Evaluating the Economic Benefits of Land Protection in the Savannah River Watershed

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Prepared by the
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Protection, Inc.

for the Savannah River Clean
Water Fund

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Definitions of Acronyms & Abbreviations

Acronym/ Abbreviation	Definition
ANCOVA	Analysis of Covariance
BJWSA	Beaufort-Jasper Water and Sewer Authority
CWP	Center for Watershed Protection, Inc.
DBP(s)	Disinfection Byproduct(s)
DBPR(s)	Disinfectant and Disinfection Byproducts Rule(s)
DOC	Dissolved Organic Carbon
EPA	United States Environmental Protection Agency
GIS	Geographic Information System
HUC	Hydrologic Unit Code
MGD	Million Gallons per Day
MRLC	Multi-Resolution Land Characteristics Consortium
MSA	(Aiken-Augusta) Metropolitan Statistical Area
NLCD	National Land Cover Database
PAC	Powdered Activated Carbon
PFAS	Per- and Polyfluoroalkyl Substances
PWS(s)	Public Water System(s)
RM	River Mile
SPARROW	Spatially Referenced Regression on Watershed Attributes
SRCWF	Savannah River Clean Water Fund
SRS	Savannah River (Nuclear) Site
SWPP	Source Water Protection Plan
TOC	Total Organic Carbon
TSS	Total Suspended Solids
USGS	United States Geological Survey
WIP	Watershed Implementation Plan
WQP	(National Water Quality Monitoring Council) Water Quality Portal

Introduction

The Savannah River Clean Water Fund (SRCWF) is a non-profit with a mission to protect the water supply for communities and businesses surrounding the Savannah River in Georgia and South Carolina. The SRCWF was formed in 2014, and it is based on the shared recognition among state and federal government agencies, non-profits, landowners, and both business and private interests in the Savannah River Basin of the explicit connection between the Basin's land resources and uses and their impacts on raw water supplies.

To maintain the quality of the Savannah River as a source water, the SRCWF has set a goal of maintaining 60% natural cover in the watershed, has applied a conservation priority model to identify priority parcels for conservation based on their higher value for water quality maintenance, and is partnering with major water utilities and other investors to permanently protect these high-priority parcels. These partners include water users and dischargers to the River who would benefit directly from land protection. While the SRCWF has documented the water quality maintenance services provided by forests and well-managed agricultural lands (Krueger & Jordan, 2009), the SRCWF, water utilities, and industries would like more information specific to their watershed and that quantifies the economic benefits.

This white paper was developed by the Center for Watershed Protection, Inc. (CWP) for the SRCWF to fill this gap. More specifically, it aims to characterize the cost saving potential that drinking water utilities may realize when forest cover within the source water area is preserved and/or increased. In order to do that, the relationships between land cover, water quality, and drinking water treatment costs must be evaluated.

The connection between upstream land cover and downstream water quality is well-documented. Developed, agricultural, and forested upstream land covers each have effects on downstream water quality parameters. Watersheds with dominant developed or agricultural areas are typically correlated with higher downstream concentrations of nutrients (e.g., nitrogen and phosphorus), sediments (e.g., total suspended solids and turbidity), organic compounds (e.g., total organic carbon, dissolved organic carbon, and disinfection byproducts), indicators of algae production (e.g., chlorophyll-a, cyanobacteria, algal growth potential bioassay results, etc.), fecal coliform bacteria, and various other parameters associated with reduced water quality (Schueler et al., 2009; Mehaffey et al., 2005; Tong & Chen, 2002; Wear et al., 1998). Research specific to EPA Region 4, which contains the entirety of the Savannah River, supporting the connection between upstream land cover and downstream water quality exists as well (Nash & Chaloud, 2011; Schoonover & Lockaby, 2006; Roy et al., 2003).

Studies on the connection between source water quality and drinking water treatment costs are less plentiful, but as concentrations of regulated pollutants increase at the intake, additional treatment (and therefore additional costs) may be required. Even fewer studies have attempted to quantify the benefits of forest cover in terms of drinking water utility treatment costs. Although several of these studies exist throughout the United States, comparable studies within the Savannah River watershed were not identified (Table 1). While some of these studies identified quantifiable economic benefits associated with the protection of forested land, a few found the opposite, and others found that results are highly variable based on the pollutant of concern, treatment plant processes, and watershed characteristics. Additionally, there are challenges associated with attributing treatment cost data to water quality at a specific intake due to the manner in which many water treatment plants report cost data.

Table 1. Overview of selected existing studies that connect land cover and drinking water treatment costs.

Citation	Reference Name	Location	Brief Description of Findings
Vedachalam et al., 2018	Source Water Quality and the Cost of Nitrate Treatment in the Mississippi River Basin	Iowa, USA and Illinois, US	Analyzed 10 years of water quality and drinking water utility treatment cost data for three drinking water utilities in Illinois and Iowa Results indicate that land conservation programs that minimize nitrogen discharges have potential to minimize costs to utilities, but extent of impact is dependent on a variety of watershed- and treatment-plant-specific factors.
Moltz et al., 2018	Forest Cover Impacts on Drinking Water Utility Treatment Costs in a Large Watershed	Potomac River Basin, Maryland, US	Modeled impacts of forest conservation and buffers on drinking water treatment costs at three utilities in the Potomac River Basin Results indicate that the effectiveness of forest conservation may be a function of the size of preservable forest (the more forested the watershed, the more cost-effective in terms of water treatment costs it is to preserve forests).
Elias et al., 2014	The Public Water Supply Protection Value of Forests: A Watershed-Scale Ecosystem Services Analysis Based upon Total Organic Carbon	Mobile, Alabama, US (2014)	Modeled changes in nutrient concentrations and loads to the Converse Reservoir under pre- and post- urbanization scenarios, and used results to quantify drinking water treatment costs The average increase in daily treatment costs when pre- and post-urbanization scenarios were compared was between $91 and $95 per square kilometer per day.
Price & Heberling, 2020	The Effects of Agricultural and Urban Land Use on Drinking Water Treatment Costs: An Analysis of United States Community Water Systems	US-wide datasets	Compared treatment costs for surface water and groundwater systems using a US-wide database of Community Water Systems In surface water systems, when the ratio of urban land to forest land was increased by 1%, annual treatment costs increased by 0.13%. Cost-effectiveness of forest preservation for treatment cost reduction varies considerably based on size of contributing area.
Warziniack et al., 2016	Effect of Forest Cover on Drinking Water Treatment Costs	US-wide dataset	Used results from a 2014 survey of water treatment utilities in forested US ecoregions in order to develop two regression models: an ecological production function (connecting watershed land use to riverine water quality), and an economic benefits function (connecting watershed characteristics and treatment processes to drinking water treatment costs)

Table 1. Overview of selected existing studies that connect land cover and drinking water treatment costs.

Citation	Reference Name	Location	Brief Description of Findings
			Results did not indicate a strong connection between land use and TOC. Converting 1% of a watershed from forested to developed cover was associated with a 3.9% increase in turbidity.
Hudak et al., 2013	Estimating Potential Costs of Watershed Development on Drinking Water Treatment	West River Watershed, Connecticut, US	Conducted a watershed build-out analysis and used results with nutrient loading and water quality response models to quantify costs/benefits of forest conservation and treatment process improvements in a reservoir in Connecticut The long-term cost of forestland acquisition and preservation was significantly lower than the annual operation and maintenance cost associated with upgrading water treatment technology.
Podolak et al., 2015	Estimating the Water Supply Benefits from Forest Restoration in the Northern Sierra Nevada	Sierra Nevada, California, US	Analyzed 11 watersheds in the northern Sierra Nevada (California) to develop benefit-cost ratios for various degrees of implementing forest restoration and thinning Found the potential economic benefits of forest thinning (measured as increased potential for hydropower production) may be sufficient to offset the cost of thinning; limited findings on the economic value of forest restoration
Heberling et al., 2015	Comparing Drinking Water Treatment Costs to Source Water Protection Costs using Time Series Analysis	Clermont County, Ohio, US	Presents framework for comparing drinking water treatment costs to source water protection costs using a plant in southeast Ohio and its contributing watershed as an example Results did not indicate a strong financial incentive supporting source water protection for water treatment cost reduction
Freeman et al., 2008	Statistical Analysis of Drinking Water Treatment Plant Costs, Source Water Quality, and Land Cover Characteristics	Northeastern US	In-depth literature review about connections between land cover, source water quality, and drinking water treatment plant costs; analyzes data (contributing watershed land cover, water quality, and treatment costs) from 60 water treatment plants in the northeastern US Identified significant relationships between percent land cover, source water quality, and drinking water treatment costs; however, variability due to confounding variables (e.g., water treatment plant processes/materials, and differences in hydrology, geology, and physiographic region) was high.

This white paper aims to build on the available resources connecting forest cover, water quality, and drinking water treatment costs specific to the Savannah River watershed. CWP compiled and analyzed data from parts of the Middle and Lower Savannah sub-basins to quantify specific elements that can be used to describe the economic benefits of land protection. The results of this analysis are presented in this white paper.

This white paper is organized into four primary sections:

1) Evaluating Relationships Between Land Cover & Water Quality
2) Evaluating Relationships Between Water Quality & Treatment Costs
3) Watershed Sources of Taste & Odor (T&O) Compounds
4) Conclusions

The key findings of this work can be found in the summary box on the following page.

Summary of Key Findings for the Middle Savannah Watershed

- **Forest cover significantly and meaningfully decreases Total Nitrogen (TN)** yield, even after accounting for the effects of developed cover.

- Developed cover (i.e., urban area) significantly and meaningfully increases yields of all evaluated water quality parameters: Total Nitrogen (TN), Total Phosphorus (TP), Total Suspended Solids (TSS), and Flow. Consequently, **preserving forest cover to reduce the amount of developed/urban cover would meaningfully reduce the yields of all evaluated water quality parameters**.

- Wetland cover statistically and meaningfully reduces yields of both TSS and flow, and it has no significant impact on TN or TP yields. Agricultural cover did not statistically impact yields of any evaluated water quality parameter, possibly because so few of the subwatersheds in the Middle Savannah are dominated by agricultural uses.

- In the raw water at the Beaufort-Jasper Water & Sewer Authority (BJWSA) intake, there were **no statistically significant relationships between TN concentrations and concentrations of five taste-and-odor (T&O) compounds (TOC, geosmin, MIB, chlorophyll-a, and algae)**, either due to a lack of sufficient overlapping data points (geosmin, MIB, algae) or no significant relationship in the available dataset (TOC, chlorophyll-a). This is surprising given the association between TN and these compounds in the literature; however, it can be explained by the limited data availability.

- From January 2021 through June 2021, treatment thresholds for TOC and geosmin in raw water at the BJWSA intake were exceeded 7 and 6 times, respectively. **The total cost of additional (and possibly preventable) treatment (not including base doses) for TOC and geosmin on just the 12 days with exceedances in the first six months of 2021 were $7,815 and $60,246, respectively.** These data are highly dependent on how high the pollutant concentrations are above the treatment threshold and are therefore difficult to use in estimating potential future increases in treatment costs given the lack of a predictive relationship between raw water TN and T&O compounds.

- Based on a literature review, **upstream land uses have an influence on loads of TOC and cyanobacteria**; however, there is so much variability from study-to-study that it is difficult to apply quantifications from those studies to the Savannah River. **Nutrient loads are linked to cyanobacteria and algal growth**, even when accounting for bioavailability. **Flow volume** (i.e., discharge), **organic matter decomposition** (from woody wetlands and forests), **urban runoff**, and **effluent from wastewater treatment plants are linked to organic compounds like TOC and resultant disinfection byproducts (DBPs)**. Land management that considers and prioritizes these influences would likely minimize contaminant loads and reduce water treatment costs.

Section 1. Evaluating Relationships Between Land Cover & Water Quality

Study Area Selection

The scope of this white paper includes a focused analysis on selected subwatersheds. This white paper focuses on the Middle Savannah watershed and the intake location for the Beaufort-Jasper Water & Sewer Authority's Chelsea Water Treatment Plant (BJWSA Chelsea Plant).

The Middle Savannah was selected as a focus area for evaluating the relationship between land cover and water quality for a few reasons. First, the Middle Savannah is substantially upstream of the Savannah River's change in hydrology from riverine to tidal. The tidal portion of the Savannah River has been extensively studied, and incorporating the tidal component into this analysis would add complexity beyond the scope of this project. Additionally, the subwatersheds in the Middle Savannah constitute a representative mix of land covers and uses, including heavily developed, heavily forested, agricultural, and wetland areas.

Lastly, this area was selected to avoid the confounding effects of a possible point source of pollution downstream of the Middle Savannah. The Source Water Protection Plan (SWPP) for the City of Savannah Industrial & Domestic Water Treatment Plant identified a statistically significant increase in nutrient concentrations was observed downstream of the Middle Savannah (CWP, 2019). As samples progress downstream from River Mile (RM) 182.5 to RM 104, the concentrations of nitrogen and phosphorus decrease. However, from RM 104 to RM 61 (Clyo bridge), these concentrations progressively increase. These results indicate a pollution source near RM 104. The Middle Savannah watershed is upstream of RM 104, so it avoids the influence of this pollution source. The excerpt of the City of Savannah SWPP that analyzes and summarizes these results can be found in Appendix A.

Study Area Overview

The Middle Savannah watershed is comprised of smaller, subwatersheds called HUC12 subwatersheds (commonly "HUC12s"). The Middle Savannah spans from Clarks Hill Lake, just north of Augusta, down to the confluence of Beaverdam Creek and the Savannah River. The Middle Savannah includes just under 120 miles of the Savannah River mainstem, and, as the Savannah River forms the state boundary between South Carolina and Georgia, the watershed spans both states. In Georgia, the Middle Savannah is located primarily in Columbia, Richmond, and Burke counties, with portions also in McDuffie and Screven counties. In South Carolina, the Middle Savannah is located primarily in Aiken, Barnwell, and Allendale counties, with portions in Edgefield and McCormick counties. Figure 1 illustrates the location of the Middle Savannah watershed.

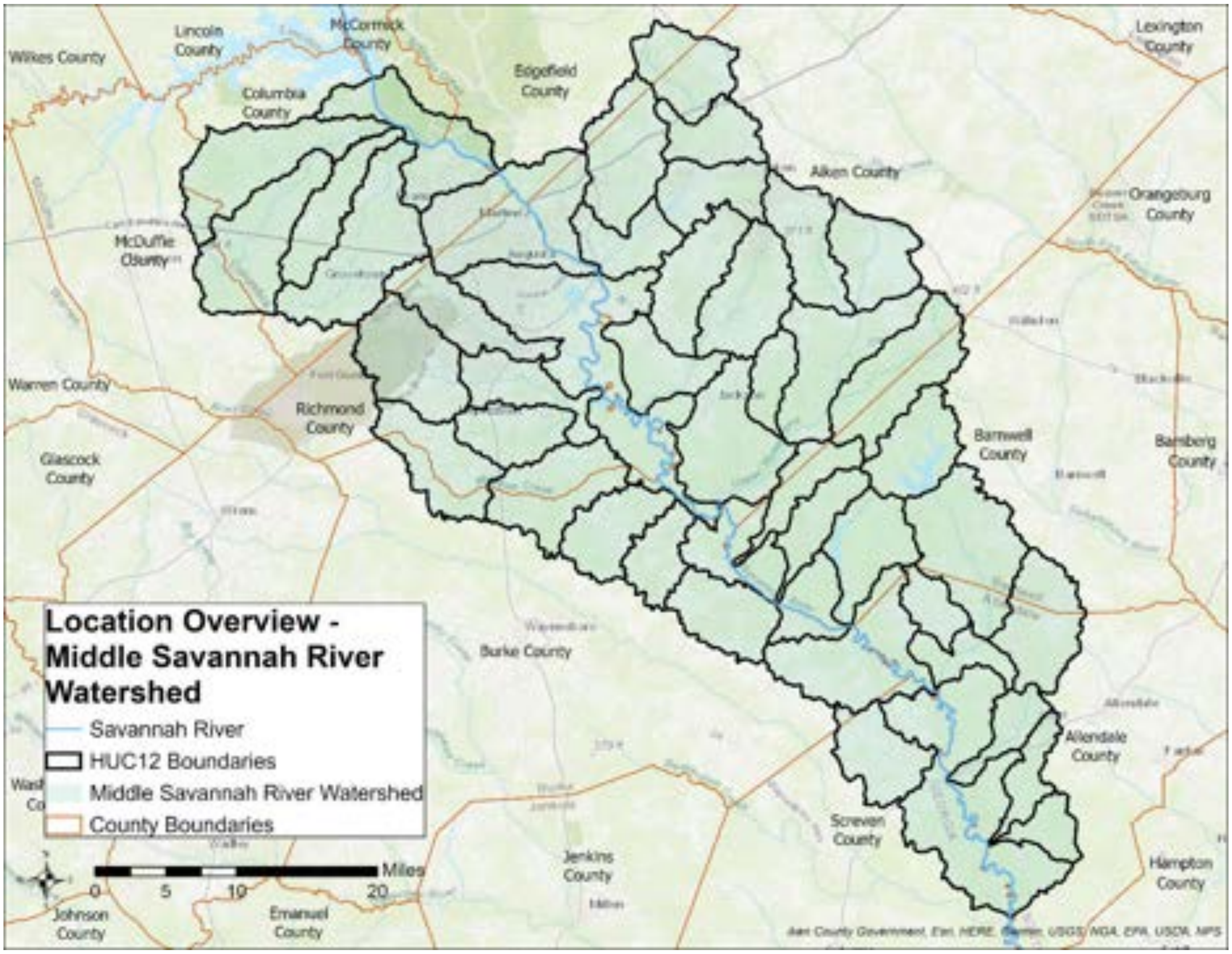

Figure 1. Location overview of Middle Savannah watershed.

Study Area Land Cover

Within the Middle Savannah River watershed, there are a variety of land cover types and land uses—everything from protected forested areas, wetlands, intensely developed urban areas, and agricultural areas exist within the watershed. Land cover within each subwatershed was quantified using the Multi-Resolution Land Characteristics Consortium's (MRLC) 2019 National Land Cover Database (NLCD). The NLCD is updated once per decade using Landsat satellite imagery and other supplemental data (MRLC, 2021).

Figure 2 illustrates the land cover within and surrounding the subwatersheds within the Middle Savannah watershed.

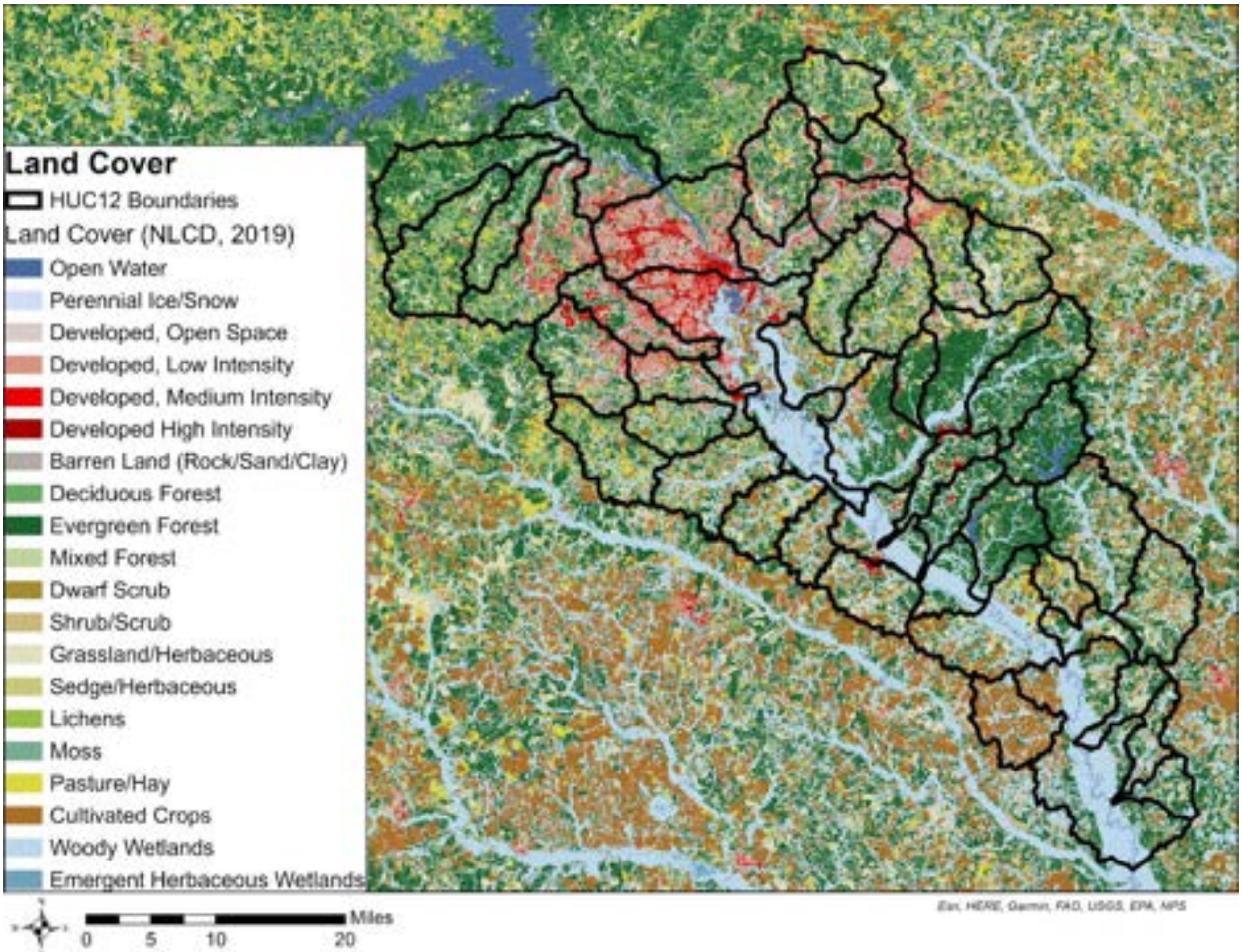

Figure 2. Land cover (NLCD, 2019) within and surrounding the Middle Savannah watershed.

The circular forested area along the east edge of the Middle Savannah is the Savannah River Site (SRS), which is an industrial complex that processes and stores nuclear materials. The SRS is managed by Savannah River Nuclear Solutions, LLC. There are multiple other occupants of the SRS, including federal, academic, and private sector organizations[1]. Approximately 170,000 acres of natural resources on the SRS, including the substantial forest cover, are managed by the U.S. Forest Service (USFS)[2].

The developed area in the northern portion of the watershed is the Augusta-Aiken Metropolitan Statistical Area (MSA). The City of Augusta is a more densely

[1] For more information about the SRS, visit: https://www.srs.gov/general/news/factsheets/srs_overview.pdf

[2] For more information about the Forest Service's role at SRS, visit: https://www.srs.gov/general/news/factsheets/usfs-sr.pdf

populated area along the west side of the Savannah River. It has population of nearly 200,000 people as of the 2019 U.S. Census. The Savannah River, from Augusta to the Atlantic Ocean is approximately 200 river miles (and 150 land miles).

Relatively substantial woody wetland areas form a buffer that surrounds the Savannah River. Additionally, primarily along the southeastern edge of the Middle Savannah watershed and immediately south of the SRS, there are both cultivated crop and hay/pasture agricultural areas.

Study Area Pollutant Yields

To begin evaluating the relationships between different types of land cover and downstream water quality, nutrient and flow contributions (referred to as “yields” or “loads”) were estimated for all of the subwatersheds in the Middle Savannah watershed. These estimates were derived using SPARROW (“Spatially Referenced Regression on Watershed Attributes”), which is model that is developed and maintained by the U.S. Geological Survey (USGS).

SPARROW is a widely evaluated, used, and supported model (Wellen et al., 2014; Robertson & Saad, 2013; Kansas Department of Health and Environment, 2004; Alexander et al., 2002; Alexander et al., 2000). It is particularly useful for studies aiming to quantify the long-distance transport and delivery of contaminants to important downstream locations like drinking water intakes or protected/sensitive environmental areas (Schwarz et al., 2006). An excellent example of a more in-depth study using this tool for a similar purpose is the North-East Midwest Institute’s report using SPARROW results to project nutrient concentrations at drinking water utility intakes in the Mississippi River Basin (Vedachalam et al., 2018).

SPARROW correlates water quality monitoring data from state and federal programs to GIS (Geographic Information System) datasets of pollutant sources, climate patterns, and hydrogeologic properties within a specified focus area (Schwarz et al., 2006). Table 2 details the specific types of data that are used as inputs for SPARROW model estimates.

Table 2. GIS data inputs to the SPARROW model.	
Pollutant Source Data Inputs	**Hydrogeologic & Climatic Data Inputs**
• Atmospheric deposition	• Precipitation
• Fertilizer usage	• Topography/elevation
• Human waste (septic systems, sanitary sewer networks)	• Vegetation type
• Animal waste from agricultural operations	• Soil type • Water flow paths

The SPARROW model correlates the GIS data inputs described above with sampled water quality data from the National Water Quality Monitoring Council's online Water Quality Portal (WQP). The WQP consolidates data from multiple, large-scale water quality databases, including USGS' National Water Information System (NWIS) and EPA's STORET database, both of which contain substantial surface water, groundwater, spring, and atmospheric monitoring data[3].

Within the Middle Savannah watershed, there are 198 surface water quality sampling sites with data in the WQP. Those 198 sites are owned and monitored by eight different organizations, which are summarized in Table 3 and illustrated in Figure 3.

Table 3. Counts of surface water sampling sites from the WQP, split by organization, within the Middle Savannah watershed. The data from these sites are used as inputs to the SPARROW model.

Organization	Count of Sample Sites
USGS Georgia Water Science Center	45
USGS South Carolina Water Science Center	28
National Park Service, Water Resources Division	3
Georgia Department of Natural Resources, Environmental Protection Division	57
South Carolina Department of Health and Environmental Control	50
EPA National Aquatic Resources Survey (NARS)	2
Southeastern Natural Sciences Academy (Georgia)	12
Tennessee Department of Environment and Conservation	1

[3] For more information on USGS NWIS: https://waterdata.usgs.gov/nwis. For more information on EPA STORET and the WQP: https://www.epa.gov/waterdata/water-quality-data-download.

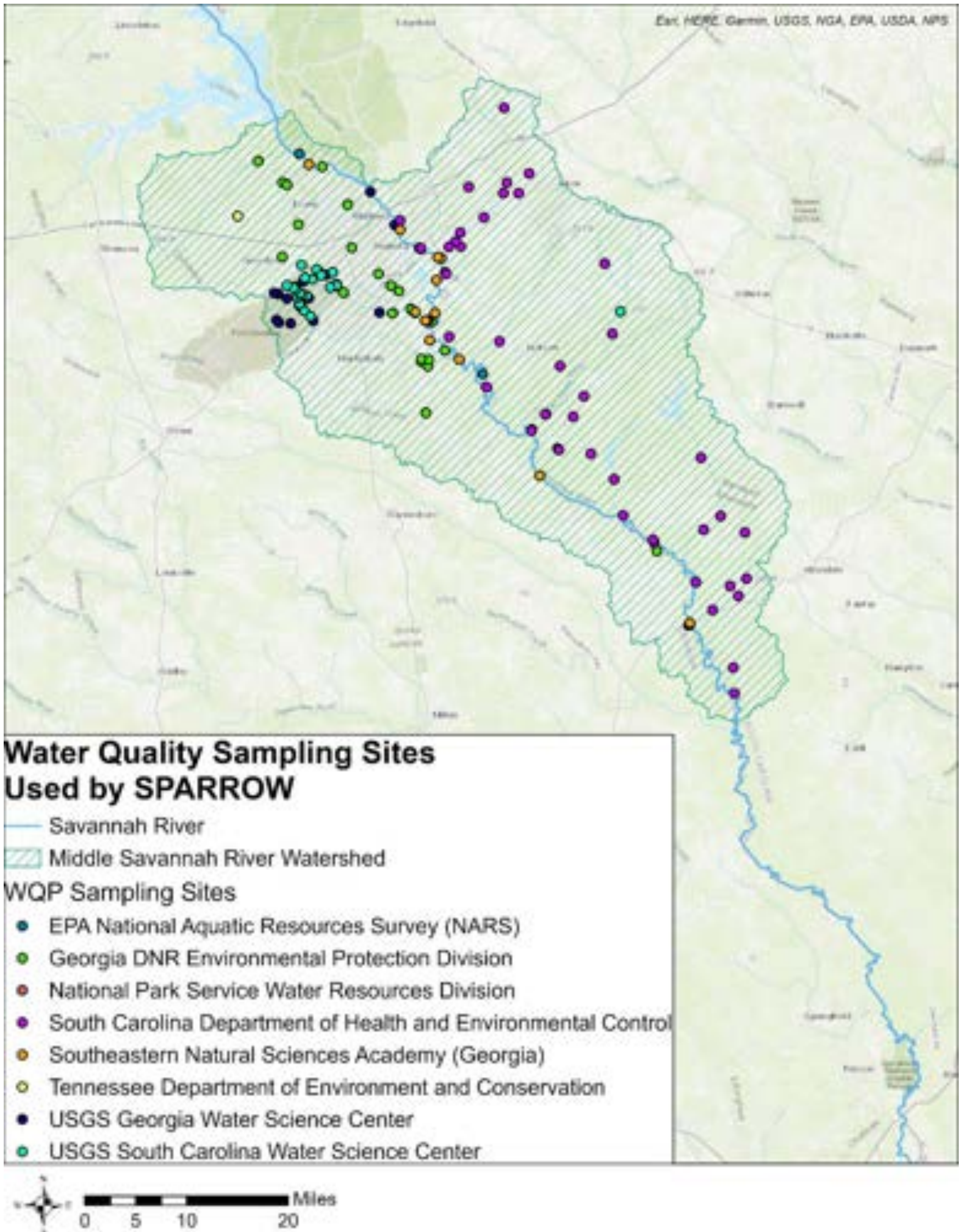

Figure 3. Sampling sites with data in the WQP used by the SPARROW model to formulate predictions for the subwatersheds in the Middle Savannah watershed.

The summarized outputs from the SPARROW model for the subwatersheds within the Middle Savannah are illustrated in the series of maps below, and the full tabular export, which contains pollutant loads separated by source (e.g., municipal wastewater treatment discharge, urban land, farm fertilizer, etc.) can be found in Appendix B. Figure 4, Figure 5, Figure 6, and Figure 7 illustrate the combined yield from all sources of Total Nitrogen (TN), Total Phosphorus (TP), Total Suspended Solids (TSS), and flow, respectively, within the subwatersheds of the Middle Savannah. These figures also contain pie charts illustrating summarized land cover (NLCD, 2019) within each subwatershed. Within these figures, distinctions between the pollutant yields in the heavily forested Savannah River Site and the heavily developed Augusta-Aiken MSA are apparent.

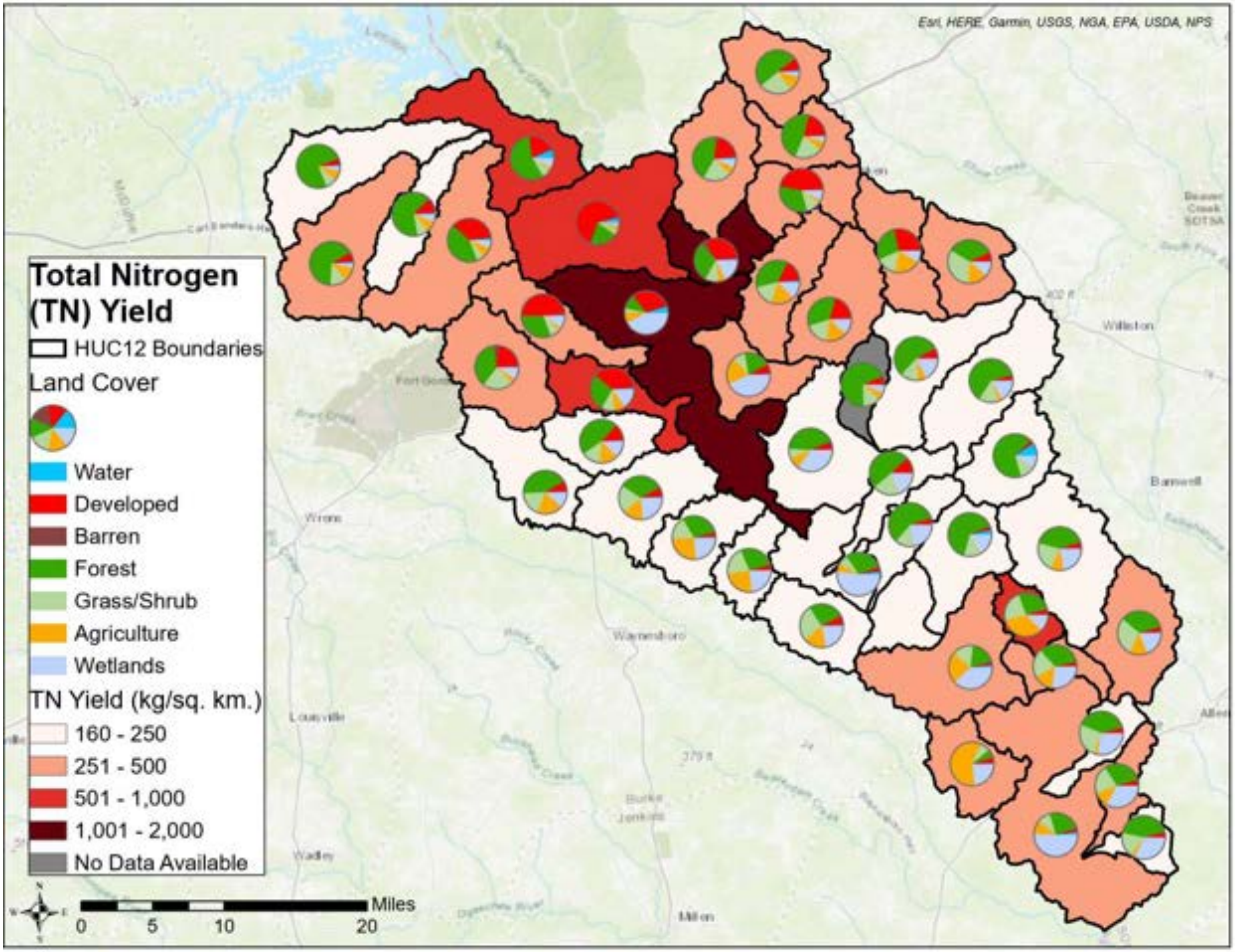

Figure 4. Total Nitrogen (TN) yield (kg/sq. km.), projected from SPARROW, within the HUC12s in the Middle Savannah watershed. Pie charts represent summarized land cover (NLCD, 2019) within each HUC12.

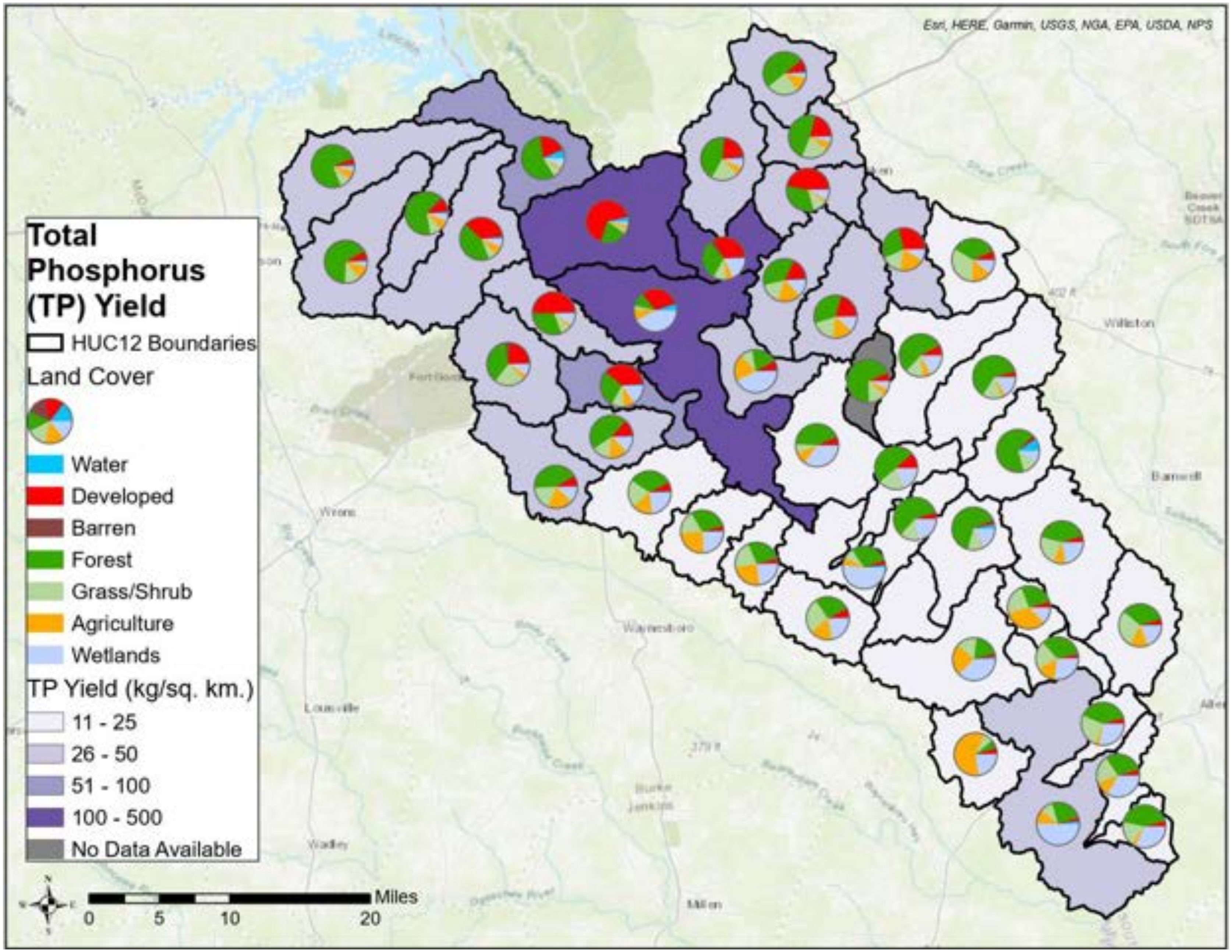

Figure 5. Total Phosphorus (TP) yield (kg/sq. km.), projected from SPARROW, within the HUC12s in the Middle Savannah watershed. Pie charts represent summarized land cover (NLCD, 2019) within each HUC12.

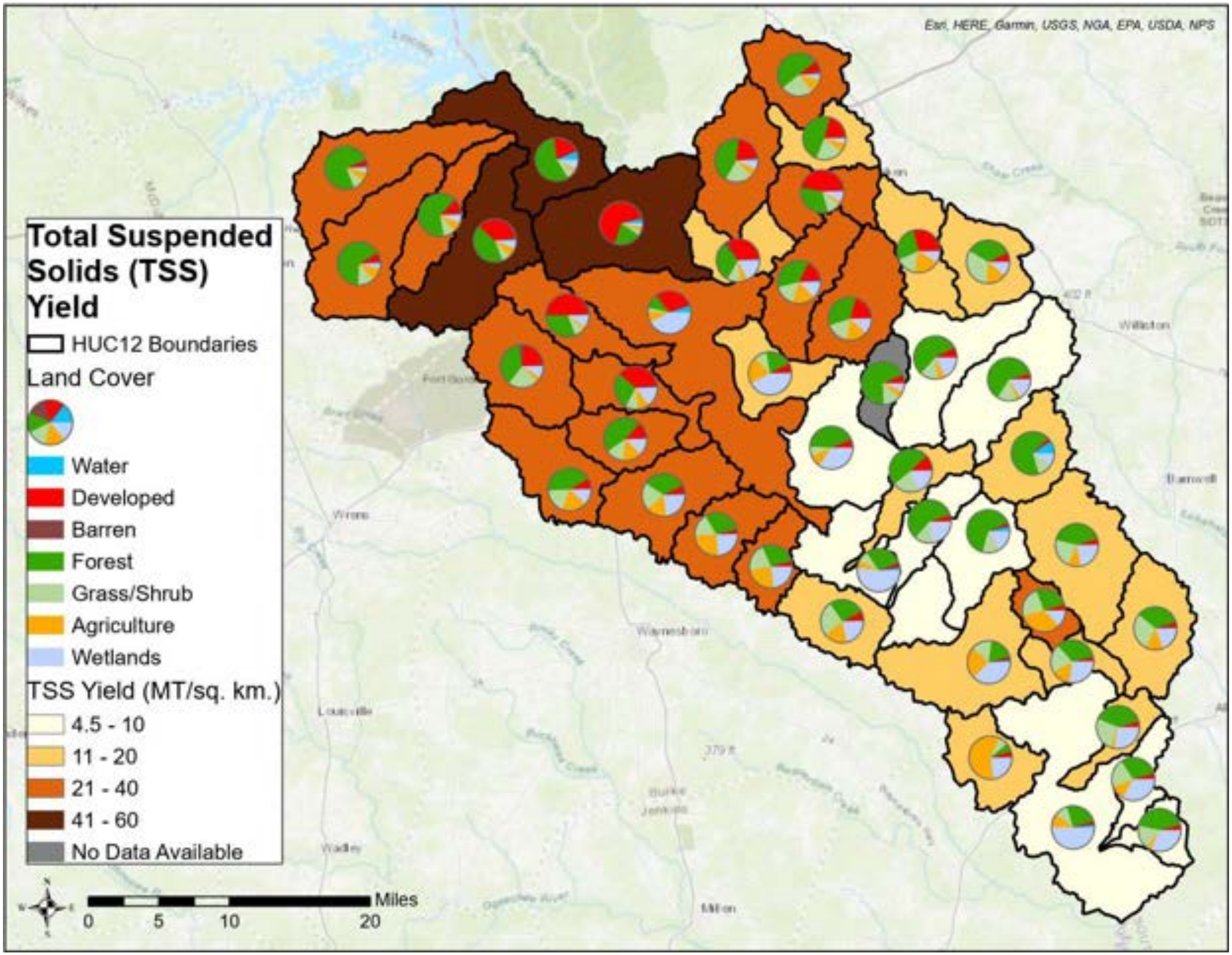

Figure 6. Total Suspended Solids (TSS) yield (MT/sq. km.), projected from SPARROW, within the HUC12s in the Middle Savannah watershed. Pie charts represent summarized land cover (NLCD, 2019) within each HUC12.

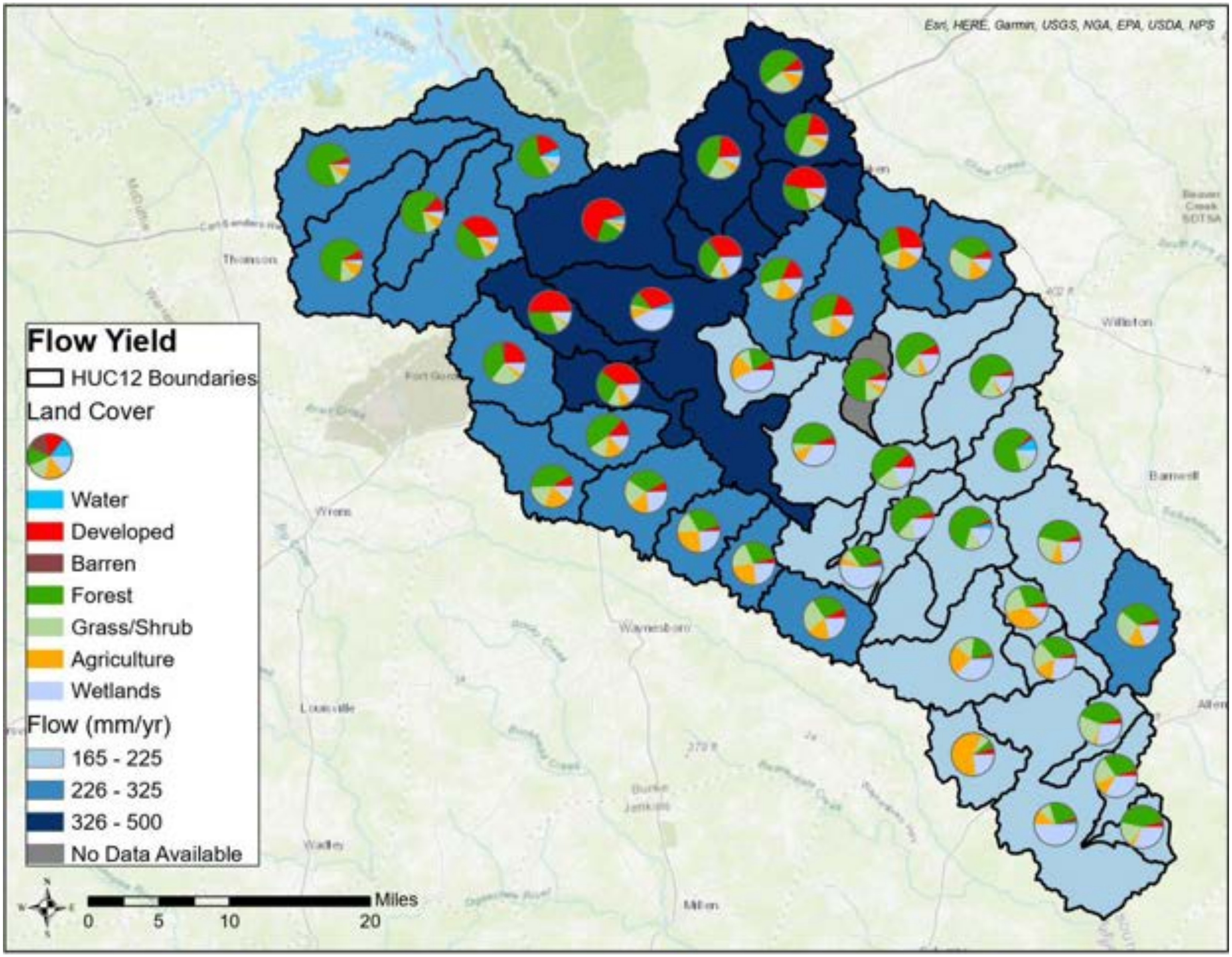

Figure 7. Flow yield (mm/yr.), projected from SPARROW, within the HUC12s in the Middle Savannah watershed. Pie charts represent summarized land cover (NLCD, 2019) within each HUC12.

Statistical Relationship between Land Cover & SPARROW Parameter Yields

Statistical analyses were conducted to evaluate the relationships between land cover and yields of water quality parameters from the SPARROW model in the subwatersheds of the Middle Savannah. After accounting for the interrelatedness between land cover categories[4], "best fit" regression equations were developed for each SPARROW parameter.

- TN yield is best predicted by developed and forest cover fractions.
- TP yield is best predicted by developed cover alone (forest cover was no longer a significant predictor after accounting for development).
- TSS and Flow yields are best predicted by developed and wetland cover fractions.

Table 4 below presents the "best fit" equations developed to explain these relationships.

Table 4. "Best fit" regression equations developed to explain the effects of land cover on TN, TP, TSS, and Flow yields.

SPARROW Parameter	"Best Fit" Equation
TN	$\log(TN) = [0.85 \times (Developed\ Fraction)] - [0.39 \times (Forest\ Fraction)]$
TP	$\log(TP) = [1.45 \times (Developed\ Fraction)]$
TSS	$\log(TSS) = [0.62 \times (Developed\ Fraction)] - [0.88 \times (Wetland\ Fraction)]$
Flow	$\log(Flow) = [0.56 \times (Developed\ Fraction)] - [0.45 \times (Wetland\ Fraction)]$

The results of this analysis suggest that forest cover is a good predictor of TN yield, but the effects of developed cover should be considered as well. While forest cover alone (and in combination with developed cover) does not appear to be a significant predictor for most yields, the overwhelming impact of developed cover suggests that preserving forest cover as a means of minimizing conversion to developed cover would be valuable to downstream water quality and would meaningfully reduce yields of all evaluated water quality parameters.

For TSS and flow, wetland cover has a statistically significant impact on yields, suggesting that wetland preservation is important for minimizing yields of these parameters.

[4] Details on the methods for developing these regressions and accounting for interrelatedness can be found in Appendix C.

Agricultural cover was not a statistically significant predictor of any of the SPARROW yields. However, it is important to note that the range of fractions of agricultural land cover was much smaller than the other land cover types (less than 30% in all but three of the 45 subwatersheds in the Middle Savannah). It is possible that more significant impacts would be observed if subwatersheds with higher fractions of agricultural land cover were included in this analysis. Further, it is possible that the presence or absence of agricultural land cover is correlated with changes in the fractions of other land covers. For example, agricultural land may be lost to either forest cover (retired land) or to developed cover, confounding the impacts of agricultural cover as a single predictor.

Figure 8 below presents a graphical representation of the statistical significance of the relationships observed in this analysis.

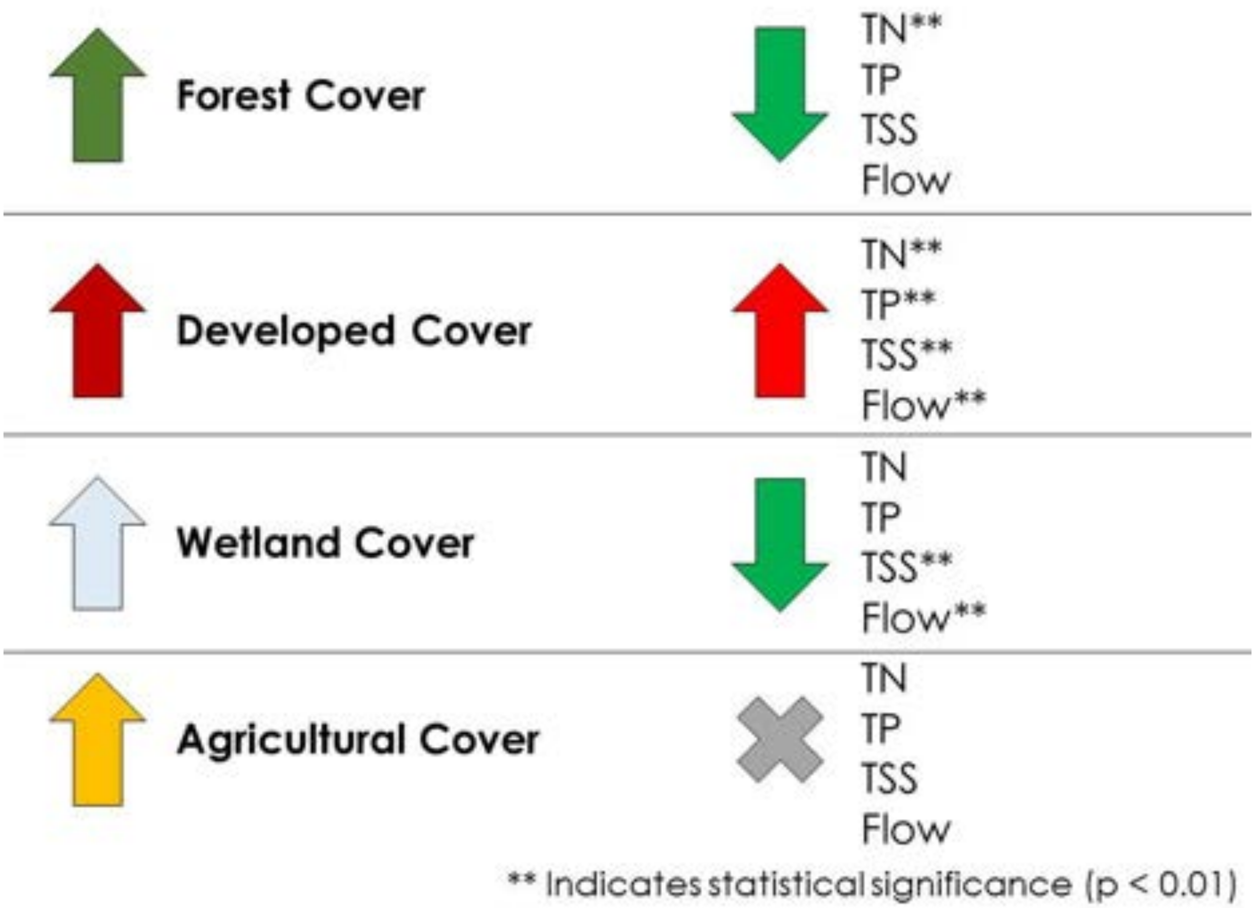

Figure 8. Graphical representation of the statistical significance of the relationships between each land cover category and each SPARROW parameter in subwatersheds of the Middle Savannah.

A more detailed explanation of the analysis methodology and results can be found in Appendix C.

Section 2. Evaluating Relationships Between Water Quality & Treatment Costs

The land cover and SPARROW analysis presented in the Section 1 of this white paper provides evidence of the water quality benefits of preserving forest cover in the Middle Savannah watershed. These benefits can be characterized as the avoided increase in flow and pollutants that would result from the conversion of forest to developed cover. The next part of the analysis aimed to evaluate the relationship between water quality and treatment costs in the Savannah River Basin, which required zooming in to water quality at a water treatment plant's intake. The methods and findings from this analysis are described below.

Location Overview

Approximately 100 miles downstream of the Savannah River Site (SRS), which is relatively central in the Middle Savannah watershed, are the drinking water plant intake locations for the City of Savannah's Industrial & Domestic Water Treatment Plant—located just upstream of RM 29 of the Savannah River, in the Abercorn Creek tributary on the Georgia side of the River—and the Beaufort Jasper Water & Sewer Authority (BJWSA) Chelsea Water Treatment Plant—located just upstream of RM 39 of the Savannah River, where the River meets Fox Lake on the South Carolina side (Figure 9).

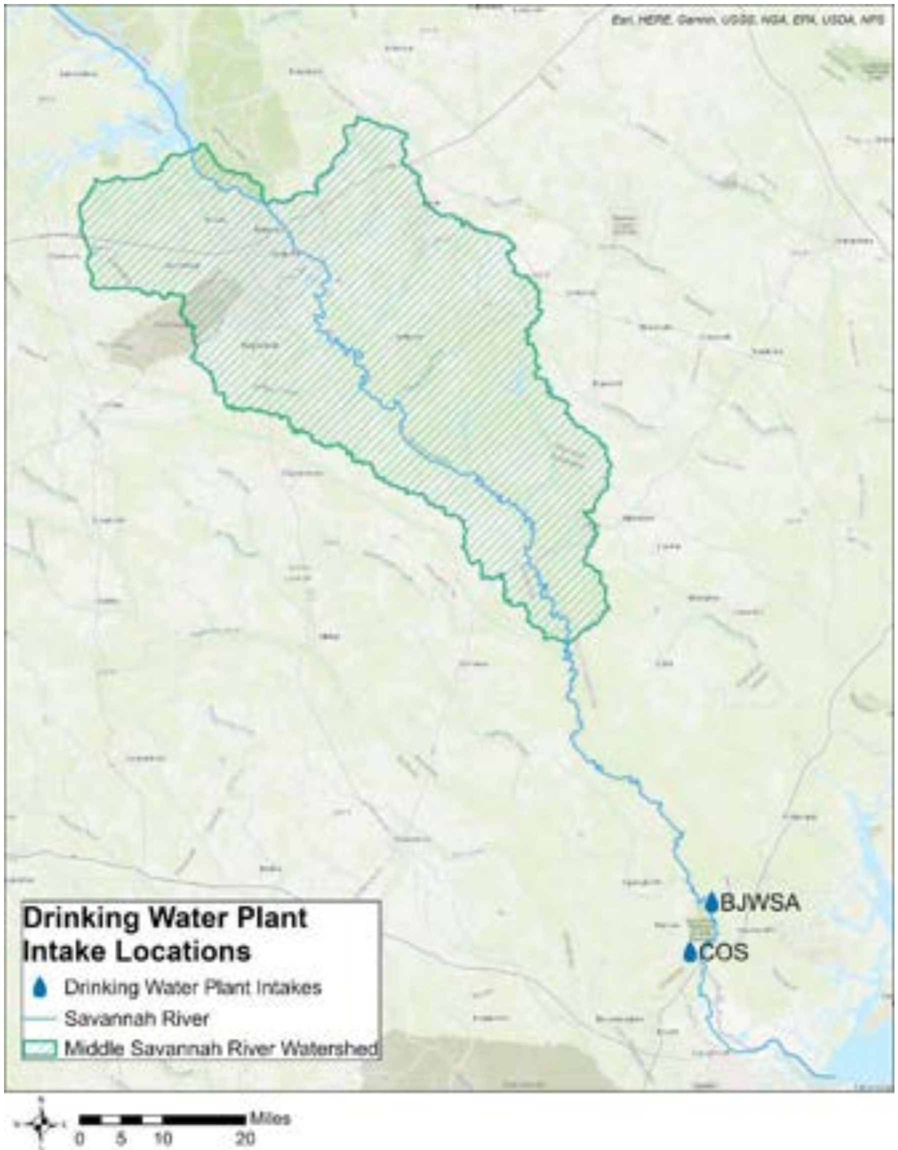

Figure 9. Locations of Savannah River drinking water treatment plant intakes relative to the Middle Savannah watershed.

CWP coordinated with the BJWSA to evaluate the relationship between raw water quality data from their intake location and treatment cost data at the BJWSA Chelsea Water Treatment Plant.

Data on production capacity, treatment processes and materials, treatment costs, and intake water quality was provided by Tricia Kilgore, PE, the Director of Technology & Innovation for the BJWSA. This data was collected and analyzed to inform the connections between source water quality and associated treatment costs in this white paper.

BJWSA Capacity

The BJWSA has two water treatment plants, Chelsea and Purrysburg, which, combined, have a capacity of 40 million gallons per day (MGD); on average, they produce 22 MGD of treated water. In 2021, the BJWSA Chelsea Water Treatment Plant ("BJWSA Chelsea Plant") serves a primary population of 150,000 people, not including wholesale customers. The BJWSA Chelsea Plant spends over $5.68 million annually on water treatment alone (not including transmission, distribution, or plant administration).

Treatment Processes, Materials, Thresholds, & Costs

Taste & Odor (T&O) Compounds at the BJWSA Chelsea Plant

BJWSA identifies geosmin and MIB as primary contributors to an earthy or musty taste and odor (T&O) in drinking water in an informative handout on frequently asked questions about water quality (BJWSA, 2019). Geosmin and MIB are odorous but harmless chemicals produced by cyanobacteria, which is commonly referred to as blue-green algae (BJSWA, 2019). Throughout this paper, cyanobacteria and algae are used interchangeably to refer to these kinds of T&O compounds.

In December 2013 and January 2014, the BJWSA Chelsea Plant experienced a taste-and-odor (T&O) event that was caused by elevated amounts of cyanobacteria and Total Organic Carbon (TOC) in the Savannah River (Rosenfeldt & Petry, 2015). Since that T&O event, BJWSA worked with Hazen and Sawyer to develop and implement a cost-effective cyanobacteria and algae monitoring program (Buerkens et al., 2020). BJWSA provided CWP with nearly-monthly water quality data from 2007 – 2021 at their intake location, which includes data collected after the installment of that monitoring program. These data were analyzed, and results are presented in the following sub-sections of this white paper.

Treatment Processes & Safe Drinking Water Act Considerations

The BJWSA Chelsea Plant uses a variety of treatment methods to process raw water into safe drinking water, including coagulation, flocculation, sedimentation, filtration, and disinfection.

As do most water treatment facilities, the BJWSA Chelsea Plant uses chlorine-containing disinfectants (called "chloramines") as part of the drinking water treatment process (BJWSA, 2019). Organic matter, including TOC, reacts with chloramines during treatment, forming disinfection byproducts (DBPs), many of which are toxic and/or carcinogenic (Richardson & Ternes, 2018; Richardson et al., 2007). These DBPs are regulated by the EPA under the Stage 1 and Stage 2

Disinfectants and Disinfection Byproducts Rules (DBPRs)[5] of the Safe Drinking Water Act (SDWA; Humphreys & Tiemann, 2021; US EPA Office of Water, 2010). According to the metrics in EPA's Enforcement and Compliance History Online (ECHO) SDWA Dashboard[6] for 2020, over 44,000 public water systems (PWSs) violated the SDWA, and over 4,000 of those violations were considered serious. After nearly 25,000 informal enforcement actions and over 2,300 formal enforcement actions (some of which are accompanied by an administrative penalty of undisclosed amounts), over 13,500 of those PWSs violating the SDWA were returned to compliance. According to the BJWSA's Consumer Confidence Reports from 2005 – 2020, the BJWSA has not been in violation of the SDWA[7].

Failure to treat TOC prior to disinfection with chloramines could push drinking water treatment plants out of compliance with the SDWA by producing unsafe levels of DBPs. As such, treating TOC—and reducing TOC loads through land management activities—should be prioritized to avoid the possible costs associated with administrative penalties that can accompany formal enforcement actions.

Treatment Materials, Thresholds & Costs

Three main materials are used at the BJWSA Chelsea Plant to treat raw water for T&O compounds like cyanobacteria and TOC: powdered activated carbon (PAC), alum, and lime. Table 5 describes the uses, base doses, treatment thresholds, and unit costs for these materials. It is important to note that while the information presented in Table 5 was provided directly by BJWSA, this information is generalized. Especially in the case of thresholds for treatment, values are subject to variability. At average flow, each 10 mg/L of alum costs $350/day, each 2 mg/L of lime costs $150/day, and each 5 mg/L of PAC costs $900/day.

It is important to note that contaminants other than TOC, associated DBPs, and cyanobacteria affect water treatment facilities' treatment costs. Increased sediment levels, elevated concentrations of nutrients, and other water quality changes influenced by upstream land use changes also necessitate modified and/or additional treatment, which may affect costs (Elias, 2010). However, this

[5] For more information on chloramines, see: https://www.epa.gov/sites/default/files/2015-09/documents/q1.pdf. For more information on the EPA's DBPRs, see: https://www.epa.gov/dwreginfo/stage-1-and-stage-2-disinfectants-and-disinfection-byproducts-rules

[6] The EPA ECHO SDWA Dashboard can be accessed here: https://echo.epa.gov/trends/comparative-maps-dashboards/drinking-water-dashboard?yearview=CY&view=activity&criteria=basic&state=National

[7] BJWSA Water Quality Consumer Confidence Reports can be accessed here: https://www.bjwsa.org/water-quality-report/

white paper will be focusing on quantifying the costs associated with treating TOC and cyanobacteria because of BJWSA's indication that these compounds are the most expensive to treat.

Table 5. Materials (and associated treatment thresholds, doses, and unit costs) used by BJWSA Chelsea Plant to treat drinking water for T&O compounds.

Material	Treated WQ Parameter(s)	Base Dose	Threshold for Treatment	Material Unit Cost
Powdered Activated Carbon (PAC)	• Geosmin • MIB	N/A	When raw water concentrations of geosmin are greater than 10 ng/L, add 5 mg/L of PAC.	$1.10/pound
Alum	• TOC • Particles	45 mg/L	For algae events or TOC spikes: for every mg/L of TOC greater than 5 mg/L, add 10 mg/L of alum and 2 mg/L of lime.	$305/ton of solution
Lime	• pH	5 mg/L		$0.06/pound

Using the January 2007 – June 2021 intake water quality data provided by BJWSA, exceedances of treatment thresholds for each of the treated water quality parameters listed in Table 5 were counted. The costs of exceedances that have occurred in the first six months of 2021 were also quantified using the information in Table 5 and the cost information at average flow provided by BJWSA[8]. A summary of these calculated treatment costs can be found in Table 6.

TOC exceeds the threshold for additional treatment when concentrations are greater than 5 mg/L. In the entire provided dataset (from 2007 – 2021), this threshold was crossed 105 times. In 2020, it was exceeded 14 times, and in the first six months of 2021, it has exceeded the threshold 7 times. Geosmin exceeds the threshold for additional treatment when concentrations are greater than 10 ng/L. In the entire provided dataset (from 2007 – 2021), this threshold was crossed 21 times. In 2020, it was exceeded 6 times, and in the first six months of 2021, it has already exceeded the threshold 6 times—the same as the total exceedances in all of 2020 in half the time.

[8] From Tricia Kilgore, PE: "At average flow, each 10 mg/L of alum costs $350/day, each 2 mg/L of lime costs $150/day, and each 5 mg/L of PAC costs $900/day."

Table 6. Summary of treatment costs for TOC and geosmin treatment threshold exceedances at the BJWSA intake between January 2021 and June 2021. Concentrations and costs associated with only base doses are highlighted in green, and those associated with additional treatment doses are highlighted in orange.				
Date	**TOC Concentration (mg/L)**	**TOC Treatment Cost ($/day)**	**Geosmin Concentration (ng/L)**	**Geosmin Treatment Cost ($/day)**
01/12/2021	5.18	$2,040	6.12	$0
02/02/2021	4.27	$1,950	12.79	$2,511
02/09/2021	4.15	$1,950	55.08	$40,572
02/23/2021	6.72	$2,810	No Data	No Data
02/24/2021	No Data	No Data	10.96	$864
03/02/2021	6.35	$2,625	No Data	No Data
03/23/2021	6.19	$2,545	4.63	$0
03/30/2021	4.40	$1,950	14.83	$4,347
04/13/2021	4.75	$1,950	20.45	$9,405
04/20/2021	8.68	$3,790	7.59	$0
04/27/2021	10.05	$4,475	9.69	$0
05/04/2021	7.46	$3,180	12.83	$2,547

When costs associated with base doses (which are non-preventable) are removed, the costs associated with additional treatment for TOC range from $90/day (01/12/2021) to $2,525/day (04/27/2021), depending on how much the threshold was surpassed. Since there is no base dose of PAC to treat geosmin, the treatment costs range from $864/day (02/24/2021) to $40,572/day (02/09/2021). On just the 12 days of exceedances listed in Table 6, the summed costs of additional treatment for TOC and geosmin were $7,815 and $60,246, respectively. Based on the literature review that is presented in Section 3, it is likely that these additional treatment costs could be minimized through upstream land management. The difficulties associated with quantifying the treatment costs associated with these land use changes are described in Section 4.

Statistical Relationship between TN & T&O Compounds at the Intake

To attempt to characterize the relationship between TN (the load of which is increased by developed land cover and reduced by forest land cover) and T&O compounds within the narrower focus of raw water at the intake, another statistical analysis was conducted.

BJWSA provided CWP with nearly-monthly water quality data from January 2007 – June 2021 at their intake location. This data was statistically analyzed to evaluate possible relationships between TN concentrations and concentrations of five T&O compounds in raw water at the intake. The five evaluated compounds were TOC, chlorophyll-a, geosmin, MIB, and algae.

Three of these indicators (geosmin, MIB, and algae) had very few (between zero and three) data points paired with observed TN data, even after aggregating the daily data to monthly averages. As a result, this analysis focused on relating TN concentrations to TOC and chlorophyll-a.

The results of this analysis did not indicate any statistically significant or meaningful relationship between TN concentrations and concentrations of TOC or chlorophyll-a. As such, there is insufficient data to draw any conclusions about the impacts of TN on the above-identified drinking water quality indicators using this dataset. This result is surprising since, in the literature, TN is typically associated with higher concentrations of both TOC and chlorophyll-a. There are a few possible explanations for this result, including:

- The TN load may be more important than the TN concentration. Higher flow events may result in lowered TN concentrations as a side effect of dilution, which could lessen the ability of the statistical analysis to recognize the relationship between TN and the evaluated T&O compounds.
- The effect of TN concentrations and/or loading may have a "lag" effect. The concentration or load over more than one month (or in the previous month) could affect the drinking water quality indicators at an undetermined-but-delayed time.

Because there was no statistically significant relationship between TN and any of the primary T&O compounds, regressions that meaningfully quantify those relationships could not be developed using available datasets. If these regressions were able to be created, then the regressions between land cover and TN could have been linked to regressions between TN and T&O compounds. This would have permitted land use changes to be inputted and results treatment costs to be calculated.

A possible quantification method for future studies could be to use literature-based estimates of export rates of TOC and other T&O compounds. Moltz et al. (2018) compiled TOC export rates from various types of land cover by reviewing studies from across the United States. Table 7 below is adapted and summarized from Moltz et al. (2018) to illustrate TOC export rates found in the literature; these values represent averages of reported ranges in some cases. For more detail, refer to Appendix B of Moltz et al. (2018). A comparable literature summary linking land uses to downstream amounts of cyanobacteria was not identified.

Table 7. TOC export rates from literature sources (adapted from Moltz et al., 2018).

Reference	Study Location	TOC Export Rate (lbs/acre/year)			
		Wetland	**Urban/ Developed**	**Forest**	**Agriculture**
Correll et al., 2001[1]	Maryland			14.9	22.2
Sickman et al., 2007[2]	California		108.0		
Shih et al. 2010[3]	Conterminous United States	424.9	65.4	16.3	21.9
Elias 2010	Literature review		108.0	8.0	
Canham et al. 2004[4]	New York	203.9		41.6	

[1] Maryland Coastal Plain watershed.
[2] California urban watershed.
[3] Average of range of median modeled values.
[4] DOC export rates transformed to TOC using method in Xenopoulos et al. 2003.

Using export rates from the literature is not a perfect method for quantification because the resultant estimates would likely rely on some difficult assumptions. Each study's reported export rates are unique to the study area's hydrology, land use, underlying soils, physiographic region, and other watershed characteristics. Additionally, the specifics of treatment (processes, materials, treated volume, etc.) vary between water treatment plants. This could make work within the Savannah River Basin that relies on these assumptions less accurate and meaningful.

Section 3. Watershed Sources of Taste & Odor (T&O) Compounds

Because meaningful regression equations linking TN to concentrations of T&O compounds were not possible to create with the data limitations in this watershed, a literature review of watershed sources of T&O compounds was conducted. Characterizing the watershed sources of T&O compounds like TOC and cyanobacteria is an important first step in managing land to minimize loads and reduce treatment costs.

Cyanobacteria & Algae

There is ample documentation on the influence of nutrients (nitrogen and phosphorus) on algal growth in surface waters (Newell et al., 2019; Moltz et al., 2018; Rosenfeldt et al., 2015). Nitrogen can be delivered to surface waters like the Savannah River from land use and/or atmospheric sources. Appendix B summarizes the nutrient loads by source for each of the subwatersheds of the Middle Savannah.

Cyanobacteria fix atmospheric nitrogen, so algal blooms are not solely dependent on land use loads. However, loads of nitrogen and phosphorus from upstream land use also contribute to algal growth. Figure 10 below is an overview of the watershed sources of nitrogen that contribute to algal growth; this figure was created and published by the DataStream Initiative, which is a program of The Gordon Foundation that collects, summarizes, and disseminates water monitoring and research results.

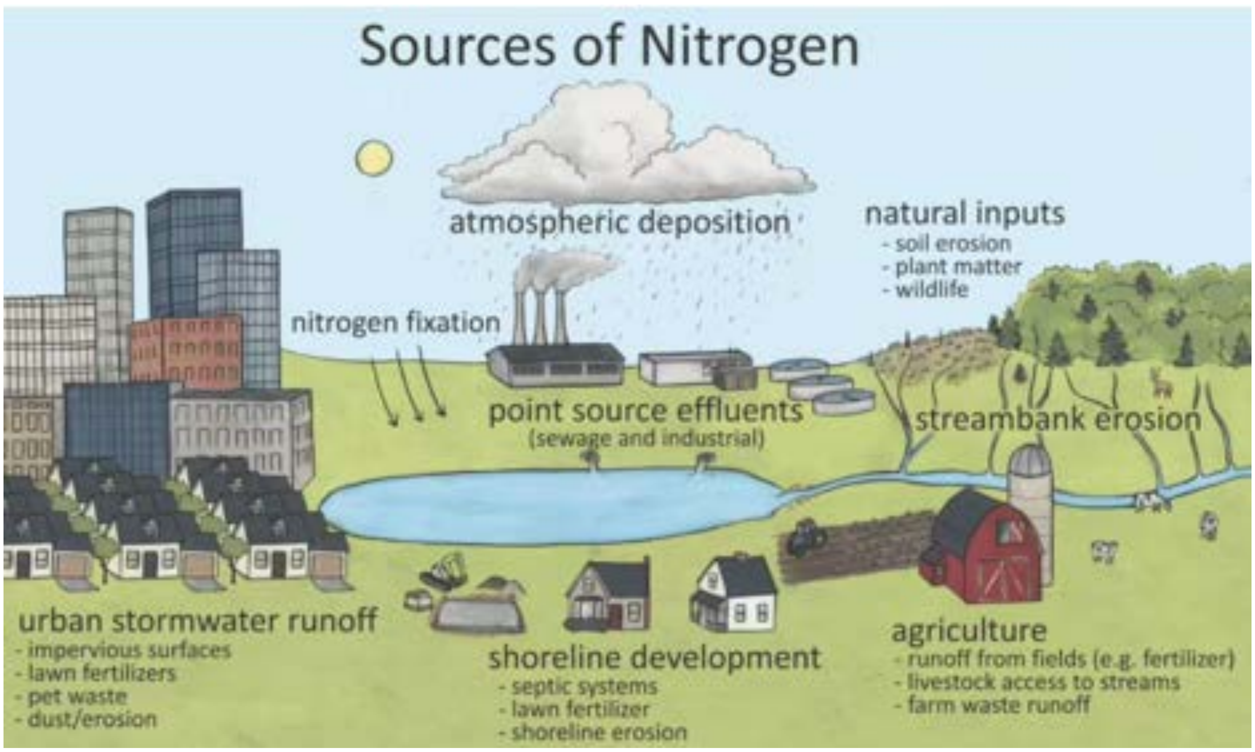

Figure 10. Sources of nitrogen (from both land use and natural processes) that can contribute to algal growth in surface waters. This figure was created and published by the DataStream Initiative (DataStream, n.d.).

It is also important to consider bioavailability. TN is the sum of organic nitrogen, reduced nitrogen, ammonia, nitrate, and nitrite (US EPA NSCEP, 2009). The most bioavailable forms of nitrogen include inorganic sources like nitrate, nitrite, ammonia, and ammonium (DataStream, n.d.). So, the entirety of TN may not be bioavailable to contribute to algal growth because it includes organic varieties. However, there is a positive relationship between TN and the amount of bioavailable nitrogen because TN still includes some inorganic, bioavailable varieties as well. There is research supporting the linkage between TN loads and bioavailable nitrogen loads that contribute to algal growth (Jørgensen et al., 2014). Journey et al. (2011) found a statistically significant influence between watershed contributions of nitrogen and phosphorus and elevated concentrations of T&O compounds in a drinking water reservoir in South Carolina as well.

Total Organic Carbon (TOC)

Total Organic Carbon (TOC) is another T&O compound that can contribute to a swampy, earthy, or musty taste in drinking water. Concentrations of TOC in streams and drinking water reservoirs have been linked to a variety of upstream land uses and watershed characteristics. Flow and discharge volume, associated with increased fractions of impervious cover in developed/urban areas, have been linked to elevated TOC concentrations due to a "washout" effect (Elias et al., 2016; Yu et al., 2015; Chang & Carlson, 2005; Correll et al., 2001; Jordan et al., 1997). Wastewater treatment effluent (often associated with industrial and developed land uses) has also been linked to increases in concentrations of organic compounds like TOC, dissolved organic carbon (DOC), disinfection byproducts (DBPs), and disinfection byproduct precursors, which are organic compounds that can transform into DBPs (Ejjada et al., 2021; Hladik et al., 2014).

Organic matter decomposition is one of the most documented contributors to elevated TOC concentrations. Leaf litter from woody wetlands and mixed forests is one of the primary sources of decomposing organic matter that contributes to these elevated concentrations (Yu et al., 2015; Shih et al., 2010; Chen et al., 2010; Chang & Carlson, 2005; Fleck et al., 2004). Agricultural land uses have also been linked to elevated TOC concentrations in some cases (Yu et al., 2015; Fleck et al., 2004; Correll et al., 2001). Additionally, TOC concentrations themselves have been correlated with internal algal growth in drinking water reservoirs (Elias, 2010).

However, the land uses that contribute the most TOC to surface waters vary from study to study. A more thorough overview of reviewed literature on the relationship between upstream land cover and downstream TOC concentrations can be found in Appendix D.

There is still a lack of definitive consensus among the scientific community about which upstream land uses and watershed characteristics contribute the most to downstream TOC concentrations. Research quantifying these relationships is even less conclusive because of the variability between studies in different physiographic regions. However, the influence of surface discharge/flow, wastewater treatment effluent, and organic matter decomposition from leaf litter (either from woody wetlands or forests) on T&O compounds appear to be the most supported connections.

Section 4. Conclusions

This white paper used a variety of data sources and analytical techniques to evaluate and quantify the relationships between upstream land cover, downstream water quality, and drinking water treatment costs in the Savannah River watershed. Using recent land cover data (NLCD, 2019) and a widely accepted model of watershed pollutant yields (SPARROW), the following relationships were identified in the Middle Savannah watershed:

- Forest cover significantly and meaningfully decreases TN yield, even after accounting for the effects of developed cover.
- Developed cover (i.e., urban area) significantly and meaningfully increases yields of all evaluated water quality parameters (TN, TP, TSS, and Flow). Consequently, preserving forest cover to reduce the amount of developed/urban cover would meaningfully reduce the yields of all evaluated water quality parameters.
- Wetland cover statistically and meaningfully reduces yields of both TSS and flow, but it does not significantly impact yields of TN or TP. Agricultural cover did not statistically impact yields of any evaluated water quality parameter, possibly because so few of the subwatersheds in the Middle Savannah are dominated by agricultural uses.

Using raw water quality sampling data at the BJWSA intake, relationships between TN concentrations (which is reduced by forest cover and increased by developed/urban cover) and concentrations of five taste-and-odor (T&O) compounds (TOC, geosmin, MIB, chlorophyll-a, and algae) were evaluated. The statistical analysis of this data did not show any significant relationship between raw water TN concentrations and concentrations of any of these T&O compounds, either due to a lack of sufficient overlapping data points (geosmin, MIB, algae) or no significant relationship in the available data (TOC, chlorophyll-a). These results are surprising given the association between TN and these compounds in the literature; however, they can be explained by the limited data availability. Based on the literature reviewed in Section 3, nutrient loads are linked to cyanobacteria and algal growth, even when accounting for bioavailability. Flow volume (i.e., discharge), organic matter decomposition (from woody wetlands and forests), urban runoff, and effluent from wastewater treatment plants are linked to organic compounds like TOC and resultant DBPs.

Using the raw water quality sampling data from the BJWSA intake, exceedances in treatment thresholds from the first six months of 2021 for TOC and geosmin and associated costs were quantified. In 2020, TOC treatment thresholds were exceeded 14 times, and in the first six months of 2021, it has exceeded the threshold 7 times. On just the 12 days with exceedances in 2021, the total cost of additional treatment for TOC was $7,815. In 2020, geosmin treatment thresholds were exceeded 6 times, and in the first six months of 2021, that threshold has already been exceeded 6 times. On just the 12 days with exceedances in 2021, the total cost of treatment for geosmin was $60,246. These data are highly dependent on how high the pollutant concentrations are above the treatment threshold and are therefore difficult to use in estimating potential future increases in treatment costs given the lack of a predictive relationship between raw water TN and T&O compounds.

Studies have shown that upstream land uses have an influence on loads of TOC and cyanobacteria. However, there is so much variability from study-to-study that it is difficult to apply values from the literature to predict future loads of these pollutants with land use change in the area upstream of the BJWSA intake. The findings presented in Section 1 validate the theory that if the watersheds upstream of the intake for the BJWSA Chelsea Plant were to experience increased conversion of forests and wetlands to developed cover, this would result in an increase in flow volume and loads of nutrients and sediment. It would also likely increase the potential for contaminants of emerging concern, which are typically associated with urban land use and point sources such as wastewater treatment plants.

While this study did confirm both the relationship between land use and water quality and the relationship between raw water quality and drinking water treatment plant costs in the Savannah River watershed, there was insufficient data to identify any relationship between land use changes and drinking water treatment costs. It is likely that forest-to-urban land conversions within source water areas would increase the frequency and extent to which additional water treatment is needed; however, it was not possible to confirm or quantify this relationship through this study. This is partly due to data limitations and partly due to the complexity of transport and transformation of the pollutants of interest in this study. Future work could attempt to develop models and quantification methodologies that address these complexities.

Planning for the Future

Modeling Efforts

There is substantial opportunity for further research on the connections between land cover, water quality, and drinking water treatment costs. The development of customized models to quantify the relationships between upstream watershed characteristics and treatment costs at downstream water treatment plants would likely provide more accurate and reliable estimates.

Integrating the kinds of data included in this white paper into existing modeling efforts in the Savannah River Basin—such as the work being done by Alec Nelson at the University of Georgia's Warnell School of Forestry & Natural Resources—would be an excellent way to create a "full circle" model that prioritizes conservation areas using inputs of site suitability, landowner willingness, vulnerability to future change, water quality benefits, and avoided treatment cost potential.

Emerging Contaminants

It is important to consider the potential future regulation of emerging contaminants and their land use associations when planning for drinking water treatment cost minimization as well. As mentioned in the "Treatment Processes & Safe Drinking Water Act Considerations" section (p. 20), there are monitoring and remediation regulations for public water systems (PWSs) provided by the US EPA and regulated under the Safe Drinking Water Act (SDWA).

Every five years, the EPA issues a new list of unregulated contaminants to be monitored by PWSs. In March 2021, a new list of contaminants was published that includes sampling requirements for 30 unregulated contaminants, 29 of which are per- and polyfluoroalkyl substances (PFAS)[9].

PFAS are widely used chemicals that have been used in the United States since the 1940s in a variety of consumer products for purposes like stain/water/heat resistance, non-stick coatings, waterproofing, and firefighting foams. They are also associated with landfills, wastewater treatment plants, and firefighter training facilities (US EPA, n.d.).

Based on their size, the BJWSA Chelsea Plant, BJWSA Purrysburg Plant, and the City of Savannah's Industrial and Domestic Water Treatment Plant would be

[9] The remaining unregulated contaminant in this list is lithium.

subject to these PFAS sampling requirements. However, as of October 2021, regulations for PFAS in drinking water have not yet been instated. There is a Lifetime Health Advisory for these compounds, but there is not yet a Maximum Contaminant Level set, which would require PWSs like the BJWSA to measure and remove PFAS. In September 2021, EPA announced the first regulated limits for PFAS in wastewater treatment effluents, indicating that further regulation may be impending (US EPA, 2021).

In 2017 and 2019, the BJWSA tested the source water in the Savannah River and water from both the Purrysburg and Chelsea Water Treatment Plants for PFAS. Small amounts of PFAS were measured in both years (between 2.5 – 4.7 ng/L, which is well below EPA's Lifetime Health Advisory of 70 ng/L). Depending on the Maximum Contaminant Level that may be set by EPA for PWSs, BJWSA may be required to conduct more consistent PFAS sampling and possibly implement treatment processes to remediate them (BJWSA, 2020), which would come at an associated cost. If the watershed upstream of the BJWSA intake location experiences increased development, the potential for increases in PFAS and other emerging contaminants also increases, given their association with urban land uses and wastewater effluent.

Recommendations

In the process of completing this white paper, a few recommended actions were identified by the project team. Those recommendations are as follows:

1. Continue to invest in water quality monitoring, particularly for TOC, geosmin, MIB, chlorophyll-a, and algae. This monitoring should occur both in the raw water at the intake and upstream.
2. Consistently update water quality datasets, preferably in a GIS-friendly format. Whenever possible, importing datasets from multiple organizations into one consolidated dataset would be most valuable.
3. Develop a Watershed Implementation Plan (WIP) for the Middle Savannah watershed. As population in the Savannah River Basin increases, additional drinking water treatment facilities may be necessary farther upstream. Characterizing this upstream area will be important when planning for possible increases to capacity. As with the City of Savannah's Source Water Protection Plan, the goal of a WIP for the Middle Savannah would be to prepare the area for potential threats to water supply (including reviewing and quantifying threats from land use related activities and from contaminants of emerging concern, like PFAS) and to consolidate information that can be shared with the area's stakeholders (CWP, 2019).

4. Pursue modeling efforts that integrate the "full circle" of conservation prioritization, including site suitability, vulnerability to future change, landowner willingness, water quality benefits, and avoided treatment cost potential.
5. Initiate research on emerging contaminants associated with developed/urban land uses, like PFAS, which may be impending regulation under the SDWA.

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Appendix A. Analysis of Savannah River Nutrient Data between RM 182.5 to RM 61

This analysis is pulled from the Source Water Protection Plan (SWPP) for the City of Savannah Industrial & Domestic Water Treatment Plant developed by the Center for Watershed Protection, Inc. (CWP) in 2019. It describes the identification of a possible point source of nutrient pollution that was avoided when selecting the study area for this white paper to avoid confounding the relationship between land cover and water quality.

Excerpt from CWP (2019)

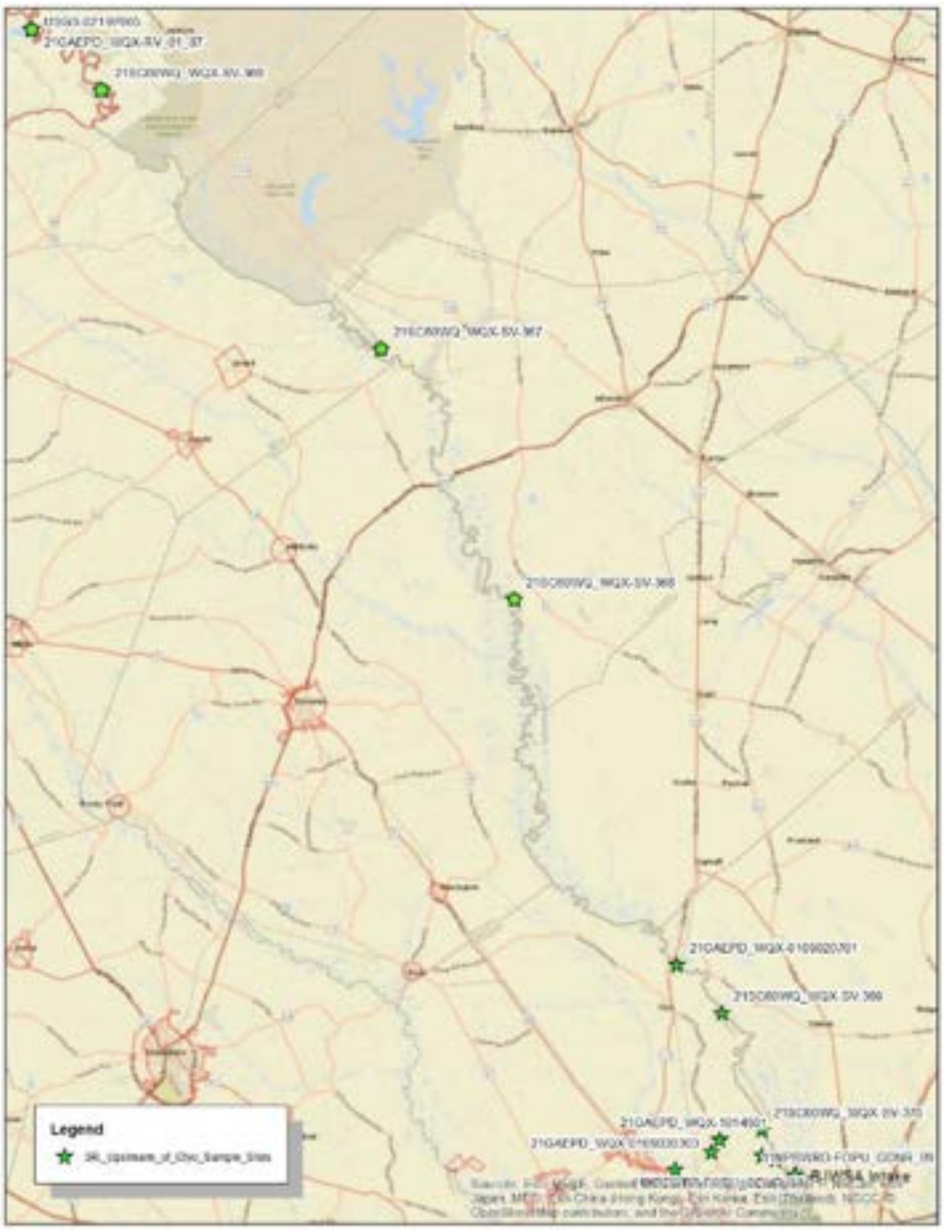


Figure 11. Savannah River water quality sampling locations (CWP, 2019).

When we look at the Georgia and South Carolina water quality data for nutrients in the period where their data sets coincide timewise (January 2014 – December 2016) the nutrient box and whiskers seem to indicate changes in concentration progressing downriver from Augusta. Sample location RV_01-87 is a GAEPD site at Spirit Creek near paper mill discharges south of Augusta at River Mile (RM) 182.5. Samples SV-366 (RM 170.5), 367 (RM 134.5), 368 (RM 104) and 370 (RM 45) are all DHEC sample sites below the mill discharges down to two miles upstream of Ebenezer Creek, and 0701 is an EPD site at the Hwy 119 bridge at Clyo (RM 61). While we generally see a decrease in concentration from the most upstream point to station 368, we see an increase from this point and downstream stations.

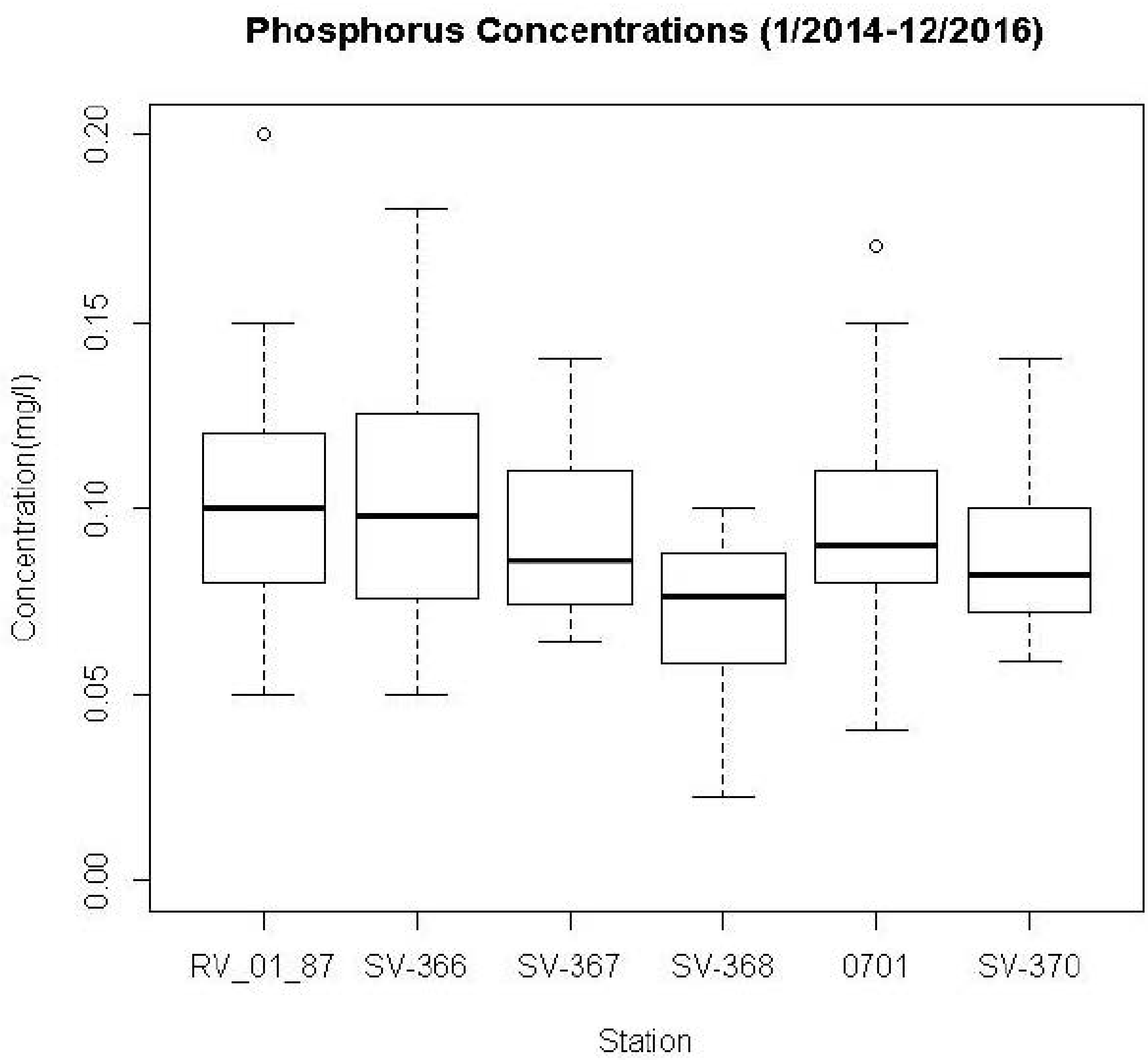


Figure 12. Box and whiskers plot of Savannah River phosphorus data.

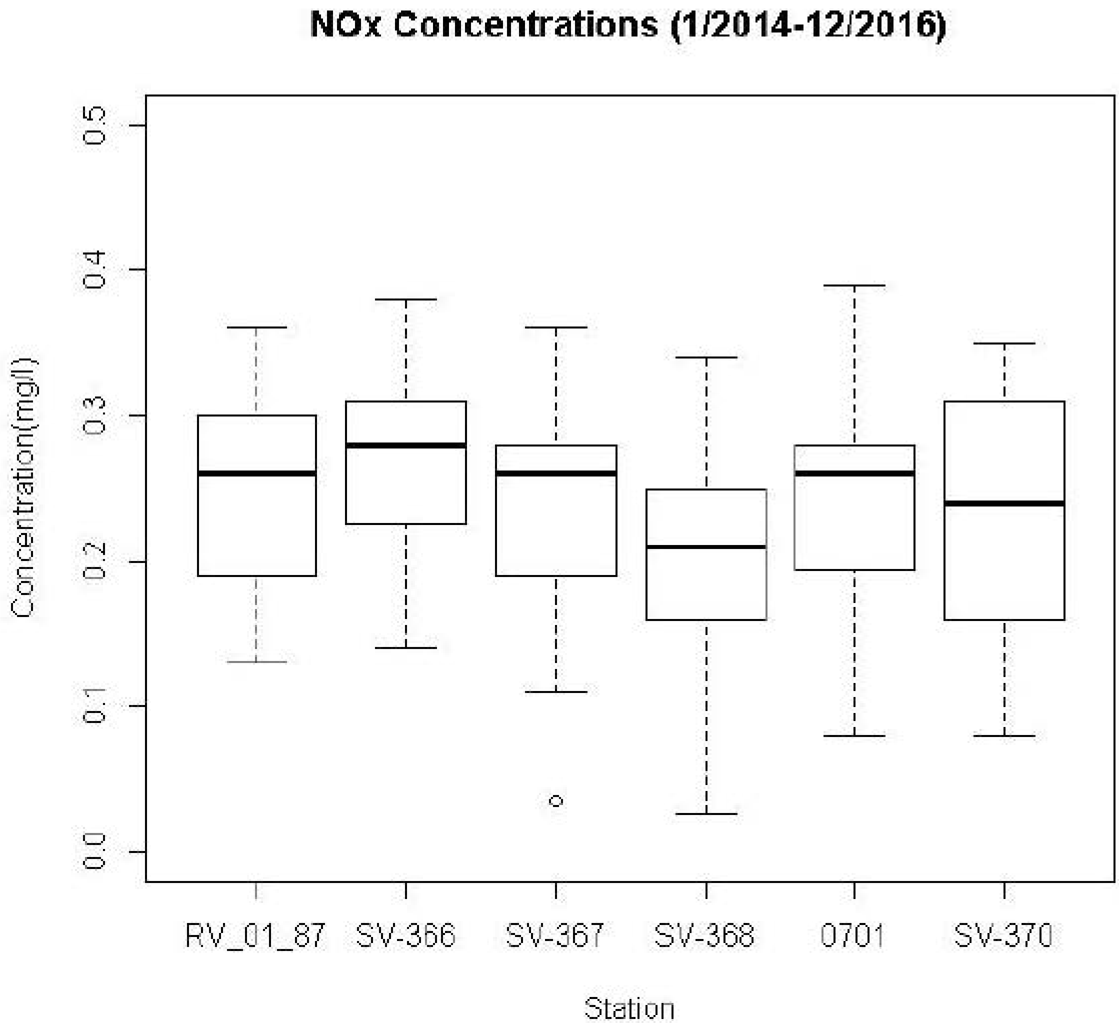


Figure 13. Box and whiskers plot of Savannah River NOx data.

To test the apparent differences indicated by the box plots, we evaluated the differences between each station using the Tukey Honest Significant Differences method, which uses an ANOVA comparison along with an adjustment to account for multiple comparisons. When performing this test, we used a log transformation of the concentrations to account for the influence of outlier points, and the lognormal nature of the data. The results (in Tables A and B), suggest that the concentrations at station 368 are significantly lower (at 5% significance) than the concentrations at stations 1_87 (RM 182.5) and Station 366 (RM 170.5), and lower than the concentration at station 0701 (RM 61) (at 10% significance) for both NOx and Phosphorus.

Table A. log-Transformed P Concentration Differences using Tukey HSD Comparison for1/2014-12/2016					
Station	1_87	366	367	368	0701
366	0.002 (1.00)				
367	-0.010 (1.00)	-0.012 (1.00)			
368	-0.151 (0.01)	-0.153 (0.05)	-0.141 (0.11)		
0701	-0.027 (0.98)	-0.028 (0.99)	-0.017 (1.00)	0.125 (0.07)	
370	-0.051 (0.88)	-0.052 (0.93)	-0.041 (0.98)	0.101 (0.39)	-0.024 (0.99)

Table B. Log-Transformed NOx Concentration Differences using Tukey HSD Comparison for 1/2014-12/2016					
Station	1_87	366	367	368	0701
366	0.036 (0.99)				
367	-0.055 (0.94)	-0.091 (0.77)			
368	- 0.175 (0.03)	-0.211 (0.02)	-0.119 (0.49)		
0701	-0.024 (1.00)	-0.060 (0.90)	0.031 (0.99)	0.151 (0.08)	
370	-0.053 (0.93)	-0.120 (0.49)	0.002 (1.00)	0.122 (0.40)	-0.029 (0.99)

Interpretation of the Tukey table:

	Column
Row	Mean(log(Row))-Mean(log(Column))* (p-value; blue rows are significant at the 5% level ($p < 0.05$); grey significant at the 10% level ($p < 0.10$) < 0.05 is statistically significant) **

*Positive values indicate concentration is increasing as one moves downstream from the column to the row; negative shows decreasing values.

**Shaded rows indicate a statistically significant difference in means.

When looking at the period from January 2014 – December, 2016 (where all five stations have data), we find:

- A significant (at the 90% confidence level) difference for NOx between station 21SC60WQ_WQX-SV-368 and two upstream stations: 21SC60WQ_WQX-SV-366 and 21GAEPD_WQX-RV_01_87, as well as the downstream station GA EPD (WQX-RV_01_109) 0701
- For phosphorus, there is a statistically significant difference between station 368 and station 0701.
- Overall, for both parameters, there is a pattern of decreasing concentrations from upstream to downstream to station 368, but then an increase from station 368 to station 0701, except for a very small (0.02 mg/L) and statistically insignificant difference in the mean concentration between stations 1_87 and station 366.
- It appears that phosphorus decreases by dilution, or adsorption to solids and either entrapped in sediments or taken up by vegetation in the river as flow moves downstream. However, sources between station 368 and 0701 are causing an increase in concentration. One possible explanation is the agricultural land use tributary to Brier Creek, which discharges to the Savannah River between 368 and 0701, along with discharge from the wastewater treatment plant at Sylvania, GA.
- Our analysis of the data show that the Savannah River is assimilating nitrogen from upstream significant point source discharges in Augusta, and non-point sources from the watersheds down to Cohens Bluff Road. But from Cohens Bluff to the Clyo Bridge there is a shift. Statistically the nutrients increase in the stretch of River below Cohens Bluff to the bridge at Clyo.

Although the data do not detect significant differences between other stations, the results are consistent with a hypothesis that some pollution source downstream of station 368 (RM 104) may be causing increased concentrations downstream of this point, given the general decreasing trend up to this point, followed by an increase and subsequent decrease downstream from Clyo.

Since nutrients are a food source for algal blooms and cyanobacteria, an ongoing monitoring program for nutrients, possibly using chlorophyll a continuous monitoring probes is recommended as an early warning system for harmful algal species occurrence upstream of the Savannah River intake's outer management zone.

Appendix B. SPARROW Results for HUC12 Subwatersheds in the Middle Savannah Watershed

Total Nitrogen (TN)

HUC12	Aggregated TN Yield (kg/sq. km)					
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Industry[2]	Sum of All Sources
030601060101, Upper Kiokee Creek	2.36	13.28	37.83	55.27	147.00	255.74
030601060102, Lower Kiokee Creek	0.00	8.51	28.76	51.00	141.50	229.78
030601060103, Little Kiokee Creek	0.00	15.31	24.04	52.70	154.66	246.72
030601060104, Uchee Creek	81.46	64.54	25.06	54.27	161.81	387.13
030601060105, Llyod Creek-Savannah River	374.19	37.97	12.38	51.29	173.62	649.46
030601060201, Headwaters Horse Creek-Savannah River	0.00	11.89	64.19	87.29	185.14	348.52
030601060202, Upper Horse Creek-Savannah River	0.00	43.38	48.61	81.95	194.92	368.86
030601060203, Middle Horse Creek-Savannah River	0.00	111.52	26.45	76.15	201.61	415.73
030601060204, Little Horse Creek	0.00	41.90	49.44	84.30	218.28	393.91
030601060205, Lower Horse	1500.59	69.90	27.60	96.29	222.47	1916.86

HUC12	Aggregated TN Yield (kg/sq. km)					
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Industry[2]	Sum of All Sources
Creek-Savannah River						
030601060301, Upper Spirit Creek	0.00	58.68	10.60	60.29	168.98	298.55
030601060302, Little Spirit Creek	5.21	28.35	7.80	51.89	126.78	220.03
030601060303, Lower Spirit Creek	257.52	90.48	7.98	70.34	173.78	600.09
030601060401, Town Creek-Hollow Creek	0.00	25.41	40.00	96.79	169.83	332.03
030601060402, Upper Hollow Creek-Savannah River	0.00	37.06	38.90	106.56	156.59	339.10
030601060403, Lower Hollow Creek-Savannah River	0.00	8.76	30.81	89.17	131.92	260.67
030601060501, Cedar Creek-Upper Three Runs	0.00	54.92	40.75	113.03	155.17	363.87
030601060502, Upper Upper Three Runs	0.00	9.12	25.87	98.22	142.49	275.70
030601060503, Tinker Creek-Upper Three Runs	0.00	4.37	11.56	60.75	146.47	223.15

HUC12	Aggregated TN Yield (kg/sq. km)					
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Industry[2]	Sum of All Sources
030601060505, Middle Upper Three Runs	0.00	10.62	17.33	68.27	147.88	244.10
030601060506, Lower Upper Three Runs	0.00	8.84	19.21	61.70	145.85	235.61
030601060601, Augusta Canal-Savannah River	250.97	161.31	11.59	94.25	267.15	785.27
030601060602, Butler Creek	0.00	113.71	6.36	64.21	187.05	371.34
030601060603, Upper McBean Creek	0.00	14.47	42.00	54.45	123.53	234.45
030601060604, Lower McBean Creek	0.00	15.46	23.08	53.34	127.82	219.70
030601060605, Broom Branch-Boggy Gut Creek	0.00	12.12	49.51	61.55	125.22	248.39
030601060606, Newberry Creek	0.00	13.26	54.54	54.32	122.93	245.05
030601060607, Beaverdam Ditch-Savannah River	1039.37	78.96	12.49	82.91	184.57	1398.31
030601060701, Upper Lower Three Runs-Par Pond	0.00	1.95	9.62	39.49	111.64	162.71
030601060702, Miller Creek	0.00	6.35	107.32	47.02	123.23	283.92

HUC12	Aggregated TN Yield (kg/sq. km)					
	Municipal Wastewater Treatment Discharge	**Urban Land**	**Farm Fertilizer[1]**	**Manure[1]**	**Industry[2]**	**Sum of All Sources**
030601060703, Middle Lower Three Runs	0.00	4.36	38.10	52.24	128.22	222.91
030601060704, Furse Mill Creek	0.00	7.59	368.71	47.66	116.55	540.51
030601060705, Lower Lower Three Runs	0.00	6.58	176.96	45.47	123.75	352.77
030601060801, Fourmile Branch	0.00	19.83	6.66	42.73	134.94	204.16
030601060802, Beaverdam Creek	0.00	16.73	59.40	52.88	120.80	249.80
030601060803, Pen Branch	0.00	6.41	10.19	42.04	131.22	189.86
030601060804, Steel Creek	0.00	2.08	8.71	41.91	127.50	180.19
030601060805, Little Beaverdam Creek-Savannah River	0.00	7.69	18.03	46.28	129.28	201.28
030601060806, Sweetwater Creek-Savannah River	0.00	6.87	96.04	50.70	111.35	264.95
030601060901, Rocky Creek	0.00	5.54	169.77	50.67	87.74	313.71
030601060902, Brier Creek-Savannah River	0.00	7.47	25.86	39.71	118.46	191.49
030601060903, Watch Call Branch	0.00	7.62	175.34	40.00	112.35	335.30

HUC12	Aggregated TN Yield (kg/sq. km)					
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Industry[2]	Sum of All Sources
030601060904, King Creek	0.00	5.69	31.67	37.76	106.28	181.39
030601060905, Smith Lake Creek-Savannah River	103.75	5.22	49.51	41.79	112.28	312.55

[1] Including indirect transport through atmosphere to stream.
[2] Defined as atmospheric emissions and subsequent deposition from power plants, other industry, vehicles, and background.

Total Phosphorus (TP)

HUC12	Aggregated TP Yield (kg/sq. km)						
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Phosphate Mining	Natural Sources	Sum of All Sources
030601060101, Upper Kiokee Creek	0.13	2.01	2.05	2.44	0.00	29.54	36.18
030601060102, Lower Kiokee Creek	0.00	1.24	1.49	1.58	0.00	23.76	28.06
030601060103, Little Kiokee Creek	0.00	2.50	1.31	2.15	0.00	29.66	35.63
030601060104, Uchee Creek	8.17	9.12	1.25	1.59	0.00	28.46	48.59
030601060105, Llyod Creek-Savannah River	55.36	6.03	0.64	0.65	0.00	27.55	90.23
030601060201, Headwaters Horse Creek-Savannah River	0.00	1.16	2.18	3.44	0.00	20.18	26.96
030601060202, Upper Horse Creek-Savannah River	0.00	4.41	1.56	2.54	0.00	22.10	30.62
030601060203, Middle Horse Creek-Savannah River	0.00	11.17	0.83	1.07	0.00	21.96	35.04
030601060204, Little Horse Creek	0.00	4.18	1.71	2.01	0.00	20.71	28.62
030601060205, Lower Horse	291.42	8.77	1.08	2.65	0.00	22.16	326.08

HUC12	Aggregated TP Yield (kg/sq. km)						
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Phosphate Mining	Natural Sources	Sum of All Sources
Creek-Savannah River							
030601060301, Upper Spirit Creek	0.00	6.34	0.38	0.44	0.00	23.77	30.93
030601060302, Little Spirit Creek	0.32	3.46	0.32	0.94	0.00	20.99	26.04
030601060303, Lower Spirit Creek	35.07	11.79	0.29	0.70	0.00	24.34	72.19
030601060401, Town Creek-Hollow Creek	0.00	2.65	1.40	4.65	0.00	18.27	26.96
030601060402, Upper Hollow Creek-Savannah River	0.00	3.61	1.28	4.36	0.00	18.16	27.41
030601060403, Lower Hollow Creek-Savannah River	0.00	1.09	1.22	6.36	0.00	19.54	28.21
030601060501, Cedar Creek-Upper Three Runs	0.00	6.74	1.34	5.98	0.00	18.99	33.04
030601060502, Upper Upper Three Runs	0.00	0.87	0.75	3.80	0.00	16.40	21.83
030601060503, Tinker Creek-Upper Three Runs	0.00	0.44	0.32	0.57	0.00	14.35	15.68

HUC12	Aggregated TP Yield (kg/sq. km)						
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Phosphate Mining	Natural Sources	Sum of All Sources
030601060505, Middle Upper Three Runs	0.00	1.14	0.46	1.25	0.00	16.52	19.37
030601060506, Lower Upper Three Runs	0.00	1.20	0.58	2.61	0.00	18.05	22.44
030601060601, Augusta Canal-Savannah River	49.26	26.48	0.50	0.97	0.00	32.50	109.72
030601060602, Butler Creek	0.00	13.15	0.20	0.28	0.00	23.82	37.45
030601060603, Upper McBean Creek	0.00	1.81	2.18	1.37	0.00	20.08	25.44
030601060604, Lower McBean Creek	0.00	1.85	1.08	1.12	0.00	20.17	24.23
030601060605, Broom Branch-Boggy Gut Creek	0.00	1.48	2.13	2.02	0.00	18.95	24.58
030601060606, Newberry Creek	0.00	1.61	2.09	1.35	0.00	17.51	22.57
030601060607, Beaverdam Ditch-Savannah River	356.93	16.58	0.68	3.77	0.00	24.61	402.57
030601060701, Upper Lower Three Runs-Par Pond	0.00	0.22	0.28	0.06	0.00	13.95	14.51
030601060702, Miller Creek	0.00	0.94	1.88	0.79	0.00	13.39	17.01

HUC12	Aggregated TP Yield (kg/sq. km)						
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Phosphate Mining	Natural Sources	Sum of All Sources
030601060703, Middle Lower Three Runs	0.00	0.45	0.80	0.89	0.00	12.17	14.31
030601060704, Furse Mill Creek	0.00	0.93	3.06	0.94	0.00	11.83	16.77
030601060705, Lower Lower Three Runs	0.00	0.96	1.67	0.56	0.00	13.35	16.55
030601060801, Fourmile Branch	0.00	2.31	0.26	0.00	0.00	15.83	18.40
030601060802, Beaverdam Creek	0.00	1.88	2.09	0.89	0.00	17.10	21.96
030601060803, Pen Branch	0.00	0.70	0.32	0.01	0.00	14.28	15.31
030601060804, Steel Creek	0.00	0.21	0.26	0.09	0.00	11.42	11.98
030601060805, Little Beaverdam Creek-Savannah River	0.00	1.03	0.72	0.46	0.00	16.69	18.89
030601060806, Sweetwater Creek-Savannah River	0.00	1.01	2.18	1.38	0.00	12.94	17.51
030601060901, Rocky Creek	0.00	0.93	4.66	2.51	0.00	13.49	21.60
030601060902, Brier Creek-Savannah River	0.00	1.45	0.47	0.11	0.00	13.34	15.37

HUC12	Aggregated TP Yield (kg/sq. km)						
	Municipal Wastewater Treatment Discharge	Urban Land	Farm Fertilizer[1]	Manure[1]	Phosphate Mining	Natural Sources	Sum of All Sources
030601060903, Watch Call Branch	0.00	1.04	1.20	0.36	0.00	12.45	15.05
030601060904, King Creek	0.00	0.92	0.53	0.14	0.00	13.03	14.62
030601060905, Smith Lake Creek-Savannah River	13.71	1.15	1.88	0.45	0.00	14.56	31.76

[1] Including indirect transport through atmosphere to stream.
[2] Defined as atmospheric emissions and subsequent deposition from power plants, other industry, vehicles, and background.

Total Suspended Solids (TSS)

HUC12	Aggregated TSS Yield (MT/sq. km)											
	Urban Land[1]	Urban Land[2]	Urban Land[3]	Ag Land[4]	Ag Land[5]	Ag Land[6]	Trans Land[7]	Trans Land[8]	Trans Land[9]	Forest Land[10]	Channel Sources [11]	Sum of All Sources
030601060101, Upper Kiokee Creek	4.38	0.06	0.00	3.21	1.15	0.00	9.39	0.81	0.00	8.74	4.57	32.31
030601060102, Lower Kiokee Creek	2.54	0.02	0.00	1.97	0.37	0.00	8.78	0.21	0.00	8.00	3.56	25.45
030601060103, Little Kiokee Creek	6.09	0.00	0.00	3.93	0.00	0.00	10.83	0.00	0.00	8.96	4.29	34.09
030601060104, Uchee Creek	15.15	1.07	0.00	2.34	4.87	0.00	5.79	1.31	0.00	5.83	5.19	41.55
030601060105, Llyod Creek-Savannah River	20.00	0.01	0.00	1.43	0.00	0.00	6.91	0.00	0.00	11.13	5.21	44.69
030601060201, Headwaters Horse Creek-Savannah River	0.18	0.16	0.14	0.08	5.22	0.13	1.22	4.68	0.25	1.96	11.48	25.51
030601060202, Upper Horse Creek-Savannah River	0.17	0.87	0.01	0.01	4.19	0.01	0.11	4.59	0.01	2.26	6.45	18.68
030601060203, Middle Horse Creek-Savannah River	3.71	1.98	2.83	0.02	2.36	0.05	1.47	4.51	0.61	2.83	6.51	26.88
030601060204, Little Horse Creek	0.98	0.73	0.24	0.09	2.49	0.00	1.25	3.87	0.05	2.30	10.63	22.64

HUC12	Aggregated TSS Yield (MT/sq. km)											
	Urban Land[1]	Urban Land[2]	Urban Land[3]	Ag Land[4]	Ag Land[5]	Ag Land[6]	Trans Land[7]	Trans Land[8]	Trans Land[9]	Forest Land[10]	Channel Sources [11]	Sum of All Sources
030601060205, Lower Horse Creek-Savannah River	0.76	0.95	2.09	0.07	1.51	0.17	0.37	3.95	0.87	1.80	6.83	19.38
030601060301, Upper Spirit Creek	0.00	2.14	0.00	0.00	5.15	0.00	0.00	8.85	0.00	2.95	5.08	24.16
030601060302, Little Spirit Creek	0.31	1.02	0.00	0.03	9.26	0.00	0.17	5.00	0.00	3.52	6.74	26.04
030601060303, Lower Spirit Creek	3.54	2.78	0.00	0.02	7.41	0.00	0.31	4.83	0.00	2.29	4.01	25.19
030601060401, Town Creek-Hollow Creek	0.00	0.14	1.34	0.00	2.26	0.84	0.00	1.37	3.31	2.05	9.61	20.91
030601060402, Upper Hollow Creek-Savannah River	0.00	0.90	0.46	0.00	7.53	0.20	0.00	6.82	0.78	1.45	7.79	25.95
030601060403, Lower Hollow Creek-Savannah River	0.00	0.03	0.45	0.03	1.15	0.90	0.12	0.38	1.77	1.13	4.45	10.42
030601060501, Cedar Creek-Upper Three Runs	0.00	0.00	4.32	0.00	0.00	1.43	0.00	0.00	3.42	1.71	4.86	15.74
030601060502, Upper Upper Three Runs	0.00	0.00	0.42	0.00	0.00	0.70	0.00	0.00	3.73	1.75	4.22	10.81

HUC12	Aggregated TSS Yield (MT/sq. km)											
	Urban Land[1]	Urban Land[2]	Urban Land[3]	Ag Land[4]	Ag Land[5]	Ag Land[6]	Trans Land[7]	Trans Land[8]	Trans Land[9]	Forest Land[10]	Channel Sources [11]	Sum of All Sources
030601060503, Tinker Creek-Upper Three Runs	0.00	0.04	0.12	0.00	0.48	0.07	0.00	2.14	0.52	2.23	4.36	9.97
030601060505, Middle Upper Three Runs	0.00	0.02	0.52	0.00	0.41	0.20	0.00	0.52	2.67	2.38	2.09	8.80
030601060506, Lower Upper Three Runs	0.00	0.02	0.35	0.01	1.34	0.18	0.06	0.96	1.45	2.01	3.09	9.47
030601060601, Augusta Canal-Savannah River	39.32	3.38	0.33	0.57	2.20	0.02	3.36	0.84	0.06	4.21	4.88	59.17
030601060602, Butler Creek	1.77	3.88	0.00	0.02	2.82	0.00	0.27	3.13	0.00	2.54	5.70	20.13
030601060603, Upper McBean Creek	0.00	0.59	0.00	0.00	13.60	0.00	0.00	8.24	0.00	3.27	4.53	30.22
030601060604, Lower McBean Creek	0.10	0.49	0.06	0.02	8.69	0.03	0.12	5.85	0.14	2.65	7.25	25.41
030601060605, Broom Branch-Boggy Gut Creek	0.00	0.26	0.28	0.00	9.57	0.27	0.02	3.56	0.95	1.99	6.97	23.88
030601060606, Newberry Creek	0.05	0.28	0.27	0.02	5.01	0.26	0.16	6.84	1.14	1.48	6.15	21.64
030601060607, Beaverdam	11.28	1.69	0.59	0.75	0.50	0.15	1.41	0.60	0.58	0.95	4.53	23.05

HUC12	Aggregated TSS Yield (MT/sq. km)											
	Urban Land[1]	Urban Land[2]	Urban Land[3]	Ag Land[4]	Ag Land[5]	Ag Land[6]	Trans Land[7]	Trans Land[8]	Trans Land[9]	Forest Land[10]	Channel Sources [11]	Sum of All Sources
Ditch-Savannah River												
030601060701, Upper Lower Three Runs-Par Pond	0.00	0.10	0.02	0.00	0.66	0.01	0.00	5.11	0.30	5.34	3.08	14.61
030601060702, Miller Creek	0.00	0.07	0.19	0.00	1.56	0.16	0.00	3.08	2.36	1.71	6.64	15.79
030601060703, Middle Lower Three Runs	0.00	0.05	0.03	0.00	1.43	0.08	0.00	2.38	0.59	1.55	3.97	10.09
030601060704, Furse Mill Creek	0.00	0.26	0.03	0.00	14.84	0.12	0.00	5.01	0.21	2.37	4.19	27.02
030601060705, Lower Lower Three Runs	0.09	0.08	0.18	0.00	5.14	0.15	0.29	1.84	1.35	2.40	3.57	15.09
030601060801, Fourmile Branch	0.00	0.01	1.14	0.00	0.00	0.00	0.03	1.19	1.76	2.42	3.79	10.34
030601060802, Beaverdam Creek	0.10	0.36	0.31	0.00	0.84	0.38	0.18	6.11	1.94	1.22	4.56	16.01
030601060803, Pen Branch	0.00	0.04	0.23	0.00	0.02	0.00	0.02	1.50	1.17	2.66	3.95	9.59
030601060804, Steel Creek	0.00	0.02	0.07	0.00	0.17	0.01	0.00	0.69	1.22	2.91	3.09	8.18
030601060805, Little Beaverdam Creek-Savannah River	0.27	0.21	0.08	0.02	1.50	0.04	0.76	2.08	0.34	1.42	2.76	9.49

HUC12	Aggregated TSS Yield (MT/sq. km)											
	Urban Land[1]	**Urban Land[2]**	**Urban Land[3]**	**Ag Land[4]**	**Ag Land[5]**	**Ag Land[6]**	**Trans Land[7]**	**Trans Land[8]**	**Trans Land[9]**	**Forest Land[10]**	**Channel Sources [11]**	**Sum of All Sources**
030601060806, Sweetwater Creek-Savannah River	0.09	0.08	0.26	0.00	3.43	0.57	0.39	1.85	1.01	1.21	4.77	13.67
030601060901, Rocky Creek	0.00	0.01	0.42	0.00	0.79	2.24	0.02	0.50	1.21	0.60	4.96	10.75
030601060902, Brier Creek-Savannah River	0.18	0.09	0.19	0.00	0.51	0.05	0.05	2.36	1.37	2.31	3.25	10.36
030601060903, Watch Call Branch	0.00	0.04	0.25	0.00	0.53	0.27	0.00	0.95	1.23	1.62	1.55	6.43
030601060904, King Creek	0.00	0.02	0.10	0.00	0.30	0.03	0.00	0.98	0.95	0.97	1.41	4.77
030601060905, Smith Lake Creek-Savannah River	0.21	0.06	0.13	0.04	1.22	0.13	0.95	1.83	0.87	1.33	2.16	8.92

[1] Urban Land and Alluvium and residuum in very fine- grained sedimentary rock and igneous and metamorphic rock
[2] Urban Land and Residuum in sedimentary rock (discontinuous)
[3] Urban Land and Fine - and medium - grained sediments, residuum in alluvium, and residuum in carbonate and fine - grained sedimentary rock
[4] Agricultural Land and Alluvium and residuum in very fine - grained sedimentary rock and igneous and metamorphic rock
[5] Agricultural Land and Residuum in sedimentary rock (discontinuous)
[6] Agricultural Land and Fine - and medium - grained sediments, residuum in alluvium, and residuum in carbonate and fine - grained sedimentary rock
[7] Transitional Land and Alluvium and residuum in very fine - grained sedimentary rock and igneous and metamorphic rock
[8] Transitional Land and Residuum in sedimentary rock (discontinuous)
[9] Transitional Land and Fine - and medium - grained sediments, residuum in alluvium, and residuum in carbonate and fine - grained sedimentary rock
[10] Forested Land and all surficial geology classes
[11] Channel Sources

Flow

HUC12	Aggregated Flow Yield (mm/yr)				
	Precipitation minus Actual Evapotranspiration	Sewerage Discharge, External Sources	Diversions into Area	Springs	Sum of All Sources
030601060101, Upper Kiokee Creek	255.21	0.26	0.00	0.00	255.47
030601060102, Lower Kiokee Creek	235.51	0.00	0.00	0.00	235.51
030601060103, Little Kiokee Creek	239.37	0.00	0.00	0.00	239.37
030601060104, Uchee Creek	288.64	7.93	0.00	0.00	296.56
030601060105, Llyod Creek-Savannah River	255.74	33.24	0.00	0.00	288.98
030601060201, Headwaters Horse Creek-Savannah River	361.83	0.00	0.00	0.00	361.83
030601060202, Upper Horse Creek-Savannah River	397.54	0.00	0.00	0.00	397.54
030601060203, Middle Horse Creek-Savannah River	353.03	0.00	0.00	0.00	353.03
030601060204, Little Horse Creek	346.46	0.00	0.00	0.00	346.46
030601060205, Lower Horse Creek-Savannah River	292.68	183.19	0.00	0.00	475.87

HUC12	Aggregated Flow Yield (mm/yr)				
	Precipitation minus Actual Evapotranspiration	Sewerage Discharge, External Sources	Diversions into Area	Springs	Sum of All Sources
030601060301, Upper Spirit Creek	317.75	0.00	0.00	0.00	317.75
030601060302, Little Spirit Creek	250.45	0.60	0.00	0.00	251.05
030601060303, Lower Spirit Creek	303.40	29.23	0.00	0.00	332.63
030601060401, Town Creek-Hollow Creek	261.06	0.00	0.00	0.00	261.06
030601060402, Upper Hollow Creek-Savannah River	286.10	0.00	0.00	0.00	286.10
030601060403, Lower Hollow Creek-Savannah River	196.01	0.00	0.00	0.00	196.01
030601060501, Cedar Creek-Upper Three Runs	281.17	0.00	0.00	0.00	281.17
030601060502, Upper Upper Three Runs	254.89	0.00	0.00	0.00	254.89
030601060503, Tinker Creek-Upper Three Runs	198.34	0.00	0.00	0.00	198.34
030601060505, Middle Upper Three Runs	204.57	0.00	0.00	0.00	204.57

HUC12	Aggregated Flow Yield (mm/yr)				
	Precipitation minus Actual Evapotranspiration	Sewerage Discharge, External Sources	Diversions into Area	Springs	Sum of All Sources
030601060506, Lower Upper Three Runs	178.73	0.00	0.00	0.00	178.73
030601060601, Augusta Canal-Savannah River	334.39	19.00	0.00	0.00	353.40
030601060602, Butler Creek	344.94	0.00	0.00	0.00	344.94
030601060603, Upper McBean Creek	239.29	0.00	0.00	0.00	239.29
030601060604, Lower McBean Creek	236.81	0.00	0.00	0.00	236.81
030601060605, Broom Branch-Boggy Gut Creek	241.70	0.00	0.00	0.00	241.70
030601060606, Newberry Creek	247.77	0.00	0.00	0.00	247.77
030601060607, Beaverdam Ditch-Savannah River	249.32	157.12	0.00	0.00	406.45
030601060701, Upper Lower Three Runs-Par Pond	182.08	0.00	0.00	0.00	182.08
030601060702, Miller Creek	233.26	0.00	0.00	0.00	233.26
030601060703, Middle Lower Three Runs	215.34	0.00	0.00	0.00	215.34

HUC12	Aggregated Flow Yield (mm/yr)				
	Precipitation minus Actual Evapotranspiration	Sewerage Discharge, External Sources	Diversions into Area	Springs	Sum of All Sources
030601060704, Furse Mill Creek	221.44	0.00	0.00	0.00	221.44
030601060705, Lower Lower Three Runs	199.78	0.00	0.00	0.00	199.78
030601060801, Fourmile Branch	222.09	0.00	0.00	0.00	222.09
030601060802, Beaverdam Creek	243.86	0.00	0.00	0.00	243.86
030601060803, Pen Branch	207.88	0.00	0.00	0.00	207.88
030601060804, Steel Creek	186.99	0.00	0.00	0.00	186.99
030601060805, Little Beaverdam Creek-Savannah River	174.84	0.00	0.00	0.00	174.84
030601060806, Sweetwater Creek-Savannah River	196.10	0.00	0.00	0.00	196.10
030601060901, Rocky Creek	202.98	0.00	0.00	0.00	202.98
030601060902, Brier Creek-Savannah River	218.93	0.00	0.00	0.00	218.93
030601060903, Watch Call Branch	210.09	0.00	0.00	0.00	210.09
030601060904, King Creek	198.57	0.00	0.00	0.00	198.57

HUC12	Aggregated Flow Yield (mm/yr)				
	Precipitation minus Actual Evapotranspiration	Sewerage Discharge, External Sources	Diversions into Area	Springs	Sum of All Sources
030601060905, Smith Lake Creek-Savannah River	162.91	5.57	0.00	0.00	168.49

Appendix C. Graphical/Tabular Representations of Statistical Relationships & Methodology Details

Two statistical analyses were conducted for this project.

1) **Analysis I**: The effects of the percent coverage of four land cover categories (Agriculture, Developed, Forest, and Wetland) on the annual yield of four water quality/quantity parameters outputted by the SPARROW model (TN, TP, TSS, and Flow) in the 45 HUC12 subwatersheds within the Middle Savannah watershed.
2) **Analysis II**: The relationship between TN concentrations and concentrations of five drinking water quality indicators (TOC, Chlorophyll-A, Geosmin, MIB, and Algae), using sampling data from the Beaufort-Jasper Water & Sewer Authority's intake location.

The methodology for both statistical analyses was as follows:

1) Graphically depicted the relationship between each land cover category (independent variable) and the log-transformed yield of each water quality parameter from the SPARROW model (dependent variable, "SPARROW parameter")
2) Developed log-log regressions between each land cover category and each SPARROW parameter
3) Progressively added predictors to the equation until the last variable was no longer statistically significant (at the 5% significance level)
4) Used the "best fit" equation (in which all predictors are statistically significant) to determine the effect and level of significance of each land cover category on each SPARROW parameter
5) Evaluated the results and summarized the relationship between each land cover category and each SPARROW parameter

Below are the tabular and graphical results of these statistical analyses.

Analysis I: Land Cover & SPARROW Yields

Analysis I was conducted in two phases (Phase I and Phase II). Phase I developed least squares regression equations for the relationships between each land cover category (Agriculture, Developed, Forest, Wetland) and each SPARROW parameter (TN, TP, TSS, Flow). An ANCOVA (Analysis of Covariance) was conducted to quantify the statistical significance of the formulated least squares regressions.

Equation 1 below presents the formulaic relationship between each land cover category and the log-transformed yields of each SPARROW parameter. The coefficients used to populate this equation are found in Table 8.

Equation 1. Least Squares Regression Template

$$log(Y_i) = a_{ij} + (c_{ij} \times L_j)$$

Where:

Y_i = Yield for SPARROW parameter *i* (TN, TP, TSS, or Flow)

L_j = Percent cover of land cover category *j* (Agriculture, Developed, Forest, or Wetland)

a_{ij} = Value of $\log(Y_i)$ when $L_j = 0$

c_{ij} = Slope relating percent of land cover category and log of the SPARROW parameter yield

Table 8. Least squares regression coefficients and ANCOVA results for Phase I of Analysis I.

Land Cover Category	TN		TP		TSS		Flow	
	Coeff.	p-Value	Coeff.	p-Value	Coeff.	p-Value	Coeff.	p-Value
Agriculture	0.024	0.94	-0.42	0.37	0.051	0.88	-0.18	0.25
Developed	0.96	<0.01	1.45	<0.01	0.92	<0.01	0.56	<0.01
Forest	-0.60	<0.01	-0.57	0.07	0.027	0.91	-0.12	0.29
Wetland	-0.19	0.48	-0.26	0.50	-1.2	<0.01	-0.45	<0.01

Phase II developed the forward stepwise regression equations, meaning that the resultant regressions only used the two most significant predictive land cover categories for each SPARROW parameter. Again, an ANCOVA was also conducted to quantify the statistical significance of the formulated forward stepwise regressions.

Equation 2 below presents the formulaic relationship between multiple statistically significant land cover categories and the log-transformed yields of each SPARROW parameter. The coefficients used to populate this equation are found in Table 9.

Equation 2. Forward Stepwise Regression Template

$$log(Y_i) = a_{ij} + \sum_j (c_{ij} \times L_j)$$

Where:

Y_i = Yield for SPARROW parameter *i* (TN, TP, TSS, or Flow)

L_j = Percent cover of land cover category *j* (Agriculture, Developed, Forest, or Wetland)

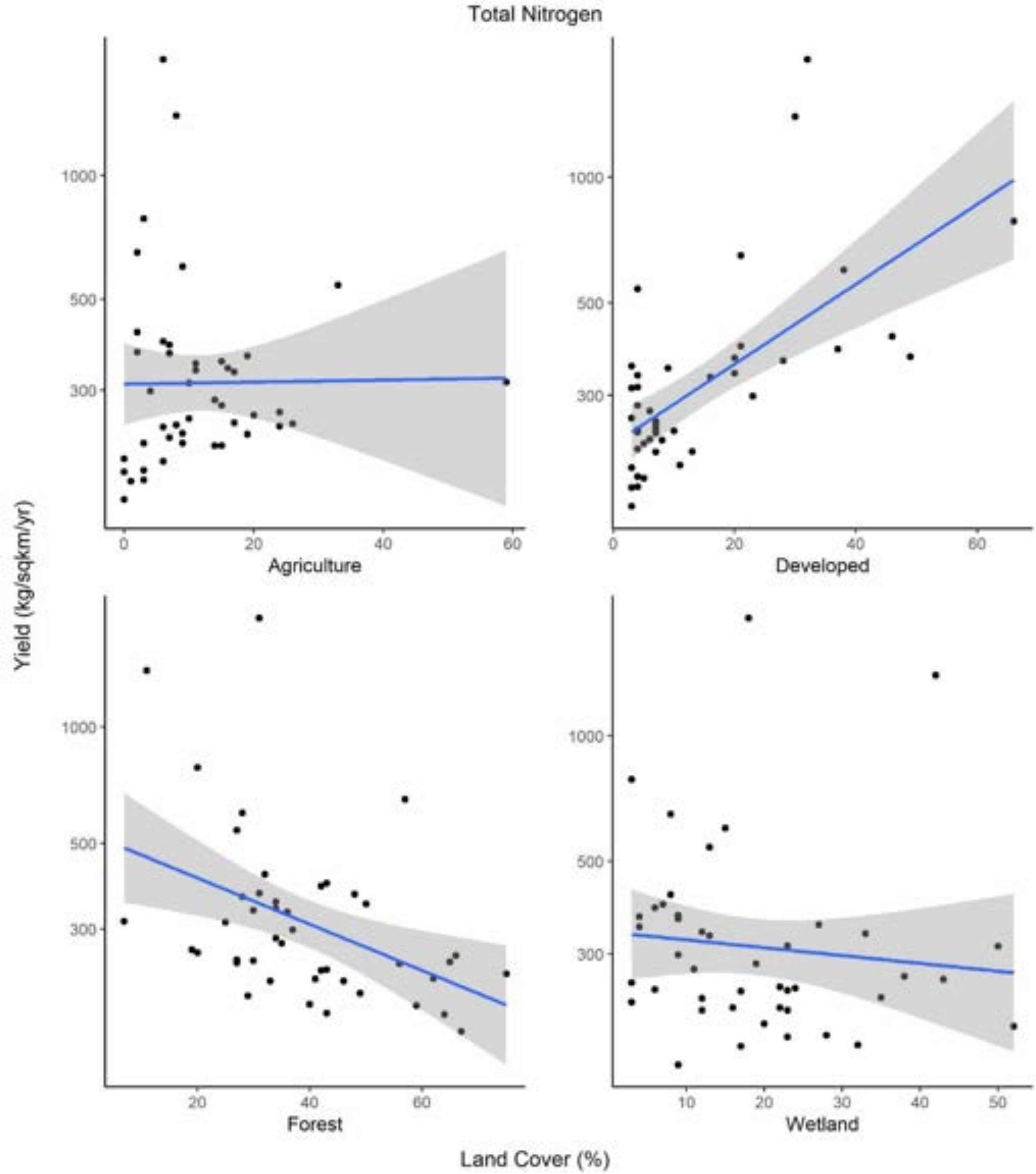
a_{ij} = Value of $\log(Y_i)$ when $L_j = 0$

c_{ij} = Slope relating percent of land cover category and log of the SPARROW parameter yield

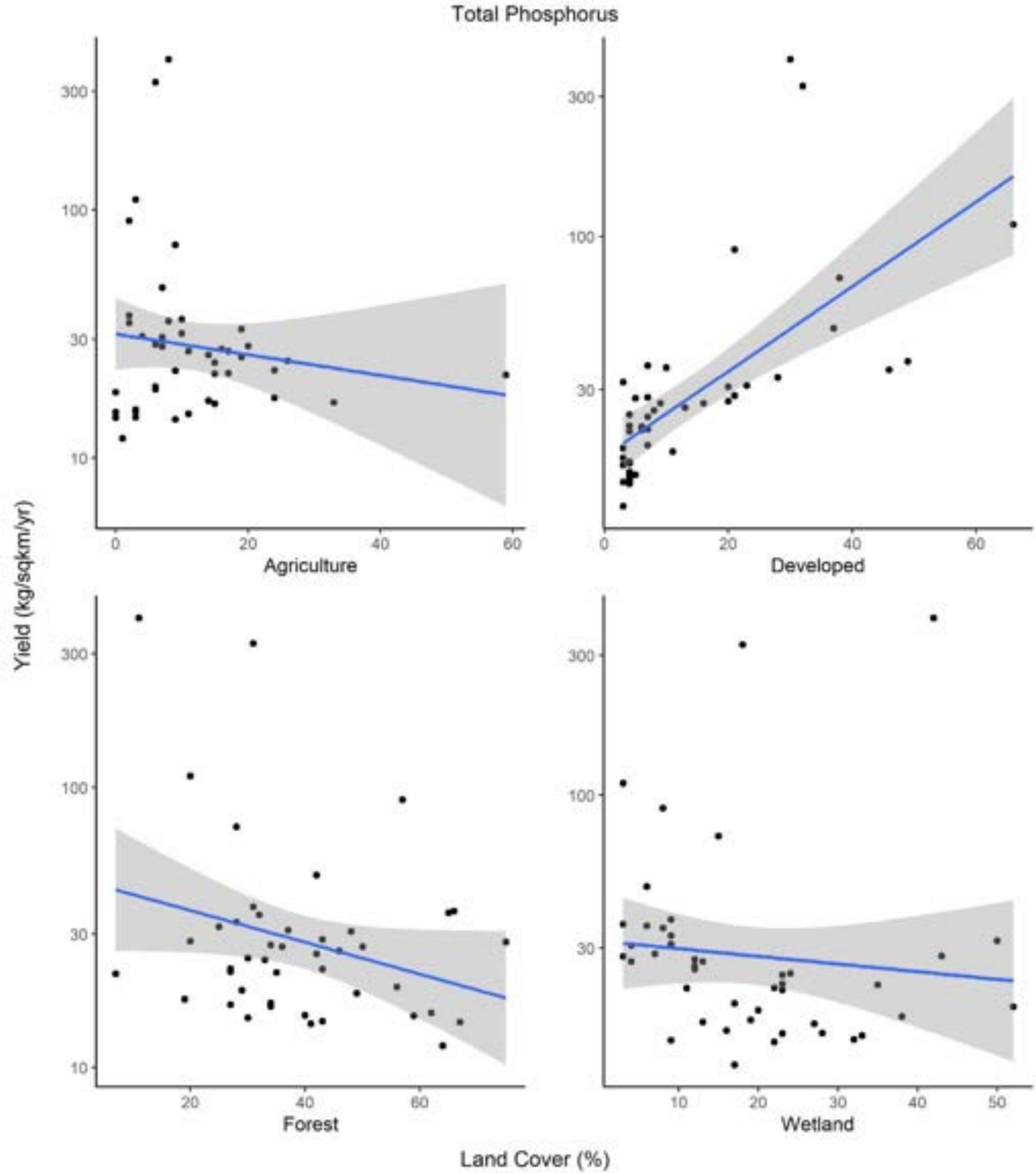
Table 9. Forward stepwise regression and ANCOVA results for Phase II of Analysis I.								
Land Cover Category	**TN**		**TP**		**TSS**		**Flow**	
	Coeff.	**p-Value**	**Coeff.**	**p-Value**	**Coeff.**	**p-Value**	**Coeff.**	**p-Value**
Developed	0.85	<0.01	1.38	<0.01	0.62	<0.01	0.56	<0.01
Forest	-0.39	0.02	x	x	x	x	x	x
Wetland	x	x	x	x	-0.88	<0.01	-0.45	<0.01

The following subsections present the graphical representations of Phase I of Analysis I.

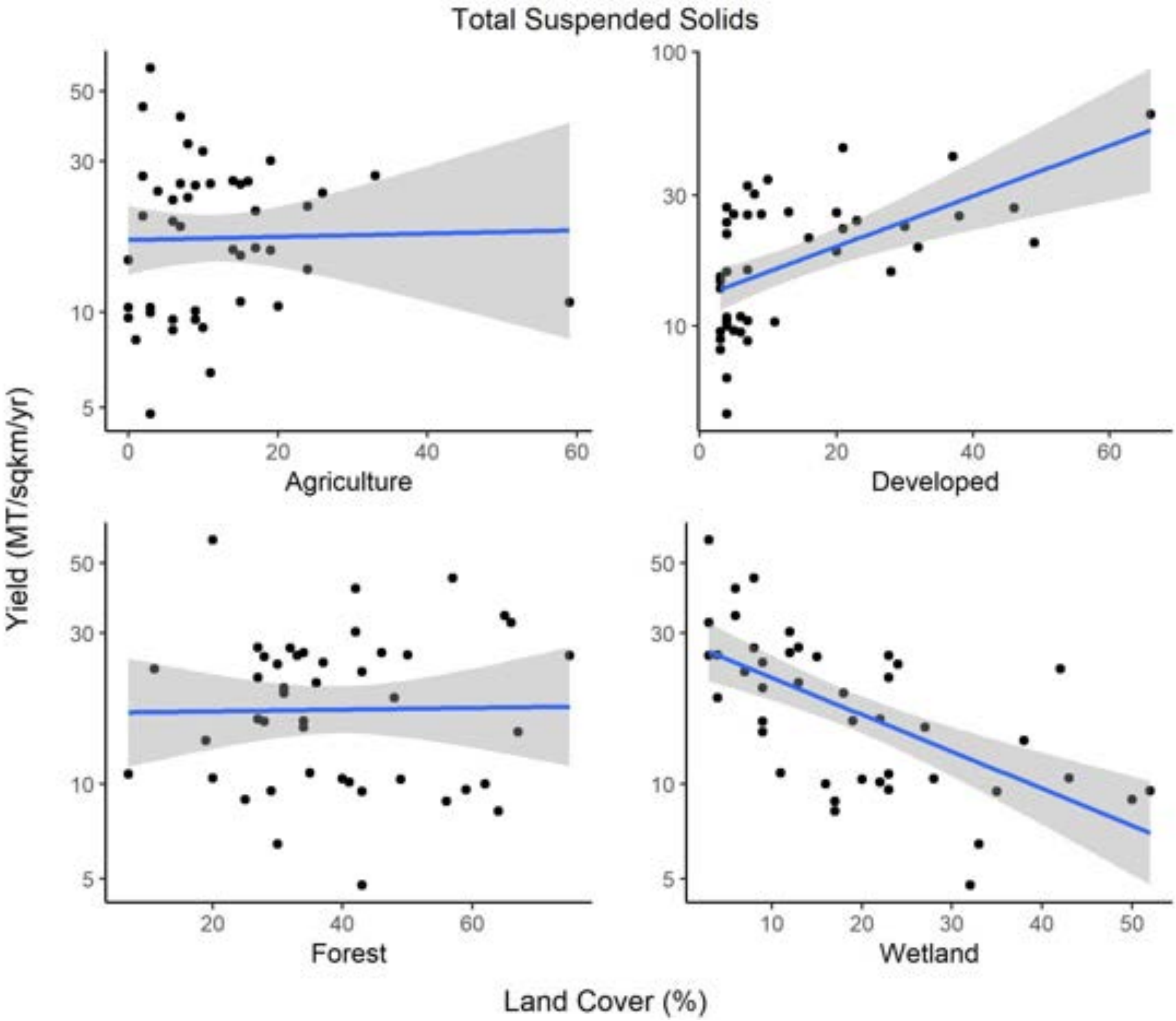
Total Nitrogen (TN)



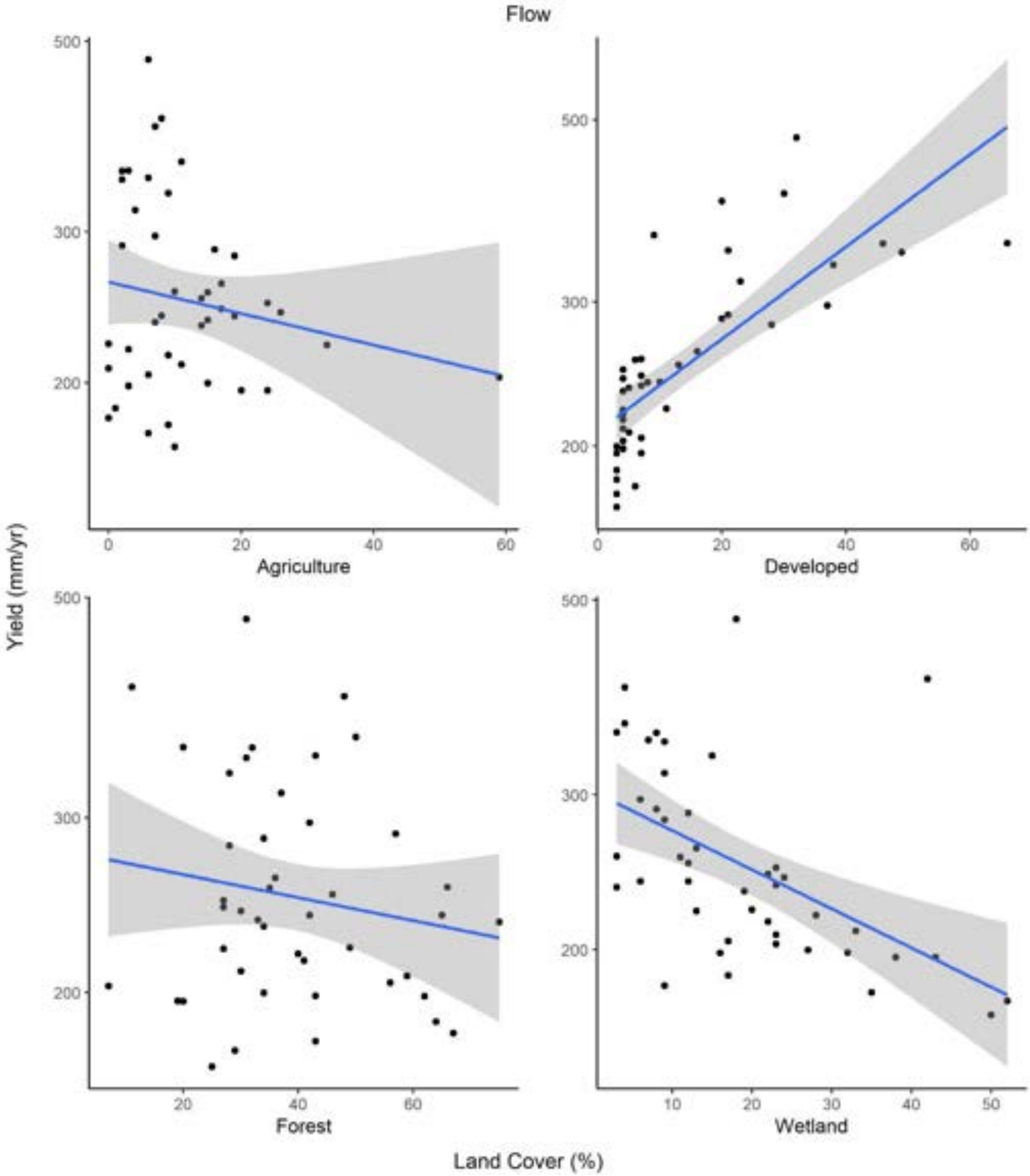
Total Phosphorus (TP)



Total Suspended Solids (TSS)



Flow



Flow
500
300
200
0
20
40
60
Agriculture
500
300
200
0
20
40
60
Developed
Yield (mm/yr)
500
300
200
20
40
60
Forest
500
300
200
10
20
30
40
50
Wetland
Land Cover (%)

Analysis II: TN & Drinking Water Quality Indicators

Analysis II utilized water quality data measured at the Beaufort-Jasper Water & Sewer Authority (BJWSA) intake location to compare TN concentrations to five indicators of drinking water quality: TOC, chlorophyll-a, geosmin, 2-methylisoborneol (MIB), and algae.

Three of these indicators (geosmin, MIB, and algae) had very few (between zero and three) data points paired with observed TN data, even after aggregating the daily data to monthly averages. Consequently, Analysis II focused on relating TN concentrations to TOC and chlorophyll-a. These parameters were compared by pairing daily data and monthly aggregated data; however, there was very little difference between the two approaches (Figure 14 and Figure 15). These figures indicate very little correlation between TN concentrations and concentrations of TOC or chlorophyll-a. An ANCOVA was conducted on both daily and monthly-aggregated datasets to evaluate whether there was any significant relationship, and, as can be seen in Table 10, no significant relationships were found.

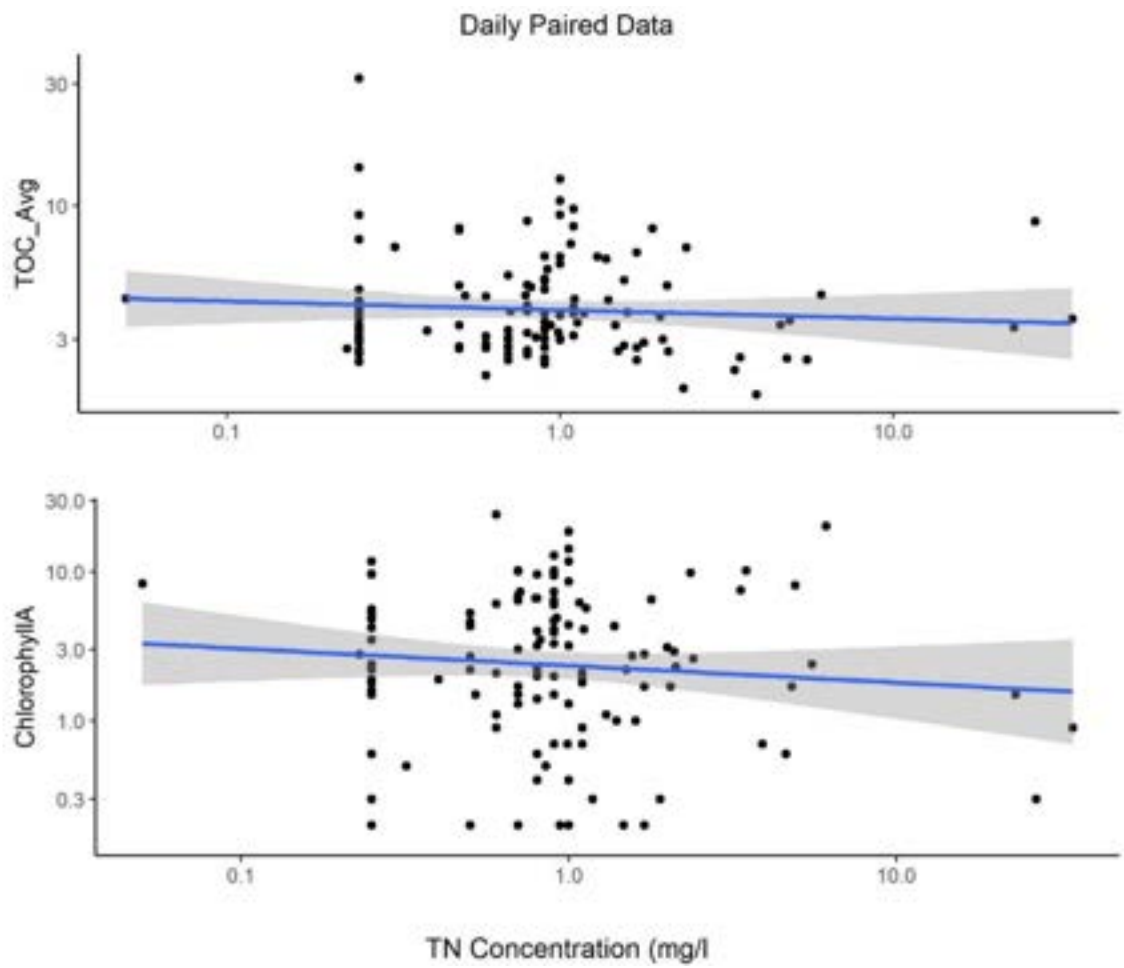


Figure 14. Paired daily observations between TN concentration and concentrations of TOC (top) and chlorophyll-a (bottom) at the BJWSA intake.

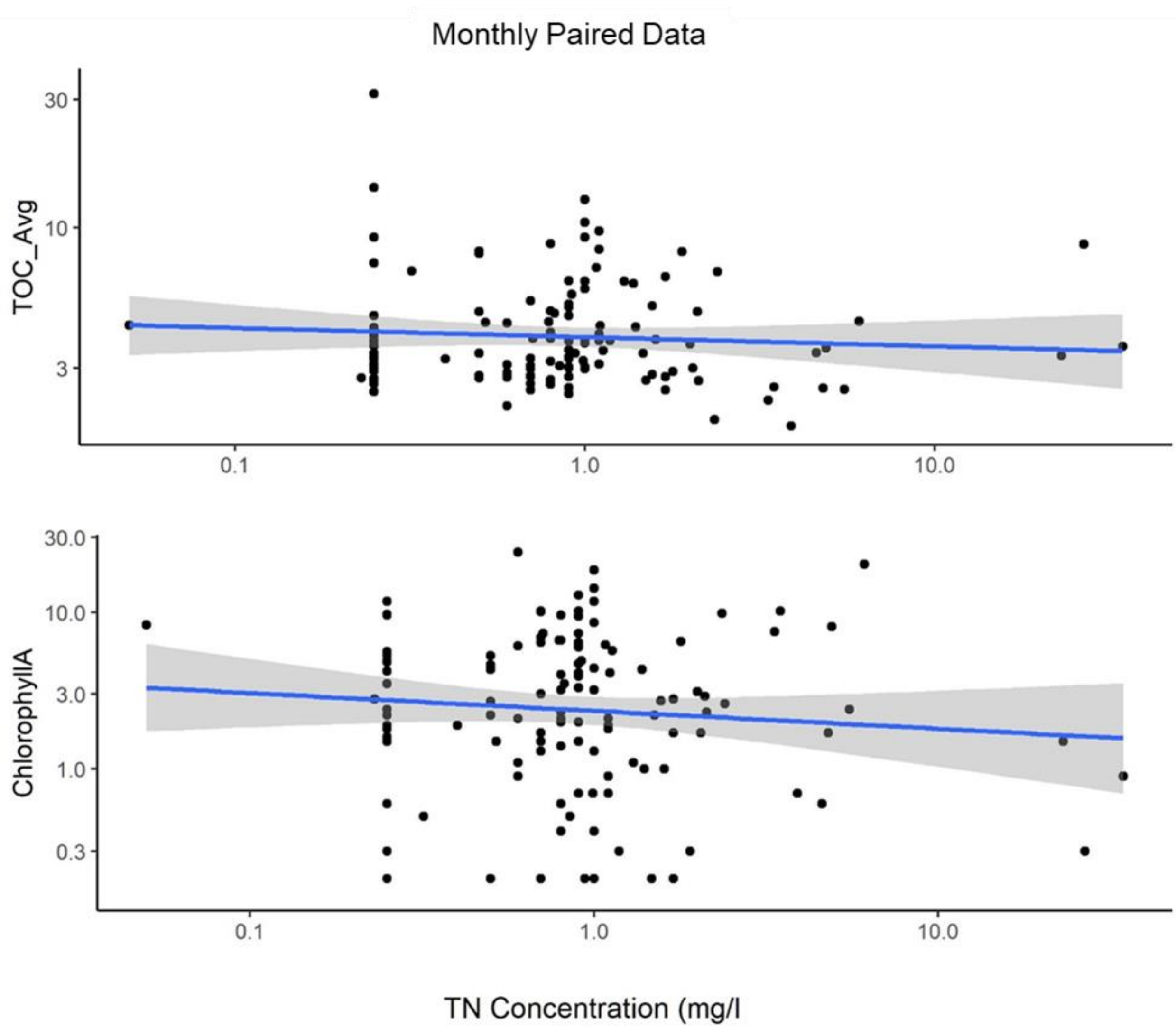


Figure 15. Paired monthly observations between TN concentration and concentrations of TOC (top) and chlorophyll-a (bottom) at the BJWSA intake.

Table 10. Regression and ANCOVA results for relationship between TN concentrations and concentrations of TOC and chlorophyll-a at BJWSA intake.

Data Pairing	TOC		Chlorophyll-a	
	Coeff.	p-Value	Coeff.	p-Value
Daily	-0.03	0.43	-0.11	0.29
Monthly Aggregates	-0.03	0.53	-0.07	0.56

These results indicate no significant or meaningful relationship between TN and either TOC or chlorophyll-a. There is insufficient data to draw any conclusions about the impacts of TN on the above-identified drinking water quality indicators using this dataset. This result is surprising since, in the literature, TN is typically associated with higher concentrations of both TOC and chlorophyll-a. There are a few possible explanations for this result, including:

- The TN load may be more important than the TN concentration. Higher flow events may result in lowered TN concentrations as a side effect of dilution, but it would still degrade water quality.
- The effect of TN concentrations and/or loading may have a "lag" effect. The concentration or load over more than one month (or in the previous month) could affect the drinking water quality indicators at an undetermined-but-delayed time.

Summary of Analysis I & II

The results of Analysis I and II indicate the following observations:

- Forest cover significantly and meaningfully decreases TN yield, even after accounting for the effects of developed land cover.
- Developed land cover has a statistically significant impact on the yields of all SPARROW parameters (TN, TP, TSS, and Flow); this relationship is greater than that of any other land cover. Consequently, preserving forest to reduce the amount of developed land cover would meaningfully reduce yields of all SPARROW parameters.
- Wetland cover is statistically significant in reducing yields of both TSS and flow.
- The water quality data at the BJWSA intake showed no statistically significant relationship between TN concentrations and concentrations of any of the five evaluated drinking water quality indicators, either due to a lack of sufficient overlapping data points (geosmin, MIB, algae) or no significant relationship in available data (TOC, chlorophyll-a). These results are surprising, but they can be explained by the limited data availability and the lack of accompanying flow data to relate TN concentrations to upstream loads.

Appendix D. Summary of Literature Relating Land Uses to Organic Compounds

Table 11. Summary of literature evaluating connections between upstream land uses and watershed characteristics to downstream concentrations of Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Disinfection Byproducts (DBPs), and DBP precursors.

Reference	Study Location	Study Design	Summary of Findings
Elias et al., 2016	Converse Reservoir (Mobile, Alabama, US)	Modeling study that evaluated the impacts of deforestation on TOC concentrations in source water under pre- and post-urbanization scenarios	Reservoir concentrations of TN, TP, TOC, and chlorophyll-a were all higher in the post-urbanization scenario, indicating a relationship between developed/urban cover and increased concentrations of T&O compounds. A positive relationship, although slightly weaker in terms of statistical significance, was also identified between streamflow and TOC concentrations in the receiving reservoir.
Shih et al., 2010	Streams across the conterminous US	Modeling study (using SPARROW) that evaluated the sources, transport, and fate of TOC in over 60,000 streams across the US	The two largest contributors to TOC loads to streams are wetlands and urban/developed lands, followed by mixed forests. Wetlands (primarily woody wetlands) and forests (primarily those with substantial unmanaged leaf litter) contribute organic matter to surface waters. When that organic matter decomposes, TOC concentrations increase, and the formation potential of disinfection byproducts (DBPs) increases as a result.
Chang & Carlson, 2005	Spring Creek (Pennsylvania, US)	Field study that evaluated the relationship between land cover and concentrations of TOC during winter rain events in 10 subwatersheds of Spring Creek, Pennsylvania	A positive relationship between surface discharge and in-stream TOC concentrations was observed. This indicates that land uses that infiltrate more and discharge less (like forested areas and well-managed agricultural areas) may contribute less TOC than land uses with more impervious area (like developed/urban areas). However, this study also observed that leaf litter from forested areas and vegetation from wetlands can increase in-stream TOC due to the decomposition of organic matter.
Chen et al., 2010	Congaree National Park (South Carolina, US)	Field study that collected 80 weeks of data on leaf litter decomposition and resulting	A strong connection between decomposing leaf litter from woody wetlands and both the yield of TOC and the formation potential of DBPs was observed.

Table 11. Summary of literature evaluating connections between upstream land uses and watershed characteristics to downstream concentrations of Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Disinfection Byproducts (DBPs), and DBP precursors.

Reference	Study Location	Study Design	Summary of Findings
		changes in DOC concentrations and formation potential of DBPs	
Fleck et al., 2004	Twitchell Island (California, US)	Field study that compared discharges of DOC, DBPs, and DBP precursors from a site converted from agricultural land to a restored wetland	Both agricultural and restored wetlands released organic compounds (measured as DOC, DBPs, and DBP precursors); the importance of historical land management practices and underlying soil characteristics were attributed as the dominant factors in the release of these compounds.
Yu et al., 2015	Wetlands throughout northwestern South Carolina (US)	Field study that evaluated water quality data from 40 seasonal wetlands in South Carolina	Wetlands with hydrological connections to surrounding urban areas contributed significantly more dissolved organic matter (DOM) than isolated wetlands. This is attributed to wastewater treatment and livestock pastures.
Correll et al., 2001	Subwatersheds in Rhode River watershed (Maryland, US)	Field study that evaluated discharges of TOC from eight contiguous watersheds with varying land uses in Maryland's coastal plain	Precipitation (and associated discharge) were found to be a highly significant indicator of TOC loads. Additionally, TOC yields were highest from watersheds with dominant agricultural uses.
Jordan et al., 1997	Chesapeake Bay watershed (US)	Field study that evaluated discharges of nutrients and carbon from 27 watersheds with varying proportions of agricultural lands	Surface runoff discharges promoted TOC loads.
Hladik et al., 2014	Pennsylvania (US)	Field study that evaluated concentrations of DBPs and DBP precursors at outfall locations of varying distances from oil and gas production facilities that discharge wastewater	Wastewater effluent discharges and in-stream concentrations of DBPs and DBP precursors were strongly correlated. Specifically, produced water brine (which is a form of wastewater from oil and gas extraction) contributes toxic DBPs even before the water is treated with chlorinated compounds for disinfection purposes. This kind of wastewater effluent is associated with industrial and developed/urban land uses.
Ejjada et al., 2021	Urban watershed (US)	Concentrations of TOC and DBPs from 20 sampling locations	TOC specifically was influenced by the amount of flow, indicating a "washout" effect. Additionally,

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Reference	Study Location	Study Design	Summary of Findings
		with varying receiving land uses, including urban runoff, wastewater effluent, and a drinking water reservoir	urban runoff (specifically from areas with unsheltered homeless populations) and wastewater effluent discharges contributed significant amounts of organic DBP precursors, indicating the importance of considering developed/urban areas as possible sources of these drinking water contaminants.