# Sediment and Nutrient Transport Through a Reservoir Sequence Along a Large River System

by

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# Abstract

Reservoirs are depositional environments for suspended sediments in river systems. Due to sediments undergoing fallout in low-flow areas, reservoirs contain 26% of all sediment and 12% of global river phosphorus behind dams. Despite most large rivers containing multiple dams, the connectivity of multiple reservoirs fragmenting a single stream system is still relatively unknown. For this thesis, paleolimnological techniques, sediment cores, and surface sediment samples were collected from five reservoirs along a large and fragmented river system in the Southeast United States. Reservoir location within the reservoir sequence was the primary driver for nutrient deposition with the initial reservoir downstream of the nutrient source acting as the primary site for nutrient deposition and accumulation. Residence time was a secondary driver of sediment deposition as shorter residence times prevent deposition.

The spatial distributions of nutrients along and within a string of reservoirs has also received little investigation. Whereas, nutrient deposition was hypothesized to follow the three zones of reservoirs (Riverine, Transitional, Lacustrine), a two-zone switch occurred with high nutrient concentrations near the dam and deposition dramatically decreasing as traveling upstream. Nutrients are found to primarily deposit near the dam pool area and within branches and coves. Deposition in branches and coves was linked to local shoreline land use. Because reservoir placement was shown as a primary driver for nutrient deposition, the need for reservoir and watershed mangers to have a fully developed understanding of nutrient sources in relation to reservoir systems is encouraged.

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# List of Abbreviations

| | |
|---|---|
| CWA | Clean Water Act |
| EU | Lake Eufaula / Walter F. George Lake |
| GR | Goat Rock Lake |
| HA | Lake Harding / Bartlett's Ferry Lake |
| OL | Lake Oliver |
| WP | West Point Lake |

# Chapter 1

## Reservoir Sediment Transport and Deposition: Chattahoochee River Case Study

### Reservoirs

Lakes are naturally formed inland bodies of water with inflows of water from streams, ground water, rainfall, or other inputs (Scheffer 1997). Compared to reservoirs which are enclosed, manmade areas for storing water and can be constructed from damming waterways. These dams enable regulation and alteration of flows leading out of reservoirs (Votruba and Broža 1989). There are primary two types of reservoirs storage and run-of-the-river. Storage reservoirs are commonly noted for having a larger volume and provide communities with water storage, flood control. While run-of-the-river reservoirs are often smaller and have a greater focus on hydroelectric power. Mechanisms of water release are also determined by the type of the reservoir. Storage reservoirs release water as volumetrically large pulses while run-of-the-river reservoirs release at consistently steady rates of less water.

Reservoirs can differ from lakes expressing a more dendritic morphology, as they are formed by flooding upstream rivers commonly increases the number of branches and coves compared to natural systems (Mulholland and Elwood 1982). Most natural lakes normally have their deepest point near the center of the system, while in reservoirs the deepest point can range from the center of the system, the dam wall, or various locations along the original river channel which impacts to the flows of the reservoir. In conjunction with the dam acting as a physical wall and the expansion of the reservoirs the stream flow is altered into three general zones riverine, transitional, and lacustrine (Figure 1) (Stefan 1980). Water release are additionally highly regulated where operators can control the exact amount of water passing through the dam which directly impacts residence time. Residence time is directly controlled by the operations of the dam, depending on the function of the reservoir water can be detained for less than a day or multiple months. Dam releases will pull water from reservoirs form the top, middle or bottom. Depending on which height the water is pulled from temperature and chemical makeup can greatly vary.

Light's ability to penetrate into the reservoir is limited based on turbidity and shading, which divides the reservoirs into the classical epilimnion and hypolimnion, division by the thermocline. The epilimnion is found at the top of the water column and reaches the thermocline where light can penetrate warming the water. Due to the available light green algae is also able to grow increasing dissolved oxygen levels and providing a substantial food source for fish and other large organisms. However, this is not always the case, under multiple conditions, a driving factor being an over bunce of available nutrients, the ecosystem can under shits to being dominated by cyanobacteria. The hypolimnion is below the thermocline reaching the bottom of reservoir. This area receives no light and is thus much colder, unable to support algal growth, and in turn is an anoxic environment. Instead of abundant green algae and fish bacteria communities can form creating a more suitable environment for some elements like P and N to become available for other processes. The thermocline is a mobile region in the water column where disappears and a shift from the epilimnion and the hypolimnion can occur. So releasees from the epilimnion or hypolimnion can have drastic impacts to downstream mechanisms with change in temperature, available nutrients, or algae/bacteria communities.

## Rationale and Significance

Reservoir research is a new area of limnological research that is much needed given over 45,000 documented large dams have been constructed globally since 2000 (Barbosa et al. 1999; World Commission on Dams 2000). The construction of reservoirs has become common practice through the world because they can providing a multitude of ecosystem services to the surrounding area, such as water storage, hydroelectric energy production, flood control, aquaculture, navigation, and recreation (Zhao and Liu 2015). Given that these dams alter flows and river processes, the materials being transported down these systems are also being altered.

Dams have been identified as major blockages to material transport down rivers with 26% of global sediments are trapped behind reservoirs (Syvitski et al. 2005) and estimates that dams have loaded 12% of global riverine phosphorus (Maavara et al. (2015). Reservoirs have been modeled to prevent approximately 20% of sediment from being coastally deposited, lessening the ability of sediment to recharge coastlines (Kirwan and Megonigal 2013). A mass balances case study of 69 reservoirs in California determined a majority of the sediment traveling through the river is sequestered in reservoirs (Minear and Kondolf 2009). However, the majority of quantifications of sediment deposition behind reservoirs have not considered the alterations in sediment quality.

Under the growing presence of climate change, reservoirs should also be impacted by increasing temperatures, altering precipitation patterns, more extreme climatic conditions, and other changes. Water disputes between countries and territories are increasing in frequency as transboundary water moved is altered, sequestered, and diverted (Cooley and Gleick 2011). Due to land use alterations working in concert with climate change, vast concentrations of reactive nutrients are being deposited in reservoirs thus causing an increase in eutrophic conditions (Smith 2003; MacKay et al. 2009). Eutrophic and hypereutrophic lakes have a higher risk of producing harmful cyanobacteria and cyanotoxins, such as microcystin (Paerl and Huisman 2009). Lake Mead National Recreation Area (LAKE), the largest reservoir in the United States, has already begun to produce moderate concentrations of microcystin (Eleuterio and Batista

2010). From a survey of 187 Florida lakes seven percent of sampled water samples had microcystin levels exceeding the World Health Organization standards (Bierman and Montgomery 2013). As a result, a knowledge gap exists in the relationship between material transport and deposition and the eutrophication of reservoirs.

By applying paleolimnological techniques to sediment cores, depositional materials of a lake including nutrients, heavy metals, pigments, charcoal, pollen, can be analyzed to provide historic environmental data.. (Cohen 2003). With this data longer temporal scales can be reconstructed provided integrated information of lake and watershed processes. Whereas most reservoirs are relatively young due to construction of dams only being prominent in the past century, paleolimnological techniques have been successfully used on natural time scales throughout multiple glacial and interglacial cycles. Application of these same techniques can be used with reservoirs, as sediments continue to deposit, longer records can be gathered enabling an understanding of how reservoirs have changed their current trajectory of development.

## Study Site

This project applied paleolimnological and sediment analysis to five reservoirs along the Chattahoochee River: West Point Lake (WP), Lake Harding (HA), Goat Rock Lake (GR), Lake Oliver (OL), and Lake Eufaula (EU). The Chattahoochee River is a portion of the Apalachicola-Chattahoochee-Flint watershed (ACF), which is a highly contested transboundary watershed between Alabama, Georgia, and Florida over water allocation rights (Schlef Katherine E. et al. 2018; Benson 2018). Conversation has primarily focused on the quantity instead of quality of water, which is unexpected as the City of Atlanta, GA, serves as a direct source of nutrients, metals and other industrial materials. Phosphorus (P) has been of primary concern into the Chattahoochee River via releases from wastewater treatment plants constructed in the Metro-

Atlanta area (Wangsness et al. 1994). Phosphorus is a highly reactive element in freshwater ecosystems with the ability to alter water quality. If water quality is poor, there could be a need for management amendments.

While these reservoirs are connected along the same river system, the management and ownership of the reservoir string is diverse. Both WP and EU are owned and operated by the United States Army Corps of Engineers and are storage reservoirs that bookend the five-reservoir sequence (Figure 2). West Point Lake and EU are the two largest reservoirs in the sequence and are primarily used for water storage. Georgia Power owns and operates the other three reservoirs, HA, GR, and OL; these systems are run-of-the-river reservoirs and are primarily used for hydroelectric power. This five-reservoir sequence provides a unique subject as a reservoir study due to the diversity between each system and the upstream nutrient source from a large urban metropolitan area.

## Study Goals

In the 1960s, the City of Atlanta experienced a population spike leading to a massive increase in P loading in the Chattahoochee River from wastewater treatment facilities and industrial expansion, which was maintained till the early 1990s. (Frick et al. 1998). Utilizing this P input as a natural experiment, paleolimnological sediment cores can be used to document the P-pulse from Atlanta's wastewater treatment to trace the transport and deposition of P through a five-reservoir system. This temporal documentation of historic P impulse will be compared to other reservoir morphological and environmental factors to identify driers of nutrient deposition in reservoir strings.

Surface sediment surveys were also performed on the three run-of-the-river reservoirs HA, GR, OL. Reservoir sedimentation distribution patterns were documented and compared to the traditional reservoir model of the three theoretical zones of a reservoir; riverine, transitional, and lacustrine. Sediment distributions and hotspots were then identified through both a single reservoir and the connection between multiple. All of these goals aim to 1) document the P deposition based on sediment records within the Chattahoochee reservoirs, 2) determine the driving factors of P deposition within reservoirs, and 3) determine the drivers of spatial distribution of materials in reservoirs.

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**Figures**

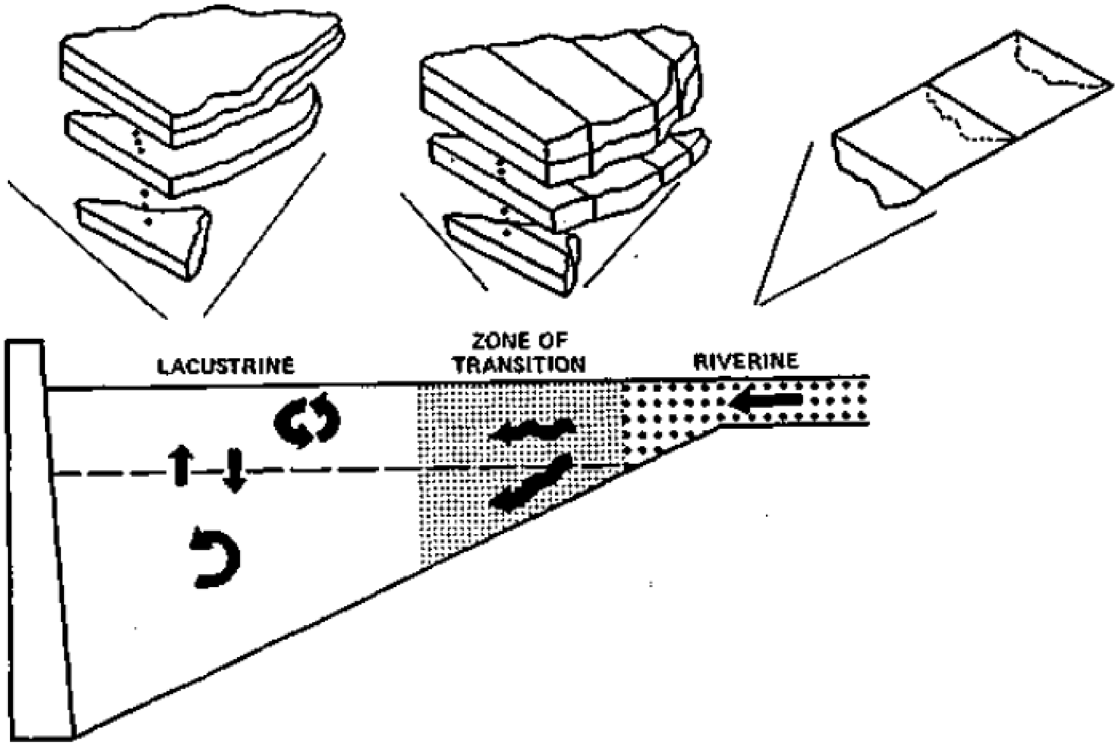

Figure 1. Reservoir depiction of the Riverine, transitional, and lacustrine zones from (Stefan 1980)

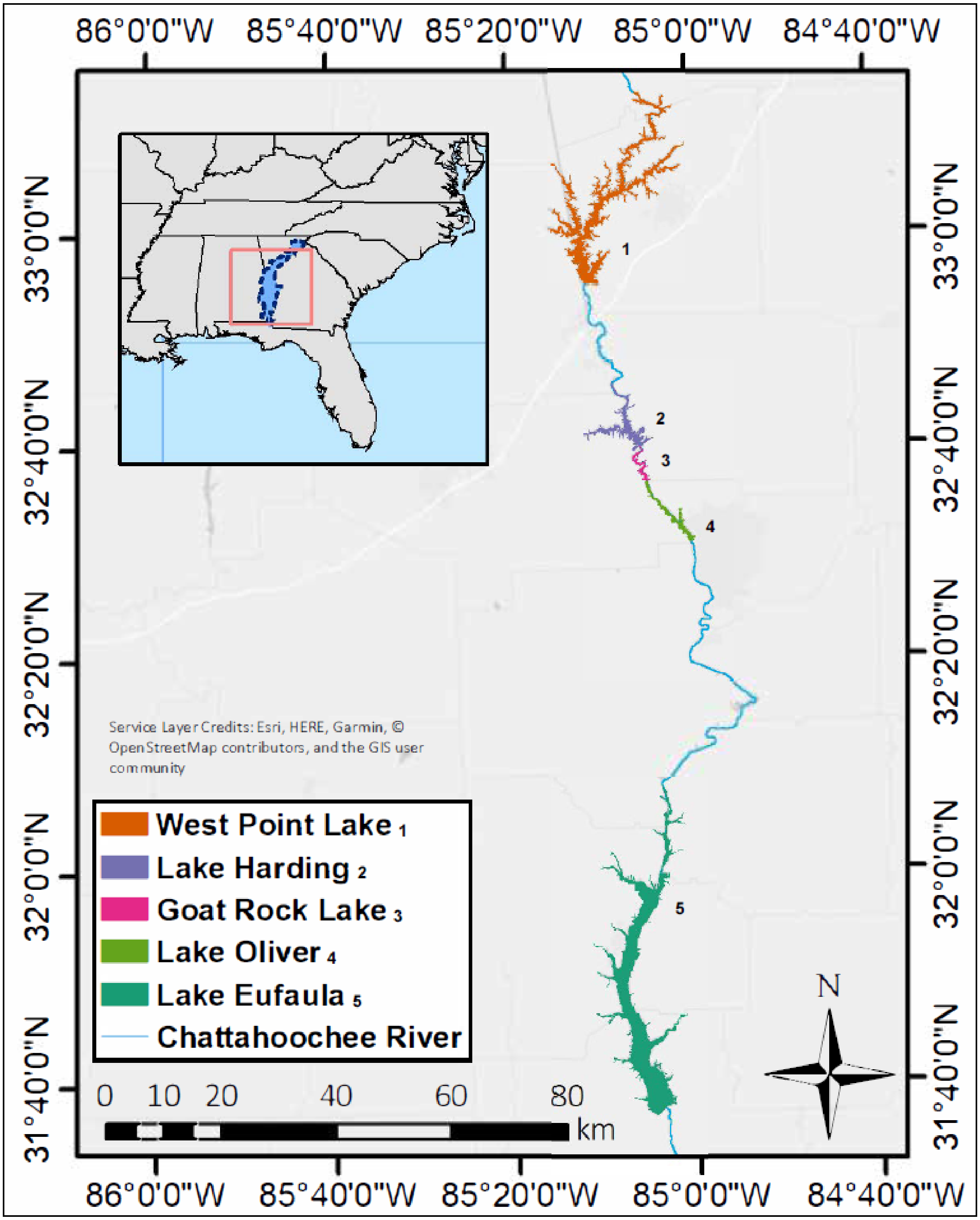

Figure 2. Overview map of the five studied reservoirs along the Chattahoochee River.

# Chapter 2

# The Mosaic Reservoir Process of Sediment Transport in Large River Systems

## Abstract

Reservoirs fragment river systems altering flows of water while providing services of flood control, hydroelectric power, water supply, and recreation. These man-made are known to store vast quantities of sediment and phosphorus (P), but less is known of the mechanisms of sediment transport between connected reservoirs. Here, a paleolimnological sediment study of a five-reservoir sequence was used to track transport and deposition of a 30-year P pulse originating from a large upstream urban area (Atlanta, GA, USA). Results indicate that the primary driver of material deposition in reservoir strings is placement of the reservoirs within the connected systems. The majority of materials are stored in the initial reservoir in the sequence through time or the first reservoir encountered downstream from the nutrient source based on the year of dam construction. A secondary driver of P storage was reservoir residence time. If residence time was too short or reservoir flows were too fast, then material would lack the opportunity to properly deposit. However, other reservoir characteristics such as volume, depth, shoreline, and management appear to drive sediment dynamics less. By placing all five reservoir P records together (mosaic process), historic P transport and deposition was reconstructed for the watershed. While individual reservoir studies are beneficial, these data suggest that other reservoir strings should be studied collectively to better understand reservoir connectivity and material transport.

## Introduction

Dam construction and the resulting reservoirs create novel aquatic ecosystems integrating alterations in land and water processes (Thornton et al. 1990). Reservoirs are highly disruptive to natural river function by permanently altering stream flow, preventing normal biological movement, and altering sediment transport (USGS Report 2018). Rivers are known traditionally as vectors transporting sediments downstream towards coastal systems but due to dams transport is prevented (Kirwan and Megonigal 2013). When rivers feed into reservoirs the water has more space to disperse, reducing the stream power allowing for sedimentation/fallout to occur (Kennedy 1998; Bierman and Montgomery 2013). However, reservoir/dam construction has been prolific in the past century providing jobs and multiple ecosystem services such as water storage, hydro power, recreation, navigation, and flood control (Zhao and Liu 2015). In the USA alone over 90,000 dams have been constructed (U.S. Army Corps of Engineers National Inventory of Dams 2019). Following dam construction, extensive monitoring of the reservoir system is common with a focus on water discharge, lake levels, and water quantity parameters. Sediment storage receives less attention despite 26% of the world’s sediments (Syvitski et al. 2005) and 12% of world’s phosphorus (Maavara et al. 2015) being stored behind dams. Most of the measurements including sediment parameters in reservoirs is based on mass balance approaches leaving physical and direct measurements of sediment deposition a needed focus for sediment transport and storage (Torres et al. 2007; Maavara et al. 2015; Powers et al. 2015).

Whereas reservoir research overall is becoming more prevalent, few studies consider the relationship between multiple reservoirs linked at the watershed scale (Barbosa et al. 1999a; Merrill et al. 2001). Given that there is a large volume of sediments stored behind dams, factors such as age, residence time, and releases could greatly impact downstream sediment transport and storage. Many fragmented river systems contain multiple reservoirs in a sequence which are generally regulated as one unit concerning water delivery and transport. However, much less is known of sediment transport and deposition between this reservoir system, and how these connected depositional basins work together as a watershed sediment transport system. One approach to better understand sediment transport and deposition through time is to apply paleolimnological techniques to reservoirs located in a string to reconstruct sediment transport through time.

Paleolimnological research in reservoirs can be challenging with irregular sedimentation rate, a lack of water column stratification, fast flushing rates, and lack of applying established dating techniques given the young age of most reservoirs (Thornton et al. 1990). However, paleolimnological studies are becoming more common. One study used reservoir sediment cores from Canada and Sweden to determine relationships between mineralization of organic carbon burial and water temperature changes suggesting that warming waters from climate change could result in a 4 to 27 percent decrease in annual organic carbon burial in temperate reservoirs (Gudasz et al. 2010). In France reservoir cores were dated using $^{137}$Cs to determine the origin and extent of heavy metal pollution from changes in smelting and waste-treatment proceedings up stream (Audry et al. 2004). Reservoir cores in Australia were also dated using both $^{210}$Pb and diatom analysis (Tibby et al. 2010), from the findings changes in the sediment deposition was recorded in two contrasting sedimentary environments urging researchers to use untapped reservoir records but with caution. Another study utilized USA reservoirs to track increasing deposition of both phosphorus (P) and nitrogen (N) following reservoir formation (Winston et al. 2014). Collectively, these studies documented increases in anthropogenic activity in the surrounding areas and demonstrated the successful application of paleolimnological techniques to reservoir sediment records.

Here, sediment cores from a sequence of five reservoirs were analyzed along the Chattahoochee River in the SE United States. These reservoirs have received a known input of P from the Atlanta metropolitan area resulting from increased population growth and subsequent nutrient input regulations. Each sediment core was dated, and phosphorus was measured throughout the period of reservoir existence. Three primary objectives were investigated: 1) to reconstruct the P increase and decrease through time based on the sediment records, 2) document the movement of P between reservoir systems, and 3) determine the driving factors promoting P deposition in the five reservoir system.

## Methods

### *Study Site*

The Chattahoochee River is located in the South Eastern United States and serves as a primary water source for Alabama, Georgia, and Florida (Figure 2). Just south of the headwaters of the Chattahoochee River is the City of Atlanta. One of the largest cities in the nation, Atlanta has had a history of major impacts to the Chattahoochee River (Hippe et al. 1997). Before the Clean Water Act (CWA) of 1972 regulations were minimal on urban inputs into the Chattahoochee River. During the 1960's Atlanta experienced a large population increase causing a sharp increase in P loading into the Chattahoochee River with maximum P loading occurring in 1988 despite the CWA (Frick et al. 1998). The City of Atlanta came into full compliance with their waste water treatment plants discharge in 1993 with P below the 0.75mgL$^{-1}$ standard (Wangsness et al. 1994). As a result, a theoretical model of P loading from Atlanta wastewater treatment plants can be constructed using known population increases and management improvements (Figure 3).

The Chattahoochee River is largest river of the Apalachicola-Chattahoochee-Flint (ACF) watershed which serves as one of largest water wars currently occurring in the United States (Feldman 2008; Schlef Katherine E. et al. 2018; Benson 2018). This transboundary dispute between Alabama, Florida, and Georgia has focused on the amount of water each state receives but has rarely considered the quality of the water even though this watershed passes though such a large urban and agricultural areas.

The five reservoirs sampled for this project were West Point Lake (WP), Lake Harding (HA), Goat Rock Lake (GR), Lake Oliver (OL), and Lake Eufaula (EU) (Figure 2). Both WP and EU are owned and operated by the Army Corps of Engineers and are characterized as storage reservoirs (US Army Corps of Engineers 2019a, b). HA, GR, and OL are maintained by the Southern Power Co., and are considered run-of-the-river reservoirs (Southern Power Co. 2019). Storage reservoirs are typically known for storing large volumes of water resulting in longer residence times, while run-of-the-river reservoirs allow frequent dam released of water causing them to store less water and have shorter residence times (Hayes et al. 2017).

The five reservoirs possess a variety of morphological and physicochemical processes. Retention times exist across the systems spanning from 55 days (WP) to 0.6 days (GR) (Table 1). However, all five of these systems are relatively shallow with mean depths between 2.5 to 9.4m. The oldest reservoir, GR, was constructed in 1912 with dam construction ending in 1976 with the building of West Point Lake. As a result, this five reservoir system receives direct inputs from the large Metro-Atlanta area and can serve as an experimental to analyze the movement of materials from a large, urban source.

*Field and Laboratory Techniques*

Two to four sediment cores were collected from each reservoir using gravity and icelandic piston coring devices. Coring sites were determined from bathymetry maps, soft sediment surveys, and preliminary core collections (Figure 4). Most core sites were located in the dam pool areas for each reservoir. Sediment cores were returned to the lab at Auburn University and immediately sectioned at 2 cm sections. A one teaspoon (4.92 $cm^3$) aliquot of wet sediment was removed and analyzed for bulk density by drying overnight in a 60ºC oven and reweighing. Bulk density is reported as g dry $cm^{-3}$ wet. Organic matter was determined as percent loss-on-ignition by burning dry sediment in a 550ºC muffle furnace for three hours and reweighing. Phosphorus and other elements including heavy metals were analyzed using ICP-ARL following acid digestion in a heated block following standard EPA methods.

The transition from river sediments to reservoir sediments for each core was determined utilizing a three-characteristic system. First, most cores contain a distinct color change from lighter riverine sediments to darker organic reservoir sediments (Van Metre et al. 1997). Second, photosynthetic pigments diagnostic for lacustrine phytoplankton (Leavitt and Hodgson 2001; Paerl et al. 2003) were absent in riverine/terrestrial sediments and dramatically increased following dam construction. Finally, sharp changes in elemental stratigraphy such as nutrients, C/N or metals were used to denote the storage of materials from dam construction. These three parameters typically showed the dam construction point within 0 to 4 cm of each other for all cores used in the study.

Sediment sections were dated following methods used in other reservoirs where traditional paleolimnological dating techniques were limited due to the young age of the reservoirs (Waters et al. 2015). Briefly, bulk density was summed from the core section corresponding to dam construction (determine as described above) and core collection (top sample) and divided by the number of years each reservoir has existed establishing a constant sedimentation rate for each reservoir. The bulk density of each core section was divided by the average sedimentation rate determining the time period representing for each core section (Albrecht et al. 1998). These time periods were subtracted from the date of collection in an additive fashion to assign each core section a distinct date.

## Results

Sediment core profiles showed asynchronous P stratigraphies from their point of construction to the date of core collection (Figure 5). The P concentration of the GR Lake core profile expresses minimal change, oscillating around 1 mg/g from the year of construction in 1912 to core collection in 2018. Lake Harding decreased in P concentration, from roughly 1.8 mg/g to around 1 mg/g, during 1926 until the 1960s. Between the 1960s to the mid 1970s HA showed a large rise and fall in P concentration peaking at about 2.2 mg/g. After the 1970s P concentrations stabilized near 1.2 mg/g until collection. Lake Oliver’s P concentration profile displayed a singular rise and gradual decrease. From the point of construction to the mid 1970s OL P profile increased from around 0.9 to 1.6 mg/g. P concentrations gradually decreased for the remainder of the core reaching 0.8 mg/g at the top of the core. Lake Eufaula showed a gradual increase in P concentrations from 1963 to present day, starting at around 0.4 and increasing to 0.8 mg/g. West Point Lake, the youngest reservoir in the study, displayed a rapid increase in P concentration during the initial years of formation remaining constant from the mid 1970s to the early 1990s at about 2.4 mg/g. From the 1990s to 2018 the P concentration appears to decrease in a reverse exponential manner leveling off at about 1.4 mg/g.

## Discussion

### *Reconstruction of P movement through the Chattahoochee Reservoir string*

Prior to the CWCA Act minimal regulations were implemented on the quantities of nutrients originating from wastewater, cleaning detergents, or agriculture. Atlanta, like many other metropolitan areas, experienced a substantial population increase in the 1960s (U.S. Census Bureau 1996) resulting in increased amounts of wastewater effluent entering the Chattahoochee and in turn increasing the P loading in the river as well. P levels continued to increase into the 1980s when the largest amount of P loading from wastewater treatment plants occurred on record (Frick et al. 1998). In 1993 the CWCA Act was fully implemented in the metro Atlanta area and reduced P loading into the Chattahoochee River (Wangsness et al. 1994). As a result, this 30-year P pulse from ~1960 to 1993 can be used as a natural experiment when reconstructed through multi-reservoir paleolimnological records.

Combing all of the records together (Figure 5 panel 7), WP and HA form a mosaic picture tracing the P loading history from Atlanta. Lake Harding deposited the maximum P concentrations from 1960 until the mid 1970s where maximum P deposition began in West Point Lake. The construction of WP in 1975 caused increased deposition of P in WP and the decrease in P deposition in HA. Due to the fluid transition of P deposition between the two reservoirs, it is assumed that WP dramatically decreased sediment delivery to HA and is sequestering the material that once reached HA. As a result, the primary driver of P deposition for the watershed is the placement of the initial reservoir of the sequence through time.

Following the construction of WP in 1975, HA’s P concentrations was similar to OL suggesting WP does release P-containing sediments to downstream reservoirs. The similarity of deposition between HA and OL could also suggest the importance of local inputs. While HA should deposit a greater amount compared to OL due to its upstream placement, OL is a more urban reservoir receiving indirect inputs from the cities of Columbus, GA and Phenix City, Alabama (Callender and Rice 2000). Goat Rock Lake contained low P deposition despite being the oldest reservoir. Goat Rock contains a very low residence time of 0.6 days which would sustain suspension of sediment thus limiting deposition. Like Goat Rock Lake, EU failed to document the P loading trend from Atlanta. Phosphorus deposition in EU gradually increased up core. This trend most likely resulted from a shift in the surrounding land use from forested areas converted to cropland, pastures and developed areas (Frick et al. 1998; U.S. Department of Agriculture 2016). Lake Eufaula is 439 river km from Buford Dam located at the north side of Atlanta, almost double the distance of WP (US Army Corps 2019) and demonstrates the deposition of P in reservoir systems is a combination of upstream inputs and local sources. While the upstream four reservoirs appear to store P based on direct inputs from the Atlanta area, P deposition in Lake Eufaula appears to be driven by more localized forested and agricultural land use.

Sediment deposition in reservoirs can be extensive where reservoirs have lost water storage capacity to sediment filling through time (Wisser et al. 2013). With the conjunction of bulk density mass balance and the two known dates of the sediment cores, sediment core dates for this study showed reproducible sediment records for each reservoir (Figure 6). In addition, known dates of P loading within the watershed correspond to calculated dates and alterations in P deposition. For example, P concentrations increase around 1960 when the population increase was occurring in Atlanta. This increase is best shown in the Lake Harding and Lake Oliver records. Also, the 1993 decrease in P loading from implementation of policy regulations corresponds to the P depositional decrease shown primarily in the West Point Lake core.

### *Drivers of P movement through reservoir strings*

After 1926 HA was the initial reservoir of the sequence causing the greatest levels of P deposition compared to the rest of the reservoirs studied. In the 1960s HA expressed an increase in P concentration coinciding with the population expansion in Atlanta. However, after WP construction, in 1975, HA was replaced as the initial reservoir and WP matched the concentration values of HA pre-1975. This “mosaic” reconstruction of historic P deposition suggests that the primary driver of material storage is geographic placement within the reservoir string, with the initial reservoir storing the bulk of the sediments. However, this mechanism is dependent on the location of the primary input, meaning the primary input of materials originating from upstream and not from local sources. Additionally, no reservoir in the sequence stores a significantly larger concentration of P compared to another upstream reservoir provided nutrient inputs are dominated by upstream sources.

Other reservoir characteristics have been shown to impact sediment depositional processes. Reservoirs with faster water velocities are a common trait of run-of-the-river reservoirs and directly correlate to shorter residence times (Thornton et al. 1990). Reservoirs with longer residence times will more efficiently deposit suspended sediments compared to reservoirs with shorter residence times (Kennedy 1998; Finlay et al. 2013). Goat Rock Lake has an extremely low residence time causing minimal sediment deposition. The relationship between reservoir residence time and sediment deposition is not linear, instead reservoirs with longer residence times might express minimal variation even if there is a substantial difference between them (Figure 7), which is seen in the interaction between WP and HA. After construction of WP, similar concentration of P deposition transitioned from HA to WP despite HA having a residence time of 13.5 days compared to WP with a residence time more than 4 times greater at 55 days. As a result, the geographic placement of these reservoirs guided depositional dynamics more than residence time, but residence time does appear to be a secondary driver of sediment deposition.

Reservoir regulation of dam release appeared to not be a primary driver of P deposition. The three run-of-the-river reservoirs are all owned and operated by Georgia Power while the initial and terminal reservoirs are storage reservoirs controlled by the Army Corps of Engineers. Given that WP and HA collectively sequestered the majority of the Atlanta P plum, the management of reservoir water storage does not appear to be dominant factor in P retention. In fact, the three reservoirs operated by Georgia Power all operated with identical discharge, while each reservoir stored varying levels of P concentrations. Storage reservoirs are typically noted for storing greater volumes of sediment compared to run-of-the-river reservoirs, however HA stored a substantial portion of P during the period of time where it was the initial reservoir while EU (a storage reservoir) expressed the lowest P concentrations. Whereas HA and OL deposited aspects of the P plum, GR failed to show stratigraphic change despite being the initial reservoir when built. GR possess an extremely low residence time of 0.6 days, suggesting that P deposition could have a secondary and positive relationship to residence time as has been shown with N retention in multiple lake systems (Finlay et al. 2013).

Additional morphological variability appeared to lack influence on P retention. Lake age spanned from 106 to 43 years since dam construction. Lake Harding, the second oldest system, showed one of the largest P concentrations while WP, the youngest, had the greatest P concentration suggesting a minimal effect of age on P retention. The size and shape of each of the reservoirs were different from each of the other studied reservoirs in the sequence with increased shoreline offering greater inputs from development, small streams and other local or point source inputs. However, Lake Eufaula, the largest reservoir, has the lowest P values while the second largest reservoir, WP, had the greatest P concentrations. Again, the size and shape of the reservoir appeared to have little impact on P deposition. Depth, which might promote the efficiency of trapping P at the dam areas also did not follow the same trend as historic P profiles. All of these reservoir aspects can and may play a role in P deposition in a singular or string of reservoirs, but they appear overshadowed by location of reservoirs in the Chattahoochee River sequence where the primary input is an upstream urban source.

## Conclusion

60% of the world's large river basins are highly or moderately fragmented by dams (World Commission on Dams 2000). Most if not all of these reservoirs are storing large volumes of sediment but depending on a multitude of factors both sediment supply and nutrient concentrations are variable. However, the reservoirs of the Chattahoochee River show that particular interest needs to be focused on documenting sediment storage in initial reservoirs receiving upstream inputs of materials. Likewise, the amount of sediment sequestered in each reservoir is also driven by the residence time of the system as well as local inputs. The relationship between geographic placement and residence time needs to be applied to other systems however, it is hypothesized that the initial reservoir will stop the flow of a significant portion of materials if residence time permits. As a result, more sediment studies are needed on reservoir strings as one river system comparing and combining reservoir sediment profiles together to form a whole basin picture of sediment transport and deposition.

Depositional material in reservoir systems originates from upstream point and nonpoint sources entering into the river system. When reservoirs are immediately connected there is minimal area for sediments or nutrients to enter the system causing most of the nutrients to originate upstream. These sediments will maintain similar nutrient concentrations and appear to function as one system. Conversely, when there is a large stretch of unimpeded river between reservoirs, materials have greater opportunities to enter into the river replenishing the sediment nutrient supply of the system and altering the nutrient stoichiometry. Identifying the primary sources of nutrients entering river systems and where these materials are being deposited, the zones of river systems can be identified. When considering heavily fragmented rivers in the future we might benefit of thinking of sections of the river as groups of reservoirs, all exhibiting a similar environmental signature. As with the Chattahoochee Reservoir system we could consider WP, HA, GR, and OL all with similar qualities of industrial inputs but very different from EU which remains independent exhibiting inputs from more agricultural-forested land use. By combining sediment records from connected reservoirs and incorporating residence time, entire watershed sediment dynamics can be reconstructed to aid future management and predictable models of reservoir function.

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## Tables

| **Reservoir** | **Year Built** | **Area** (km$^2$) | **Volume** (m$^3$) | **Depth** (m) | **Discharge** (cms) | **Retention** (days) | **Type** |
|---|---|---|---|---|---|---|---|
| West Point Lake (WP) | 1975 | 83.4 | 545562000 | 7.1 | 120.7 | 55 | Storage |
| Lake Harding (HA) | 1926 | 23.7 | 223259000 | 9.4 | 190.9 | 13.5 | Run-of-River |
| Goat Rock Lake (GR) | 1912 | 4.2 | 9744000 | 2.5 | 190.9 | 0.6 | Run-of-River |
| Lake Oliver (OL) | 1959 | 8.7 | 39471000 | 4.5 | 190.9 | 2.4 | Run-of-River |
| Lake Eufaula (EU) | 1963 | 159.4 | 989463000 | 6.2 | 234.6 | 44 | Storage |

Table 1. Overview table for all five reservoirs.

## Figures

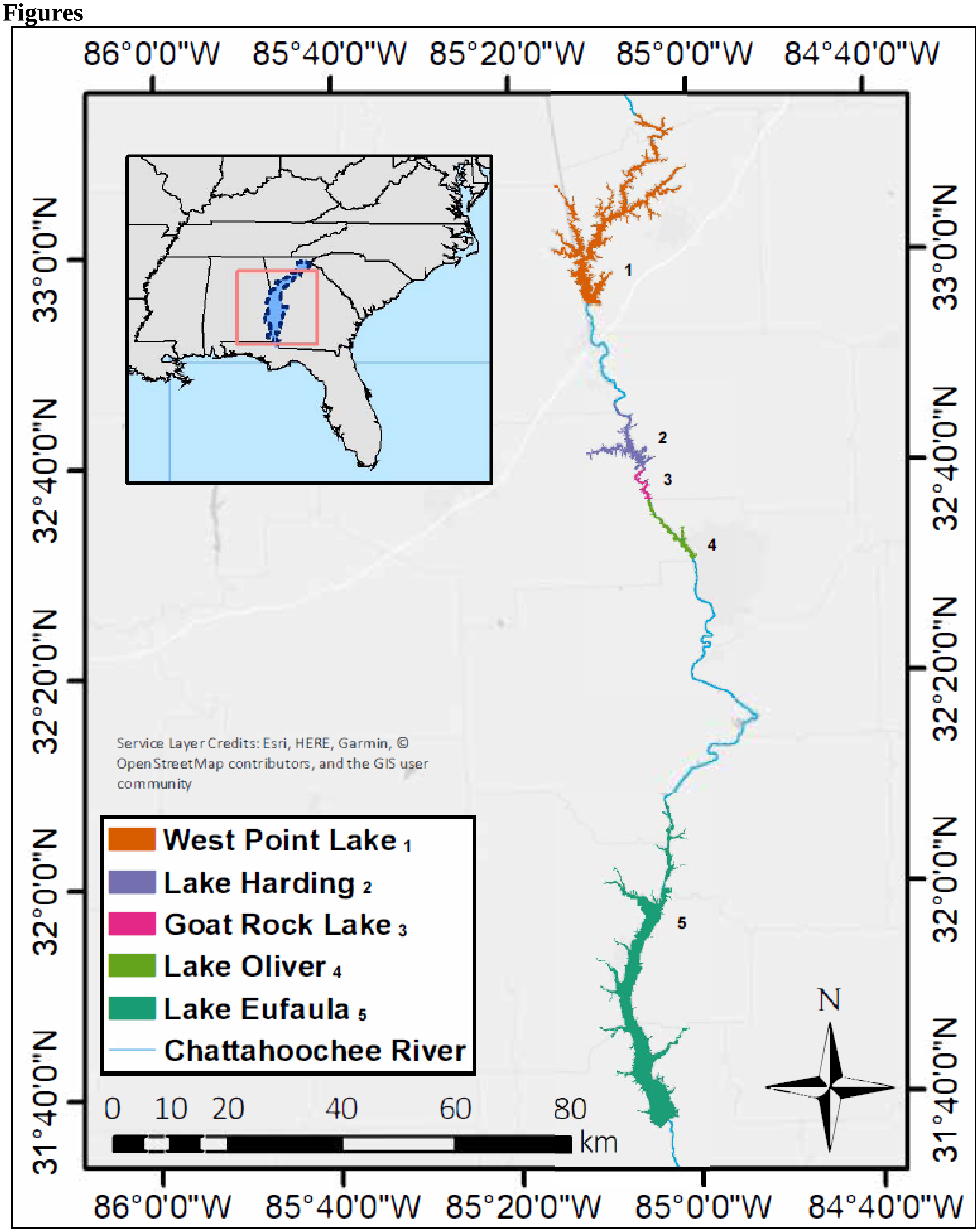

Figure 2. Overview map of the five studied reservoirs.

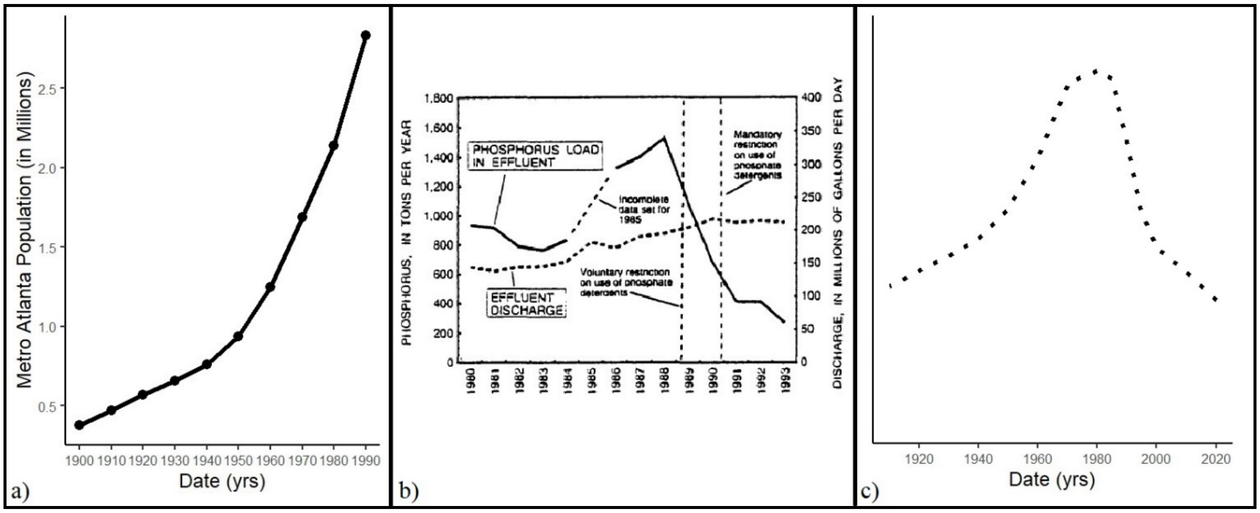

Figure 3. The panel a) shows the population increase of the metro Atlanta from 1900 to 1990. Panel b) is P effluent loading from Atlanta wastewater against population increase (Wangsness et al. 1994). Panel c) is a theoretical model of P loading from Atlanta wastewater plants into the Chattahoochee.

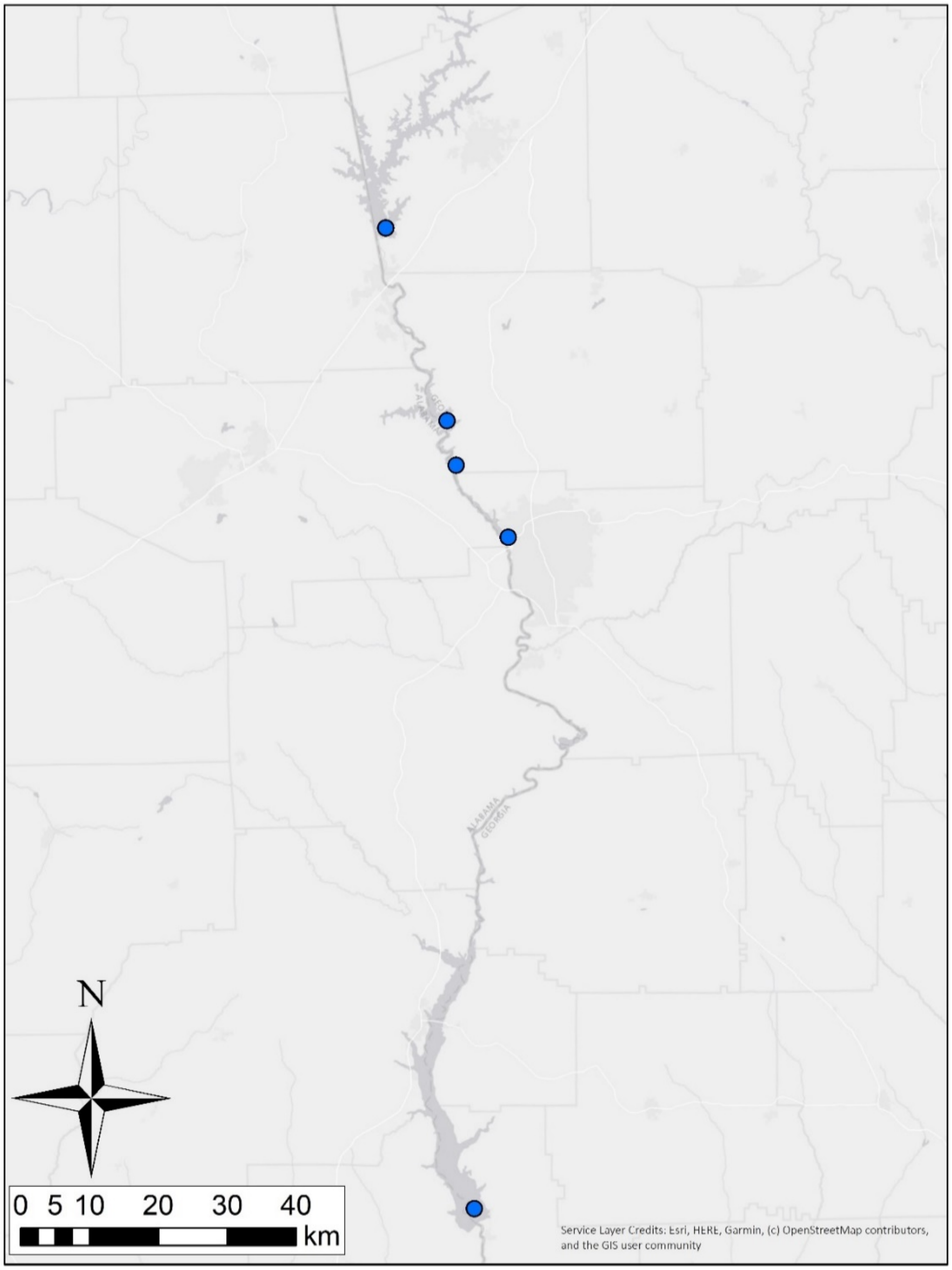

Figure 4. Map of the five core sites from WP, HA, GR, OL, and EU. Blue dots indicate core sites.

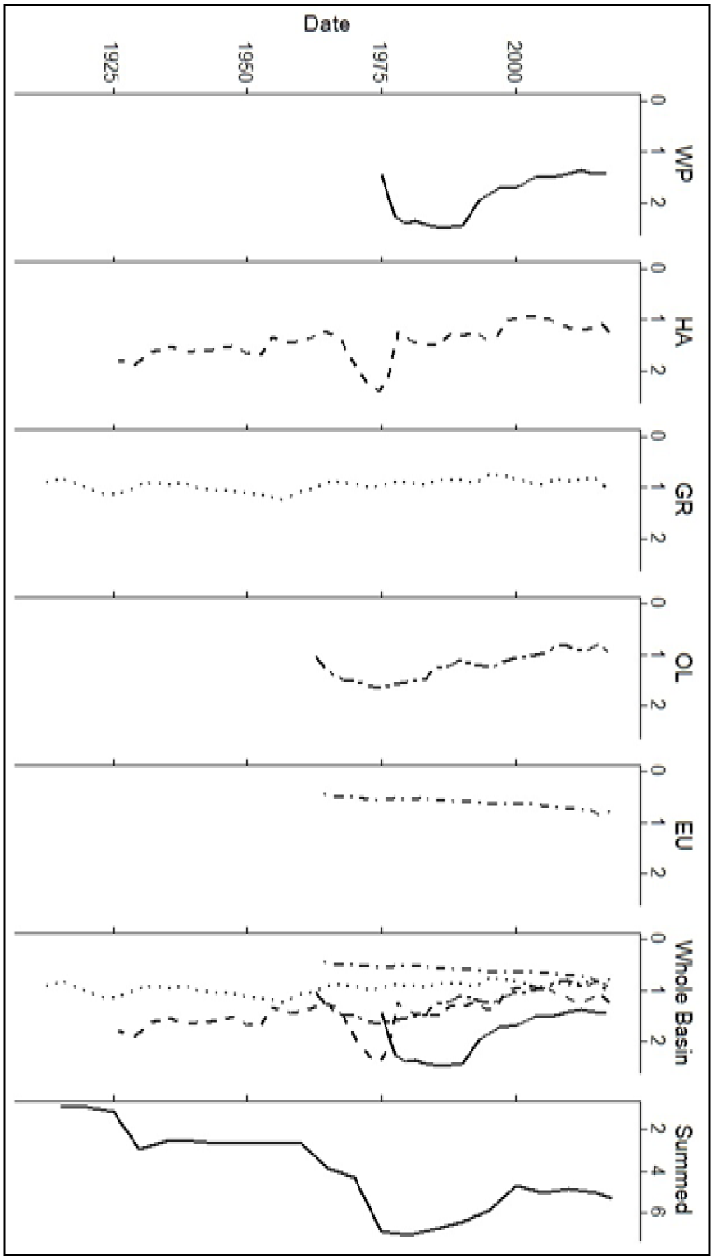

Figure 5. P concentration (mg/g) profiles dated for each reservoir in the sequence. Whole Basin shows all five reservoir profiles plotted together and Summed is the P concentrations per time added together.

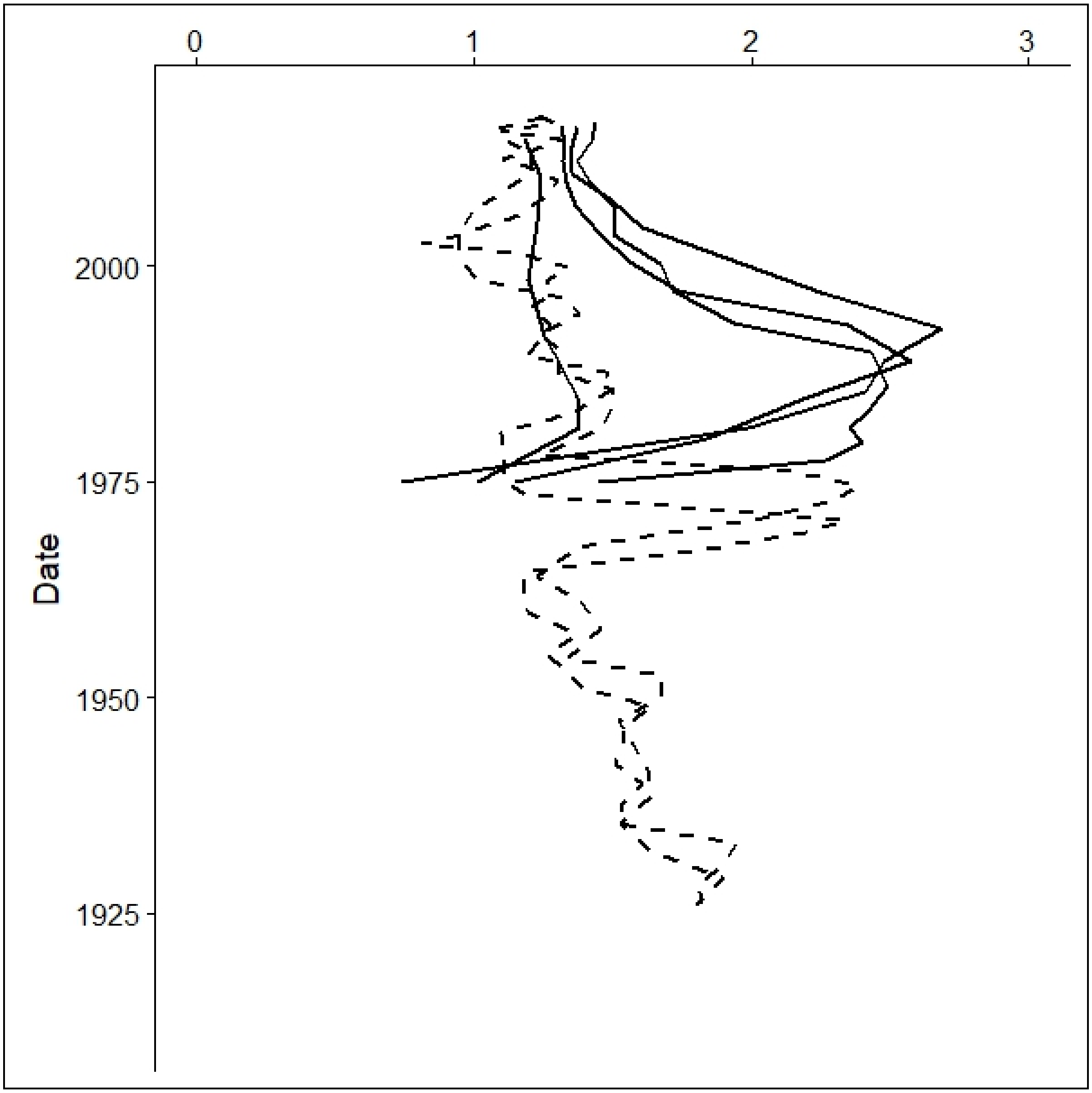

Figure 6. P (mg/g) profiles dated form multiple cores collected from WP (solid line) and HA (dashed line) in different areas of each reservoir.

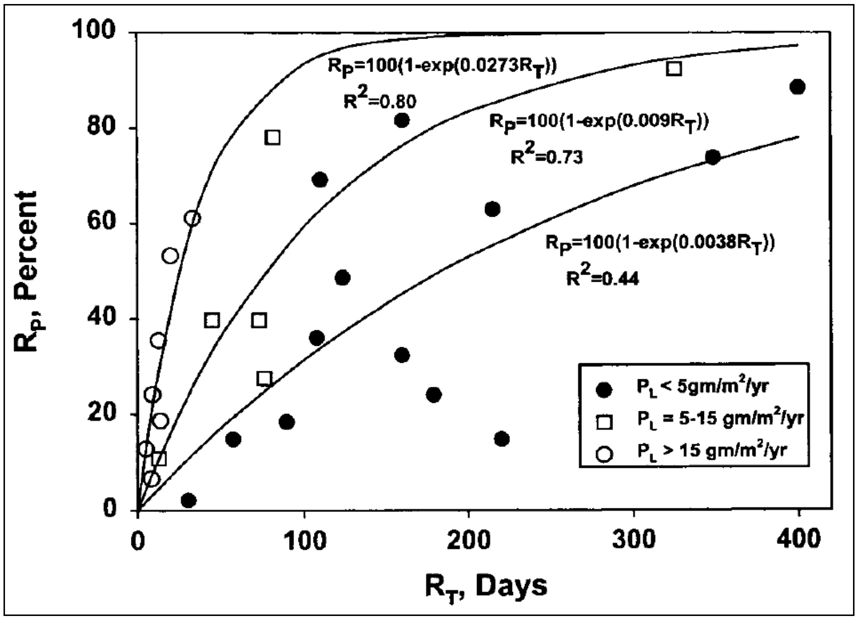

Figure 7. Relationship between time and percent fallout (figure from Kennedy 1999).

# Chapter 3

## Spatial Distribution of Surface Sediment Characteristics in Three Connected Reservoirs on the Chattahoochee River

### Abstract

Reservoirs provide a multitude of ecosystem services including hydroelectric power, water storage, flood control and recreation. These services can be critical to surrounding communities and stakeholders creating the need for monitoring strategies to understand water quality processes. However, some monitoring programs are based on sporadic water sampling collections, possibly missing biogeochemical and physical mechanisms that occur over longer timescales. One sampling technique capable of identifying materials stored on annual to sub-decadal temporal resolution in reservoir systems is the analysis of surface sediment samples. In this study we collected surface sediment surveys from three reservoirs in a sequence on the Chattahoochee River downstream from the Atlanta metropolitan area. Nutrients, organic matter, stable isotopes, metals, and photosynthetic pigments were measured on sediment samples from ~20 stations for each lake and used to answer two primary objectives: 1) to determine the drivers of spatial distribution of stored materials in single reservoirs as whole basin systems, and 2) to define the sediment transport interactions of reservoirs connected in a sequence. The most upstream reservoir from the primary nutrient source for this portion of the Chattahoochee, Lake Harding, sequestered the greatest concentrations of nutrients compared to the other downstream reservoirs, which has also been shown over longer timescales (see chapter 2). Individual reservoir nutrient concentrations were greatest closer to the dam in the dam pooling area and appeared to greatly diminish moving upstream. Sediment deposition between connected reservoirs followed a “sawtooth” pattern with higher concentrations building toward the dam followed by a rapid decrease after the dam. Drivers of this movement of sediments appear to be upstream material source and placement within the reservoir string with less input from local

land use, residence time and other morphological factors. This pattern of nutrient deposition might be common as a sediment depositional pattern of materials delivered from upstream areas.

## Introduction

Material transport in reservoir systems is typically measured by mass balance approaches of total suspended solids (Vörösmarty et al. 2003; Syvitski et al. 2005). Coupling the dynamic nature of reservoir water inputs, flows, and dam release with the variability of buoyancy, solubility, and settling of solid constituents, an understanding of deposition and sediment transport on longer timescales (>1 year) would provide spatiotemporal information needed to understand long term sediment dynamics in reservoir systems. For lake systems, sediment cores can provide historic data over millennia while surface sediment surveys can provide a sub-decadal detailed account of lake inputs, outputs, nutrient deposition, and autochthonous mechanisms (Cohen 2003). Traditional monitoring techniques can be limited by temporal resolution or finances potentially missing longer temporal processes and critical data for management applications.

It has been long understood that reservoirs possess the ability to capture vast amounts of sediment (Fan and Morris 1992). For example, a case studied performed using 69 different California reservoirs estimated that roughly 2.1 billion $m^3$ of sediment are stored in reservoirs globally as of 2009 (Minear and Kondolf 2009). Reservoir nutrient storage for phosphorus (P) has been modeled estimating that globally 12% of total P load is trapped in reservoirs (Maavara et al. 2015). However, research considering reservoirs as connected basins or string of systems in a watershed is less common (Barbosa et al. 1999; Minear and Kondolf 2009). Despite understanding that reservoirs are capable of sequestering vast amounts of sediment less is known on spatial depositional patterns and sediment transport between connected reservoirs. Many reservoir strings are managed by a variety of agencies (federal, state, private) for a variety of reasons (flood control, hydroelectric, thermoelectric) (U.S. Army Corps of Engineers National Inventory of Dams 2019) making whole basin understanding of sediment transport complex. A studied sequence of seven reservoirs in Brazil monitoring water column temperature, turbidity, and phytoplankton biomass and community change, showed that as materials traveled through each individual reservoir, shifts in both water quality and phytoplankton occurred in a nonlinear manner (Barbosa et al. 1999). Research on sediment and nutrient transport through reservoirs and watersheds has become a topic of importance requiring the development of new models to understand how these systems function in tandem with each other.

Reservoirs are often modeled as three longitudinal zones; riverine, transitional, and lacustrine (Hayes et al. 2017). These zones describe the changes that occur as water from the river travels into a reservoir resulting in decreased flows and potentially increased sediment deposition (Stefan 1980). Riverine is the most upstream portion possessing qualities most like a river while lacustrine is the most downstream portion where the reservoir resembles a natural lake system. Some models have simplified these systems by treating them as a linear continuum with the bulk of water and sediment traveling unidirectionally thus minimizing other complex variables (Chen et al. 1978). With the use of multiple liner models stacked in tandem, models can be improved to predict reservoir dynamics but most models require large amounts of information not collected by most monitoring programs (Greimann et al. 2008).

This study focused on a surface sediment survey (n=72) from three connected cascading reservoirs along the Chattahoochee River. Surface sediments were analyzed for nutrients, organic matter, stable isotopes, metals, and photosynthetic pigments. This dataset was spatially analyzed both within each reservoir and between the reservoirs to complete two primary objectives: 1) to determine the drivers of spatial distribution of stored materials in individual reservoirs and 2) to define the sediment transport interactions of reservoirs connected in a sequence.

## Methods

### *Study Sites*

Lake Harding (HA), Goat Rock Lake (GR), and Lake Oliver (OL) are run-of-the-river reservoirs located on the Chattahoochee River, which are owned and operated by Georgia Power (Figure 8, Table 2). The three reservoirs have a express a wide range of variety, of in terms of age HA is 92 years old, GR is 106 years old, and OL is 59 years old at the time of sediment collection (Couch et al. 1996). All three of the reservoirs have completed early reservoir formative years (Hall et al. 1999) but there is still a substantial gap in time between HA/GR and OL. In terms of surface area HA is the largest at roughly 23.7 km$^2$ at bank full, GR the smallest with only 4.2 km$^2$, and OL at 8.7 km$^2$. Again, in terms of global lake systems each of these lakes are relatively small, but with comparison to each other, Harding is almost 3 times the size of OL and over 5 times that of GR. Both GR can be classified as a shallow lake system with a depth of 2.5 m. Harding and OL is just deep enough, at 9.4 m and 4.5 m respectively, to be considered a more moderate depth (Scheffer 1997). Lake Harding also expresses greater dendritic qualities compared to the other two reservoirs with 251 km of shoreline and a large westward branching arm. Compared to GR with a shoreline of only 40 km and OL at 64 km both of which lack any sizable branching arms. Because these systems are all owned by Georgia Power and receive a regulated water supply from West Point Lake they have maintained constant water elevation with minimal flux in shoreline or mean depth over time. Both HA and OL have recently developed significant stands of *Hydrilla verticillata*. These *Hydrilla verticillata* populations are treated by Georgia Power in targeted areas, focusing on portions surrounded be residential development. Previous sedimentary core work showed deposition and storage of Pb and Zn along the reservoir string (Callender and Rice 2000). Upstream from this three-reservoir string is West Point Lake, which is managed by the Army Corps of Engineers and receives direct inputs from the metropolitan area of Atlanta, GA (Frick et al. 1998), which currently has a population of roughly 5.6 million people.

### *Field and Laboratory Techniques*

Surface sediment samples were collected in the field using a ponar dredge between January and March of 2018. During these dates *Hydrilla verticillata* was dormant and is assumed to have caused minimal impact to surface sediments. Ponar dredges were homogenized in a bucket and multiple subsamples were collected in whirl bags. Samples were stored in a cooler and returned to the lab at Auburn University. A wet sediment aliquot was archived, and a separate wet aliquot was used for gravimetric analysis of organic matter as loss on ignition (LOI) by burning in a muffle furnace for three hours at 550ºC. During this period samples were kept in the dark and cold to prevent pigment degradation in the sediment. The remaining samples were frozen, freeze dried and ground using a mortar and pestle. Large rocks, shells, and woody debris were separated when necessary by utilizing a 1mm sieve.

Photosynthetic pigments were extracted and analyzed using high-performance liquid chromatography (HPLC) following the techniques of Leavitt and Hodgson (2001) and Waters et al. (2012) (see Chapter 2). Carbon and nitrogen were analyzed using a Costech Combustion Elemental Analyzer with an attached autosampler. For organic carbon, samples were acidified in HCl vapor for 24 hours prior to analysis. For additional elements and heavy metals, sediment samples were analyzed using and ICP-ARL following acid digestion in a heated block following EPA 3050B.

A k-means cluster analysis (k=3) was used to examine in lake spatial separation. Three clusters were chosen to separate surface sediment samples based on the respective theoretical zones of riverine, transitional, and lacustrine zones.

Multivariate analyses of variance (MANOVA) were used to compare whole basin and dam pooling nutrient connections of P, C, N, $\delta^{15}N$, Ca, Mn, Pb, Zn, Fe, Al, and Na between the three reservoirs. However, MANOVAs with a smaller sample sets of $n=72$ for the whole basin of all reservoirs and $n=25$ for the dam pool of all reservoirs caused concern for over predictions and resulting in a false statistical difference. MANOVAs were performed for the whole basin and dam pool to verify they would not result as a lack of significant difference between the three reservoirs. ANOVAs were subsequently used to confirm a significant difference for each individual element across all three reservoirs, this is ideal since ANOVA is a more robust statistical analysis for sample size and normality. T-Tests were used to determine reservoir differences between reservoir pairs for each element. T-Tests, the most basil analysis is the most robust of the three analyses used for small sample sets.

Assumptions for MANOVAs, ANOVAs, and T-Tests were considered (O’Brien and Kaiser 1985). All outliers and multivariate outliers were removed from the data set using the outlier determination package MVN in R, leaving sample sizes of $n = 67$ and $n = 25$. Normality and multivariate normality was verified in each dataset using the Shapiro-Wilk test (Shapiro and Francia 1972). Multivariate normality for MANOVAs were violated as well as normality for all of the whole basin ANOVAs excluding Pb as their $P < 0.05$. Environmental data sets can often lack normality but ANOVAs with a validation of normality are still robust enough to derive significant results (Blanca et al. 2017). Normality dam pool ANOVAs were all achieved excluding the elements C, N, Zn, Al, Ca all of which had $P > 0.007$. A linear relationship was exhibited between the dependent and independent variable(s), and there was homogeneity of variance-covariance matrices, shown using box plots. There was no evident multicollinearity in the dataset. For example, this would have failed if percent organic material (OM) and C were both considered as both can account for the same element.

Smooth kernel interpolation with barriers was used to create a theoretical spatial distribution of sediment nutrients. ArcMap, using a kernel interpolation with polynomial of order 5, projected a map of nutrient deposition creating an assumption for each individual location then verified accuracy of projected points against the actual collected data. Barriers were necessary due to the dendritic shape of the shore lines and branches and by dam separation between each reservoir. If barriers were not used, values would have been predicted through boundaries such as terrestrial land and dam walls. Smooth kernel performs best if samples are taken as a grid format which despite the irregular shape of the reservoir was the original intention of my sample sites. Accuracy of the interpolation map is reported as a Root Mean Square (RMS) value, located map descriptions. The RMS value can be interpreted as the amount of variance at any given location, for example if a site reported 6 (mg/g) in the map but has an RMS value of 0.5 then we can read that point as 6 ± 0.5 (mg/g).

Scatter plots were made using sample site distance from OL dam compared against nutrient concentration. Only sample locations closest to the original river channel were used excluding points outside of branches or coves. Both distance and proximity to the river channel was determined using ArcGIS. Lake Oliver dam was selected as the point of origin because we aimed to plot the transition of nutrient depositional change traveling through a cascading sequence of reservoirs and OL dam provided a static point at the end of the sequence unlike the most upstream collected point from HA.

## Results

Boxplots in conjunction with MANOVA's, ANOVAS, and T-Tests were used to compare if a significant difference was present between the surface sediment samples collected in each reservoir (Figure 9 & 10, Tables 3 &4). The whole basin MANOVA still showed a significant difference in stoichiometric nutrient concentrations between the three reservoirs p >0.001, but due to the low sample set n=67 some strength in this test is lost (Table 3). According to both the ANOVAS for the whole basin only Ca lacked a significant difference between the three reservoirs strengthening the pervious MANOVA. The T-Tests for the whole basin showed a uniform relationship of HA being statistically different from both GR and OL while GR and OL were not statistically different from each other (Figure 9). Given that multiple samples in both GR and OL failed to contain sediment (reported as 0s), large variance is expressed in the data sets when comparing whole basins, skewing comparative nutrient deposition.

Variance in Figure 9 is reduced by only comparing samples with similar and consistent deposition, these were determined by using the k-means clusters (k=3). Each element accounted for >80% accuracy for the entire sample set. The area near the dam or the dam pool appeared less variable and more reproducible across all three reservoirs, unlike the large branches which was only present in HA. MANOVA, ANOVAS, and T-Tests were conducted on the dam pool samples alone in the same fashion as the whole basin (Table 4). Both the MANOVA and ANOVAs for the dam pool were consistent to the whole basin as to which elements had P values < 0.05 when comparing the whole basin to the dam pool (Table 3). The T-Tests showed only a marginal difference, with differences being carbon (C) was no longer statistically different between HA and GR and $\delta^{15}N$ is no longer statistically different between HA and OL. Mn across all three reservoirs was no longer statically different from each other when paired, and both Pb and Zn became statistically different from each other between all three reservoirs (Table 4). These findings are repeated in the dam pool boxplots of Figure 10.

For each of these boxplots a general pattern emerges with greater concentrations in the most upstream Lake Harding for sediment measurements P, N, Fe, Zn, Pb, and Na. For elements Al, Zn, and Pb concentrations were highest in Lake Harding with lowest concentrations in Goat Rock Lake. For Fe, a stepwise decrease from the most upstream reservoir to the most downstream reservoir occurred. Finally, Ca and Mn, was similar between all reservoir dam pool samples.

Principal Component Analysis (PCA) was used on the dam pooling samples to determine similar ordination between certain sediment characteristics and the different reservoirs (Figure 11). Most of the elements positively ordinated with HA and were negatively ordinated with GR and OL, excluding Ca. Additionally, GR and OL expressed overlap meaning they act similarly to each other when comparing all three reservoirs to each other.

Nutrient concentrations were plotted against each sample's location from the distance of OL dam (Figures 12, 13, and 14). The distance was calculated by measuring the distance in ArcMap from each point to the next using points following the historic river channel. Multiple locations in both GR and OL lacked acquirable sediment by use of a ponar dredge due to large boulders being the only visible bedload. These locations were marked as zeros for nutrient concentrations, bulk density, and other factors.

Smooth kernel interpolation maps with barriers depicted for most nutrient concentrations were greatest near the dam pooling area and branches or coves (Figures 15-25) with minimal deposition in the upstream portion of the reservoir.

## Discussion

### *Whole Basin and Connected Basin Sediment Deposition and Delivery*

Whereas traditional reservoir zones (riverine, transitional, lacustrine) were expected to be visible from the nutrient concentrations of the surface sediment samples, all three reservoirs appeared to possess a singular switch between high too low nutrient deposition in the sediments thus combining the transitional and lacustrine areas of each reservoir. Within GR and OL this switch is more dramatic than HA, with areas of little to no apparent sediment. Sense the riverine section retains a similar stream power as the upstream river, most suspended materials are prevented from being deposited out of the water column, but this area was still expected to have a moving bed load of sediment undergoing siltation reflecting that of the river (Sen et al. 2007). Five attempts to collect sediment samples were made with the ponar dredge at these sites to assure that these locations failed to possess collectable sediments with a ponar dredge. Lake Harding had sediment present throughout the reservoir however a large portion of the surface sediment samples collected in the upstream area were rich in sand, which might impact the nutrient concentration. The transitional zone, located between the riverine and lacustrine zone, is often noted as the portion of the reservoir where reservoir volume will increase causing a decrease of stream power allowing heavier materials to fallout and deposit (Bierman and Montgomery 2013). The transitional zone typically noted as the zone with the largest levels of sedimentation and the heaviest particles accumulate, such as sand (Stefan 1980). Potentially this sand bar could represent the beginning of a transitional zone in HA. There is no distinct change in nutrient deposition indicating a shift from the transitional to lacustrine zone in all three reservoirs. In addition, the reservoir upstream from HA, West Point Lake, has been shown to contain a majority of the material from the Atlanta-Metro area serving as a high concentration input source that could have caused the measurable concentrations found in the riverine HA area (Chapter 2). As a result, sediment transport and deposition appears to follow an unexpected two zone pattern.

For such a distinct pattern Lake Harding, Goat Rock Lake, and Lake Oliver share only a few limnological qualities in common. Each reservoir is owned and operated by Georgia Power and is classified as run-of-the-river reservoirs, meaning dam release is constant and long term storage of water is not a management target (World Commission on Dams 2000). In terms of hydrologic movement, the only characteristic all three reservoirs share is a constant average monthly discharge. Again, this is because these reservoirs are owned by the same company, so they release water at similar rates when producing electricity and to maintain mandated delivery to the downstream reservoir of Lake Eufaula, which is managed and owned by the Army Corps of Engineers. However, residence times of each reservoir is substantially different from each other. Lake Harding has the longest time of 13.5 days, Lake Oliver at 2.6 days, and Goat Rock Lake at 0.6 days. Residence time has been linked as an important driver for sedimentation with longer residence times supporting finer particles to deposit from the water column while shorter residence times can maintain particle suspension (Kennedy 1998; Finlay et al. 2013). The statistical significance between GR and OL demonstrated that residence time is less likely to determine sedimentation in this system. Lake Harding and OL are both considered to exhibit historic straight river channels, sinuosity values < 1.3, while GR is considered a meandering channel, > 1.3. Meandering channels can create pools along the outer banks for deposition to occur and increased flows and erosion on the inside of the bend (Bierman 2014). Straightened channels lack the same level of hydrological oscillation providing fewer pools for sediments to fall out (Solé R. V. et al. 2002). In terms of sinuosity alone GR would be expected to have the greatest deposition of materials, which was not the case for my data (Figure 10, Table 2). Both GR and OL are bordered by dams meaning all river channel inflows and outflows can be controlled and altered. Dam releases often act as pulses which could potentially blow out sediment away from their release points. This could lead to an extended riverine section until flows are slowed by the downstream dam and not allowing for space for the transitional zone.

However, the three reservoirs vary in terms of age, surface area, depth, and dendritic shape. Despite the surface area differences between GR and OL, most depositional patterns between the two systems appear similar with respect to nutrients. One exception would be Ca which expresses no significant variation between the systems and only Fe showing a stepwise decrease between the two (Figures 19 & 23). Likewise, surface area, depth, and dendritic shape differences would place HA as the primary depositional basin, which is the case for most elements, but by the same mechanism OL should store the second greatest concentrations followed by GR, which was not supported with our data (Figures 15-20 & 23).

When considering these morphological and hydrological qualities of the reservoirs, a distinct driver of a two-zone sediment deposition pattern fails to emerge. The three reservoirs' age, surface area, depth, shoreline, residence time, and sinuosity are all inconsistent across the system. The two-zone nutrient deposition pattern might be caused by reservoir position/location in the sequence and the location of the nutrient source. Lake Harding is the most upstream reservoir and has a significantly greater concentration of nutrients compared to both GR and OL excluding Ca and Mn (Figures 9 & 10, Tables 3 & 4). While concentrations between GR oscillate between statically grater, less, or equal to that of OL, OL is greater primarily with nutrients linked to industry/ urban land use. As materials enter from the upstream Atlanta-Metro area most nutrients are deposited in West Point Lake (chapter 2), then HA, leaving a smaller amount of lighter suspended material released downstream to both GR and OL. But because GR and OL are immediately boarded by dams there is minimal available area for nonpoint nutrient sources to directly enter each of these reservoirs, additionally the water released from the upstream dam will have greater velocities preventing the lighter suspended materials from being able to deposit. As materials enter HA most of the remaining heavy sandy material deposits first, reducing nutrient concentrations, and as flows continue to slow closer towards the dam, the system undergoes a shift and the lighter martials deposit. Then for both GR and OL the flows from the upstream dam releases are so great the lighter materials are unable to deposit causing deposition to occur closer towards the dam.

The PCA further supports the importance of material delivery from upstream with most measured elements (excluding Ca) ordinating with HA. P and Pb less strongly associate with HA as they ordinate with a different PC. Goat Rock and OL samples cluster together in the PCA meaning they are extremely similar in their sedimentary characteristics measured in this study. From these data, riverine sections of reservoirs do not deposit enough sediment despite differences in reservoir characteristics.

The Chattahoochee reservoirs pose a unique experiment due to the large nutrient source from the Metro Atlanta area feeding a sequence of reservoirs with a variety of ages, size, type, and primary functions. So, understanding the changes of these sediments undergo traveling through multiple reservoirs could potentially impact upstream and local management decisions. The linear continuum (Figures 12, 13, and 14) allowed a visualization of material deposition from OL dam to upstream HA. The branches of the reservoirs are not considered here due to the over representation of local hotspots. Again, the greatest concentrations of nutrients occur near the dam. Moving upstream a switch occurs from high to low material deposition resulting in a “sawtooth” like shape between reservoirs. This depositional pattern is consistent for multiple nutrients which have the ability to act differently in aquatic systems (P, C, N, $\delta^{15}$N, Mn, Zn, Fe, Al, and Na). These figures clearly depict how location of sample collection can greatly impact sediment depositional patterns suggesting sediment collected from upstream locations in each reservoir possessed a different signature from those closer to the dam. The only element that dose not resemble the “sawtooth” pattern is Pb, which appears to only deposit in HA and OL with GR displaying almost 0 (mg/g) of Pb in all sediment samples collected. The Pb deposited in OL most likely originated from a different nutrient source other than metro Atlanta. One proposed source is increased traffic from Columbus, GA that has led to increased levels of both Pb and Zn to OL (Callender and Rice 2000).

### *Local inputs compared with upstream inputs*

The interpolation maps (Figures 15-25) support a consistent pattern within each reservoir with increased nutrient concentration occurring in the downstream portion of the reservoir as well as branches and coves. When considering spatial distribution across all three reservoirs as well as box plots, elements such as P and Fe clearly depict greater concentrations in HA, the most upstream reservoir studied (Figure 10). Upstream reservoirs possessing the greatest nutrient concentrations is consistent on longer timescales from paleolimnological reconstructions (Chapter 2). From previous explanations deposition in the dam pool, branches, and coves is expected. These areas are known to have potentially slower flows allowing for deposition to occur. However, coves and branches would receive local inputs from shoreline developments and local sources. Whereas these hotspot areas suggest the importance of shoreline management to reservoir systems, the whole-basin depositional pattern appears to be linked to upstream sources in my study systems. Other reservoirs receiving lesser upstream inputs could potentially possess differing drivers of sediment deposition.

$\delta^{15}N$ is a stable isotope of nitrogen which can be used as a tracer to track nutrient sources to reservoir systems. Fertilizers derived from atmospheric N will have a $\delta^{15}N$ signature around 0‰ while sewage and manure-based fertilizers would possess a signature roughly from 8-12‰ (Savage and Elmgren 2004). Along the large branch of HA (site A in Figure 26) and some of the coves in HA and OL (sites C, D, F, G, and H in Figure 26) the $\delta^{15}N$ signature is > 9‰ with a root mean square value of 2.79 (Figure 18). Both this branch and these coves have large presence of residential development along their shoreline with multiple houses which use septic tanks. The main body of all three reservoir basins lack $\delta^{15}N$ signatures to the same degree as these hotspots, leading to an inference of the source of this material is form the local residential land use. These were not the only branches/coves that expressed higher concentrations of nutrients, the smaller branch in HA (site B 2 in Figure 26) had elevated levels of C, N, Pb, and Zn (Figures 16, 17, 21, 22). In addition, GR's cove (site E in Figure 26) has an extremely active boat launch ramp and large concentrations of P, Pb, and Zn. The materials coming from the exhaust of cars, materials covering vehicles and tires, and potentially boat engine leaks all could lead to increased levels of these materials (Christensen and Guinn 1979; Mielke 1993). For the reservoirs of the Chattahoochee River, the dendritic branches and coves are less representative of the reservoir, due to the connectivity to the coastline allowing for greater input from the local land use and the lack of flows dispersing these inputs throughout the system. However, the shoreline and local input must also be considered when examining other water bodies, but when deriving comparisons and changes from systems of this study, the data suggest an asynchronicity between whole basin deposition and local inputs.

### Application to other river systems

Reservoirs integrate environmental and cultural parameters and typically exist with very targeted management goals. With growing importance for reservoirs, reservoir research has increased, but rarely do studies focus on relational dynamics between reservoirs in a sequence. Materials entering a reservoir can originate from two primary sources, upstream delivery or local inputs. When considering sediment deposition, all three reservoirs investigated in this study expressed a two-zone depositional pattern and lacked a riverine, transitional, and lacustrine zones from the sampled area. This trend was constant for all three reservoirs despite other characteristics such as age, surface area, depth, shoreline, residence time, and sinuosity. Consistent with paleo-reconstructions of nutrient sedimentation from Chapter 2, the most upstream reservoir, HA, sequestered the greatest amount of nutrients. However, it is important to understand where the primary source of nutrients for the studied sections is originating and how it enters the system. Despite the inputs from upstream sources, local inputs can play a significant role in material inputs as shown by the city of Columbus, GA and Pb inputs. While this local input caused hotspots for certain elements, the upstream input of materials was maintained between reservoirs in the Chattahoochee River system and appeared to be the primary driver of material inputs. Furthermore, the placement of a reservoir in the reservoir string also served as a primary mechanism with the more upstream reservoirs maintaining the greater concentrations of most materials.

Reservoir managers should include the analysis of surface sediment samples to determine if these or other depositional nutrient patterns are reproduced. Variations in other river/reservoir systems dam location and nutrient source could greatly alter this pattern. Reservoirs further separated from each other most likely will exhibit greater variation as materials will have more opportunities to replenishes the river's suspended load, while river systems lacking a primary large nutrient source may express other portions of the watershed's land use with greater resolution. The next step for this research is to compare these patterns to other fragmented rivers with multiple reservoirs immediately sequenced or cascading to each other, like the Maotiao River in the middle of Guizhou province of China, or the São Francisco river basin in Brazil (Callisto et al. 2005; Wang et al. 2011). If these patterns are consistent then expansion to larger systems can be incorporated such as the Colorado River in the United States or the Yellow River in China, both of which have a greater number of reservoir fractures compared to the Chattahoochee River. If successful these practices could lead to new targeted samplings for nutrient deposition in the system to more quickly assess and understand global reservoir sediment patterns.

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## Tables

| Reservoir | Year Built | Area (km$^2$) | Shoreline (km) | Volume (m$^3$) | Depth (m) | Discharge (cms) | Retention (days) | Sinuosity | Type |
|---|---|---|---|---|---|---|---|---|---|
| Lake Harding (HA) | 1926 | 23.7 | 251.1 | 223259000 | 9.4 | 190.9 | 13.5 | 1.13 | Run-of-River |
| Goat Rock Lake (GR) | 1912 | 4.2 | 40.9 | 9744000 | 2.5 | 190.9 | 0.6 | 1.52 | Run-of-River |
| Lake Oliver (OL) | 1959 | 8.7 | 64.4 | 39471000 | 4.5 | 190.9 | 2.4 | 1.02 | Run-of-River |

Table 2. A table describing qualities of all three reservoirs.

| MANOVA | P Value | ANOVA | P Value | t.test | HA_GR | HA_OL | GR_OL |
|---|---|---|---|---|---|---|---|
| All Basins | > 0.001 | P | > 0.001 | P | > 0.001 | > 0.001 | *0.80 |
| | | C | 0.0038 | C | > 0.001 | 0.0012 | *0.33 |
| | | N | 0.0011 | N | > 0.001 | > 0.001 | *0.24 |
| | | Del_N | 0.034 | Del_N | 0.013 | 0.018 | *0.73 |
| | | Ca | *0.27 | Ca | - | - | - |
| | | Mn | 0.0078 | Mn | *0.17 | 0.0043 | *0.28 |
| | | Pb | > 0.001 | Pb | > 0.001 | > 0.001 | *0.058 |
| | | Zn | > 0.001 | Zn | > 0.001 | > 0.001 | *0.26 |
| | | Fe | > 0.001 | Fe | 0.0021 | > 0.001 | *0.80 |
| | | Al | > 0.001 | Al | > 0.001 | > 0.001 | *0.054 |
| | | Na | 0.0056 | Na | > 0.001 | 0.0019 | 0.039 |

Table 3. A table displaying the P-value for each of the analyses run for the whole basin dataset without outliers. Grayed out cells with an asterisk have P-values > 0.05.

| MANOVA | P Value | ANOVA | P Value | t.test | HA_GR | HA_OL | GR_OL |
|---|---|---|---|---|---|---|---|
| Dam Pool | > 0.001 | P | > 0.001 | P | > 0.001 | > 0.001 | *0.87 |
| | | C | 0.0084 | C | *0.28 | > 0.001 | *0.52 |
| | | N | > 0.001 | N | > 0.001 | > 0.001 | *0.59 |
| | | Del_N | 0.026 | Del_N | 0.023 | *0.097 | *0.44 |
| | | Ca | *0.053 | Ca | - | - | - |
| | | Mn | 0.026 | Mn | *0.58 | *0.20 | *0.42 |
| | | Pb | > 0.001 | Pb | > 0.001 | > 0.001 | 0.0019 |
| | | Zn | > 0.001 | Zn | > 0.001 | > 0.001 | 0.036 |
| | | Fe | > 0.001 | Fe | > 0.001 | > 0.001 | 0.027 |
| | | Al | 0.0022 | Al | > 0.001 | > 0.001 | > 0.001 |
| | | Na | 0.031 | Na | > 0.001 | 0.0085 | > 0.001 |

Table 4. A table displaying the P-value for each of the analyses run for the dam pool dataset without outliers. Grayed out cells with an asterisk have P-values > 0.05.

## Figures

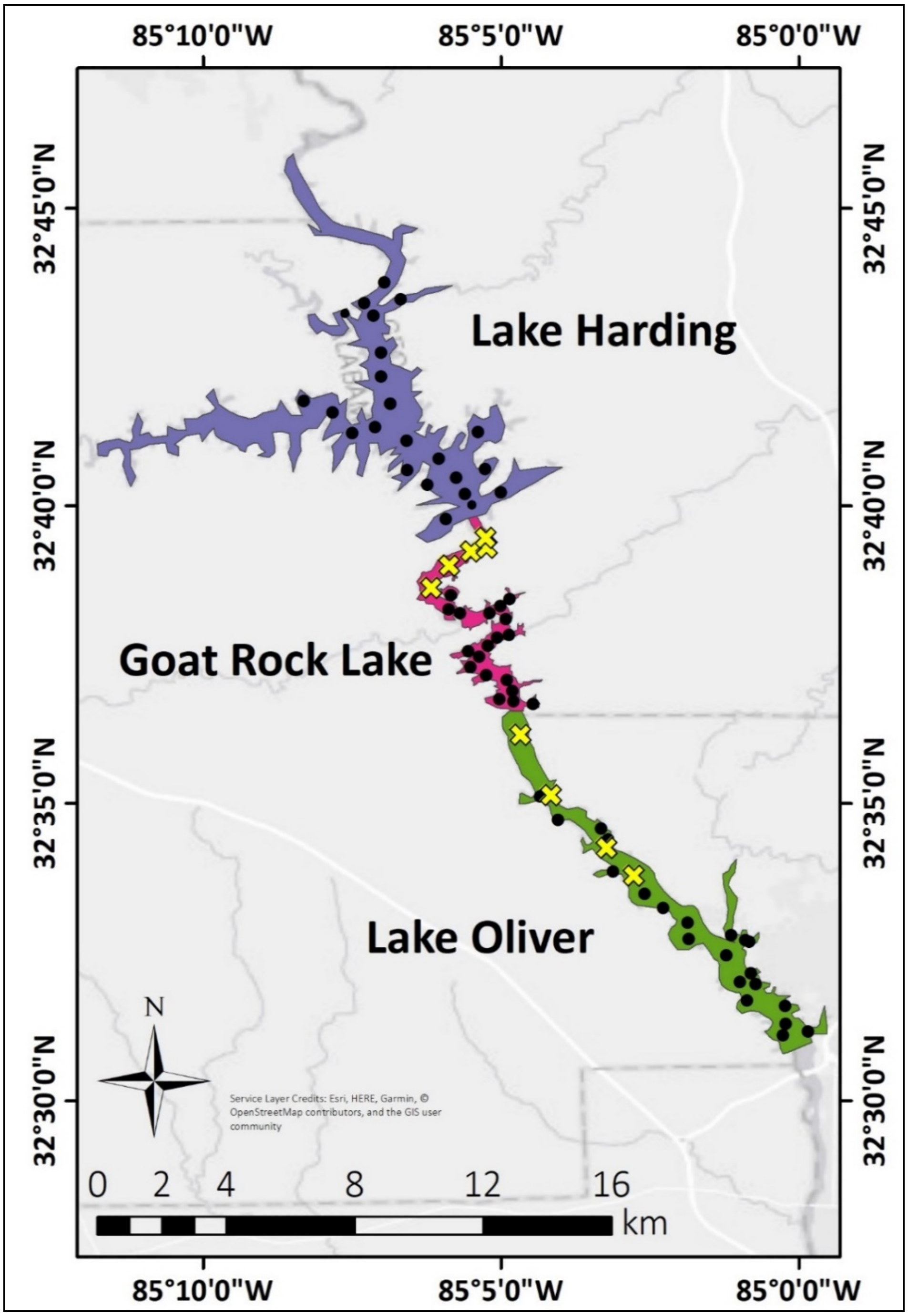


Figure 8. A map of all three studied reservoirs; Lake Harding (HA), Goat Rock Lake (GR), and Lake Oliver (OL). Both black dots and yellow x's were all surface sediment sample sites. Yellow x's were sample sites where no sediment was present.

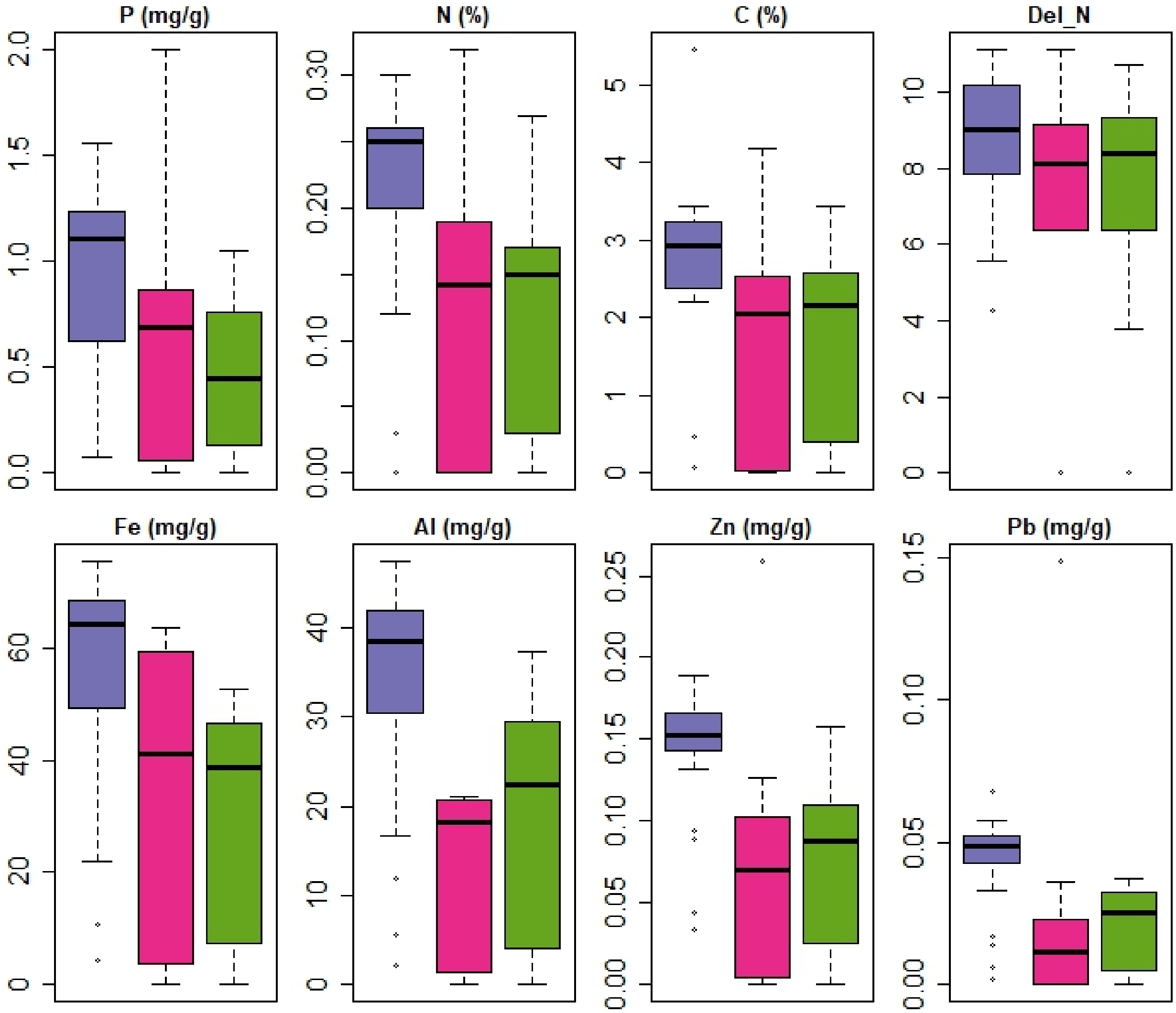


Figure 9. A boxplot comparing concentrations of nutrients and pigment of all three reservoirs using all of the surface sediment samples taken from each reservoir.

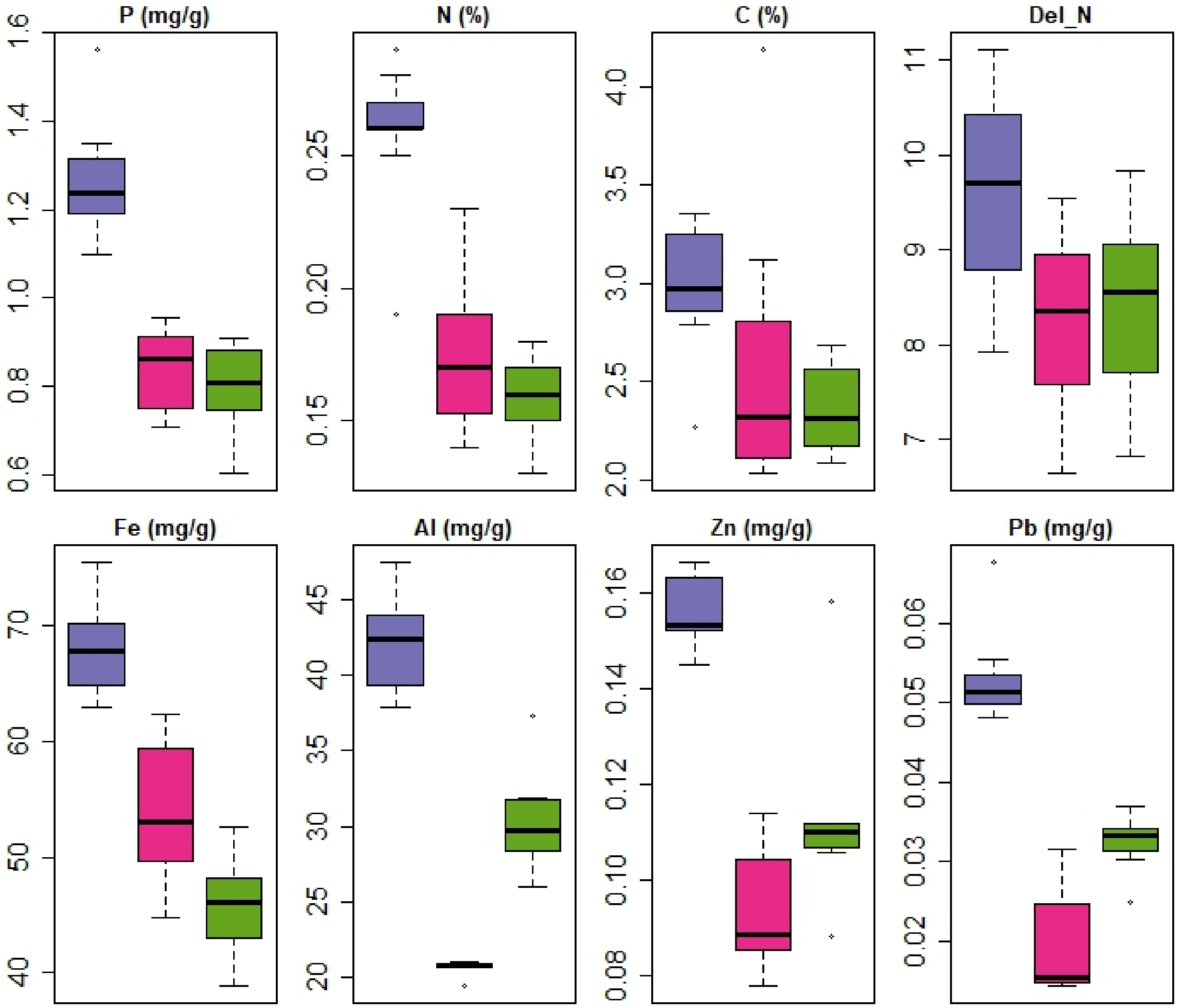


Figure 10. A boxplot comparing concentrations of nutrients and pigment of all three reservoirs using only the surface sediment samples taken from the dam pooling area.

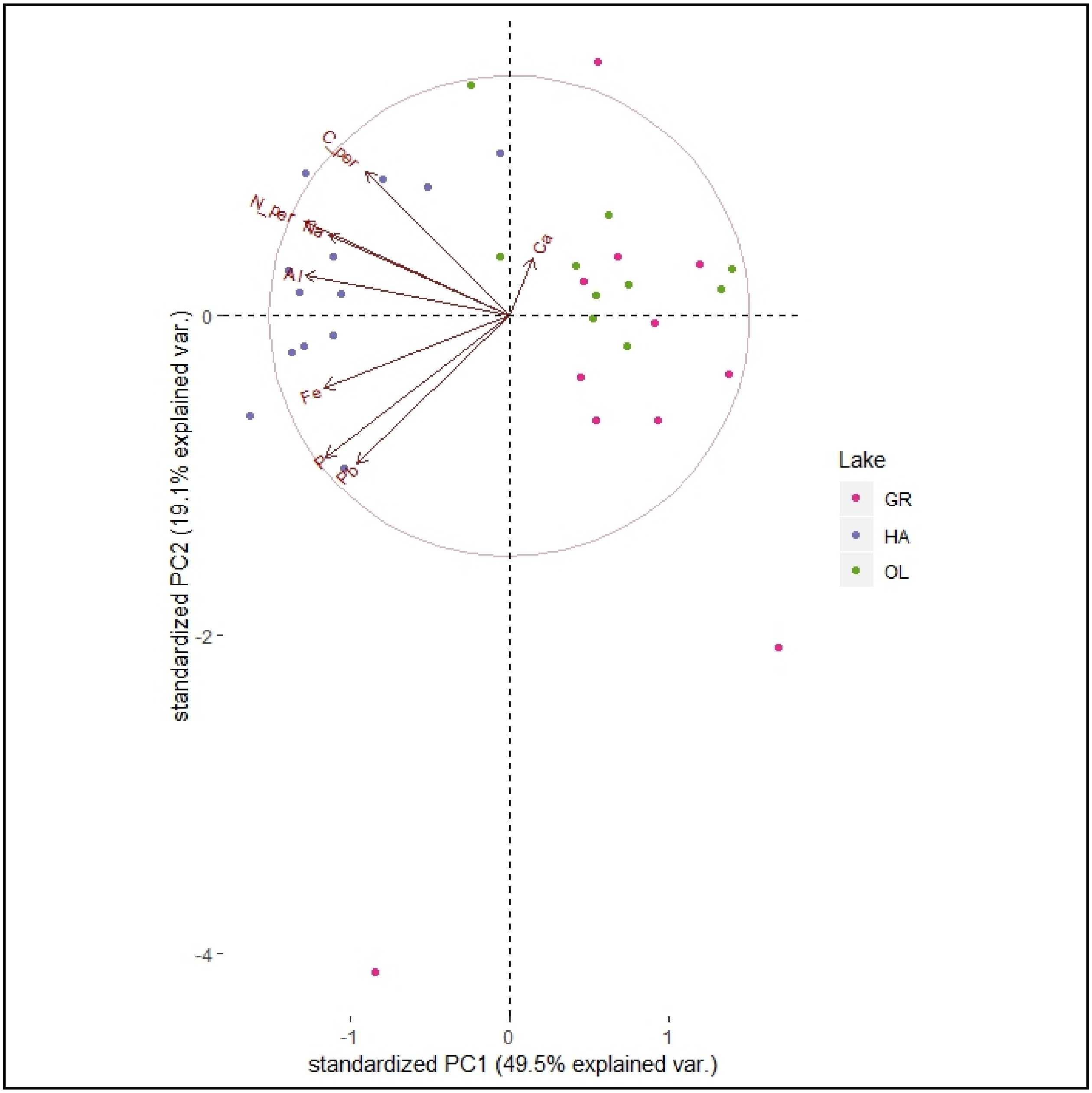


Figure 11. A PCA of all three lakes dam pooling area.

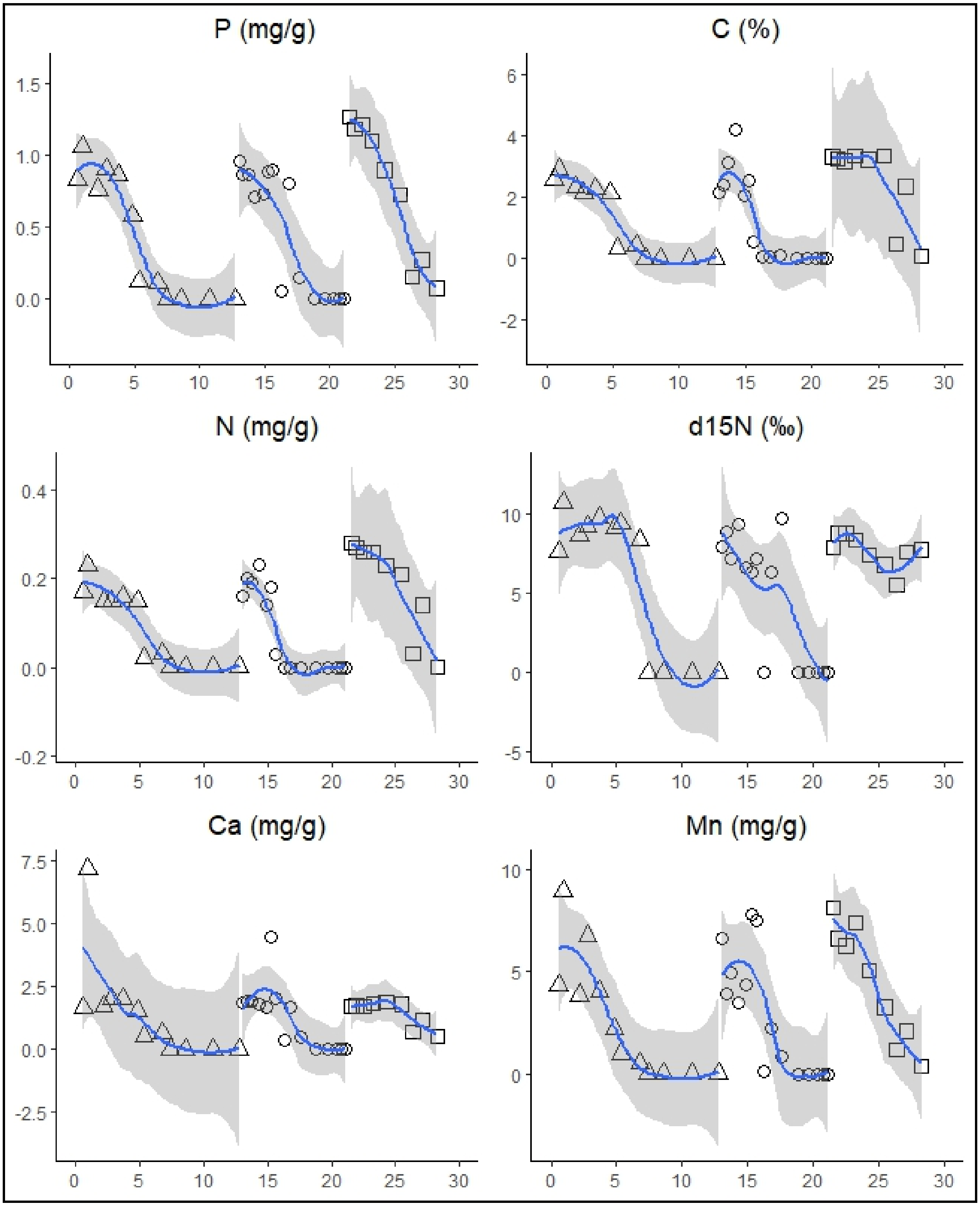


Figure 12. A scatter plot, plotting nutrients concentrations against distance (river km) from OL dam.

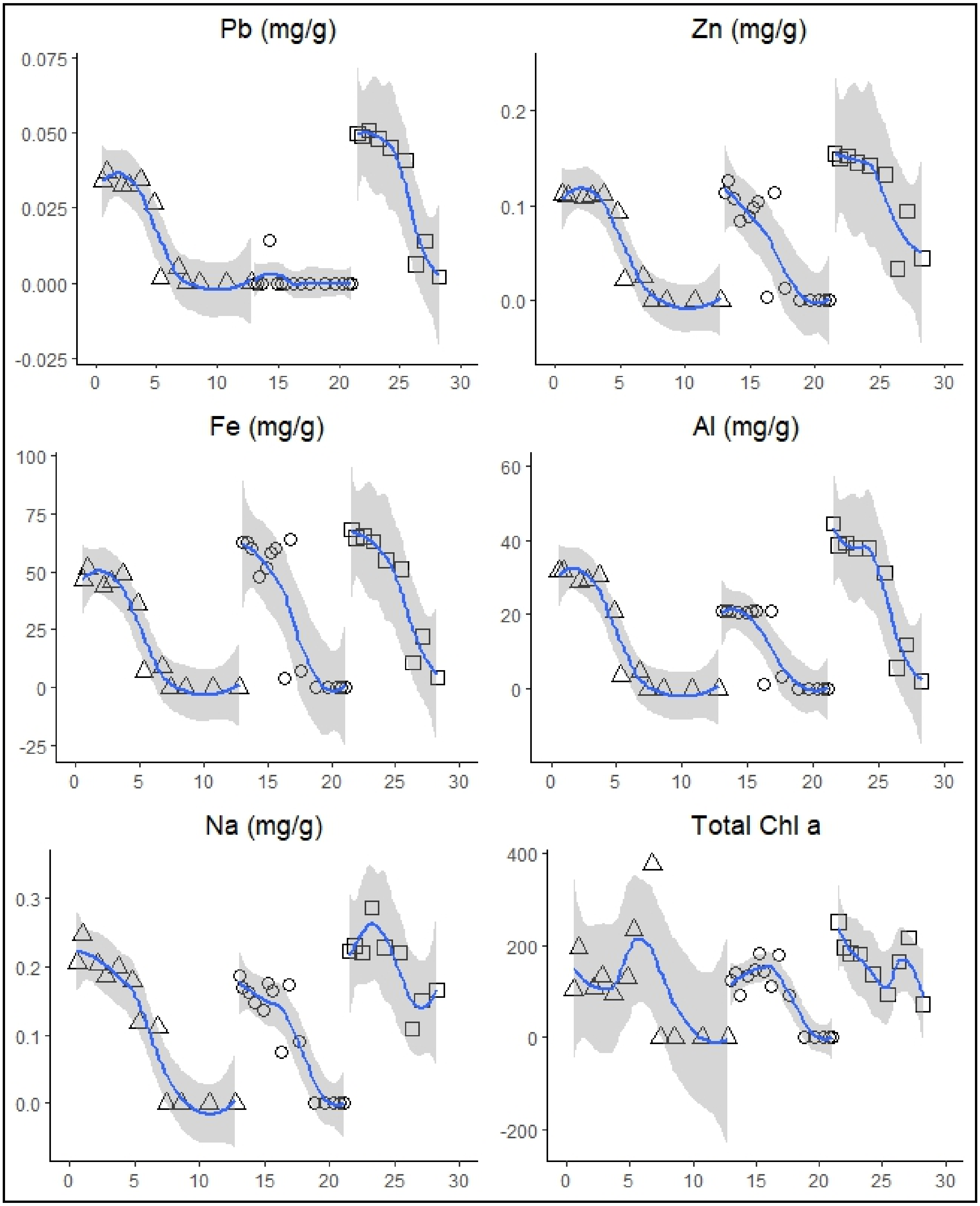


Figure 13. A scatter plot, plotting nutrients concentrations against distance (river km) from OL dam.

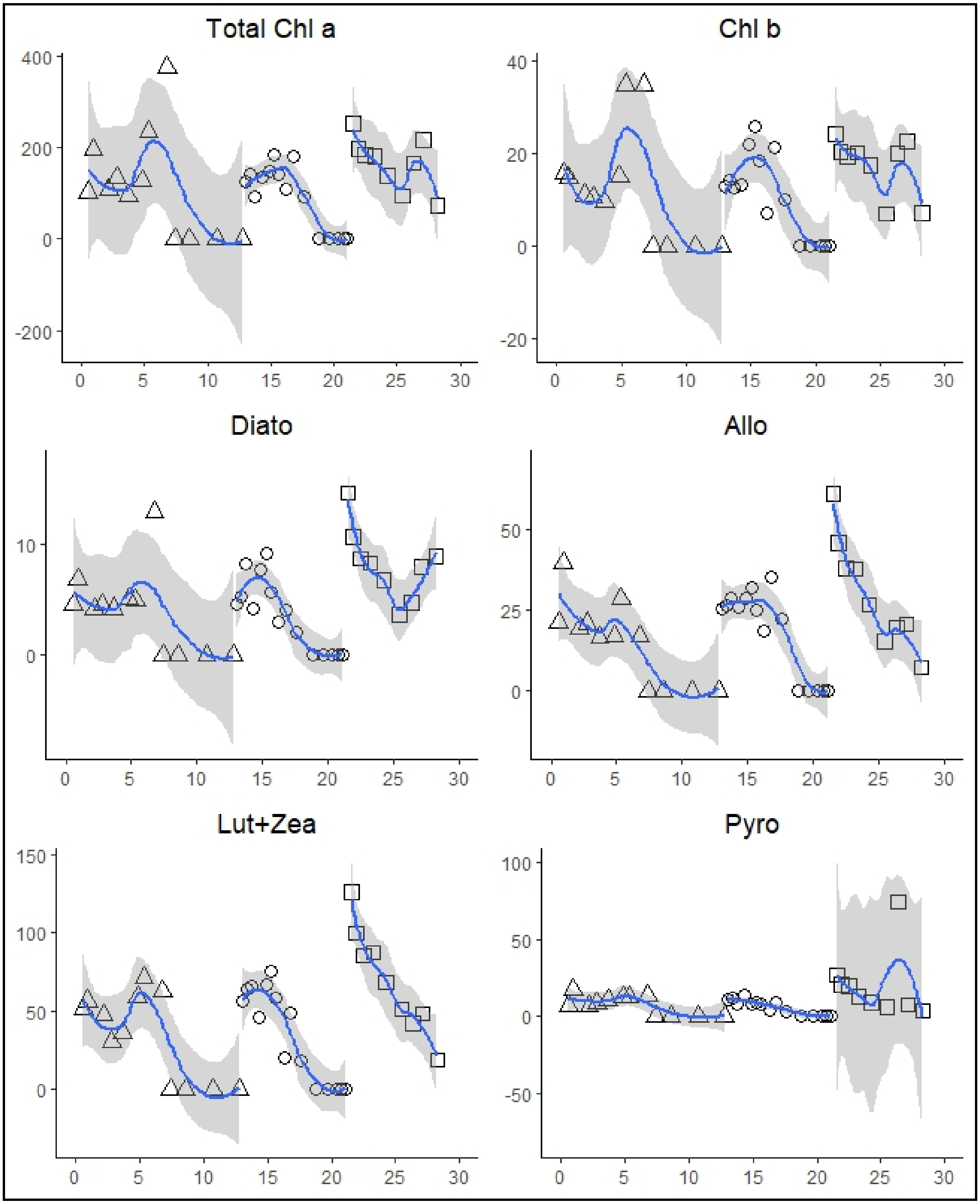


Figure 14. A scatter plot, plotting pigments against distance (km) from OL dam.

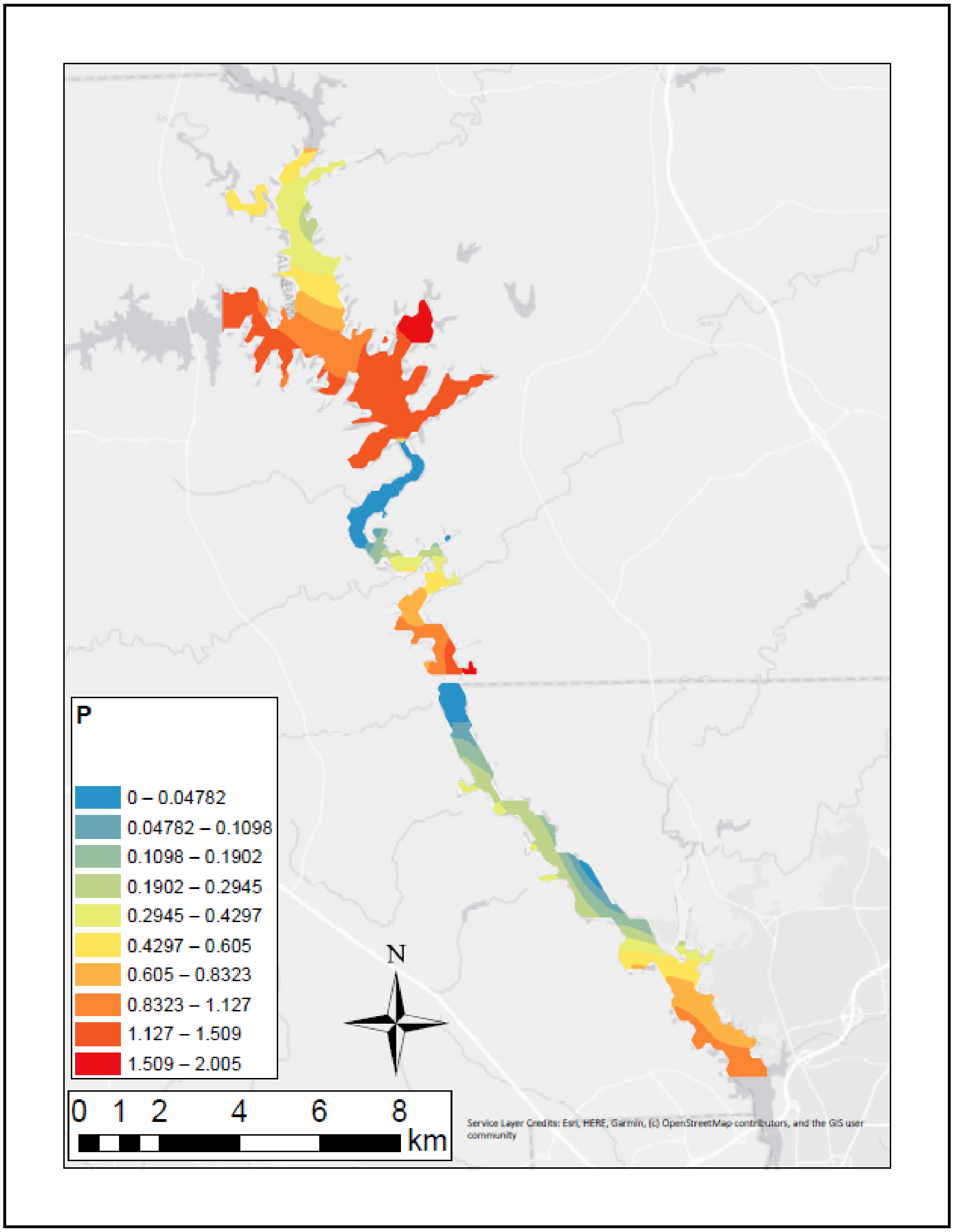


Figure 15. A smooth kernel interpolation map with barriers of P (mg/g). The RMS error is 0.24459.

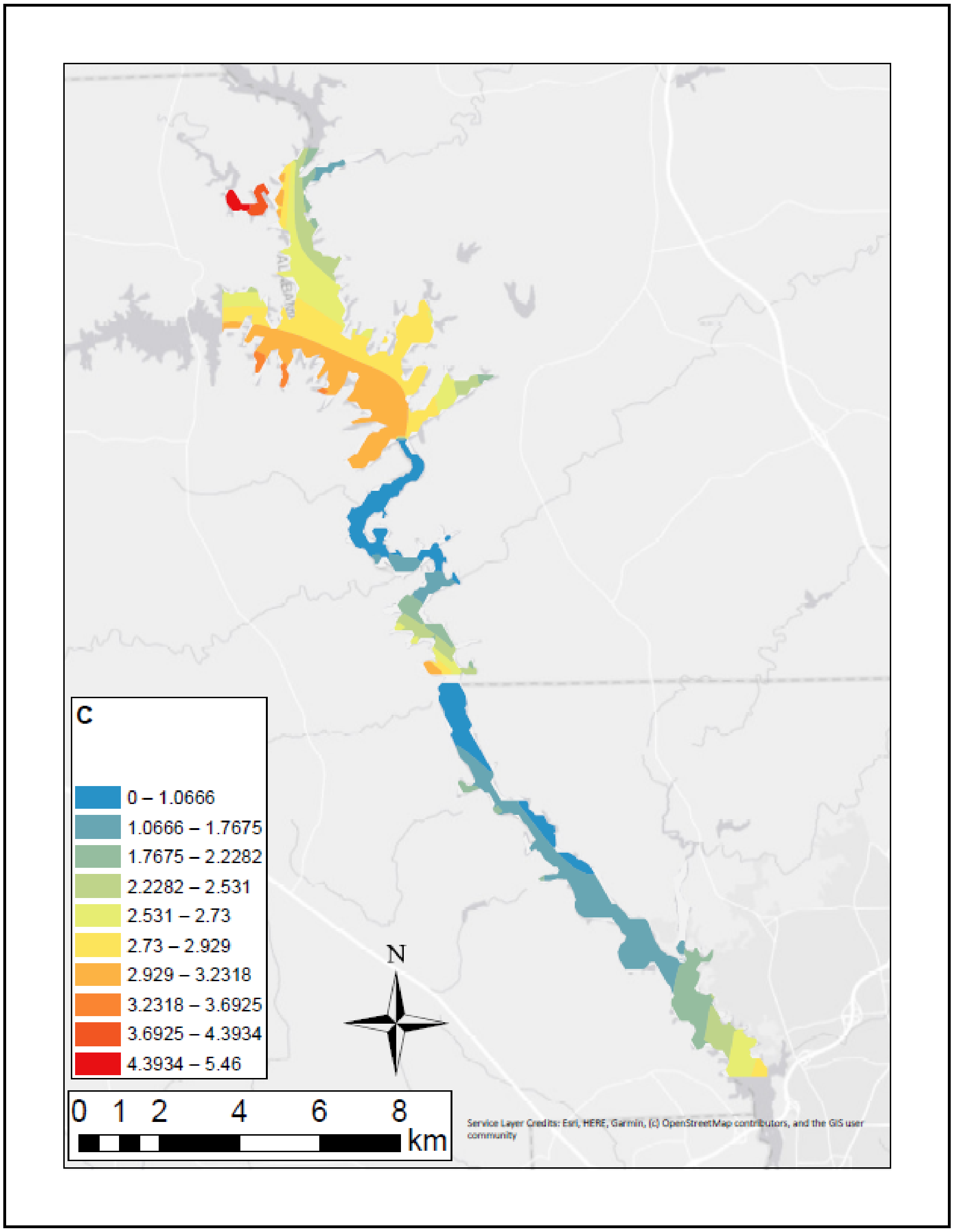


Figure 16. A smooth kernel interpolation map with barriers of C (%). The RMS error is 1.21185.

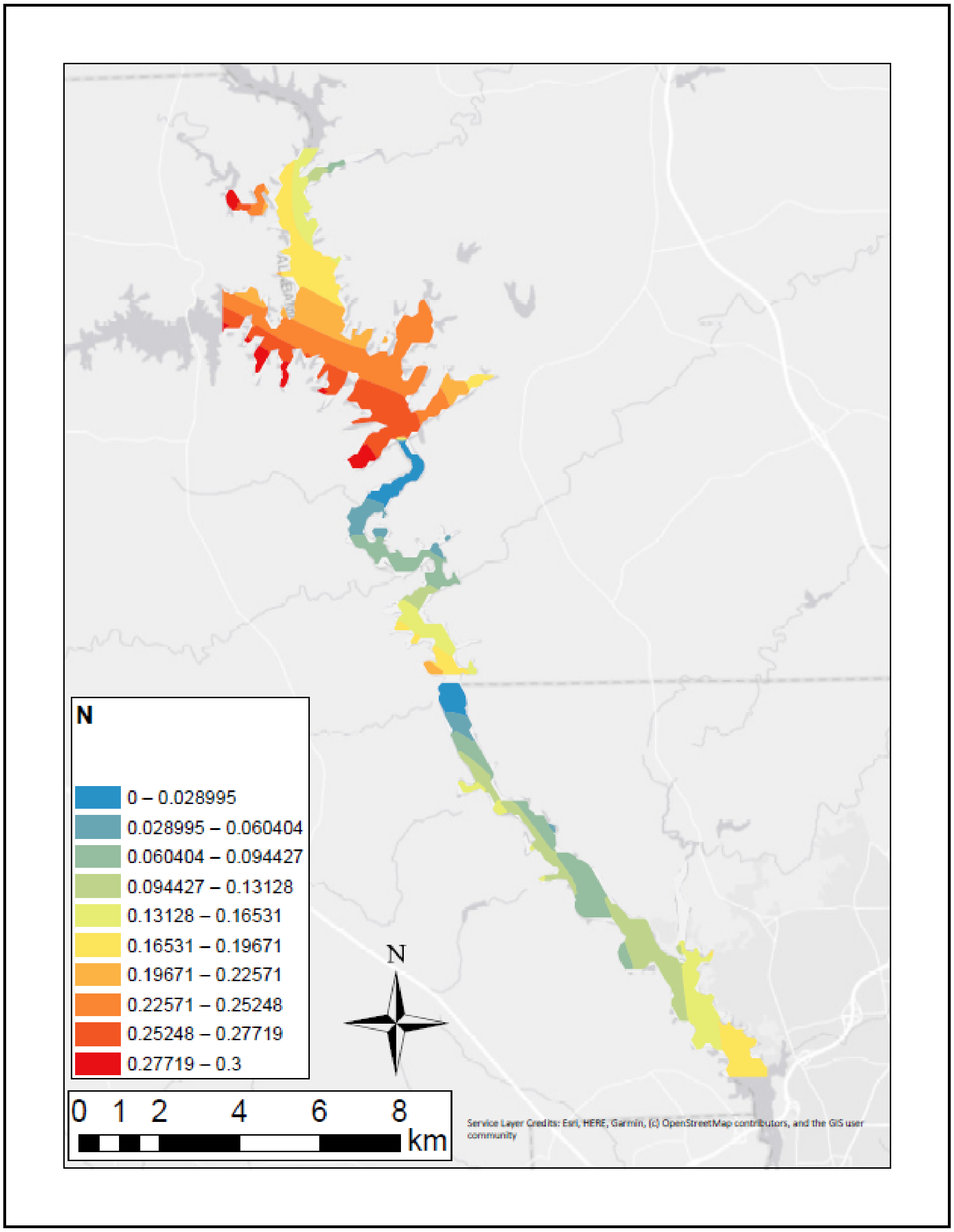
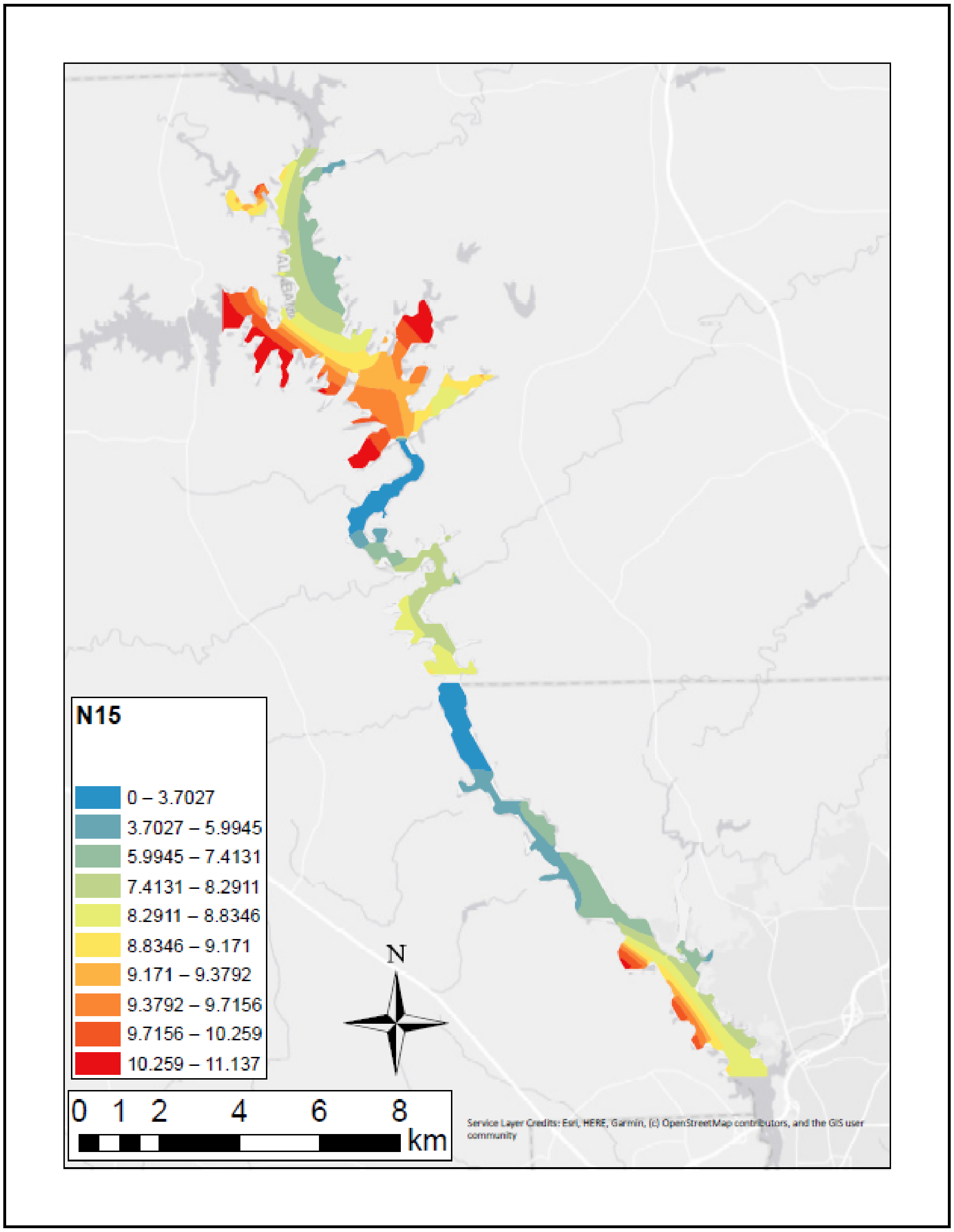


Figure 17. A smooth kernel interpolation map with barriers of N (%). The RMS error is 0.0836.



Service Layer Credits: Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 18. A smooth kernel interpolation map with barriers of $\delta^{15}N$ (‰). The RMS error is 2.79212.

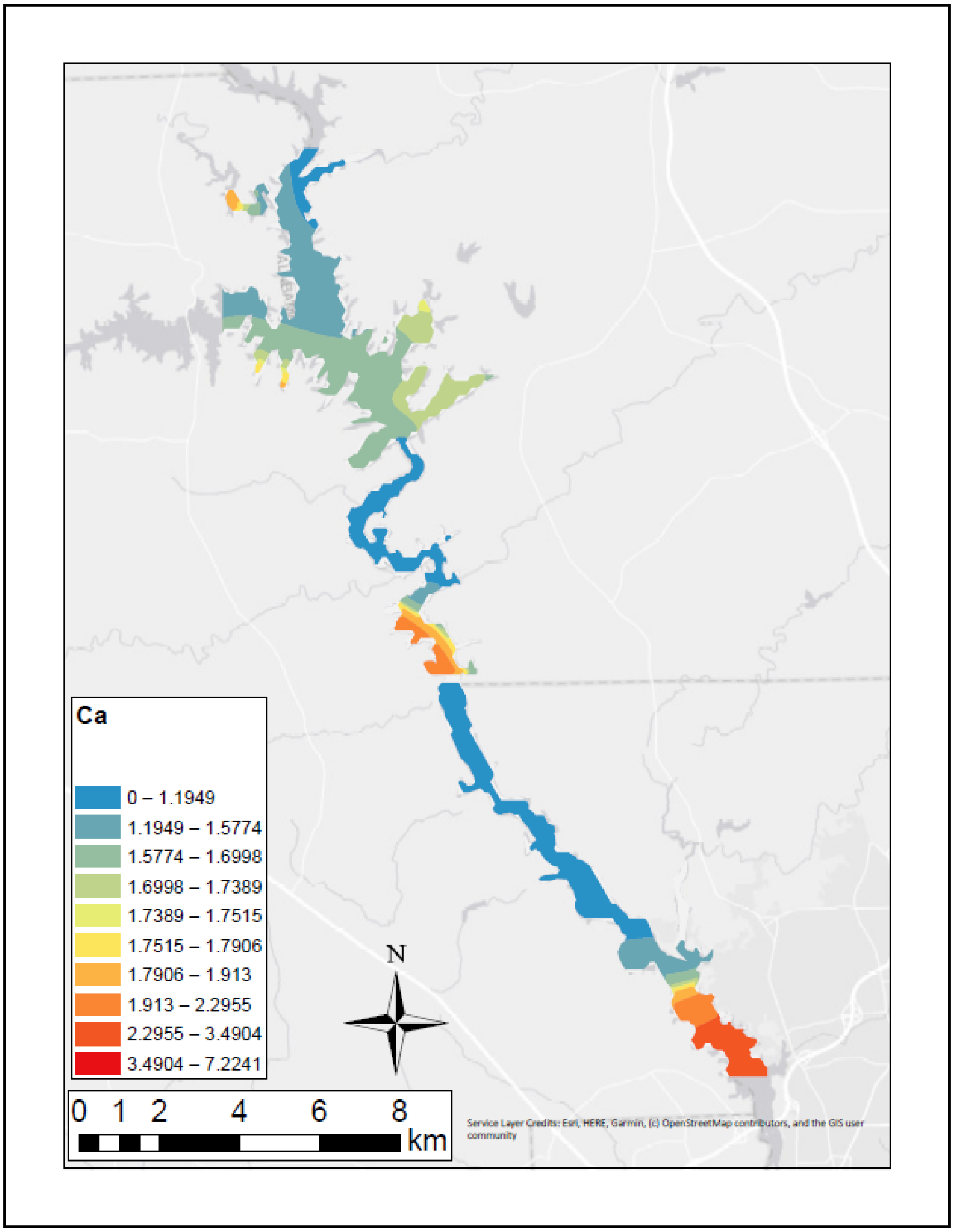


Figure 19. A smooth kernel interpolation map with barriers of Ca (mg/g). The RMS error is 0.92250.

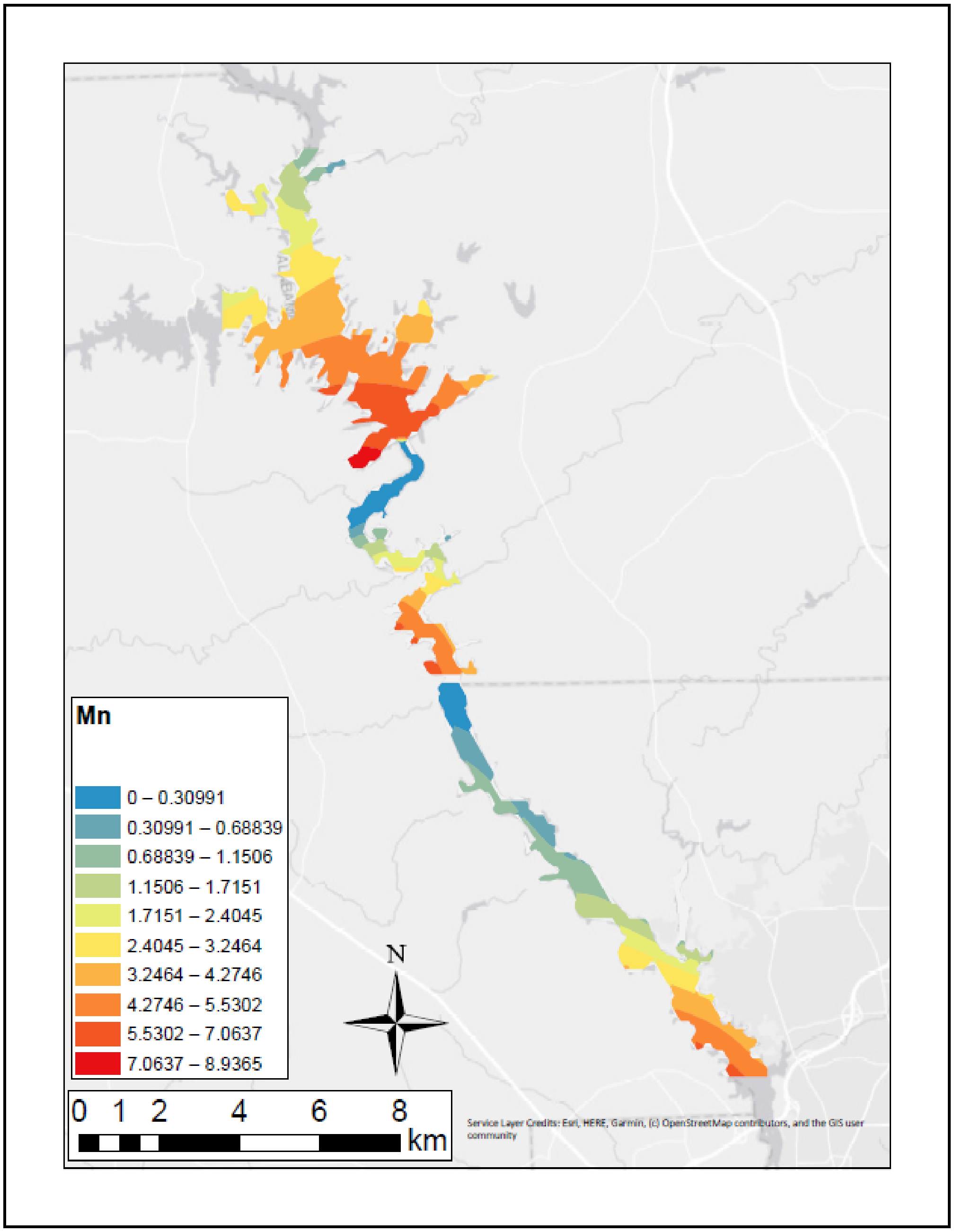


Figure 20. A smooth kernel interpolation map with barriers of Mn (mg/g). The RMS error is 1.60842.

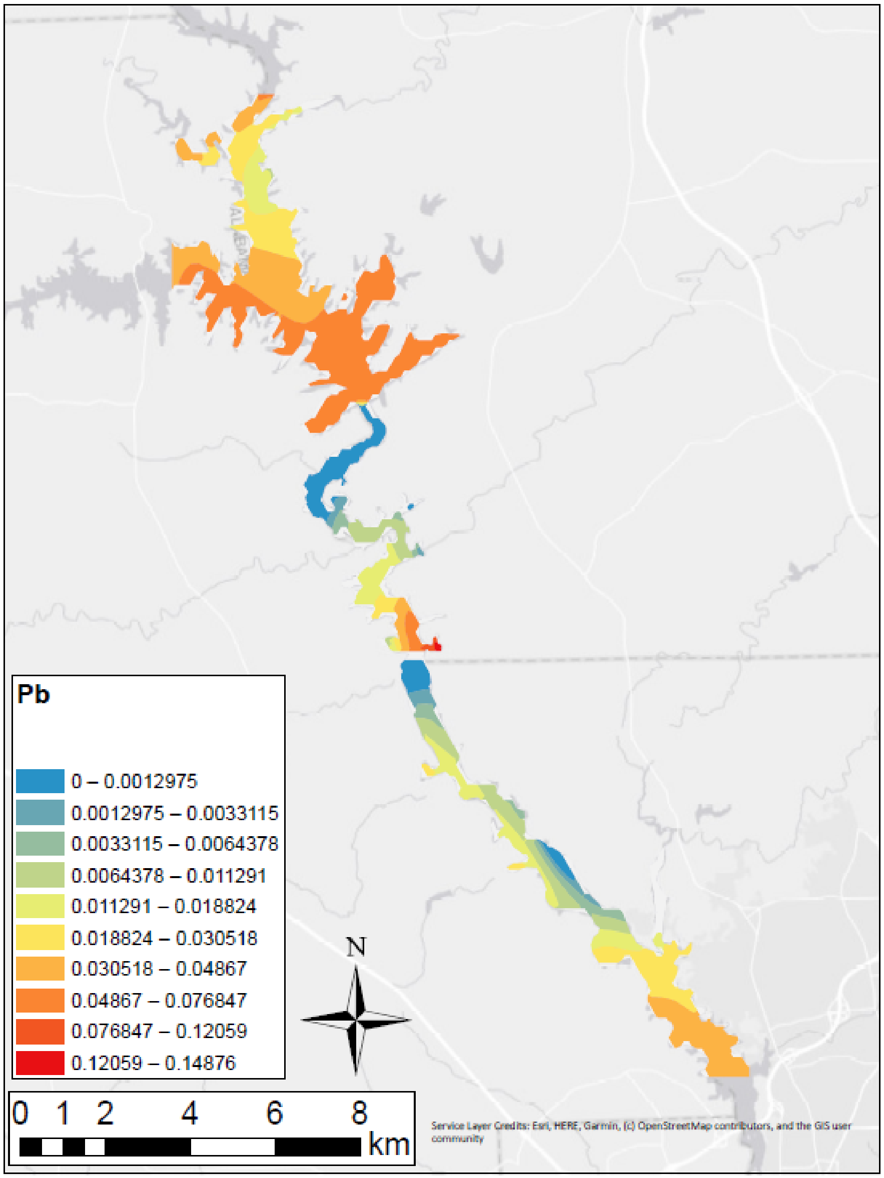


Figure 21. A smooth kernel interpolation map with barriers of Pb (mg/g). RMS error is 0.01893.

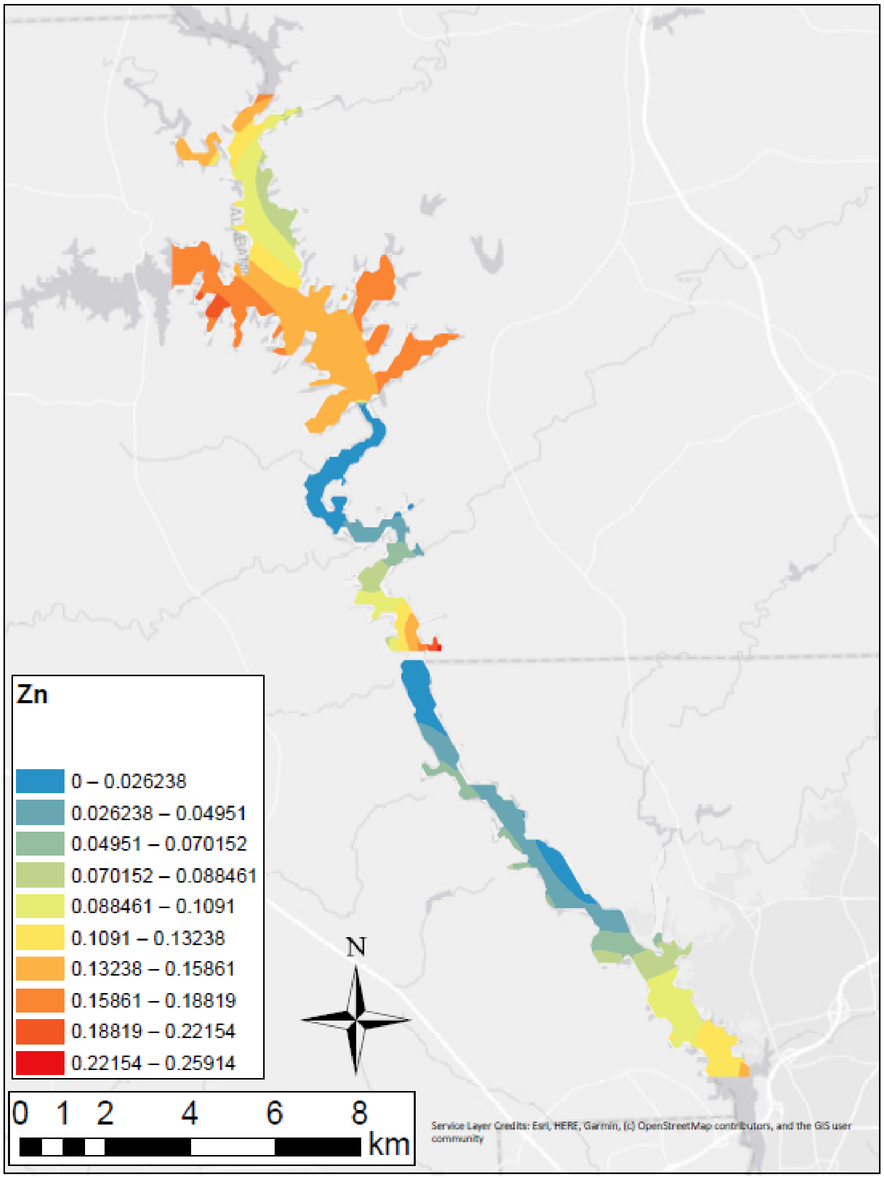


Figure 22. A smooth kernel interpolation map with barriers of Zn (mg/g). The RMS error is 0.03920.

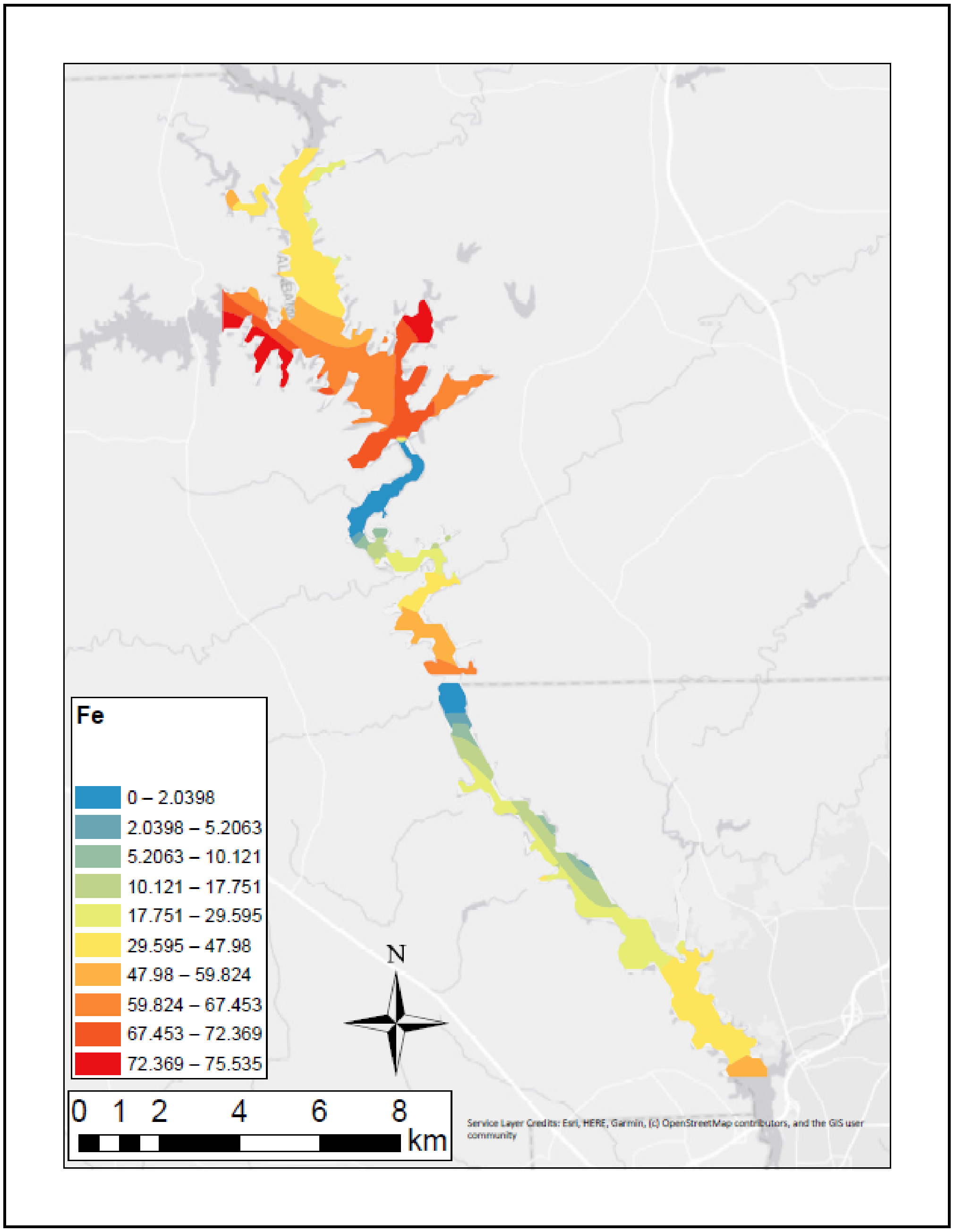


Figure 23. A smooth kernel interpolation map with barriers of Fe (mg/g). The RMS error is 15.3219.

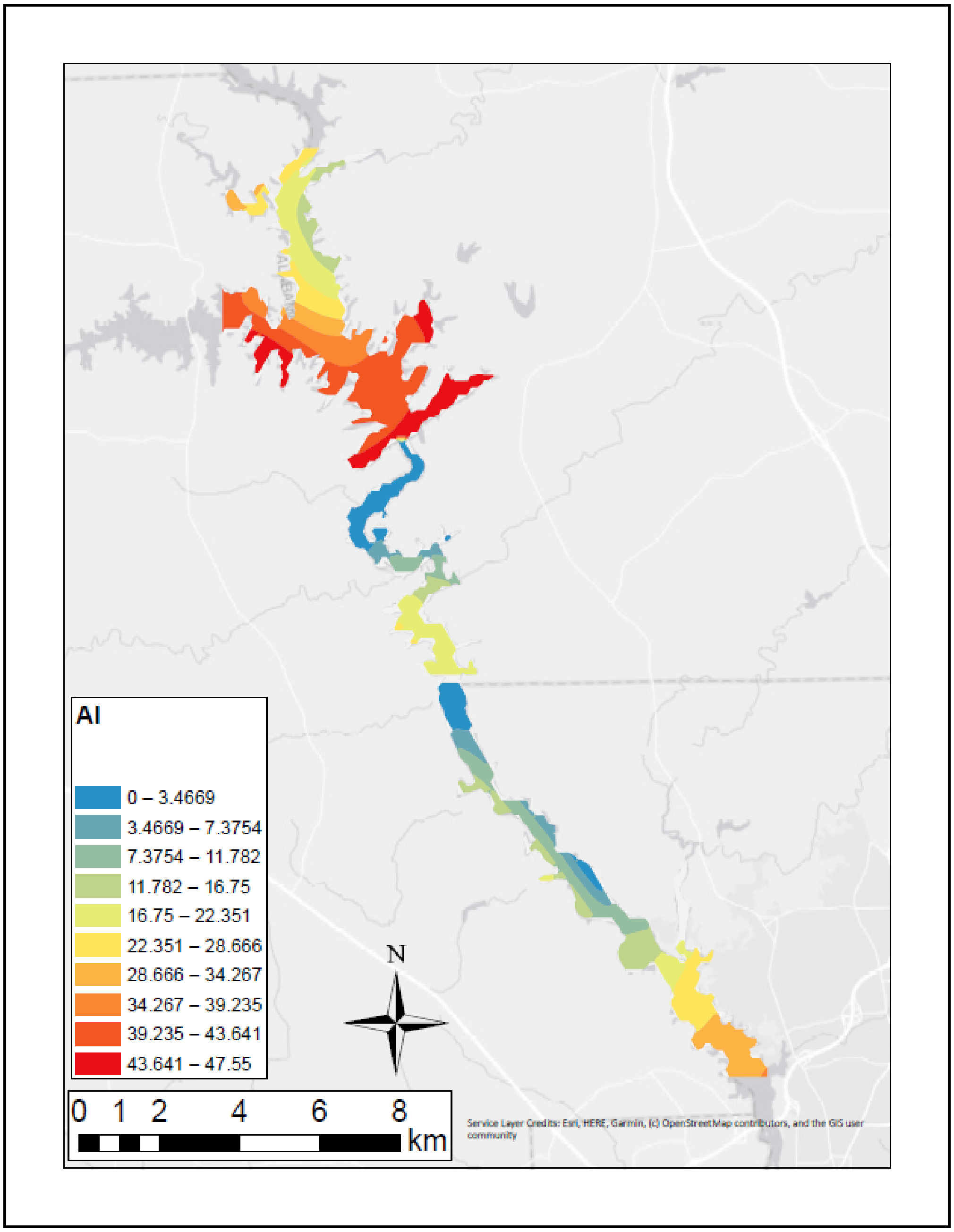


Figure 24. A smooth kernel interpolation map with barriers of Al (mg/g). The RMS error is 8.22885.

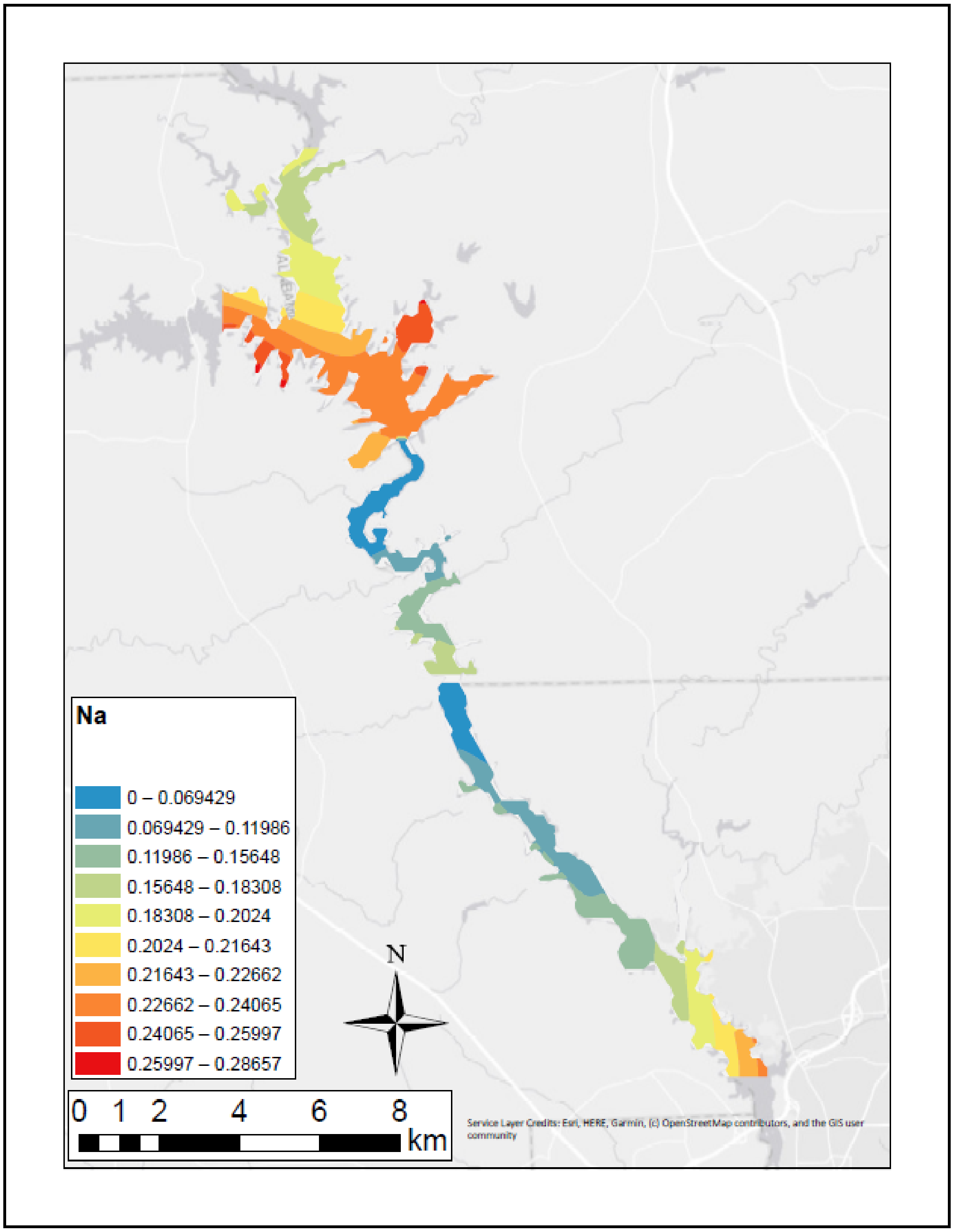


Figure 25. A smooth kernel interpolation map with barriers of Na (mg/g). The RMS error is 0.04752.

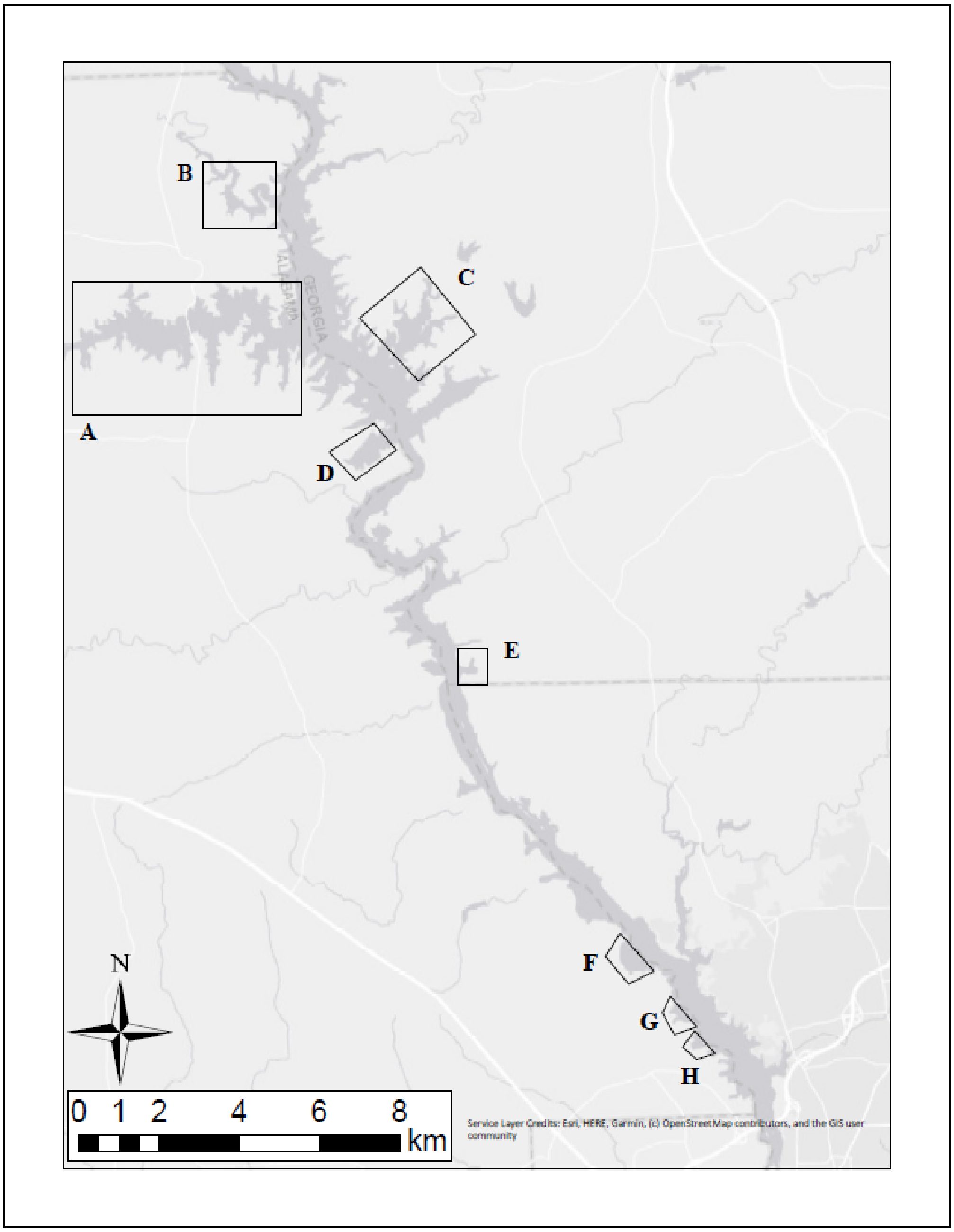


Figure 26. A map of specific sites within each of the three reservoirs. Sites A and B are both branches while sites C-H are all coves.