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

Supplement: Impact of point sources on phosphorus loading to Lake Greenwood

Final Report

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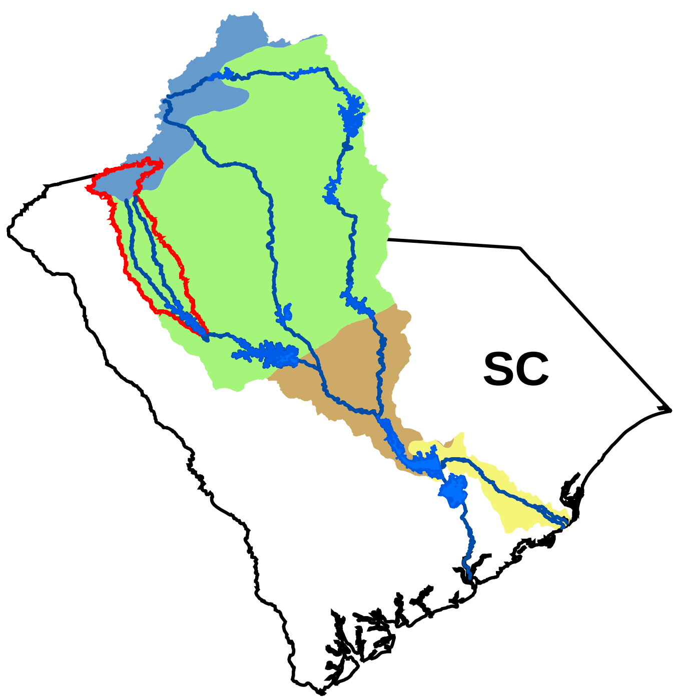

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ACKNOWLEDGMENTS

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INTRODUCTION

Our main report demonstrated that the nine major domestic wastewater treatment plants in the Saluda-Reedy watershed contribute substantial loads of phosphorus to the Saluda and Reedy Rivers (Taylor, Bulak, and McKellar, 2008). In this supplement we use watershed models to quantify the contributions of these facilities to the loads of phosphorus delivered to Lake Greenwood and to predict the impact of reducing the point source loads.

In the main report, we estimated contributions of the point sources to the total load carried by the rivers at various points in the watershed directly from gaged daily streamflow, measured monthly water quality data, and reported monthly point source discharges. These estimates demonstrated the importance of point sources to the phosphorus loads carried by the rivers at those points, although with considerable uncertainty resulting from the low frequency of water quality samples. However, because some of this load is evidently lost to in-stream processes (Figs. 17 and 18 in Taylor et al., 2008), and because we did not have good estimates of nonpoint loads downstream of the point loads, we felt that we could not quantify the contribution of the point sources to the loads delivered to Lake Greenwood.

A watershed model provides computational mechanisms to generate nonpoint loads, to account for in-stream processing of nutrients, and to generate closer interval data, thus addressing these limitations to direct, data-based estimates of the point source contributions. These models have a history of several decades of application and refinement. The model that we used, WinHSPF (Hydrological Simulation Program in Fortran for Windows), is a widely used, exhaustively documented, and well-supported system available under the auspices of the US Environmental Protection Agency.

The limitations of watershed models lie in their complexity. They require assumptions about numerous rates and processes for which data are typically lacking. Building and calibrating models is laborious. Given the constraints of information and time, our goal for the Saluda and Reedy watersheds was to set up relatively simple models that would provide estimates of the fate of phosphorus discharged by the wastewater treatment plants.

The Saluda and Reedy watershed models were calibrated with full discharges from the nine wastewater treatment plants permitted for major domestic discharges into the Saluda-Reedy Watershed during 1999-2006. This eight-year period is the base scenario of full phosphorus discharge from the point sources (FULL scenario). It spans a wide range of weather conditions, including two extremely dry years and one very wet year (Figure 1). Because measurements of total phosphorus in the streams are lacking for 1999-2001 (Taylor et al., 2008), we hoped that the predictions for this period might provide insight into the conditions supporting extensive algal blooms in the Reedy Arm of Lake Greenwood in 1999-2000.

Discharges from the point sources were modeled using monthly data for water volume and total phosphorus from the discharge monitoring reports to the US EPA. During this period, total discharges of phosphorus from the major point sources were relatively constant in the Saluda watershed and decreased by about 30% in the Reedy watershed (Figure 2; also Tab. 4 in Taylor et al., 2008).

In two additional scenarios, the point sources of phosphorus were reduced by half (HALF scenario) or eliminated entirely (NONE). The NONE scenario estimates the magnitude of the point source contributions. In all scenarios, the volume of water discharged from the point sources was maintained at reported levels.

WATERSHED MODELS

The models focus on the tributaries of Lake Greenwood that receive water from the major domestic wastewater treatment plants (Figure 3). The Saluda watershed discharges into the Saluda Arm of Lake Greenwood; the Reedy watershed discharges into the Reedy. Both watersheds are predominately forested and agricultural land (Taylor et al., 2008). Only the upper portion of the Reedy watershed is heavily urbanized.

The watershed model consists of a series of connected stream or reservoir segments and their associated subwatersheds. Stream hydrology is driven by climate and modified by the watershed. Nutrient input to the streams includes point sources and nonpoint sources. The nonpoint sources are modeled as a function of land cover and other attributes of the watershed. Point sources are specified directly. The main sources of data used in building and calibrating the Saluda and Reedy watershed models are given in Table 1.

The Saluda and Reedy watershed models are described in Figure 2 and Table 3. Subwatersheds from the National Hydrography Dataset were variously combined to simplify the models or subdivided to provide outlets near USGS gages.

All of the water segments were modeled as streams rather than as impoundments. Mean retention times are 4 days or less for the two impoundments on the Reedy River and the four impoundments on the Saluda River below Saluda Lake (estimates based on USGS streamflow data for 2002-2006 and normal storage capacities from the National Inventory of Dams).

Full meteorological data for 1999-2006 were available only for stations outside the watershed boundaries. The meteorological stations for the simulations were chosen on the basis of proximity, availability of data, and geographic patterns. Precipitation from Cleveland 3S was combined with other data from Greenville Spartanburg International Airport.

Landcover was modeled according to GIRAS categories (Figure 3). Impervious landcover was set at 35% of urban and built-up land, based on analysis of total impervious cover for the Reedy watershed.

Simulations were set up to generate predictions for the period 1999-2006. The simulations were begun one year earlier to allow effects of initial conditions to decay. Data from this year (1998) were not used in analyses.

The watershed models were built using the BASINS 4 (Better Assessment Science Integrating Point and Nonpoint Sources) interface from the U. S. Environmental Protection Agency. WinHSPF modules used in the simulations included hydrology, heat exchange and water temperature, sediment, simple nutrient relationships, and plankton. Parameters from a starter set were adjusted during the calibration process. Discharge data at USGS gages (three in the Saluda watershed; four in the Reedy watershed) were used as references for the hydrologic calibrations. Calibrations for nonpoint sources of phosphorus focused on subwatersheds upstream of point sources, particularly R5, which is heavily urbanized, and R3, which is predominately agricultural. The same parameters for nutrient processes, etc., were used in both models.

Manuals, technical notes, and training materials were consulted extensively for guidance in building and calibrating the model (for example, Bicknell et al., 2001).

RESULTS

Performance of the watershed models

The watershed models described the general patterns and ranges of values observed for stream flow (Figure 5). Over the eight-year simulation period, average annual discharge at the outlet of Reach S1 of the Saluda Watershed differed by about 5% from annual discharge at the USGS gage on the Saluda River at Ware Shoals (USGS 02163500). Average annual discharge at the outlet of Reach R4 differed by 3% from average annual discharge at the USGS gage on the Reedy River at Fork Shoals (USGS 02164110); records for the entire eight-year period were not available for gages further downstream on the Reedy River.

Under the scenario of full point source loads, the models reproduced the main patterns of total phosphorus concentrations observed in the streams (Figures 6a,b, 7a,b). Total phosphorus concentrations were generally low in the reaches upstream of the point source discharges (for example, Reach S8 in Figure 6a, Reaches R5 and R3 in Figure 7a), but fluctuated with precipitation-driven input. Total phosphorus concentrations were much higher in the reaches receiving point source discharges (Reach S6 in Figure 6a, Reach R4 in Figure 7b), then diminished downstream (Reach S3 in Figure 6b; Reach R1 in Figure 7b).

The models produced fluctuations generally approximating the observed ranges for the upstream reaches of both watersheds. The Saluda model did not produce values as high as the extremes ($\geq$ 0.3 mg/liter) observed downstream at Reaches S2 and S1 (Figure 6b); these extremes were associated with periods of low or moderate stream discharge. The Reedy model did not produce values as high as the extremes ($\geq$ 0.2 mg/liter) observed at Reach R3 (Figure 7b); these extremes were probably associated with periods of high stream discharge (inference based on the Reedy River at Fork Shoals; Huff Creek is not gaged).

For both models, simulated median total phosphorus concentrations at the downstream stations were similar to DHEC water quality data in most years (Figure 8). We compared medians rather than averages, because the averages for the DHEC data were strongly influenced by the extreme values in a few years due to the small sample size. The greatest overestimates occurred in 2003, the year of highest annual precipitation, for both watersheds.

For Saluda River in 2002, 2003, and 2006, the simulated annual loads were similar to the computed annual loads (80% in 2002, 120% in 2003, 130% in 2006; Tab. 7 of Taylor et al., 2008). For the Reedy River in these years, the simulated annual loads were higher (180% in 2002, 230% in 2003, 160% in 2006). As we noted above, the computed loads carry large uncertainties, with 95% confidence intervals on the order ±25% (Taylor et al., 2008), due to the low frequency of water quality samples. The most extreme difference between the simulated and computed annual loads corresponded to the most extreme difference between the simulated and observed median total phosphorus concentrations.

In 2004 and 2005, the simulated loads were substantially lower than the computed loads for both watersheds. Use of additional data collected during storm events may have biased the computed loads for those two years (Taylor et al., 2008). However, the correlations with stream discharge explain small proportions of the variation in total phosphorus concentrations at the lower ends of the watersheds (Taylor et al., 2008).

Contributions of point sources to phosphorus loads to Lake Greenwood

Phosphorus loads in the FULL scenarios (Table 3, Figure 9) varied substantially among years, with the highest loads occurring in 2003, the wettest year. Loads from the Saluda River were consistently higher than loads from the Reedy River. The phosphorus loads to the Reedy River in 1999-2000, the years of the algal bloom, were near or below the median for the eight years of simulations.

The difference between the phosphorus loads delivered to Lake Greenwood in the FULL and NONE scenarios represents the contributions of the point sources. The point sources accounted for 35-71% of the annual loads delivered to Lake Greenwood by the Saluda River and 45-73% of the annual loads delivered by the Reedy River (Table 3, Figure 9). Reducing the point sources by half reduced the annual load from the Saluda River by 18-37% and from the Reedy River by 23-46%. For each watershed, the point source loads delivered annually to Lake Greenwood were about 40-60% of the phosphorus discharged into the watershed by the point sources.

The phosphorus loads in NONE scenario represent the contribution of nonpoint sources in the simulations (Table 3, Figure 9). These nonpoint contributions were greater in the years of higher precipitation, particularly 2003.

Impact of point sources on phosphorus concentrations of water entering Lake Greenwood

In the FULL scenario, annual average concentrations of total phosphorus were moderate in the Saluda River, substantially higher in the Reedy River (Table 4). The lower average concentrations in the Reedy River after 2003 reflected the drop in point source discharges. High concentrations (> 0.1 mg/liter) in the Reedy River in 1999, particularly during late winter and spring (Figure 7b), were associated with elevated point source discharges and low stream flow.

Lower total phosphorus concentrations in the NONE scenario for the Saluda watershed reflected the greater proportion of forested land (Figure 2; Tab. 2 in Taylor et al., 2008).

DISCUSSION AND CONCLUSIONS

In the simulations, point source contributions of phosphorus to Lake Greenwood accounted for 35-71% of the annual loads delivered to Lake Greenwood by the Saluda River and 45-73% of the annual loads delivered by the Reedy River (Table 3, Figure 9). Because the watershed models reproduce the main patterns of stream discharge and phosphorus concentrations in the Saluda and Reedy Rivers above Lake Greenwood under the base scenarios, we believe that they provide useful estimates of the magnitude of the contribution of point source discharges to the phosphorus loads entering Lake Greenwood over the eight-year period of the simulations (1999-2006). The models also indicate the potential impact of reducing phosphorus discharges from these point sources on both loads and concentrations of total phosphorus reaching Lake Greenwood.

During 1999, the first year of the algal blooms, the simulated concentrations of phosphorus reaching Lake Greenwood were high, especially during the winter and spring (Table 4, Figure 7b), although the annual load was moderate. We speculate that low stream flow, resulting from low rainfall, fueled development of the bloom. Low flow reduces in-stream dilution of the phosphorus discharges from point sources and increases retention times of the nutrient-enriched water in the Reedy Arm. This interpretation reinforces Anderson, Lewis, and Sargent (2006), who concluded that high concentrations of nutrients were more important that nutrient influxes to eutrophication of the Reedy Arm.

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Table 1. Sources of data used to build and calibrate the watershed models.

Attribute	***Sources***
Weather	BASINS 4.0 Meteorological Data (Version 2006), which provides hourly precipitation, air temperature, etc., from National Climatic Data Center stations, formatted for WinHSPF
Topography	National Elevation Dataset from USGS
Land cover	USGS GIRAS 2001 for land use, USGS NLCD 2001 for impervious surfaces
Streams and waterbodies	National Hydrography Dataset from USGS; Reach File 1.0 from US EPA
Watersheds	National Hydrography Dataset from USGS
Stream flow	USGS National Water Information System
Water quality	US EPA STORET database
Point source discharges	Data from Discharge Monitoring Reports to US EPA, provided by W. Harden, SC DHEC

Table 2. Subbasins for the watershed models. Subbasins S1-S8 belong to the Saluda watershed model; R1-R5, to the Reedy model.

Subbasin	***Stream***	***Weather station***	***Point sources***
S1	Saluda River	Laurens SC385017	Town of Ware Shoals/Dairy Street SC0020214
S2	Saluda River	Laurens SC385017	Belton/Ducworth Saluda SC0045896; Town of Williamston SC0046841
S3	Saluda River	Greenville-Spartanburg Int. Airport SC383747	
S4	Grove Creek	Greenville-Spartanburg Int. Airport SC383747	WCRSA/Grove Creek Plant SC0024317
S5	Saluda River	Greenville-Spartanburg Int. Airport SC383747	WCRSA/Piedmont Plant SC0023906; WCRSA/Georges Creek Plant SC0047309
S6	Middle Branch	Greenville-Spartanburg Int. Airport SC383747	Easley Combined Utility/Middle Branch Plant SC0039853
S7	Saluda River	Greenville-Spartanburg Int. Airport SC383747	
S8	Saluda River	Cleveland SC381804	
R1	Reedy River	Laurens SC385017	
R2	Reedy River	Greenville-Spartanburg Int. Airport SC383747	
R3	Huff Creek	Greenville-Spartanburg Int. Airport SC383747	
R4	Reedy River	Greenville-Spartanburg Int. Airport SC383747	WCRSA/Lower Reedy River Plant SC0024261; WCRSA/Mauldin Road Plant SC0041211
R5	Reedy River	Greenville-Spartanburg Int. Airport SC383747	

Table 3. Phosphorus loads delivered to Lake Greenwood.

	Annual load (metric tons)			Reduction in load (% of FULL)		Point source contribution (metric tons)
Scenario	***FULL***	***HALF***	***NONE***	***HALF***	***NONE***	***FULL***
Saluda watershed						
1999	21.5	14.0	6.9	35%	68%	14.7
2000	19.6	13.7	8.3	30%	58%	11.4
2001	22.6	14.3	6.6	37%	71%	16.0
2002	28.3	19.1	11.0	33%	61%	17.3
2003	45.1	37.1	29.3	18%	35%	15.8
2004	25.2	19.7	14.5	22%	42%	10.7
2005	35.2	28.1	21.6	20%	39%	13.6
2006	20.0	15.7	11.8	22%	41%	8.2
Reedy watershed						
1999	17.3	9.4	4.7	46%	73%	12.7
2000	11.4	7.9	5.5	31%	52%	5.9
2001	16.4	9.3	5.7	43%	66%	10.8
2002	21.5	13.2	7.9	39%	63%	13.6
2003	36.6	26.8	20.0	27%	45%	16.6
2004	14.8	11.0	8.2	26%	44%	6.6
2005	19.4	14.9	11.5	23%	41%	7.9
2006	14.0	9.5	6.4	33%	54%	7.6

Table 4. Annual average total phosphorus concentrations in water delivered to Lake Greenwood.

Scenario	Average concentration (mg/liter)			Reduction in concentration (% of FULL)	
	FULL	HALF	NONE	HALF	NONE
Saluda watershed					
1999	0.049	0.031	0.012	37%	75%
2000	0.043	0.027	0.012	36%	71%
2001	0.053	0.032	0.013	39%	76%
2002	0.056	0.034	0.014	39%	75%
2003	0.043	0.029	0.020	32%	54%
2004	0.034	0.024	0.014	28%	58%
2005	0.037	0.026	0.017	29%	55%
2006	0.030	0.022	0.014	26%	53%
Reedy watershed					
1999	0.090	0.044	0.020	46%	73%
2000	0.049	0.032	0.020	31%	52%
2001	0.085	0.041	0.020	43%	66%
2002	0.079	0.041	0.021	39%	63%
2003	0.074	0.047	0.028	27%	45%
2004	0.050	0.034	0.022	26%	44%
2005	0.055	0.036	0.024	23%	41%
2006	0.052	0.034	0.021	33%	54%

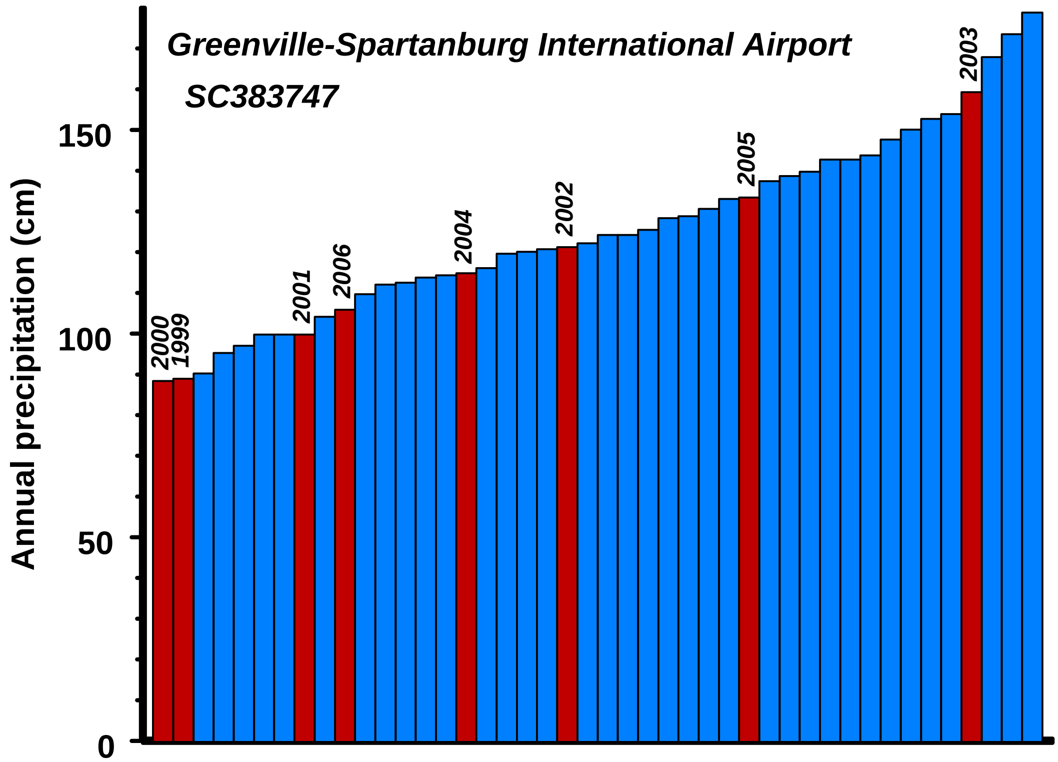


Figure 1. Annual precipitation at Greenville-Spartanburg International Airport, 1964-2006.

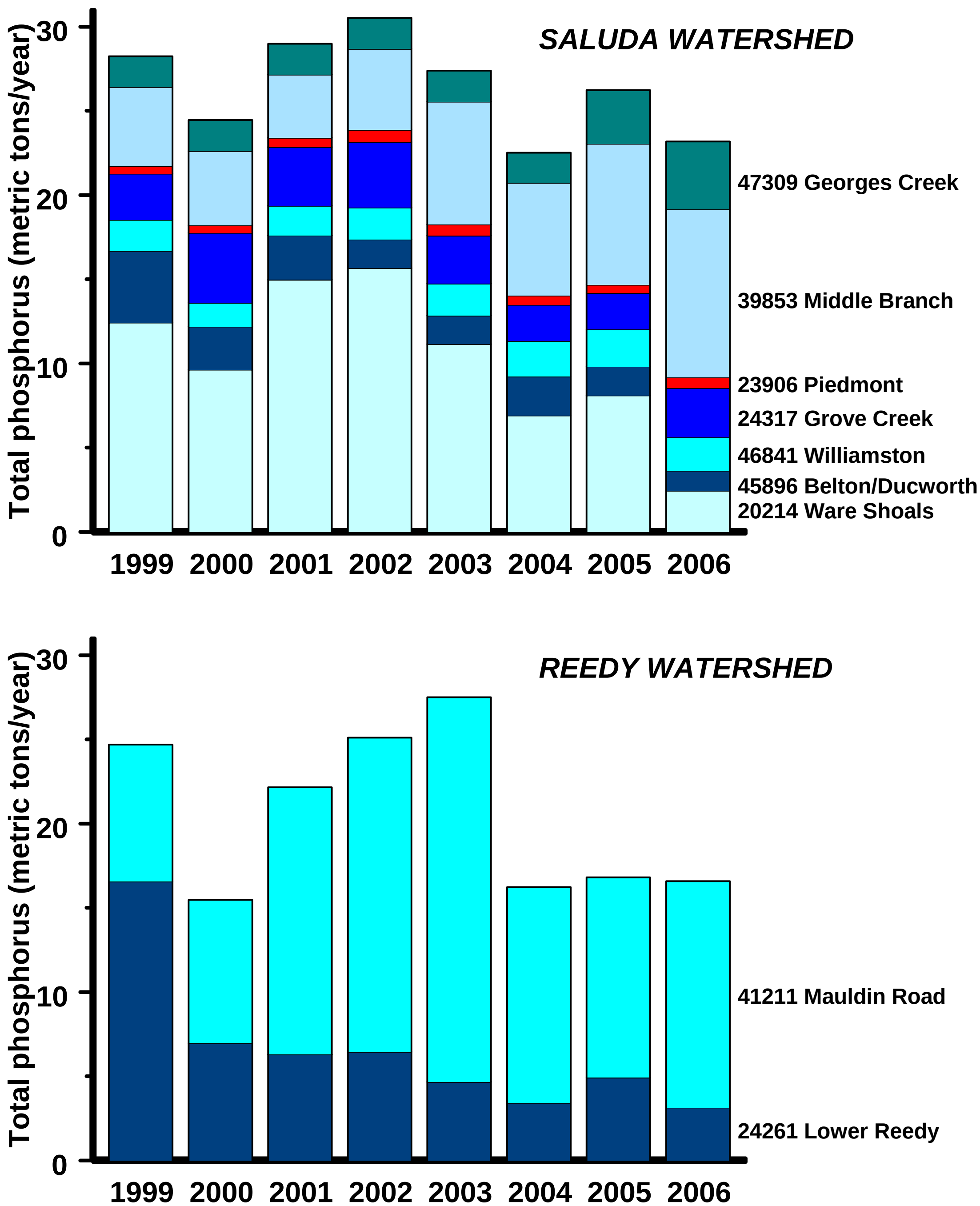


Figure 2. Annual discharges of total phosphorus by major domestic wastewater treatment plants, 1999-2006. Missing values for Williamston in 1999 and Georges Creek in 1999-2003 were replaced with values from subsequent time periods.

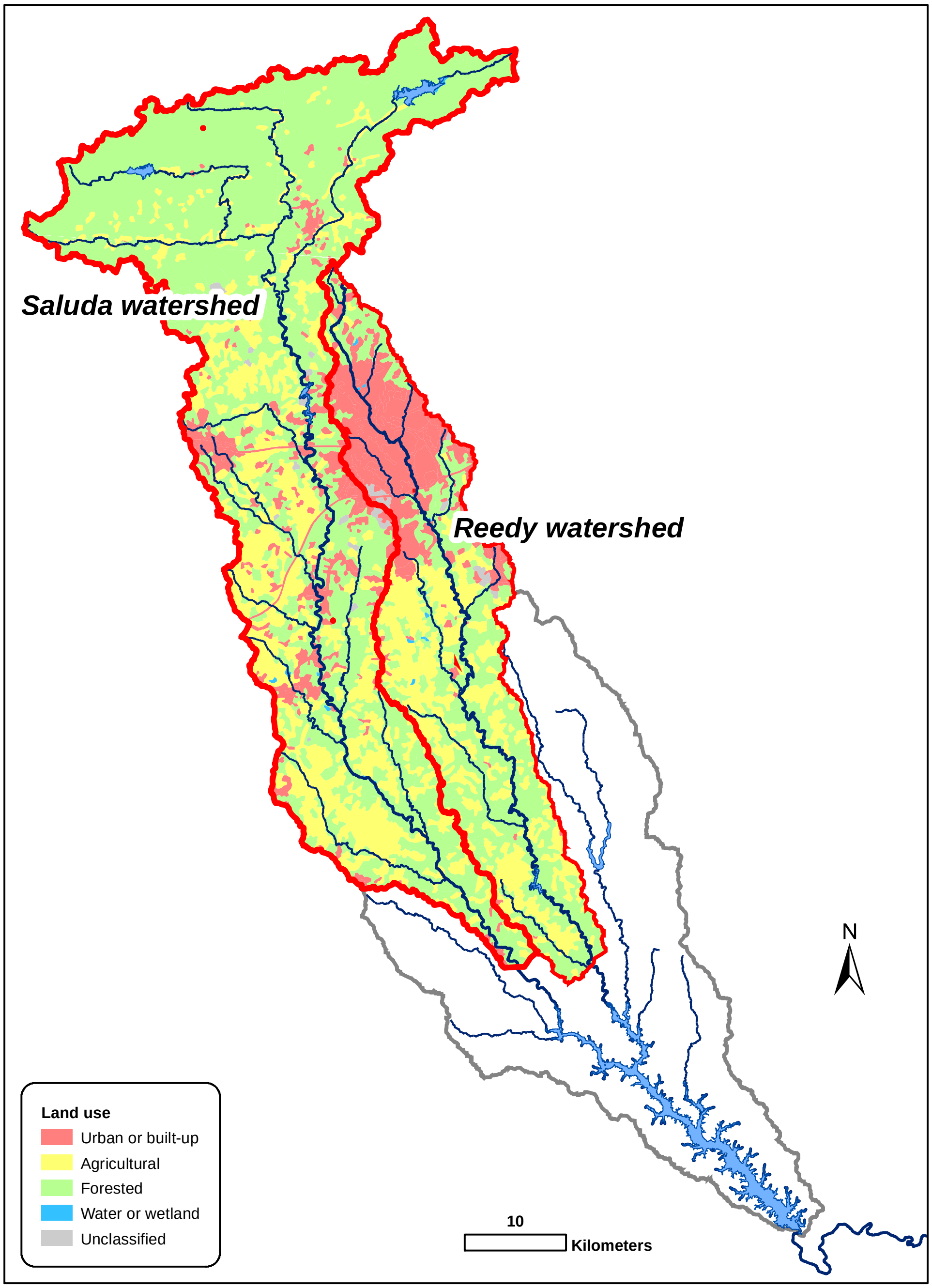


Figure 3. The Saluda and Reedy watersheds.

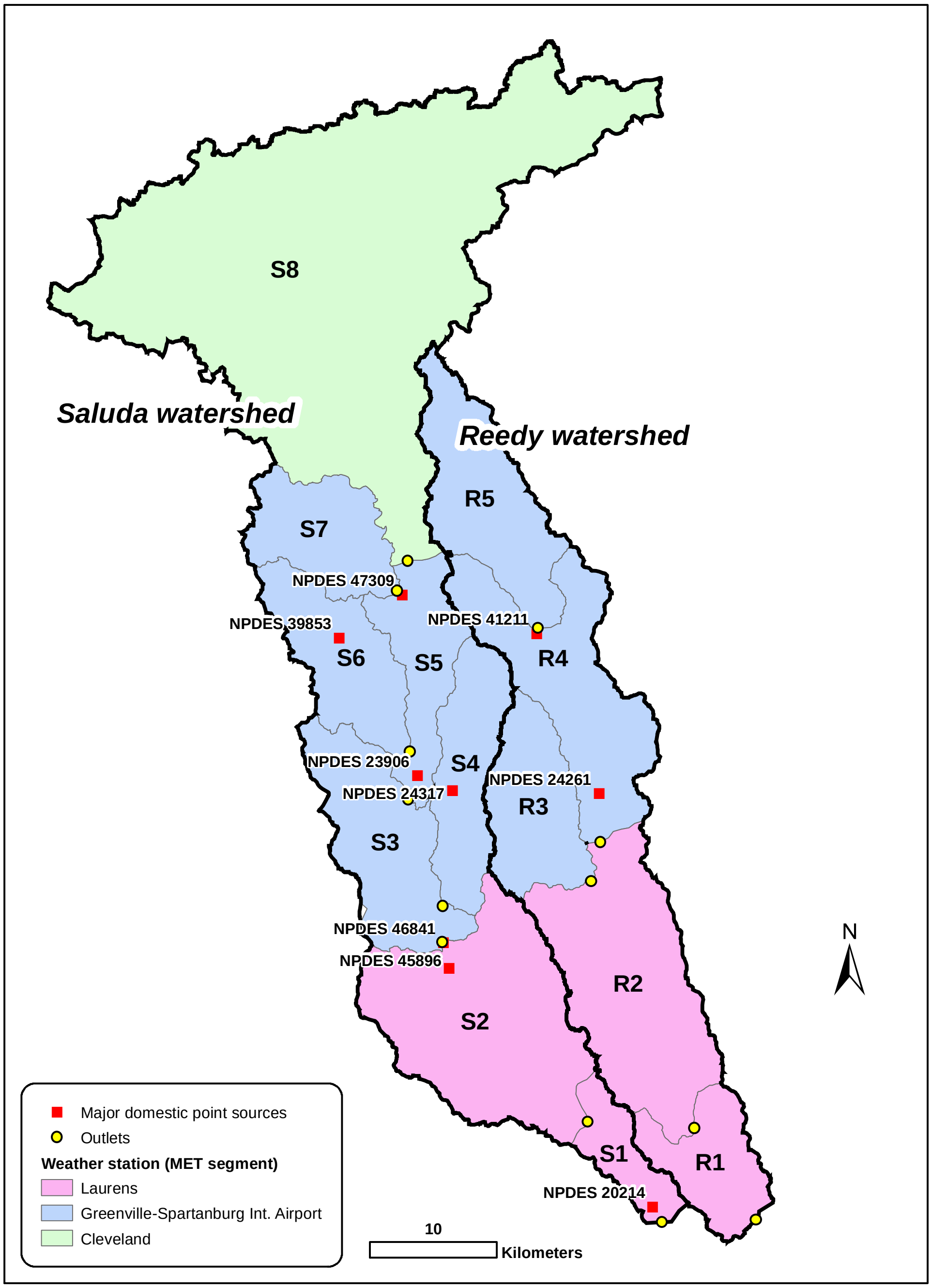


Figure 4. Subbasins for the watershed models.

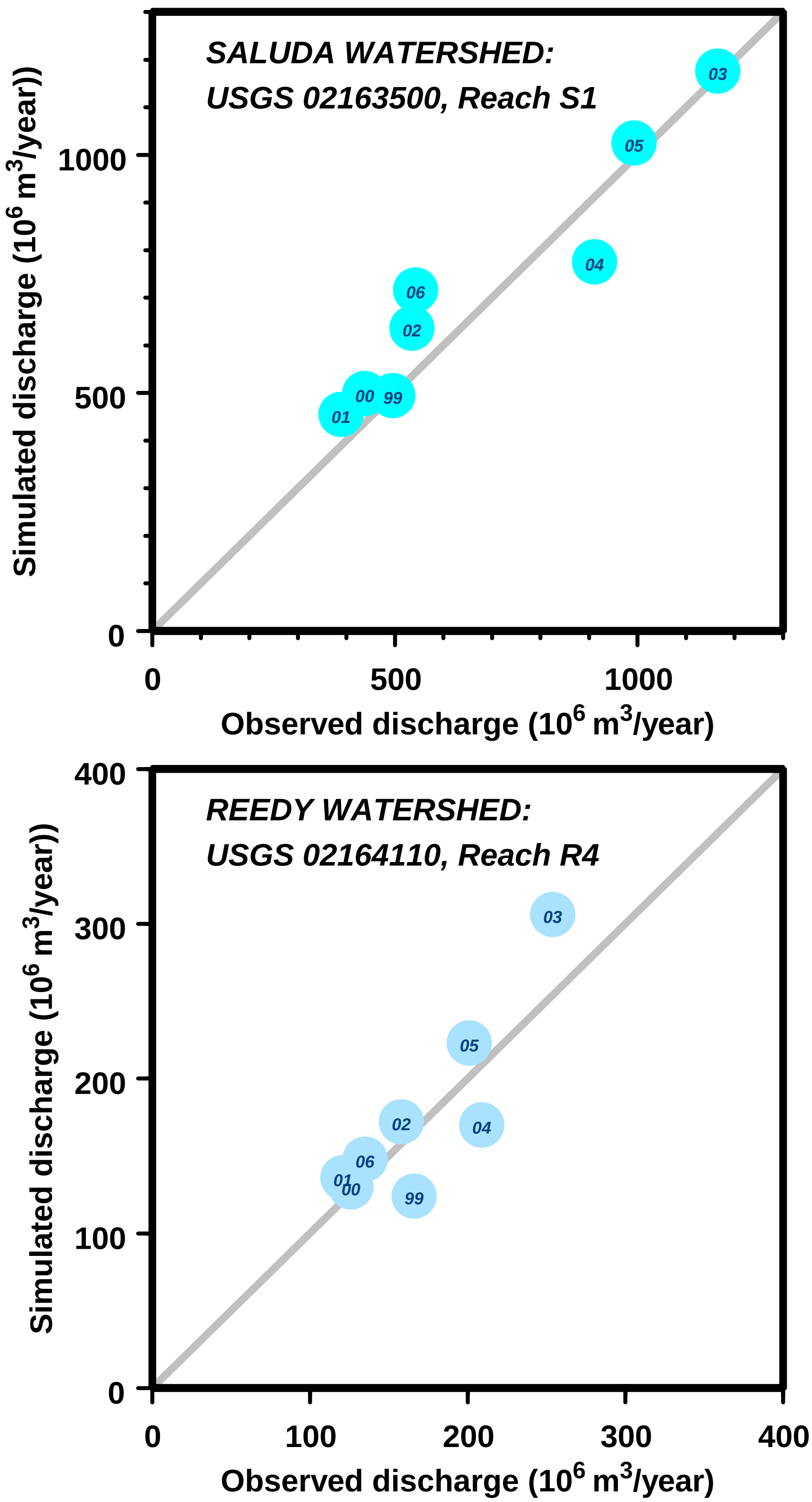
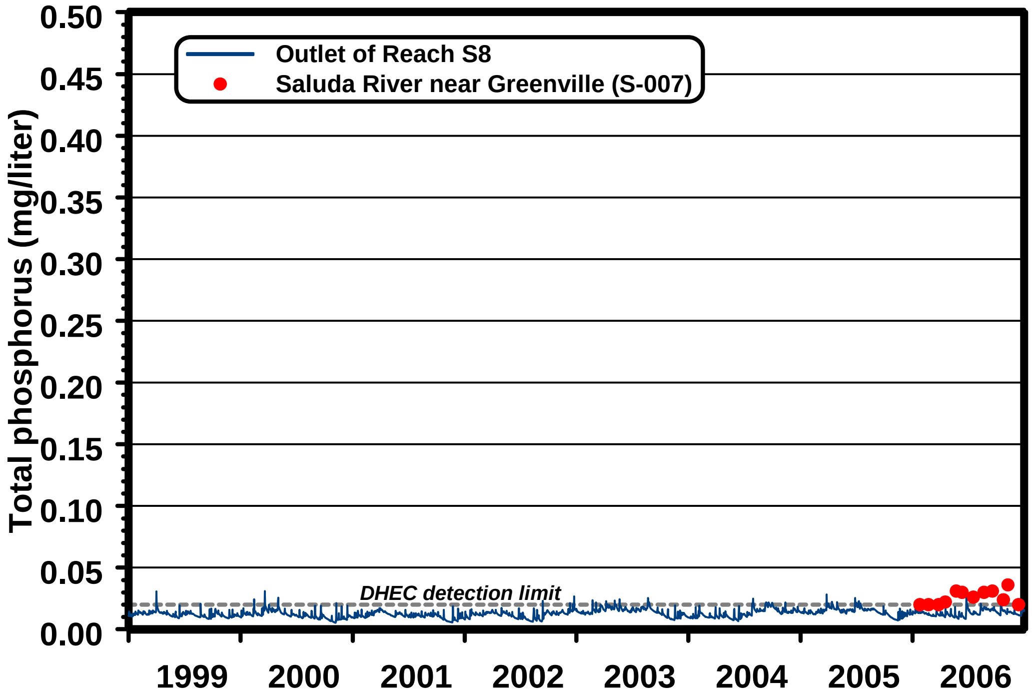


Figure 5. Simulated and observed annual discharges in the Saluda and Reedy watersheds.



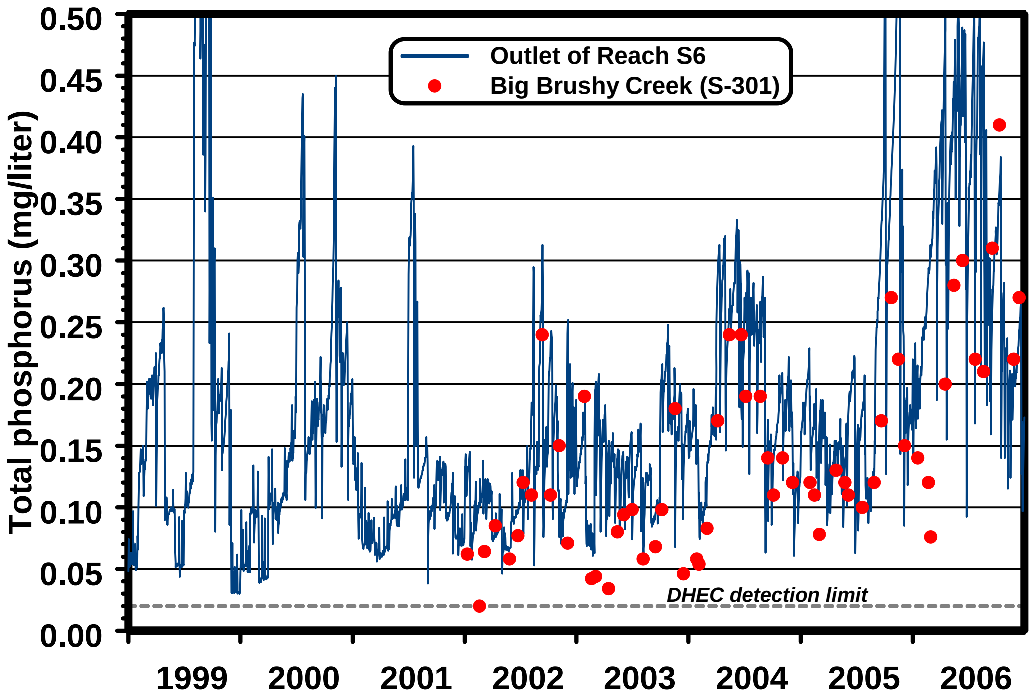


Figure 6a. Simulated and observed total phosphorus concentrations in the Saluda watershed at the outlets of Reaches 8 and 6.

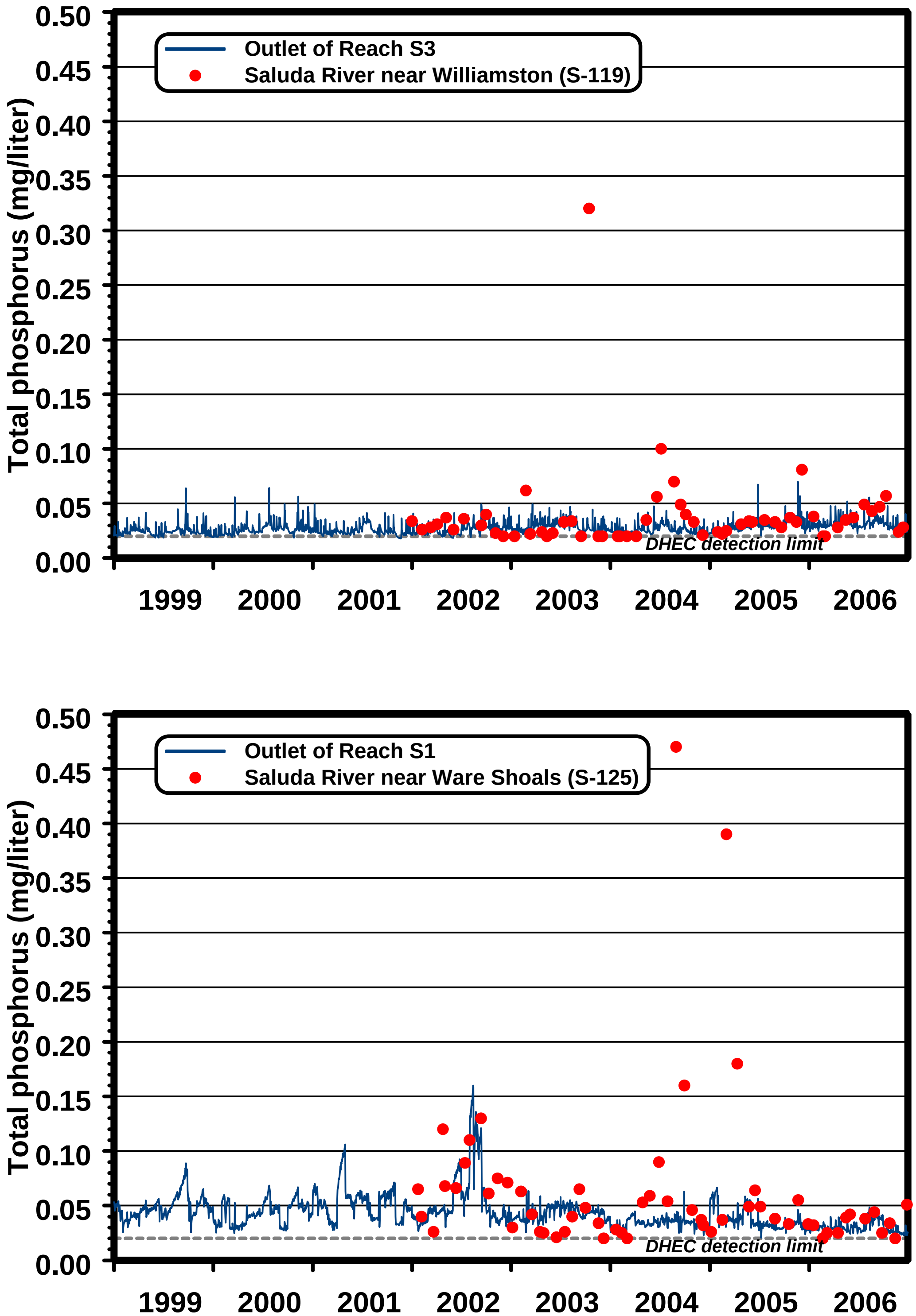
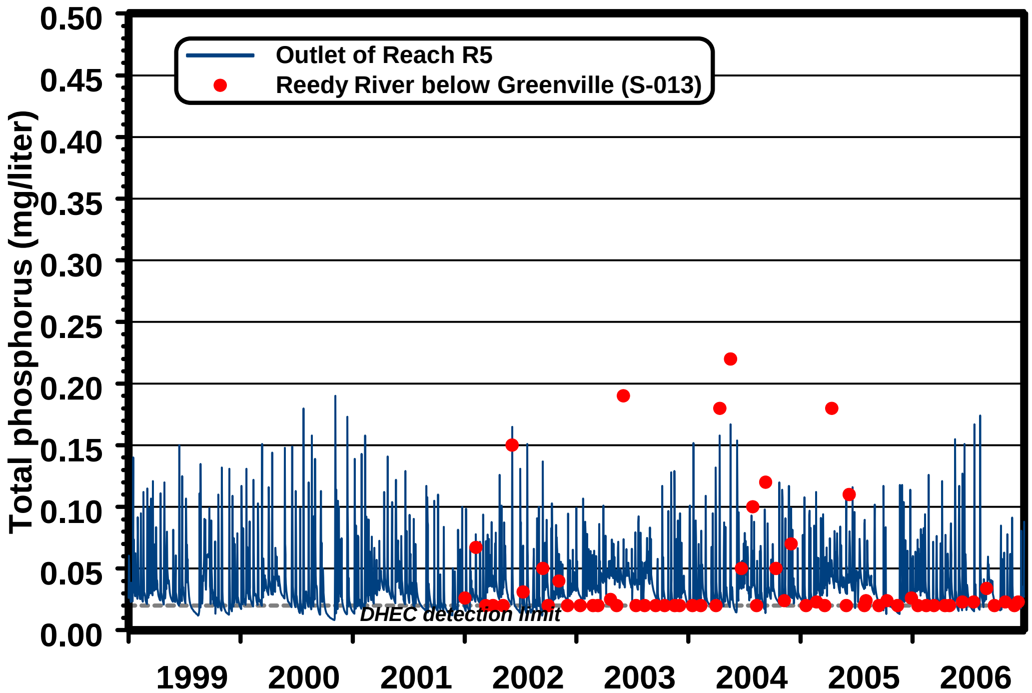


Figure 6b. Simulated and observed total phosphorus total phosphorus concentrations in the Saluda watershed at the outlets of Reaches 3 and 1.



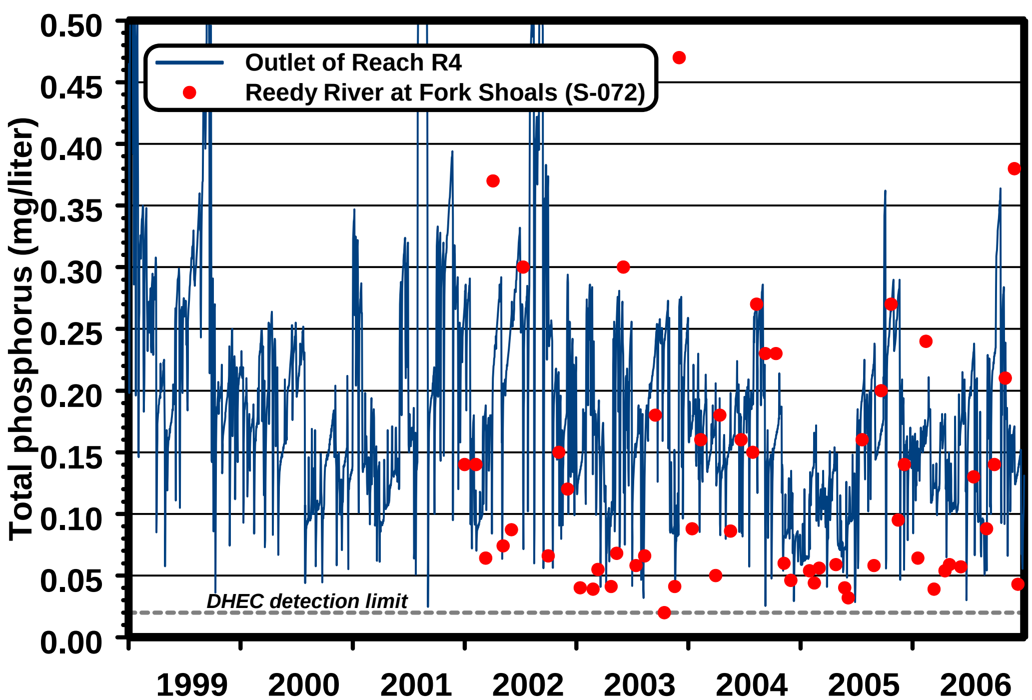
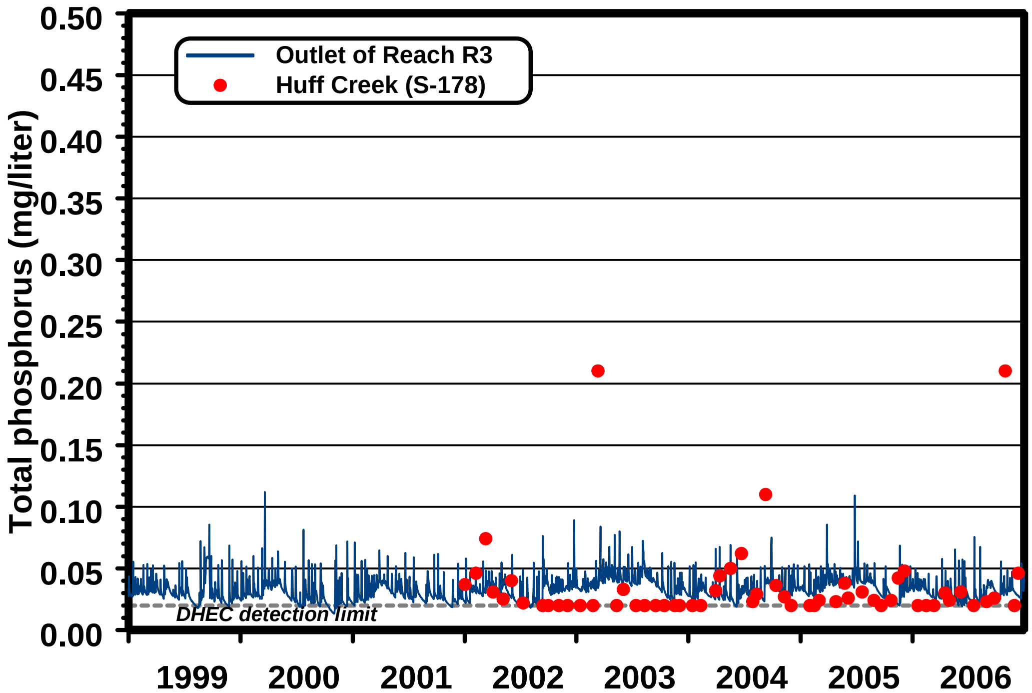


Figure 7a. Simulated and observed total phosphorus total phosphorus concentrations in the Reedy watershed at the outlets of Reaches 5 and 4.



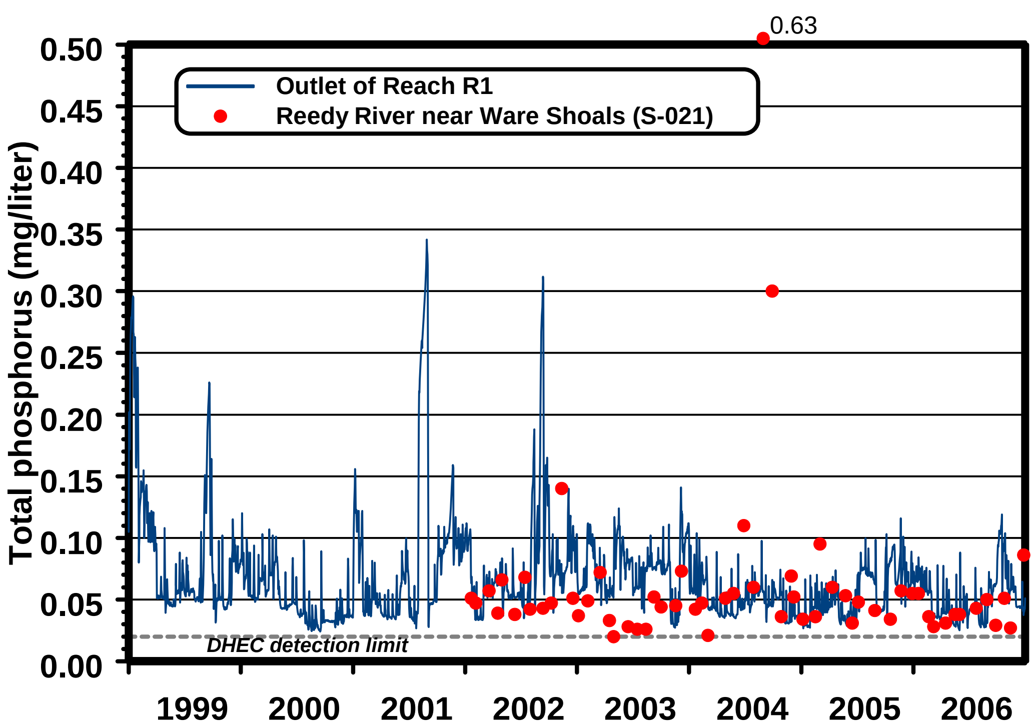


Figure 7b. Simulated and observed total phosphorus total phosphorus concentrations in the Reedy watershed at the outlets of Reaches 3 and 1.

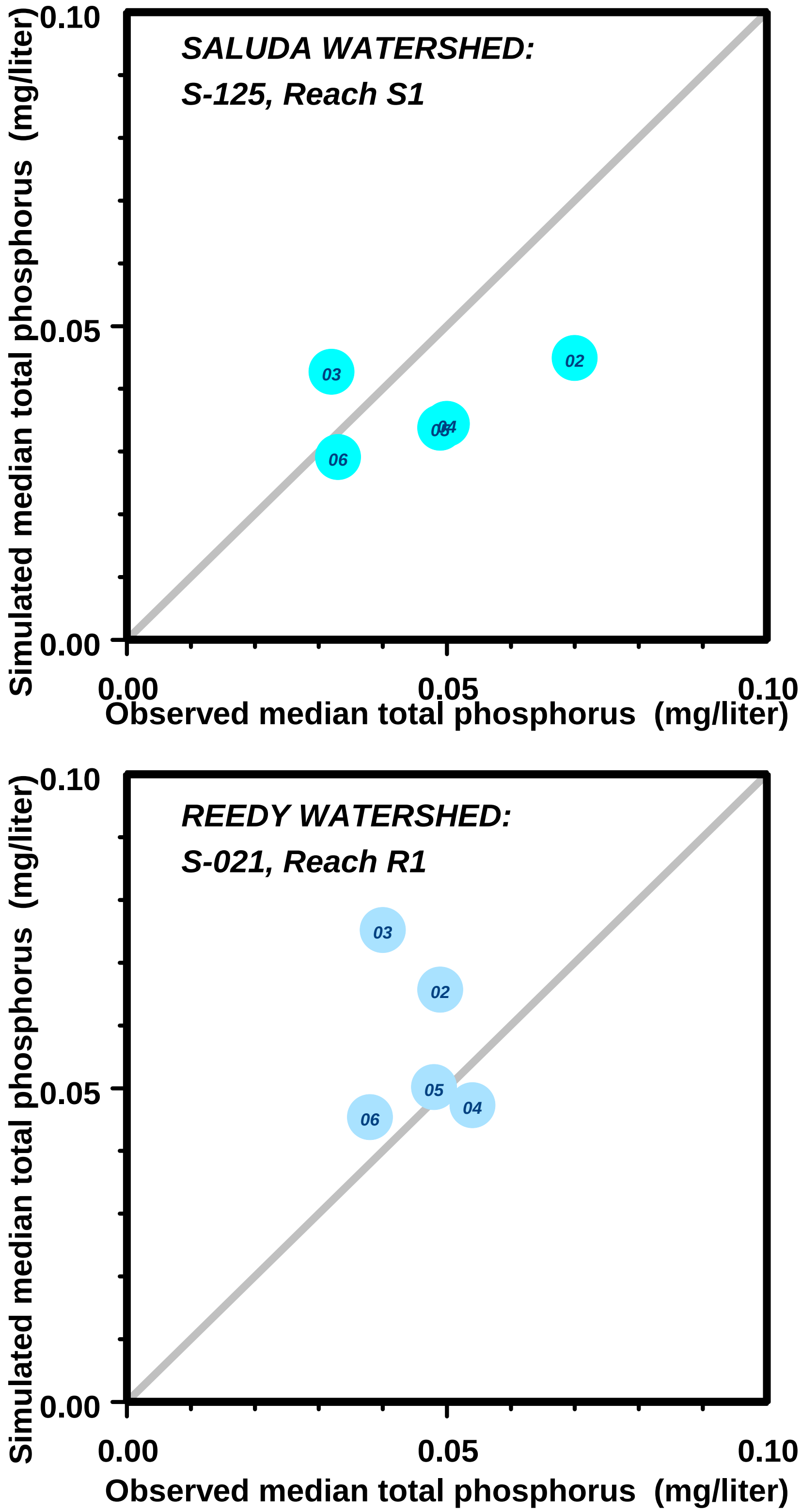


Figure 8. Simulated and observed annual median phosphorus concentrations in the Saluda and Reedy watersheds. Sample sizes are n=11 or 12 for the DHEC data and n=365 or 366 for the simulations.

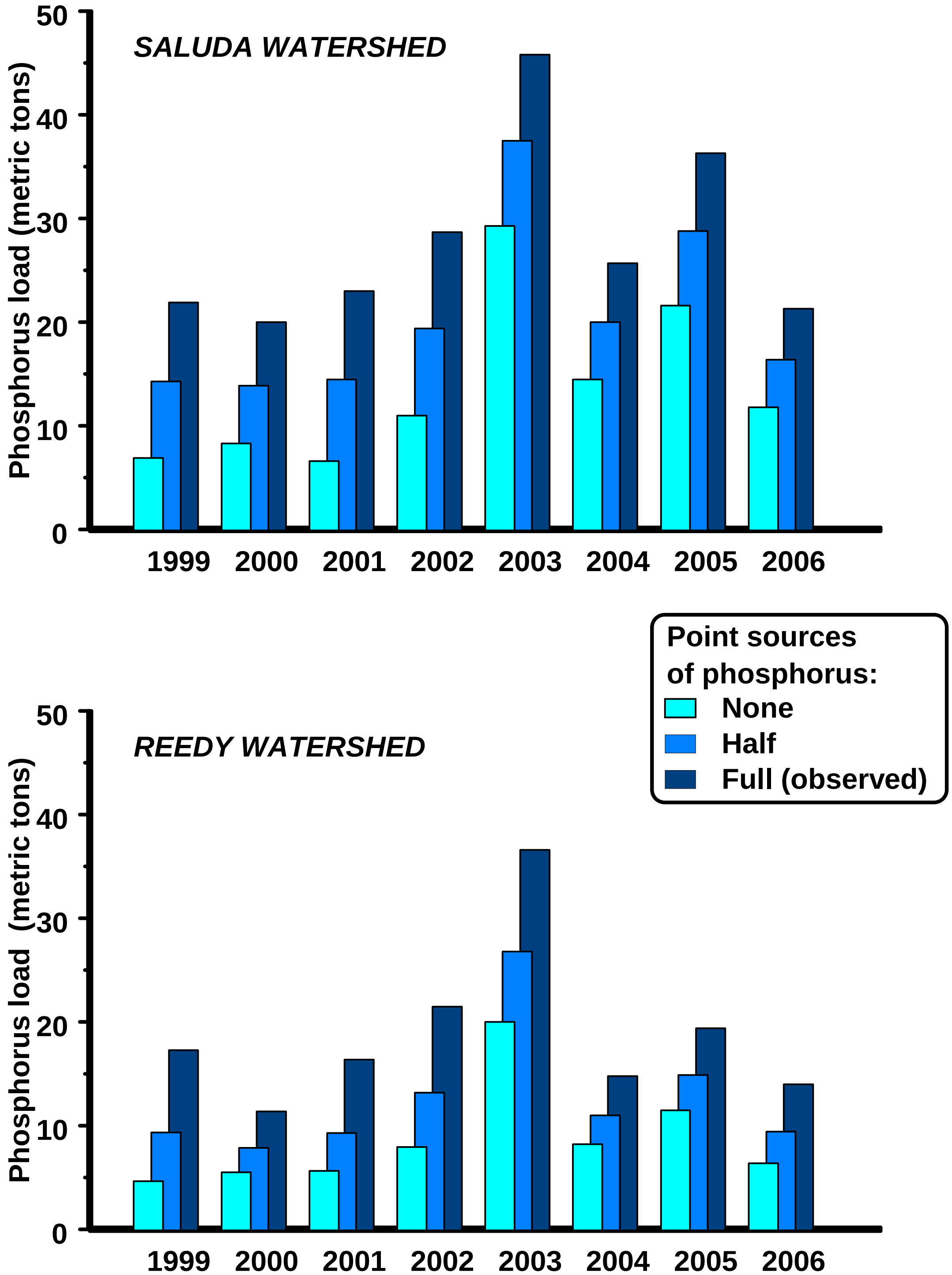


Figure 9. Simulated phosphorus loads to Lake Greenwood.