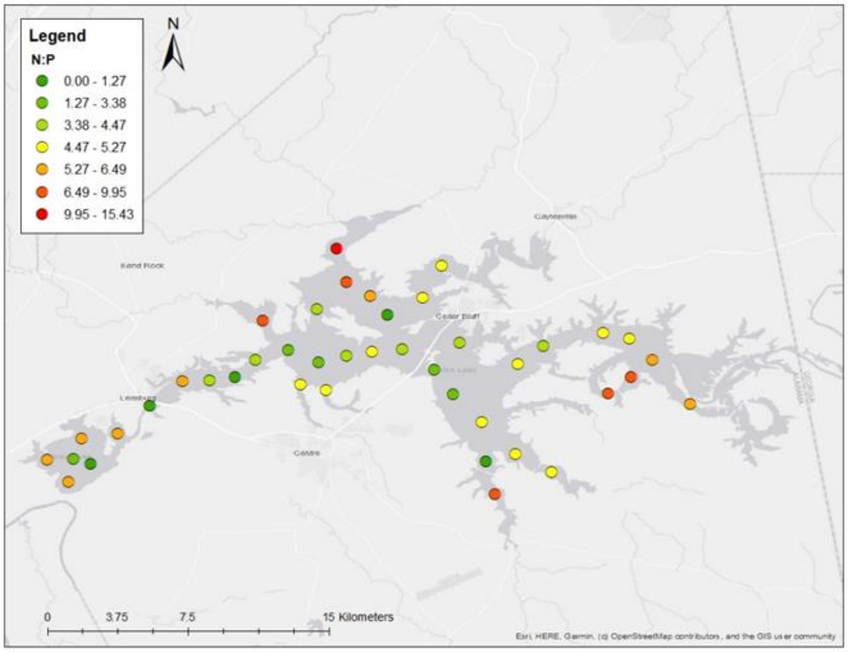


Figure 3.11. Heat maps of C:N (top) and N:P (bottom) in sediment samples throughout Weiss Lake. Values are molar ratios.

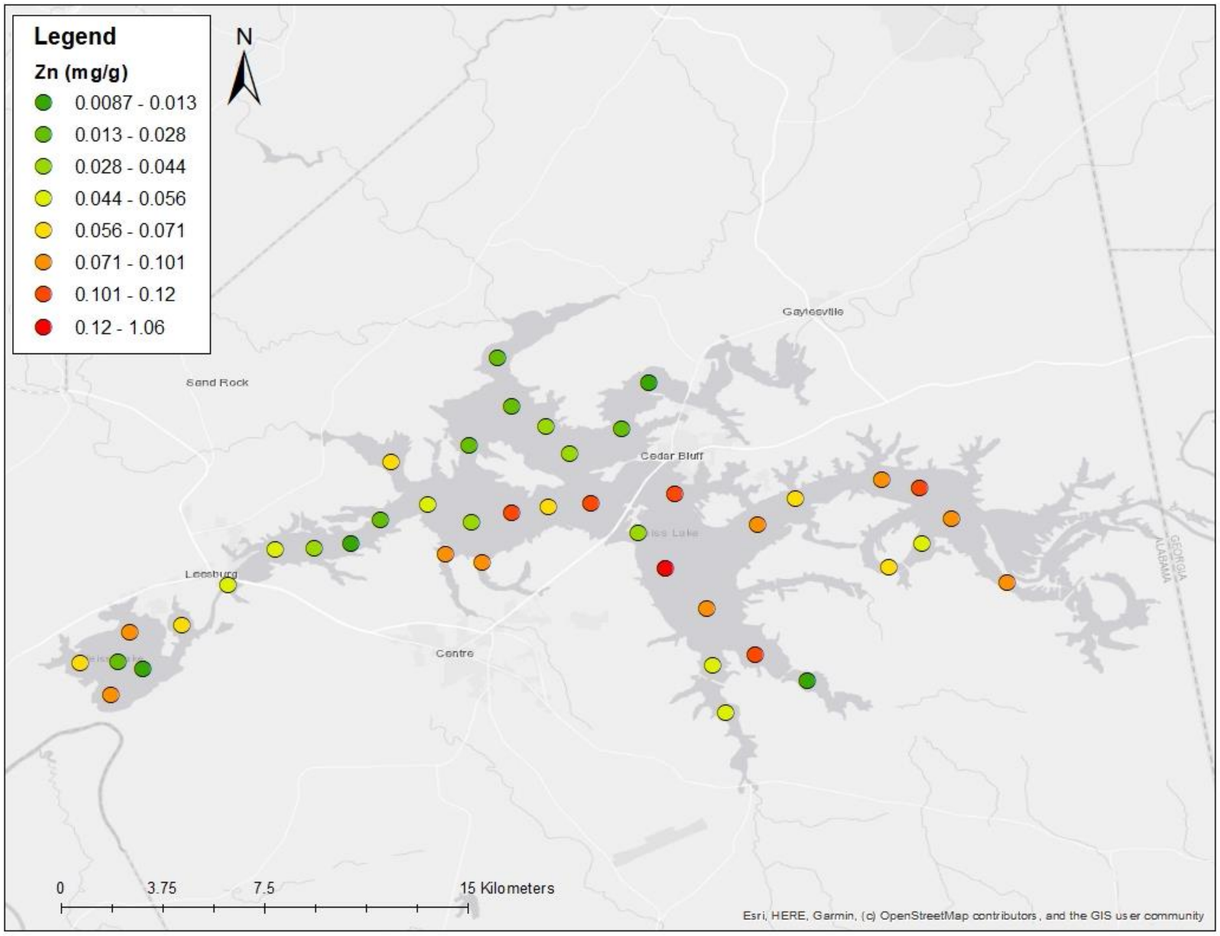


Figure 3.12. Heat map of zinc (Zn) in sediment samples throughout Weiss Lake. Values are reported in mg g^{-1}.

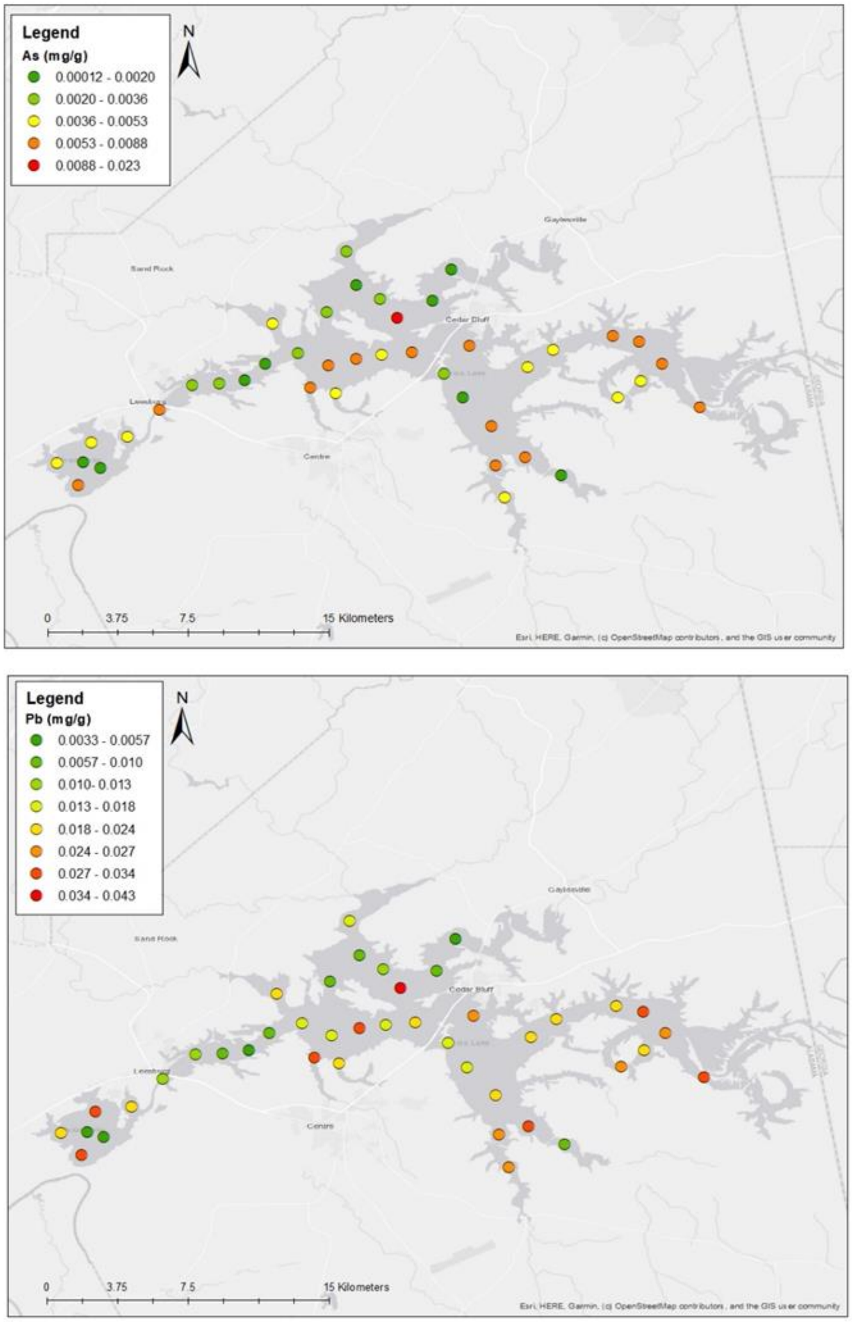


Figure 3.13. Heat maps of As (top) and Pb (bottom) in sediments throughout Weiss Lake. Values are reported in mg g^{-1}.

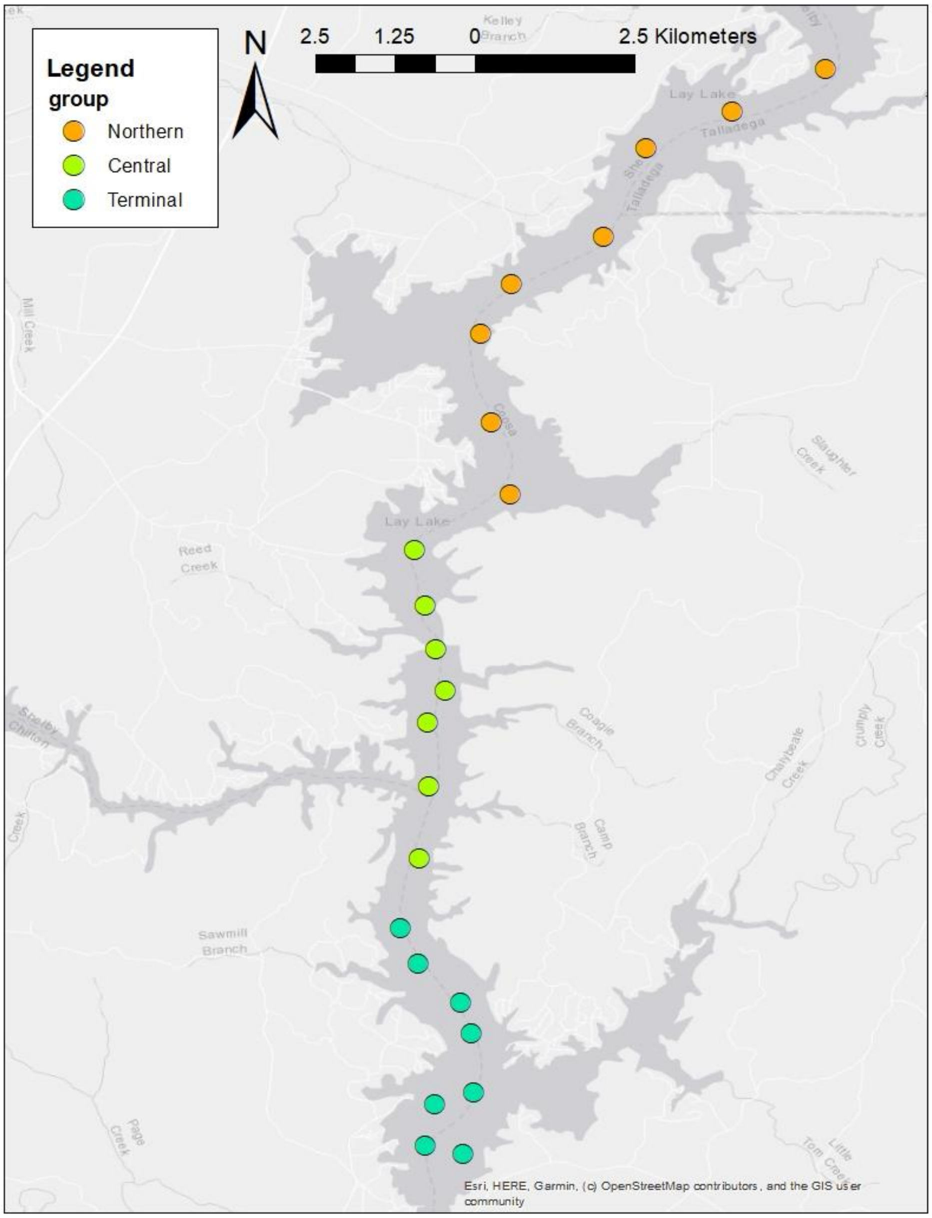


Figure 3.14. Map of Lay Lake illustrating sediment sample groupings into the 3 zones. Samples were grouped into northern (tan), central (green), and terminal (teal) zones based on Thornton et al. (1980).

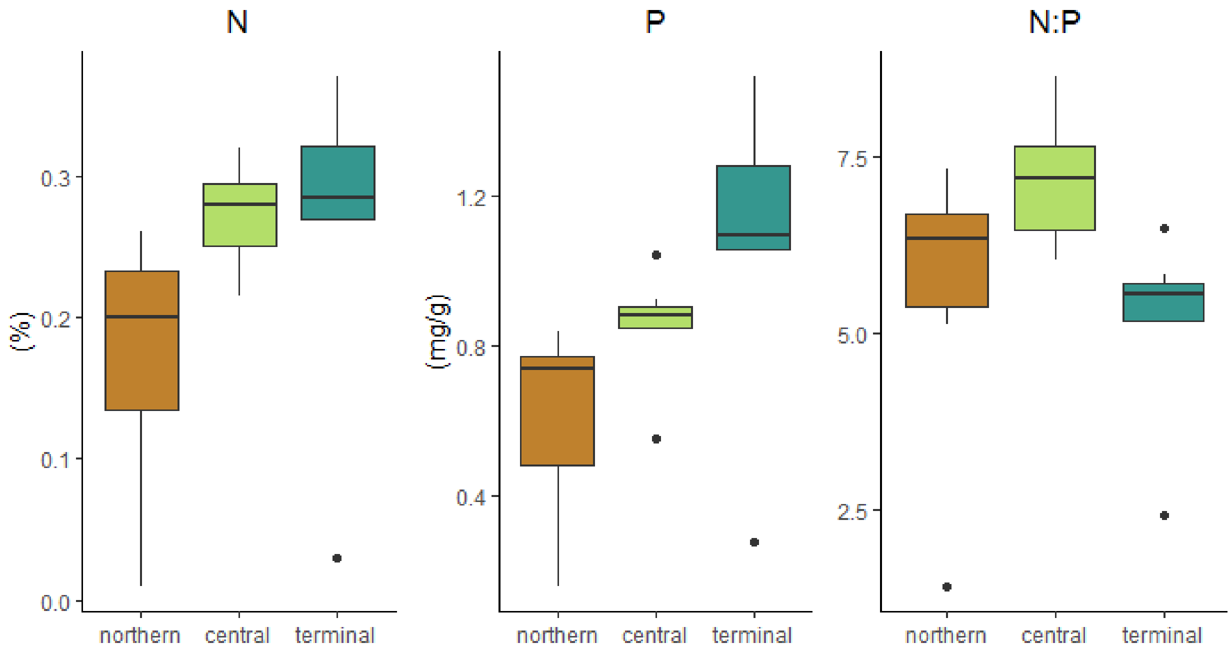


Figure 3.15. Boxplots of nitrogen (N), phosphorus (P), and N:P concentrations between sediment samples in the 3 zones in Lay Lake. N is reported in %, P is reported in mg g^{-1}, while N:P is a molar ratio of N to P.

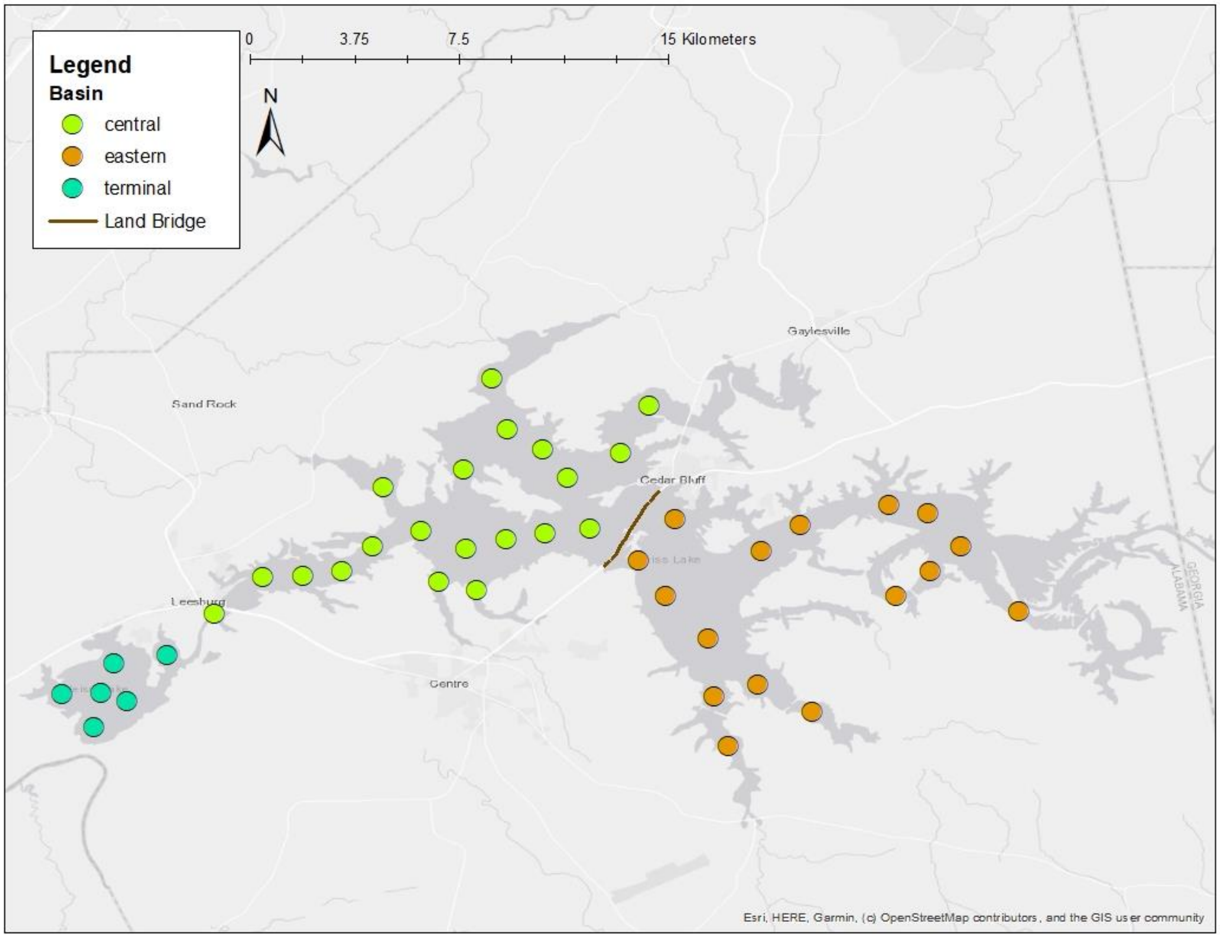


Figure 3.16. Map of Weiss Lake illustrating sediment sample groupings by basins. Samples in the eastern side were illustrated in tan, samples in the central basin were illustrated in green, while samples in the terminal basin near the dam were illustrated in teal. The brown line between the eastern and central basins is a land bridge.

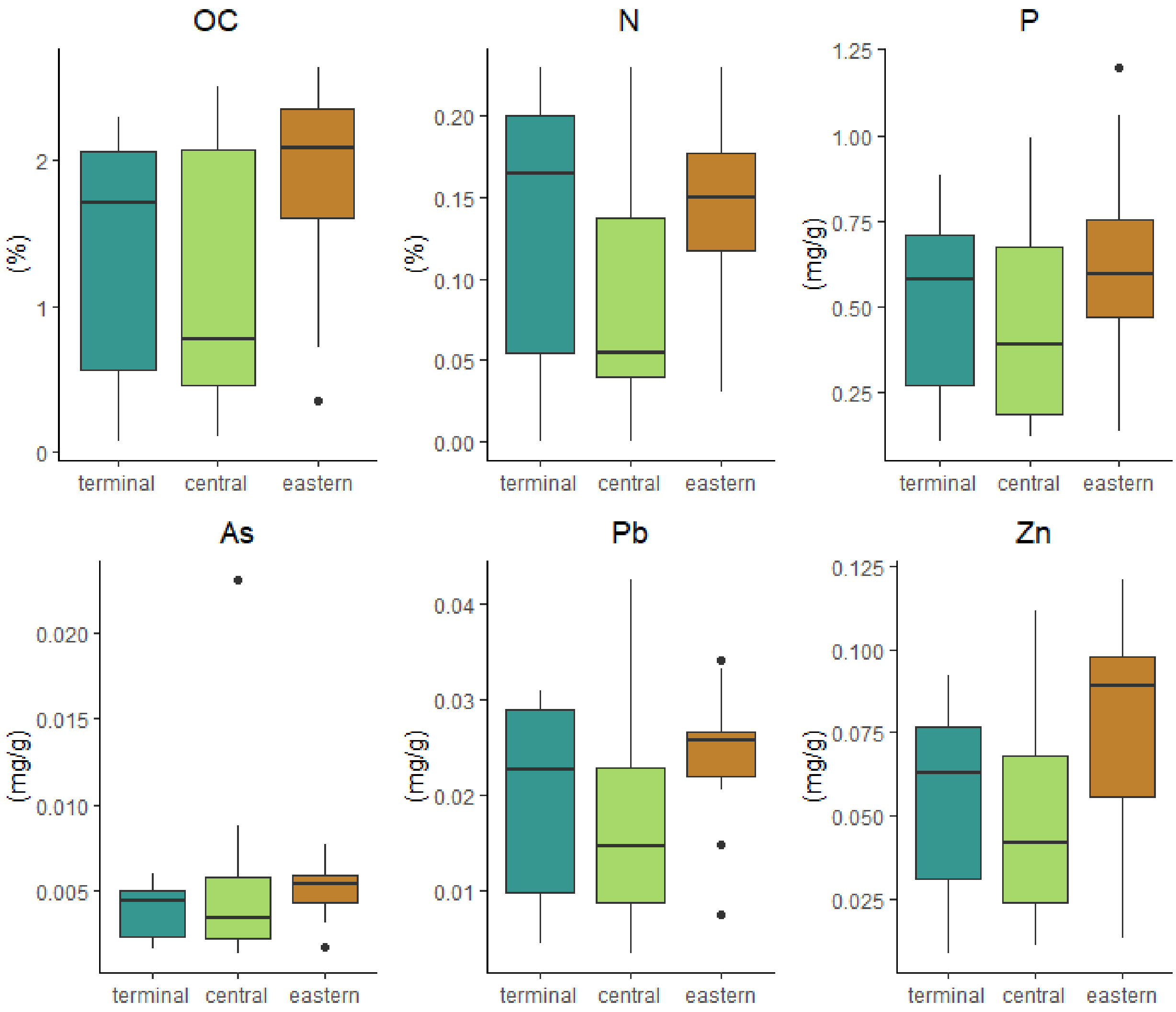


Figure 3.17. Weiss Lake box plots of nutrients and heavy metals in sediments between the 3 basins.

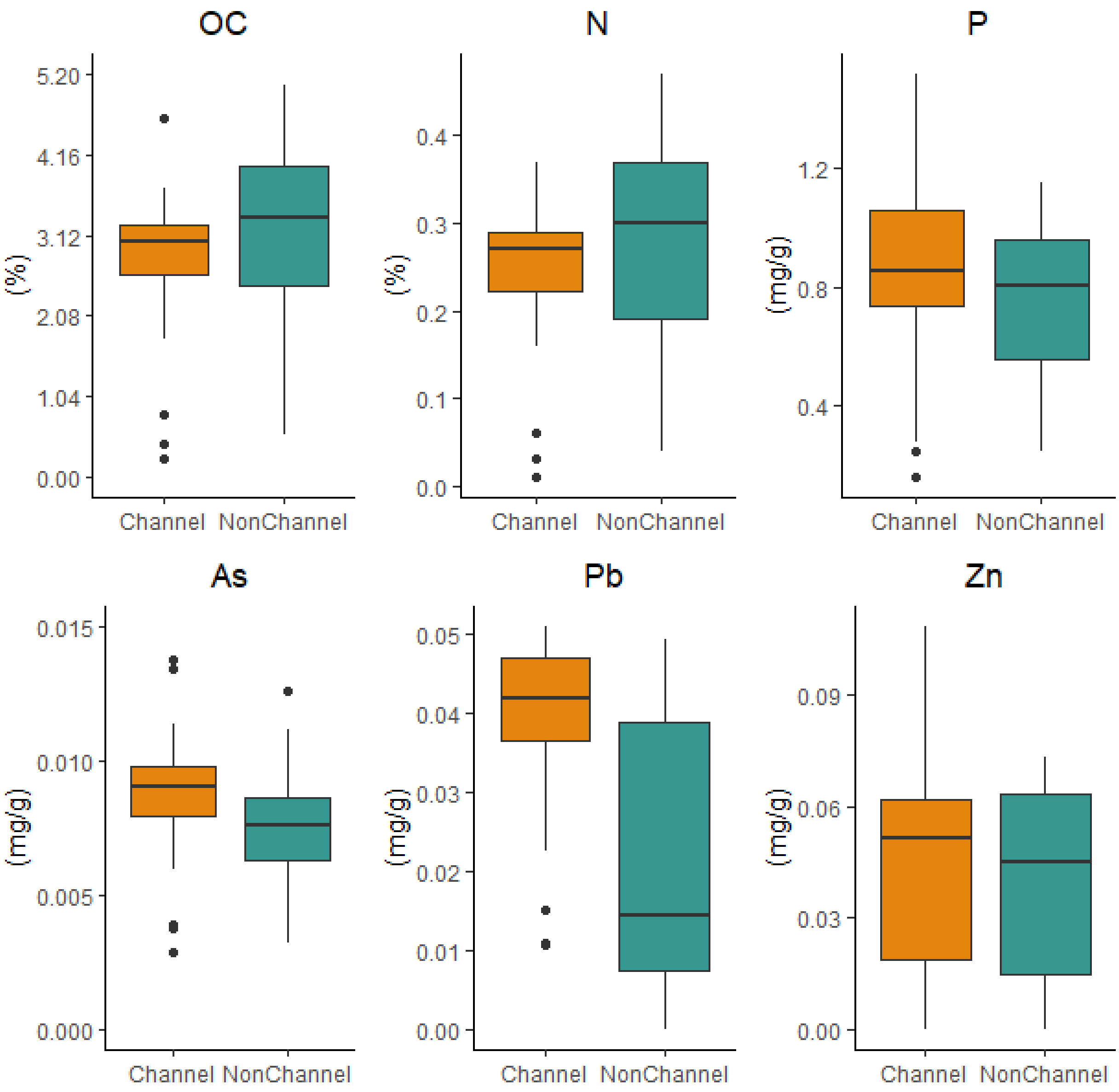


Figure 3.18. Lay Lake box plots of nutrients and heavy metals in sediment samples between channel (orange) and non-channel (teal) groupings.

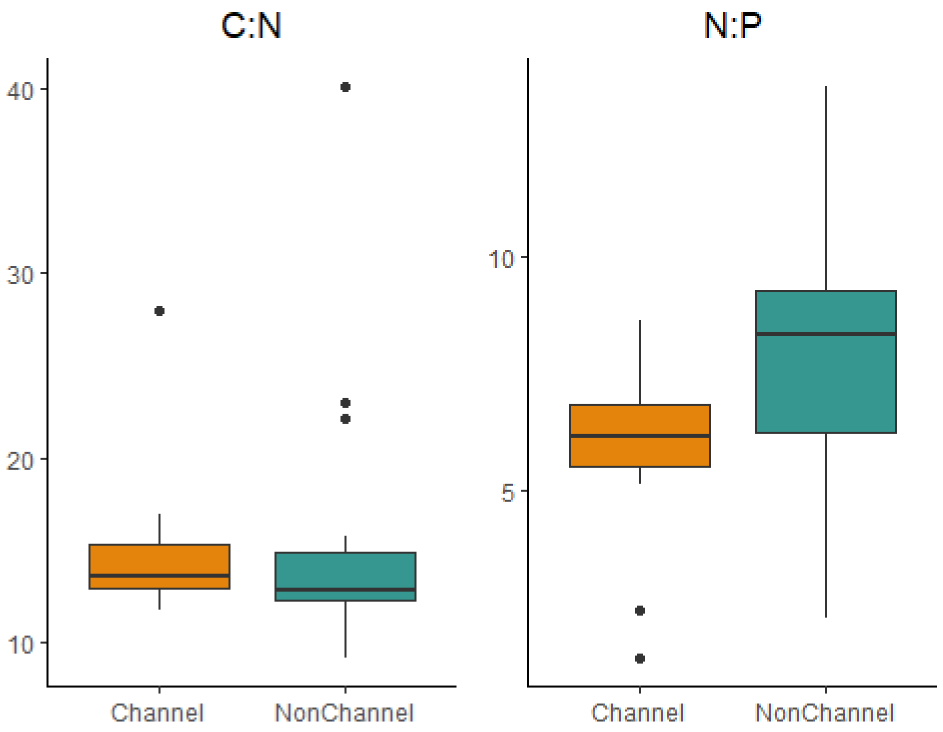


Figure 3.19. Lay Lake boxplots of C:N and N:P in sediment samples between channel (orange) and non-channel (teal) groupings.

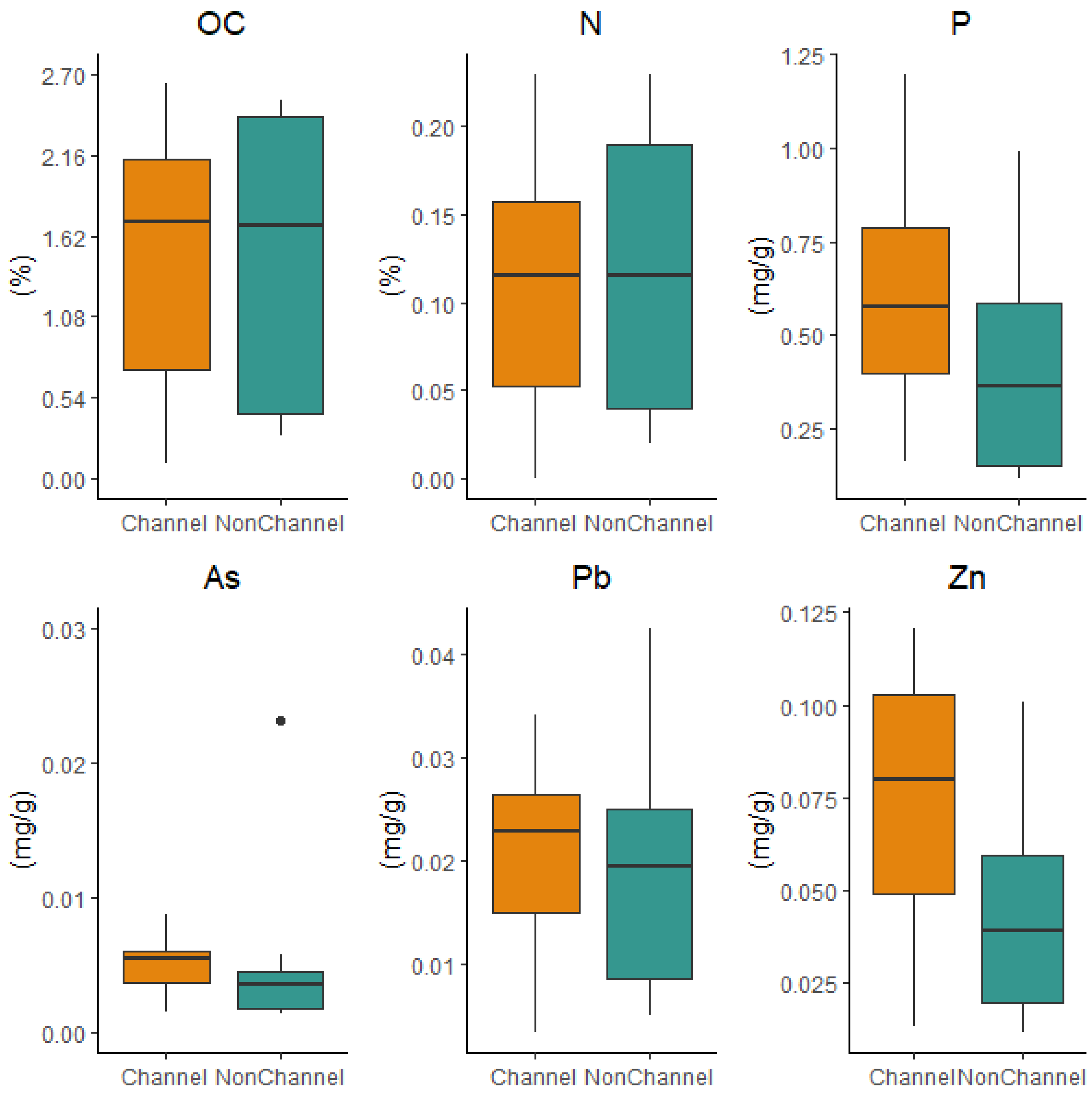


Figure 3.20. Weiss Lake box plots of nutrients and heavy metals in sediment samples between channel (orange) and non-channel (teal) groupings.

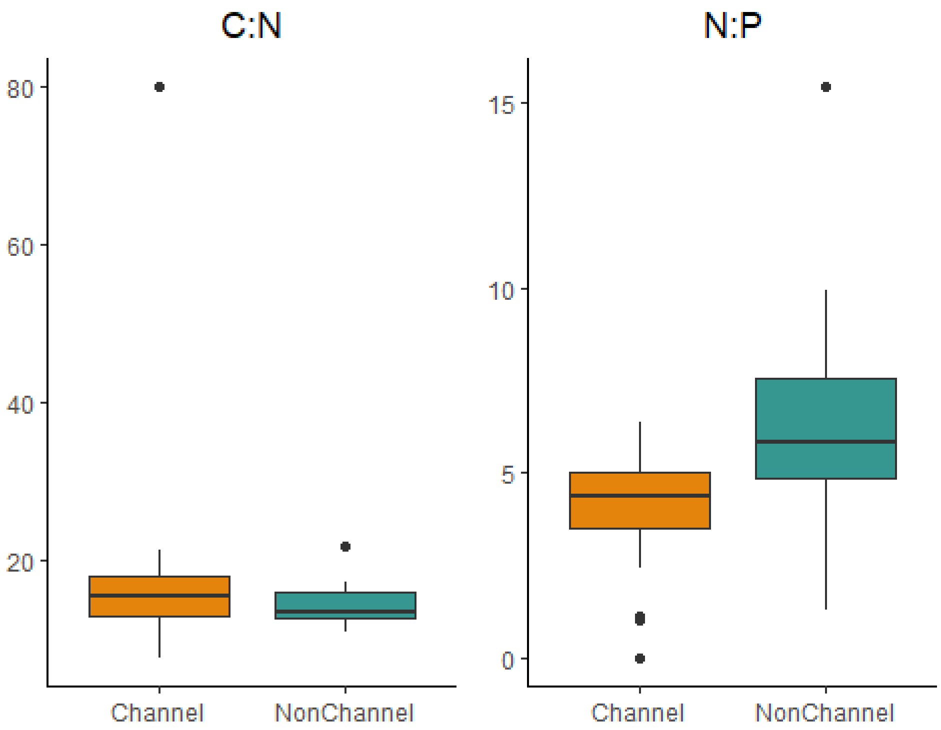


Figure 3.21. Weiss Lake box plots of C:N and N:P in sediment samples between channel (orange) and non-channel (teal) groupings.

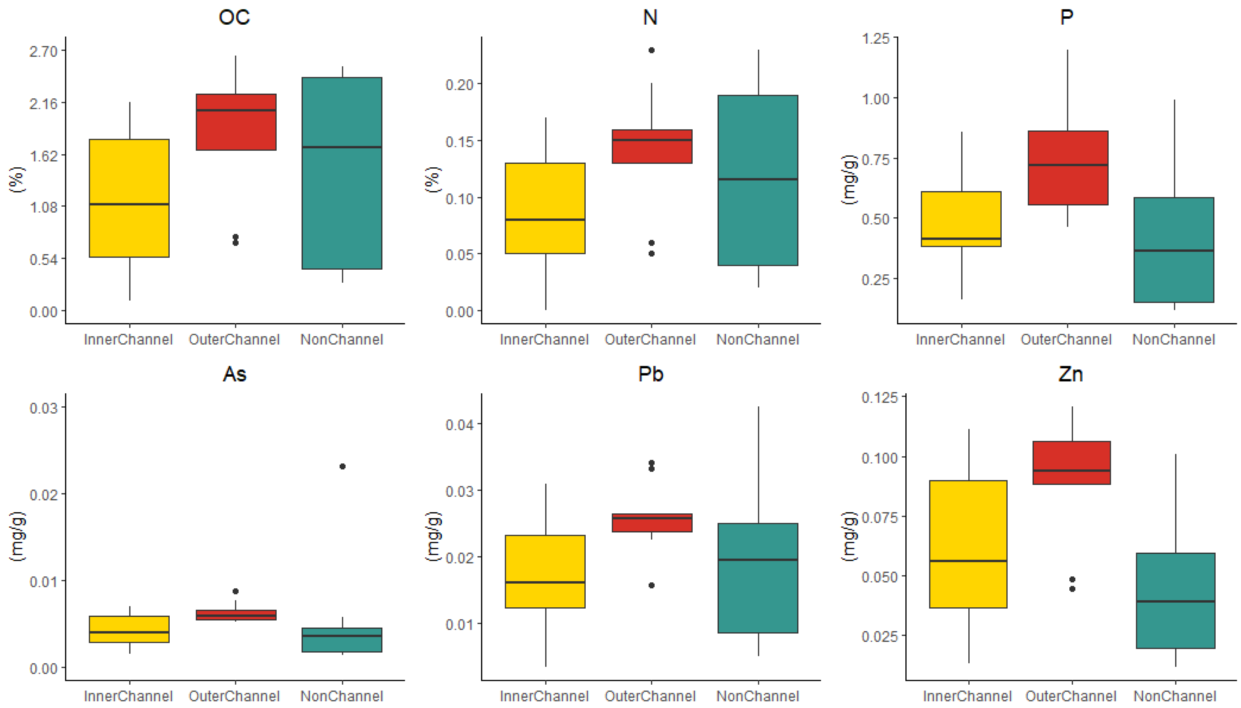


Figure 3.22. Weiss Lake box plots of nutrients and heavy metals in sediment samples between the inner channel (yellow), outer channel (red), and non-channel (teal) groupings. The outer channel region contained the highest concentration of material.

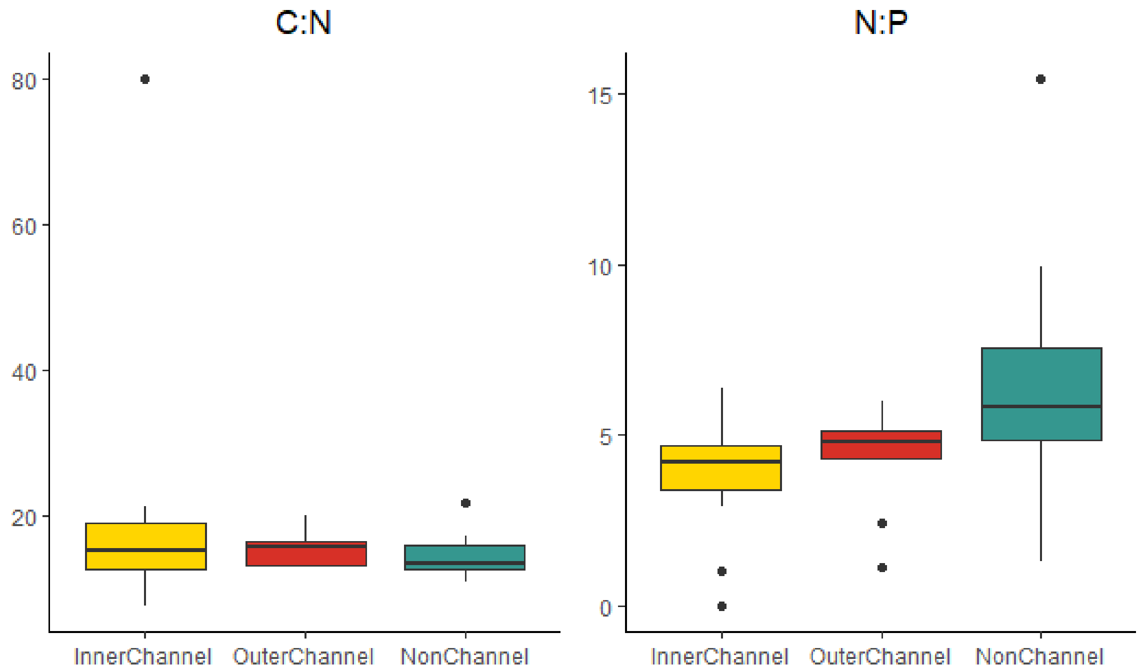


Figure 3.23. Weiss Lake box plots of C:N and N:P in sediment samples between the inner channel (yellow), outer channel (red), and non-channel (teal) groupings. The non-channel region consisted mainly of coves and yielded the highest N:P values.

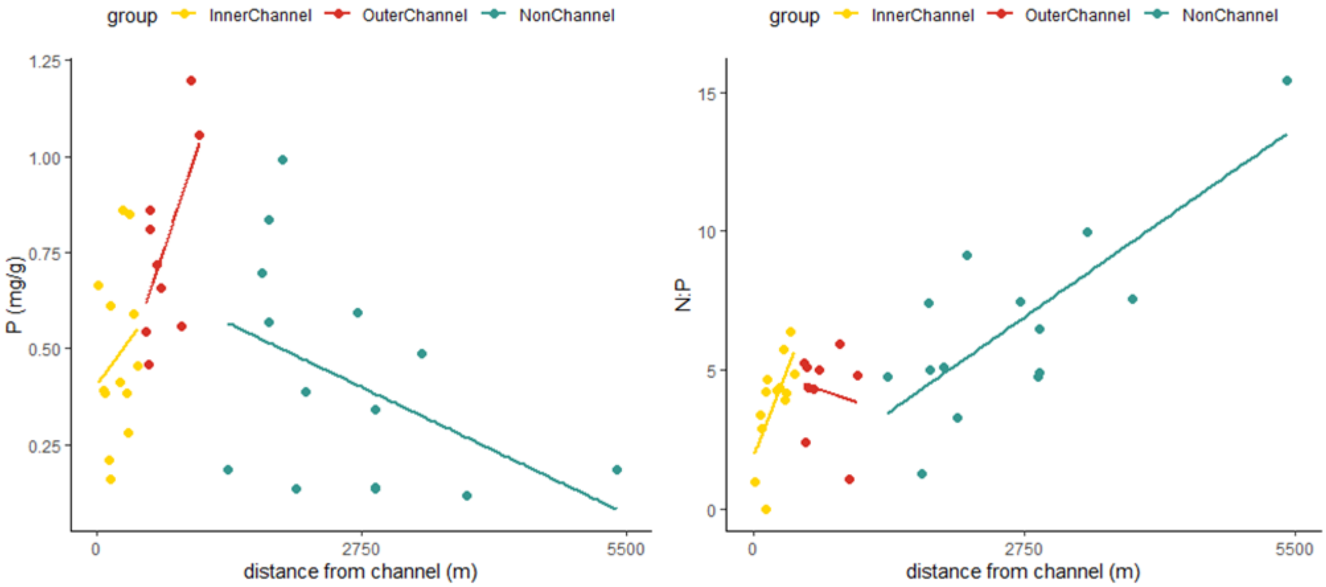


Figure 3.24. Weiss Lake scatter plot of P (left) and N:P (right) concentrations between the inner channel (yellow), outer channel (red), and non-channel (teal) groupings. Sediment groups were based on proximity to the river channel.

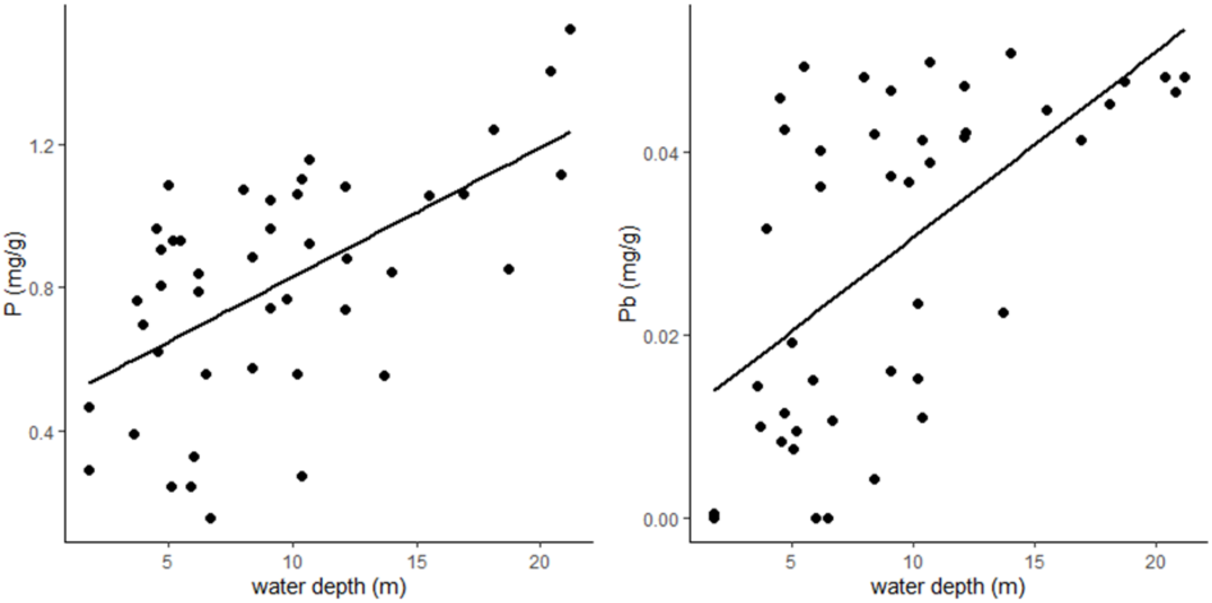


Figure 3.25. Lay Lake scatter plots of P vs. water depth (left) and Pb vs. water depth (right). Notice the 2 clusters of points on the Pb vs. water depth plot.

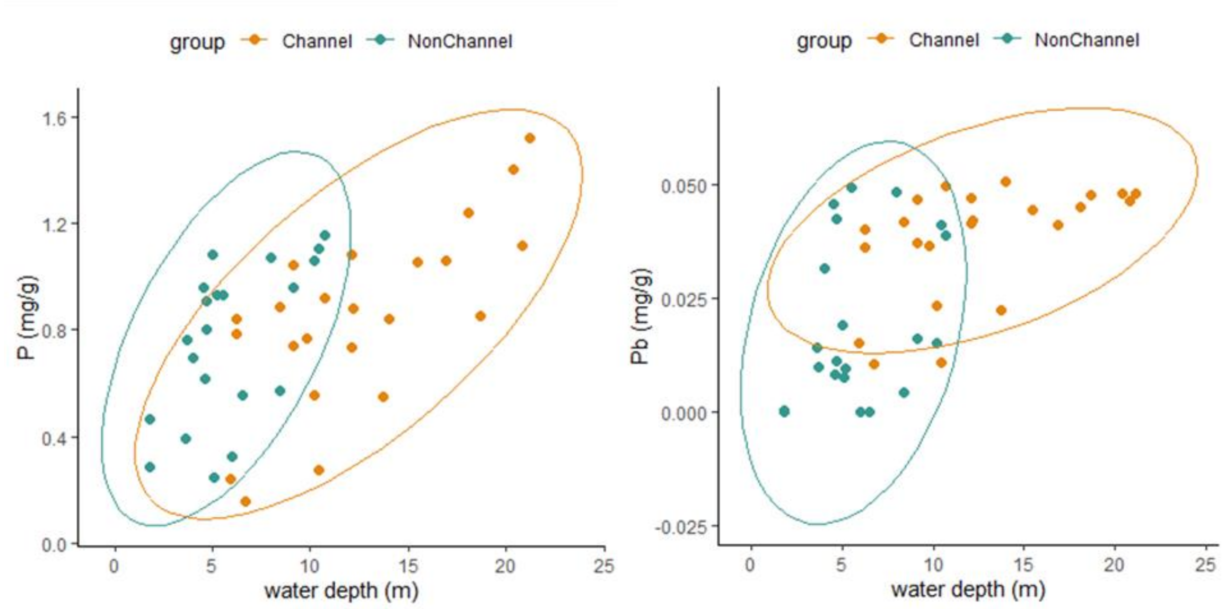


Figure 3.26. Lay Lake scatter plots of P vs. water depth (left) and Pb vs. water depth (right). Samples are split into channel (orange) and non-channel (teal) groupings. Ellipse represents 1 standard deviation.

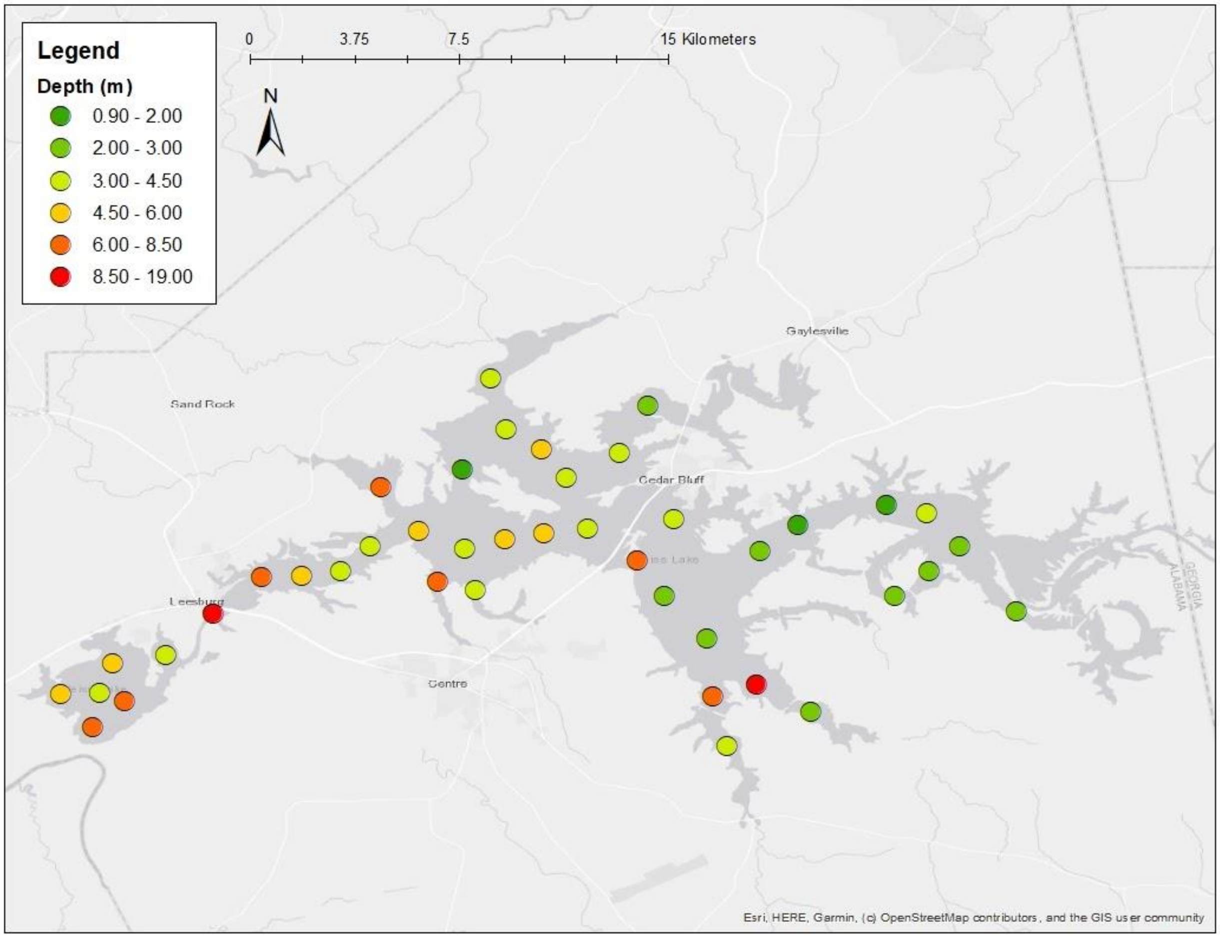
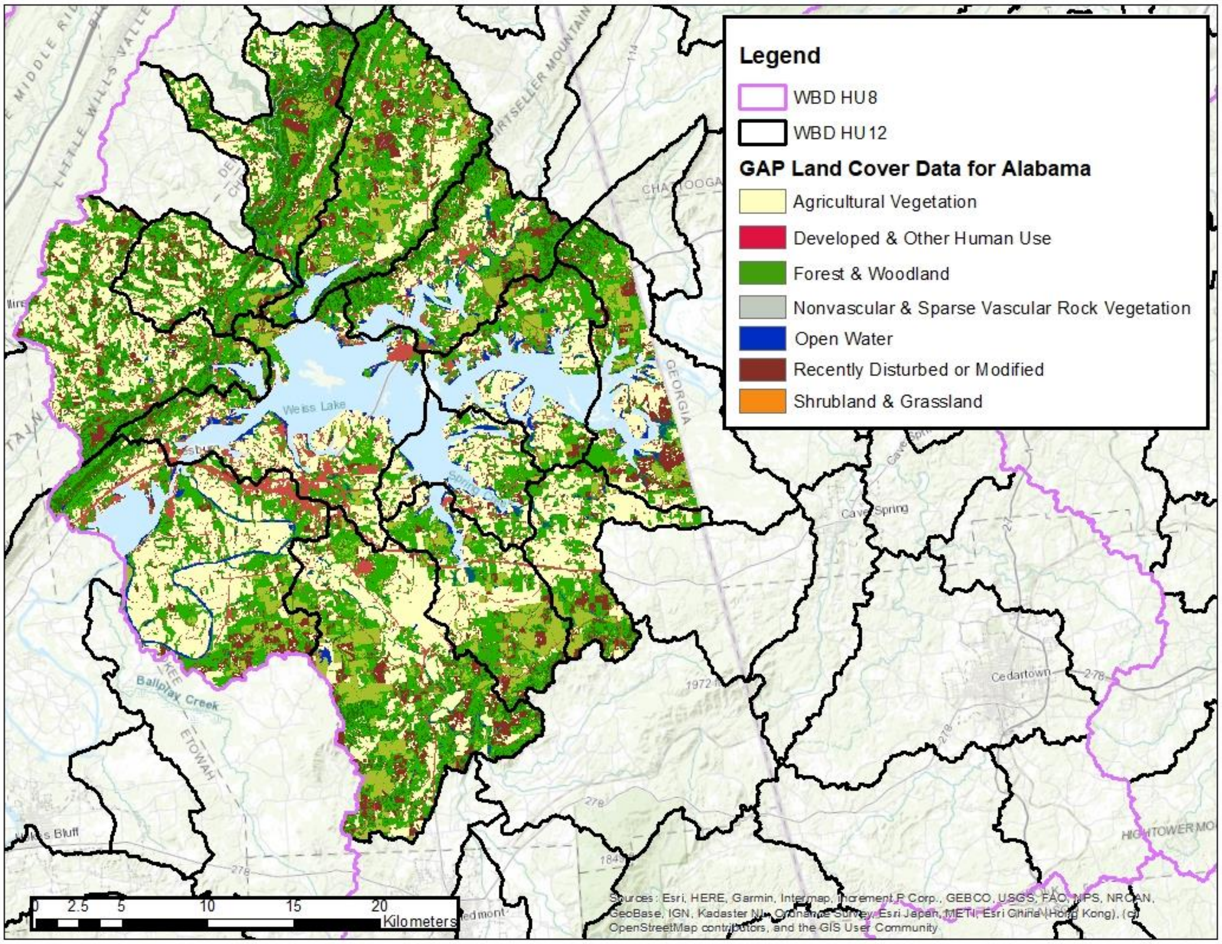


Figure 3.27. Weiss Lake map showing water depths at sample collection sites. Depths are reported in meters (m).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.28. Land use immediately surrounding Weiss Lake. Chosen watersheds with hydraulic unit code 12 were determined based on proximity to the lake and were clipped to the GAP Land Cover Data set to determine land use types for the northern and southern portions of the lake. The northern watershed contained 27% agriculture, 56% forest, 7% developed, and 9% recently disturbed lands, while the southern watershed contained 39% agriculture, 43% forest, 7% developed, and 9% recently disturbed lands.

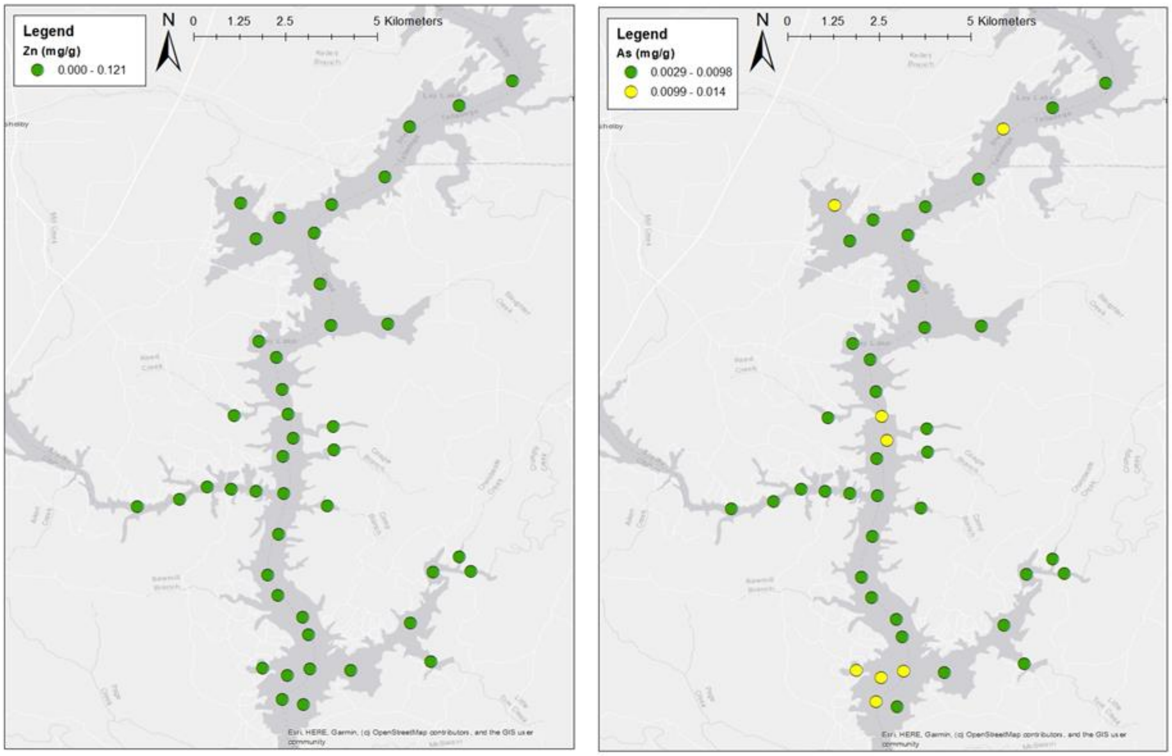


Figure 3.29. Sediment toxicity guidelines from Macdonald et al. (2000) applied to Lay Lake surface sediment. Zn (left) was completely under the threshold effects concentration (TEC) for Zn toxicity, while As (right) was slightly above the TEC in some samples. Concentrations were considered relatively safe to benthic organisms.

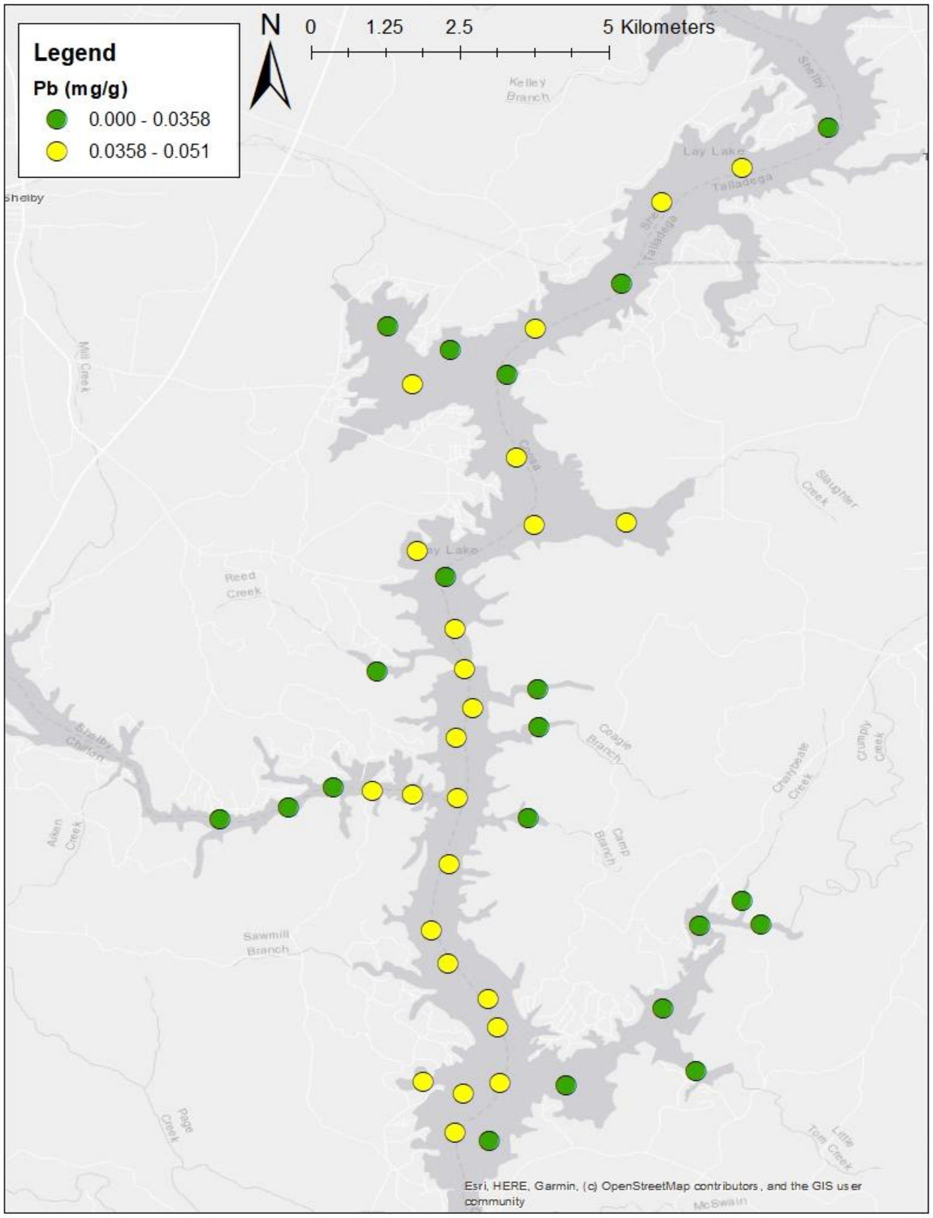


Figure 3.30. Sediment toxicity guidelines from Macdonald et al. (2000) applied to Lay Lake surface sediment. Pb was generally below the TEC in coves, but was often above the TEC in channel samples. These values never reached the probable effects concentration (PEC), therefore these values are only moderately concerning for benthic organisms.

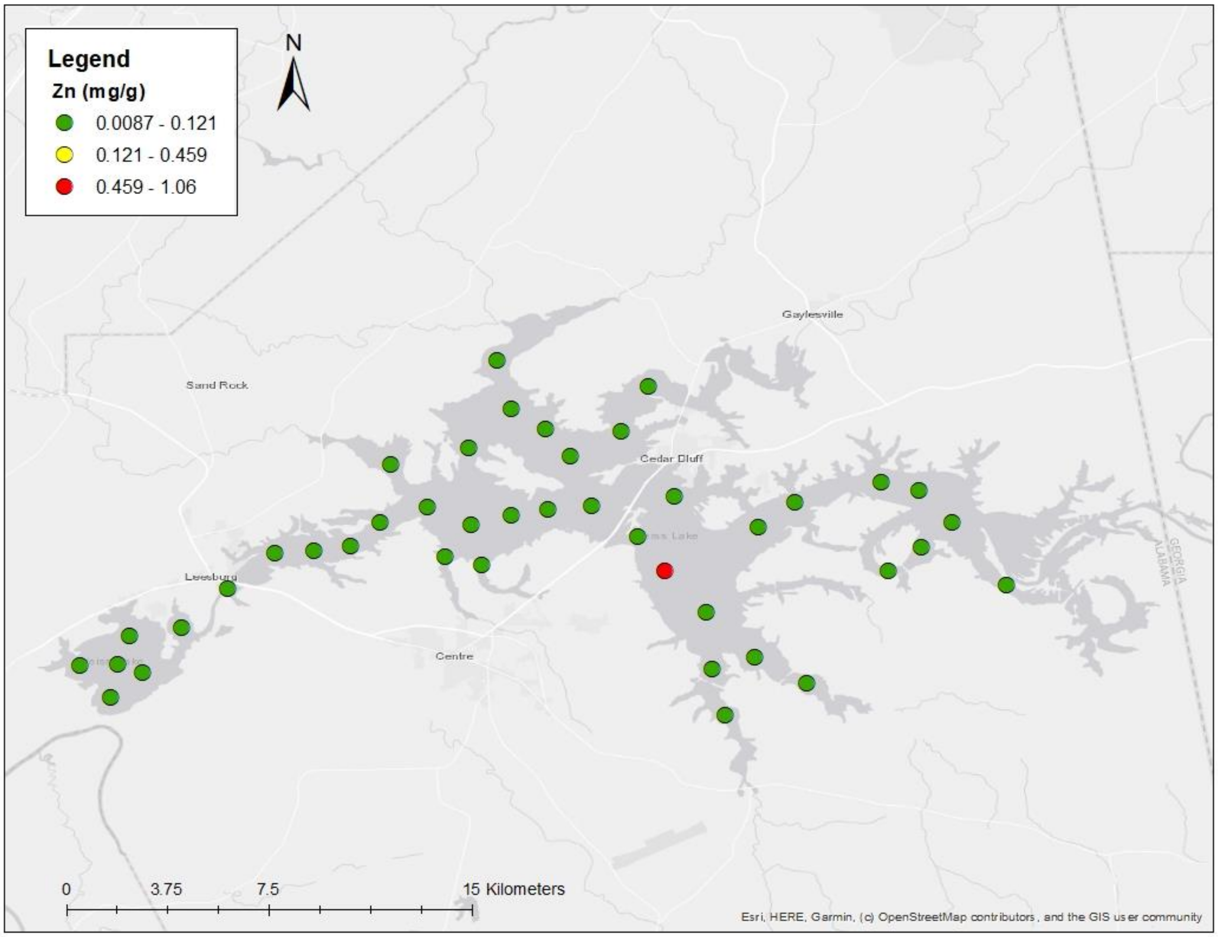


Figure 3.31. Sediment toxicity guidelines from Macdonald et al. (2000) applied to Weiss Lake surface sediment. All but one of the samples were below the TEC for Zn. The one red sample was above the PEC making it dangerous for benthic organisms in this region.

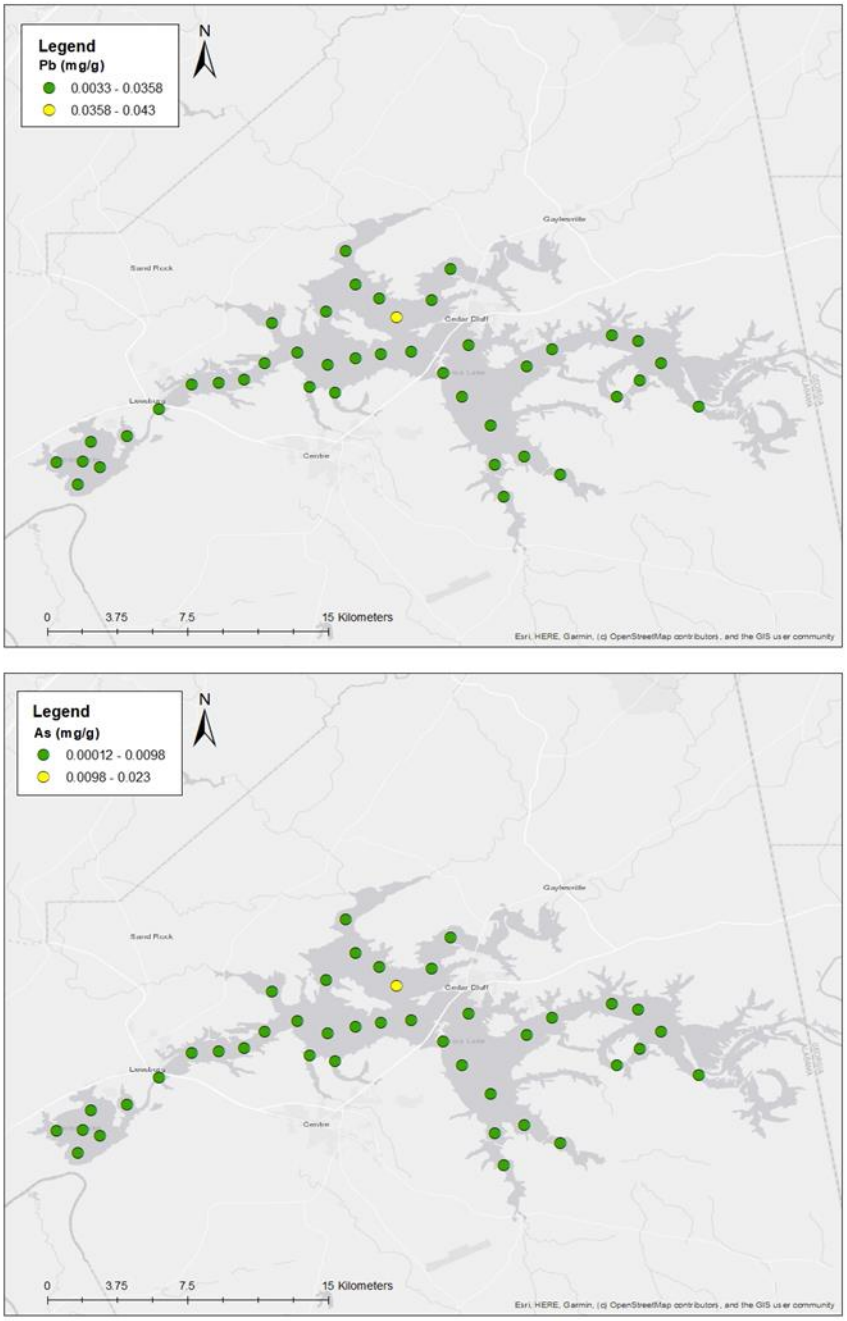


Figure 3.32. Sediment toxicity guidelines from Macdonald et al. (2000) applied to Weiss Lake surface sediment. Only one of the samples was above the TEC for Pb (top) and As (bottom). This location (yellow circle) is where mud was lacking and reddish granules were found. Green samples on the map are considered extremely safe for benthic organisms.

Appendix

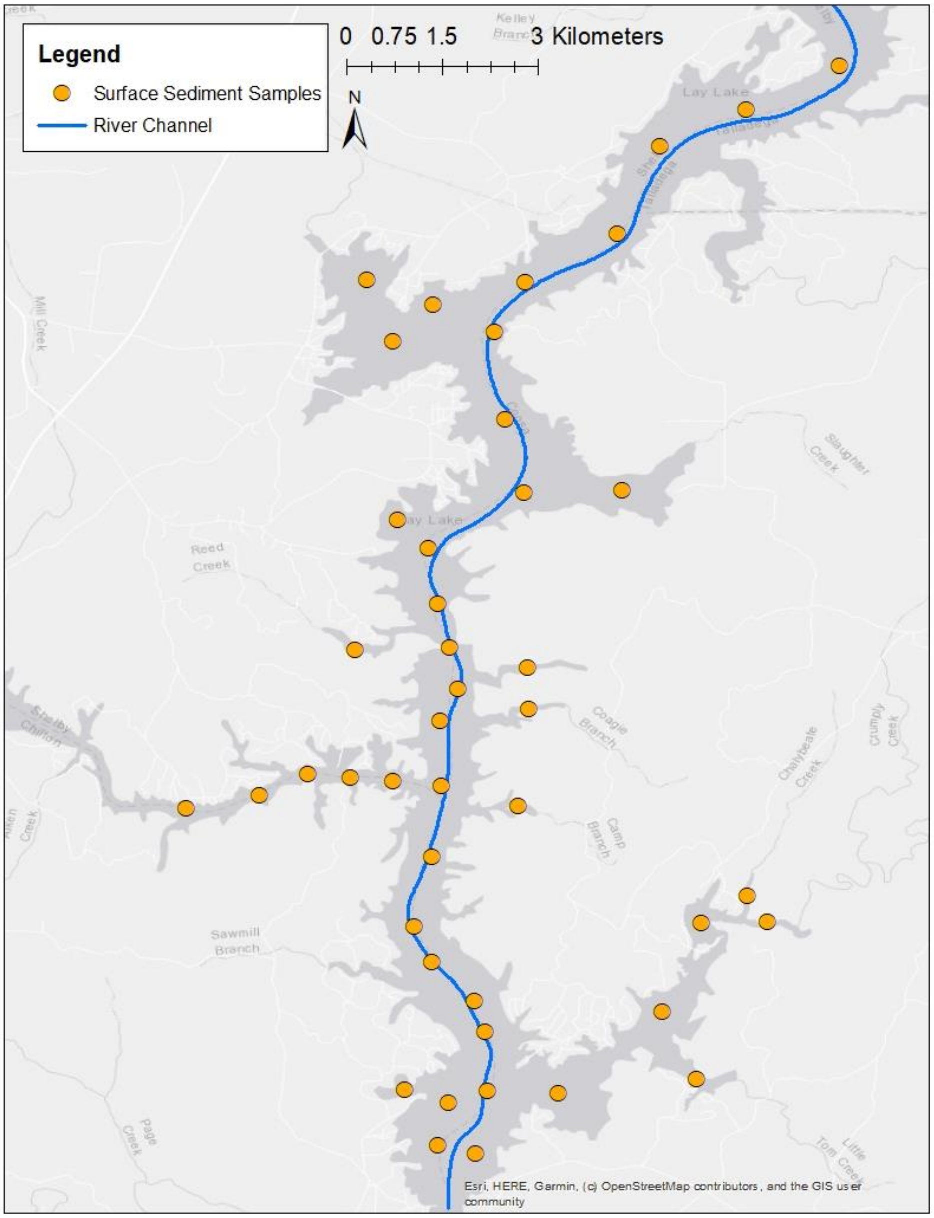


Figure A.1. Map of Lay Lake illustrating the perennial river channel (blue) and samples sites (tan).

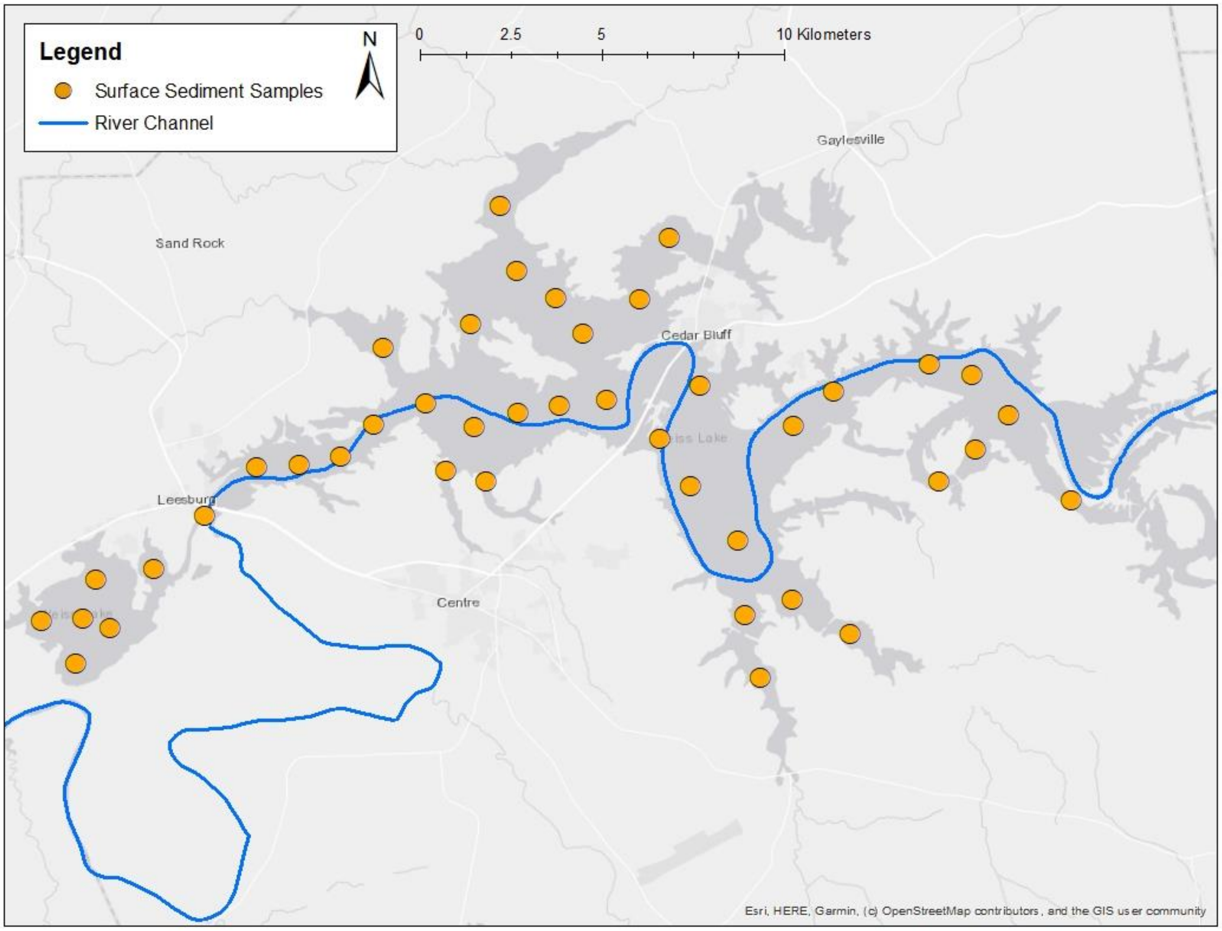


Figure A.2. Map of Weiss Lake illustrating the perennial river channel (blue) and samples sites (tan). Notice the river channel exits Weiss Lake through a spillway, not the dam. Distance from sample sites to the channel center was calculated in ArcMap 10.7.1 using the Near tool.

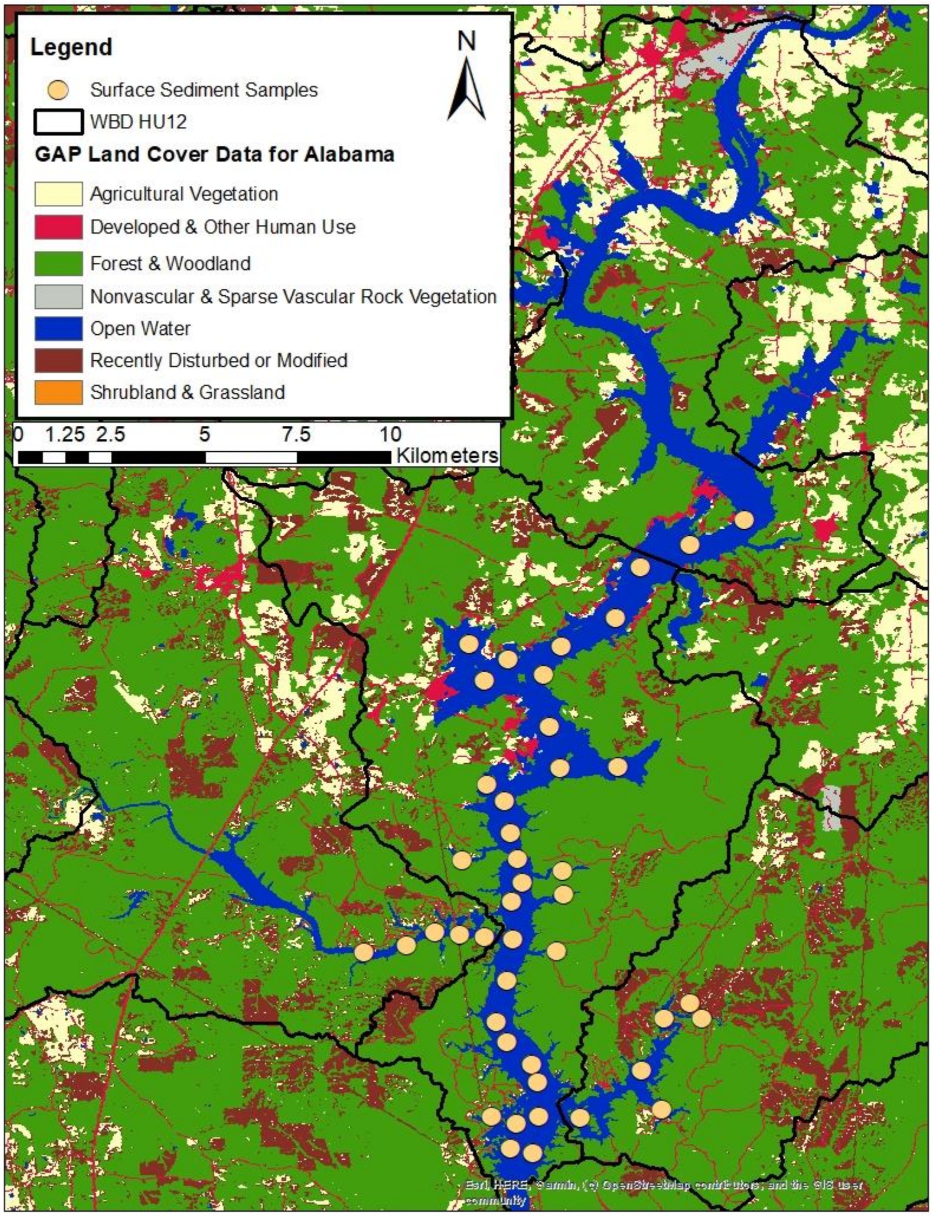


Figure A.3. Map of Lay Lake and the surrounding land use. Watersheds with the hydraulic unit code 12 are indicated by black lines, samples sites are indicted by tan circles. Land use data is GAP Land Cover Data for the State of Alabama.

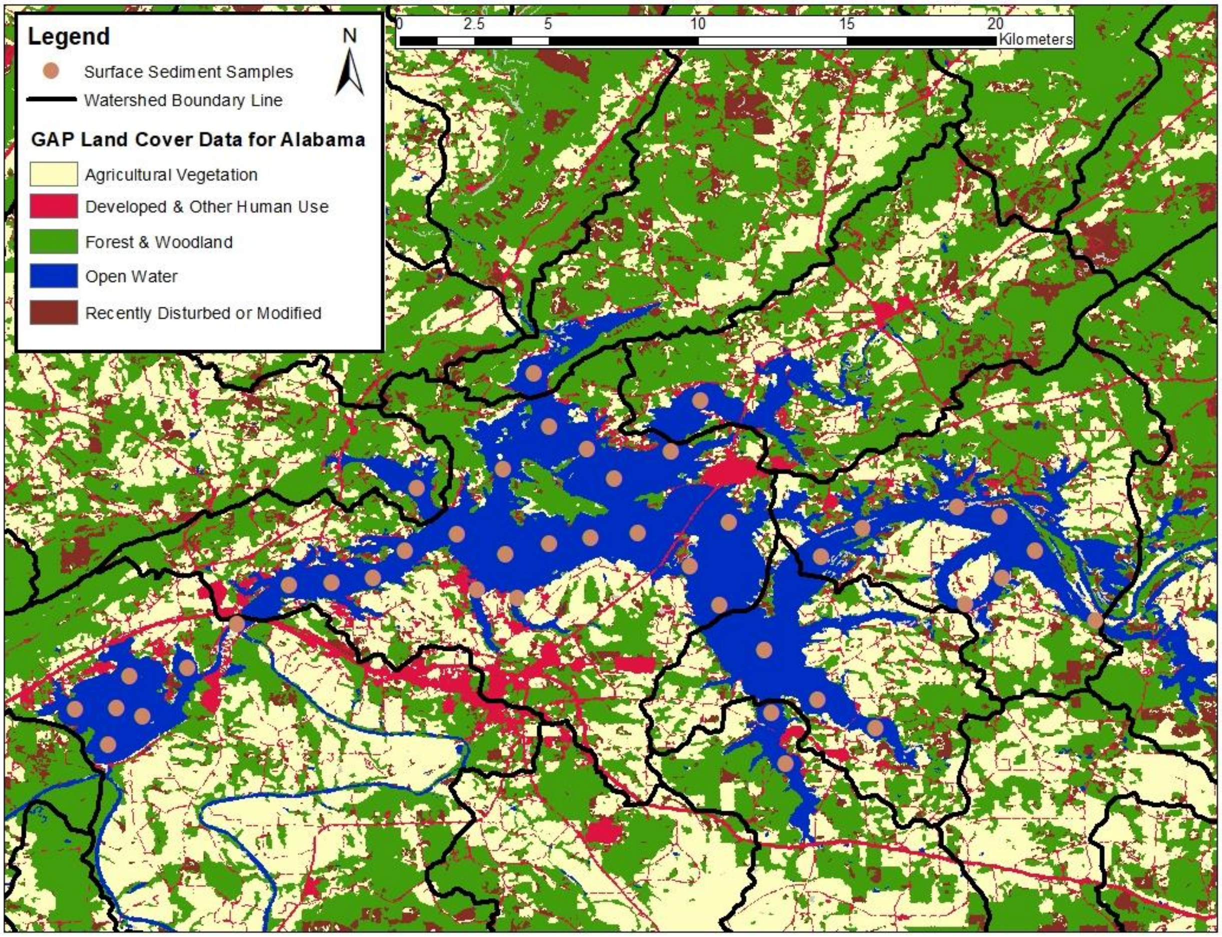


Figure A.4. Map of Weiss Lake and the surrounding land use. Watersheds with the hydraulic unit code 12 are indicated by black lines, samples sites are indicted by tan circles. Land use data is GAP Land Cover Data for the State of Alabama.

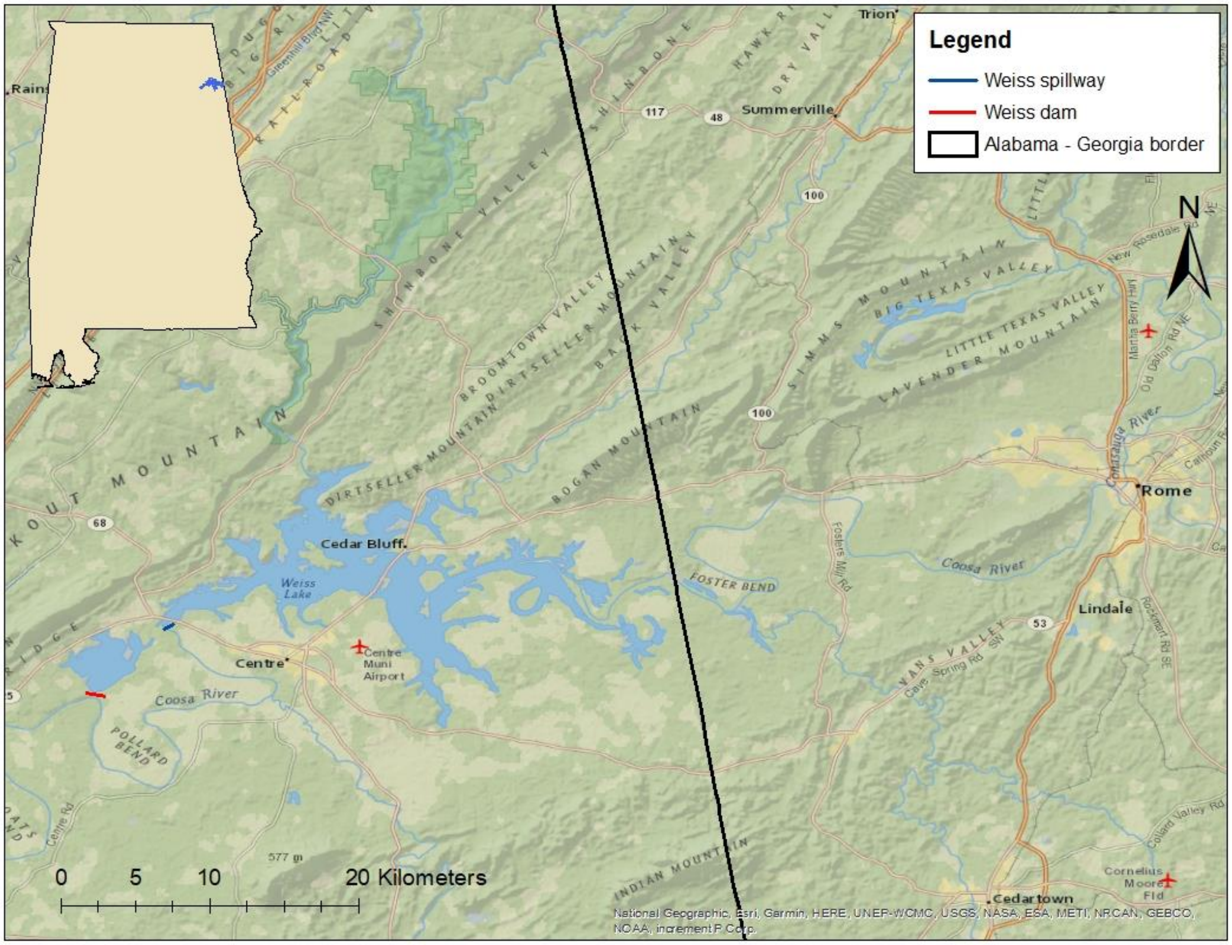


Figure A.5. Map of Weiss Lake showing its proximity to Rome, Georgia an urban and industrialized city where the Coosa River begins. The spillway is shown in blue and Weiss dam is shown in red.

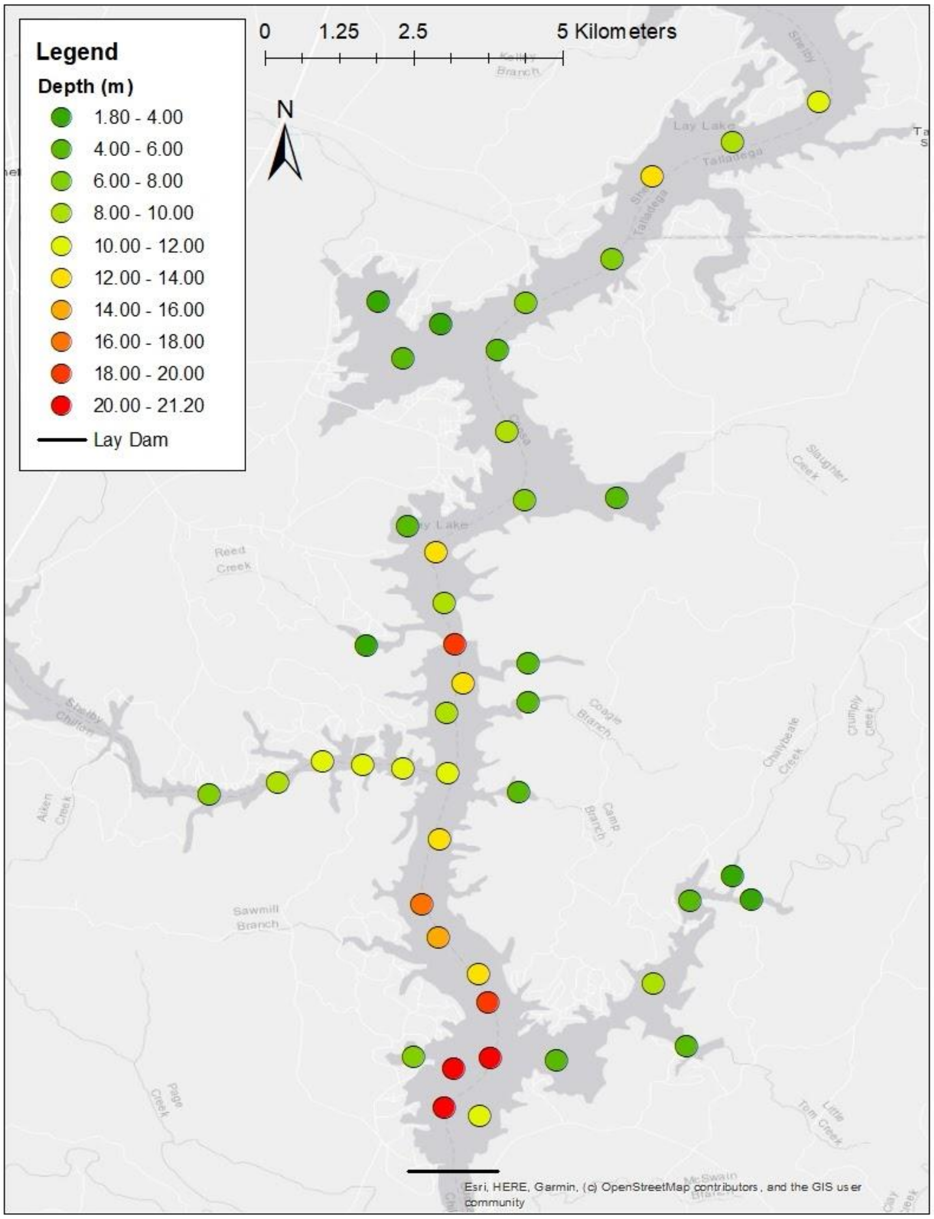


Figure A.6. Map of Lay Lake depicting water depth at sample sites. Depth is reported in meters (m). Lay dam is indicated by a black line.

Figure A.7. Area near Lay dam that contained new pine growth and is a possible prescribed fire area.

Figure A.8. Sample 16 from Weiss Lake. Residue from granules were extremely high in iron and other heavy metals, including As and Pb.

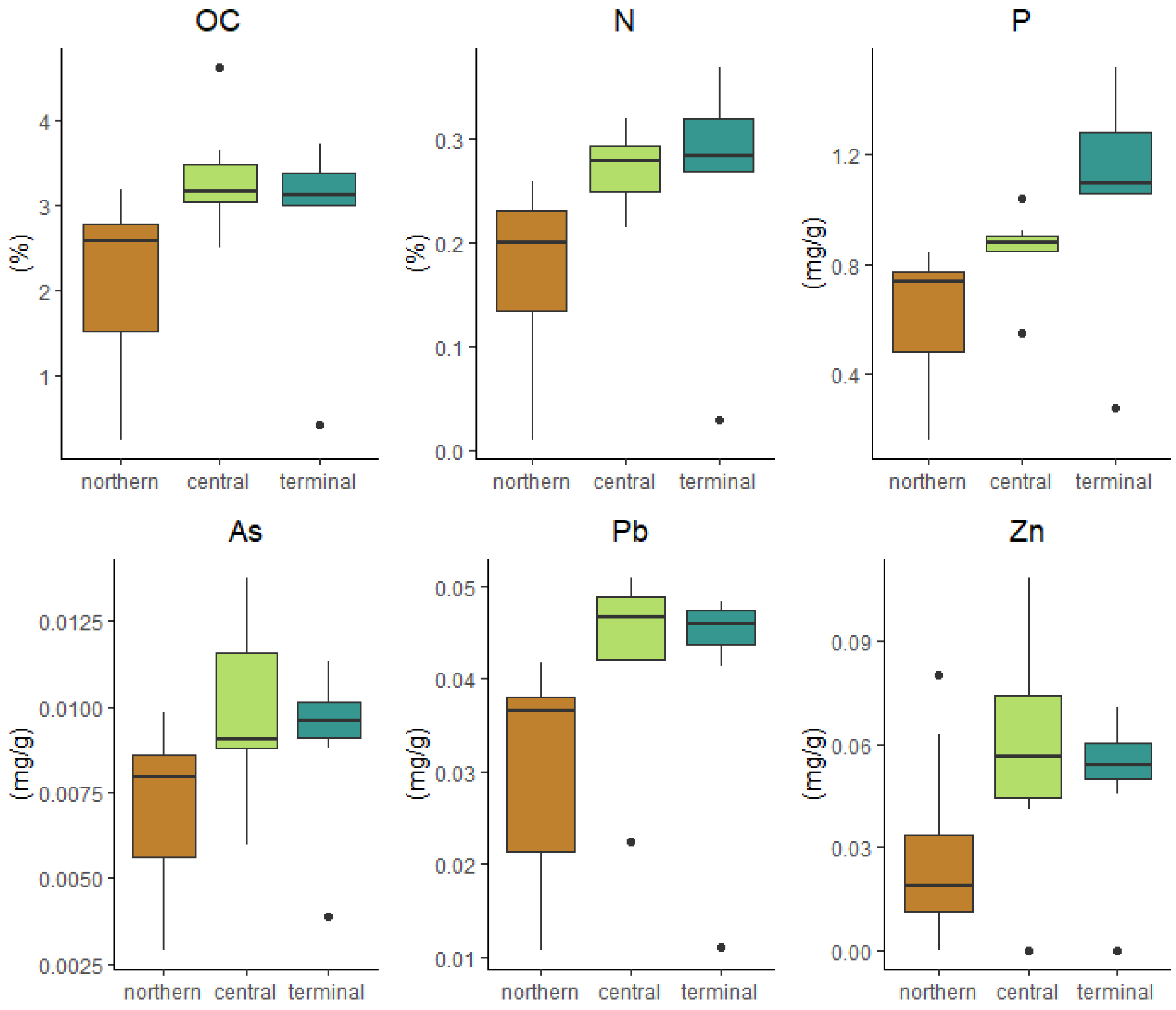


Figure A.9. Lay Lake box plots of nutrients and heavy metals in sediment samples between the 3 zones.