Assessing Effects of Watershed Change on Phosphorus Loading to Lake Greenwood, South Carolina

Final Report

Research supported by:
South Carolina Department of Natural Resources,
Buzzard's Roost Fisheries Mitigation Trust Fund,
and
Saluda-Reedy Watershed Consortium

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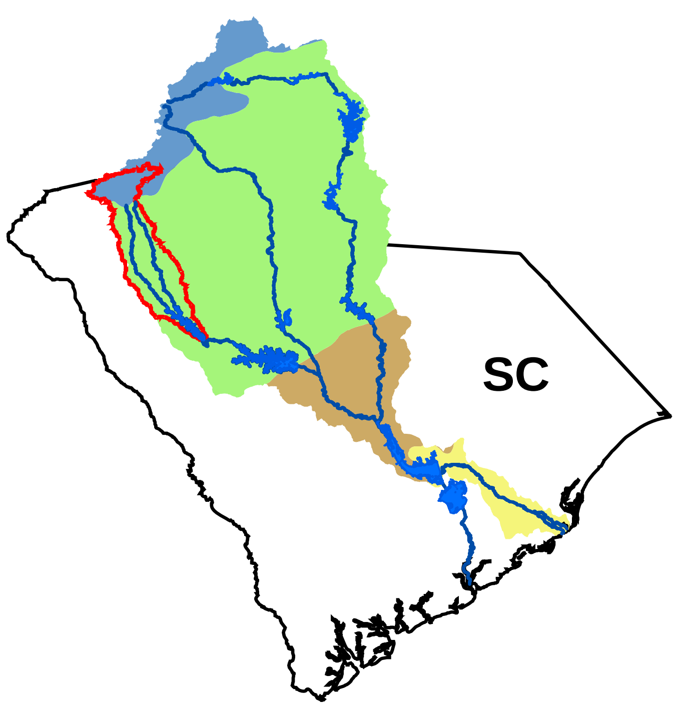
10 June 2008



SALUDA-REEDY WATERSHED CONSORTIUM

SOUTH CAROLINA DEPARTMENT OF NATURAL RESOURCES

DNR

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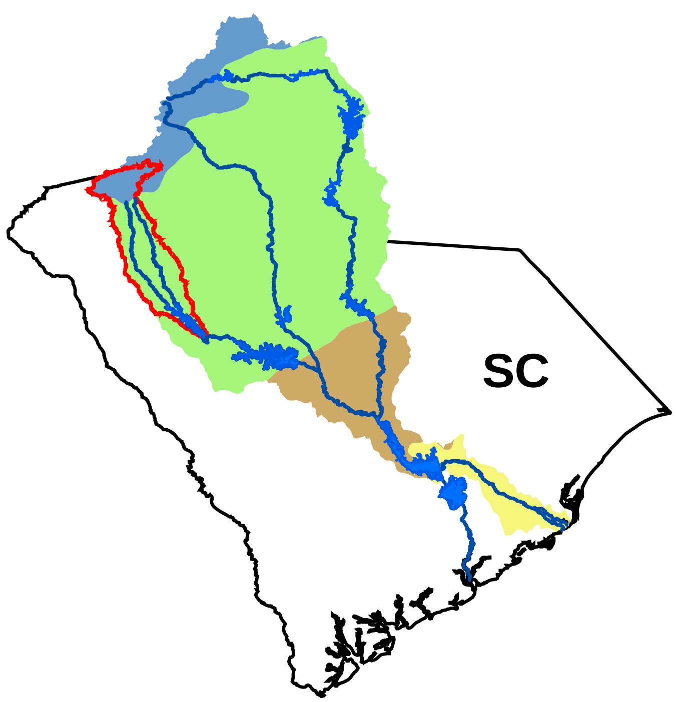

SALUDA-REEDY WATERSHED CONSORTIUM

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ACKNOWLEDGMENTS

This study was supported by the Buzzard's Roost Fisheries Mitigation Trust Fund, which is administered by Duke Energy, the US Fish and Wildlife Service, and the South Carolina Department of Natural Resources, and by a grant from the V. Kann Rasmsussen Foundation to the Saluda-Reedy Watershed Consortium. Wayne Harden, South Carolina Department of Health and Environmental Control, provided advice and data on NPDES-permitted discharges. Vivianne Vejdani and Bob Perry, Office of Environmental Programs, South Carolina Department of Natural Resources, and Wayne Harden reviewed draft versions of the report. Jason Van Driesche, Director of the Clean Air and Water Program for Upstate Forever, ably coordinated the activities of the diverse researchers and other partners in the Saluda-Reedy Watershed Consortium toward the ultimate goal of promoting stewardship of the region's rich natural resources.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

This report covers work on a second study of water quality in Lake Greenwood and the Saluda-Reedy Watershed.

In the first study, McKellar, Bulak, and Taylor (2008) investigated how changes in nutrient input to Lake Greenwood would affect water quality in the lake. Phosphorus is typically the limiting nutrient for production of algae in freshwater lakes. Algal blooms, oxygen depletion in the deeper waters of the lake, and habitat restriction for striped bass *Morone saxatilis* during summer were the conditions of primary interest. McKellar et al. constructed a dynamic water quality model of Lake Greenwood (CE-QUAL-W2), basing calibration of the model on extensive field studies in Lake Greenwood (McKellar and Bulak, 2005). They applied the model to test the effects of changing the amount of phosphorus brought to the lake by the Saluda and Reedy Rivers, its main tributaries. The model predicted that a 50% reduction in the phosphorus load and a concomitant reduction in sediment organic decay rates in both rivers would substantially reduce the annual mean phosphorus concentration and the risk of algal blooms throughout the lake. This load reduction would also decrease the extent of extreme oxygen depletion by 28-31% and would increase the tolerable habitat for striped bass by almost 10% during periods of oxygen depletion.

Our plan for the second study was build a watershed model to predict changes in phosphorus loading to Lake Greenwood resulting from changes in the Saluda-Reedy Watershed, using Hydrologic Simulation Program in Fortran (HSPF). We determined that some of the main questions about watershed processes and phosphorus loading required further analysis of the data for the watershed before we could confidently calibrate and test the model. If one doesn't understand the input to a model, one can't reliably judge and apply the output. The analysis of watershed data, presented in this report, permits us to assess the strengths and limitations of the data and establishes a firmer understanding of the watershed processes.

Our analysis covers the years 2002-2006. We built on the base of information developed by other partners in the Saluda-Reedy Watershed Consortium, including the thoughtful work on water quality trends from 1955-2002 by Hargett, Hargett, and Springs (2005) and the close interval sampling in the Saluda and Reedy Rivers in 2004-2005 by Klaine and Smink (2005). Our analysis reveals important recent variation and change in phosphorus loading to Lake Greenwood from the Saluda-Reedy Watershed.

In this report, we consider inputs of phosphorus from the watershed and responses of Lake Greenwood. As in the Lake Greenwood model, we focus on phosphorus here because of its critical role in regulating production of algae. The questions of interest include:

1) What are the sources of phosphorus to Lake Greenwood? Does phosphorus loading derive mainly from point sources, such as industrial or domestic discharges, or nonpoint sources, including runoff from agricultural and urban lands?
2) How does phosphorus loading vary within and among years?
3) Is phosphorus loading strongly linked with sediment loading?
4) How will Lake Greenwood respond to changes in phosphorus loading?

Geographic setting and changing environment of Lake Greenwood

Lake Greenwood is situated about 100 km downstream from headwaters of the Saluda River (Fig. 1). Its main tributaries are the Saluda and Reedy Rivers. It is the largest of about 1800 lakes and ponds, all man-made, in the watershed. Lake Greenwood was built in 1940 to supply hydroelectric power to the city of Greenwood. The lake is now owned by Santee Cooper, a public power utility, and its power generation capacity is reserved for backup. The primary uses of the lake and shoreline are recreational and residential. The lake supports valuable sport fisheries. It also serves as a minor source of drinking water.

The Saluda-Reedy Watershed, the watershed of Lake Greenwood, represents the upper reaches of a tributary in the Santee drainage (Fig. 1). The watershed lies mainly within the gently rolling hills of the Piedmont. The upper tributaries of the Saluda River arise in the steeper slopes of the Blue Ridge.

Greenville is the main urban center within the watershed. Interstates 85 and 26 connect Greenville directly to other urban centers in North and South Carolina. The population of the region is expanding (Campbell, Allen, and Lu, 2007). Accompanying this growth are modifications of the landscape and demands on water for domestic and industrial use, waste removal, and recreation.

Weather also contributes to variation and change in the watershed. For example, since 1920, annual rainfall has varied by a factor of two and annual mean temperature has varied by more than 3 ºC at Laurens, South Carolina. Climate change assessments for southeastern region of North America predict modest to substantial warming over the next century, but diverge widely in predictions about rainfall, with predictions ranging from a 10% decrease to a 20% increase in average annual precipitation (Burkett et al., 2001). The extreme drought of 2007 has heightened public concerns about the impact of weather and climate on water resources of the region.

Threats to Lake Greenwood

Water quality in the Saluda-Reedy Watershed has improved over the last four decades, most markedly as a consequence of the Clean Water Act of 1972 (Hargett, Hargett, and Springs, 2005). However, the most recent water quality assessment for the Saluda River basin (SC DHEC, 2004a) noted that water quality at several stations in Lake Greenwood did not meet state standards for Aquatic Life Use Support. These standards define conditions required to maintain a balanced aquatic community. The violations of these standards at Lake Greenwood were due mainly to excessive total phosphorus and insufficient dissolved oxygen. Three stations in Lake Greenwood appeared on the 2006 list of impaired waters for excessive total phosphorus concentrations (SC DHEC, 2006).

Excessive phosphorus concentrations can cause algal blooms. As the algae die and settle to the bottom of the lake, their decomposition consumes oxygen. Extensive oxygen depletion occurs in deeper waters of Lake Greenwood during spring and summer (McKellar and Bulak, 2005), when the lake is thermally stratified for prolonged periods. (Warmer, lighter water in the upper part of the water column doesn’t mix with the cooler, denser water below.) Although some oxygen depletion is expected in any stratified lake, particularly in warmer climates, the

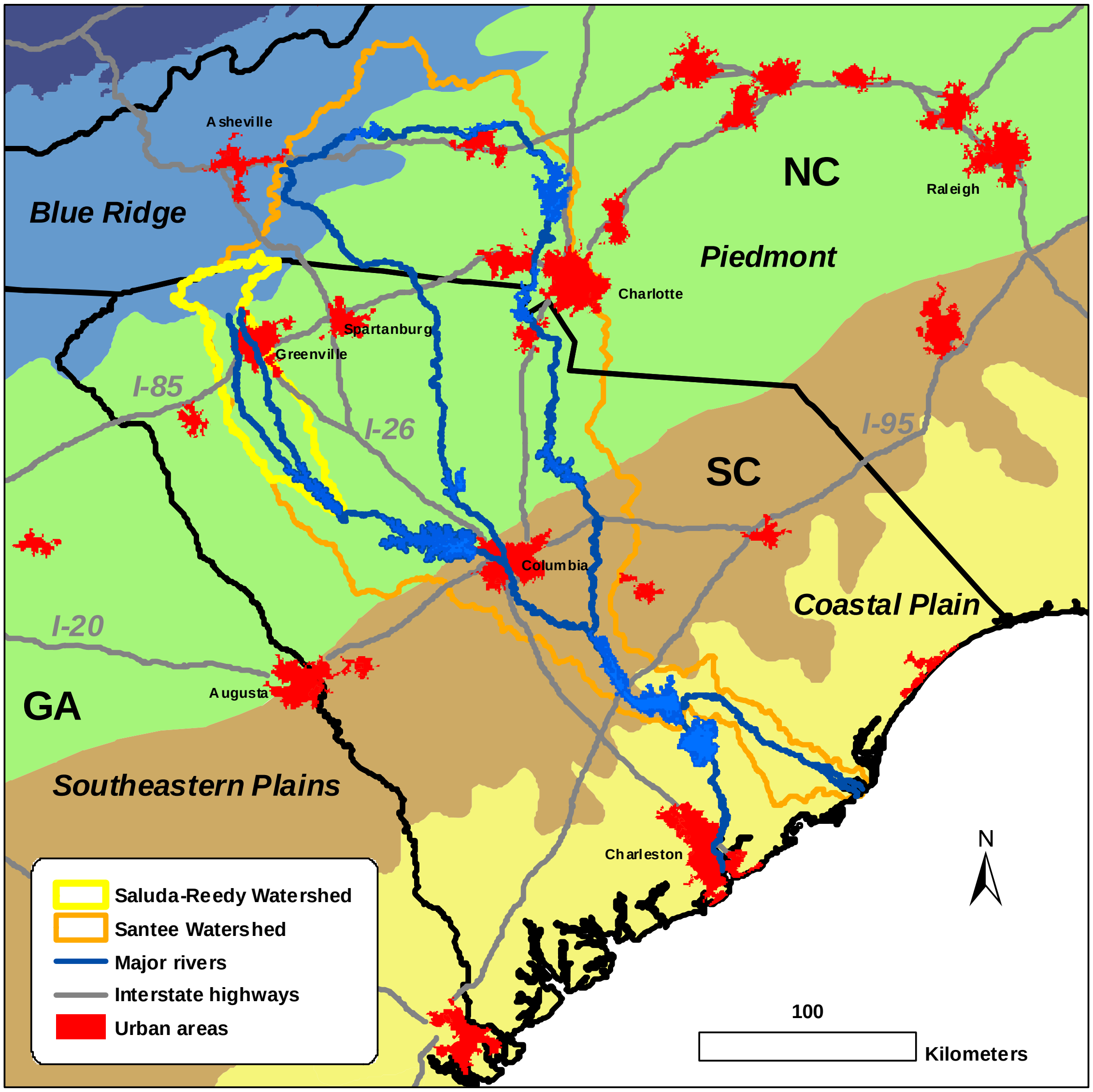

Figure 1. Map of the Saluda-Reedy Watershed.

conditions in Lake Greenwood become extreme. Depletion of oxygen in summer severely limits the deep water habitat available to fish and other aquatic organisms in Lake Greenwood.

Lake Greenwood also receives a heavy load of sediment. About 3% of the total area of Lake Greenwood has been lost due to sedimentation in the upper reaches of the lake since 1940 (Hargett, 2004). Local consequences of sedimentation include input of sediment-bound pollutants, loss of habitat, change in configuration and value of waterfront property, increased water treatment costs, and loss of water supply capacity.

Resources for watershed assessment

We used BASINS 4 (Better Assessment Science Integrating Point and Nonpoint Sources) as a platform for organizing and obtaining watershed data. BASINS is the watershed analysis system currently supported by EPA. It provides mechanisms for obtaining and organizing information (weather data, digital elevation maps, census data, land use, etc.) in convenient geographic blocs. It provides capabilities for summarizing, analyzing, and modeling these data in spatial format. It also provides interfaces to several watershed models, including Pollutant Loading Estimator (PLOAD) and Hydrologic Simulation Program in Fortran (HSPF).

Most of the geospatial analysis was performed in BASINS. The maps were created in ArcMap (ESRI, Inc.). Most of the statistical analyses and other computations were performed in S-Plus (Insightful Corporation, Seattle, Washington).

The large base of monthly water quality data collected by the South Carolina Department of Health and Environmental Control (SC DHEC) has been an essential resource for this project. Of particular importance are stations that are sampled on a monthly basis every year. These stations have allowed us to detect changes in impacts of point sources that would have been impossible if the sampling locations had been chosen randomly each year. The watershed assessment for the Saluda basin (SC DHEC, 2004a) has been invaluable.

HYDROLOGY, PHOSPHORUS SOURCES, AND WATER QUALITY

Water delivers phosphorus to the lake. Distributions of phosphorus concentrations in relation to point sources, such as industrial or domestic discharges, and nonpoint sources, including runoff from agricultural and urban lands, provides a basis for inferences about the sources of phosphorus. The data reveal wide temporal variation in the phosphorus concentrations and water flows that are critical to estimating phosphorus loads to Lake Greenwood.

Hydrology

The Saluda Reedy Watershed contains about 4900 km of mapped streams and nearly 1800 lakes and ponds (Fig. 2). The lakes and ponds are all man-made, and the total area of impounded water is about 64 km^2. The larger lakes are: Lake Greenwood (42 km^2) on the Saluda River, North Saluda Reservoir or Poinsett Reservoir (4.2 km^2) on the North Saluda River, Lake Rabon (2.3 km^2) on Rabon Creek, Table Rock Reservoir (1.8 km^2) on the South Saluda River, Saluda Lake (1.2 km^2) on the Saluda River, and Boyd Mill Pond (0.8 km^2) on the Reedy River. Ninety-nine per cent of lakes and ponds are less than 0.1 km^2 (10 ha) in area. They constitute about 16% per cent of the impounded area.

Daily stream discharge records for 2002-2006 are available from ten gages within the Saluda Reedy Watershed and one gage in the tailrace downstream of Lake Greenwood (Table 1). During the period of this analysis, total annual discharge at each of these gages varied by a factor of about two. Such wide variation among years appears to be usual for the watershed (Fig. 3). For the Saluda River near Ware Shoals, annual discharges for 2002 and 2006 were among the lowest 15% of the 67-year record. Annual discharge in 2007 (not shown) was nearly identical to annual discharge in 2006. Annual discharges for 2004 and 2005 were near or just above the median. Annual discharge for 2003 was high, but distinctly below the most extreme years.

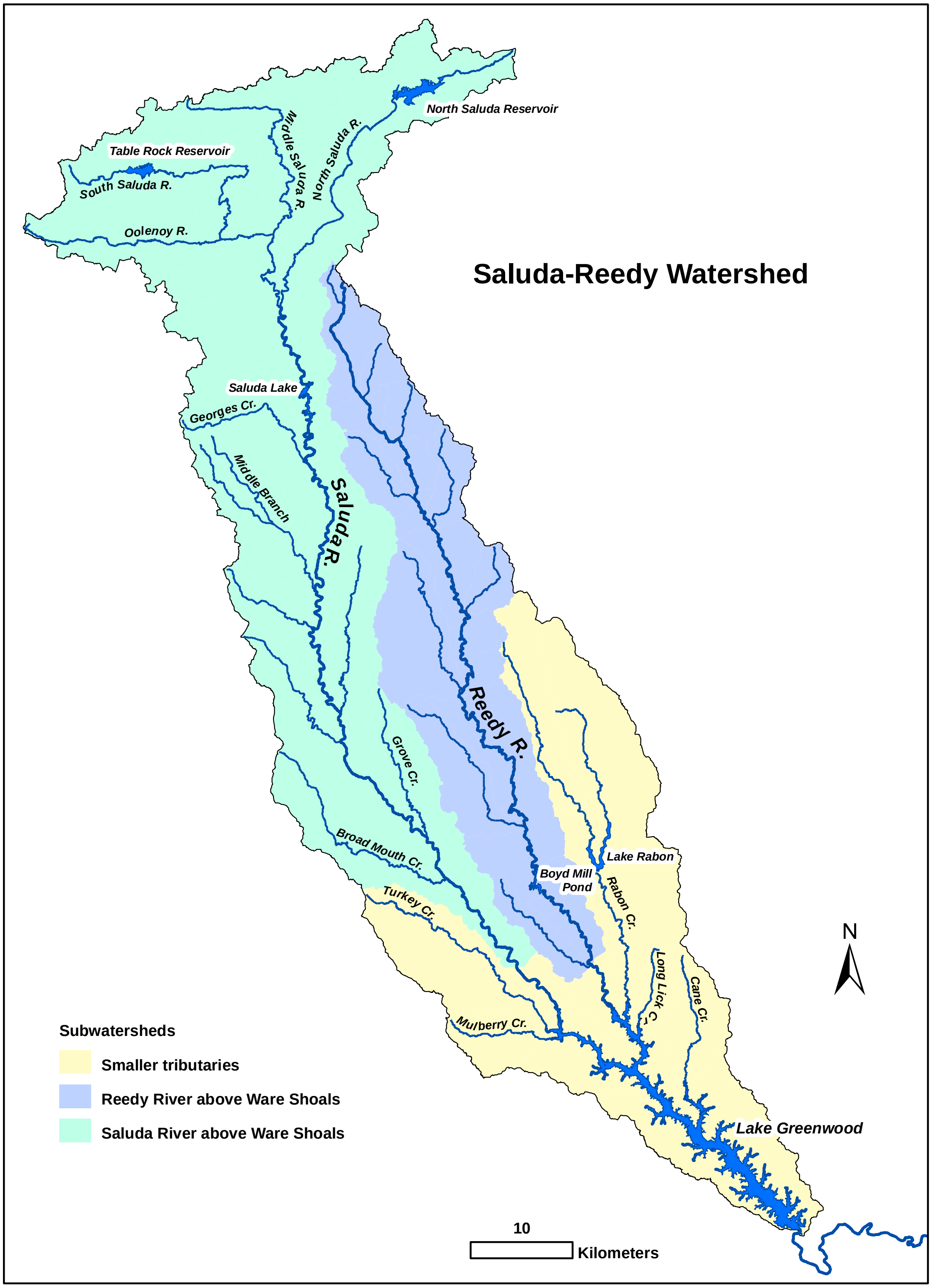

Figure 2. Map of main streams and impoundments in the Saluda-Reedy Watershed.

Table 1. USGS gages with daily records during 2002-2006. Range of annual discharge is based on complete years only.

Gage	*Location*	*Period of record, 2002-2006*	*Annual discharge, 2002-2006, in 10^6 m^3*
2162350	Middle Saluda River near Cleveland	2002-2003 (in part)	37
2162500	Saluda River near Greenville	2002-2006	295-693
2163001	Saluda River near Williamston	2002-2006	403-863
21630967	Grove Creek near Piedmont	2002-2006	17-30
2163500	Saluda River near Ware Shoals	2002-2006	537-1,168
2164000	Reedy River near Greenville	2002-2006	50-102
2164110	Reedy River above Fork Shoals	2002-2006	135-253
2165000	Reedy River near Ware Shoals	2002-2004 (in part)	235-418
21650905	Reedy River near Waterloo	2004 (in part)-2006	194-389
2165200	South Rabon Creek near Gray Court	2002-2006 (in part)	19-38
2166501	Lake Greenwood tailrace near Chappells	2002-2006	849-2,004

Daily discharge in the long-term record for the Saluda River near Ware Shoals typically varies by a factor of about 40 within years. Factors for 2002-2006 ranged from 35 to 85. Pulses of high discharge are important. In 2004, for example, the upper 10% of daily discharges accounted for 33% of the annual discharge.

Data sources. Hydrographic information was derived from the National Hydrographic Dataset (NHD) published by the United States Geologic Survey (USGS). The data are available at http://nhd.usgs.gov/data.html. We used the Hydrography Feature Dataset for the Santee Watershed (version dated 23-Mar-07), which includes streams, waterbodies, and HUC 12-digit subwatersheds. We added Lake Rabon to the waterbodies layer. USGS gages with daily discharge estimates were identified using Basins 4 data downloads cross-referenced to inventories obtained directly from USGS at http://nwis.waterdata.usgs.gov/nwis/dvstat. Drainage areas for the gages and other subbasins were delineated from HUC subwatersheds.

Land use and nonpoint sources of phosphorus

More than half of the Saluda Reedy Watershed is forested, and about a quarter of the land is in agricultural use (Table 2, Fig. 4). Urban development is heaviest in the middle reaches of the watershed, centered on the city of Greenville. Default loading rates (Table 3) from PLOAD indicate the potential for nonpoint phosphorus loading to the streams according to land use.

Data sources. The USGS Geographic Information Retrieval and Analysis System land use shapefiles for the region were downloaded through the BASINS interface. These shapefiles were derived from 2001 imagery; land use classifications follow the USDA NRCS (Natural Resource Conservation Service). Minimum polygons are10 acres (4 hectares) for man-made features and 40 acres (16 hectares) for natural features (http://edc.usgs.gov/products/landcover/lulc.html).

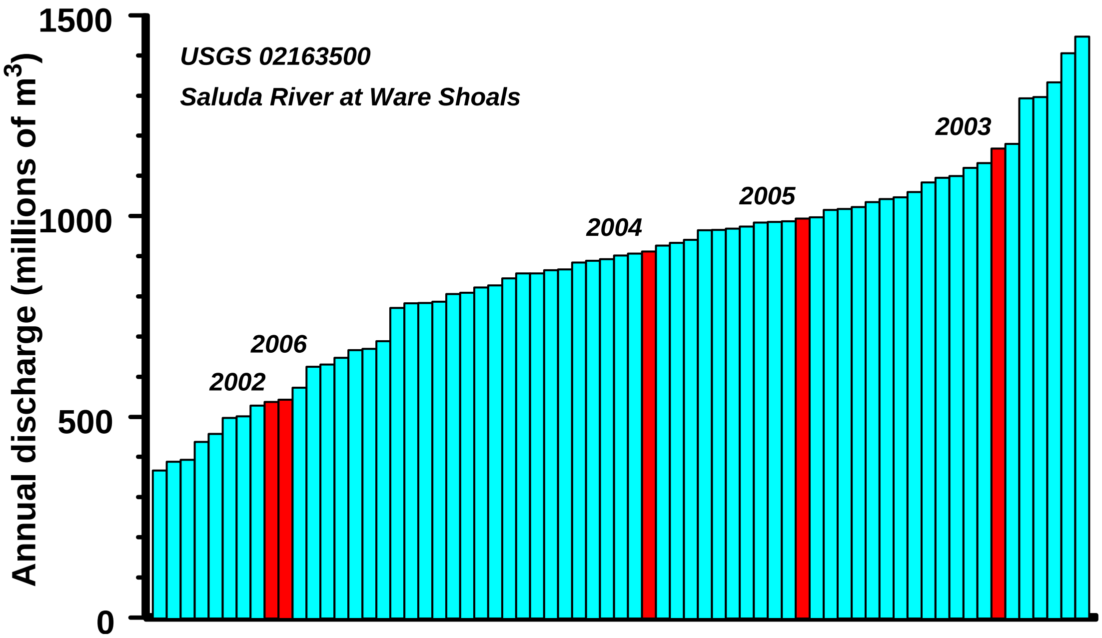

Figure 3. Distribution of annual discharge of Saluda River near Ware Shoals, 1940-2006.

Table 2. Summary of land use within the Saluda-Reedy Watershed.

Land use class	*Entire watershed*		*Saluda River above Ware Shoals*		*Reedy River above Ware Shoals*		*Rabon Creek and other tributaries*	
	Area (km^2)	*Percentage*	*Area (km^2)*	*Percentage*	*Area (km^2)*	*Percentage*	*Area (km^2)*	*Percentage*
Developed land	325	10.7%	122	8.0%	170	26.0%	33	3.8%
Agricultural land	815	26.7%	386	25.3%	199	30.3%	231	26.4%
Forest land	1,847	60.5%	998	65.5%	278	42.4%	570	65.4%
Water	50	1.6%	10	0.7%	3	0.4%	38	4.3%
Other	16	0.5%	9	0.6%	6	0.9%	1	0.1%
ALL	3,053	100.0%	1,525	100.0%	656	100.0%	873	100.0%

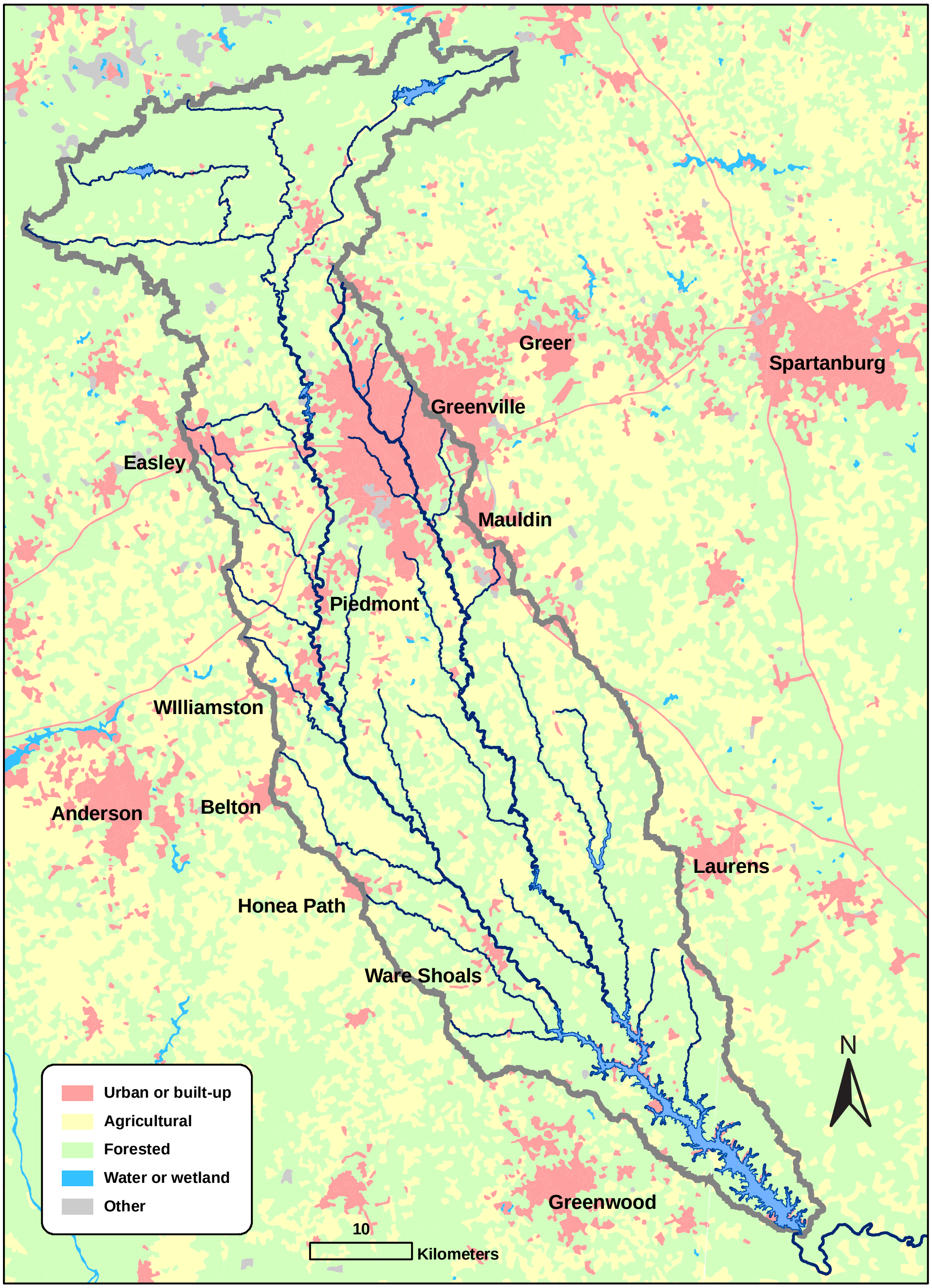

Figure 4. Map of land use in the Saluda-Reedy Watershed. Land use is based on GIRAS 2001 coverage.

Table 3. Loading rates of total phosphorus from PLOAD by land use class. Rates are given for reference, not for prediction.

Land use class	***Annual loading rate for total phosphorus kg/ha***
Developed land	2.2
Agricultural land	1.1
Forest land	0.2
Water	0.1
Other	0.2

Major point sources of phosphorus

There are about three dozen facilities with NPDES permits within the Saluda-Reedy Watershed. Eleven are classified as major dischargers: nine, for discharge of domestic wastewater at more than one million gallons per day; two, for discharge of industrial wastewater. Permitted discharges for the nine major domestic facilities (Table 4) include total phosphorus. Because permitted discharges for the two major industrial dischargers do not include phosphorus, they are not considered further in this analysis.

Seven of these facilities discharge into the Saluda River or its tributaries, and two discharge into the Reedy River. Discharges to both rivers changed significantly from 2002 to 2006 (Table 4, Fig. 5; note missing data, which result in modest underestimates of total discharges to the Saluda River for 2002-2003). For the Reedy River, the peak discharge of phosphorus occurred in 2003. In 2006, the amount was 40% lower, due mainly to the decrease at the Mauldin Road facility. For the Saluda River in 2006, the decrease from the peak in 2002 was about 20%. However, while discharges from the largest downstream facility (Ware Shoals, SC0020214) decreased by 85%, discharges from an upstream facility (Easley/Middle Branch, SC0039853) doubled.

In 2002-2004, combined discharge of total phosphorus into the Reedy River was similar to combined discharge into the Saluda River and tributaries. In 2005-2006, combined discharge to the Reedy River was about 30% lower than combined discharge into the Saluda River and tributaries.

In the Saluda River, the load-weighted mean distance of discharge points from Lake Greenwood nearly doubled from 2002 to 2006 (Fig. 6). The mean was calculated as the sum of the products of load and distance for each facility divided by the sum of the loads; distance was measured from Lake Greenwood to point of entry into the Saluda River. Load-weighted mean distance of discharges into the Reedy River did not change substantially during this time.

Patterns of discharge from these point sources will continue to change in the near future. Upgrades and expansions for various facilities, including Mauldin Road, Lower Reedy, Grove Creek, and Georges Creek, are presently under construction (Western Carolina Regional Sewer Authority, http://www.wcrsaonline.org/capitalimprovements.php).

Table 4. Annual discharges of effluent and total phosphorus from wastewater treatment plants permitted for major domestic discharges, 2002-2006. Total phosphorus values are rounded to the nearest 10 kg; uncertainty is unquantified.

Facility name, location, and NPDES permit	***Receiving stream***	***Effluent (10^6 m^3)***					***Total phosphorus (kg)***				
		2002	***2003***	***2004***	***2005***	***2006***	***2002***	***2003***	***2004***	***2005***	***2006***
WCRSA/Georges Creek Plant Greenville SC0047309	Saluda River	-*	-*	1.3	1.7	1.5	-*	-*	1,790	3,180	4,020
Easley Combined Utility/Middle Branch Plant Easley SC0039853	Middle Branch	2.5	2.9	2.5	2.7	2.8	4,820	7,300	6,690	8,350	9,980
WCRSA/Piedmont Plant Piedmont SC0023906	Saluda River	5.0	5.1	3.9	4.3	5.2	720	660	550	500	630
WCRSA/Grove Creek Plant Piedmont SC0024317	Grove Creek	1.5	1.8	1.5	1.5	1.3	3,890	2,850	2,150	2,160	2,900
Town of Williamston Williamston SC0046841	Saluda River	0.7	0.8	0.8	0.8	0.7	19,010	1,910	2,120	2,200	2,000
Belton/Ducworth Saluda Belton SC0045896	Saluda River	1.1	1.3	0.9	1.0	0.7	1,700	1,680	2,310	1,710	1,200
Town of Ware Shoals/Dairy Street Ware Shoals SC0020214	Saluda River	4.1	4.0	3.6	2.2	1.1	15,660	11,160	6,920	8,120	2,450
WCRSA/Mauldin Road Plant Greenville SC0041211	Reedy River	26.6	29.1	28.0	25.2	22.1	18,660	22,830	12,810	11,900	13,440
WCRSA/Lower Reedy River Plant Simpsonville SC0024261	Reedy River	6.8	7.6	7.2	7.1	7.0	6,450	4,670	3,420	4,920	3,150

*No data

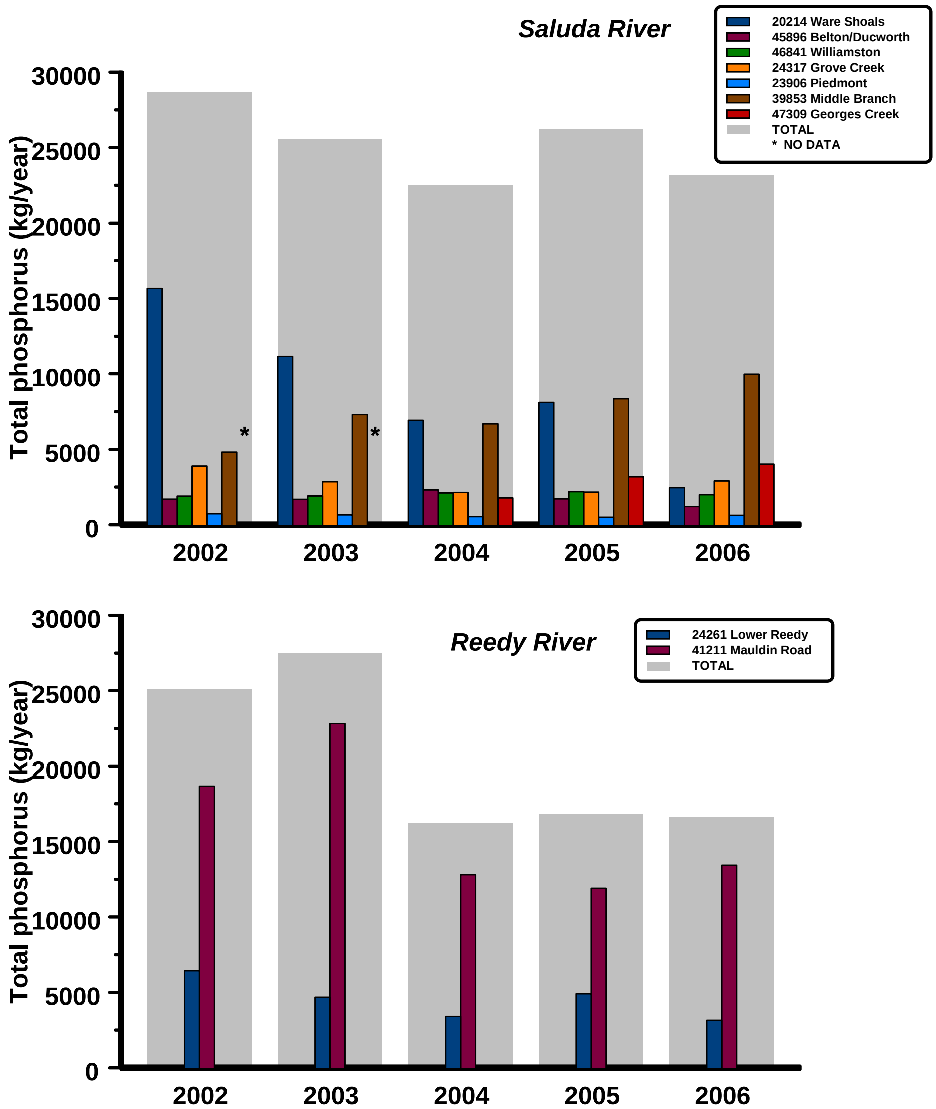

Figure 5. Annual discharges of total phosphorus by major domestic wastewater treatment plants, 2002-2006.

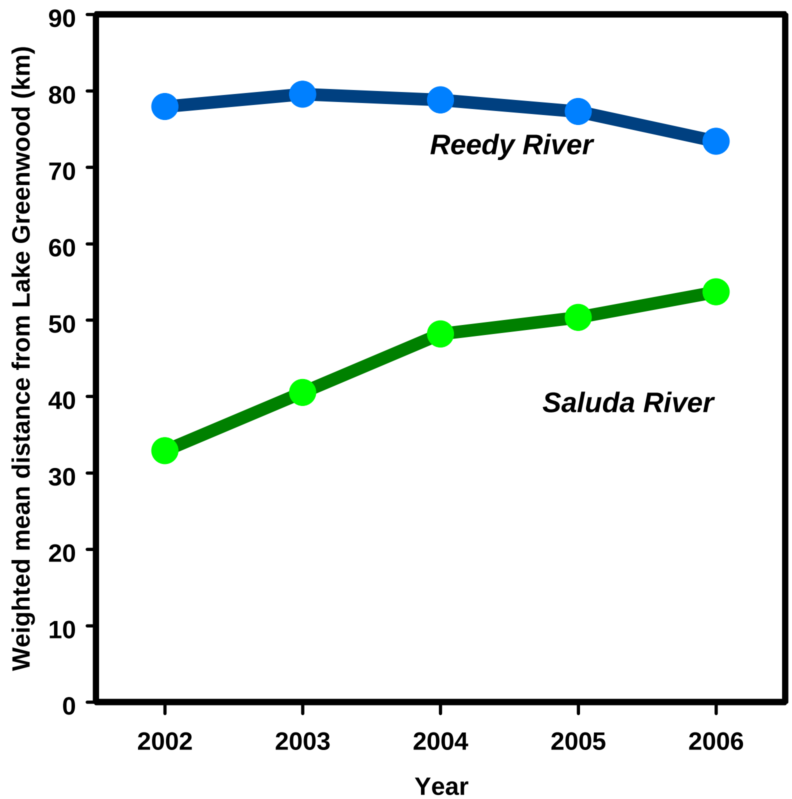

Figure 6. Weighted mean distance from Lake Greenwood of total phosphorus discharges from major domestic wastewater treatment plants, 2002-2006.

Data sources. NPDES permits are tracked by the US Environmental Protection Agency. We used the Geospatial Data File (17-Jul-07 version), available at http://www.epa.gov/enviro/geo_data.html, for initial identification of facilities of interest in the Saluda Reedy Watershed. Information was checked against accounts in SCDHEC (2004) and additional data in the EPA Envirofacts Data Warehouse. Monthly summaries of the discharge monitoring reports for each facility were provided by Wayne Harden, SC DHEC.

Spatial and temporal variation in water quality

The water quality monitoring program conducted by SC DHEC included a year or more of monthly samples of phosphorus and other nutrients from 46 stream stations within the Saluda Reedy Watershed during 2002-2006 (Fig. 7). Land use recoded by phosphorus loading potential and wastewater treatment plants with major domestic permits are also mapped.

Phosphorus data were available from STORET for the entire period for 15 stations. Phosphorus data were available for 26 additional stations in 2006, as part of five-year cycle of

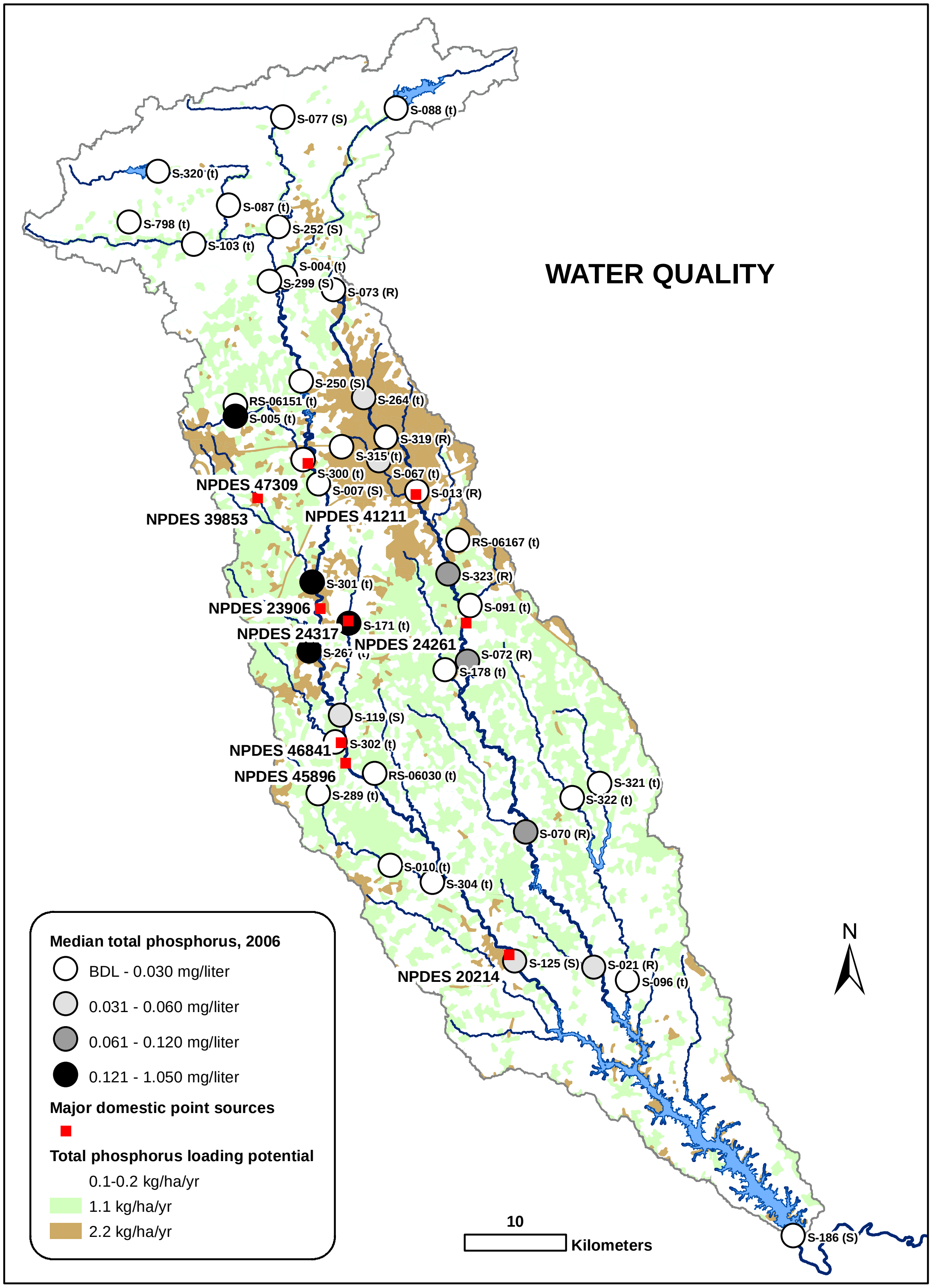

Figure 7. Map of median total phosphorus concentrations at SC DHEC stream water quality stations, 2006. Default values of total phosphorus loading from PLOAD rate indicate nonpoint loading potential; they are not predictions. Letter in parenthesis designates whether DHEC station is located on the Saluda River (S), the Reedy River (R), or a tributary (t). Major point sources (Table 4) are identified by the last five digits of the NPDES permit.

intensified sampling in each of the state's river basins, and for five other stations in other years (three stations in 2002, and two in 2004).

Phosphorus concentrations in 2006 were generally highest in the middle reaches of the Saluda Reedy Watershed (Fig. 7). Detection limit for the samples was 0.02 mg/liter. Median concentrations at three stations on the Reedy River exceeded 0.06 mg/liter. Waters of Boyd Mill Pond, just downstream of S-070, were listed as impaired due to high total phosphorus concentrations (SC DHEC, 2006); the water quality standard for Piedmont lakes is 0.06 mg/liter (SC DHEC, 2004b). Median concentrations of total phosphorus at four stations on tributaries of the Saluda River were very high, exceeding 0.12 mg/liter. Median concentrations of total phosphorus were low at stations upstream of Saluda Lake, in the Rabon Creek drainage, and at the outfall of Lake Greenwood.

Each of the stations where the median total phosphorus exceeded 0.12 mg/liter was situated downstream of a wastewater treatment plant permitted for major or minor domestic discharge. These major point sources, as described in Table 4, are shown (Fig. 7): the WCRSA/Grove Creek Plant (SC0024317) discharges into Grove Creek above S-171; the Easley/Middle Branch Plant (SC0039853) discharges into Middle Branch above S-301. The minor point sources are not mapped: Easley/Georges Creek Lagoon (SC0023043) discharges into Georges Creek above S-005; the Town of West Pelzer (SC0025194) discharges into an unnamed tributary above S-267.

Along both the Saluda and Reedy Rivers, total phosphorus concentrations increased downstream of major domestic discharges. In the Reedy River, the increase occurred between S-013 and S-323; one major domestic wastewater treatment plant discharges into this reach. The increase was not associated with the extensive urban development and higher nonpoint loading potential of Greenville, which lies upstream of S-013. In the Saluda River, the increase occurred between S-007 and S-119. S-119 is downstream of the confluence with Grove Creek; three major domestic wastewater treatment plants discharge into this reach. Nonpoint loading potential from the landscape is also higher in this reach than upstream.

Median phosphorus concentrations varied among years for the 15 stations with 5-year data sets (Figs. 8 and 9; note that concentrations are shown on a logarithmic scale). In the Saluda above Ware Shoals, Middle Branch (S-301) showed an increasing trend from 2002-2006. In 2003, the year of highest annual stream discharge, very low medians occurred at all of the tributary stations, except Middle Branch, and at the upstream stations on the Saluda (S-299) and Reedy (S-013) rivers. Medians were also low at most stations in 2006, a year of low stream discharge. S-301 lies downstream of the Easley/Middle Branch Plant (SC0039853); discharges of total phosphorus from this facility doubled between 2002 and 2006 (Table 4).

Data sources. Water quality data for the entire Saluda watershed (HUC 03050109) were downloaded from the Environmental Protection Agency modernized STORET system. Station locations were mapped according to coordinates associated with each station in the downloaded data. Stream stations within the Saluda Reedy Watershed were extracted using geographic and logical criteria. Locations and descriptions of the selected stations were checked against information in SC DHEC (2004). Although modernized STORET contains extensive water quality data for 1999-2006, phosphorus data are reported for 2002-2006 only. Unavailability of 1999-2001 data was confirmed by D. Eargle (SC DHEC).

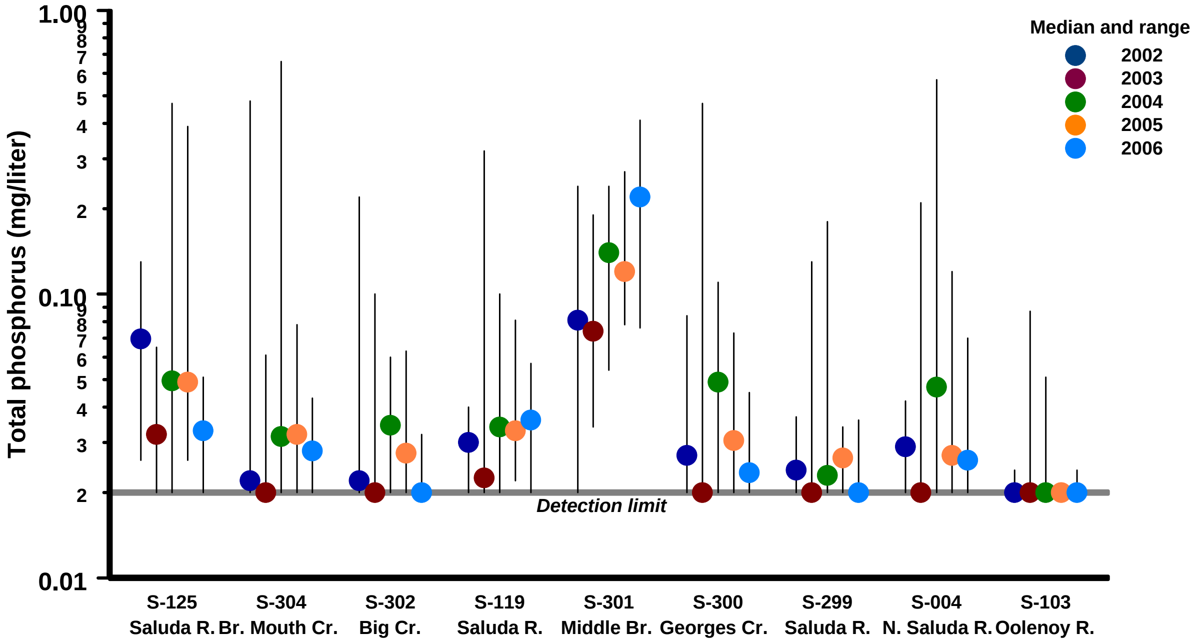

Figure 8. Medians and ranges of total phosphorus concentrations at SC DHEC water quality stations in the Saluda River (above Lake Greenwood) and its tributaries, 2002-2006.

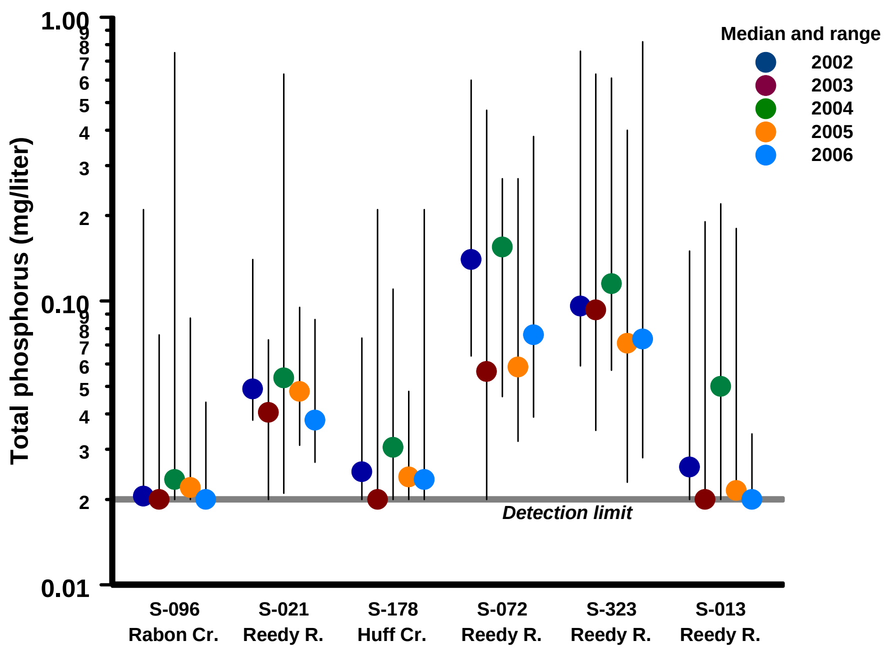

Figure 9. Medians and ranges of total phosphorus concentrations at SC DHEC water quality stations in South Rabon Creek and in the Reedy River and its tributaries, 2002-2006.

PHOSPHORUS LOADS BASED ON INTENSIVE SAMPLING, 2004-2005

We examined the consequences of fluctuations in discharge volume and phosphorus concentrations in the Saluda River near Ware Shoals and the Reedy River near Ware Shoals in 2004-2005. Phosphorus loads in the rivers at these stations represent the main outputs from the watershed and the main inputs to Lake Greenwood. The analysis depends heavily on results from the intensive sampling conducted by Clemson University in 2004-2005 (Klaine and Smink, 2005). The study was designed to examine the consequences of storm flow on water quality; measured parameters included pH, alkalinity, nutrients, major anions, dissolved organic carbon, metals, and total suspended solids. Water was collected by automated samplers at 4- to 6-hr intervals during episodes of elevated river stage.

Pulses in discharge have the potential to cause large pulses in nutrient loading to Lake Greenwood. The higher temporal resolution of the Clemson data allowed us to estimate these effects more accurately than we could with monthly samples collected in standard SC DHEC monitoring program. The combined data provided a basis for estimating uncertainties in loading estimates based on monthly water quality samples.

Computations

We combined the Clemson storm event data (Klaine and Smink, 2005) with the South Carolina DHEC data for corresponding stations (Saluda River near Ware Shoals: Clemson SR-02A and DHEC S-125; Reedy River near Ware Shoals: Clemson RR-02 and DHEC S-021). From extensive preliminary work, we concluded that computations based on Clemson data alone substantially overestimated annual phosphorus loads. Interpolating between sampled storm events from the Clemson data often yielded values higher that the DHEC samples during these intervening periods (see Figs. 10 and 11).

For the Clemson phosphorus data, average values on measurement dates were recomputed from sample data supplied to H. McKellar by J. Smink. Total phosphorus (January-June 2004) was estimated from total dissolved phosphorus (McKellar et al., 2008). The daily values needed for loading and other computations were obtained by linear interpolation from the combined data. We used the water flow data from USGS gages (Saluda River near Ware Shoals: USGS 02163500; Reedy River near Ware Shoals: USGS 02165000). Flows for the Reedy River after destruction of the gage in September, 2004 were predicted from flows in the Saluda River (McKellar et al., 2008, p. 8). (Note that this estimate for the missing stream discharge data differs from the one used in the next section.) Nutrient loads were computed by summing of the products of daily stream discharges and nutrient concentrations.

Sensitivity of the load estimates to sampling interval was tested with a bootstrap procedure. One value was chosen randomly for each month from a set of daily values for an entire year. The total phosphorus load was computed by interpolating between samples, then summing the products of daily stream discharges and nutrient concentrations. This process was repeated to compute a thousand estimates of the phosphorus load for each test.

Sensitivity of the load estimates to a sampling intensity similar to that used in the Clemson study was tested with a bootstrap procedure using 115 samples distributed randomly throughout the year. Again, the process was repeated to compute a thousand estimates. Randomly selecting episodes of elevated stream discharge for sampling, a scheme more similar to that actually employed in the Clemson study, would overestimate the phosphorus load, as noted above.

Temporal variation in total phosphorus concentrations

Flow and total phosphorus concentrations for both the Saluda and Reedy Rivers showed wide variation in both rivers in 2004 and 2005 (Figs. 10 and 11). Spikes in stream discharge in September 2004 were associated with tropical storms Frances and Jeanne.

For both rivers, concentrations of total phosphorus correlated with stream discharge (Fig. 12). The correlations were highly significant but explained only a small part of the variation in total phosphorus concentration. Reduced dilution of phosphorus from point sources during times of low stream discharge probably explains some of this variation. In the Saluda River, the highest total phosphorus concentrations occurred with low stream discharge.

Total phosphorus concentrations were also positively correlated with total suspended sediment concentrations (Fig. 13). Clearly, the events that mobilized sediments also mobilized phosphorus. However, a ten-fold increase in suspended sediment yielded only a two-fold increase in total phosphorus carried by the rivers.

Phosphorus loads

Annual loads of total phosphorus from the Saluda River were about three times greater than the loads from the Reedy River (Table 5). Loads were greater in both rivers in 2004 than in 2005, although annual discharge was higher in 2005.

Combinations of high flow and total phosphorus concentrations produced episodes of extremely high loading from the rivers to Lake Greenwood (Figs. 14 and 15). About 9% of the annual load from the Reedy River in 2004 occurred on one day, 31 July; about 30%, during September. Similarly, about 40% of the annual loading from the Saluda River occurred during September. In contrast, only 15% of the annual loading from either river occurred in the first half of the year. Loading was less uneven in 2005, but the last quarter of the year accounted for about 10% of the annual load for both rivers.

Uncertainty in estimates of phosphorus loads

Sources of uncertainty in phosphorus loads include: measurement error in stream discharge; measurement error in phosphorus samples, sampling error (including error due to spatial variation within the stream), and error due to sampling a continuously varying quantity at discrete intervals.

The distribution of bootstrap estimates indicate that a load computed from 12 monthly samples of total phosphorus should fall within about 10% of the original or “true” estimate about 50% of the time, within about 25% percent of the “true” estimate about 95% of the time. Similarly, estimates from 115 samples should fall within 10% of the “true” estimate about 95% of the time. Based on comparisons of medians to the “true values”, the monthly bootstrap estimates underestimated the “true” value by around 5%. Bias in the closer interval samples was smaller. These intervals are NOT confidence limits appropriate for rigorous statistical testing, because our daily data sets were constructed partly from sampled data and partly from interpolated data. Also, they account for only one source of uncertainty in the estimates. However, these intervals are valuable as an indicator of the magnitude of an important source of uncertainty.

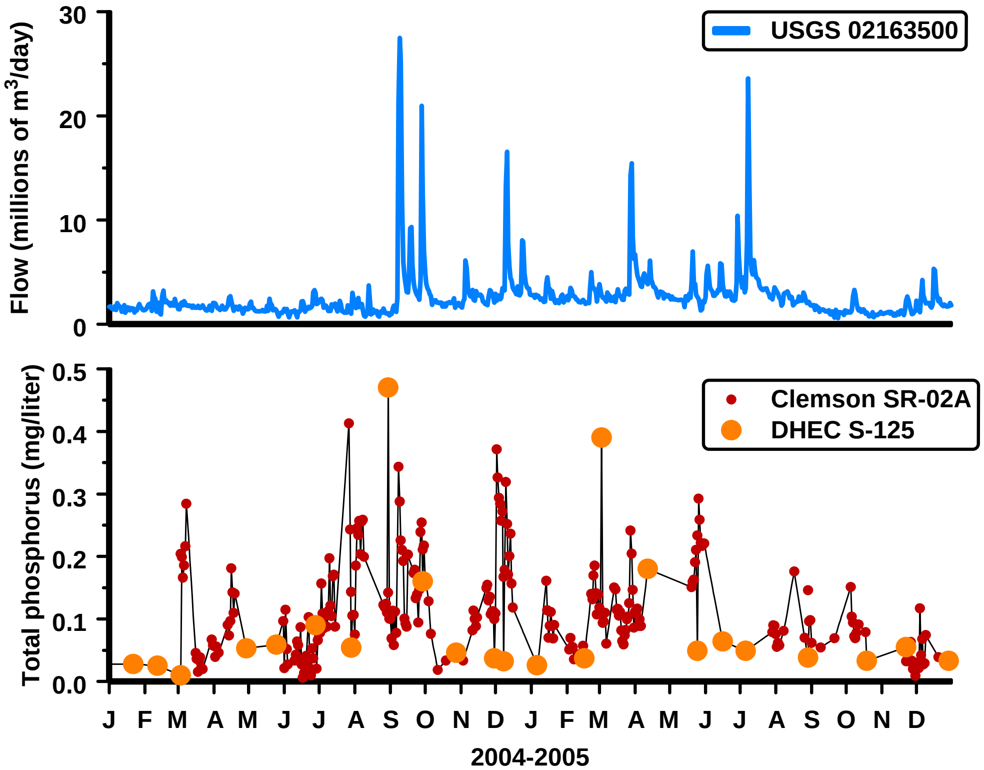

Figure 10. Daily discharge and total phosphorus concentrations in the Saluda River near Ware Shoals, 2004-2005.

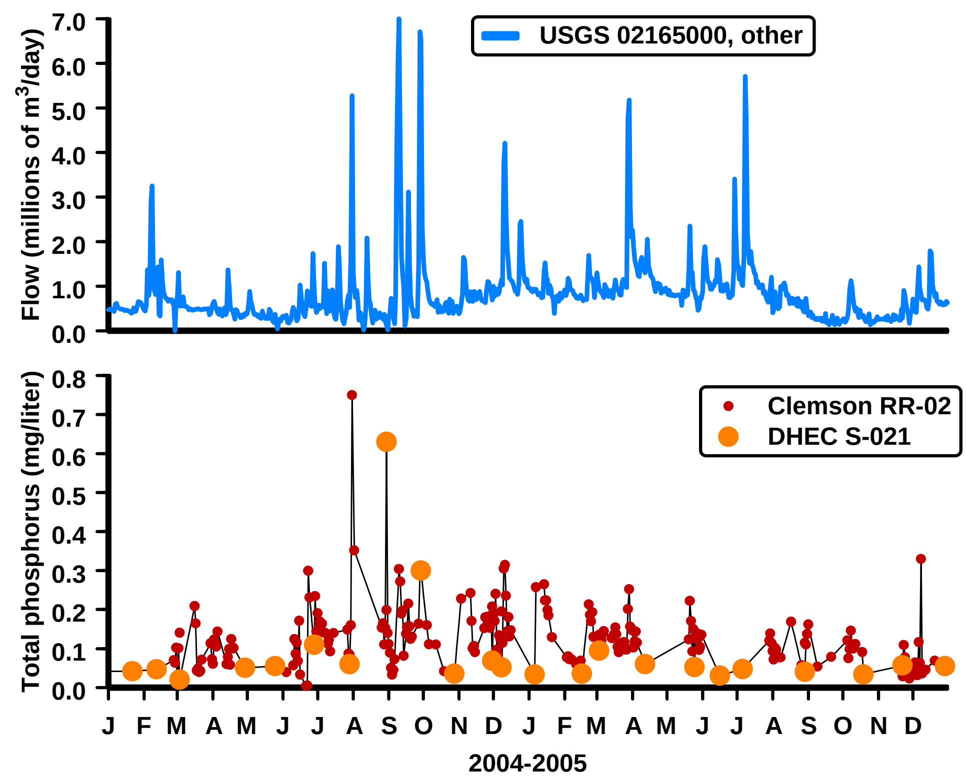

Figure 11. Daily discharge and total phosphorus concentrations in the Reedy River near Ware Shoals, 2004-2005.

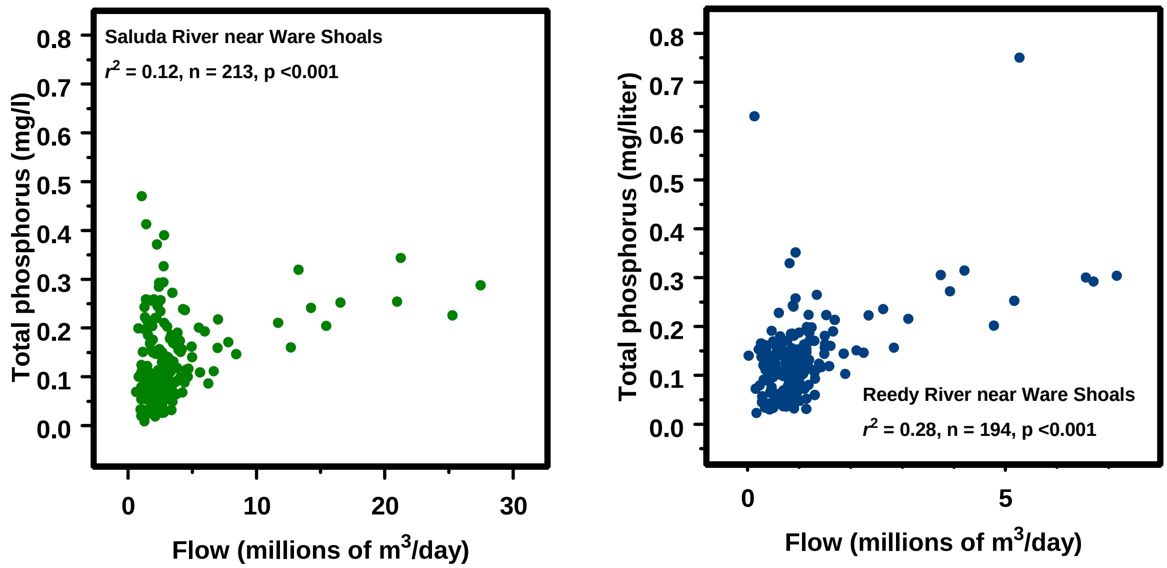

Figure 12. Correlations between daily total phosphorus concentrations and daily discharge in the Saluda River at Ware Shoals and the Reedy River at Ware Shoals, 2004-2005. Data from SC DHEC and Clemson University were combined. Samples prior to July 2004 were excluded from analysis, because only dissolved phosphorus was measured in the Clemson study.

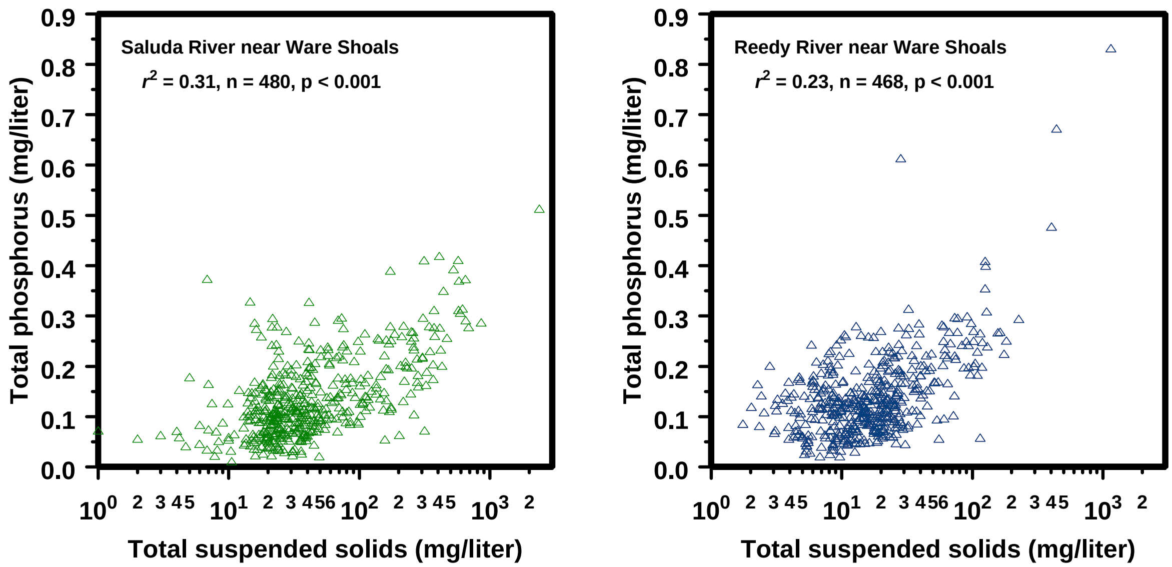

Figure 13. Correlations between total phosphorus and total suspended sediment concentrations in the Saluda River near Ware Shoals and the Reedy River near Ware Shoals, 2004-2005. Data from Clemson University were used; each point represents a single sample, not a daily average. Samples prior to July 2004 were excluded from analysis, because only dissolved phosphorus was measured.

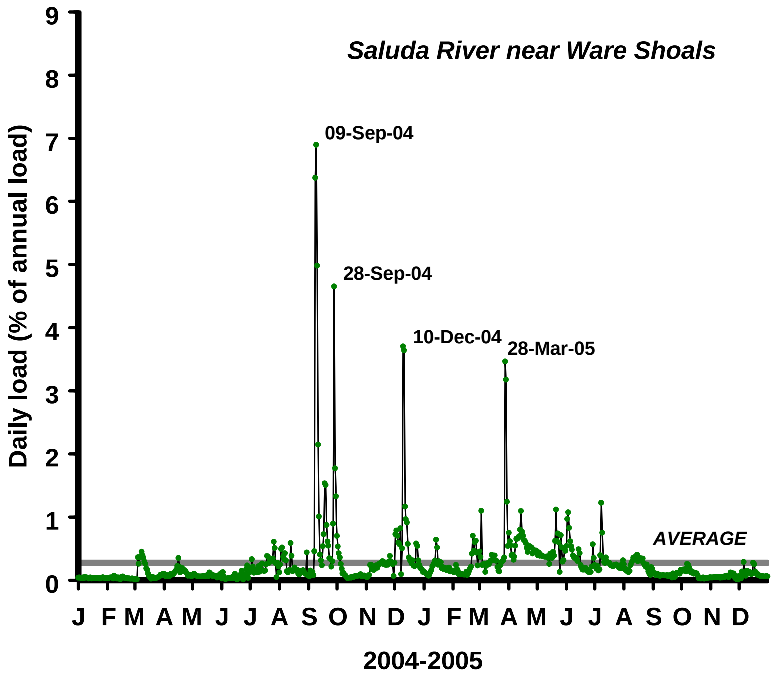

Figure 14. Daily phosphorus load as percentage of annual load in the Saluda River at Ware Shoals, 2004-2005.

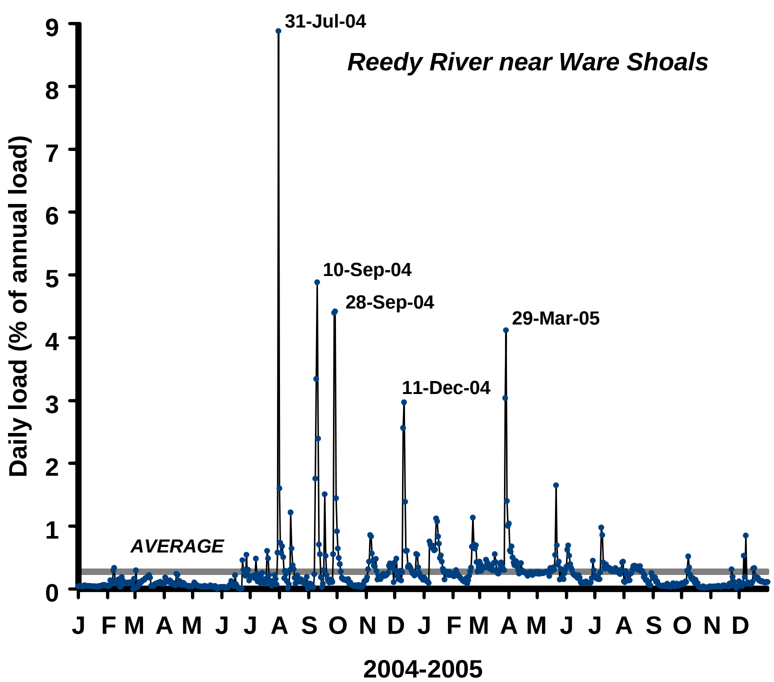

Figure 15. Daily phosphorus load as percentage of annual load in the Reedy River at Ware Shoals, 2004-2005.

Table 5. Annual stream discharge and annual phosphorus loads, Saluda River near Ware Shoals and Reedy River near Ware Shoals, 2004-2005. Stream discharge data were taken from Lake Greenwood model input files. Phosphorus loads are rounded to the nearest 10 kg.

	Saluda River near Ware Shoals		*Reedy River near Ware Shoals*	
Year	***Discharge (10^6 m^3)***	***Total P (kg)***	***Discharge (10^6 m^3)***	***Total P (kg)***
2004	896	114,600	285	44,540
2005	1,000	99,340	317	31,710

PHOSPHORUS LOADS, 2002-2006

Using data from USGS, SC DHEC, and Clemson University, we estimated annual loads of phosphorus carried by streams at five points in the Saluda-Reedy Watershed in 2002-2006, and at three additional points in 2006, the year of more extensive sampling in the basin (Fig. 16). For stations near major point sources, we estimated portion of the load contributed by the facility, and we also estimated a loading rate per area for the remaining portion of the load.

Computations

To estimate annual phosphorus loads, we summed the products of daily flows and daily total phosphorus concentrations for every day in the year. Daily total phosphorus concentrations were generated by linear interpolation between observations. Water quality samples were taken by SC DHEC at approximately monthly intervals; all computations are based on at least 11 observations within a year. Daily averages from water quality samples taken by Clemson University were included for S-125 and S-021.

We estimated daily discharge at the new USGS gage on the Reedy River near Ware Shoals (USGS 21650905 "Waterloo") in 2002-2004 from a regression with daily discharge at the Saluda River near Ware Shoals in 2005-2006: $y = 0.9583 x + 8159815$ ($r^2 = 0.72$, n =730). Observed annual means upstream at the old gage (USGS 2165000 "Ware Shoals") were 10-20% higher in 2002-2003 than the estimates for the new gage; we do not know whether this difference reflects biased estimates in one of the gages. The discrepancy does serve as a further caution against overly precise interpretations of the data. For these estimates, we chose to work with the data from new gage because of its closer proximity to water quality station S-021.

For several of the load estimates, we made adjustments to compensate for small disjunctions between water quality stations and USGS gages (see Table 6). Except one case, we matched water quality data only to flow data for the same year. Because appropriate data for smaller tributary streams were so sparse, we combined data between the two low flow years (2002 and 2006) to estimate the load for South Rabon Creek; otherwise the discharge and water quality data came from matching years.

The occurrence of total phosphorus concentrations below detection limit (BDL) introduces additional uncertainty. For the SC DHEC samples, detection limit was 0.02 mg/liter; at some stations (Figs. 9, 10), half or more of the samples for a year were reported below detection limit. We followed the common practice of using one-half the detection limit (0.01 mg/liter) in computations for these samples. We tested the effect of substituting 0.02 mg/liter for 0.01 mg for the values below detection limit. In most cases, the effect was small. Where it was not small, we report only the range of loads computed with these alternate values.

Annual loads of phosphorus, 2002-2006

Evaluation of the annual loads (Table 7) is supplemented with assessments of the contributions of nearby (upstream or downstream) major point sources (Table 8) and estimates of the loading rate of nonpoint sources, expressed per unit hectare (Table 9).

The downstream stations, on the Saluda River near Ware Shoals (S-125) and on the Reedy River near Ware Shoals (S-021), represent our best estimate of the phosphorus delivered to Lake Greenwood (Figs. 17 and 18). For both streams, loads from all of the major point sources are shown. At each point where availability of water quality data enabled us to estimate the load carried by the river, we show the portion of that load, if any, due to nearby major point sources. The remainder is due to nonpoint sources or distant point sources.

Not all of the phosphorus that enters the rivers upstream will be delivered to Lake Greenwood. The phosphorus carried at any point represents the difference between contributions and losses, including deposition to the stream channel and impoundments.

In the Saluda River (Fig. 17), the load at Greenville (S-007, 2006 only) was small in comparison to the loads further downstream. The nearby major point source (Georges Creek wastewater treatment plant, SC0047309) contributed about half of this load. The remainder represented nonpoint and distant point sources in the watershed upstream, nearly 60% of the watershed for the Saluda River portion of the Lake Greenwood watershed. The areal loading rate from these sources was low (less than 0.1 kg/ha/year). At the maximum, assuming that none of this phosphorus was lost to stream processes, it would have contributed about 20% of the load delivered to Lake Greenwood, as estimated downstream at Ware Shoals.

The phosphorus load increased substantially between Greenville and Williamston (S-119). The loads from the upstream major point sources entering the river between Williamston and Greenville plausibly contributed a large portion of the nonpoint and distant point source load measured in the dry years (2002 and 2006). Higher loads in the wet years (2003-2005) were likely due to greater nonpoint loading, but absence of estimates of nonpoint loading at Greenville for these years makes it impossible to infer whether the sources were between Greenville and Williamston or further upstream.

The phosphorus load changed inconsistently between Williamston and Ware Shoals (S-125), remaining similar in two years, but increasing substantially in three of the five years. In the dry year of 2002, the load doubled. The major point source just above Ware Shoals (Ware Shoals/Dairy Street wastewater treatment plant, SC0020214) accounted for much of the increase, contributing nearly half of the load at Ware Shoals in 2002. Due to greatly reduced discharges from the facility, this share was much smaller in 2006, the other of the two dry years. In 2006 and in 2003, a wet year, the loads were similar between Williamston and Ware Shoals. For these three years, the changes do not suggest a large contribution from nonpoint sources between Williamston and Ware Shoals.

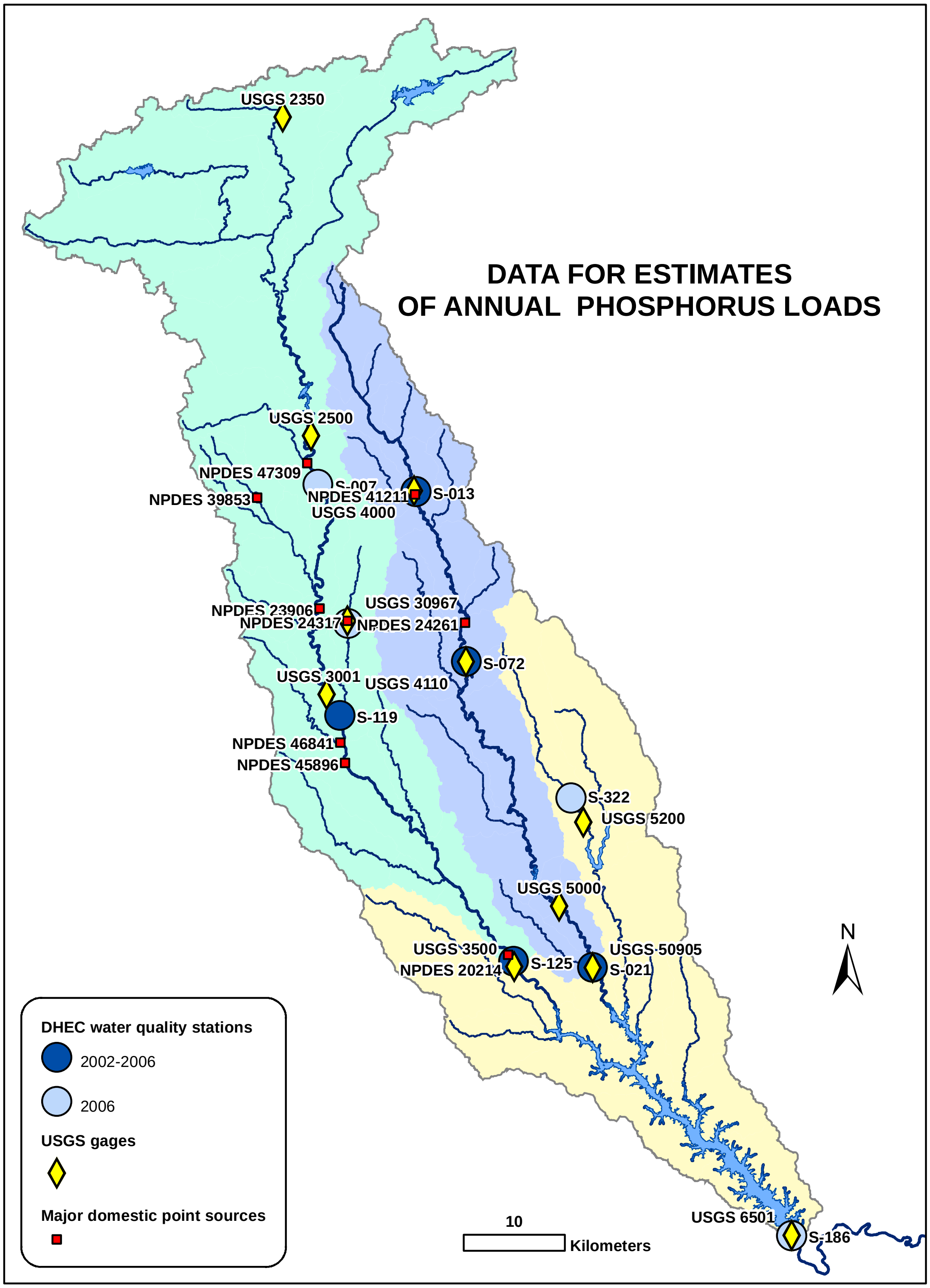

Figure 16. Map of water quality stations for estimates of annual phosphorus loads.

Table 6. Data for estimates of annual phosphorus loads. Locations are named according to the DHEC water quality station name, which may differ from the USGS gage name.

Location	*DHEC station*	*USGS gage*	*Years*	*Nearby major point sources*
Saluda River near Ware Shoals	S-125	2163500	2002-2006	SC0020214, 1.3 km upstream
Saluda River near Williamston	S-119	2163001, 21630967[1]	2002-2006	SC0046841, 3.4 km downstream SC0045896, 5.7 km downstream
Saluda River near Greenville	S-007	2162500[2]	2006	SC0047309, 3.5 km upstream
Grove Creek	S-171	21630967	2006	SC0024317, 0.3 km upstream
Reedy River near Ware Shoals	S-021	21650905	2002-2006	
Reedy River at Fork Shoals	S-072	2164110	2002-2006	SC0024261, 6.0 km upstream
Reedy River near Greenville	S-013	2164000	2002-2006	SC0041211, 0.3 km downstream
South Rabon Creek	S-322	2165200[3]	2006	
Saluda River below Lake Greenwood	S-186	2166501	2006	

[1] Grove Creek (USGS 30967) daily discharge added to Saluda River (USGS 3001) daily discharge; Grove Creek daily discharge adjusted by factor of 1.82 to account for contribution from watershed below gage

[2] Discharge adjusted by 1.14 to account for contribution from watershed below gage

[3] 2002 daily discharge used in place of 2006 data, which were incomplete

However, the loads at Ware Shoals in 2004-2005, both wet years, were more than three times as large the loads upstream at Williamston. These loads were about four times as large as the loads from all major point sources in the Saluda River combined. One possible explanation is that heavy nonpoint loading occurred in the lower part of the watershed in 2004-2005, but not in the preceding wet year. The portion of the watershed contributing to the river below S-119 represents about 20% of the total watershed for S-125; most of the land within this area is agricultural or forested land, so the loading potential is not obviously high. Remobilization of phosphorus sequestered in the sediments in or along the stream channels, including the numerous impoundments on the tributaries, may have contributed to the load. Another possible explanation entails some lack of comparability between the load estimates based on combined close interval and monthly samples and the load estimates based on monthly samples only. The Ware Shoals estimates for 2004 and 2005 included close interval samples.

On the Reedy River, nonpoint loading from the upper part of the watershed was also low (Fig. 18). For S-013 on the Reedy River, below Greenville but upstream of major point sources, lower loads in dry years (2002 and 2006) implicate a larger but erratic contribution of nonpoint sources during the wet years (Fig. 18). Nonpoint loading rates were about two to five times greater in the wet years (2003-2005) than in the dry years (2002 and 2006). However, immediately downstream, these nonpoint loads were dwarfed in all years by loads from the Mauldin Road facility. The nonpoint load from the heavily urbanized portion of the watershed made, at best, only a minor contribution to Lake Greenwood downstream at Ware Shoals (S-021). If all of this nonpoint phosphorus had reached the lake, it would have contributed only 10-20% of the annual load from the Reedy River.

Table 7. Annual phosphorus loads, 2002-2006. Uncertainty is shown as ±25% of computed value for estimates based on monthly samples or ±10% for estimates based on more intensive sampling in 2004-2005. All values are rounded to the nearest 100 kg. Where uncertainty due to values below detection limit is very large, only a range is given (see text for explanation). For stations with major domestic discharges within 6 km downstream, the additional effect of those discharges on the load is also given.

	Annual load of total phosphorus (kg)				
Location	***2002***	***2003***	***2004***	***2005***	***2006***
Saluda River near Greenville (S-007)	-	-	-	-	7,800 ±2,000
Saluda River near Williamston (S-119)	11,000 ±2,800	33,600 ±8,400	29,000 ±7,300	27,200 ±6,800	17,100 ±4,300
Below SC0046841 and SC0045896	14,600 ±3,700	37,200 ±9,300	33,400 ±8,400	31,100 ±7,800	20,300 ±5,100
Saluda River near Ware Shoals (S-125)	35,900 ±9,000	39,500 ±9,900	114,500 ±11,500	98,400 ±9,800	16,800 ±4,200
Grove Creek (S-171)	-	-	-	-	3,400 ±900
Reedy River below Greenville (S-013)	1,800 ±400	3,500 ±900	6,500 ±1,600	4,300 ±1,100	900 ±200
Below SC0041211	20,400 ±5,100	26,300 ±6,600	19,300 ±4,800	16,200 ±4,100	14,400 ±3,600
Reedy River at Fork Shoals (S-072)	30,800 ±7,700	27,000 ±6,700	31,700 ±7,900	18,000 ±4,500	16,100 ±4,000
Reedy River near Ware Shoals (S-021)	12,000 ±3,000	15,800 ±3,900	44,500 ±4,400	34,000 ±3,400	8,700 ±2,200
South Rabon Creek (S-322)	-	-	-	-	300-400
Saluda River below Lake Greenwood (S-186)	-	-	-	-	10,700-17,700

Table 8. Contributions of nearby major point sources to annual phosphorus loads, 2002-2006. Percentages are calculated for major point sources within 6 km upstream or downstream of DHEC station. Estimated percentage applies directly downstream of NPDES discharge point. Distances are based on GIS-mapped locations. Ranges in parentheses reflect uncertainties in estimates of total phosphorus loads.

Location for load estimate,	*Percentage of load*				
NPDES permit and distance	***2002***	***2003***	***2004***	***2005***	***2006***
Saluda River near Greenville (S-007)	-	-	-	-	51%
SC0047309, 3.5 km upstream					(41%-68%)
Saluda River near Williamston (S-119)	25%	10%	13%	13%	16%
SC0046841, 3,4 km downstream	(21%-30%)	(8%-12%)	(11%-17%)	(10%-16%)	(13%-20%)
SC0045896, 5.7 km downstream					
Saluda River near Ware Shoals (S-125)	44%	28%	6%	8%	15%
SC0020214, 1.3 km upstream	(35%-58%)	(23%-38%)	(5%-7%)	(7%-9%)	(12%-19%)
Grove Creek (S-171)	-	-	-	-	85%
SC0024317, 0.3 km upstream					(68%-*)
Reedy River below Greenville (S-013)	91%	87%	66%	73%	93%
SC0041211, 0.3 km downstream	(89%-93%)	(84%-90%)	(61%-72%)	(69%-79%)	(92%-95%))
Reedy River at Fork Shoals (S-072)	21%	17%	11%	27%	20%
SC0024261, 6.0 km upstream	(17%-28%)	(14%-23%)	(9%-14%)	(22%-36%)	(16%-26%)

* Upper limit approaches 100%

Table 9. Annual loading rates of phosphorus per unit area. Values in black include nonpoint sources only; they exclude nearby upstream major point sources (Table 6). Values in grey include distant major point sources as well as nonpoint sources. A range based on uncertainty estimates (Table 5) is given for the rates.

		Loading rate for phosphorus (kg/ha/year)				
Location for load estimate	***Subwatershed area (ha)***	***2002***	***2003***	***2004***	***2005***	***2006***
Saluda River near Greenville (S-007)	88,403	-	-	-	-	0.02-0.07
Saluda River near Williamston (S-119)	119,609	0.07-0.12	0.21-0.35	0.18-0.30	0.17-0.28	0.11-0.18
Saluda River near Ware Shoals (S-125)	152,530	0.07-0.19	0.12-0.25	0.63-0.78	0.53-0.66	0.07-0.12
Grove Creek (S-171)	5,010	-	-	-	-	0*-0.27
Reedy River below Greenville (S-013)	12,706	0.10-0.17	0.21-0.34	0.38-0.64	0.26-0.43	0.06-0.09
Reedy River at Fork Shoals (S-072)	28,755	0.58-1.12	0.54-1.01	0.71-1.26	0.30-0.61	0.31-0.59
Reedy River near Ware Shoals (S-021)	65,585	0.14-0.23	0.18-0.30	0.61-0.75	0.47-0.57	0.10-0.17
South Rabon Creek (S-322)	7,820	-	-	-	-	0.04-0.05

* Lower limit approaches 0

Table 10. Annual input of phosphorus to Lake Greenwood from the Saluda Reedy Watershed, 2006. Total phosphorus loads were rounded to the nearest 100 kg; percentages of loads, to the nearest 5%.

	Area		***Total phosphorus (kg)***	
Subwatersheds	***ha***	***%***	***kg***	***%***
Saluda River near Ware Shoals	152,530	51%	16,800 ±4,200	55%
Reedy River near Ware Shoals	65,585	22%	8,700 ±2,200	30%
Rabon Creek, smaller tributaries around Lake Greenwood	83,117	28%	4,200[1]	15%
Totals for Lake Greenwood watershed	301,233	100%	29,700 ±7,400[2]	100%

[1] Estimated at 0.05 kg/ha
[2] Uncertainty of 25% assigned to sum

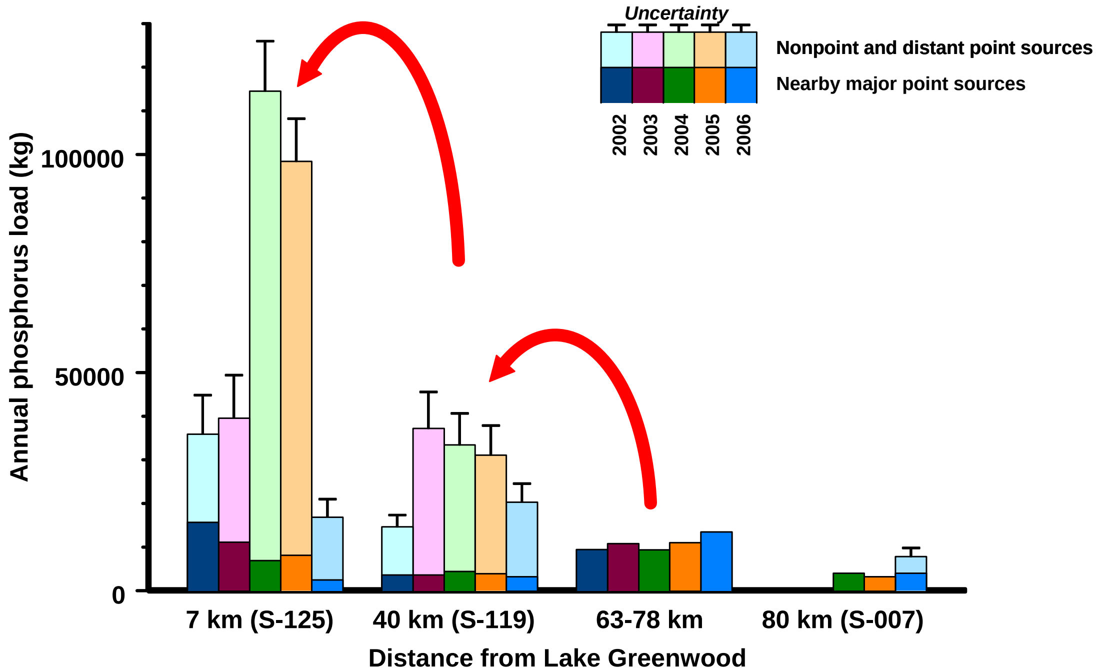

Figure 17. Annual phosphorus loads in the Saluda River. Distances are given from Lake Greenwood to SC DHEC sampling station or downstream nearby major point source (see Table 6). The major point source load at 63-78 km combines data for SC003853, SC0023906, and SC0024317; distances are measured to discharge points, whether on the Saluda River or a tributary; contributions from nonpoint and distant point sources were not estimated. At S-007, contributions from nonpoint and distant point sources were estimated for 2006 only. Arrows indicate how upstream loads can contribute to downstream loads from nonpoint and distant sources.

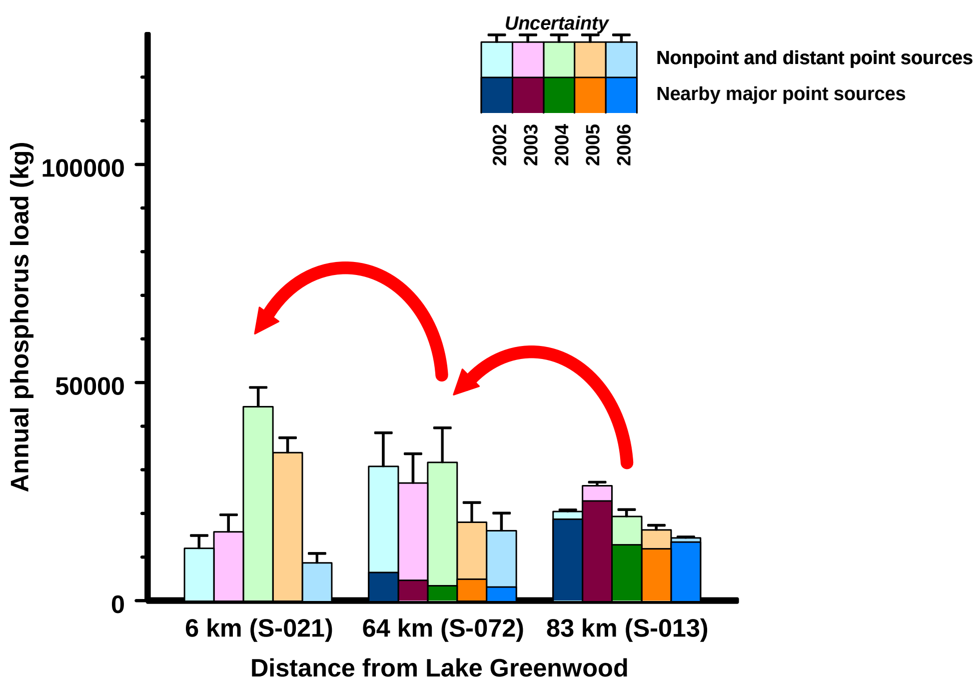

Figure 18. Annual phosphorus loads in the Reedy River. See Fig. 17 for explanation.

Between Greenville and Fork Shoals (S-072), the phosphorus load did not increase substantially. The nearby major point source (Lower Reedy wastewater treatment plant, SC0024261) made only a small contribution to the load. Losses of the load from S-013 were more or less equivalent to additional loading from nonpoint sources.

From Fork Shoals to Ware Shoals (S-021), major point sources were absent. In three of five years, the phosphorus load diminished by about 50%, outside the range of uncertainty for load estimates at the two stations. Losses exceeded contributions from nonpoint sources, and potential mechanisms for losses include retention in Boyd Mill Pond.

However, in the other two years, 2004 and 2005, the loads increased between Fork Shoals and Ware Shoals. Again, these two years coincide with the two years for which we used the close interval samples. As discussed above for the Saluda River, these higher loads indicate either greater nonpoint loads in two of the three wet years or problems in comparability of estimates.

The possible inconsistencies between the load estimates made with the close interval and monthly samples combined and the load estimates made with the monthly samples only remain a matter of concern. If the estimates are comparable, the higher load estimates for those years imply that substantially greater nonpoint source loading occurred in the lower portions of the both the Saluda and the Reedy watersheds during those two years, but not the preceding or following years. If the estimates are not comparable, we must infer that the loads based on monthly samples are probably underestimates, and that other inferences based on them must be interpreted accordingly.

The bootstrap analysis indicated that the monthly samples should not introduce a strong bias in the estimates, if the monthly samples were taken on randomly chosen days. If the sampling days do not represent a random sample of stream conditions, then the biases may be greater. Another possibility is that, even with the inclusion of the monthly DHEC samples, the calculations using the close interval samples overestimate the phosphorus loads.

The truth probably lies somewhere between the extremes. The consequence is that we can be fairly confident about strong effects, such as the modest contribution of nonpoint loads from the upper portions of both the Saluda and Reedy watersheds, but less confident about relative impact of major point sources and nonpoint sources in the lower portions of the watersheds.

These issues must be considered carefully in the interpretation of results from lake or watershed models based on these data.

Phosphorus budget for Lake Greenwood, 2006

We applied the loading rate calculated for South Rabon Creek (Table 9) to the remainder of the area immediately surrounding Lake Greenwood to estimate a phosphorus budget for Lake Greenwood (Table 10). From the difference between the estimated input to Lake Greenwood and the estimated output from Lake Greenwood at S-186 (Table 4), we estimate that 20-70% of the load of total phosphorus was stored in the lake. The remainder was exported downstream to the Saluda River, Lake Murray, and beyond.

RESPONSES OF LAKE GREENWOOD

The Lake Greenwood model was calibrated with data for 2004-2005, which yielded total annual phosphorus loads of 141,000 kg phosphorus for the two rivers combined (McKellar et al, 2008, Table 5). The model predicts that a 50% reduction in the combined annual phosphorus load would substantially improve conditions in the lake, reducing the annual average concentration of total phosphorus throughout surface waters of the lake to less than 0.06 mg/liter and diminishing the extent of extreme oxygen depletion by nearly one-third. Based on the load estimates for the Saluda River near Ware Shoals and the Reedy River near Ware Shoals, reductions of this magnitude actually occurred in 2002, 2003, and 2006.

The reductions of the annual phosphorus loads in 2002 and 2006, relative to 2004 and 2005, were due in substantial measure to reduced flow. All other things being equal, reducing annual stream discharge by half, roughly the difference between the dry and wet years (Fig. 3) would reduce the annual load by half. Additionally, phosphorus concentrations were reduced, particularly in 2006. The discharge-weighted daily mean concentrations of total phosphorus entering the lake were well below 0.06 mg/liter, the water quality standard applicable to Lake Greenwood, from both the Saluda River at Ware Shoals and the Reedy River at Ware Shoals in 2006. The discharge-weighted daily means substantially exceeded the standard at these stations in 2004 and 2005.

The response of water quality to reduced phosphorus loads in dry years remains an important area for further work. The most infamous of the nuisance blooms of algae in Lake Greenwood occurred during the drought year of 1999. Additional field studies, including vertical profiles of dissolved oxygen and nutrients at the mid-lake stations used in the 2004-2005 DNR field studies (McKellar and Bulak, 2005), during dry years would be valuable for testing predictions from the Lake Greenwood model.

Phosphorus loading to Lake Greenwood is strongly episodic, driven mainly by wide fluctuations in stream discharge. Responses of the lake are complex. The growth of the algae responds to the chemical form, as well as the absolute concentration of phosphorus, light, temperature, other nutrients, and losses including dilution and washout. Very high loading, accompanied by high discharge, as in September 2004, greatly diminished abundances of algae (Fig. 19; abundance of algae is measured by abundance of the photosynthetic pigment chlorophyll a), by flushing nutrients and algae downstream. Pulses of nutrient in April 2005 were also accompanied by reductions in algae, but then followed by much higher abundances in summer. Response of the lake to the episodes of loading remains an important area for further work.

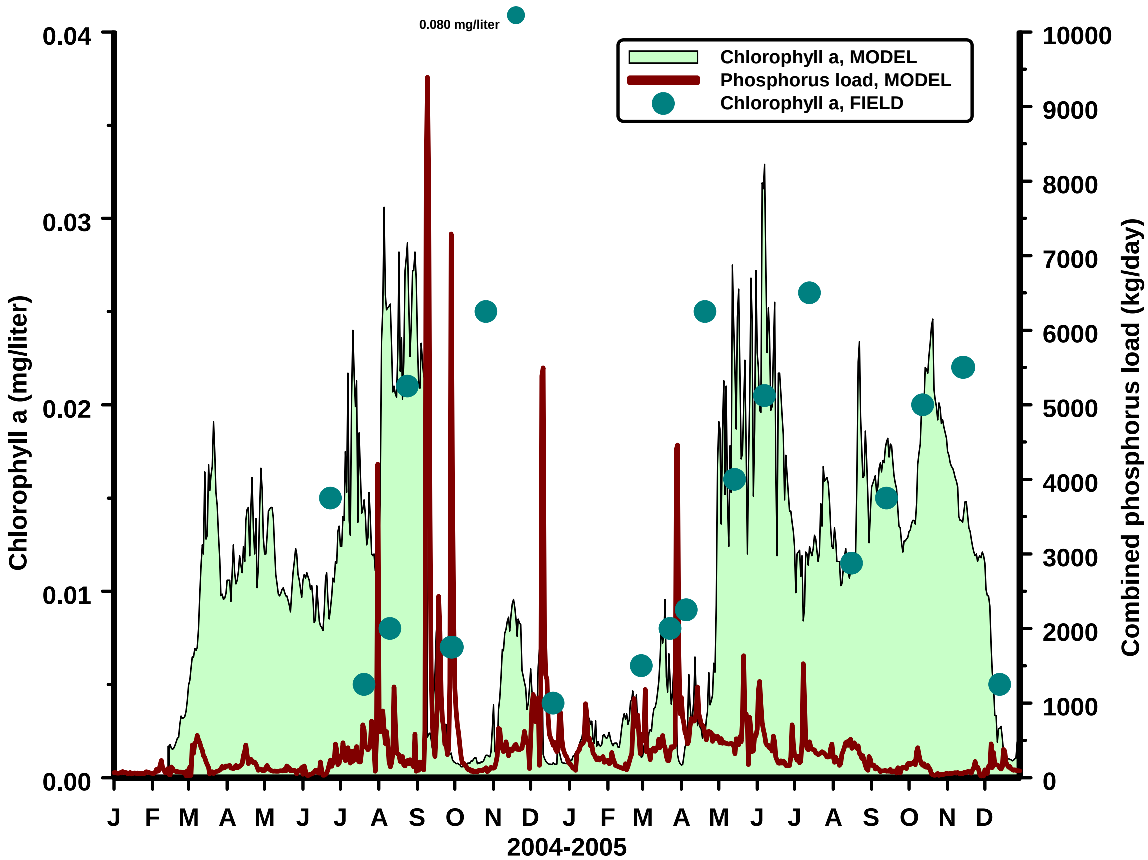

Figure 19. Response of chlorophyll a in Lake Greenwood water quality model to combined total phosphorus load from the Saluda and Reedy Rivers. Chlorophyll a is predicted at the mid-lake (Highway 72) station; results are compiled from the baseline simulation (#301c).

SUMMARY

Phosphorus loading to Lake Greenwood was dominated by the Saluda River, which constitutes about half of the watershed and contributes about 55% of the annual load (2006 estimate), and the Reedy River, which constitutes about a fifth of the watershed and contributes about 30% of the annual load. The remainder of the watershed contributed about 15% of the annual load. Uncertainties in these estimates notwithstanding, the Saluda and Reedy Rivers dominated as sources of phosphorus for Lake Greenwood.

Elevated phosphorus concentrations in the Saluda-Reedy Watershed were generally associated with permitted point source discharges. Recent (2002-2006) changes in discharges from major domestic wastewater treatment plants are changing patterns of point source loading to Lake Greenwood. The discharge from the wastewater treatment plant at Ware Shoals supplied nearly half the load to Lake Greenwood from the Saluda River in 2002, about one-sixth of the load in 2006, a hydrologically similar year. Loading to the upper portion of the Reedy River was dominated by the Mauldin Road Wastewater Treatment Plant, although the load decreased substantially.

Relative to phosphorus loads entering Lake Greenwood, nonpoint loading was small from the sparsely developed, mainly forested upper half of the Saluda River watershed, as well as from the heavily urbanized upper portion of the Reedy River watershed.

Annual phosphorus loads fluctuated widely. They were generally lower during the two dry years (2002 and 2006), but erratically higher during the wet years (2003-2005).

Although the correlation between total phosphorus concentrations and stream discharge was weak, the combination of wide fluctuations in stream discharge with fluctuations in phosphorus concentrations caused strong pulses in phosphorus loads carried by the rivers. Total phosphorus was also weakly correlated with total suspended sediment. The correlation was positive, but disproportionate, so that total phosphorus loads would not increase proportionately with sediment loads.

The Lake Greenwood model predicts that a 50% reduction from the in the combined annual phosphorus load from the Saluda and Reedy Rivers would reduce total phosphorus concentrations in surface waters throughout the lake and substantially diminish the extent of oxygen depletion. These levels were actually achieved in 2002, 2003, and 2006, due in part to reduced stream discharge (2002, 2006) and in part to reduced phosphorus concentrations. Additional field studies, particularly during dry years, would be extremely useful for testing predictions from the model.

Among the gaps in our understanding of processes in this system, we feel that the response of Lake Greenwood to episodes of high phosphorus loading looms largest. The magnitude of nonpoint sources in the lower portions of the Saluda and Reedy watersheds also remains unresolved, due to limitations in the information available. Working with the watershed model would be useful for studying the dynamics of nonpoint contributions to loading. A clear understanding of the biases in the water quality data is essential, however, for calibrating and interpreting results from the models.

RECOMMENDATIONS

1) To improve water quality in Lake Greenwood, place a strategic emphasis on improving water quality in the rivers, particularly the Saluda River, which dominates phosphorus loading.

2) The importance of major point sources to water quality and phosphorus loads emphasizes the need for careful planning of wastewater treatment facilities, as population growth will increase demand for these services.

3) Additional data collection or review of current monitoring protocols is needed to better define the relative contribution of point and nonpoint sources of phosphorus, especially in the lower Saluda River, and to resolve apparent discrepancies between load estimates based on monthly or closer interval samples.

4) Update phosphorus load estimates to include current (2007-2008) extreme drought.

5) Refine and use the newly developed Lake Greenwood reservoir and watershed models as water quality planning tools. Test predictions about oxygen depletion and other responses in Lake Greenwood with additional monitoring studies.

Although controlling sediment loads is important to Lake Greenwood for other reasons, it is probably of secondary importance to phosphorus loads and algal production.

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