Appendix H: Additional Evaluations, Sensitivity Analyses, Scenario Comparisons, and Subject Matter Expert and Third-Party Review of the UNRBA Watershed Model

Contents

Introduction

The UNRBA modeling team calibrated a watershed model for the Falls Lake Watershed using the Watershed Analysis Risk Management Framework (WARMF). The WARMF model for the Falls Lake watershed includes an initialization year (2014) and then four years considered for calibration (2015 and 2016) and validation (2017 and 2018). When model development began, it was not known that iterative model runs (described below) would be required, and the initialization year was used for establishing the initial conditions prior to evaluating the model's performance.

This model development process included an extensive, ongoing review and assessment effort. "Third-party" model reviewers funded by the NC Collaboratory, Subject Matter Experts, DWR and the UNRBA member representatives through the Modeling and Regulatory Support Workgroup (MRSW) participated in meetings and received information and materials for their review and input. The modeling team responded to this input and this process is documented in this appendix.

A preliminary calibration was achieved in the spring of 2021 using the default model structure that assumes the soils within a modeling catchment respond as a uniform unit rather than separate units underlying specific land uses. Review of the nutrient loads per unit area generated by the land uses in the watershed model (i.e., areal loading rates) indicated that a change to the model structure was needed. Because of the chemistry of the soils in the watershed (model inputs based on US Department of Agriculture National Cooperative Soil Survey data), when the soils are simulated as uniform under all of the land uses in a catchment, the resulting simulated areal loading rates are very similar across land uses. Because the watershed is 60 percent forested and the modeling team had access to areal loading rates published by the US Forest Service based on monitoring studies in the Falls Lake watershed, a key goal of the change in model structure was to align the loading rates from forested areas within the ranges of those reported by the Forest Service. This change to separate the soils under each land use in a catchment was implemented in the summer of 2021 and revised calibration results were presented to the UNRBA Modeling and Regulatory Support Workgroup and Path Forward Committee in August and September 2021. The model results were evaluated after running the five-year model three times to observe some separation in the soils beneath respective land uses. Following additional review (see below), it was decided to run the model for five iterations rather than three to achieve further stabilization of the land use loading rates. The results of the fifth iteration represent the calibrated model for the UNRBA Study Period summarized in this report and its appendices. Scenarios evaluated with the watershed model are also evaluated for five iterations.

Additional information regarding how the WARMF model simulates land uses and underlying soils is provided in the section WARMF Simulations of Soils and Land Uses. The importance of hydrology on watershed loading is discussed in the sections Importance of Annual Precipitation on Watershed Response and Evaluation of Storm Size and Delivered Nutrient and Carbon Loads. A summary of the US Forest Service monitoring studies is provided in the section Local Monitoring Studies in Forested Headwater Streams in the Falls Lake Watershed. The section Sensitivity Analyses for Rainfall (Hydrologic Condition) provides additional information on these topics.

The revised model output was distributed to Subject Matter Experts and "third-party" reviewers (SMEs) in October 2021 to review the model output and specifically the areal loading rates. These SMEs provided input on the model development and calibration to water quality concentrations throughout the project. Prior to finalizing the model and relying on its output to develop the revised nutrient management strategy for Falls Lake, this final review step was conducted. An initial conference call was scheduled on November 3, 2021, and a follow-up call was held December 15, 2021, during which the following questions and suggestions for additional evaluation were provided:

- In addition to evaluating average loading rates delivered to Falls Lake, some smaller scale, catchment level results were requested. The section Evaluation and Testing of Catchment-Scale Nutrient Loading Rates provides catchment scale loading rates for three headwater catchments as well as comparisons of simulated and observed concentrations where available.
- Loading rates predicted by the WARMF model compared to ranges reported in the literature. SMEs provided several references to include in the comparison, and these have been summarized in this document in section Comparison of WARMF-Simulated Nutrient Loading Rates to Other Modeling Studies
- Additional questions were raised during these meetings:
    - How does the WARMF Watershed Model simulate the processes occurring in the watershed?
    - What happens if you run the model more than three times? Would you get further separation of the soil quality beneath the land uses and more variation in the areal loading rates? [ultimately five iterations were conducted]
    - Why are forest loading rates simulated by the UNRBA model for 2014 to 2018 higher than those measured by the Forest Service from 2008 to 2013?
    - Why aren't the WARMF simulated forest loading rates for the Falls Lake watershed much lower than rates simulated for urban areas?
    - Does the simulated nutrient load from stream bank erosion differ when the predominant land use in the catchment is urban versus forested?
    - How do simulated urban loading rates change under different hydrologic conditions?
    - How do simulated urban loading rates compare to other modeling studies?
    - Why are simulated loading rates from agriculture for 2014 to 2018 higher than those typically measured at edge of field?
    - How do the loading rates for agriculture vary spatially across the modeling catchments?
    - How does the source load allocation vary with precipitation condition?

This initial set of questions raised by the subject matter experts and "third-party" reviewers was answered by running a series of tests and sensitivity analyses using the watershed model. These analyses were tested on representative catchments rather than the entire watershed model and are summarized in the section Evaluation and Testing of Catchment-Scale Nutrient Loading Rates.

The preliminary draft watershed modeling report and all appendices were provided to the MRSW, the subject matter experts, and DWR modeling staff in June 2022. As part of this review process, additional questions were raised, two of which are also addressed in this appendix:

- What are the areal nutrient loading rates simulated by the model for each land use?
- How does the uncertainty in the rates of atmospheric deposition summarized in Appendix D affect the modeling results?
- Why are the simulated loads from forested areas so much different than the loads simulated by DWR in their 2009 modeling effort that was used to develop the Falls Lake Rules?

The first question is answered using output from the calibrated model and summarized in the section WARMF Simulated Average Delivered Loading Rates to Falls Lake for UNRBA Study Period. To answer the second question, additional sensitivity analyses were conducted that adjust the rates of atmospheric deposition of all parameters by plus or minus 25 percent. To answer the third question, a sensitivity analysis for decreased precipitation was evaluated for the entire watershed.

The results of these analyses are summarized in the sections called Sensitivity Analyses for Rainfall (Hydrologic Condition) and the Sensitivity Analyses on Rates of Atmospheric Deposition.

This appendix also includes the results of a watershed modeling scenario prioritized by the UNRBA Scenario Screening Group (SSG) and approved for evaluation by the Modeling and Regulatory Support Workgroup (MRSW) and Path Forward Committee (PFC). This hypothetical scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantly converts all land uses to forests. This scenario provides a loading estimation of the lowest nutrient load that could be realized for a watershed of this size given its history and past activities. Watershed sub-impoundments were left in place. Removal of these reservoirs would have actually increased watershed loading for the wooded-watershed scenario (significant nutrient reduction results from sub-watershed drainage moving through the impoundments). The results of this scenario are summarized in the section Land Conversion Scenario to All Forest or Wetland.

To compare the simulated nutrient loads delivered to Falls Lake for these evaluations, a summary section called Comparison of Delivered Loads to Falls Lake for the Sensitivity Analyses and Model Scenarios is provided. Summaries of delivered loads from only the upper five tributaries are also provided for comparison to the nutrient load allocations prescribed by the State in the Falls Lake Rules.

This appendix also includes a section called Comparison of WARMF-Simulated Nutrient Loading Rates to Other Modeling Studies. Additional details about these other modeling studies are provided in a section called Supplemental Information - Study Details.

Note: This appendix provides areal loading rates in both pounds per acre per year (lb/ac/yr) and kilograms per hectare per year (kg/ha/yr) for comparison to areal loading rates summarized by other sources (different sources present different units). Note that one lb/ac/yr is 1.12 kg/ha/yr.

This appendix documents the iterative review process of the Falls Lake watershed model. Several rounds of questions, analyses, additional questions and expanded analyses were conducted in response to input from the reviewers. This process continued until reviewers and the MRSW and Path Forward Committee (PFC) were sufficiently comfortable with the model structure and results to move forward with the lake water quality modeling. Because the WARMF watershed model provides the input to two of the three lake models, this review and approval process was important for transitioning to lake modeling. Based on this review and input, the MRSW and PFC approved the application of the WARMF watershed model for use in developing two of the lake models at the August 2021 and September 2021 meetings, respectively.

An abbreviated list of contents follows to orient the reader to the iterative review process documented in this appendix:

WARMF Simulations of Soils and Land Uses

This section helps address the following questions:

- *How does the WARMF Watershed Model simulate the processes occurring in the watershed?*
- *What happens if you run the model more than three times? Would you get further separation of the soil quality beneath the land uses and more variation in the areal loading rates?*

WARMF is a lumped parameter model, so the land use and soils in each of the 264 modeling catchments are simulated as a unit. WARMF keeps track of the nutrient balances associated with land uses within a catchment (nutrient application, crop uptake, harvesting, etc.), but the soils are usually simulated as uniform across the catchment. For watersheds with soils that bind nutrients and release them slowly over time like the Falls Lake watershed, this modeling assumption yields somewhat similar areal loading rates (pounds per acre per year) from sources across the watershed. In order to better distinguish the loading by land use, the WARMF option to isolate soils by land use was applied. However, the initial conditions must still be assigned as a catchment average, and iterative runs are necessary for the soil nutrient balances to "separate" and for the model to provide loading information that is distinguishable across land use types.

The changes to the model structure and running the model three times resulted in the model being able to better distinguish loading rates of nitrogen, but phosphorus loading rates remained relatively similar across land use types (there are more differences between catchments than land uses within a catchment). The phosphorus results are consistent with the general chemical/physical behavior of phosphorus applied to the land (generally, phosphorus has a high soil adsorption characteristic whereas nitrogen is less absorbable, particularly the inorganic forms). WARMF specifies all soils within a catchment with the same initial soil chemistry, including the nutrient-related soil parameters. Once the simulation begins, using the new model configuration allows for tracking the nutrient balance separately for the soils under each land use. As the model runs, the soils beneath each land use receive varying rates of nutrient application in addition to atmospheric deposition. Unmanaged areas like forests only receive atmospheric deposition. Thus, differences in soil chemistry and areal loading rates become more apparent the more times the model is run.

Urban land uses are assumed to receive nutrient application (nitrogen and phosphorus) for groundcover and landscaping. Based on local homeowner surveys in the Falls and Jordan Lake watersheds (Osmond and Hardy 2004, Fleming 2013), the model used application rates consistent with this information. Cropland and pasture assume county- and crop-specific nitrogen application at rates provided by the NC Department of Agriculture. Assumptions regarding phosphorus application rates were obtained from the report "Delineating Agriculture in the Neuse River Basin" (Osmond and Neas 2011). The soils are affected by these varying rates of nutrient application. Section 3 of the main report list the nutrient application rates for urban and agricultural land uses.

The calibration presented to the MRSW and PFC in August and September reflected results after running the model three times. The SMEs asked the modeling team to evaluate additional iterations to see if further separation of the soils would occur. This evaluation results in changes to the nitrogen calibration as well. Running the model five times (25 years) results in a relatively stable model where the load from any single tributary to Falls Lake does not change by more than 3 percent between successive model runs. The results in this appendix reflect the output following five runs.

Importance of Annual Precipitation on Watershed Response

This section helps address the following questions:

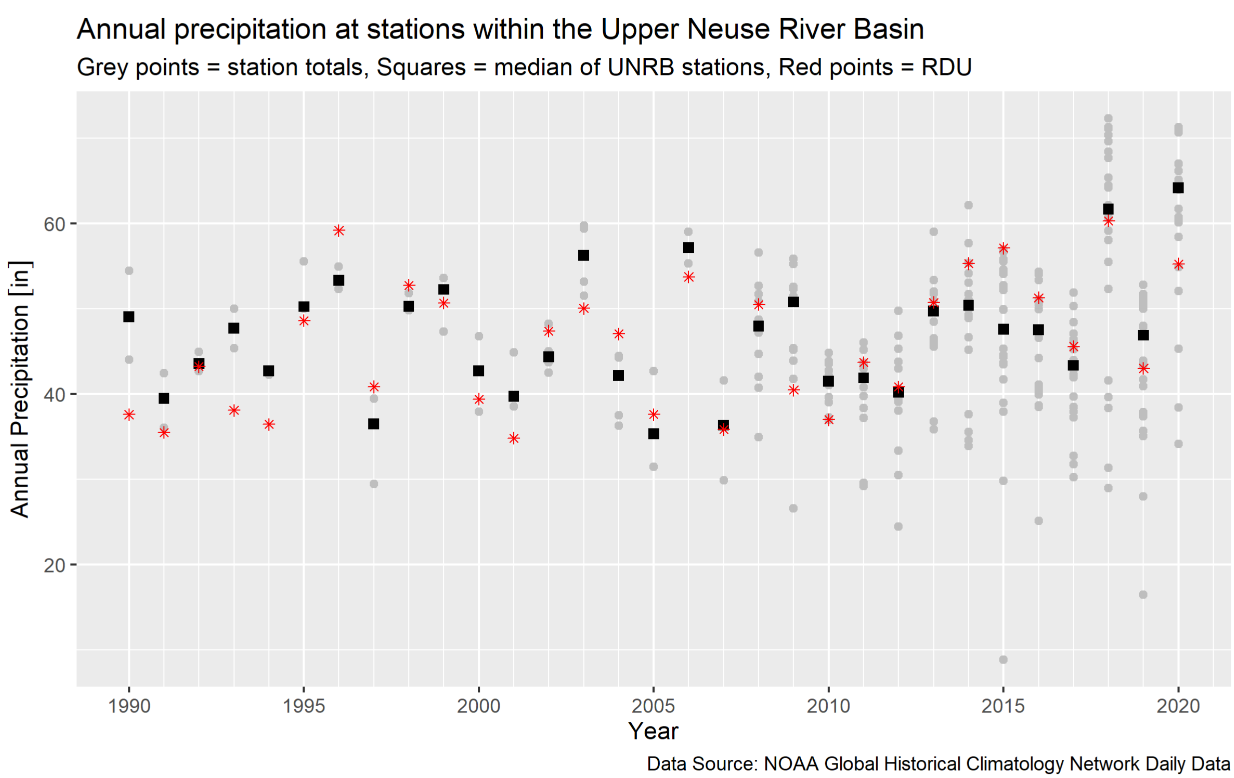
- How does the WARMF Watershed Model simulate the processes occurring in the watershed?
- Why are forest loading rates simulated by the UNRBA model for 2014 to 2018 higher than those measured by the Forest Service from 2008 to 2013?

Precipitation is a primary driver of hydrologic and loading responses in watersheds. In the Falls Lake WARMF model, precipitation is simulated for 78 stations based on NEXRAD data provided by the State Climate Office. For a given year, annual precipitation can vary by up to 20 inches across the precipitation stations (Figure H-1). Loading rates simulated for one catchment can vary greatly from another based on this and other factors (slope, etc.). For simplicity, this document refers to precipitation at RDU as an example of the annual variability.

Loading is a function of flow rate and concentration. Figure H-2 shows the stream flows at the Flat River above Lake Michie (USGS gage 02085500) for different years. At this example gage, average annual stream flow in 2007 (a dry year during a historic drought) was approximately 68 cfs. During 2017 (an average precipitation year), mean annual streamflow was almost twice as high at 121 cfs. 2018 (a wet year) had a mean annual stream flow of 260 cfs, almost four times higher than the 2007 average streamflow.

At the Flat River above Lake Michie, average annual stream flow in 2007 (a dry year during a historic drought) was approximately 68 cfs. During 2017 (an average precipitation year), mean annual streamflow was almost twice as high at 121 cfs. 2018 (a wet year) had a mean annual stream flow of 260 cfs, almost four times higher than the 2007 streamflow.

Precipitation is the key driver of the annual variation in loading from the watershed to Falls Lake. For example, the annual precipitation at RDU in 2018 was **30 percent higher** compared to 2017 (60.3 inches versus 45.6 inches). Nutrient and total organic carbon loads delivered to Falls Lake in 2018 were **over two times higher** than those in 2017. In other words, the precipitation did not need to double in order to double the loading rates. This clearly illustrates the critical role of rainfall in determining watershed loading. Table H-1 shows the annual precipitation at RDU and simulated TN, TP, and TOC loads delivered to the lake loading water quality monitoring stations (excluding the area around Falls Lake). The ratios of precipitation and loading relative to 2017 are shown in brackets. Once the soils in the watershed are saturated, stream flows and loads can increase at a non-linear rate. 2015 had approximately 25 percent higher precipitation than 2017 and nutrient and total organic carbon loading was 20 to 60 percent higher depending on the parameter. 2018 had approximately 30 percent higher precipitation than 2017 and nutrient and total organic carbon loading was 110 to 140 percent higher depending on the parameter.



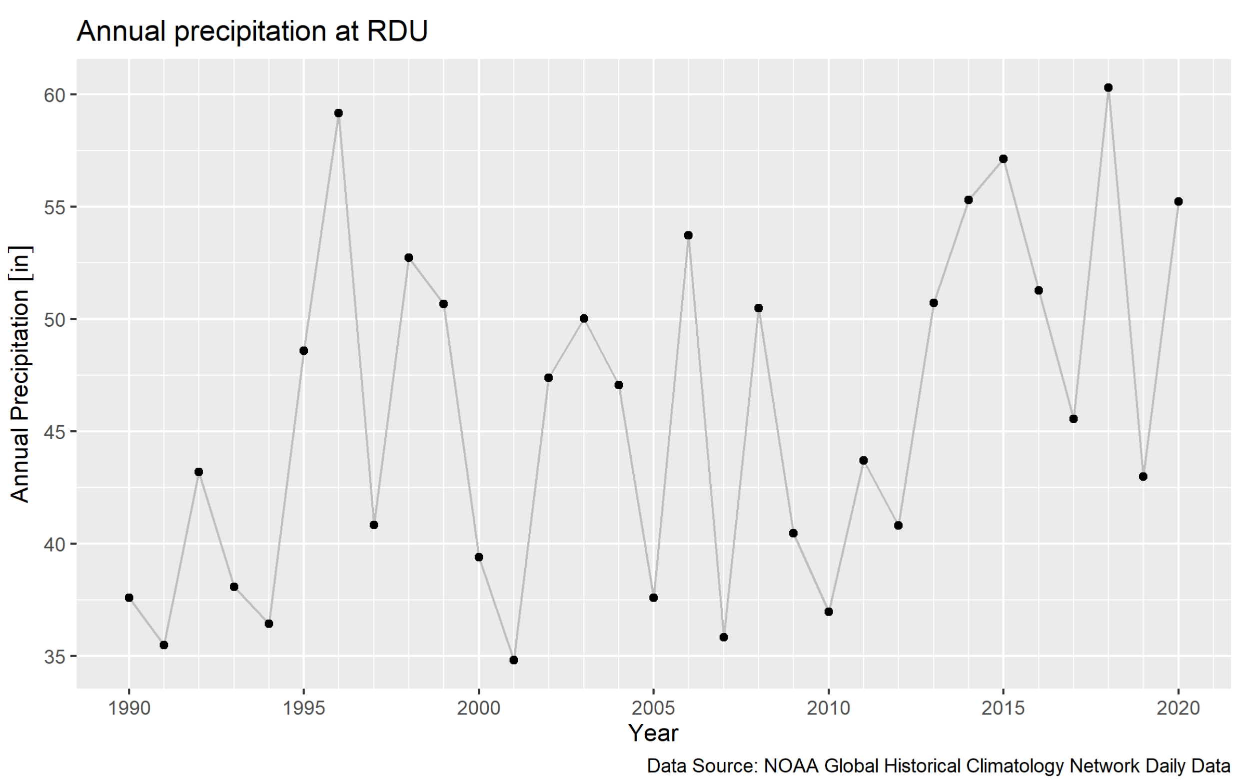


Figure H-1. Annual Precipitation (1990 to 2020) across the Falls Lake Watershed (top) and at RDU (bottom)

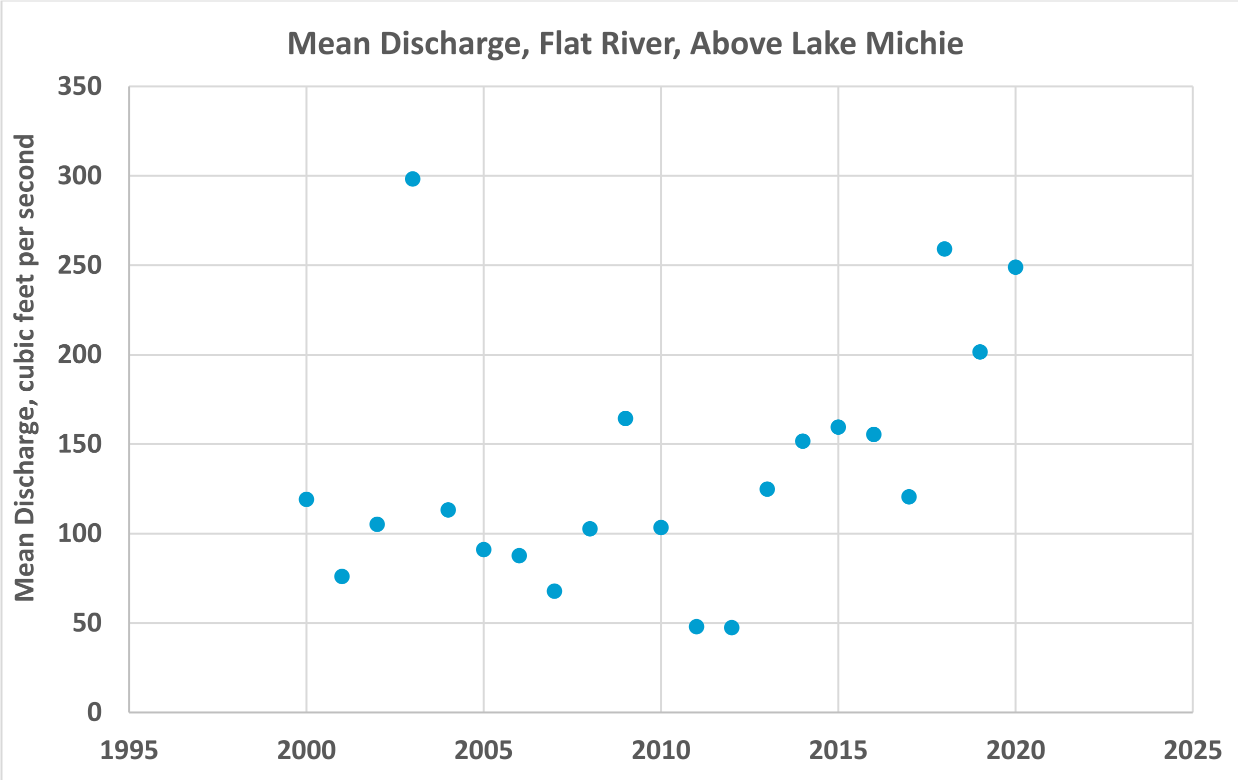


Figure H-2. Mean Annual Streamflow at Flat River above Lake Michie (USGS gage 02085500)

Table H-1. Annual Precipitation at RDU and Simulated TN, TP, and TOC Loads Delivered to the Lake Loading Stations Upstream of Falls Lake for the UNRBA Study Period (2015 to 2018)

Year	Annual Precipitation at RDU (in) [ratio to 2017]	TN (lb/yr) [ratio to 2017]	TP (lb/yr) [ratio to 2017]	TOC (lb/yr) [ratio to 2017]
2015	57.1 [1.25]	1,306,800 [1.6]	128,000 [1.2]	10,031,000 [1.5]
2016	51.3 [1.13]	1,053,800 [1.3]	123,000 [1.1]	8,344,000 [1.3]
2017	**45.6 [1.00]**	**826,800 [1.0]**	**108,800 [1.0]**	**6,671,000 [1.0]**
2018	60.3 [1.32]	1,859,400 [2.2]	224,200 [2.1]	15,738,000 [2.4]

Evaluation of Storm Size and Delivered Nutrient and Carbon Loads

This section helps address the following questions:

- *How does the WARMF Watershed Model simulate the processes occurring in the watershed?*

To evaluate the frequency of storms by size and their impact on simulated loading to Falls Lake, NEXRAD data for the UNRBA study period (2015 to 2018) were processed at four locations representing areas near Hillsborough, Durham, Roxboro, and Butner. The six-hour precipitation files for these stations were analyzed to calculate the total precipitation over individual storm events of different size classes as well as the rolling 24-hour cumulative precipitation for displaying on time series figures and evaluating 24-hour loads (i.e., precipitation for that time step and the preceding three).

For the individual storm analysis, storms were identified as periods with continuous precipitation occurring in sequential time steps which could span multiple days (e.g., over eight inches of rain were recorded in the Durham area from September 14, 2018, to September 17, 2018). During this period, the highest 24-hour cumulative precipitation was 6 inches at this location. At the Butner location, this storm lasted from September 13, 2018, to September 17, 2018; the total precipitation amount was 10.3 inches and the highest precipitation within a 24-hour period was 8.1 inches.

Figure H-3 shows the counts by size for individual storms totaling more than 0.25 inches at the four representative locations. Most of the storms were below 1 inch, which is the design size required by NC DEQ for sizing stormwater control measures in the Piedmont. As the size class increases, fewer storms were recorded. In the baseline period (2005 to 2007) and in 2015, no storms exceeded 4 inches at these four NEXRAD locations. During the UNRBA study period, at least one 4-inch storm occurred in each area in 2016, 2017, and 2018.

Larger storms generate greater pollutant loads over their duration because they saturate the soil and exceed the design criteria for stormwater control measures. Figure H-4 displays the simulated daily loads versus the 24-hour precipitation at the Ellerbe Creek lake-loading station. Most of the 24-hour precipitation depths are less than 2 inches, and the loads are relatively low. Figure H-5 displays the average simulated daily load for different size classes. Both figures illustrate how loading of total nitrogen, total phosphorus, and total organic carbon increases with storm size. Figure H-6 and Figure H-7 show this data for the Knap of Reeds Creek lake-loading station where the patterns are similar. A comparison of the WARMF simulated daily loads to those that would be estimated from observed water quality and USGS gaged flows is provided in the main report; this comparison shows that the simulated daily loads are reasonable compared to estimates based on individual water quality samples and estimated stream flows.

Table H-2 through Table H-7 shows the total load delivered to Falls Lake at the lake loading stations on Ellerbe Creek and Knap of Reeds Creek, by year and storm size for the UNRBA study period (2015 to 2018). Both tributaries include major wastewater treatment plants that discharge during all flow conditions, and the annual contribution from these facilities is also listed in the tables. Most of the load reaching the lake occurs when flows are low and 24-hour precipitation totals are less than 0.25 inches (this includes baseflow conditions). These conditions represent approximately 80 percent of the days of each simulated year, and the average load over a 24-hour period is much lower than any other category. The next largest contribution to total delivered load comes from storms ranging from 0.25 inches to 1 inch, and these conditions represent less than ten percent of the of simulated days. The average delivered load during a 24-hour period from storms this size is 4 to 5 times higher than those delivered during baseflows. One-to-two-inch storms contribute the next largest portion of the total load, and these loads represent approximately 3 percent of the hydrologic conditions. These storms contribute more than ten times the baseflow load during a 24-hour period. The next highest contributors to the total load are storms ranging in size from 2 to 3 inches. These storms occur on approximately 0.5 percent of the days each year during the UNRBA study period. Loads over a 24-hour period following storms are approximately 20 to 60 times higher than baseflow conditions, depending on the parameter. Storms ranging in size from 3 to 4 inches occur on 0.1 percent of the simulated days, but they deliver loads over the course of a 24-hour period that are approximately 50 to 150 times higher than baseflow conditions. Storms exceeding 4 inches also occur approximately 0.1 percent of simulated days; these storms can contribute hundreds of times more than the baseflow load in a 24-hour period. Thus, the large storms do not contribute the largest portion of total load delivered to Falls Lake because they occur relatively infrequently, but over a 24-hour period they can contribute tens to hundreds of times more load than loads delivered under baseflow conditions. Based on algal response and lake detention times during these high flow events, this additional loading could be critical in impacting algal levels following these events. This could be localized in arms of the lake or more widespread if the high rainfall event is distributed over a large area of the watershed (such as a hurricane or tropical storm systems moving across the watershed).

Thus, the large storms do not contribute the largest portion of total load delivered to Falls Lake because they occur relatively infrequently, but over a 24-hour period they can contribute tens to hundreds of times more load than loads delivered under baseflow conditions.

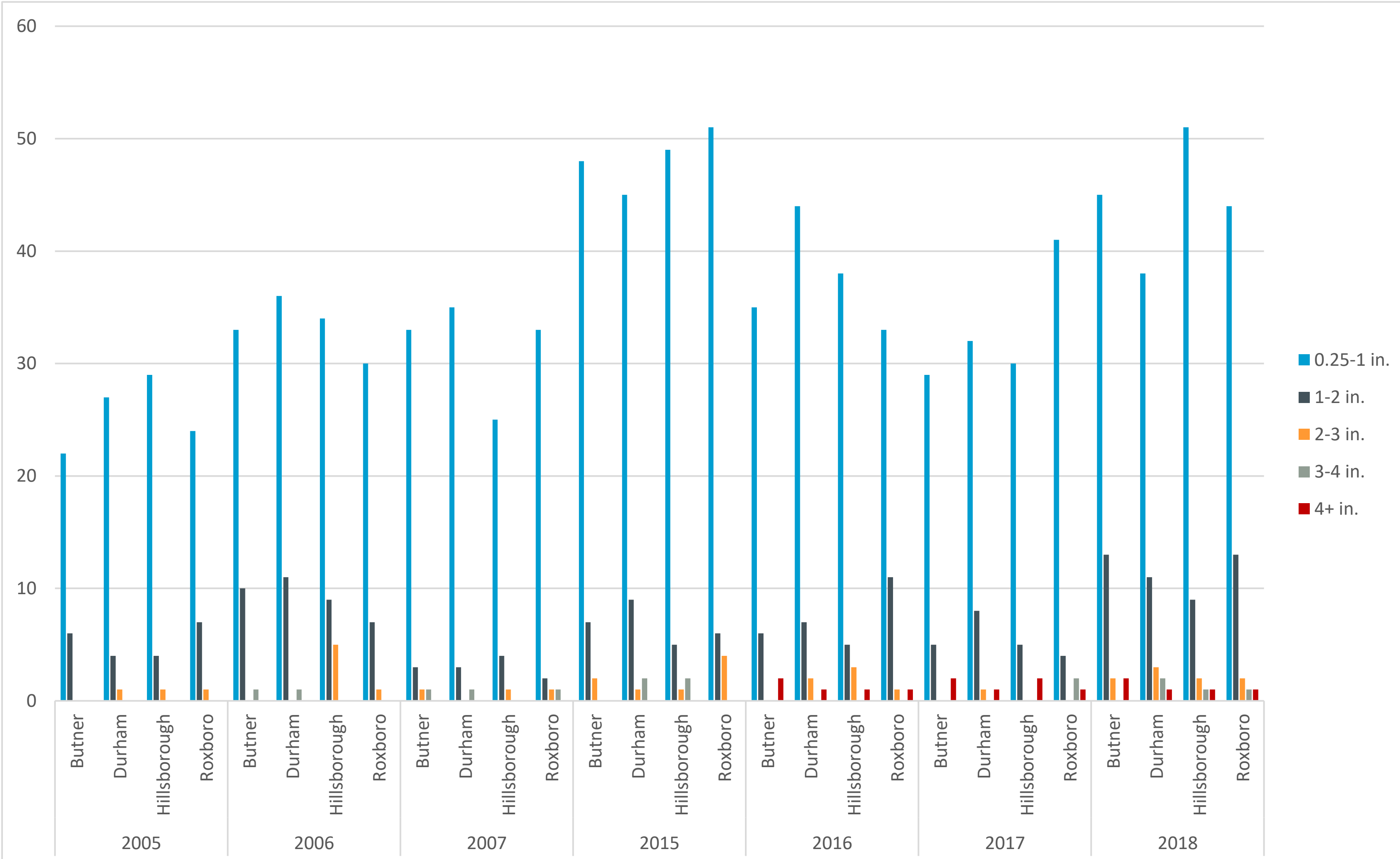


Figure H-3. Storm Sizes by Year and Station for Representing Four Areas in the Watershed

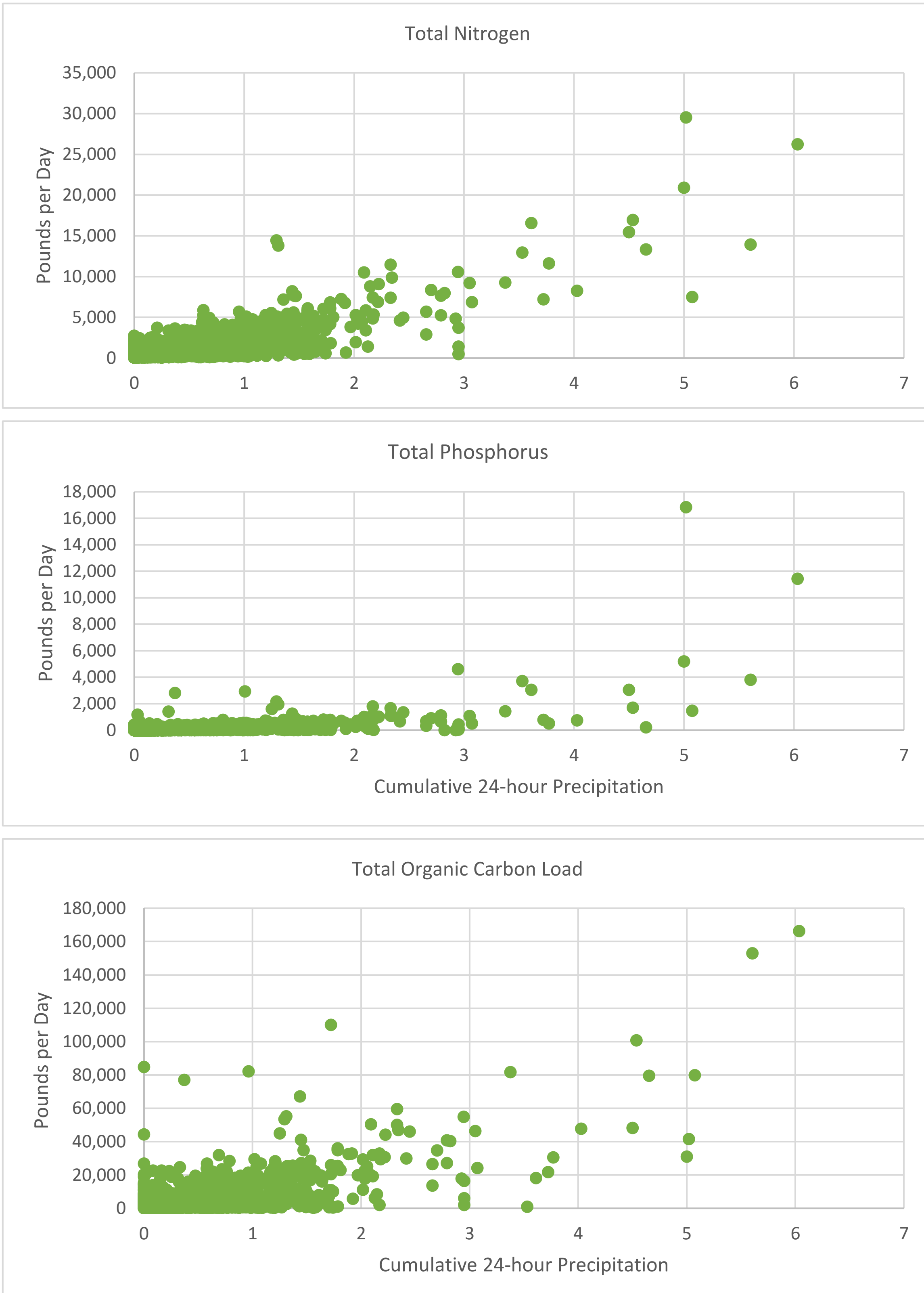


Figure H-4. Daily Simulated Loads and 24-hour Cumulative Precipitation at Ellerbe Creek Lake Loading Station

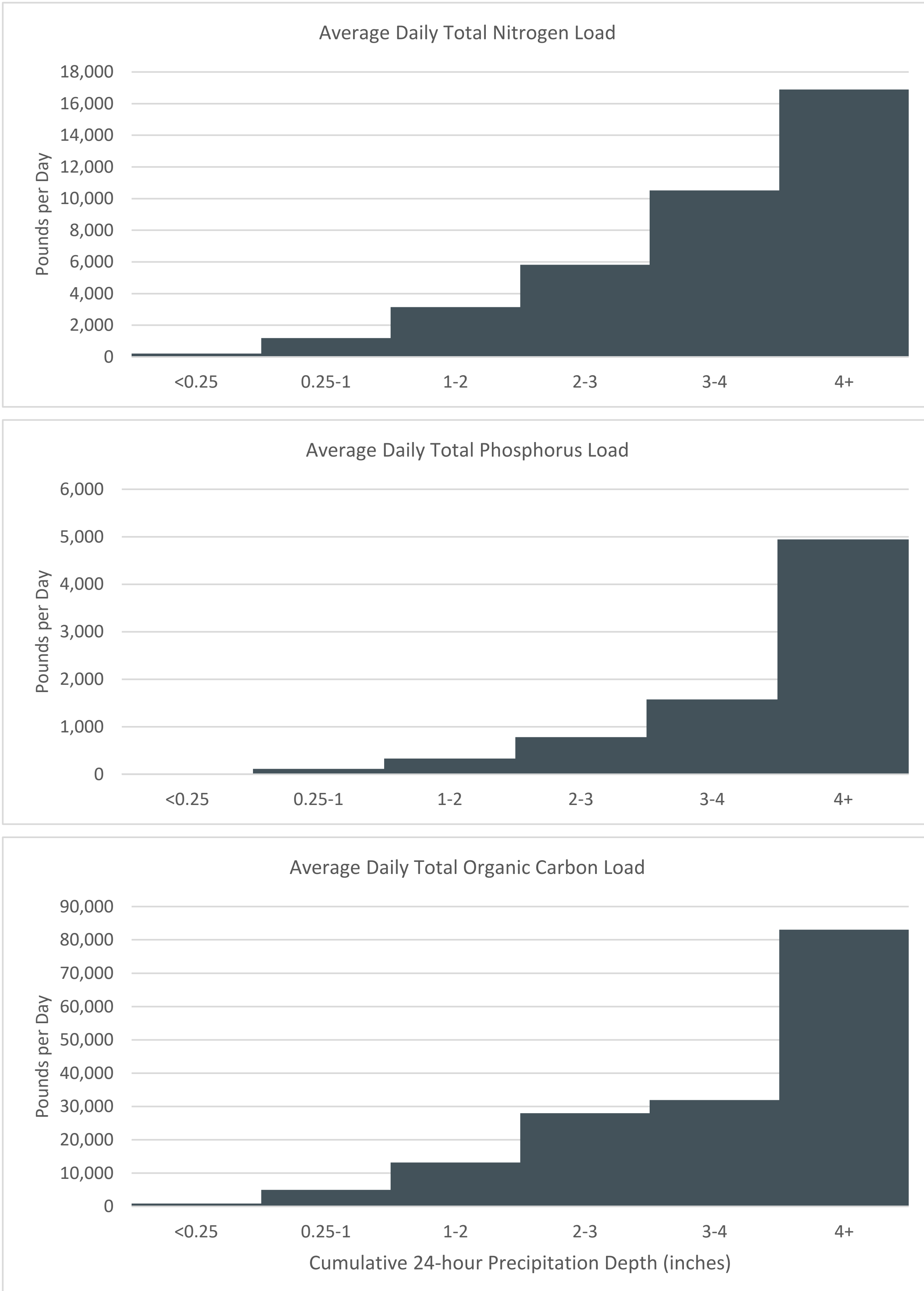


Figure H-5. Average Daily Simulated Loads by 24-hour Cumulative Precipitation Size at Ellerbe Creek Lake Loading Station

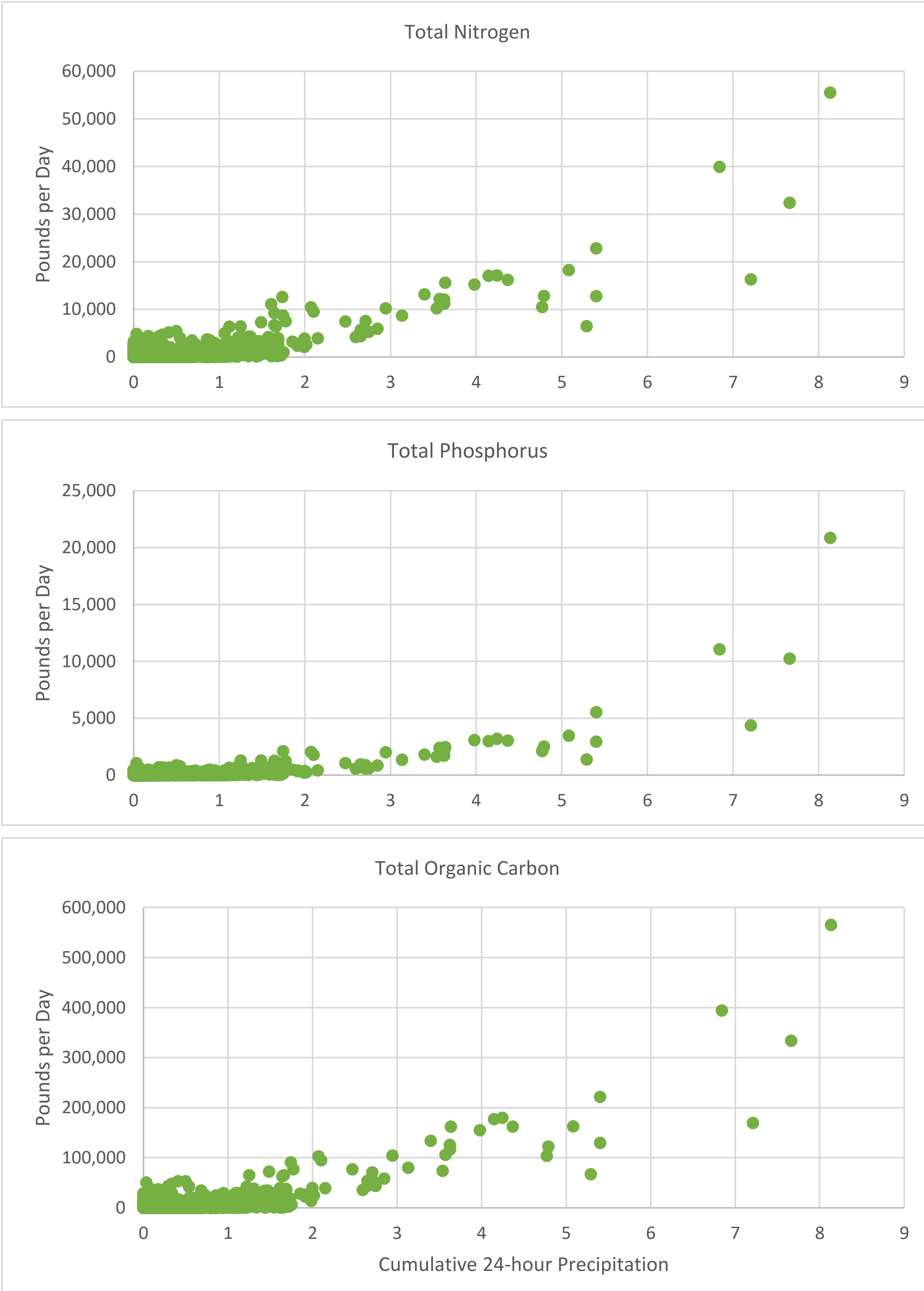


Figure H-6. Simulated Loads and 24-hour Cumulative Precipitation Amounts at Knap of Reeds Creek Lake Loading Station

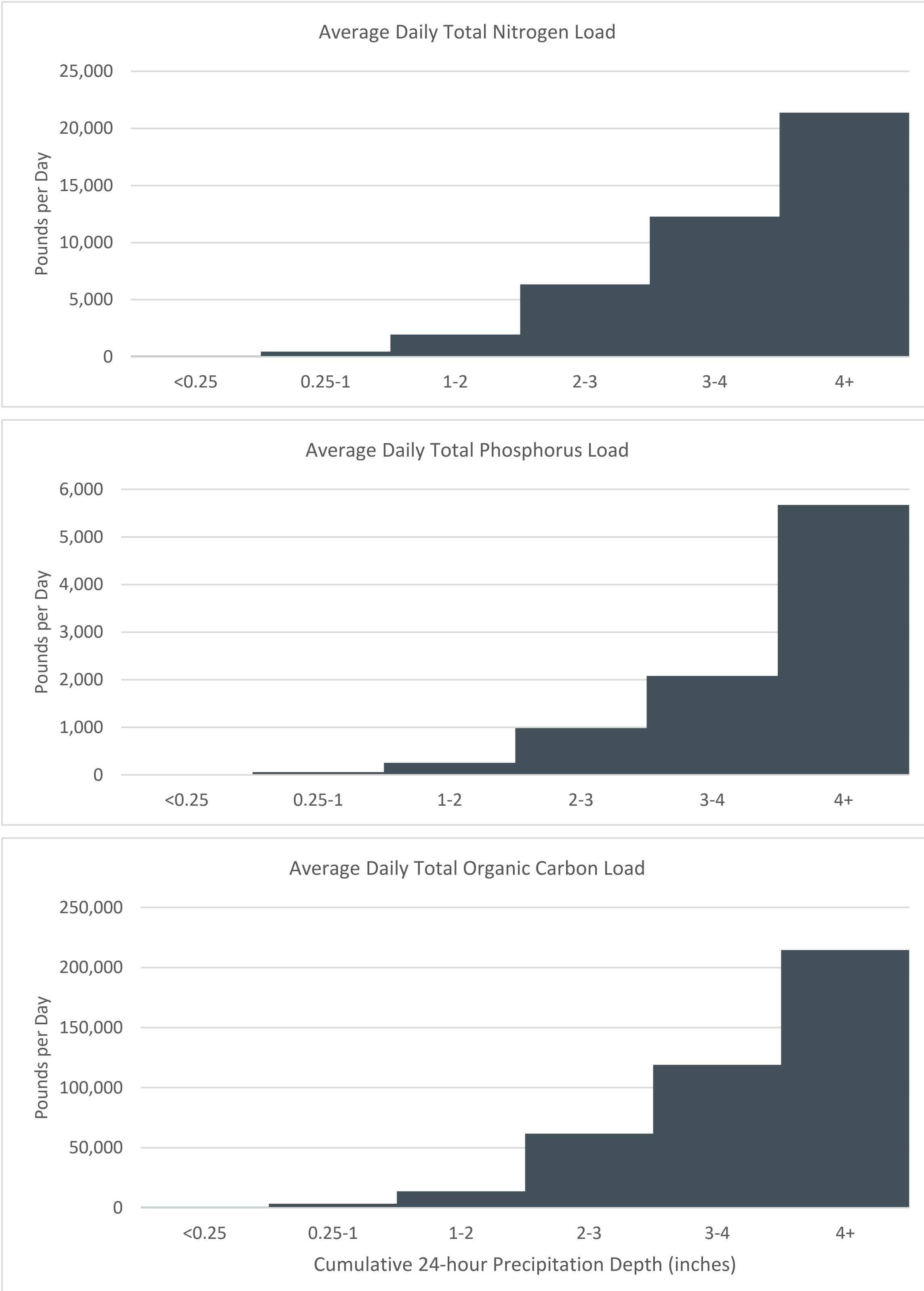


Figure H-7. Average Daily Simulated Loads by 24-hour Cumulative Precipitation Size at Knap of Reeds Creek Lake Loading Station

Table H-2. Total Nitrogen Load Delivered to Falls Lake from Ellerbe Creek at the Lake Loading Station				
Total Load Delivered to Falls Lake from the Lake Loading Station	2015	2016	2017	2018
24-hr Cumulative Precipitation (inches)				
<0.25	69,747	63,587	53,291	69,897
0.25-1	60,867	38,997	33,025	68,923
1-2	44,035	30,975	17,811	49,175
2-3	13,430	11,144	4,989	16,961
3-4	4,014	N/A	6,456	7,941
4+	N/A	9,625	9,088	19,287
Total	192,093	154,329	124,660	232,184
Load discharged from major WWTP	*82,210*	*75,839*	*61,457*	*83,337*
Number of 24-hour periods within Each Size Class				
<0.25	307	310.5	317.5	298.5
0.25-1	42	42.5	37.75	48
1-2	13.75	10.25	7.75	13.25
2-3	1.75	2	1	3.25
3-4	0.5	0	0.5	0.75
4+	0	0.75	0.5	1
Total	365	366	365	365
Average Load per 24-hour Period				
<0.25	227	205	168	234
0.25-1	1,449	918	875	1,436
1-2	3,203	3,022	2,298	3,711
2-3	7,674	5,572	4,989	5,219
3-4	8,028	N/A	12,911	10,588
4+	N/A	12,833	18,176	19,287
Load discharged from major WWTP	*225*	*208*	*168*	*228*

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

Load discharged from major WWTP is partially attenuated prior to reaching Falls Lake. For Ellerbe Creek this load represents the majority of total nitrogen load under zero to low precipitation conditions.

Table H-3. Total Phosphorus Load Delivered to Falls Lake from Ellerbe Creek at the Lake Loading Station				
Total Load Delivered to Falls Lake from the Lake Loading Station	**2015**	**2016**	**2017**	**2018**
24-hr Cumulative Precipitation (inches)				
<0.25	5,352	4,821	4,730	6,528
0.25-1	5,357	3,494	3,106	7,143
1-2	4,502	4,072	1,564	4,687
2-3	1,862	2,079	484	1,847
3-4	396	N/A	1,118	1,245
4+	N/A	667	2,062	8,391
Total	17,469	15,133	13,065	29,840
Load from major WWTP	*2,764*	*2,520*	*3,152*	*3,066*
Number of 24-hour periods within Each Size Class				
<0.25	307	310.5	317.5	298.5
0.25-1	42	42.5	37.75	48
1-2	13.75	10.25	7.75	13.25
2-3	1.75	2	1	3.25
3-4	0.5	0	0.5	0.75
4+	0	0.75	0.5	1
Total	365	366	365	365
Average Load per 24-hour Period				
<0.25	17	16	15	22
0.25-1	128	82	82	149
1-2	327	397	202	354
2-3	1,064	1,039	484	568
3-4	793	N/A	2,236	1,660
4+	N/A	889	4,124	8,391
Load from major WWTP	*8*	*7*	*9*	*8*

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

Table H-4. Total Organic Carbon Load Delivered to Falls Lake from Ellerbe Creek at the Lake Loading Station				
Total Load Delivered to Falls Lake from Ellerbe Creek Lake Loading Station	2015	2016	2017	2018
24-hr Cumulative Precipitation (inches)				
<0.25	277,420	235,704	205,156	328,086
0.25-1	246,633	155,202	150,357	292,088
1-2	183,922	132,184	94,962	183,142
2-3	66,393	51,739	17,712	87,621
3-4	17,641	N/A	24,952	13,291
4+	N/A	56,994	19,788	110,096
Total	277,420	235,704	205,156	328,086
Number of 24-hour periods within Each Size Class				
<0.25	307	310.5	317.5	298.5
0.25-1	42	42.5	37.75	48
1-2	13.75	10.25	7.75	13.25
2-3	1.75	2	1	3.25
3-4	0.5	0	0.5	0.75
4+	0	0.75	0.5	1
Total	365	366	365	365
Average Load per 24-hour Period				
<0.25	904	759	646	1,099
0.25-1	5,872	3,652	3,983	6,085
1-2	13,376	12,896	12,253	13,822
2-3	37,939	25,869	17,712	26,960
3-4	35,281	N/A	49,904	17,721
4+	N/A	75,992	39,576	110,096

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer this level of precision in the modeling results.

Table H-5. Total Nitrogen Load Delivered to Falls Lake from Knap of Reeds Creek at the Lake Loading Station				
Total Load Delivered to Falls Lake from the Lake Loading Station	2015	2016	2017	2018
24-hr Cumulative Precipitation (inches)				
<0.25	42,254	22,886	14,228	41,555
0.25-1	27,904	10,704	11,673	28,421
1-2	38,223	10,901	5,200	24,689
2-3	4,989	1,475	2,549	11,611
3-4	N/A	8,601	5,970	9,982
4+	N/A	14,377	19,113	36,002
Total All Flows	113,370	68,944	58,734	152,260
Load from major WWTP	*53,395*	*14,573*	*14,387*	*11,747*
Number of 24-hour periods within Each Size Class				
<0.25	306	316	320.5	296
0.25-1	48	40	36	50
1-2	10.75	7.75	7	15
2-3	0.5	0.25	0.25	2
3-4	0	0.75	0.5	0.75
4+	0	1	1.25	1
Total	365	366	365	365
Average Load per 24-hour Period				
<0.25	138	72	44	140
0.25-1	581	266	329	568
1-2	3,556	1,407	743	1,646
2-3	9,978	5,900	10,197	5,160
3-4	N/A	11,468	11,940	13,309
4+	N/A	14,377	15,290	36,002
Load from major WWTP	*146*	*40*	*39*	*32*

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.
Upgrades to the South Granville Water and Sewer Authority (SGWASA) wastewater treatment plant (WWTP) occurred in 2015 and 2016.

Table H-6. Total Phosphorus Load Delivered to Falls Lake from Knap of Reeds Creek at the Lake Loading Station				
Total Load Delivered to Falls Lake from the Lake Loading Station	**2015**	**2016**	**2017**	**2018**
24-hr Cumulative Precipitation (inches)				
<0.25	5,553	3,669	1,441	4,920
0.25-1	3,383	2,007	1,436	3,492
1-2	4,549	1,880	693	3,239
2-3	960	212	504	1,518
3-4		1,549	1,112	1,498
4+		2,713	4,087	11,635
Total	14,445	12,031	9,275	26,302
Load from major WWTP	*4,265*	*2,072*	*661*	*645*
Number of 24-hour periods within Each Size Class				
<0.25	306	316	320.5	296
0.25-1	48	40	36	50
1-2	10.75	7.75	7	15
2-3	0.5	0.25	0.25	2
3-4	0	0.75	0.5	0.75
4+	0	1	1.25	1
Total	365	366	365	365
Average Load per 24-hour Period				
<0.25	18.2	11.6	4.5	16.6
0.25-1	70.5	49.9	40.5	69.8
1-2	423.2	242.6	99.1	215.9
2-3	1,920.0	847.0	2,017.6	674.7
3-4	N/A	2,065.4	2,223.9	1,998.0
4+	N/A	2,713.3	3,269.8	11,635.0
Load from major WWTP	*12*	*6*	*2*	*2*

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.
Upgrades to the SGWASA WWTP occurred in 2015 and 2016.

Table H-7. Total Organic Carbon Load Delivered to Falls Lake from Knap of Reeds Creek at the Lake Loading Station				
Total Load Delivered to Falls Lake from the Lake Loading Station	2015	2016	2017	2018
24-hr Cumulative Precipitation (inches)				
<0.25	263,870	188,487	93,249	384,436
0.25-1	149,418	89,109	92,699	258,889
1-2	184,587	99,494	41,706	229,138
2-3	49,458	14,575	26,067	110,911
3-4		76,310	58,680	103,137
4+		145,807	185,784	365,569
Total	647,333	613,782	498,186	1,452,078
Number of 24-hour periods within Each Size Class				
<0.25	306	316	320.5	296
0.25-1	48	40	36	50
1-2	10.75	7.75	7	15
2-3	0.5	0.25	0.25	2
3-4	0	0.75	0.5	0.75
4+	0	1	1.25	1
Total	365	366	365	365
Average Load per 24-hour Period				
<0.25	863	596	291	1,299
0.25-1	3,113	2,214	2,611	5,178
1-2	17,171	12,838	5,958	15,276
2-3	98,915	58,300	104,268	49,294
3-4	N/A	101,746	117,361	137,516
4+	N/A	145,807	148,627	365,569

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.
Upgrades to the SGWASA WWTP occurred in 2015 and 2016.

Local Monitoring Studies in Forested Headwater Streams in the Falls Lake Watershed

This section helps address the following question:

- *Why are forest loading rates simulated by the UNRBA model for 2014 to 2018 higher than those measured by the Forest Service from 2008 to 2013? The Forest Service data is presented in this section. Comparison to model results is provided in the catchment-scale WARMF simulation results.*

The USDA Forest Service has monitored stream flows and nutrient and carbon concentrations in six forested, headwater streams in the Falls Lake watershed from 2008 to 2013 (Boggs et al. 2012). Hill Forest is in WARMF Catchment #14 (60 percent forest) which includes a UNRBA monitoring station on Deep Creek. Umstead Research Farm is in Catchment #19 which does not include a UNRBA monitoring station. The locations of these research stations are shown in Figure H-8.

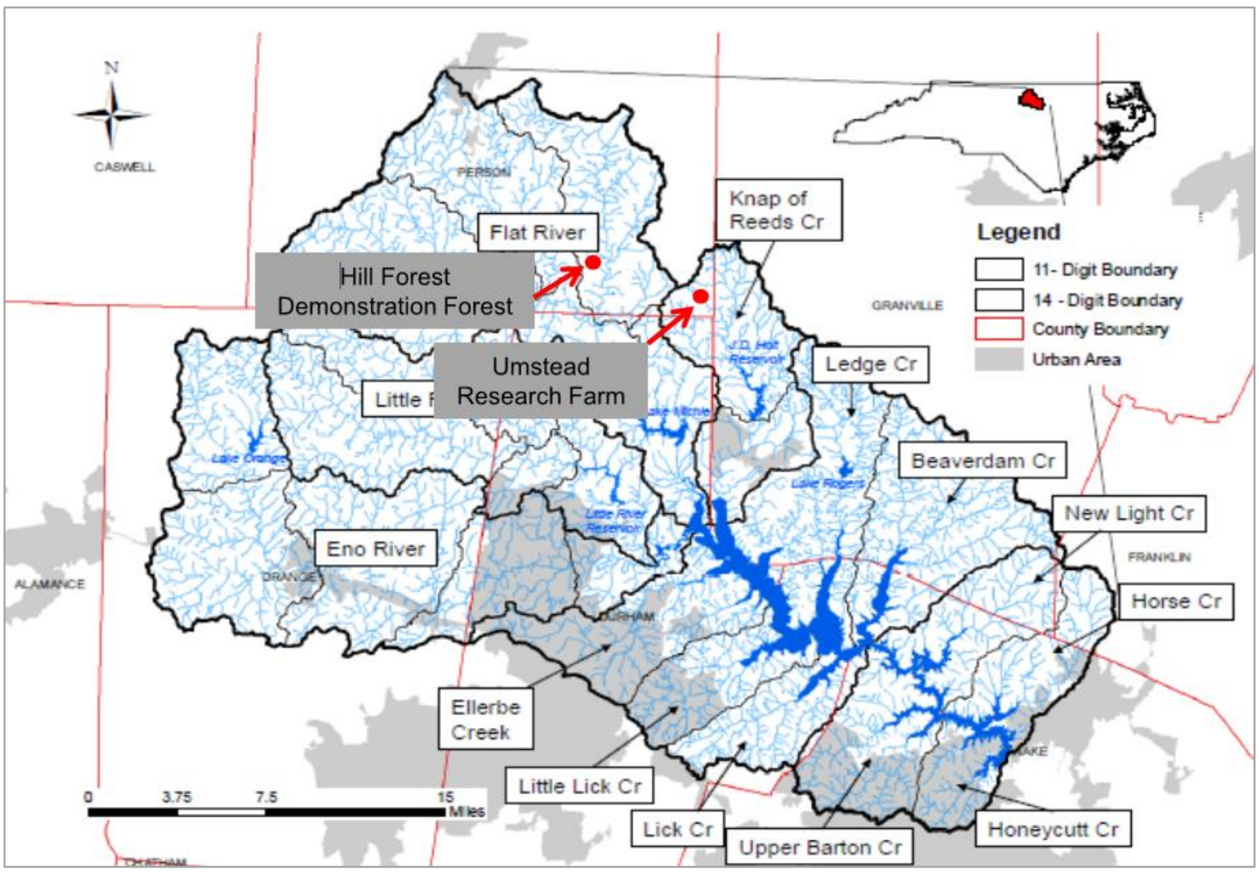


Figure H-8. Location of Forest Service Forest Research Stations (Boggs et al., 2013)

The average precipitation during these years was 42 inches per year, and the range was 37 to 51 inches per year. Note that 2008 followed a significant drought, and the recent monitoring period for the UNRBA modeling (2014 to 2018) was generally wetter than the years monitored by Boggs et al.

The average precipitation during the US Forest Service monitoring study was 42 inches per year, and the range was 37 to 51 inches per year.

Johnny Boggs (work referenced above) at the Forest Service participated in the SME review process and provided the following notes about the data collected as well as the box plots of the relevant data for comparison to the WARMF model results (Figure H-9 through Figure H-11).

- Baseflows and stormflows were monitored at small-scale, forested catchments from 2008-2013; HF2, UF2, and HFW2 are control watersheds
- HF1, UF1, and HFW1 are treatment watersheds that were clear cut at the end of 2010, so only 2008-2010 data are summarized in the box plots provided by the Forest Service
- About 10 percent of UF2 is covered by an ag field that was where nutrients were being applied prior to the study. The nutrient application contributed to higher stream nutrient concentrations in UF2 than UF1 through leaching and lateral flow explaining the higher nitrogen values.

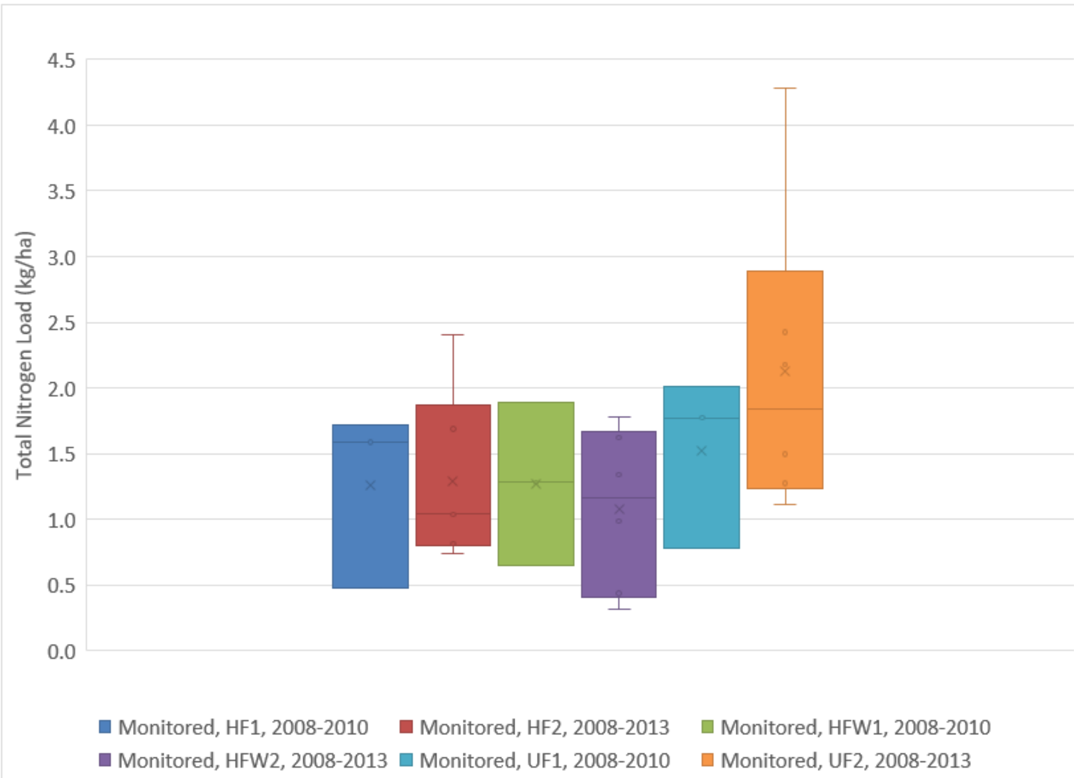


Figure H-9. Distribution of TN Loading Rates from the Forest Service

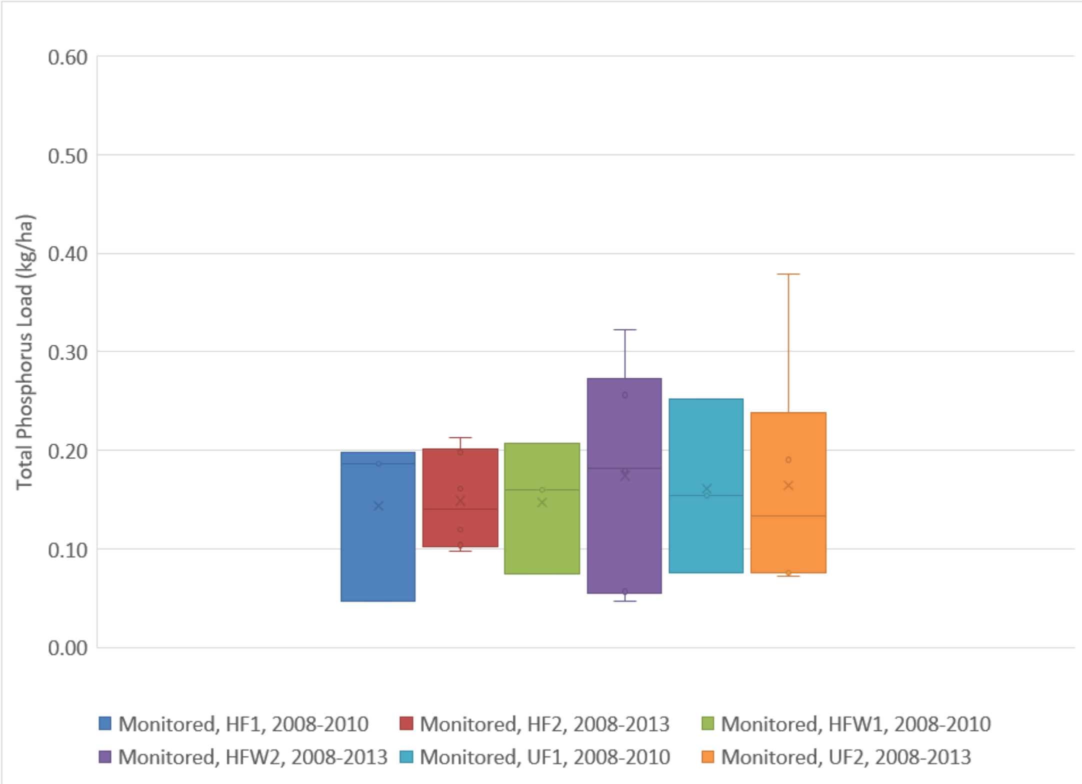


Figure H-10. Distribution of TP Loading Rates from the Forest Service

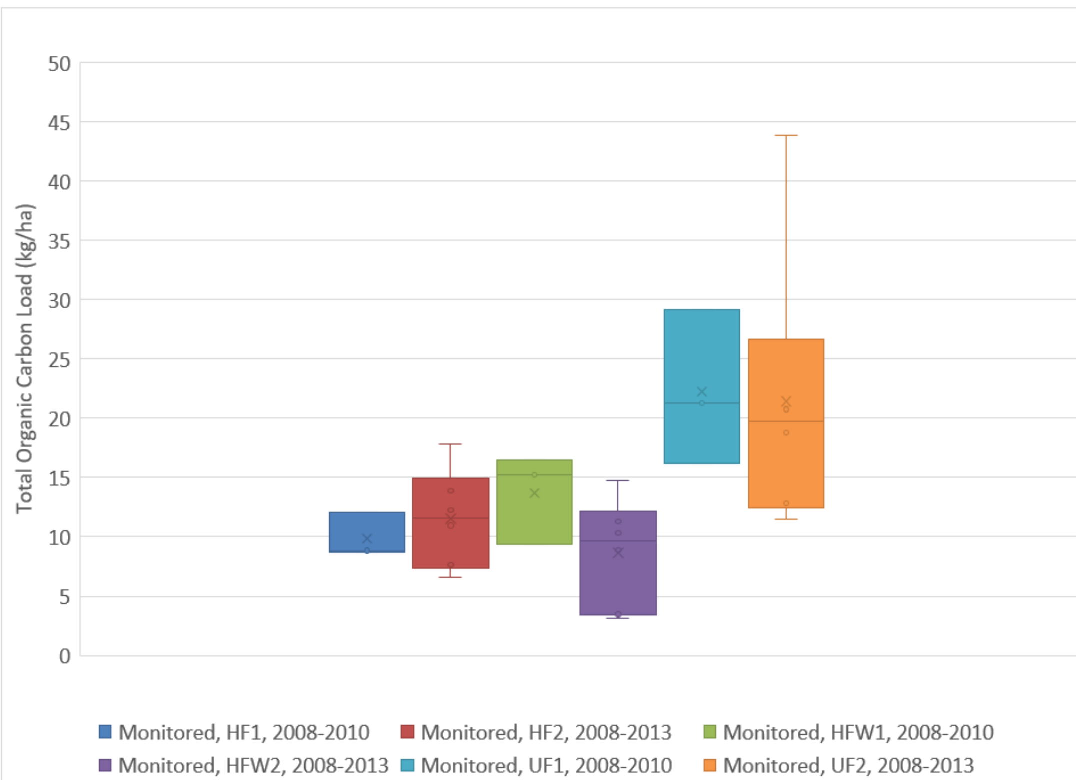


Figure H-11. Distribution of TOC Loading Rates from the Forest Service

Evaluation and Testing of Catchment-Scale Nutrient Loading Rates

This section helps address the following questions:

- *Why are forest loading rates simulated by the UNRBA model for 2014 to 2018 higher than those measured by the Forest Service from 2008 to 2013?*
- *Why aren't the WARMF simulated forest loading rates for the Falls Lake watershed much lower than rates simulated for urban areas?*
- *How do simulated urban loading rates change under different hydrologic conditions?*
- *Why are simulated loading rates from agriculture for 2014 to 2018 higher than those typically measured at edge of field?*
- *How do the loading rates for agricultural vary spatially across the modeling catchments?*
- *Does the simulated nutrient load from stream bank erosion differ when the catchment is urban versus forested?*

The NC Collaboratory has funded "third-party" reviews of the UNRBA models, and the modeling team has coordinated with these subject matter experts throughout development of this project. Drs. Charlie Humphrey, Guy Iverson, and Mike O'Driscoll suggested that in addition to evaluating average loading rates delivered to Falls Lake, some smaller scale, catchment-level results would be helpful for comparison. The modeling team initially selected four of the 264 catchments and a subwatershed for this evaluation, focusing on headwater catchments with large proportions of a specific land use type. Several additional catchments were selected to provide additional information on agricultural land uses following input from the MRSW on January 4, 2022.

For headwater catchments, the loading rates output by the model have not been subject to downstream transformations reflected in the delivered loadings to Falls Lake. Where possible, representative catchments for specific land uses that included a UNRBA monitoring station were selected so that simulated concentrations from the calibrated model could also be compared to observed data. Figure H-12 shows the monitoring stations for the watershed, and Figure H-13 shows the catchment boundaries.

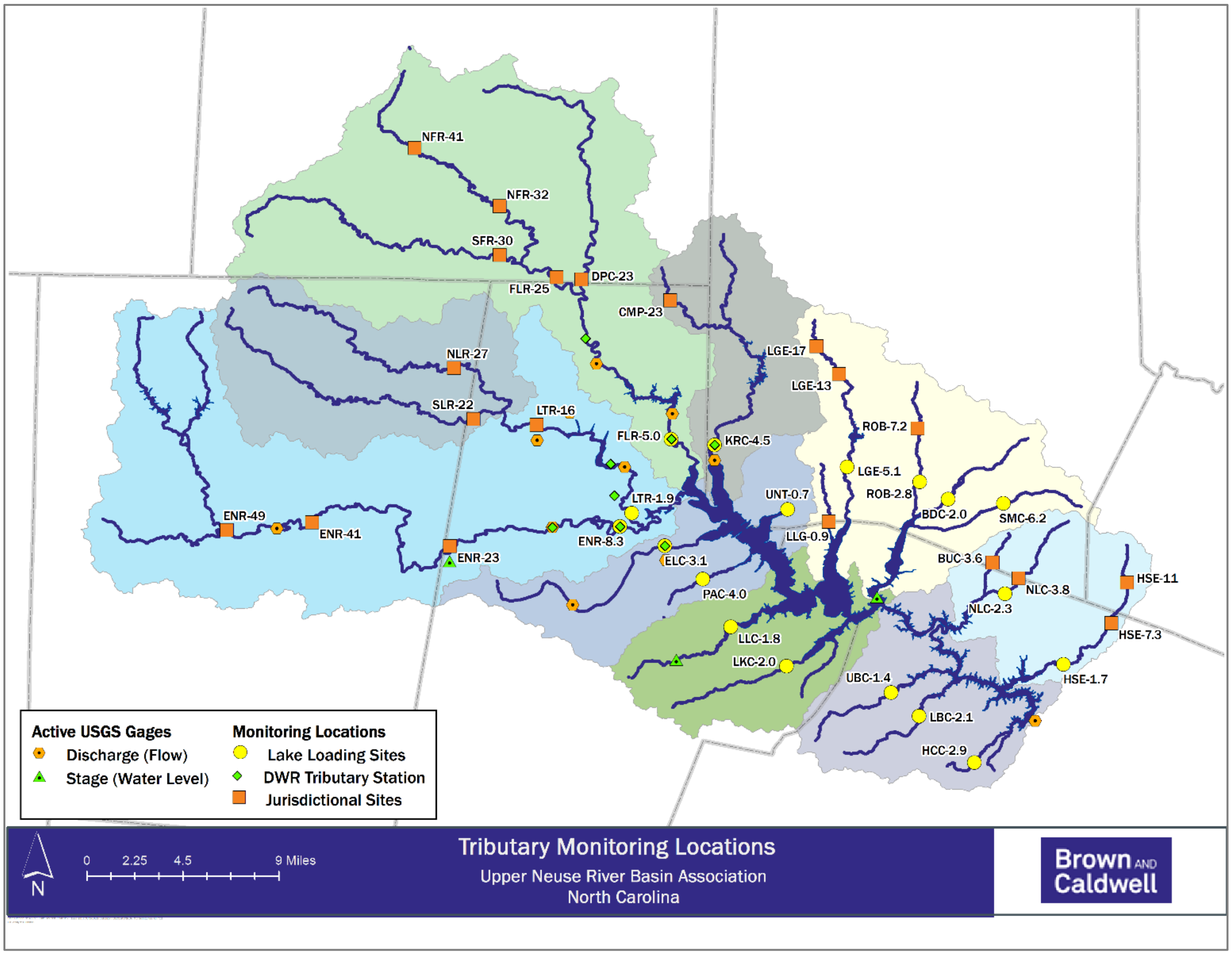


Figure H-12. Location of Monitoring Stations in the Falls Lake Watershed

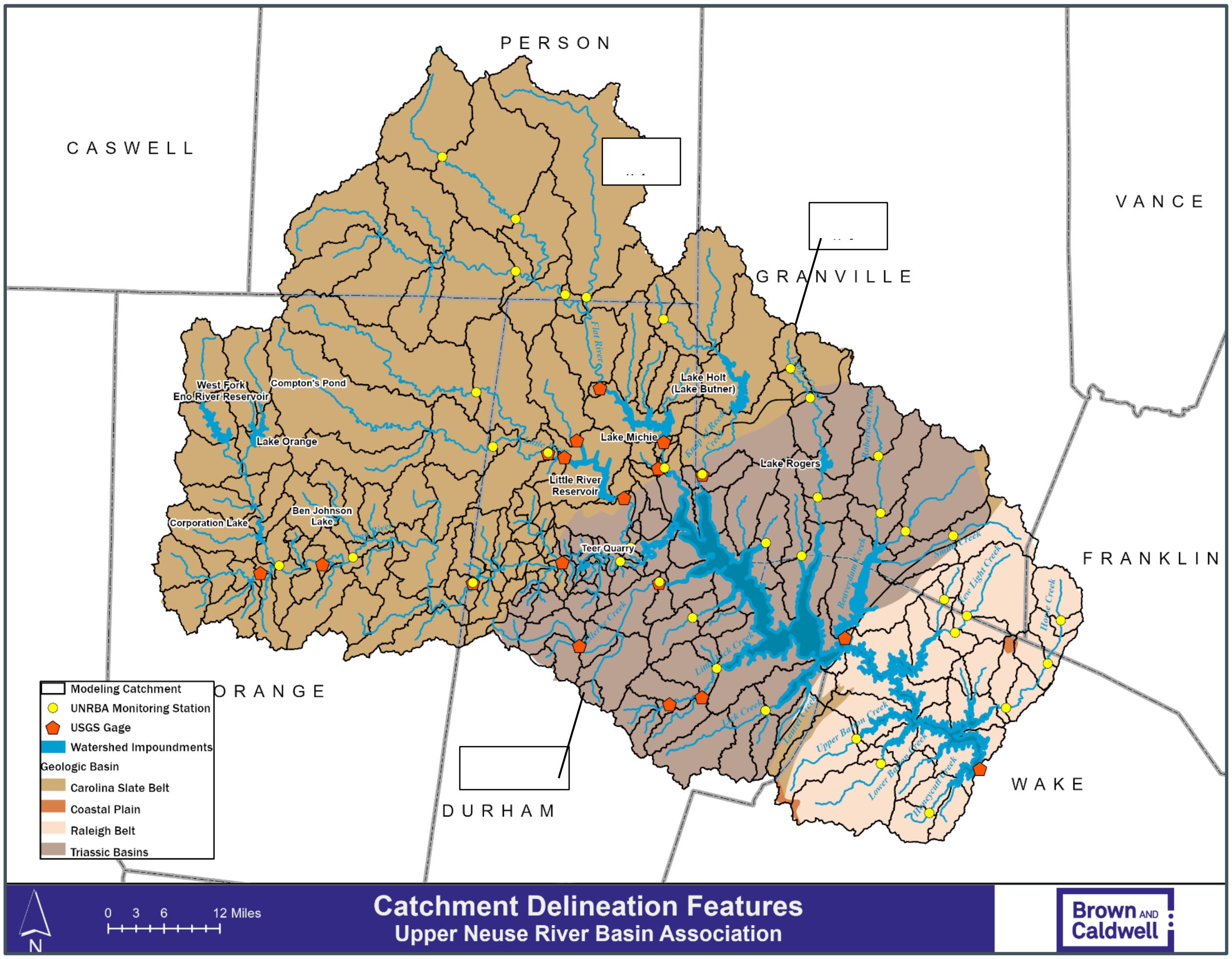


Figure H-13. Catchment Delineations for the Falls Lake WARMF Model

Catchments with High Percentages of Forest Land

Catchments #14 and #42 were selected as the representative forested catchments to compare WARMF simulated areal loading rates to those monitored by the Forest Service. Both of these catchments are approximately 60 percent forested and both have a UNRBA monitoring station at their mouth. Catchment 14 is 80 percent unmanaged as approximately 20 percent of the area is unmanaged grass or shrubland. These two catchments were evaluated with the calibrated model for varying precipitation conditions. Table H-8 summarizes the hydrologic conditions for the Forest Service monitoring period (2008 to 2013), the UNRBA study period (2014 to 2018), the representative dry year (2007), and the representative average year (2017).

Table H-8. Annual Precipitation and Mean Flow Rate at Flat River above Lake Michie for Test Conditions		
Years	Annual Precipitation at RDU (inches)	Annual Mean Flow Rate at Flat River above Lake Michie (cfs)
2007	36	68
2008-2013 (Forest Service monitoring study)	37 to 51 (avg=42)	48 to 164 (avg=98) (<50 cfs in 2011 and 2012)
2017	46	121
2014-2018 (model period)	46 to 60 (avg=54)	121 to 260 (avg=170)

Simulated forest loading rates for 2007, 2017, and the 2014 to 2018 UNRBA study period were compared for these two catchments to the loading rates provided by the Forest Service, and results are presented in Figure H-14 through Figure H-16. The delivered forest loading rates to Falls Lake for the 2014-2018 simulation are also shown on the figures with the figure marker shadowed along the bottom. The average annual precipitation for the Forest Service study was ~42 inches and it ranged from 37 to 51 inches. The WARMF-simulated catchment results do not represent transformations in downstream river segments or impoundments. The average "delivered to Falls Lake" results do include these transformations. Delivered loads of phosphorus are more affected by transformations in streams and impoundments than nitrogen because phosphorus is more likely to be bound to sediment and subject to settling.

The WARMF simulated forest loading rates for TN, TP, and TOC for 2007 and 2017 yield a similar distribution as the forest monitoring studies because similar rainfall amounts occurred (Figure H-14 through Figure H-16). The dry year, 2007, yields loading rates near the lower 25th percentile of those measured; the average year, 2017, yields loading rates near the upper 75th percentile. **For all three parameters, the 2014-2018 model has higher rates because of increased precipitation, runoff, interflow, and loading.**

The WARMF simulated forest loading rates for TN, TP, and TOC for 2007 (dry) and 2017 (average rainfall) yield a similar distribution as the forest monitoring studies because similar rainfall amounts occurred.

For these two catchments, the WARMF simulated forest total nitrogen loading rate during the relative wet UNRBA study period is approximately 2.9 kg-N/ha/yr to 3.4 kg-N/ha/yr. **These are lower than the loading rates simulated by Tetra Tech (2012) for the High Rock Lake watershed (3.9 kg/ha/yr to 4.5 kg/ha/yr for Hydrologic Group B and C soils, respectively).** The WARMF simulated total phosphorus loading rates during the study period is approximately 0.5 kg-P/ha/yr to 0.55 kg-P/ha/yr. **These are approximately half the rates simulated for High Rock Lake watershed (0.9 kg-P/ha/yr to 1.0 kg-P/ha/yr).** In response to questions from DWR about why the loading rates for forest were high relative to other modeling studies, Tetra Tech explained that

> "It is important to note that the final model is calibrated to observed data at multiple locations, including locations that are individually dominated by forest, agriculture, and urban land uses. Thus the total load estimates are consistent with the observed data. A second important point is that the model load estimates incorporate loading by groundwater pathways, which are often omitted or not fully captured in small-scale land use studies that focus on storm event loads. The average model estimates of stormwater forest loading rates for total N without ground water load are 0.9 and 2.2 lb/ac/yr for forest on B and C soils, respectively, in line with the cited storm runoff studies", and

> "Regarding overall [nonpoint source] NPS loading rates, the rates included in the calibrated model are those necessary to achieve mass balance, assuming that point source loading estimates are reasonably accurate. The partitioning of load between individual upland nonpoint source load categories is admittedly uncertain and could be refined if future intensive monitoring studies are undertaken."

Other researchers have shown that nutrient concentrations and loading rates from forested areas tend to increase when runoff and flow increase. Oyarzún and Hervé-Fernandez (2015) state "nutrient exportation [from forested catchments in Chile] is related to hydrology, since water transports chemical compounds and particles. The relations of TDN [total dissolved nitrogen] and TDP [total dissolved phosphorus] with catchment discharge were positive for all nutrients except DIN [dissolved inorganic nitrogen], which showed a negative relation with discharge." The decrease in DIN and increase in TDN indicates that the organic nitrogen load is increasing, similar to findings from Paerl et al. 2018, 2019, 2020. Klimaszyk et al. (2014) note that "The greatest changes of the studied chemical parameters [in forested catchments in Poland] were noted in runoff occurring during heavy rainfall and snow melting." Several researchers note that nitrate concentrations following hurricanes can remain elevated for 2 to 3 years. Schaefer et al. (2000) report that "Nitrate-N fluxes [from forested watersheds in Puerto Rico] ranged from 1.0 to 2.3 kg/ha/yr across watersheds for all except the first post-hurricane year, during which they increased to 2.6 to 8.4 kg/ha/yr." Yeakley et al. (2003) report that nitrate concentrations in groundwater at the Coweeta research forest (NC mountains) increased four times in groundwater and two times in stream water following a hurricane.

Bol et al. (2016) report similar findings for phosphorus (P) in their compilation and assessment of forest ecosystem studies:

- "Most P found in percolates and pore waters belongs to the so-called dissolved organic P (DOP) fractions."
- "Losses itself are controlled by runoff and interflow, with the preferential flow and hillslope peak flows being driven by soil types, catchment topography, and climate conditions."
- "There are only a few field studies quantifying the fluxes of different P forms in forest soils, but they all indicated DOP to dominate in soil waters."
- "The large contribution of organic forms to nutrient leaching from forest soils has also been recognized before for N. The importance of organic forms to drive leaching may be even greater for P than for N. Inorganic P forms may over time bind to or become incorporated into secondary minerals. Thus, despite ongoing mineral weathering and mineralization of organic matter, the concentrations in soil solution of inorganic P forms are therefore usually small."
- "The general accumulation of (predominantly organically bound) P in topsoils and surface layers with progressing pedogenesis promotes P recycling, but it may also increase the risk of P losses with interflow or runoff."
- "Water and P may bypass large parts of the soil matrix, resulting in high P losses during heavy rainfall events when preferential-flow pathways are connected."
- "High P loads in stream water, particularly at high flow, suggest that rapid flow processes, either in the soil by macropore flow or during flood events in streams and rivers, may lead to significant P losses."

Nutrient loading from forested areas is positively correlated with stream flow. Forested areas have the potential to release much higher nutrient loads following large storm events (Oyarzún and Hervé-Fernandez 2015; Paerl et al. 2018, 2019, 2020; Klimaszyk et al. 2014, Bol et al. 2016). The

UNRBA study period had annual rainfall amounts up to 60 inches with three of the four study years exceeding 51 inches (Table H-1). In contrast, the annual rainfall collected during the Forest Service study period ranged from 37 to 51 inches. Forests can infiltrate most of the rainfall in a dry to average year depending on the soil type and infiltration rates. Very wet years or very large storms overcome the storage capacity of the forests, and nutrients are exported. These studies report trends of increased nutrient loading from forests in response to large rain events. The UNRBA watershed modeling results are consistent with these studies.

The average delivered load from forested areas across the watershed is lower than the catchment-scale results for the same period (2014 to 2018) because delivered loads account for processes in streams and impoundments that reduce loading prior to delivery to the lake.

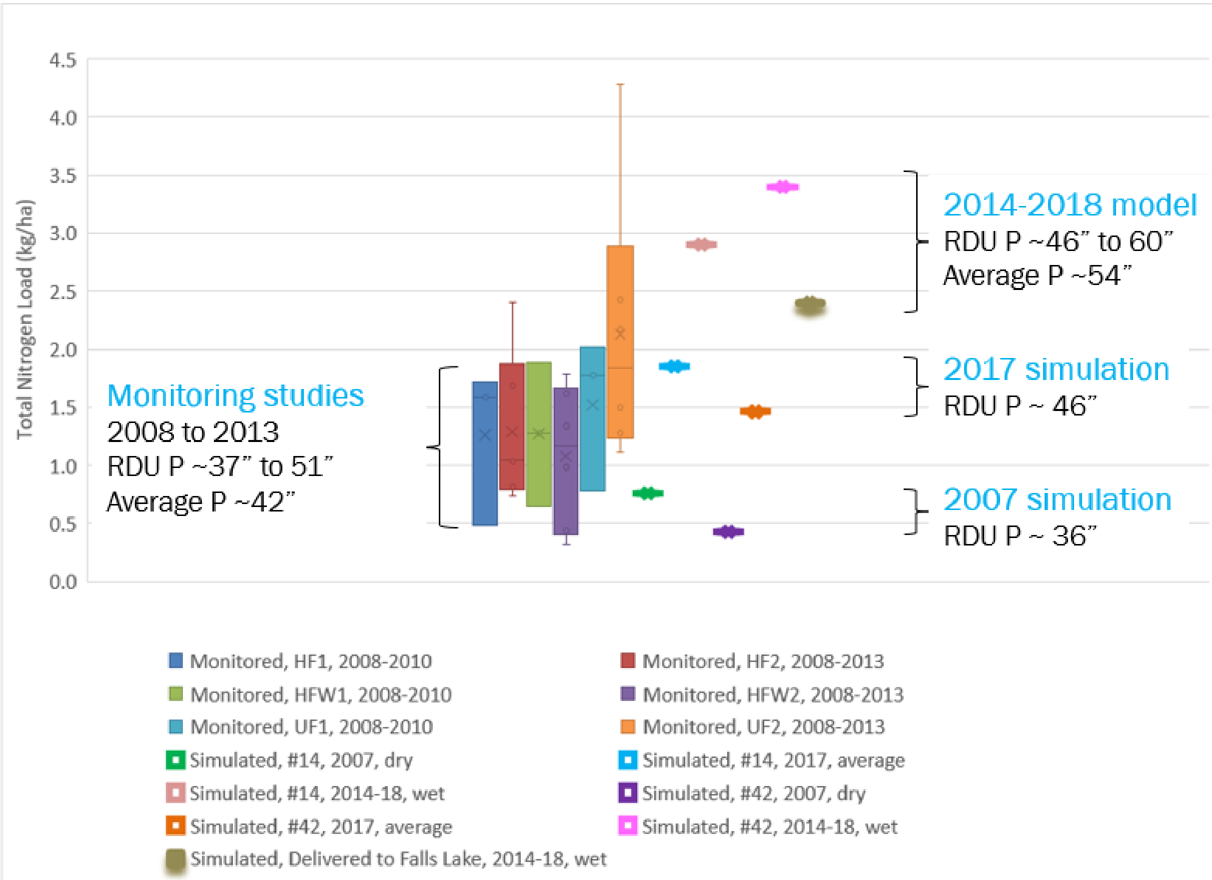


Figure H-14. Distribution of Forest TN Loading Rates from the Forest Service Compared to Catchment 14, Catchment 42, and the Average Delivered Load to Falls Lake for Three Precipitation Conditions

The catchment results do not represent transformations in downstream river segments or impoundments.
The "delivered to Falls Lake" result does include these transformations.
P = annual precipitation; " = inches

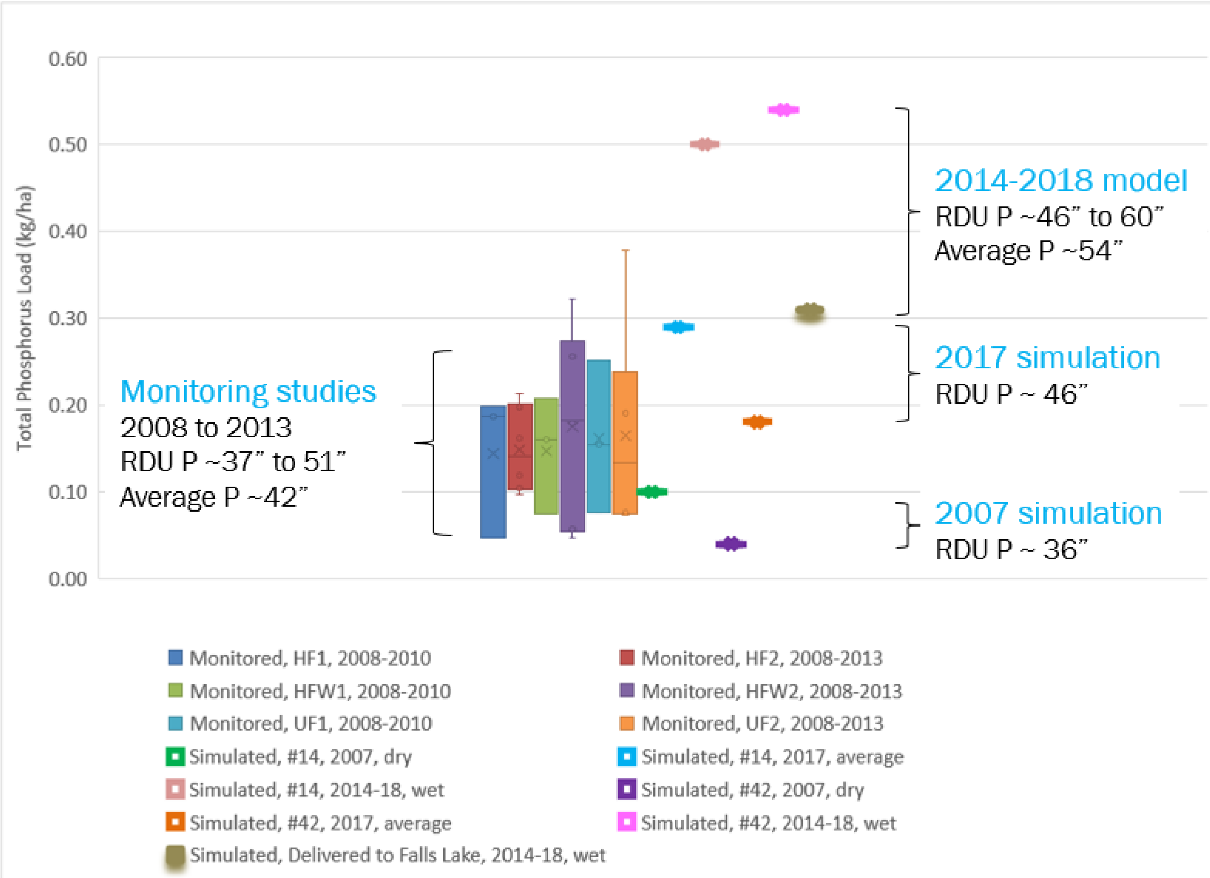


Figure H-15. Distribution of Forest TP Loading Rates from the Forest Service Compared to Catchment 14, Catchment 42, and the Average Delivered Load to Falls Lake for Three Precipitation Conditions (y-axis extended manually to show higher loading rates)

The catchment results do not represent transformations in downstream river segments or impoundments. The "delivered to Falls Lake" result does include these transformations.

P = annual precipitation; " = inches

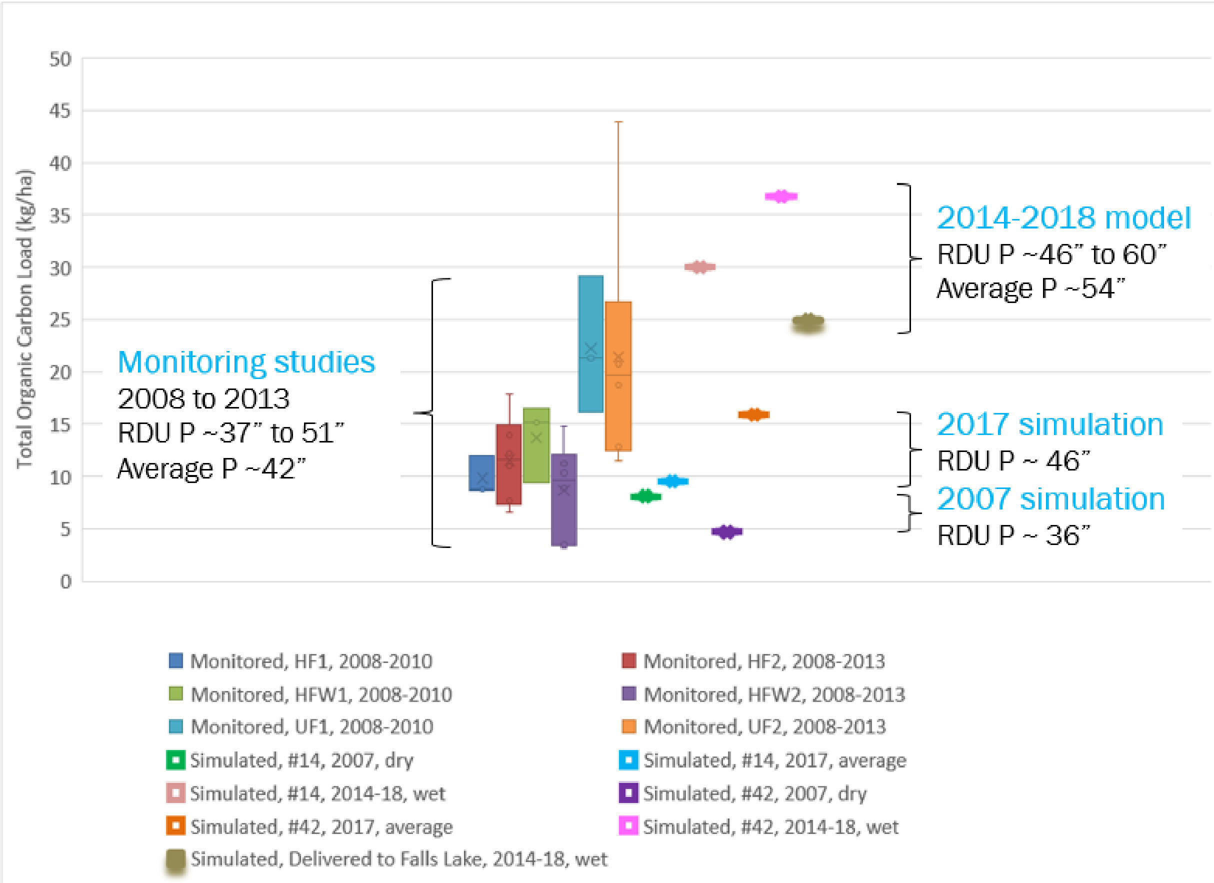


Figure H-16. Distribution of Forest TOC Loading Rates from the Forest Service Compared to Catchment 14, Catchment 42, and the Average Delivered Load to Falls Lake for Three Precipitation Conditions

The catchment results do not represent transformations in downstream river segments or impoundments.
The "delivered to Falls Lake" result does include these transformations.
P = annual precipitation; " = inches

Figure H-17 shows the simulated versus observed concentrations for TN, TOC, and TP at the monitoring station near the outlet of Catchment 14 (DPC-23). This station was not a calibration station, so the model was not adjusted during calibration to match the water quality observations at this location. Only tributaries with a USGS stream gage were used for model calibration. However, the simulated concentrations match the magnitude and trend for these parameters in this mostly undisturbed watershed. Given that this catchment is 62 percent forested and 18 percent unmanaged grassland, it would be difficult to match the observations at DPC-23 if the simulated loading rates for unmanaged land uses were not reasonable.

Given that this catchment is 62 percent forested and 18 percent unmanaged grassland, it would be difficult to match the observations at water quality monitoring station (DPC-23) if the simulated loading rates for unmanaged land uses were not reasonable.

Figure H-18 shows the simulated daily loads at this station compared to daily load estimates on days the UNRBA collected water quality samples. These load estimates have a lot of uncertainty as flows are not measured at this location but rather estimated based on a basin proration approach (i.e., scaling flows observed elsewhere on that day by a ratio of drainage areas.) The daily loads generally match the expected ranges and patterns at this location based on the estimates. Note the figure shows log scale in the top panel and arithmetic scale in the lower panel to fully display the range of daily loads.

Similar figures are presented for Catchment 42 in the next section.

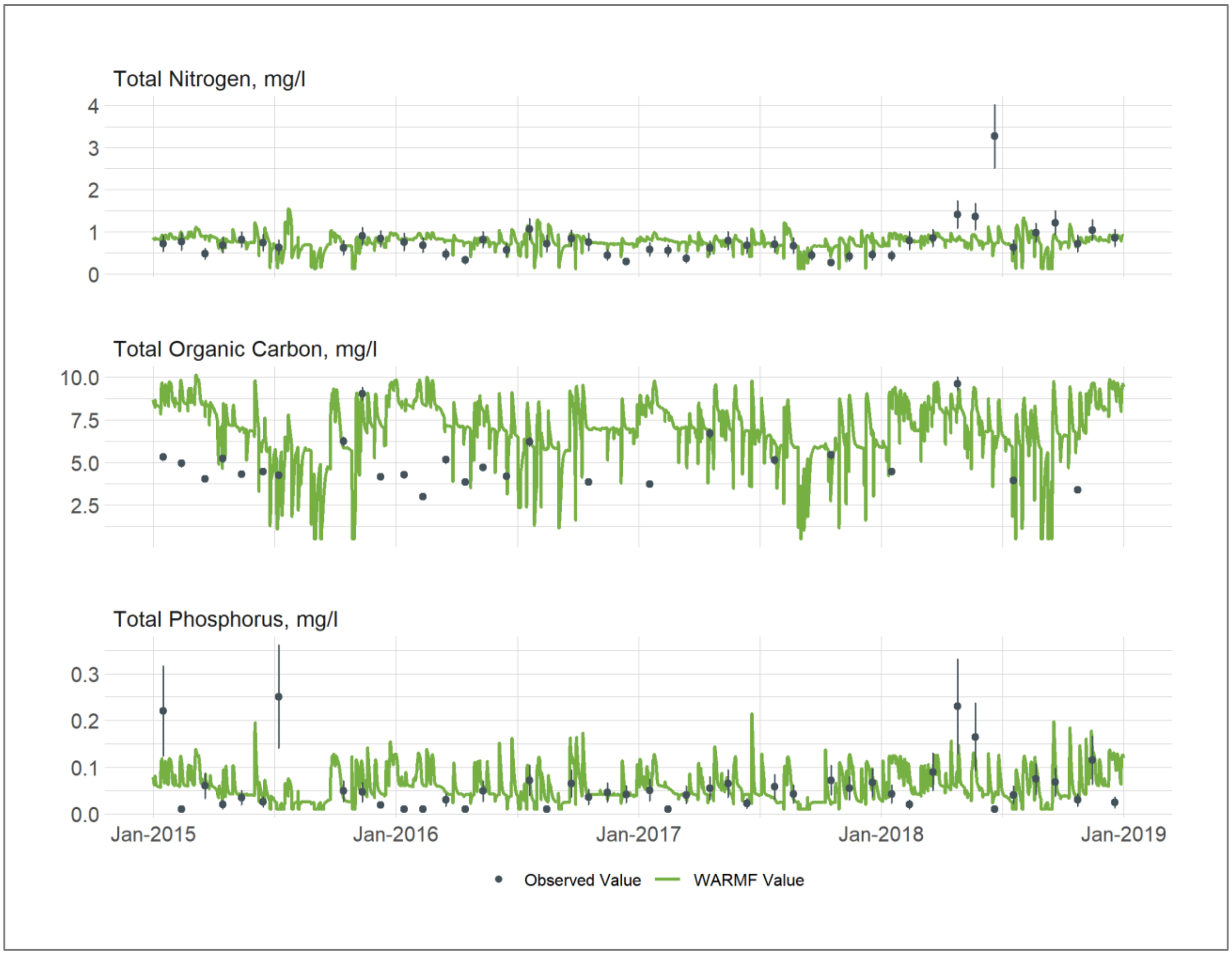
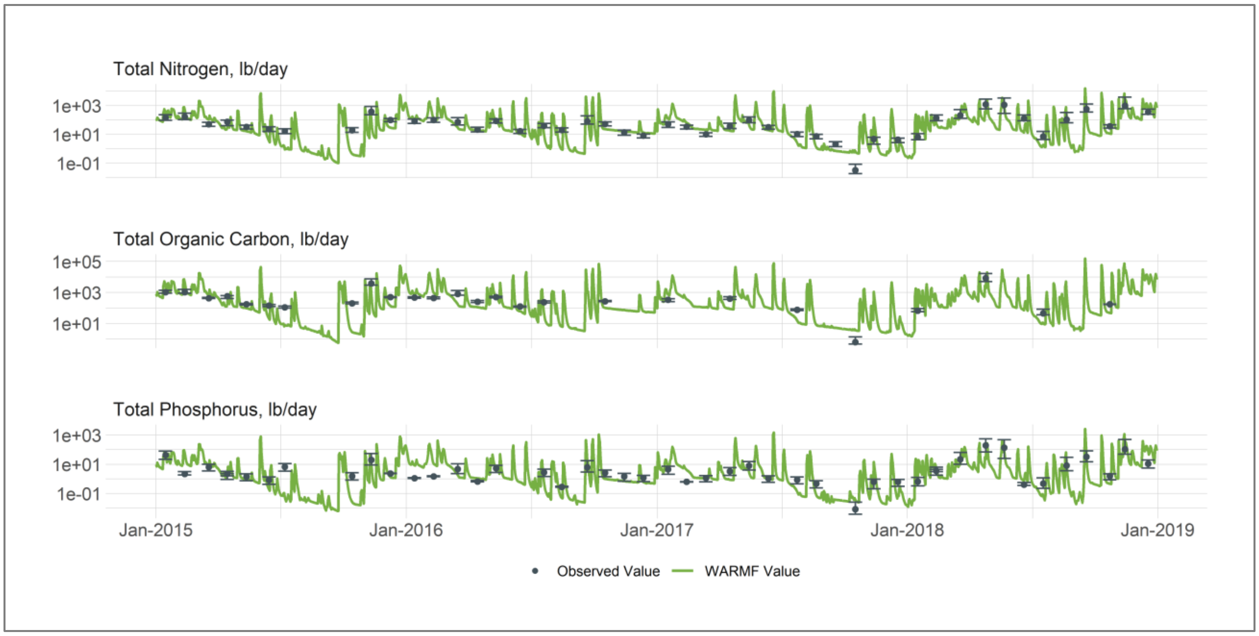
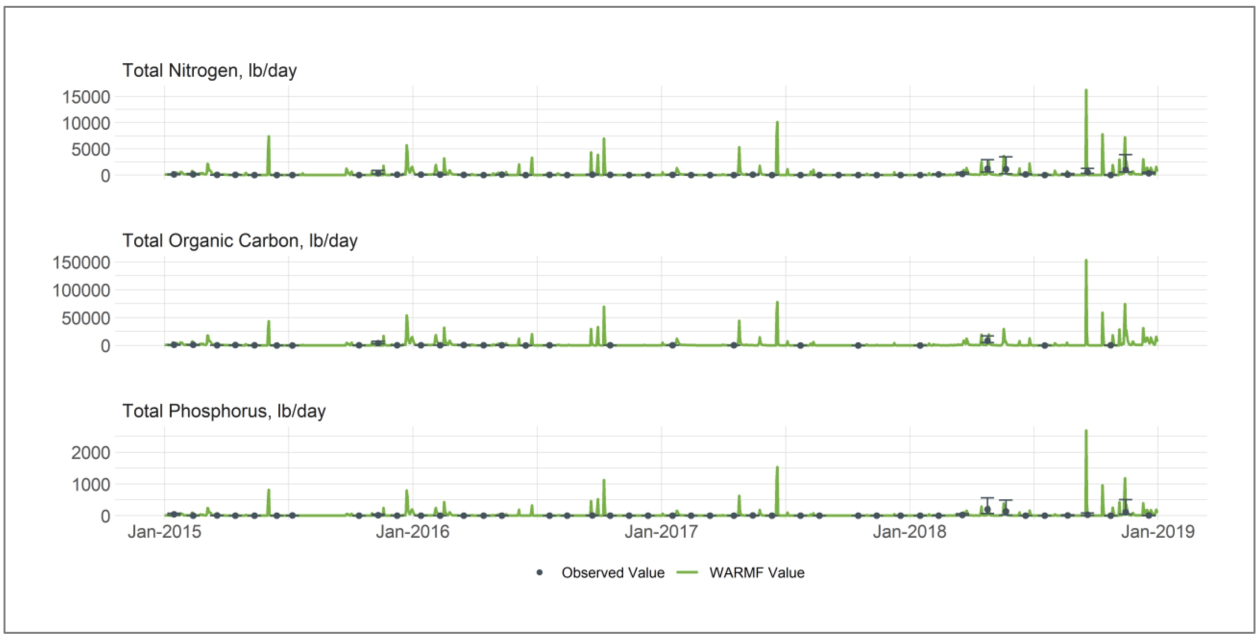


Figure H-17. Comparison of WARMF Simulated Total Nitrogen (top), Total Organic Carbon (middle), and Total Phosphorus (bottom) Concentrations to Observations Collected at DPC-23 (vertical bars represent the 95th percentile confidence interval for the observation)



A) Log Scale



B) Arithmetic Scale

Figure H-18. Comparison of WARMF Simulated Daily Loads (log scale A, arithmetic scale B) for Total Nitrogen (top), Total Organic Carbon (middle), and Total Phosphorus (bottom) to Estimates based on Observations Collected at DPC-23 and Estimated Stream flows (vertical bars represent the load when the 95th percentile confidence interval for the observation)

Catchments with High Percentages of Agricultural Land

The WARMF model conserves mass. Loading inputs and exports from each land use are accounted for and tracked through time and space (including soil impacts) by the model. Atmospheric deposition occurs on all land surfaces using the same data and assumptions and accounts for approximately 37 percent of the total nitrogen applied to the land surface each year. The amounts and schedule for nutrient application to agricultural areas was provided by crop type and county by staff at the NC Department of Agriculture and Consumer Services (NCDA&CS). Nutrient application rates include fertilizer, manure, and biosolids if applicable. The rates of nutrients deposited from the atmosphere are factored into agricultural nutrient management plans to estimate the amount of additional nutrients that are needed to support plant growth. The goal is to provide the right amount of nutrients to produce yield for harvest. Fertilizer is expensive, and that cost is factored into decision making as well. According to the NCDA&CS, the agricultural community has conducted significant work to reduce nutrient application to an amount equivalent to that which is required by each crop for optimum growth, thus limiting the availability of excess nutrients for watershed export.

The NCDA&CS also provided information on growing season start dates and harvest dates for input to the model. Harvested material removes nutrients from the system.

The original catchment identified for this analysis is Catchment 42. This catchment is approximately 1,140 acres and drains to UNRBA monitoring station LGE-17. It was selected because it has one of the highest proportions of agricultural land use in the watershed at 24 percent. Of the 272 acres of agricultural land in this catchment, 72 percent is pasture, 9 percent hay, 7 percent full season soybeans, and 4 percent each is flue-cured tobacco, double-cropped soybean, and no-till grain corn; conventional grain corn is approximately 1 percent. Forests comprise approximately 62 percent of this catchment, and developed open space or non-DOT road rights of way are 7 percent. Several other land uses comprise the remaining 7 percent of the watershed area.

Tables H-9 and H-10 provide the simulated loading rates for this catchment for each agricultural land use. However, most of the agricultural area in this catchment is pasture (196 acres which is 72 percent of the agricultural production acres and 17 percent of the total catchment area). Similarly, most of the agricultural land in the Falls Lake watershed is pasture (26.600 acres which is 5 percent of the total watershed area). The simulated loading rates from pasture in this catchment are higher than any other land use in the catchment (or the watershed) and are more than four times the amount of total nitrogen referenced above for forests in Catchment 42. Simulated per acre phosphorus loading rates for pasture are the sixth highest of the land uses simulated. Three crops (conventional grain corn, flue-cured tobacco, and wheat), low intensity existing development, barren land, and woody wetlands have higher rates than pasture. Deanna Osmond at NC State University College of Agriculture and Life Sciences Department of Crop and Soil Sciences contributed as a subject matter expert for the watershed model. She mentioned several times that pasture in the watershed is under fertilized for phosphorus; this is why the relative loading rates for phosphorus is only 1.3 times higher compared to the nitrogen loading rate, which is 4.4 times higher.

Hay is the next largest type of agricultural land in this catchment (24.5 acres; 2 percent of the total catchment area) and the third highest in the watershed (~4,500 acres which is 0.9 percent of the total watershed area). Two-thirds of the hay production acres in the watershed (including those in this catchment) are in counties that reduced their per acre nitrogen application rates by more than one-half since the baseline period (Table 3-11 of the main report).

The third largest acreage of crop grown in this catchment (1.6 percent of the total catchment area) and the second largest type grown in the watershed is full-season soybeans (1.2 percent of the total watershed area), which do not require nitrogen application. Like unmanaged areas, soybeans receive their nitrogen input from the atmosphere through deposition. Legumes like soybeans can also fix nitrogen from the atmosphere. Due to plant uptake of nitrogen, crop harvesting, and removal from the system, the per acre nitrogen loading rates delivered from soybean acres are similar to forested areas in the UNRBA study period.

The UNRBA model incorporates extensive information from the NCDA&CS, NC State University College of Agriculture and Life Sciences Department of Crop and Soil Sciences, and the national atmospheric deposition monitoring programs to input the mass of nutrients applied to specific plants each month along with harvest/removal times. Soil properties were obtained from US Department of Agriculture Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) and the USDA National Cooperative Soil Survey (NCSS) data collected in the counties in the Falls Lake Watershed. Soils in the watershed contain considerable amounts of aluminum and iron that increase phosphorus adsorption and limit its movement in dissolved form.

The simulated TN and TP loading rates for agriculture (not accounting for downstream attenuation) vary by approximately an order of magnitude based on the amount of precipitation simulated.

Table H-9 and Table H-10 provide the areal loading rates for TN and TP for the agricultural land uses in Catchment 42. The TN and TP loading rates vary by approximately an order of magnitude based on the amount of precipitation simulated depending on the crop. These catchment-scale loading rates do not account for transformations that occur in stream segments and impoundments between the catchment and Falls Lake.

Table H-9. TN Loading Rates for Agricultural Land Catchment 42 (No Downstream Attenuation)

Land Use	Acres (percent of agricultural area)	TN kg/ha/yr 2007	TN kg/ha/yr 2017	TN kg/ha/yr 2014-2018
Fescue (Pasture)	194.6 (71.5)	0.64	3.84	15
Fescue (Hay)	23.4 (8.6)	0.4	1.68	3.31
Full Season Soybeans	18.3 (6.7)	0.43	1.55	3.46
Flue-Cured Tobacco	12.1 (4.4)	1.43	2.89	6.44
Double-cropped Soybeans	10.5 (3.8)	0.42	1.54	3.45
No-Till Grain Corn	9.8 (3.6)	0.4	1.91	3.48
Conventional Grain Corn	2.5 (0.9)	0.24	1.64	3.35
Wheat	0.9 (0.3)	0.1	0.99	4.05

Table H-10. TP Loading Rates for Agricultural Land Catchment 42 (No Downstream Attenuation)

Land Use	Acres (percent of agricultural area)	TP kg/ha/yr 2007	TP kg/ha/yr 2017	TP kg/ha/yr 2014-2018
Fescue (Pasture)	194.6 (71.5)	0.04	0.29	0.72
Fescue (Hay)	23.4 (8.6)	0.04	0.25	0.59
Full Season Soybeans	18.3 (6.7)	0.04	0.23	0.61

Table H-10. TP Loading Rates for Agricultural Land Catchment 42 (No Downstream Attenuation)				
Land Use	**Acres (percent of agricultural area)**	TP kg/ha/yr 2007	TP kg/ha/yr 2017	TP kg/ha/yr 2014-2018
Flue-Cured Tobacco	12.1 (4.4)	0.04	0.29	0.95
Double-cropped Soybeans	10.5 (3.8)	0.04	0.23	0.6
No-Till Grain Corn	9.8 (3.6)	0.04	0.24	0.75
Conventional Grain Corn	2.5 (0.9)	0.03	0.25	0.79
Wheat	0.9 (0.3)	0.01	0.15	0.5

Figure H-19 shows the simulated versus observed concentrations for TN, TOC, and TP at LGE-17. This station was not a calibration station and so a detailed calibration was not performed. However, the simulated concentrations match the magnitude and trend for these parameters. Given that this catchment is 62 percent forested and 24 percent agriculture, it would be difficult to match the observations if the loading rates for these land uses were not reasonable. This is a small catchment at just over 1,000 acres and simulated water quality concentrations are highly variable due to simulated runoff concentrations diluting ambient stream concentrations.

Figure H-20 shows the simulated daily loads at this station compared to daily load estimates on days the UNRBA collected water quality samples. These load estimates have a lot of uncertainty as flows are not measured on this tributary but rather estimated based on a basin proration approach (i.e., scaling flows observed elsewhere on that day by a ratio of drainage areas.) The daily loads generally match the expected ranges and patterns at this location based on the estimates. Note the figure shows log scale (top) and arithmetic scale (bottom) to display the range of daily loads.

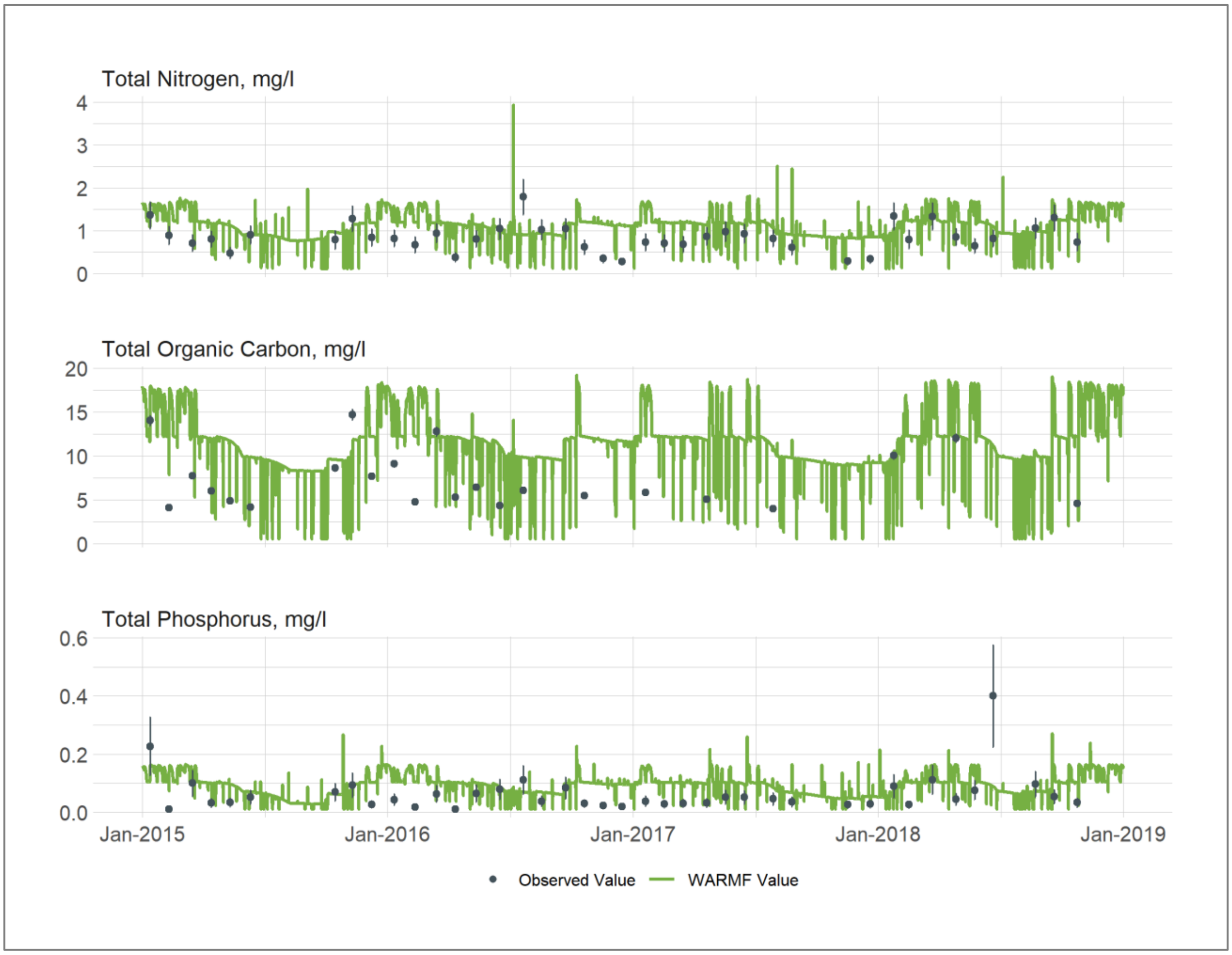
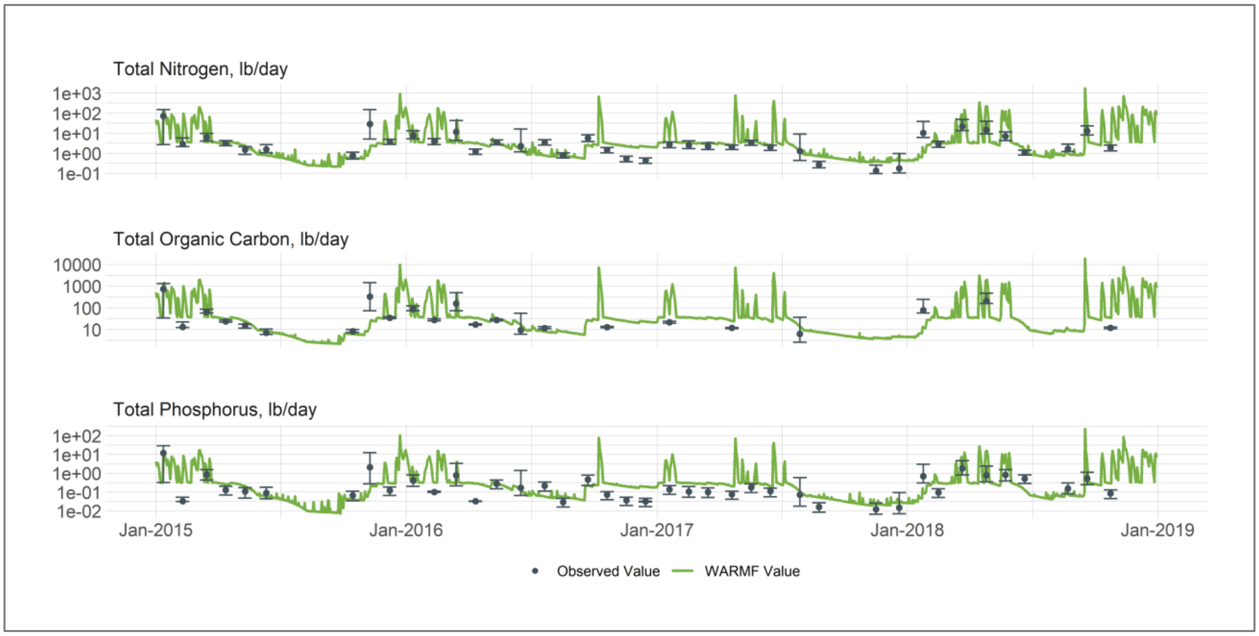
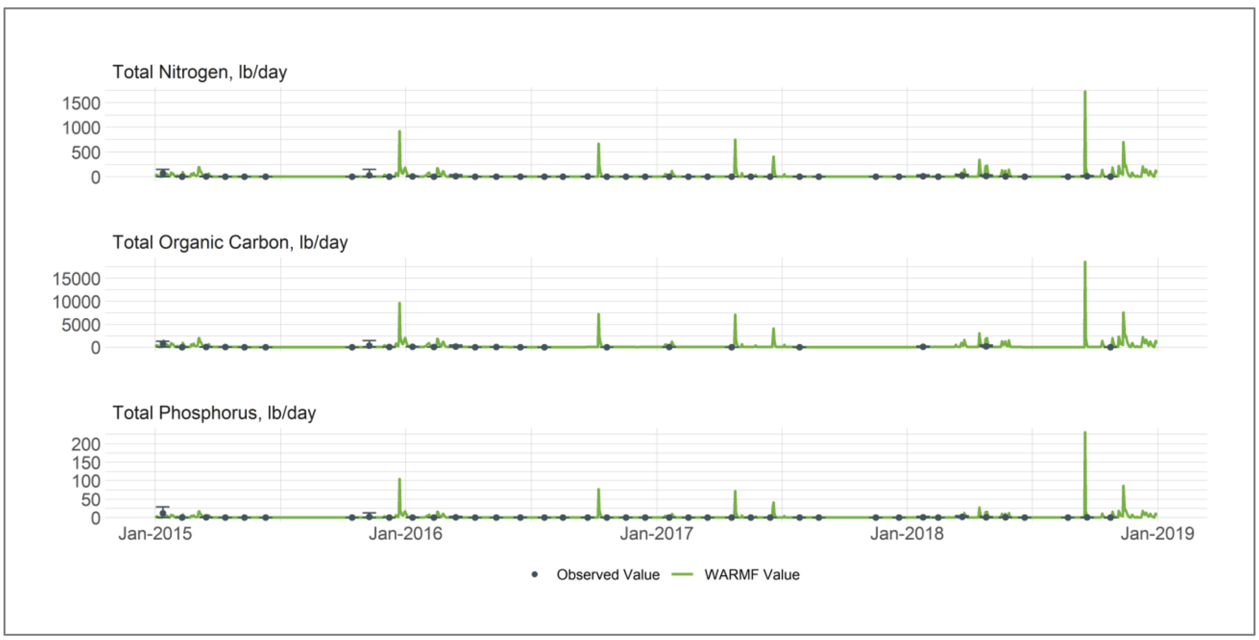


Figure H-19. Comparison of WARMF Simulated Total Nitrogen (top), Total Organic Carbon (middle), and Total Phosphorus (bottom) Concentrations to Observations Collected at LGE-17 (vertical bars represent the 95th percentile confidence interval for the observation)



A) Log Scale



B) Arithmetic Scale

Figure H-20. Comparison of WARMF Simulated Daily Loads (log scale A, arithmetic scale B) of Total Nitrogen (top), Total Organic Carbon (middle), and Total Phosphorus (bottom) to Estimates based on Observations Collected at LGE-17 and Estimated Stream flows (vertical bars represent the load when the 95th percentile confidence interval for the observation)

Several additional catchments were selected to show a range of simulated catchment-scale loading rates (before instream or impoundment processing) for different crop types using the calibrated model developed for 2014 to 2018. Acreages for each agricultural land use are provided in Table

H-11 along with the County the catchment is located. Catchment-scale nutrient loading rates are shown in Table H-12. The average delivered loading rate from the entire watershed to Falls Lake by crop type is also provided in Table H-12. Compared to the average of the catchment-scale loading rates, the delivered rates are lower because of processing that occurs in the streams and impoundments. There are some catchments for a few crop types where the catchment-scale rate is less than the delivered rate. These catchments have very small areas of those crops and do not significantly affect the loading to the lake.

Table H-11. Acreages of Agricultural Land Use in Representative Agricultural Catchments for the UNRBA Study Period (2014 to 2018)

County	Orange	Person	Granville	Granville	Granville	Person	Granville	Person
Land Use	C4	C14	C42	C19	C62	C81	C96	C203
Conventional Grain Corn	6.2	0	2.5	8.5	6.8	0	14.1	0
Double-cropped Soybeans	102	406	10.5	77.0	29.2	231	60.5	342
Fescue (Pasture)	1,526	1,086	195	787	538	617	1,117	916
Fescue (Hay)	365	113	23.4	93.4	64.6	64.4	134	95.5
Flue-Cured Tobacco	72.0	339	12.1	75.9	33.5	192	69.5	285
Full Season Soybeans	219	506	18.3	114	50.5	288	105	427
No-Till Grain Corn	199	154	9.8	49.9	27.2	87.7	56.3	130
Wheat	33.4	27.0	0.9	6.4	2.4	15.3	5.0	22.7

C: Catchment

Table H-12. Comparison of Catchment-Scale (Before Instream/Impoundment Processing) Nutrient Loading Rates to Average Delivered Loading Rate to Falls Lake (After Instream/Impoundment Processing) for Eight Example Catchments

Land Use	C4	C14	C42	C19	C62	C81	C96	C203	Average of these 8 example catchments	Average delivered to lake
Total Nitrogen (kg-N/ha/yr)										
Conventional Grain Corn	3.3	NA	3.4	3.0	6.0	NA	5.8	NA	4.3	4.0
Double-cropped Soybeans	2.8	3.0	3.5	2.9	6.0	2.9	4.6	2.9	3.6	2.2
Fescue (Pasture)	11.6	15.3	15.0	14.8	28.0	14.5	15.2	15.5	16.2	10.2
Fescue (Hay)	3.4	3.6	3.3	3.4	5.8	3.1	5.3	3.4	3.9	2.8
Flue-Cured Tobacco	11.6	5.9	6.4	16.5	9.0	6.8	13.8	6.6	9.6	6.8
Full Season Soybeans	2.9	3.0	3.5	2.9	6.0	2.9	4.6	3.0	3.6	2.4
No-Till Grain Corn	3.1	3.9	3.5	3.0	6.1	3.1	5.7	3.2	3.9	2.8
Wheat	4.7	4.7	4.1	4.8	8.2	4.5	6.7	4.8	5.3	3.8
Total Phosphorus (kg-P/ha/yr)										
Conventional Grain Corn	0.69	NA	0.79	1.08	2.02	NA	1.61	NA	1.24	0.79
Double-cropped Soybeans	0.46	0.65	0.60	0.81	1.44	0.62	1.33	0.72	0.83	0.38
Fescue (Pasture)	0.57	0.75	0.72	1.01	1.66	0.70	1.69	0.83	0.99	0.46
Fescue (Hay)	0.48	0.68	0.59	0.76	1.24	0.63	1.25	0.72	0.79	0.35
Flue-Cured Tobacco	0.83	1.09	0.95	1.26	2.42	1.02	1.78	1.20	1.32	0.70
Full Season Soybeans	0.49	0.66	0.61	0.83	1.44	0.64	1.37	0.73	0.85	0.42
No-Till Grain Corn	0.56	0.74	0.75	0.91	1.62	0.71	1.23	0.80	0.91	0.43
Wheat	0.44	0.72	0.50	0.74	1.05	0.67	1.04	0.74	0.74	0.48

C: Catchment, NA: no land use area for this crop in this catchment
The average is not area weighted by crop; the average is expected to be higher than the average delivered load because the catchment-scale results do not include processing that occurs in streams or impoundments.

Urbanized Subwatershed and Simulation of Streambank Erosion

The Ellerbe Creek subwatershed was used to test the model in a developed area under different hydrologic conditions and with and without best management practices (BMPs), stormwater control measures (SCMs), and topographic routing of runoff from impervious areas onto pervious areas (e.g., a driveway running off onto a lawn).

In the Falls Lake watershed, the local governments have been implementing BMPs and SCMs to address nutrient loading from development in the watershed in advance of the Falls Lake Nutrient Management Strategy passed in 2011. Some communities like the City of Durham started implementation well before 2011 in anticipation of the Rules.

Figure H-21 shows the practices installed by the City of Durham through December 2015, within the UNRBA study period (2014 to 2018). As a result of the different regulatory pressures in each basin, nearly five times the number of projects have been implemented in the Falls Lake Basin than the Jordan Lake Basin. Of the 348 practices installed in the Falls Lake Basin, most are cisterns or rain gardens, and several are pocket wetlands, constructed wetlands, or bioretention cells. Each of these practices detain water on site and delay hydrologic response; they also provide water quality treatment. In addition, several stream restoration projects had been implemented by December 2015, reducing sediment and nutrient loading from this source. Hopkins et al. (2022) report that decentralized stormwater management practices can have a positive impact on hydrologic response, especially when storms are less than the design size for the practices.

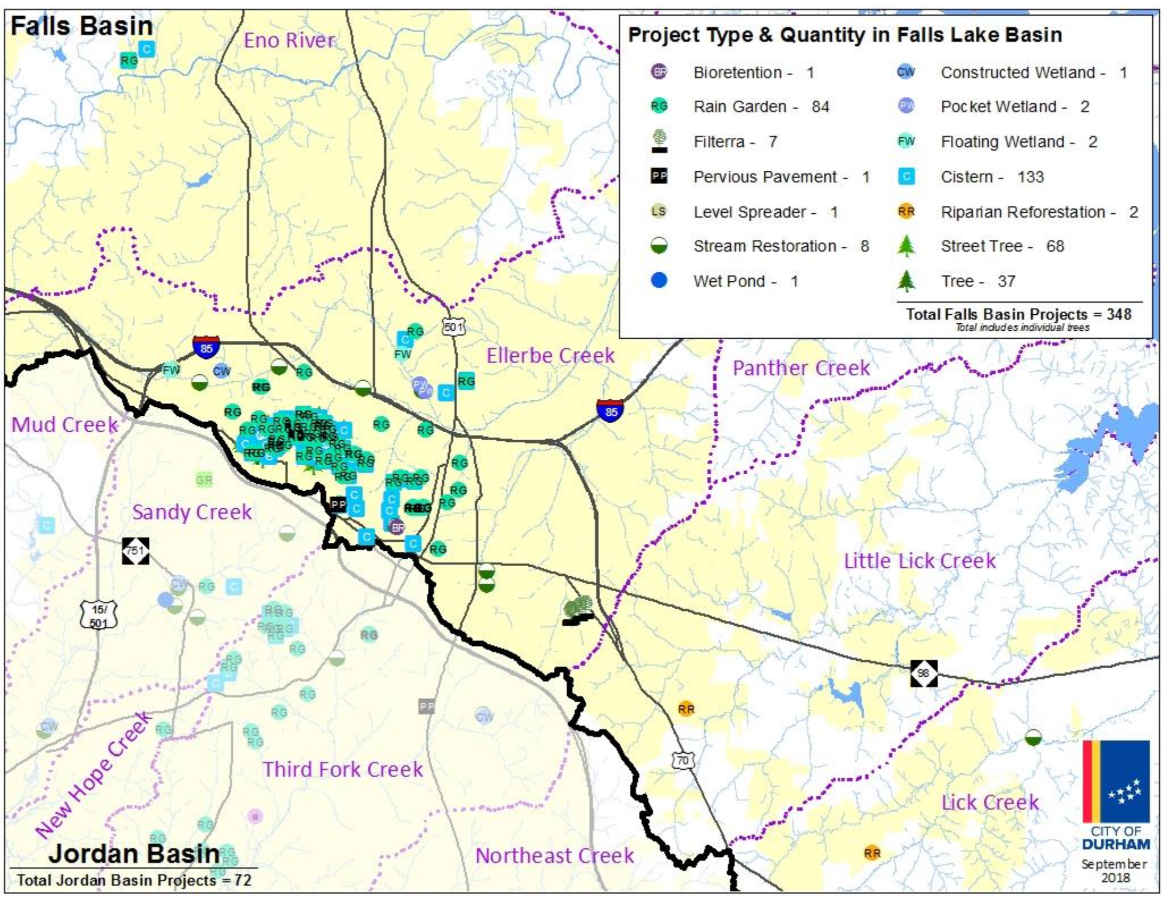


Figure H-21. City of Durham Existing Development Retrofits as of December 2015

In its simulation of developed areas, WARMF designates the percentages of pervious and impervious areas for each land use class. Fertilizer and nutrients can only be applied to pervious areas in the model, but atmospheric deposition affects both surface types. WARMF assumes that runoff from impervious surfaces immediately reaches the stream reach in the catchment unless it is detained. If the precipitation/runoff has a lower concentration of a parameter than the stream, rapid dilutions are simulated. Natural topography results in some runoff from impervious surfaces flowing over pervious areas where it either runs off or is infiltrated where it can interact with soil particles and travel to the stream. Some features in the watershed also retain water, release it more slowly, allow for evaporation, and pollutant processing (increase or decrease). Some BMPs like street sweeping remove pollutants from impervious areas. The WARMF model allows the user to account for these processes by assigning some of the runoff from impervious surfaces to go to “detention” or turning on BMPs like street sweeping or stream buffers.

Stream bank erosion is simulated by WARMF separately from the individual land uses. Stream bank erosion is calculated as an average condition for the reach in each catchment and accounts for soil erosivity, simulated shear stress, bank and vegetation characteristics, etc. The hydrologic impacts of impervious surfaces are not reflected in the nutrient loading rates reported by land use - these are the loading rates from the land surface and underlying soil layers that account for nutrient application/deposition, soil interactions, etc. This approach is very different than other models that relate land use characteristics in a watershed to water quality observations in streams or assign export coefficients to land uses (Dodd 1992, Harden et al. 2013, Lin 2004, Miller et al. 2019 and 2021). In those studies, the hydrologic impacts of stream bank erosion and resulting nutrient loading rates are associated with the land uses in the drainage area (i.e., runoff, interflow, and streambank erosion are reported with one value). It is important when reviewing or communicating the WARMF model results to note that stream bank erosion is not included in the land use loading rates. This is particularly important for phosphorus which binds to sediments. Streambank erosion is an important component of the phosphorus load delivered to Falls Lake, and rates of streambank erosion are higher in intensely developed areas. Comparison of nutrient loading rates associated with streambank erosion from catchments with different land use compositions are provided in the next section.

Stream bank erosion is simulated by WARMF separately from the individual land uses. The hydrologic impacts of impervious surfaces are not reflected in the nutrient loading rates reported by land use - these are the loading rates from the land surface and underlying soil layers that account for nutrient application/deposition, soil interactions, etc.

During model calibration, small volumes of detention were assigned to detain a portion of the runoff from impervious areas. This was necessary to calibrate the model and simulate stream flows of similar magnitude following precipitation events as recorded at USGS gages in the watershed. Figure H-22 shows the simulated stream flow in the Ellerbe Creek subwatershed compared to observations at USGS 02086849 – Ellerbe Creek Near Gorman, NC for the calibrated model and with the removal of detention and BMPs/SCMs in the watershed (top panel) and zoomed into the summer of 2015 (bottom panel). Without accounting for detention and routing of impervious surface runoff across pervious surfaces, storm peaks are too high relative to observations for small to medium size storms. Large storms (>40 cubic meters per second (cms)) are less affected because detention volumes were prescribed to retain a relatively small volume of runoff.

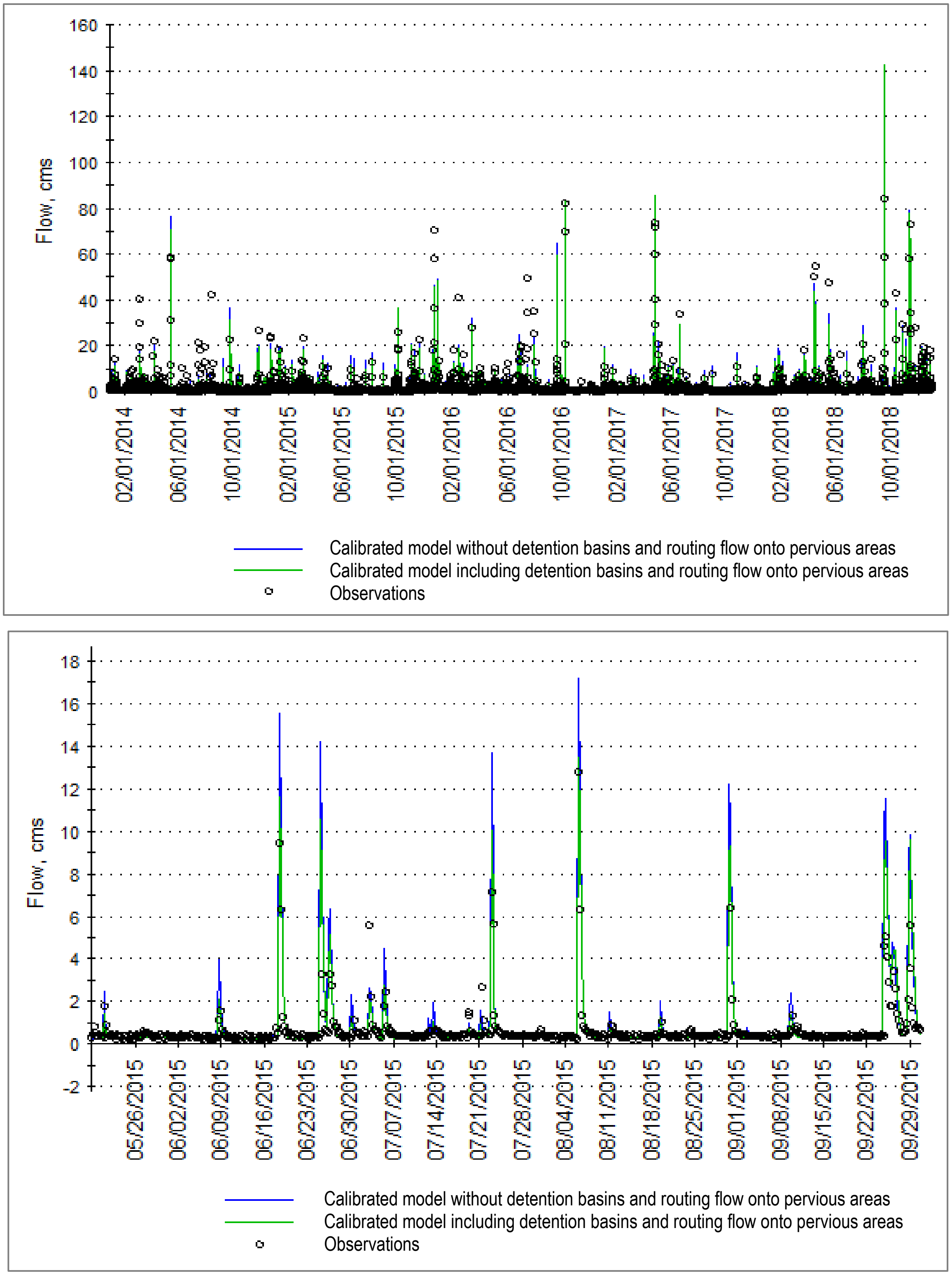


Figure H-22. Simulated Stream Flow for Ellerbe Creek with and without BMPs, 2014-18 (top) and summer of 2015 (bottom)

Detention basins and routing also improve the calibration for water quality parameters that have low concentrations in precipitation, like TOC (Figure H-23). Without some detention, rainfall that has low concentrations of a parameter relative to stream concentrations would otherwise reach the stream instantaneously and cause large drops in simulated concentrations due to dilution. Detention basins and routing have less of an effect on parameters like TN which are present in rainwater and therefore do not produce the simulated dilution effect (Figure H-24).

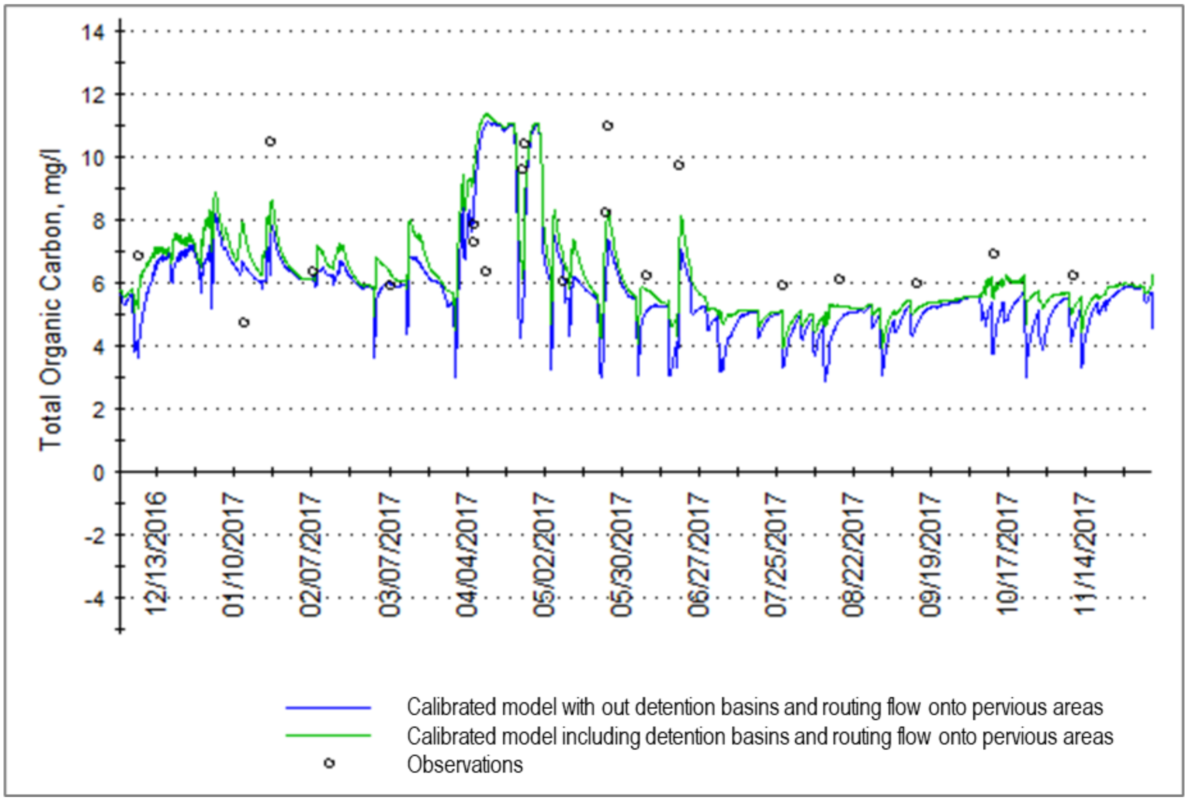


Figure H-23. Simulated TOC for Ellerbe Creek with and without BMPs, summer 2015

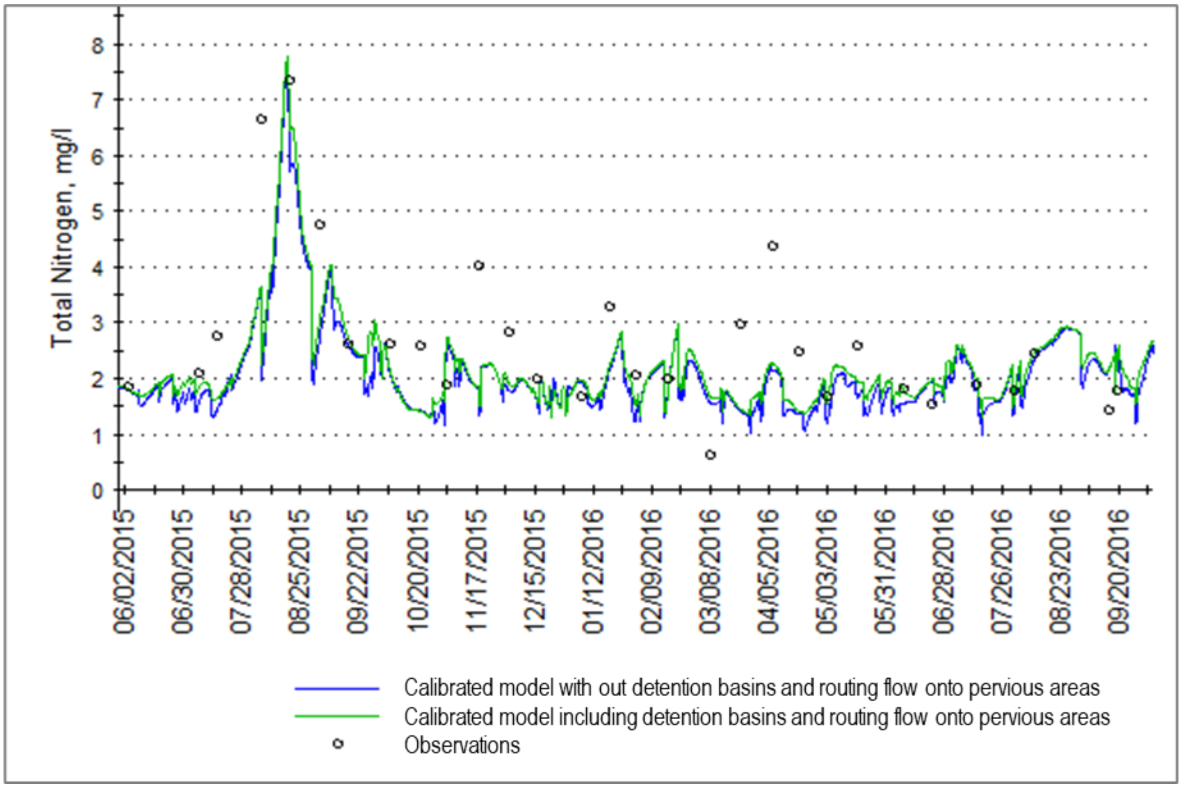


Figure H-24. Simulated TN for Ellerbe Creek with and without BMPs, summer 2015

Table H-13 shows the nitrogen and phosphorus loading rates for land uses in the Ellerbe Creek subwatershed for the calibrated model and with the removal of BMPs and SCMs. The urban nitrogen loading rates are slightly higher when the BMPs are removed. Nitrogen in dissolved form, associated with fertilizer leaching and atmospheric deposition, is less affected by BMPs than particulate-bound parameters like phosphorus. Low and medium intensity existing development has the highest TN loading rates of the urban land uses, approximately three times higher in the Ellerbe Creek subwatershed compared to the catchment-scale loading rate for forest. Developed open space has a catchment-scale loading rate that is approximately twice as high as forest. Developed open space is often road right of ways, parks, etc. and not subject to the same level of maintenance as other developed land use categories like low intensity existing development. The nitrogen loading rate for high intensity development is slightly lower than medium and low intensity development. This is because following initial washoff, there is little additional reaction to increase nutrients during flow to the stream. This loading rate does not account for the hydrologic impacts and stream bank erosion associated with high intensity development; as previously discussed, stream bank erosion is calculated separately.

These results are similar to monitoring studies of pervious and impervious surfaces conducted by Dr. William Hunt at NC State University. Dr. Hunt presented his preliminary results to the UNRBA at a PFC meeting on October 3, 2023. His research shows that monitored parking lots had total nitrogen concentrations ranging from 1 mg-N/L to 2.5 mg-N/L with a mean of 1.63 mg-N/L. In comparison, two wooded sites (on hydrologic soil types A or C/D) had total nitrogen concentrations generally ranging from 1.79 to 3.97 mg-N/L, but the site on hydrologic soil type A (sandy soils with high infiltration rates) generated very little runoff. The highest total nitrogen concentration occurred at a wooded site on hydrologic soil group B (6.85 mg-N/L) and coincided with the largest runoff event at that site. When both runoff volume and concentration are high relative to typical conditions, the resulting load will be very high. A managed lawn site on hydrologic soil group B at NC State

University generated the most runoff and had a total nitrogen concentration of 6.53 mg-N/L. A meadow on hydrologic soil type C/D had total nitrogen concentrations ranging from 0.84 to 1.49 mg-N/L. **Therefore, the total nitrogen concentrations from wooded sites were higher than the parking lot and meadow and lower than the managed lawn.**

For phosphorus, the WARMF-simulated urban loading rates are more strongly affected by removal of the simulated BMPs and SCMs. Land uses with higher percentages of pervious area have higher phosphorus loading rates because only pervious areas receive fertilizer, and soil-bound phosphorus can be eroded and transported. These lower intensity land uses are more affected by BMPs and SCMs because more of their phosphorus load is in the particulate form. Development with more impervious area (i.e., high intensity development) is less affected by the BMPs than those with more pervious area because most of their loading is transported in runoff, and most of that is assumed to enter the stream directly. Particulate phosphorus is treated more effectively due to trapping and settling where dissolved phosphorus dominates impervious surface runoff and is quickly transported. Again, these loading rates do not account for the hydrologic impacts and stream bank erosion associated with high intensity development.

The UNRBA WARMF model results are similar to Dr. Hunt's research for total phosphorus. The lowest phosphorus concentrations were observed from parking lot runoff (0.1 to 0.3 mg-P/L). Concentrations at the meadow on hydrologic soil type C/D ranged from 0.08 to 0.44 mg-P/L. **The wooded sites on hydrologic soil types A or C/D had total phosphorus concentrations higher than both the parking lot and the meadow** and ranged from 0.37 to 0.58 mg-P/L. The highest concentrations were observed at the managed lawn at 1.56 mg-P/L. During his presentation to the PFC, Dr. Hunt noted that while impervious surfaces appear to produce limited amounts of nutrient loading from runoff, downstream impacts on stream bank erosion can be substantial.

During his presentation to the PFC, Dr. Hunt noted that while impervious surfaces appear to produce limited amounts of nutrient loading from runoff, downstream impacts on stream bank erosion can be substantial.

The catchment-scale (before instream processing) nitrogen and phosphorus loading rates from all land uses including forest are high in the Ellerbe Creek watershed relative to other catchments because of the unique hydrology in this subwatershed. Due to the Triassic Basin soils and extent of development, Ellerbe Creek is a very "flashy" system with peak flows in the streams occurring rapidly based on USGS gaged flows. To mimic the observed hydrograph, vertical hydraulic conductivity was restricted in these catchments. This results in precipitation interacting mostly with the upper soil layer in this watershed prior to running off to the stream, regardless of land use type. The hydraulic conductivity cannot be specified uniquely in the catchment by land use as WARMF is a lumped parameter model. There are approximately 3,100 acres of forests in this approximately 14,000-acre subwatershed, and this is a small portion of the forested area in the entire Falls Lake watershed. Most of the forests in the Ellerbe Creek subwatershed is located near Falls Lake with less stream processing than other parts of the watershed. If loading rates from forests are overestimated in this watershed for the calibrated model, that would not significantly affect the total delivered load to Falls Lake. A sensitivity analysis on vertical hydraulic conductivity for the Ellerbe Creek watershed under an "All Forest" scenario is discussed in the section Land Conversion Scenario to All Forest or Wetland.

Table H-13. Simulated Nutrient Loading Rates[1] for Existing Development and Developed Open Space in Ellerbe Creek, 2014 to 2018 (No Downstream Attenuation and Not Accounting for Stream Bank Erosion)

Land use	TN kg/ha/yr Calibrated Model	TN kg/ha/yr No BMPs/SCMs	TP kg/ha/yr Calibrated Model	TP kg/ha/yr No BMPs/SCMs
ExDev, High Intensity	10.3	11.8	0.37	0.39
ExDev, Medium Intensity	12.7	13.8	0.90	2.0
ExDev, Low Intensity	12.3	13.2	1.8	5.2
Developed Open Space	8.5	8.9	1.4	2.7
Forest	4.0	4.0	1.4	2.3

[1] *These loading rates do not include the portion of loading due to stream bank erosion.*

A separate evaluation of the Ellerbe Creek subwatershed was conducted to determine how the source load allocation would change under various hydrologic conditions: dry represented by 2007, and average-to-wet conditions represented by the calibrated model for years 2014 to 2018. The sources of loading output by WARMF are annual averages over the simulation period. While 2014 was originally established as an initialization year, there is no way to exclude this year from the figures that show sources of loading. Because the watershed model is run five times as described in other sections, including this year in the five-year average should not introduce significant inaccuracies. Figure H-25 and Figure H-26 show the comparisons for total nitrogen and total phosphorus, respectively. For the dry condition, the total nitrogen load delivered to Falls Lake is approximately 23 percent less (34,000 lb-N/yr less) than the average-to-wet condition. Under the dry condition, the percent contribution of total nitrogen from point sources (wastewater treatment plants (WWTPs), discharging sand filter systems (DSFs), and sanitary sewer overflows (SSOs)) increases, and the loads associated with urban runoff decrease. For phosphorus, the total delivered load is almost half as much under the dry condition with a reduction in average annual load of 7,600 lb-P/yr. For phosphorus, the relative contribution from point sources almost doubles under the dry condition, and the relative contribution from stream bank erosion is approximately one-fifth of the average-to-wet condition.

Table H-14 and Table H-15 compare the nitrogen and phosphorus delivered loads and areal loading rates, respectively, for these two hydrologic conditions in the Ellerbe Creek watershed for land uses that make up at least 100 acres of the drainage area. Ellerbe Creek comprises approximately 3 percent of the total watershed area. As noted above, the loading rates (catchment-scale and delivered) for forested areas are higher than elsewhere in the basin. Precipitation that falls on pervious areas interacts with nutrients deposited or applied to the surface, erodes and transports soil particles, and/or may soak into the ground and pick up additional nutrients as the water moves through the soil toward the stream. In the Ellerbe Creek watershed, the hydrology was calibrated such that much of the precipitation runs off quickly and does not percolate into the ground. Restricting the percolation in this drainage area was needed to calibrate the stream flows and capture the flashy nature of this subwatershed which is situated in the Triassic Basin. There are approximately 2,500 acres of forests in the Ellerbe Creek watershed, and these acres make up a small fraction of the total forested area in the Falls Lake watershed. Additionally, most of the forests in this drainage are close to Falls Lake. This proximity means that nutrient transformations in streams are limited because the length of stream between the forested land and Falls Lake is short. Forest areal loading in the Falls Lake watershed is characteristic of this specific watershed and reflects a careful evaluation of this source in the overall nutrient balance. The resultant rates are consistent with the model development, the confirmation information available from this watershed, and more recent research on the impact of forest areas on watershed nutrient balance.

For comparison, the simulated delivered nutrient load associated with streambank erosion is also provided in the tables, but an areal loading rate for this source is not applicable. Under dry conditions, the nutrient loading from this source decreases by approximately one order of magnitude. Loads from land areas are lower under dry conditions, but the percent reduction is less significant compared to stream bank erosion.

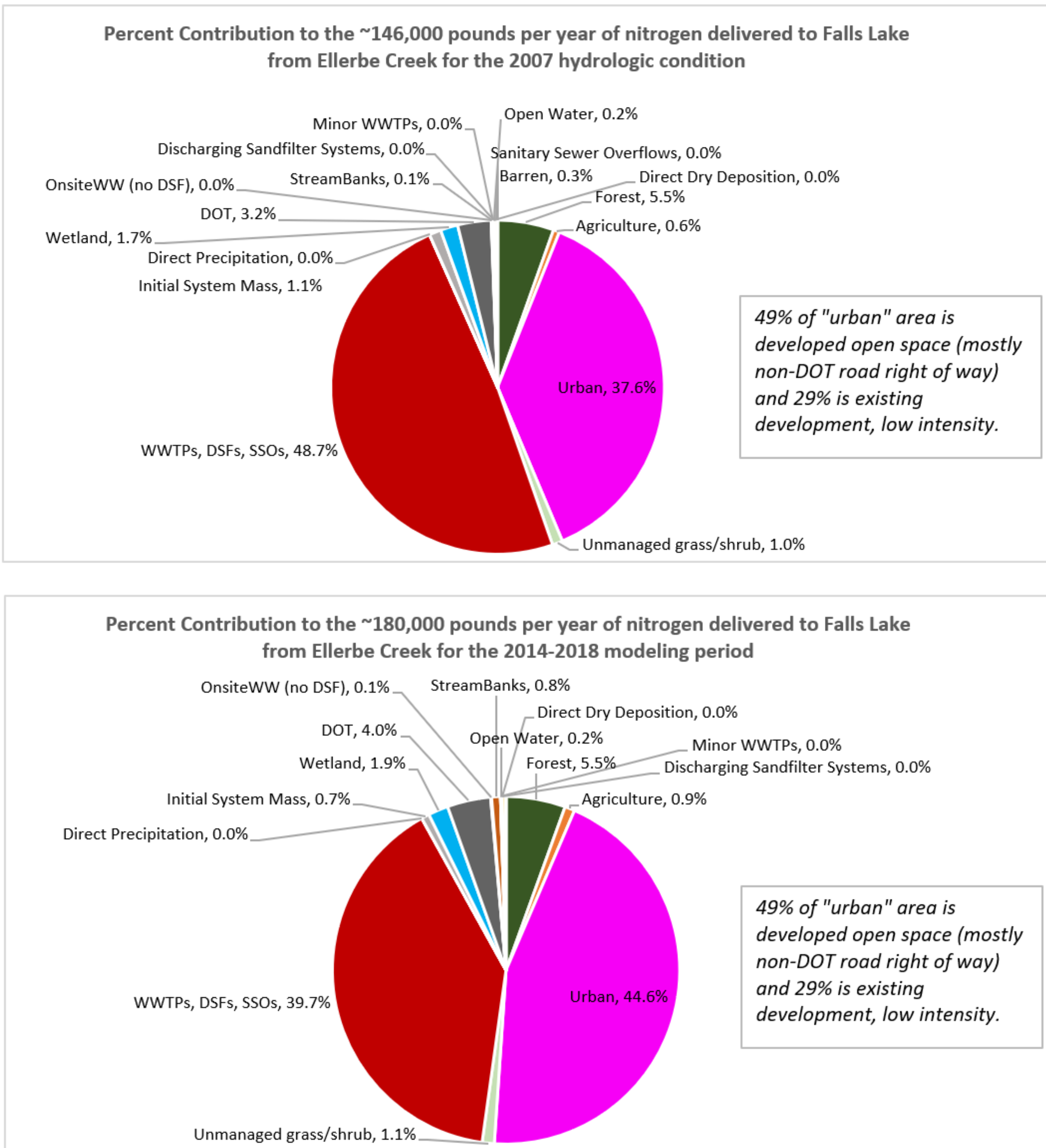
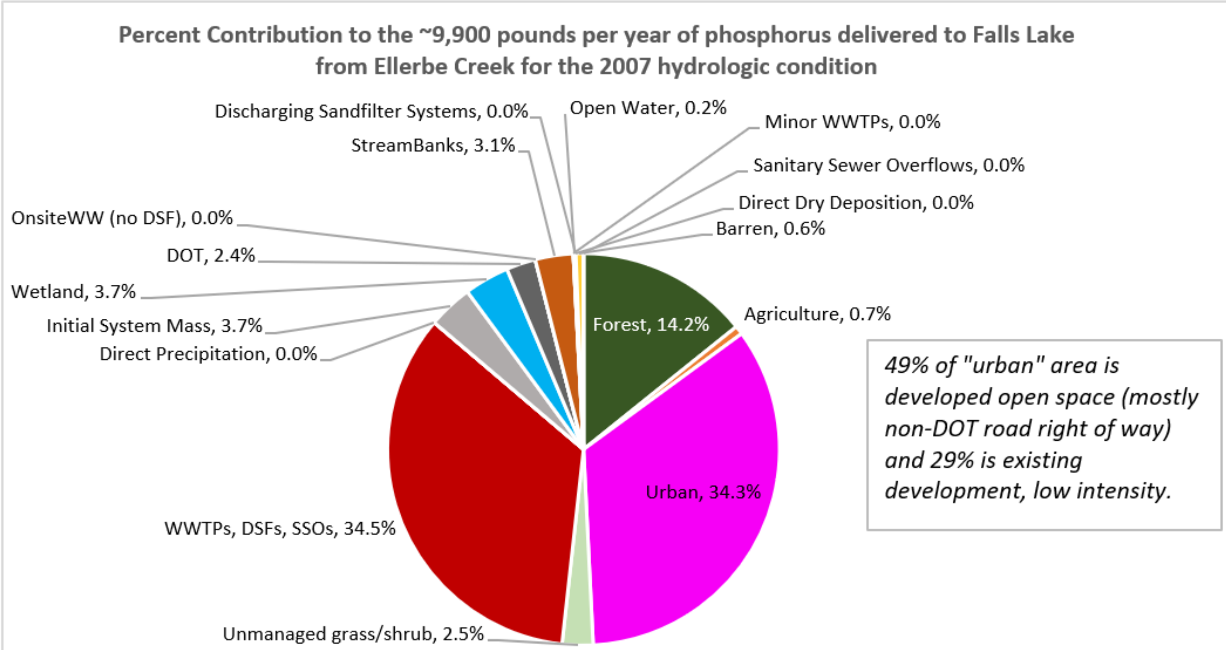


Figure H-25. Comparison of Total Nitrogen Delivered Loads to Falls Lake for 2007 (dry year, top panel) compared to 2014-2018 (average to wet years, bottom panel)



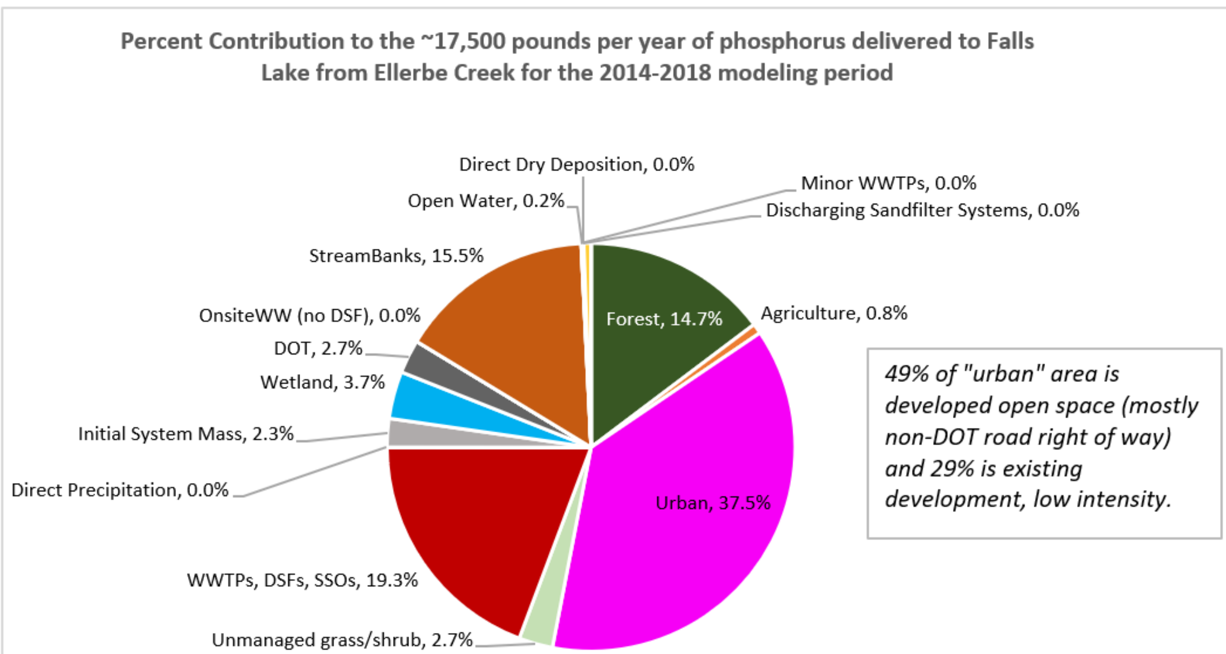


Figure H-26. Comparison of Total Phosphorus Delivered Loads to Falls Lake for 2007 (dry year, top panel) compared to 2014-2018 (average to wet years, bottom panel)

Table H-14. Delivered Total Nitrogen-Loading Rates from Ellerbe Creek Watershed for Two Hydrologic Conditions

Source	Drainage Area (ac)	Source Group	Average-to-wet TN lb/yr	Average-to-wet TN lb/ac/yr	Dry TN lb/yr	Dry TN lb/ac/yr
DOT Roads, Connected	719	DOT	6,360	8.9	4,112	5.8
DOT Roads, Unconnected	134	DOT	906	9.4	628	6.5
Existing Development, High Intensity	525	Urban	4,462	8.6	3,154	6.0
Existing Development, Medium Intensity	1,330	Urban	14,102	10.6	10,139	7.6
Existing Development, Low Intensity	2,783	Urban	28,039	10.1	21,002	7.6
Developed Open Space	4,697	Urban	32,333	6.9	19,876	4.3
Deciduous Forest	1,105	Forest	3,667	4.3	3,001	3.6
Coniferous Forest	1,031	Forest	3,216	3.8	2,478	2.9
Mixed Forest	1,007	Forest	3,045	3.9	2,478	3.2
Unmanaged Grassland	430	Unmanaged grass/shrub	1,884	5.3	1,360	3.8
Woody Wetland	705	Wetland	3,262	5.4	2,390	4.0
Stream Bank Erosion	NA	Stream Banks	1,481	NA	141	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

Table H-15. Delivered Total Phosphorus-Loading Rates from Ellerbe Creek Watershed for Two Hydrologic Conditions

Source	Drainage Area (ac)	Source Group	Average-to-wet TP lb/yr	Average-to-wet TP lb/ac/yr	Dry TP lb/yr	Dry TP lb/ac/yr
DOT Roads, Connected	719	DOT	388	0.54	201	0.28
DOT Roads, Unconnected	134	DOT	80	0.83	39	0.41
Existing Development, High Intensity	525	Urban	112	0.22	59	0.11
Existing Development, Medium Intensity	1,330	Urban	628	0.47	315	0.24
Existing Development, Low Intensity	2,783	Urban	2,406	0.87	1,191	0.43
Developed Open Space	4,697	Urban	3,345	0.72	1,794	0.39
Deciduous Forest	1,105	Forest	879	1.0	494	0.59
Coniferous Forest	1,031	Forest	866	1.0	458	0.54
Mixed Forest	1,007	Forest	835	1.0	460	0.59
Unmanaged Grassland	430	Unmanaged grass/shrub	433	1.2	232	0.65
Woody Wetland	705	Wetland	638	1.0	357	0.59
Stream Bank Erosion	NA	Stream Banks	2,723	NA	311	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

Catchment-Scale Nutrient Loads from Streambank Erosion

WARMF accounts for loading associated with stream bank erosion as an individual source (it is not lumped into the loading tracked by individual land use). Peak flow is an important factor in the simulation of stream bank erosion because high stream flows exert shear stresses on the stream banks and can cause erosion. The more impervious surface in a catchment, the higher the stream flow, resulting erosive forces, and nutrient loads from stream bank erosion. However, all land uses draining to a stream contribute flow, and the model cannot parse out from where the flow originated. So, while more intensely developed catchments have higher rates of streambank erosion and associated nutrient loading, the model cannot output which portion of the load is due to a particular land use.

To illustrate the connection between land use and stream bank erosion, the modeling team evaluated results from catchments with varying land use compositions. Three catchments with 75 percent or more forest and unmanaged grass/shrubland, three urban catchments from the Ellerbe Creek watershed, and one suburban catchment from the Upper Barton Creek watershed were selected for the comparison (Table H-16).

Since stream bank erosion is a more significant component of the phosphorus load compared to nitrogen, the modelers compared phosphorus loading from streambank erosion on a per foot basis for six catchments. To calculate the per foot load, the total catchment load for stream bank erosion was divided by length of simulated stream in the catchment to yield estimates with units of grams per meter per year (g/m/yr)).

Land use and hydrologic response are important drivers of phosphorus loading rates from stream bank erosion, but other catchment characteristics are also important, especially in comparing loading rates among catchments with similar land uses. Cumulative drainage area is an important consideration because more area for a given land use generally yields more flow that can erode banks. Percent clay, silt, and sand is important because sand tends to settle out quickly. Soil erodibility factor is an important distinction as well.

Phosphorus loading rates from streambanks associated with two of the forested catchments are generally three to four orders of magnitude lower than the urban catchments. The forested catchment with streambank phosphorus loads near the low end of the urban range also has a lower percentage of sand, the highest erodibility factor of these catchments, and a drainage area three to four times higher than the urban catchments evaluated. Even though the developed catchments have higher percentages of sand than the forested catchments, the impervious surfaces result in hydrologic changes that increase peak flows and stresses on stream banks. As the cumulative drainage area increases, so does stream flow, which can generate additional stress on the streambanks in the catchment.

Phosphorus loading rates from streambanks associated with two of the forested catchments are generally three to four orders of magnitude lower than the phosphorus loading rates from urban catchments.

Table H-16. WARMF Simulated Phosphorus Loads Associated with Stream Bank Erosion in Forested and Development Catchments, Annual Averages for 2014 to 2018 (10 model iterations); Catchments are Sorted in Order of Increasing Phosphorus Loading Rate from Stream Banks

Catchment Number	Dominant Land Use in Catchment	Cumulative Drainage Area (ac) including upstream Catchments	SSURGO Soil erodibility factor	SSURGO Percent clay, silt, sand	Streambank Phosphorus load for this reach (g/m/yr)	Percent of Catchment Phosphorus load from stream reach
42	79 % forest, unmanaged grass	1,133	0.297	15,32,53	0.01	0.01%
14	77% forest, unmanaged grass	20,284	0.150	16,47,37	0.03	0.02%
228	66% forest, unmanaged; 22% developed open	5,258	0.228	12,23,65	0.18	0.09%
4	76% forest, unmanaged grass	14,421	0.414	16,48,46	10.2	8.2%
55	50% developed open, 33% existing development	3,696	0.211	15,23,62	10.7	5.4%
56	33% developed open, 40% existing development	4,122	0.222	14,22,64	20.0	3.9%
249	39% developed open, 28% existing development	6,804	0.241	13,27,60	150.7	36.2%

WARMF Simulated Average Delivered Loading Rates to Falls Lake for UNRBA Study Period

The loading rates presented in the previous sections were catchment-scale loading rates from the land area to the stream and do not include instream or impoundment processing. The modeling team also calculated delivered loading rates to Falls Lake from the land uses in the watershed. These reflect the net effect of loading from all 264 modeling catchments and all of the processing that occurs in the streams and impoundments before the load reaches Falls Lake.

For the UNRBA study period, the model simulates approximately 1.65 million pounds per year of total nitrogen; 183,000 pounds per year of total phosphorus; and 13.1 million pounds per year of total organic carbon delivered to Falls Lake. Table H-17 summarizes the loads and loading rates by individual source and source group; colors correspond to those used elsewhere in the report for source groups. These loading rates are annual averages delivered from each land use category for 2014 to 2018 and include loading from catchments with a range of soils, land uses, slopes, catchment widths, reach lengths, and precipitation. Some catchments drain to other impoundments in the watershed before reaching Falls Lake. Losses that occur in streams and impoundments affect all loading sources to that point in the model, though processes and reactions will differ based on season, hydrology, dissolved/particulate fractions, and nutrient speciation. The loadings are generally reduced during transport to Falls Lake with particulate fractions likely exhibiting more reductions than dissolved fractions due to settling.

Figure H-27 shows the sources of delivered load to Falls Lake during the UNRBA study period for total nitrogen, total phosphorus, and total organic carbon. The largest source of total nitrogen, total phosphorus, and total organic carbon delivered to Falls Lake comes from unmanaged areas which comprise approximately 75 percent of the total watershed area and 87 percent of the Near Lake area. Forested areas comprise approximately 60 percent of the land area and are important to the health of the watershed as they store and cycle nutrients and carbon. Loading from these areas increases with higher precipitation depths as the storage capacity of the soil becomes saturated and runoff occurs. Natural areas generally contribute a balanced amount of nutrient loading that is necessary for ecosystem health and loads from these areas respond to hydrologic condition when soils become saturated. An important goal of the UNRBA is to conserve these natural areas for the long-term protection of the watershed and Falls Lake.

Natural areas contribute a balanced amount of nutrient loading that is necessary for ecosystem health. An important goal of the UNRBA is to conserve these natural areas for the long-term protection of the watershed and Falls Lake.

The second and third largest contributors of total nitrogen and total organic carbon are agriculture and urban areas, respectively. In this watershed, developed open space, which is mostly non-DOT right of ways, comprises 68 percent of the total area of urban source group, and low intensity development comprises 20 percent of the urban category. Only 1.5 percent of the watershed area is in medium or high intensity development. Agriculture is predominantly small family farms, and over one-half of the agriculture in the basin

Only 1.5 percent of the watershed area is in medium or high intensity development.

is pasture. The second largest source of total phosphorus delivered to Falls Lake is streambank erosion. Urban areas and agriculture are similar and have the next highest phosphorus loads.

Stream bank erosion is simulated by WARMF separately from the individual land uses. Stream bank erosion is an average condition for the reach that accounts for soil erosivity, simulated shear stress, bank and vegetation characteristics, etc. The hydrologic impacts of impervious surfaces are not reflected in the nutrient loading rates reported by land use - these are the loading rates from the land surface that account for nutrient application/deposition, soil interactions, etc.

The WARMF modeling approach is very different than other models that relate land use characteristics in a watershed to water quality observations in streams or assign export coefficients to land uses (Dodd 1992, Harden et al. 2013, Lin 2004, Tetra Tech 2014, Miller et al. 2019 and 2021). In those studies, the hydrologic impacts on stream bank erosion and resulting nutrient loading rates are accounted for in the observed water quality. Empirical models that use watershed characteristics like land use to predict observed water quality inherently include the stream bank loading component along with the land area loading in the models.

While stream bank erosion does not contribute significantly to the nitrogen or total organic carbon loads relative to other sources (approximately 1 percent for both), it contributes approximately 15 percent of the total phosphorus load to Falls Lake. Phosphorus loading rates from streambanks associated with forested catchments are lower than urban catchments because impervious surfaces result in hydrologic changes that increase peak flows and stresses on stream banks. Woody vegetation also provides significant streambank stability.

Care will need to be taken when disseminating results to stakeholders and the broader community because nutrient loading results from WARMF show higher intensity development having lower nutrient loading rates than lower intensity development. This result does not capture the hydrologic impacts of increasing impervious surface area, or the resulting streambank erosion component of nutrient loading.

The WARMF simulated delivered total nitrogen loading rates for agriculture range from 2 to 9 lb/ac/yr and account for varying rates of nitrogen application and deposition from the watershed; the loading rates do account for crop harvesting, which is an important part of the nutrient balance on agricultural lands. Urban loading rates range from 2.5 to 5.7 lb/ac/yr for new development and existing development, respectively. New development rules went into effect in this watershed in 2011, and nitrogen loading rates are not to exceed 2.2 lb/ac/yr on average. The UNRBA WARMF model simulates slightly higher loads, likely because the rainfall condition ranged from average to wet in 2015 to 2018. Because there is so little acreage of new development in the UNRBA study period (~700 acres), this should not greatly affect the total loading to the lake. Forests and unmanaged grass and shrub have average nitrogen loading rates of 2.2 lb/ac/yr for the calibrated model (average to wet rainfall conditions).

For phosphorus, agricultural loading rates range from 0.32 to 0.71 lb/ac/yr. Delivered average loading rates from urban areas (excluding stream bank erosion) range from 0.11 to 0.46 lb/ac/yr depending on the development type. The lower loading rates are associated with higher percentages of impervious area, but these rates do not include loading from stream bank erosion. Streambank erosion contributes more phosphorus load to Falls Lake than all of the urban land uses combined, and areas with high percentages of impervious area generate hydrologic effects which lead to increased streambank erosion. Forests and undisturbed lands have an average phosphorus loading rate of 0.3 lb/ac/yr for the calibrated model (average to wet rainfall conditions). The land use loading rates are higher for land uses with higher percentages of pervious areas because of the chemical interactions that happen at the surface or within the soil profile. Impervious areas are limited in the amount of nutrients that can be generated from the land surface and do not receive nutrient applications in the WARMF model.

Table H-17. Load Delivered to Falls Lake and Areal Loading Rate by Individual Source (All Contributing Areas) for UNRBA Study Period

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Conventional Grain Corn	169	Agriculture	605	3.6	120	0.71	3,740	22.1
Double-cropped Soybeans	3,350	Agriculture	6,691	2.0	1,137	0.34	64,794	19.3
Fescue (Pasture)	6,324	Agriculture	238,762	9.1	10,710	0.41	2,550,410	96.9
Fescue (Hay)	4,564	Agriculture	11,495	2.5	1,443	0.32	94,302	20.7
Flue-Cured Tobacco	2,736	Agriculture	16,545	6.0	1,712	0.63	54,251	19.8
Full Season Soybeans	5,861	Agriculture	12,339	2.1	2,205	0.38	120,261	20.5
No-Till Grain Corn	2,627	Agriculture	6,507	2.5	997	0.38	51,940	19.8
Wheat	820	Agriculture	2,802	3.4	353	0.43	17,267	21.1
DOT Roads, Connected	2,888	DOT	13,903	4.8	760	0.26	47,245	16.4
DOT Roads, Unconnected	9,976	DOT	28,867	2.9	1,498	0.15	105,629	10.6
ExDev, High Intensity	1,554	Urban	7,106	4.6	169	0.11	12,004	7.7
ExDev, Medium Intensity	4,449	Urban	25,270	5.7	1,072	0.24	71,136	16.0
ExDev, Low Intensity	12,610	Urban	65,935	5.2	5,761	0.46	322,261	25.6
Developed Open Space	42,981	Urban	140,667	3.3	12,063	0.28	967,549	22.5
IntDev, High Intensity	64	Urban	239	3.7	9	0.14	599	9.4
IntDev, Medium Intensity	330	Urban	1,159	3.5	75	0.23	5,241	15.9
IntDev, Low Intensity	252	Urban	898	3.6	87	0.35	5,816	23.1
NewDev, High Intensity	72	Urban	177	2.5	8	0.11	586	8.1
NewDev, Medium Intensity	298	Urban	732	2.5	60	0.20	4,641	15.6
NewDev, Low Intensity	339	Urban	845	2.5	118	0.35	7,021	20.7
Deciduous Forest	146,587	Forest	305,600	2.1	31,536	0.22	3,089,973	21.1
Coniferous Forest	68,503	Forest	164,583	2.4	26,518	0.39	1,696,787	24.8
Mixed Forest	75,917	Forest	164,719	2.2	22,542	0.30	1,703,900	22.4
Shrub / Scrub	7,368	Unmanaged grass/shrub	16,092	2.2	1,982	0.27	158,061	21.5
Unmanaged Grassland	41,484	Unmanaged grass/shrub	95,166	2.3	11,639	0.28	887,793	21.4
Barren	471	Barren	2,684	5.7	356	0.76	13,174	28.0
Emerg Herbaceous Wetland	406	Wetland	1,150	2.8	169	0.41	11,789	29.0
Woody Wetland	9,495	Wetland	31,789	3.3	4,171	0.44	330,440	34.8
Waterfowl Impoundment	839	Wetland	2,225	2.7	269	0.32	23,129	27.6

Table H-17. Load Delivered to Falls Lake and Areal Loading Rate by Individual Source (All Contributing Areas) for UNRBA Study Period

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Water	4,455	Open Water	19,455	4.4	1,607	0.36	104,609	23.5
General Nonpoint Sources	NA	GeneralNPS	19,796	NA	6,197	NA	161,931	NA
Stream Bank Erosion	NA	StreamBanks	13,718	NA	26,761	NA	132,888	NA
Direct Precipitation	NA	Direct Precipitation	85,066	NA	59	NA	121,522	NA
Direct Dry Deposition	NA	Direct Dry Deposition	11,265	NA	2,112	NA	8,217	NA
Privy	NA	Onsite WW (no DSF)	7	NA	0	NA	58	NA
Conventional Functioning	NA	Onsite WW (no DSF)	17,145	NA	2	NA	4,447	NA
Conventional Malfunctioning	NA	Onsite WW (no DSF)	6,318	NA	32	NA	64,875	NA
Advanced Treatment, Functioning	NA	Onsite WW (no DSF)	306	NA	0	NA	230	NA
Advanced Treatment, Malfunctioning	NA	OnsiteWW (no DSF)	201	NA	1	NA	2,198	NA
Advanced Treatment, Functioning >3000gpd	NA	OnsiteWW (no DSF)	1	NA	0	NA	1	NA
Major WWTPs	NA	Major WWTPs	90,489	NA	6,093	NA	160,033	NA
Minor WWTPs	NA	Minor WWTPs	16,403	NA	295	NA	15,673	NA
Discharging Sandfilter Systems (DSF)	NA	Discharging Sandfilter Systems	10,589	NA	1,013	NA	7,136	NA
Sanitary Sewer Overflows	NA	Sanitary Sewer Overflows	50	NA	7	NA	47	NA
Total	492.267		1,656,361	NA	183,717	NA	13,205,602	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

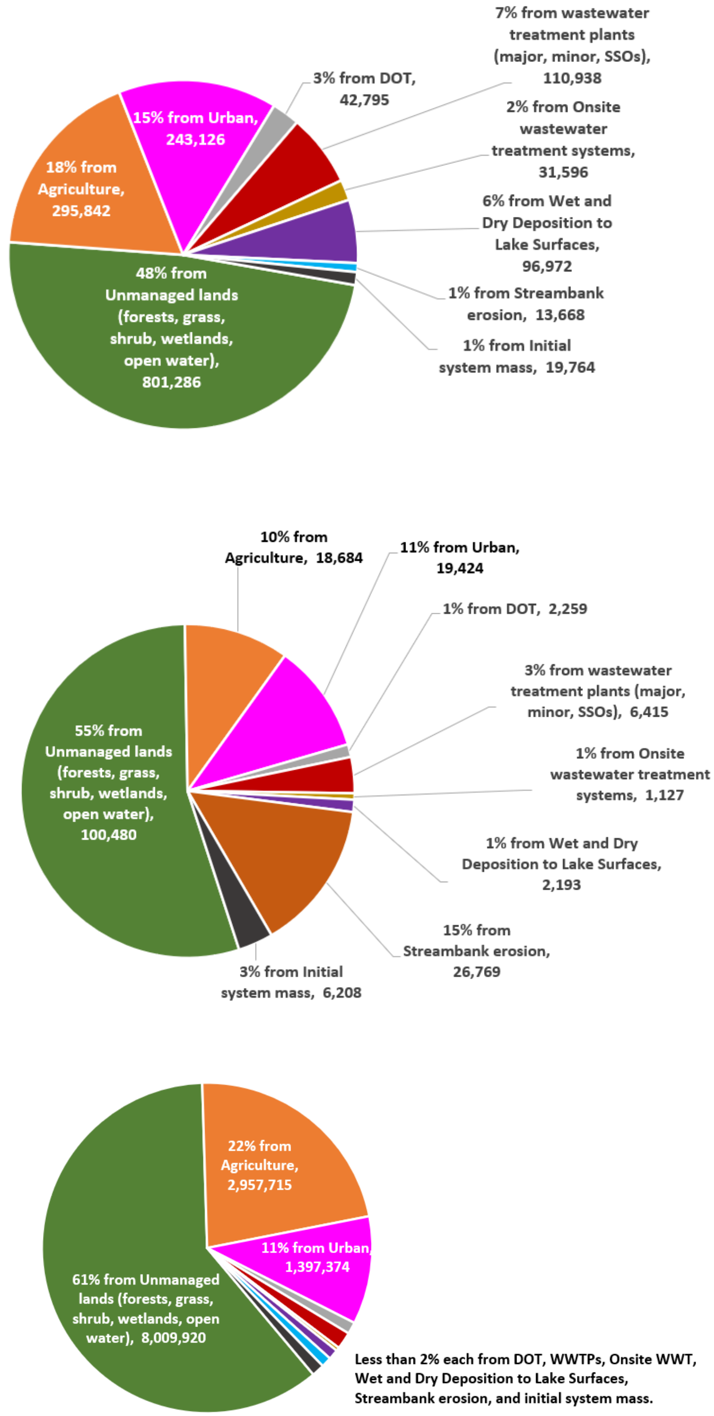


Figure H-27. Sources of Delivered Total Nitrogen (1.65 million pounds per year, top), Total Phosphorus (183,000 pounds per year, middle), and Total Organic Carbon (13.1 million pounds per year, bottom) for the UNRBA Study Period (2014-2018)

Sensitivity Analyses for Rainfall (Hydrologic Condition)

As described throughout this appendix, the UNRBA study period represents an average to wet hydrologic condition (range of annual precipitation from 45.6 to 60.3 inches with an average of 53.9 inches). This section discusses the effects of decreasing or increasing the rainfall amounts by 20 percent to assess the impacts on delivered nutrient loading to Falls Lake.

To test the effects of a dry to average hydrologic condition on nutrient and carbon loading to Falls Lake, a sensitivity analysis on precipitation amount was conducted where each precipitation depth (78 stations, 6-hour precipitation depth) was multiplied by a factor of 0.8. For example, this factor reduced annual precipitation at RDU airport from a range of 45.6 to 60.3 inches per year for the UNRBA study period down to a range of 36.5 to 48.2 inches per year with an average of 43.1 inches. This lower range of annual precipitation is similar to the condition during which the USFS conducted monitoring studies of forested headwater catchments (37 to 51 inches with an average of 43.8 inches) as well as the baseline modeling conducted by DWR (37.6 to 53.7 inches with an average of 42.4 inches). No other model inputs were changed for this sensitivity analysis including other meteorological inputs (humidity, wind speed, etc.) which would also affect hydrology.

Simulating 20 percent less rainfall across the watershed lowered delivered nutrient and carbon loads to Falls Lake by 34 to 42 percent compared to the 2015 to 2018 conditions, depending on the parameter. Delivered total nitrogen load decreased from 1.65 million to 1.08 million (34 percent reduction), delivered total phosphorus load decreased from 184 thousand to 107 thousand (42 percent reduction), and delivered total organic carbon load decreased from 13.2 million to 8 million (39 percent reduction)).

Simulating 20 percent less rainfall across the watershed lowered delivered nutrient and carbon loads to Falls Lake by 34 to 42 percent compared to the 2015 to 2018 conditions, depending on the parameter.

Table H-18 shows the delivered loads and areal loading rates by source for this dry to average hydrologic condition. Note that areal loading rates for total nitrogen from forested areas range from 1.2 to 1.5 pounds of total nitrogen per acre per year and 0.13 to 0.24 pounds of total phosphorus per acre per year. These are approximately 1 pound per acre per year less of total nitrogen and 0.1 to 0.15 pound per acre per year less of total phosphorus compared to the UNRBA study period.

During the model development and review process, subject matter experts and DWR modeling staff inquired about the simulated loading rates from forested areas for the UNRBA study period relative to monitoring studies. Figure H-28 shows the average annual load measured by the US Forest Service for each monitoring year and site compared to the five-year average simulated by WARMF for each forest type for the dry hydrologic condition. Note the simulated forest loading rates for WARMF include the 37,000 acres that drain directly to Falls Lake and do not have the benefit of instream processing (settling, denitrification, etc.). The average simulated forest loading rates for WARMF under the dry to average hydrologic condition are within the ranges reported by the US Forest Service.

The average simulated forest loading rates for WARMF under the dry to average hydrologic condition are within the ranges reported by the US Forest Service which were conducted under dry to average hydrologic conditions.

Table H-18. Load Delivered to Falls Lake and Areal Loading Rates by Individual Source (All Contributing Areas) for the Dry to Average Condition (20 percent less rainfall than 2015 to 2018)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Conventional Grain Corn	169	Agriculture	387	2.3	72	0.42	2,366	14.0
Double-cropped Soybeans	3,350	Agriculture	3,633	1.1	605	0.18	35,517	10.6
Fescue (Pasture)	6,324	Agriculture	135,855	5.2	6,074	0.23	1,446,979	55.0
Fescue (Hay)	4,564	Agriculture	7,058	1.5	859	0.19	56,362	12.3
Flue-Cured Tobacco	2,736	Agriculture	10,295	3.8	916	0.33	29,742	10.9
Full Season Soybeans	5,861	Agriculture	7,071	1.2	1,243	0.21	69,636	11.9
No-Till Grain Corn	2,627	Agriculture	3,761	1.4	579	0.22	29,828	11.4
Wheat	820	Agriculture	1,638	2.0	216	0.26	10,339	12.6
DOT Roads, Connected	2,888	DOT	9,985	3.5	484	0.17	29,697	10.3
DOT Roads, Unconnected	9,976	DOT	17,628	1.8	868	0.09	58,852	5.9
ExDev, High Intensity	1,554	Urban	5,927	3.8	131	0.08	8,316	5.4
ExDev, Medium Intensity	4,449	Urban	20,091	4.5	709	0.16	45,739	10.3
ExDev, Low Intensity	12,610	Urban	47,386	3.8	3,614	0.29	208,598	16.5
Developed Open Space	42,981	Urban	88,196	2.1	7,511	0.17	598,776	13.9
IntDev, High Intensity	64	Urban	188	2.9	7	0.10	419	6.6
IntDev, Medium Intensity	330	Urban	769	2.3	49	0.15	3,348	10.1
IntDev, Low Intensity	252	Urban	564	2.2	52	0.21	3,589	14.2
NewDev, High Intensity	72	Urban	124	1.7	5	0.08	370	5.1
NewDev, Medium Intensity	298	Urban	469	1.6	37	0.12	2,852	9.6
NewDev, Low Intensity	339	Urban	530	1.6	71	0.21	4,391	13.0
Deciduous Forest	146,587	Forest	174,614	1.2	18,427	0.13	1,775,366	12.1
Coniferous Forest	68,503	Forest	105,483	1.5	16,435	0.24	1,086,683	15.9
Mixed Forest	75,917	Forest	102,093	1.3	13,772	0.18	1,056,366	13.9
Shrub / Scrub	7,368	Unmanaged grass/shrub	8,850	1.2	1,143	0.16	89,707	12.2
Unmanaged Grassland	41,484	Unmanaged grass/shrub	53,544	1.3	6,739	0.16	515,725	12.4
Barren	471	Barren	2,005	4.3	219	0.47	8,912	18.9
Emerg Herbaceous Wetland	406	Wetland	770	1.9	107	0.26	7,843	19.3
Woody Wetland	9,495	Wetland	21,127	2.2	2,678	0.28	218,848	23.0
Waterfowl Impoundment	839	Wetland	1,548	1.8	176	0.21	16,205	19.3
Water	4,455	Open Water	13,289	3.0	1,018	0.23	66,988	15.0
Initial System Mass	NA	GeneralNPS	17,336	NA	4,923	NA	138,456	NA

Table H-18. Load Delivered to Falls Lake and Areal Loading Rates by Individual Source (All Contributing Areas) for the Dry to Average Condition (20 percent less rainfall than 2015 to 2018)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Stream Bank Erosion	NA	StreamBanks	3,910	NA	7,291	NA	38,033	NA
Direct Precipitation	NA	Direct Precipitation	67,967	NA	48	NA	96,967	NA
Direct Dry Deposition	NA	Direct Dry Deposition	11,267	NA	2,147	NA	8,211	NA
Privy	NA	Onsite WW (no DSF)	1	NA	0	NA	4	NA
Conventional Functioning	NA	Onsite WW (no DSF)	10,597	NA	1	NA	1,163	NA
Conventional Malfunctioning	NA	Onsite WW (no DSF)	1,948	NA	62	NA	19,061	NA
Advanced Treatment, Functioning	NA	Onsite WW (no DSF)	183	NA	0	NA	59	NA
Advanced Treatment, Malfunctioning	NA	OnsiteWW (no DSF)	67	NA	2	NA	720	NA
Advanced Treatment, Functioning >3000gpd	NA	OnsiteWW (no DSF)	0	NA	0	NA	0	NA
Major WWTPs	NA	Major WWTPs	92,526	NA	6,251	NA	197,804	NA
Minor WWTPs	NA	Minor WWTPs	16,772	NA	302	NA	19,372	NA
Discharging Sandfilter Systems (DSF)	NA	Discharging Sandfilter Systems	10,827	NA	1,040	NA	8,820	NA
Sanitary Sewer Overflows	NA	Sanitary Sewer Overflows	51	NA	8	NA	59	NA
Total	492.267		1,078,331	NA	106,894	NA	8,017,088	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

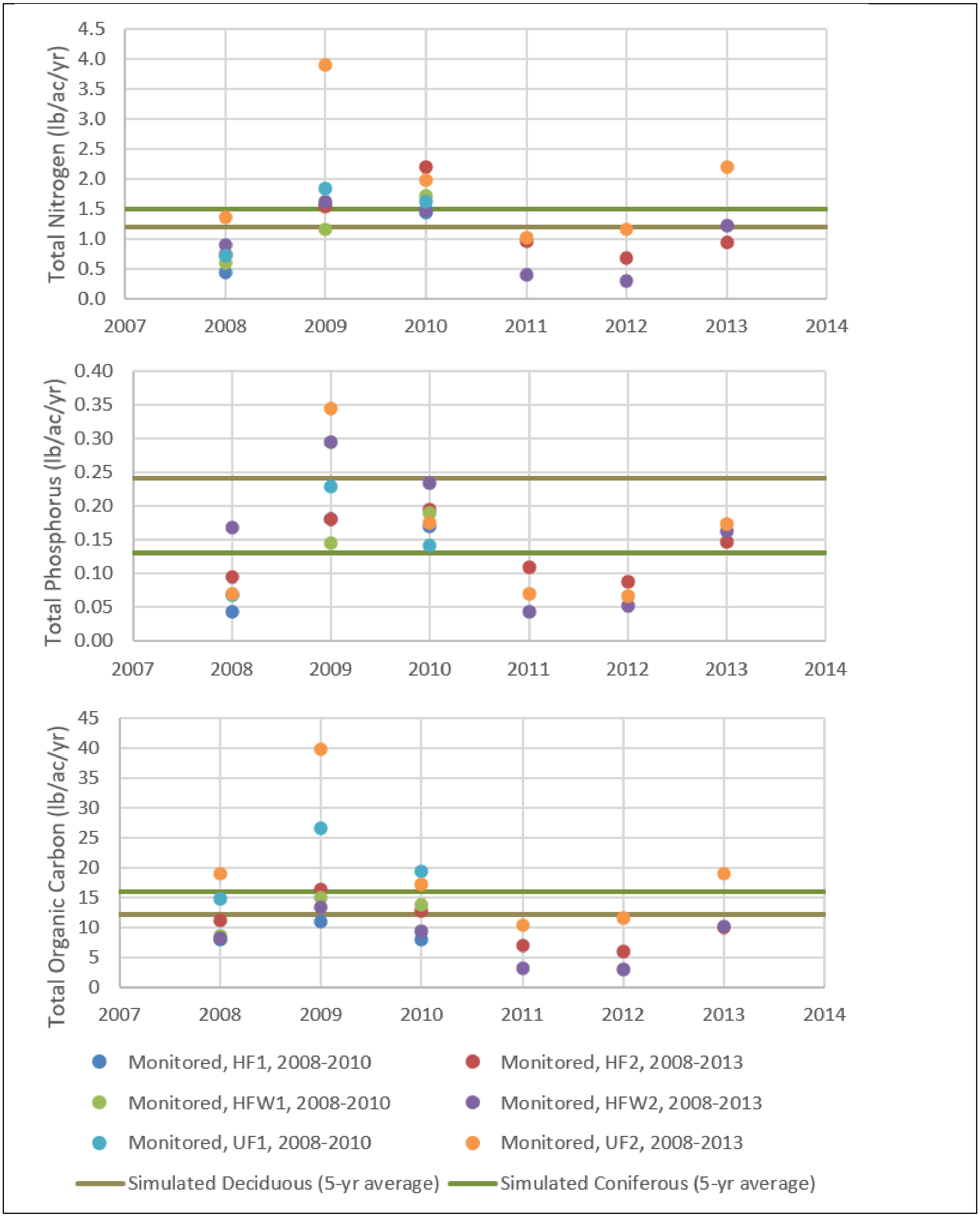


Figure H-28. Comparison of Five-Year Average Simulated Forest Areal Loading Rates for the Dry to Average Hydrologic Condition to Annual Estimates from the US Forest Service; WARMF Simulation Includes Areas that Drain Directly to Falls Lake with No Instream Processing

Previous WARMF watershed modeling conducted by DWR (2009) estimated that loads from forested areas were much smaller than the WARMF simulated loads for the UNRBA study period and the dry-condition sensitivity analysis summarized in Table H-18. The DWR (2009) report summarizes delivered nutrient loads for each of the five major tributaries to Falls Lake. Based on the DWR report, the areal loading rates for forests simulated by the DWR model can be compared to recent modeling by the UNRBA and to the monitoring studies conducted by the US Forest Service. For example, for the Eno River subwatershed, the DWR report indicates that approximately 57.2 percent of the subwatershed area was forested based on the 2001 National Land Cover Database (NLCD). The area of the Eno River subwatershed is approximately 108,700 acres, so the acreage of forest in the subwatershed was approximately 62,176 acres in the DWR model. The total phosphorus load delivered by Eno River subwatershed in the DWR model (which represented a dry to average hydrologic condition) was simulated to be 16 kilograms per day or 12,875 pounds per year from all sources in the watershed. The DWR model estimated that 0.8 percent of the total phosphorus load from the Eno River subwatershed was due to forested areas, or 0.008*12,875=103 lb/yr. Dividing by the forested area of 62,176 acres yields an average areal loading rate of 0.0016 lb/ac/yr. Thus, the DWR simulated loading rate for forests was one to two orders of magnitude lower than the typical range reported for the US Forest Service monitoring sites (0.044 lb/ac/yr to 0.24 lb/ac/yr [0.05 kg/ha/yr to 0.27 kg/ha/yr] based on Figure H-10). One explanation for the difference between the two models is that the DWR model did not include atmospheric deposition of phosphorus to the watershed and would not have had access to the USGS forest soils data provided by the subject matter experts reviewing the UNRBA model. Neither the City of Durham (AMEC 2012) atmospheric deposition study which included phosphorus analysis nor the UGSS soil chemistry data (Smith et al., 2013) were available at the time the DWR model was developed.

Cardno ENTRIX (2013) previously compared the simulated loads to Falls Lake from the DWR WARMF model to other estimates available at the time including the DWR EFDC model inputs to Falls Lake. This comparison demonstrated that the DWR WARMF watershed model likely underestimated the total phosphorus load delivered to Falls Lake by a factor of 2. The total simulated load (DWR 2009) from the upper five tributaries was approximately 58,000 lb-P/yr, but the average total phosphorus load used to develop the DWR Falls Lake EFDC model inputs was 117,000 lb-P/yr (a difference of 59,000 lb-P/yr). The DWR EFDC model inputs were estimated from gaged flows in the watershed and bi-weekly water quality sampling at the five largest tributaries. The EFDC model inputs were similar on an annual scale to USGS SPARROW estimates (Cardno ENTRIX 2013).

Evaluation of the tributary-level UNRBA WARMF model output for the dry to average hydrologic condition indicates that forested areas from these upper five tributaries contributes approximately 23,000 lb-P/yr compared to the DWR simulated load from forested areas in these five tributaries of 263 lb-P/yr. The under simulation of total phosphorus loads from forested areas may account for some of the discrepancy between the DWR WARMF simulated loads to Falls Lake and the DWR EFDC modeled inputs to Falls Lake. The remainder of the discrepancy is likely due to the assumed soil phosphorus concentrations which apply throughout the watershed and which DWR would not have had the data provided by Smith et al. (2013).

It is important to note when comparing the results of the dry to average rainfall condition to the 2009 DWR WARMF model and particularly the relative source contributions, several improvements to nutrient loading have occurred in the watershed since the mid-2000s. These changes are described in more detail in the main report:

Several significant improvements to nutrient loading have occurred in the watershed since the mid-2000's.

- Total nitrogen loads from the three major WWTPs have decreased by 24 percent when comparing the average of 2005 to 2007 to the average of 2014 to 2018 and by 38 percent when comparing 2006 to 2018. Total phosphorus loads from these facilities have decreased by 69 percent or 81 percent when comparing either the averages of these periods or 2006 to 2018, respectively. Most of the minor WWTPs have also reduced loading from their facilities.
- Acres of agricultural production have declined by 44 percent. Nutrient management plans have reduced the rates of nutrient application to many of the crops grown in the Falls Lake watershed. Restoration of stream buffers, livestock exclusion, conservation tillage, and cover crops has expanded. The NC Department of Agriculture and Consumer Services indicates there is little opportunity for additional reductions from agricultural areas.
- Over 350 stormwater control retrofits had been installed by December 2015 to reduce nutrient loading from existing development.
- Rates of nitrogen deposition to the watershed and lake surface have decreased by approximately 25 percent.

To assess loading under a higher precipitation condition, an analysis was conducted to increase the rainfall by 20 percent relative to what occurred in 2015 to 2018. This analysis was generated by multiplying each 6-hr precipitation input by 1.2. This factor results in simulated annual precipitation at RDU airport ranging from 54.7 to 72.4 inches per year with an average of 64.3 inches.

Simulating 20 percent more rainfall across the watershed increased delivered nutrient and carbon loads to Falls Lake by 36 to 41 percent compared to the 2015 to 2018 conditions, depending on the parameter. Annual average delivered total nitrogen load increased from 1.65 million to 2.25 million (36 percent increase), delivered total phosphorus load increased from 183 thousand to 294 thousand (38 percent increase), and delivered total organic carbon load increased from 13.1 million to 18.5 million (41 percent increase).

Simulating 20 percent more rainfall across the watershed increased delivered nutrient and carbon loads to Falls Lake by 36 to 41 percent compared to the 2015 to 2018 conditions, depending on the parameter.

Table H-19 shows the delivered loads and areal loading rates by source for this “very wet” hydrologic condition. Note that areal loading rates for total nitrogen from forested areas range from 3.0 to 3.2 pounds of total nitrogen per acre per year and 0.3 to 0.55 pounds of total phosphorus per acre per year. These are approximately 1 pound per acre per year more of total nitrogen and 0.1 pound per acre per year more of total phosphorus compared to the UNRBA study period.

Table H-19. Load Delivered to Falls Lake and Areal Loading Rates by Individual Source (All Contributing Areas) for the Very Wet Condition (20 percent more rainfall than 2015 to 2018)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Conventional Grain Corn	169	Agriculture	823	4.9	175	1.03	5,101	30.1
Double-cropped Soybeans	3,350	Agriculture	9,690	2.9	1,728	0.52	92,961	27.7
Fescue (Pasture)	6,324	Agriculture	350,575	13.3	15,782	0.60	3,755,855	142.7
Fescue (Hay)	4,564	Agriculture	16,089	3.5	2,062	0.45	133,132	29.2
Flue-Cured Tobacco	2,736	Agriculture	22,364	8.2	2,607	0.95	77,697	28.4

Table H-19. Load Delivered to Falls Lake and Areal Loading Rates by Individual Source (All Contributing Areas) for the Very Wet Condition (20 percent more rainfall than 2015 to 2018)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Full Season Soybeans	5,861	Agriculture	17,550	3.0	3,265	0.56	169,316	28.9
No-Till Grain Corn	2,627	Agriculture	9,479	3.6	1,438	0.55	74,274	28.3
Wheat	820	Agriculture	4,053	4.9	494	0.60	24,079	29.4
DOT Roads, Connected	2,888	DOT	17,978	6.2	1,062	0.37	65,464	22.7
DOT Roads, Unconnected	9,976	DOT	41,016	4.1	2,237	0.22	160,679	16.1
ExDev, High Intensity	1,554	Urban	8,320	5.4	208	0.13	15,990	10.3
ExDev, Medium Intensity	4,449	Urban	31,135	7.0	1,480	0.33	98,988	22.3
ExDev, Low Intensity	12,610	Urban	84,486	6.7	8,145	0.65	436,786	34.6
Developed Open Space	42,981	Urban	195,345	4.5	16,976	0.39	1,348,460	31.4
IntDev, High Intensity	64	Urban	295	4.6	11	0.18	798	12.5
IntDev, Medium Intensity	330	Urban	1,527	4.6	106	0.32	7,363	22.3
IntDev, Low Intensity	252	Urban	1,220	4.8	130	0.51	8,115	32.2
NewDev, High Intensity	72	Urban	228	3.2	11	0.15	833	11.6
NewDev, Medium Intensity	298	Urban	1,016	3.4	85	0.28	6,568	22.0
NewDev, Low Intensity	339	Urban	1,159	3.4	169	0.50	9,576	28.3
Deciduous Forest	146,587	Forest	434,317	3.0	44,917	0.31	4,355,564	29.7
Coniferous Forest	68,503	Forest	221,261	3.2	37,377	0.55	2,275,110	33.2
Mixed Forest	75,917	Forest	224,862	3.0	31,831	0.42	2,320,304	30.6
Shrub / Scrub	7,368	Unmanaged grass/shrub	23,140	3.1	2,843	0.39	223,069	30.3
Unmanaged Grassland	41,484	Unmanaged grass/shrub	138,587	3.3	16,792	0.40	1,260,395	30.4
Barren	471	Barren	3,380	7.2	519	1.10	17,105	36.3
Emerg Herbaceous Wetland	406	Wetland	1,508	3.7	234	0.58	15,471	38.1
Woody Wetland	9,495	Wetland	41,943	4.4	5,745	0.61	435,590	45.9
Waterfowl Impoundment	839	Wetland	2,836	3.4	366	0.44	29,230	34.8
Water	4,455	Open Water	24,964	5.6	2,206	0.50	139,599	31.3
Initial System Mass	NA	GeneralNPS	23,603	NA	9,979	NA	197,795	NA
Stream Bank Erosion	NA	StreamBanks	32,053	NA	73,871	NA	302,509	NA
Direct Precipitation	NA	Direct Precipitation	103,365	NA	71	NA	147,479	NA
Direct Dry Deposition	NA	Direct Dry Deposition	11,446	NA	2,118	NA	8,320	NA
Privy	NA	Onsite WW (no DSF)	5	NA	0	NA	20	NA
Conventional Functioning	NA	Onsite WW (no DSF)	22,239	NA	3	NA	3,484	NA

Table H-19. Load Delivered to Falls Lake and Areal Loading Rates by Individual Source (All Contributing Areas) for the Very Wet Condition (20 percent more rainfall than 2015 to 2018)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Conventional Malfunctioning	NA	Onsite WW (no DSF)	4,637	NA	151	NA	47,652	NA
Advanced Treatment, Functioning	NA	Onsite WW (no DSF)	395	NA	0	NA	184	NA
Advanced Treatment, Malfunctioning	NA	OnsiteWW (no DSF)	147	NA	5	NA	1,590	NA
Advanced Treatment, Functioning >3000gpd	NA	OnsiteWW (no DSF)	1	NA	0	NA	1	NA
Major WWTPs	NA	Major WWTPs	94,735	NA	5,825	NA	204,640	NA
Minor WWTPs	NA	Minor WWTPs	17,172	NA	282	NA	20,042	NA
Discharging Sandfilter Systems (DSF)	NA	Discharging Sandfilter Systems	11,086	NA	969	NA	9,125	NA
Sanitary Sewer Overflows	NA	Sanitary Sewer Overflows	52	NA	7	NA	61	NA
Total	492.267		2,252,084	NA	294,278	NA	18,506,373	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

Figure H-29 through Figure H-31 compare the UNRBA WARMF simulated total nitrogen, total phosphorus, and total organic carbon loads delivered to Falls Lake for the dry to average condition (20 percent less rainfall) and the very wet condition (20 percent more rainfall). Only rainfall was changed for these analyses – all other drivers of pollutant loading remained constant across the two simulations. As the figures illustrate, simulating different hydrological conditions (e.g., dry years versus wet years) also affects the relative contribution of loading from each source to Falls Lake. As expected, under a dryer condition, the relative contribution from wastewater treatment plants increases as the loads from non-point sources decrease and under wet conditions the opposite occurs.

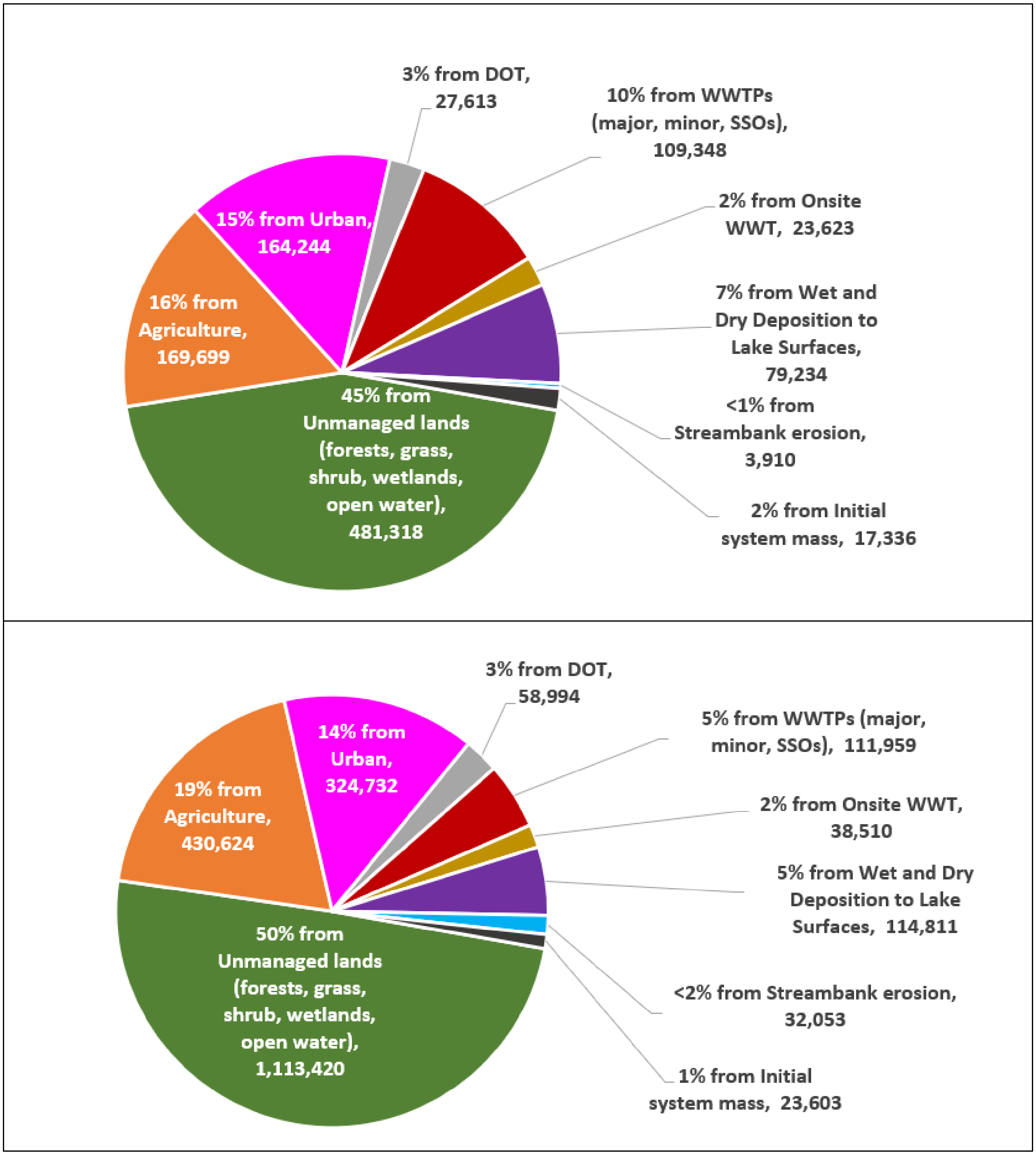


Figure H-29. Comparison of Annual Average Total Nitrogen Loads Delivered to Falls Lake for the Dry to Average Condition (1.1 million pounds per year, top panel) and the Very Wet Condition (2.25 million pounds per year, bottom panel)

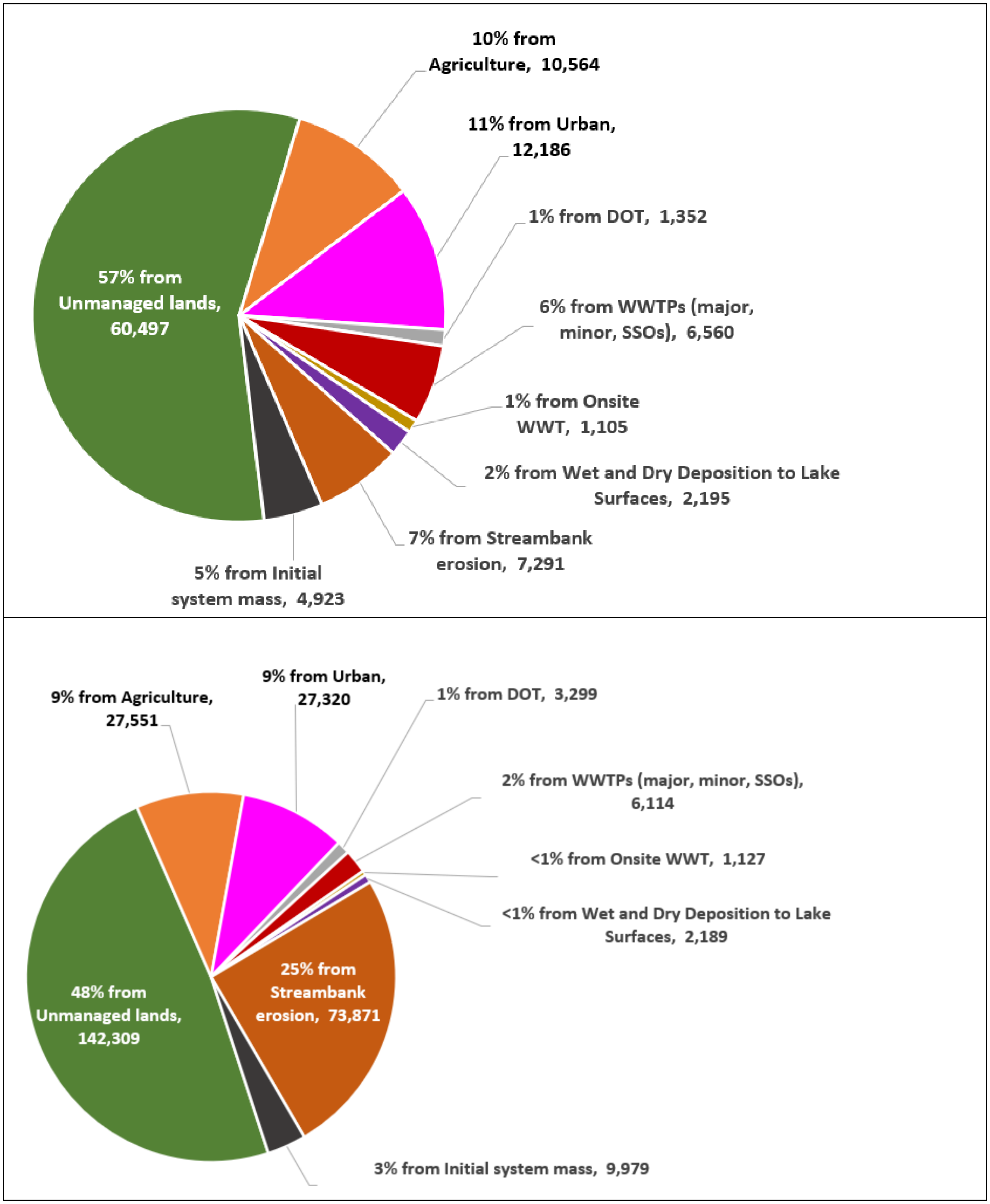


Figure H-30. Comparison of Annual Average Total Phosphorus Loads Delivered to Falls Lake for the Dry to Average Condition (107 thousand pounds per year, top panel) and the Very Wet Condition (294 thousand pounds per year, bottom panel)

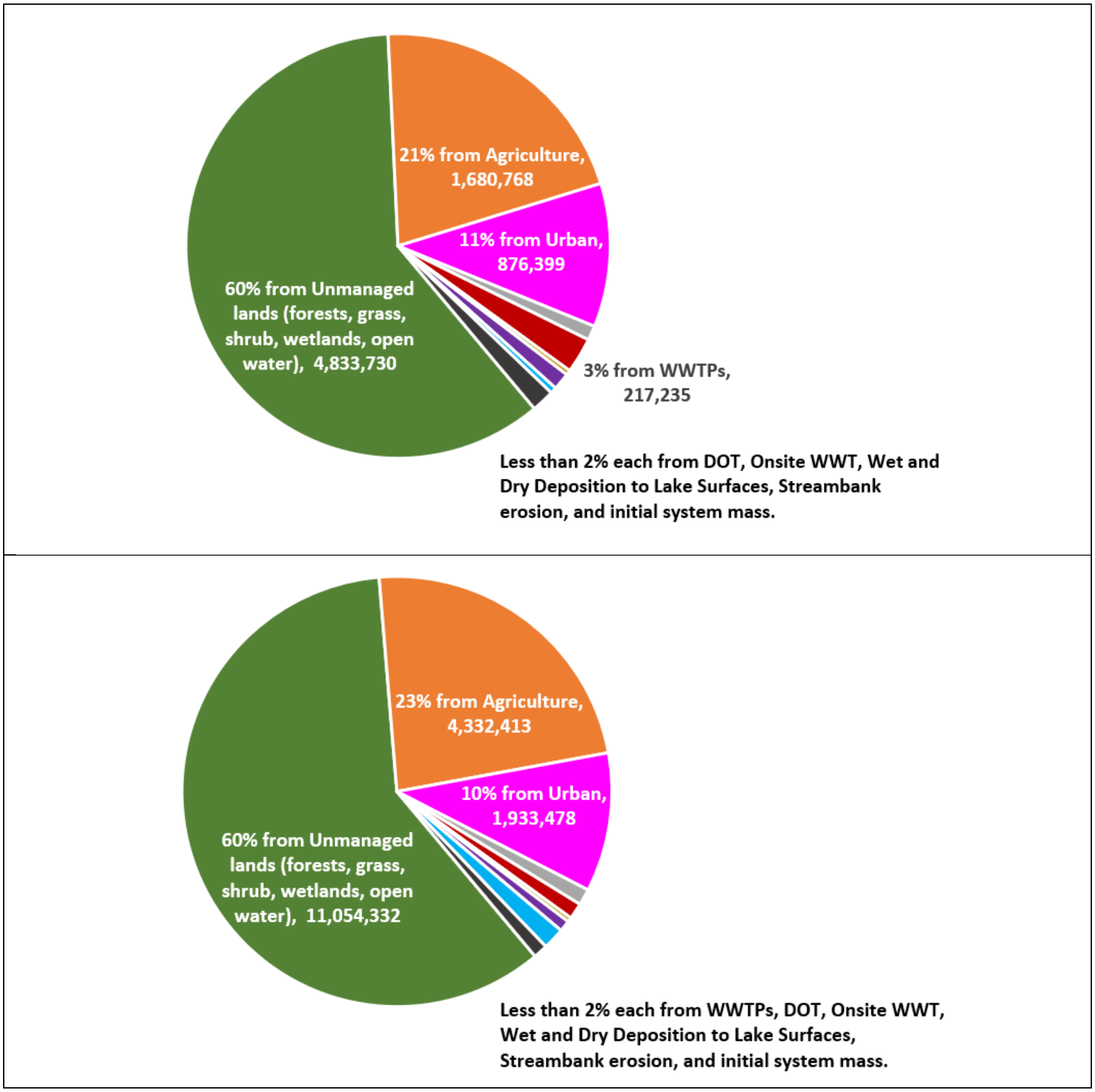


Figure H-31. Comparison of Annual Average Total Organic Carbon Loads Delivered to Falls Lake for the Dry to Average Condition (8.0 million pounds per year, top panel) and the Very Wet Condition (18.5 million pounds per year, bottom panel)

Sensitivity Analyses on Rates of Atmospheric Deposition

Atmospheric deposition of pollutants occurs as both dry deposition (i.e., the settling of dust and particulates) and wet deposition (associated with precipitation). Deposition that occurs on the watershed may be taken up by plants, infiltrated into the soil, washed off surfaces by stormwater runoff, or lost due to watershed processes (crop harvesting, denitrification, etc.). The WARMF model accounts for these processes in its simulations. Tributary water quality sampling used for model calibration accounts for the net effects all sources and processes that occur upstream of the sampling location.

WARMF simulates wet and dry atmospheric deposition of several modeled constituents. For nitrogen, the UNRBA WARMF model uses weekly precipitation chemistry and air chemistry data collected at stations that are 20 to 70 miles from the watershed. Other models for the region indicate that air deposition can be highly variable spatially, and that rates of nitrogen deposition are higher near urban areas compared to rural areas (Appendix D). The median total nitrogen deposition rate is 12 kg/ha/yr based on CASTNET data for 2000-2017 and 10 kg/ha/yr based on EPA EnviroAtlas models for 2011. Spatially distributed estimates of total nitrogen deposition for 2010-2012 ranged from 8-14 kg/ha/yr based on USGS SPARROW models. Since the time Appendix D was developed by researchers at the NC Collaboratory, online EPA EnviroAtlas models for 2016 have been published. This update reports nitrogen deposition rates for the watershed ranging from 8.1 kg/ha/yr in the rural areas and up to 9.4 kg/ha/yr in the more developed areas of the watershed which are lower than the 2011 estimates.

To address both the uncertainty with atmospheric deposition and potential changes due to additional air quality improvements, sensitivity analyses were developed that vary the deposition rates by plus or minus 25 percent applied to all deposition constituents simulated by the model (see Figures H-32 through H-34). This evaluation was requested by DWR modeling staff and subject matter experts during the model review process. Table H-20 and Table H-21 show the delivered loads and areal loading rates by source when 6-hour inputs of atmospheric deposition are multiplied by 0.75 (25 percent less) or 1.25 (25 percent more), respectively. The effect of these sensitivity analyses on loading rates and delivered loads to Falls Lake is much less than the effect of simulating a dry to average hydrologic condition or a very wet hydrologic condition. As noted in the main report, only a fraction of the nutrients applied or deposited to the watershed is delivered to Falls Lake (21 percent of total nitrogen and 16 percent of total phosphorus for the UNRBA study period).

Table H-20. Load Delivered to Falls Lake and Areal Loading Rates (All Contributing Areas) for the 25 Percent Less Atmospheric Deposition Sensitivity Analysis

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Conventional Grain Corn	169	Agriculture	591	3.5	120	0.71	3,700	21.8
Double-cropped Soybeans	3,350	Agriculture	6,470	1.9	1,134	0.34	63,792	19.0
Fescue (Pasture)	6,324	Agriculture	237,982	9.0	10,676	0.41	2,535,188	96.3
Fescue (Hay)	4,564	Agriculture	11,244	2.5	1,436	0.31	92,907	20.4
Flue-Cured Tobacco	2,736	Agriculture	15,900	5.8	1,708	0.62	53,384	19.5
Full Season Soybeans	5,861	Agriculture	11,929	2.0	2,196	0.37	118,402	20.2
No-Till Grain Corn	2,627	Agriculture	6,316	2.4	993	0.38	51,157	19.5
Wheat	820	Agriculture	2,735	3.3	350	0.43	16,874	20.6
DOT Roads, Connected	2,888	DOT	12,327	4.3	750	0.26	45,885	15.9
DOT Roads, Unconnected	9,976	DOT	25,682	2.6	1,480	0.15	103,315	10.4
ExDev, High Intensity	1,554	Urban	6,092	3.9	154	0.10	10,885	7.0
ExDev, Medium Intensity	4,449	Urban	22,942	5.2	1,047	0.24	68,848	15.5
ExDev, Low Intensity	12,610	Urban	61,881	4.9	5,739	0.46	317,470	25.2
Developed Open Space	42,981	Urban	128,984	3.0	11,998	0.28	952,505	22.2
IntDev, High Intensity	64	Urban	197	3.1	8	0.13	552	8.6

Table H-20. Load Delivered to Falls Lake and Areal Loading Rates (All Contributing Areas) for the 25 Percent Less Atmospheric Deposition Sensitivity Analysis

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
IntDev, Medium Intensity	330	Urban	1,038	3.1	73	0.22	5,085	15.4
IntDev, Low Intensity	252	Urban	845	3.3	87	0.35	5,741	22.8
NewDev, High Intensity	72	Urban	150	2.1	7	0.10	552	7.7
NewDev, Medium Intensity	298	Urban	666	2.2	59	0.20	4,547	15.2
NewDev, Low Intensity	339	Urban	801	2.4	118	0.35	6,931	20.5
Deciduous Forest	146,587	Forest	294,165	2.0	31,543	0.22	3,013,335	20.6
Coniferous Forest	68,503	Forest	160,074	2.3	26,398	0.39	1,668,970	24.4
Mixed Forest	75,917	Forest	159,979	2.1	22,450	0.30	1,670,982	22.0
Shrub / Scrub	7,368	Unmanaged grass/shrub	15,389	2.1	1,972	0.27	154,678	21.0
Unmanaged Grassland	41,484	Unmanaged grass/shrub	89,977	2.2	11,585	0.28	872,360	21.0
Barren	471	Barren	2,483	5.3	356	0.75	12,996	27.6
Emerg Herbaceous Wetland	406	Wetland	1,127	2.8	168	0.41	11,652	28.7
Woody Wetland	9,495	Wetland	31,148	3.3	4,160	0.44	326,231	34.4
Waterfowl Impoundment	839	Wetland	2,143	2.6	264	0.32	22,636	27.0
Water	4,455	Open Water	17,931	4.0	1,598	0.36	102,516	23.0
Initial System Mass	NA	GeneralNPS	18,917	NA	6,041	NA	156,039	NA
Stream Bank Erosion	NA	StreamBanks	12,553	NA	26,409	NA	122,282	NA
Direct Precipitation	NA	Direct Precipitation	64,266	NA	45	NA	91,498	NA
Direct Dry Deposition	NA	Direct Dry Deposition	8,539	NA	1,594	NA	6,200	NA
Privy	NA	Onsite WW (no DSF)	2	NA	0	NA	11	NA
Conventional Functioning	NA	Onsite WW (no DSF)	15,588	NA	2	NA	2,268	NA
Conventional Malfunctioning	NA	Onsite WW (no DSF)	3,276	NA	105	NA	33,075	NA
Advanced Treatment, Functioning	NA	Onsite WW (no DSF)	270	NA	0	NA	117	NA
Advanced Treatment, Malfunctioning	NA	OnsiteWW (no DSF)	104	NA	3	NA	1,119	NA
Advanced Treatment, Functioning >3000gpd	NA	OnsiteWW (no DSF)	0.47	NA	0	NA	0	NA
Major WWTPs	NA	Major WWTPs	93,718	NA	6,113	NA	201,639	NA
Minor WWTPs	NA	Minor WWTPs	16,988	NA	296	NA	19,748	NA
Discharging Sandfilter Systems (DSF)	NA	Discharging Sandfilter Systems	10,967	NA	1,017	NA	8,991	NA

Table H-20. Load Delivered to Falls Lake and Areal Loading Rates (All Contributing Areas) for the 25 Percent Less Atmospheric Deposition Sensitivity Analysis

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Sanitary Sewer Overflows	NA	Sanitary Sewer Overflows	51	NA	7	NA	60	NA
Total	492.267		1,574,429	NA	182,259	NA	12,957,123	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

Table H-21. Load Delivered to Falls Lake and Areal Loading Rates (All Contributing Areas) for the 25 Percent More Atmospheric Deposition Sensitivity Analysis

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Conventional Grain Corn	169	Agriculture	623	3.7	120	0.71	3,800	22.4
Double-cropped Soybeans	3,350	Agriculture	6,915	2.1	1,138	0.34	65,833	19.7
Fescue (Pasture)	6,324	Agriculture	238,811	9.1	10,705	0.41	2,553,917	97.0
Fescue (Hay)	4,564	Agriculture	11,709	2.6	1,445	0.32	95,603	20.9
Flue-Cured Tobacco	2,736	Agriculture	17,188	6.3	1,710	0.63	55,107	20.1
Full Season Soybeans	5,861	Agriculture	12,741	2.2	2,207	0.38	122,108	20.8
No-Till Grain Corn	2,627	Agriculture	6,677	2.5	997	0.38	52,633	20.0
Wheat	820	Agriculture	2,837	3.5	352	0.43	17,440	21.3
DOT Roads, Connected	2,888	DOT	15,486	5.4	769	0.27	48,193	16.7
DOT Roads, Unconnected	9,976	DOT	32,227	3.2	1,515	0.15	107,693	10.8
ExDev, High Intensity	1,554	Urban	8,137	5.2	184	0.12	13,160	8.5
ExDev, Medium Intensity	4,449	Urban	27,695	6.2	1,096	0.25	73,500	16.5
ExDev, Low Intensity	12,610	Urban	70,161	5.6	5,784	0.46	327,171	25.9
Developed Open Space	42,981	Urban	152,716	3.6	12,120	0.28	979,087	22.8
IntDev, High Intensity	64	Urban	281	4.4	9	0.15	647	10.1
IntDev, Medium Intensity	330	Urban	1,283	3.9	76	0.23	5,396	16.3
IntDev, Low Intensity	252	Urban	953	3.8	88	0.35	5,891	23.4
NewDev, High Intensity	72	Urban	205	2.9	8	0.12	620	8.6
NewDev, Medium Intensity	298	Urban	801	2.7	60	0.20	4,736	15.9
NewDev, Low Intensity	339	Urban	892	2.6	118	0.35	7,115	21.0
Deciduous Forest	146,587	Forest	310,212	2.1	31,484	0.21	3,094,524	21.1
Coniferous Forest	68,503	Forest	168,590	2.5	26,694	0.39	1,717,434	25.1
Mixed Forest	75,917	Forest	167,863	2.2	22,612	0.30	1,719,741	22.7
Shrub / Scrub	7,368	Unmanaged grass/shrub	16,658	2.3	1,977	0.27	158,916	21.6

Table H-21. Load Delivered to Falls Lake and Areal Loading Rates (All Contributing Areas) for the 25 Percent More Atmospheric Deposition Sensitivity Analysis

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN lb/ac/yr	TP lb/yr	TP lb/ac/yr	TOC lb/yr	TOC lb/ac/yr
Unmanaged Grassland	41,484	Unmanaged grass/shrub	100,835	2.4	11,657	0.28	897,257	21.6
Barren	471	Barren	2,888	6.1	357	0.76	13,359	28.3
Emerg Herbaceous Wetland	406	Wetland	1,175	2.9	169	0.42	11,942	29.4
Woody Wetland	9,495	Wetland	32,349	3.4	4,179	0.44	333,757	35.2
Waterfowl Impoundment	839	Wetland	2,303	2.7	272	0.32	23,668	28.2
Water	4,455	Open Water	20,772	4.7	1,606	0.36	105,522	23.7
Initial System Mass	NA	GeneralNPS	20,568	NA	6,350	NA	167,451	NA
Stream Bank Erosion	NA	StreamBanks	13,306	NA	26,468	NA	126,771	NA
Direct Precipitation	NA	Direct Precipitation	106,924	NA	74	NA	152,307	NA
Direct Dry Deposition	NA	Direct Dry Deposition	14,221	NA	2,664	NA	10,338	NA
Privy	NA	Onsite WW (no DSF)	3	NA	0	NA	11	NA
Conventional Functioning	NA	Onsite WW (no DSF)	18,346	NA	2	NA	2,271	NA
Conventional Malfunctioning	NA	Onsite WW (no DSF)	3,288	NA	105	NA	33,100	NA
Advanced Treatment, Functioning	NA	Onsite WW (no DSF)	321	NA	0	NA	117	NA
Advanced Treatment, Malfunctioning	NA	OnsiteWW (no DSF)	104	NA	3	NA	1,122	NA
Advanced Treatment, Functioning >3000gpd	NA	OnsiteWW (no DSF)	1	NA	0	NA	0	NA
Major WWTPs	NA	Major WWTPs	93,864	NA	6,094	NA	201,598	NA
Minor WWTPs	NA	Minor WWTPs	17,014	NA	295	NA	19,744	NA
Discharging Sandfilter Systems (DSF)	NA	Discharging Sandfilter Systems	10,984	NA	1,014	NA	8,989	NA
Sanitary Sewer Overflows	NA	Sanitary Sewer Overflows	52	NA	7	NA	60	NA
Total	492.267		1,730,978	NA	184,586	NA	13,339,653	NA

Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

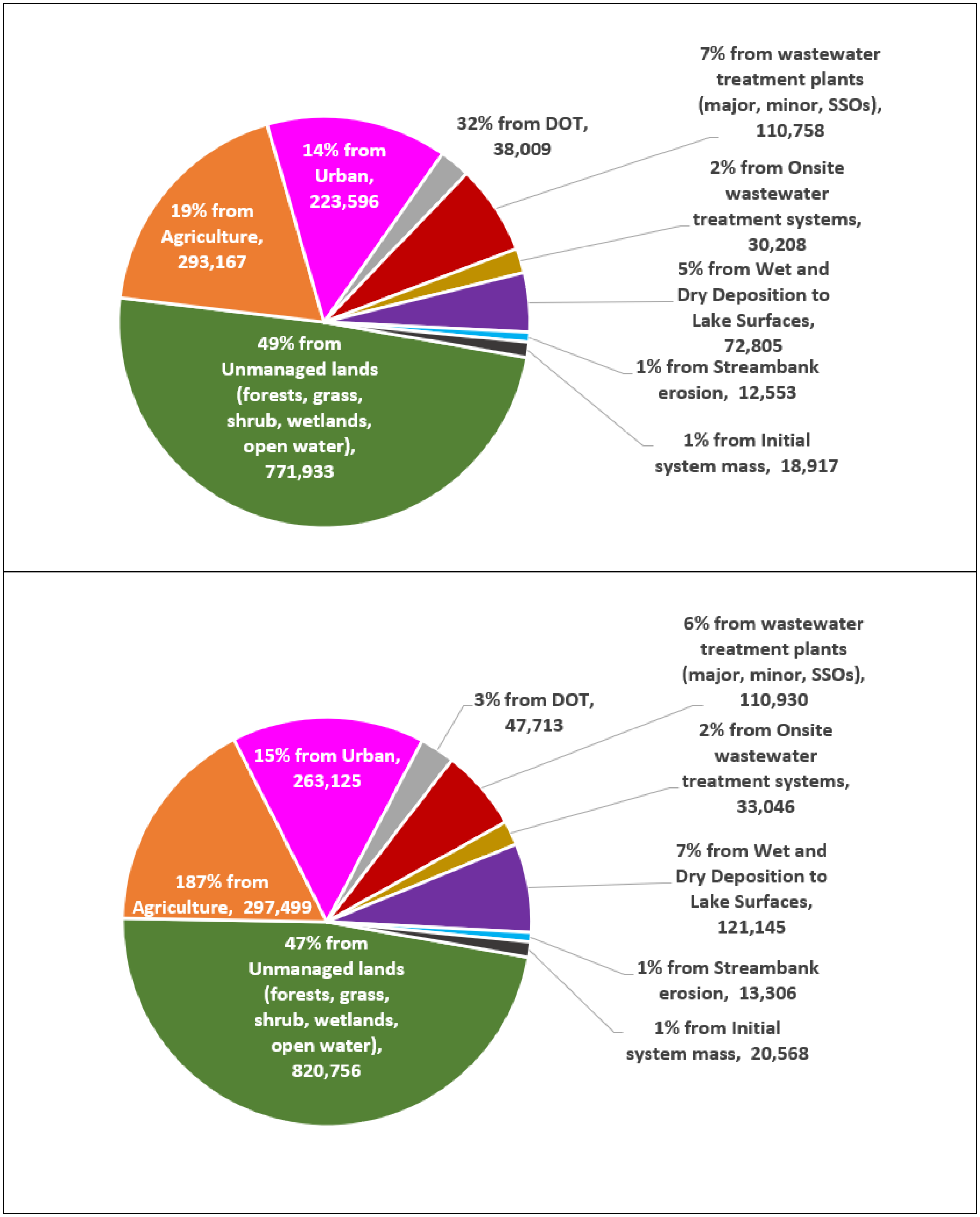


Figure H-32. Comparison of Annual Average Total Nitrogen Loads Delivered to Falls Lake for the 25 Percent Less Atmospheric Deposition (1.57 million pounds per year, top panel) and the 25 Percent More Atmospheric Deposition (1.73 million pounds per year, bottom panel)

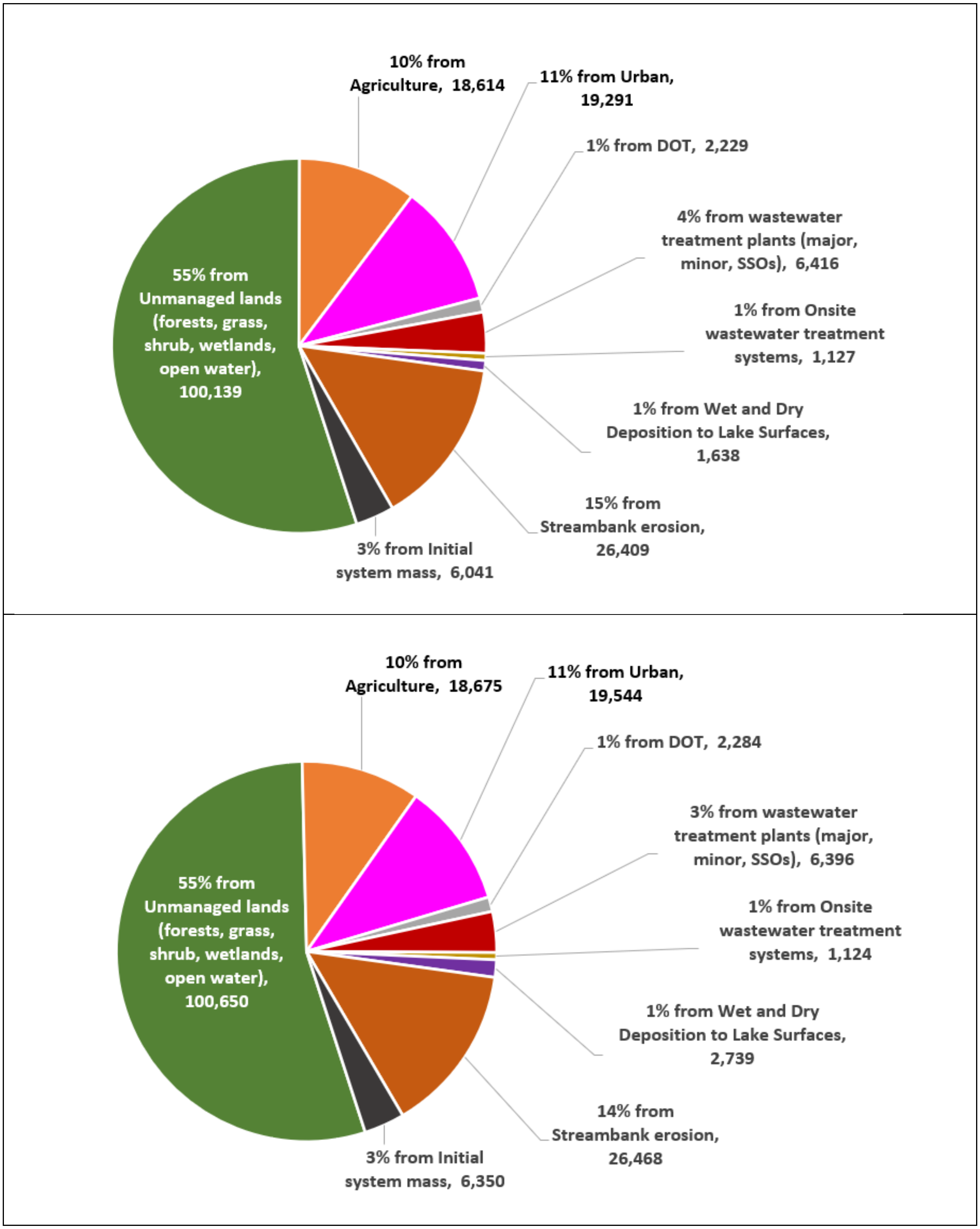


Figure H-33. Comparison of Annual Average Total Phosphorus Loads Delivered to Falls Lake for the 25 Percent Less Atmospheric Deposition (182 thousand pounds per year, top panel) and the 25 Percent More Atmospheric Deposition (184 thousand pounds per year, bottom panel)

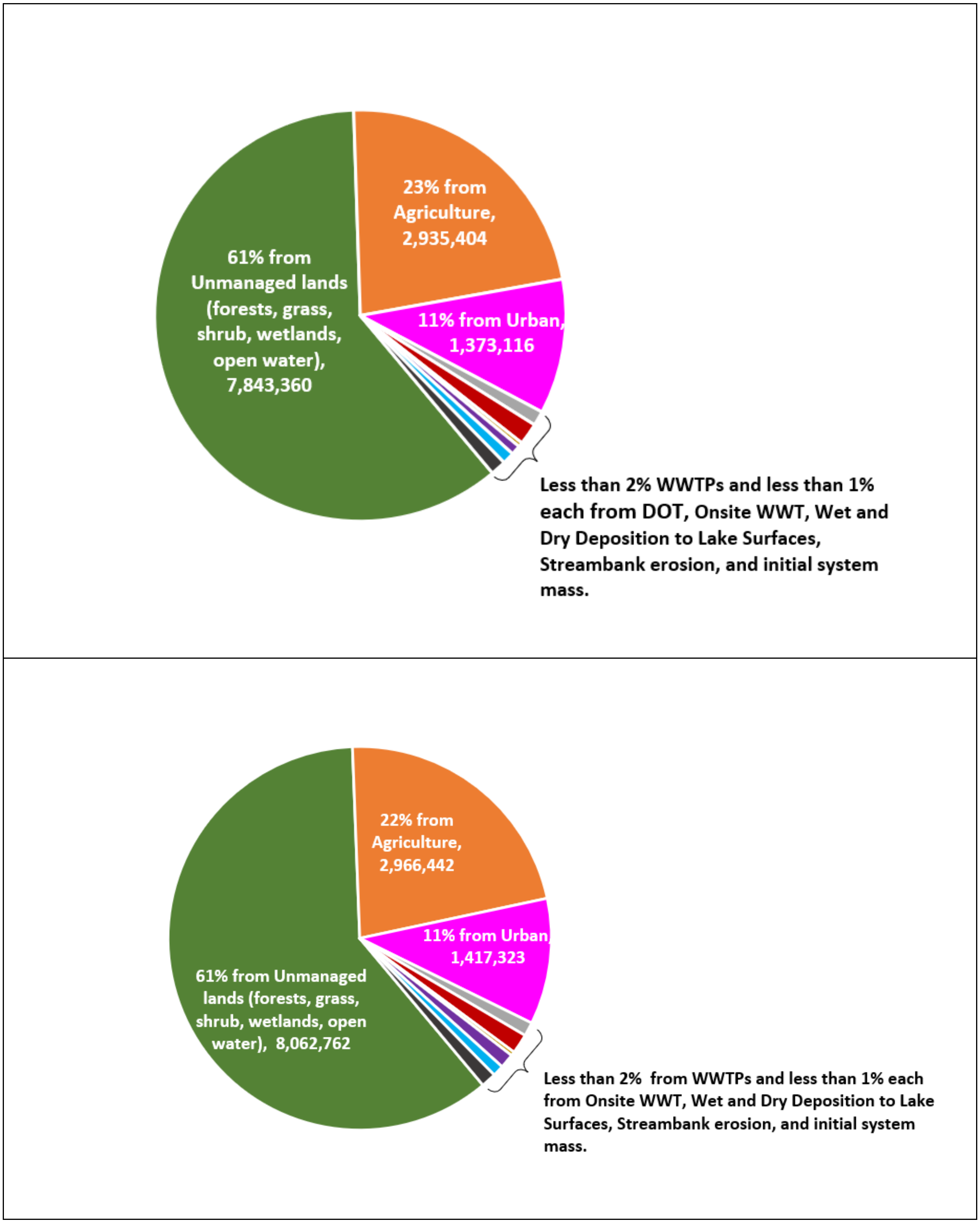


Figure H-34. Comparison of Annual Average Total Organic Carbon Loads Delivered to Falls Lake for the 25 Percent Less Atmospheric Deposition (13.0 million pounds per year, top panel) and the 25 Percent More Atmospheric Deposition (13.3 million pounds per year, bottom panel)

Land Conversion Scenario to All Forest or Wetland

The Scenario Screening Workgroup (SSG) of the MRSW selected this scenario to place a limit on what would be possible in Falls Lake with most human watershed inputs and impacts instantaneously removed. While there is no logistical way to reforest the watershed and remove humans and their impacts, this scenario simulates the “best case” condition for the watershed and the lake under a hypothetical condition given the size of the watershed, current soil characteristics, and current rates of atmospheric deposition. The human inputs and impacts removed from this scenario include point source discharges, nutrient application, impervious surfaces, and onsite wastewater treatment systems. All land uses except for wetlands and sub-impoundments were converted to mixed forests for this scenario.

By setting this scenario as the limit to the range of possible watershed modification conditions (i.e., the best that could hypothetically be achieved) the number of nutrient reduction scenarios that need to be evaluated for reduction curves is also moderated. In other words, no watershed management action would achieve better than full conversion to forest.

Wetlands were simulated as wetlands in this scenario rather than converted to forest given the hydrology of these areas. Processes in place for sub-impoundments were left as well. From an overall loading standpoint, removing the sub-impoundments would actually increase loading to the lake under the “all forest” scenario. During their work, the SSG discussed that in the absence of human activity, wildlife activity in the watershed would be different. For example, the prevalence of beaver impoundments might be much higher absent human activity which would create more wetlands. However, it would be difficult to project future beaver activity absent human activity under this scenario. Similarly, it would be difficult to project any wildlife behavioral or population changes under this scenario. Therefore, wildlife behavior and increased presence of beaver impoundments were not considered in this scenario.

This scenario predicts what would happen if the changes to land use and human activities were made instantly to present conditions: it does not represent conditions if humans were never present in the watershed. Beyond the land use conversion, removal of onsite and centralized wastewater treatment systems, and cessation of nutrient application, other characteristics of the watershed were not altered for this scenario, nor were the meteorologic and atmospheric deposition inputs. The hydrologic response characteristics and initial conditions of the soils in the watershed are the same as the calibrated model, and these had been adjusted during model calibration to simulate the flashy nature of some of these streams and to calibrate to tributary streamflow and water quality observations. In addition, the parameters that describe the stability of stream banks were not changed from the calibrated model.

This scenario predicts what would happen if all land in the watershed were suddenly converted to a wooded condition, onsite and centralized wastewater treatment systems were removed, and nutrient application ceased. However, it does not represent a projection of conditions if humans were never present in the watershed.

As noted, the other water supply impoundments (i.e., sub-impoundments) were also simulated in this scenario including Lake Orange, West Fork Eno River Reservoir, Little River Reservoir, Lake Michie, Lake Butner, and Lake Rogers. Compton’s Pond, Lake Ben Johnson, Lake Rogers, and Corporation Lake are simulated in the UNRBA WARMF model as river reaches. The SSG originally indicated this scenario should be run without these impoundments. However, these impoundments result in a loss of nutrients from the system, and their simulated removal would cause nutrient loads delivered to

Falls Lake to increase over the loading from forest conversion with sub-impoundments. Also, the nutrient reduction curves that were evaluated with the lake models account for these impoundments. Because the UNRBA intends to compare this scenario to the load reduction curves, the PFC requested this scenario be evaluated with the impoundments in place.

This scenario was named “Hypothetical Land Conversion to Forest” to include the changes noted above. This scenario is sometimes abbreviated to “All Forest” for easier display on figures, tables, and presentation materials. The Hypothetical Land Conversion to Forest scenario was evaluated for two hydrologic conditions: the average to wet rainfall condition represented by the UNRBA study period and the dry to average hydrologic condition (20 percent lower rainfall). The average to wet rainfall condition provides a comparison to the UNRBA calibrated model. The dry to average rainfall condition provides a comparison to the hydrologic condition used to establish the Falls Lake Rules. See Figures H-35 through H-37.)

This scenario also informs the petition for a site-specific chlorophyll-a standard for Falls Lake and address the feasibility of achieving the current chlorophyll-a standard of 40 μg/L. The UNRBA lake modeling (summarized in a separate report) shows that even this hypothetical scenario cannot achieve the chlorophyll-a standard everywhere in Falls Lake. This finding provides another reason a site-specific chlorophyll-a standard is needed (i.e., humans cannot be forcibly removed from the watershed with all land uses converted instantly to forests). The primary cause of exceedances of the standard is the dam and the artificial hydraulic conditions in the reservoir. EPA acknowledges the following justification for use attainability analysis in 40 CFR 131.10(g): “Dams, diversions or other types of hydrologic modifications preclude the attainment of the use, and it is not feasible to restore the water body to its original condition or to operate such modification in a way that would result in the attainment of the use.” While this justification is specific to use attainability analyses and variances, it also can be used as justification for a site-specific standard, particularly for a non-toxic constituent like chlorophyll-a.

Site-specific modeling for the Falls Lake watershed reflects conditions that are different than most studied waterbodies that are often located in more intensely managed watersheds. The site-specific characteristics and uncertainty associated with the previous modeling is why the Falls Lake Rules include an adaptive management provision allowing a more detailed evaluation of the lake and watershed. The role of unmanaged areas in the nutrient balance of Falls Lake is a critical finding and forms a different view of how to effectively manage nutrients in the watershed to protect and improve water quality in the lake. This is the result of a careful scientific evaluation, and it challenges some long-held views of how developed areas and unmanaged areas impact watershed nutrient loading. One of the prominent researchers in stormwater management, Dr. Bill Hunt at NCSU, has noted this recently (as noted, he came to a UNRBA PFC meeting and shared his findings relative to recent research and evaluation). He noted that depending on hydrologic condition, wooded areas can export more nutrient load than urban developments. He also showed that when rainfall amounts increase, nutrient concentrations from pervious areas, including wooded areas, increase. **He described his findings as an important “Aha Moment” that have resulted in a change in his own perspective.** The UNRBA conclusions are consistent with Dr. Hunt’s work and findings.

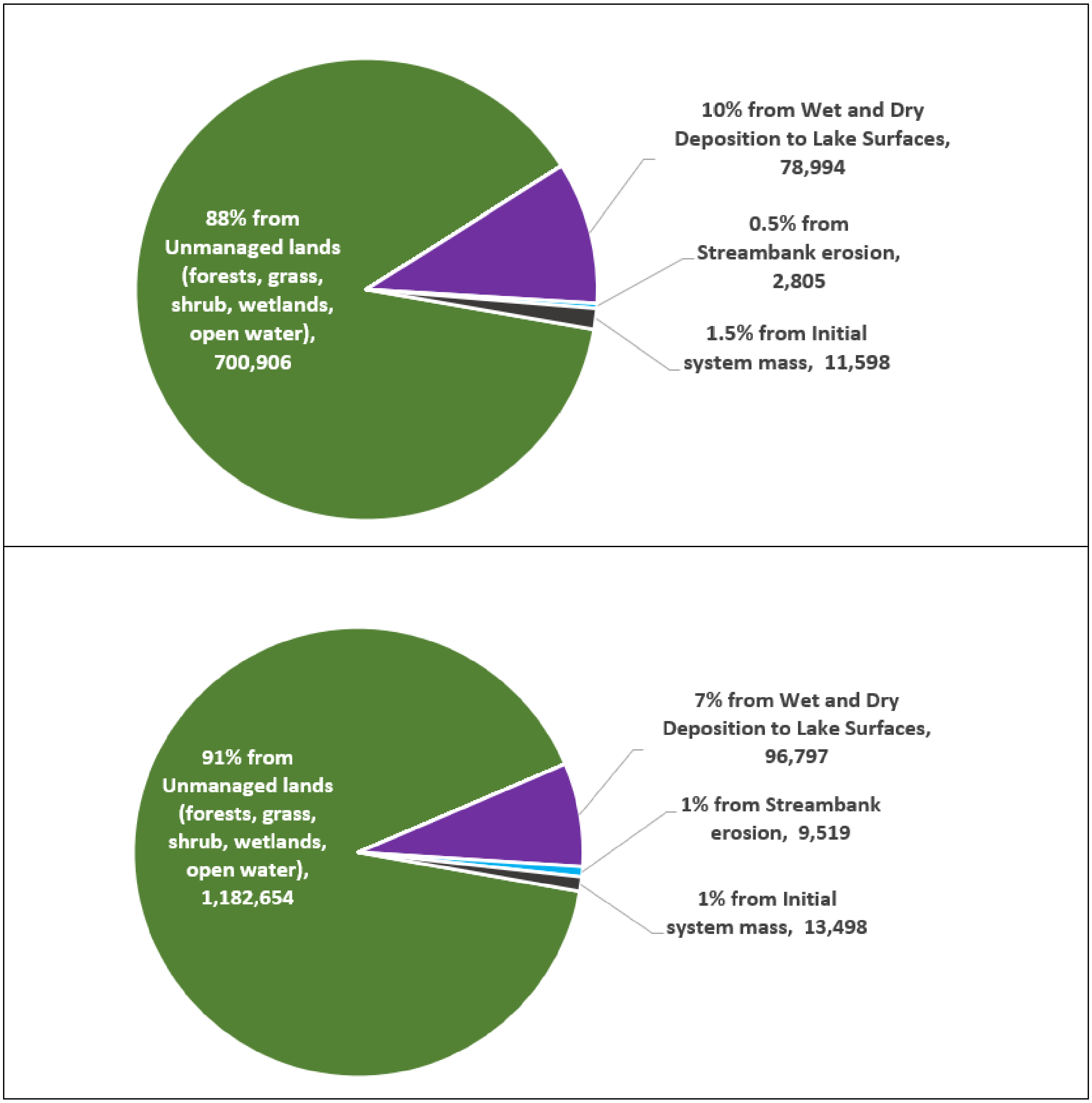


Figure H-35. Comparison of Annual Average Total Nitrogen Loads Delivered to Falls Lake for the Hypothetical Land Conversion to Forest under the Dry to Average Rainfall Condition (0.8 million pounds per year, top panel) and the Average to Wet Rainfall Condition (1.3 million pounds per year, bottom panel)

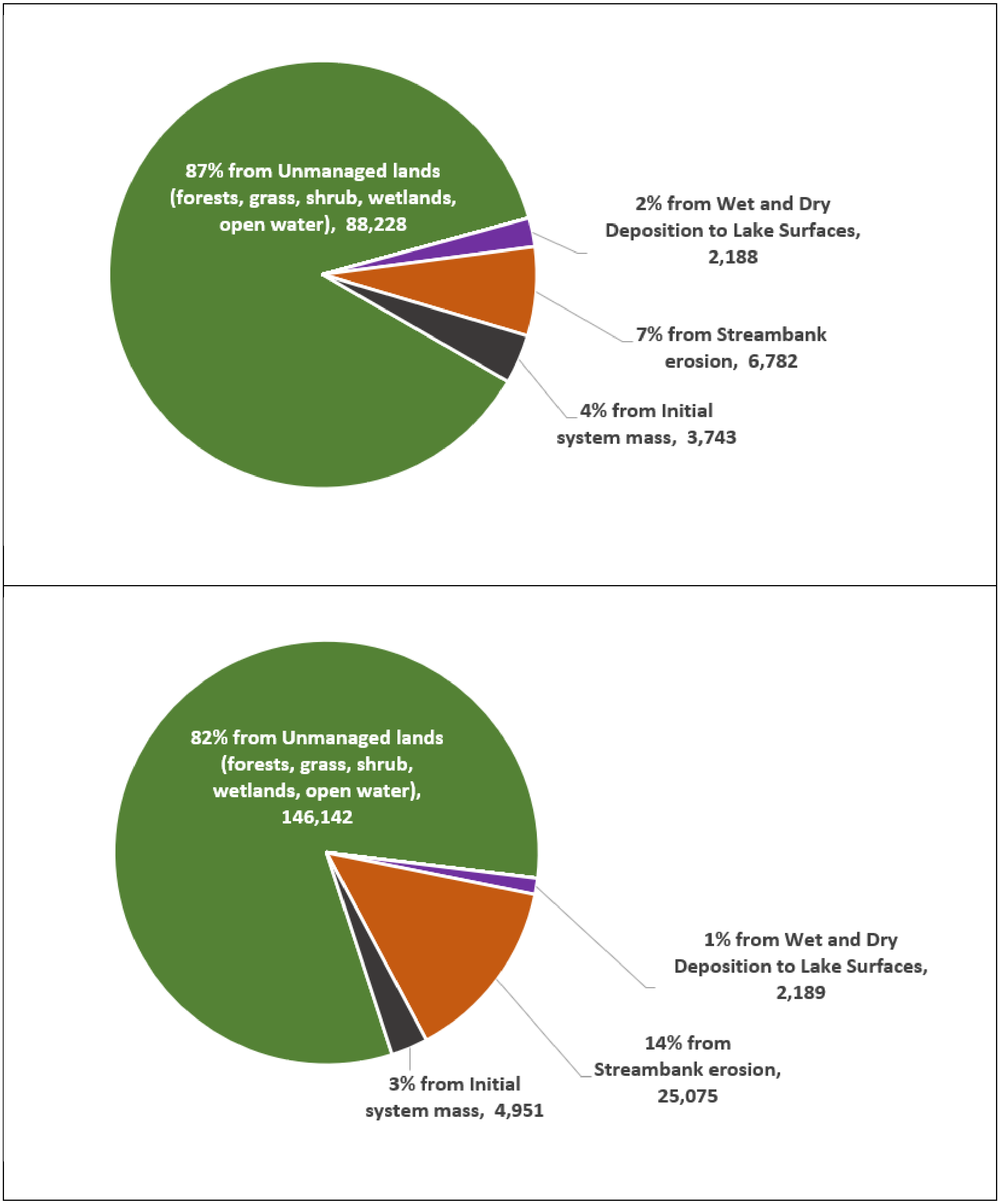


Figure H-36. Comparison of Annual Average Total Phosphorus Loads Delivered to Falls Lake for the Hypothetical Land Conversion to All Forest for the Dry to Average Rainfall Condition (101 thousand pounds per year, top panel) and the Average to Wet Rainfall Condition (178 thousand pounds per year, bottom panel)

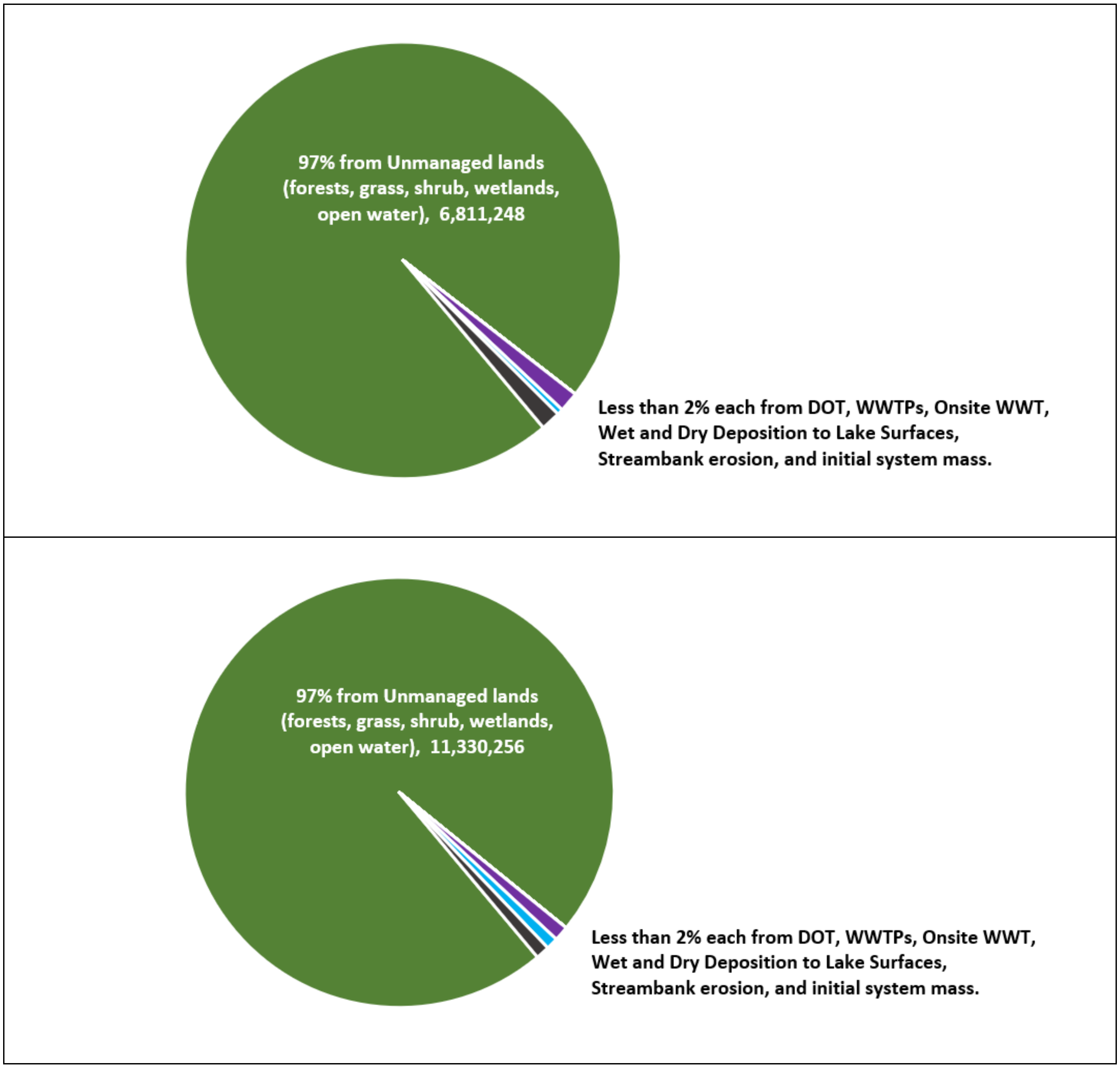


Figure H-37. Comparison of Annual Average Total Organic Carbon Loads Delivered to Falls Lake for the Hypothetical Land Conversion to All Forest for the Dry to Average Rainfall Condition (7 million pounds per year, top panel) and for the Average to Wet Rainfall Condition (11.7 million pounds per year, bottom panel)

The Hypothetical Land Conversion to Forest scenario was evaluated using the same vertical hydraulic conductivities as the calibrated model. This parameter was adjusted during model calibration such that catchments draining to a gage were assigned the same set of vertical hydraulic conductivities for the five soil layers. The ten USGS gages in the Falls Lake watershed drain catchments that either in the Carolina Slate Belt or the Triassic Basin. The land use composition of catchments draining to a particular gage is also similar. Maps of geologic basin, land use, and USGS gage locations are provided in the main report. “Third-party” reviewers raised the issue of the impact of conversion of developed land to forest on the hydraulic conductivity. To address this, the modeling team looked at a subwatershed with a high level of development (Ellerbe Creek subwatershed) where the vertical hydraulic conductivities were modified during model calibration to match observed stream flows.

The Ellerbe Creek subwatershed has two USGS gages along the tributary. This subwatershed is in the Triassic Basin and includes a higher percentage of urban lands than other catchments in the watershed which are relatively rural. During model calibration, the vertical hydraulic conductivities in the Ellerbe Creek subwatershed were adjusted down relative to other catchments in the Triassic Basin. However, these catchments also have relatively low vertical hydraulic conductivities because Triassic Basin soils are predominantly clay and already have relatively low infiltration rates. During review of the Hypothetical Land Conversion to Forest scenario, one of the “third-party” reviewers inquired about adjusting the vertical hydraulic conductivities in the catchments that had been adjusted during calibration to evaluate the effects that reduced vertical hydraulic conductivities would have on delivered loading rates to Falls Lake.

A separate sensitivity analysis was conducted that adjusted the Ellerbe Creek vertical hydraulic conductivities to match those of the other Triassic Basin catchments for the Hypothetical Land Conversion to Forest Scenario. Ellerbe Creek represents 3 percent of the drainage area to Falls Lake and includes 25 percent of the existing development and 11 percent of the developed open space present in the Falls Lake watershed. Increasing the vertical hydraulic conductivities to those of the more rural catchments in the Triassic Basin resulted in 15.5 percent less total nitrogen, 19.1 percent less total phosphorus, and 15.7 percent less total organic carbon delivered from Ellerbe Creek to Falls Lake. The However, Ellerbe Creek only comprises 3 percent of the total area of the Falls Lake watershed, so the total delivered loads to Falls Lake only decreased by 0.7 percent, 1.6 percent, and 0.7 percent, respectively. This sensitivity analysis was discussed at the April 2023 PFC meeting.

Comparison of Delivered Loads to Falls Lake for the Sensitivity Analyses and Model Scenarios

This section compares the simulated delivered loads of total nitrogen, total phosphorus, and total organic carbon for the UNRBA WARMF calibrated model to the watershed-wide sensitivity analyses and scenarios described in the preceding section. Comparisons are first presented for the total loads delivered to Falls Lake from the entire watershed (approximately 492 thousand acres). Comparisons are also provided for the total delivered loads from only from the upper five tributaries which are approximately 316 thousand acres, or approximately 64 percent of the watershed area. Only the upper five tributaries were assigned load allocations in the Falls Lake Rules, so these five-tributary loading summaries are included for comparison to the Falls Lake Rules.

The allowable loads and the baseline loads from the Falls Lake Rules are included for comparison to the model simulations for the upper five tributaries. The baseline loads in the Falls Lake Rules were based on conditions present in the watershed in 2006 (rainfall, stream flows, land use, loading from WWTPs, atmospheric deposition, and nutrient application rates, etc.). The baseline loads stated in the Rules were based on gaged flows and tributary water quality data from the five largest tributaries in the watershed for 2006. The baseline period for the DWR watershed model (2005 to 2007) occurred during a historic drought for central North Carolina so stream flows and delivered loads are much lower than the UNRBA study period. 2006 had a total rainfall similar to average rainfall conditions, but most of that rainfall was delivered in three very large storms, and the preceding year was very dry (37.5 inches).

Several scenarios and sensitivity analyses are compared in this section. Possible variants among these analyses are listed in the comparison tables and include the following:

- **Land uses** are represented as 2015 to 2018 average conditions, 2006 conditions, or the hypothetical land conversion to forest condition ("All Forest")
- **Rainfall** is simulated as either average to wet based on the 6-hr precipitation inputs for the 2015 to 2018 model, dry to average rainfall where each of the 6-hr precipitation inputs is multiplied by 0.8, or very wet where each of the 6-hr precipitation inputs is multiplied by 1.2
- **Onsite and centralized wastewater treatment systems and nutrient application** are based on the 2015 to 2018 average condition, 2006 average condition, or "none" to represent the hypothetical land conversion to forest
- Rates of **atmospheric deposition** are based on the CASTNET and NADP data collected near the watershed and used to develop 6-hour inputs for 2015 to 2018, the 2015 to 2018 rates multiplied by 0.75 to represent 25 percent less atmospheric deposition, the 2015 to 2018 rates multiplied by 1.25 to represent 25 percent more atmospheric deposition, or the 2006 conditions inherently captured in the baseline tributary monitoring data.
- **Vertical hydraulic conductivities** in the Ellerbe Creek watershed were increased for the hypothetical land conversion to forest scenario. These conductivities had been reduced during model calibration to better reflect the flashiness of the Ellerbe Creek watershed. Vertical hydraulic conductivities were increased to match other catchments in the Triassic Basin.

Table H-22 and Table H-23 compare the delivered total flow and total nutrient loads to Falls Lake for total nitrogen and total phosphorus, respectively, <u>for the entire watershed</u>. The first row of each table represents the loading from the "UNRBA Study Period" which is the calibrated watershed model for 2015 to 2018. These calibrated loads are called "recent loads" in the last column, and these are the loads that all other analyses are compared to. For both total nitrogen and total phosphorus, the largest simulated reduction in delivered loading results under a dry to average rainfall condition when delivered flows are lowest. When all other watershed characteristics stay the same, the total nitrogen delivered load decreases by 35 percent and the total phosphorus delivered load decreases by 42 percent when precipitation is 20 percent lower (the short name for this scenario in the tables is "20 percent less rainfall"). Even under a hypothetical scenario where onsite and centralized wastewater treatment systems and nutrient application are removed and all land is instantly converted to forests, if the hydrologic condition is simulated with average to wet rainfall, the total nitrogen delivered load only decreases by 25 percent and the total phosphorus delivered load only decreases by 3 percent (the short name for this scenario in the tables is "All Forest, study period rainfall"). If the hypothetical land use/no wastewater or nutrient application inputs are simulated under a dry to average rainfall condition, then the total nitrogen delivered load decreases by 52 percent and the total phosphorus delivered load decreases by 45 percent (the short name for this scenario in the tables is "All Forest, 20 percent less rainfall"). Even if rates of atmospheric deposition are adjusted across the watershed by plus or minus 25 percent, the total nitrogen delivered load only changes by up to 5 percent and the total phosphorus load only changes by up to 1 percent (the short names for these scenarios in the tables are 25 percent less atm. dep and 25 percent more atm. dep). These scenarios further support that hydrologic condition and rainfall are the primary drivers of loading to Falls Lake. Land use conversion or treatment of existing land under management will have a limited impact on overall lake nutrient loading.

The Falls Lake watershed is currently 75 percent unmanaged. This condition is the reason the lake continues to meet its designated uses. The UNRBA is focused on developing a nutrient management strategy that conserves and protects these natural areas.

The results of the "All Forest" scenario do not significantly affect delivered loading to Falls Lake when evaluated using the same rainfall as the calibrated model. This is largely because the calibrated model reflects a land use condition that is already 75 percent unmanaged (forests, wetlands, and unmanaged grassland/scrubland). Changing the remaining 25 percent of watershed area that is under management does not have a huge effect on delivered loads when rainfall amounts are relatively high. Many of these managed lands are low intensity development or pastureland that is typically under fertilized in this basin according to representatives of agriculture and the data they track. The "All Forest" scenario also converts unmanaged lands in a grassland or scrubland condition to forest. Forest soils become saturated during wet periods and surface runoff or lateral flow through the soils to the streams is increased. The contribution of flow and nutrients from natural areas is an important component of a diverse, health ecosystem. Loading from forested areas should not be expected to be zero, especially in periods of wet weather. The All Forest scenario has a greater impact on delivered nutrient loads to Falls Lake compared to the current watershed condition when dry to average rainfall is simulated because the soils do not become saturated as frequently. It is important to consider the hydrologic condition when evaluating delivered loads to Falls Lake and setting expectations associated with management strategies.

The best condition for a watershed is its natural state. As noted, the Falls Lake watershed is currently 75 percent unmanaged. This condition is one important reason the lake continues to meet its designated uses. As a result, the UNRBA is focused on developing a nutrient management strategy that conserves and protects these natural areas.

Table H-22. Average Annual Total Nitrogen (TN) Delivered Loads from the Entire Watershed

Short Name	Land use	Rainfall	Onsite and Centralized Wastewater Treatment Systems and Nutrient Application	Atmospheric Deposition	Delivered Flow (MG/yr)	TN lb/yr (change relative to recent load)
UNRBA Study Period	2015-18	Average to wet	2015-18	2015-18	209,698	1,650,800 (recent load)
20% less rainfall	2015-18	Dry to average	2015-18	2015-18	120,977	1,078,331 (35% lower)
20% more rainfall	2015-18	Very wet	2015-18	2015-18	312,259	2,252,084 (36% higher)
25% less atm. Dep	2015-18	Average to wet	2015-18	-25%	209,698	1,574,429 (5% lower)
25% more atm. Dep	2015-18	Average to wet	2015-18	+25%	209,698	1,730,978 (5% higher)
All Forest, study period rainfall	Forest	Average to wet	None	2015-18	200,418	1,302,468 (21% lower)
All Forest, increase VHC's in Ellerbe Creek watershed	Forest	Average to wet	None	2015-18	198,668	1,293,984 (22% lower)
All Forest, 20% less rainfall	Forest	Dry to average	None	2015-18	90,299	794,303 (52% lower)

Loads are presented to the single pound for comparisons across the model report and appendices that present the data for various analyses. This reporting is not to infer precision in the modeling results.

The All Forest scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantaneously converts all lands except wetlands to forests. This scenario does not alter soil chemistry or soil hydrologic properties relative to the calibrated watershed model.

Table H-23. Average Annual Total Phosphorus (TP) Delivered Loads from the Entire Watershed						
Short Name	Land use	Rainfall	Onsite and Centralized Wastewater Treatment Systems and Nutrient Application	Atmospheric Deposition	Delivered Flow (MG/yr)	TP lb/yr (change relative to recent load)
UNRBA Study Period	2015-18	Average to wet	2015-18	2015-18	209,698	183,351 (recent load)
20% less rainfall	2015-18	Dry to average	2015-18	2015-18	120,977	106,894 (42% lower)
20% more rainfall	2015-18	Very wet	2015-18	2015-18	312,259	294,278 (60% higher)
25% less atm. dep	2015-18	Average to wet	2015-18	-25%	209,698	182,259 (1% lower)
25% more atm. dep	2015-18	Average to wet	2015-18	+25%	209,698	184,586 (1% higher)
All Forest, study period rainfall	Forest	Average to wet	None	2015-18	200,418	178,357 (3% lower)
All Forest, increase VHC's in Ellerbe Creek watershed	Forest	Average to wet	None	2015-18	198,668	175,416 (4% lower)
All Forest, 20% less rainfall	Forest	Dry to average	None	2015-18	90,299	100,942 100,731 (45% lower)

Loads are presented to the single pound for comparisons across the model report and appendices that present the data for various analyses. This reporting is not to infer precision in the modeling results.

The All Forest scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantaneously converts all lands except wetlands to forests. This scenario does not alter soil chemistry or soil hydrologic properties relative to the calibrated watershed model.

Table H-24 and Table H-25 compare the delivered total nitrogen and total phosphorus loads to Falls Lake, respectively, from only the upper five tributaries (Eno, Little, Flat Rivers and Ellerbe and Knap of Reeds Creeks). The baseline loads and allowable Stage II loads prescribed by the Falls Lake Rules (based on year 2006) are also provided for comparison in this table. For both total nitrogen and total phosphorus, the delivered load to Falls Lake under an average to wet rainfall condition with current watershed characteristics (short name is "UNRBA study period") is similar to the baseline loads prescribed in the Rules based on 2006. Therefore, even though rainfall and streamflows increased in the UNRBA study period (2014 to 2018), delivered nutrient loads did not. Improvements in the watershed since 2006 including upgrades at wastewater treatment plants, a 44-percent decline in the acreage of agriculture, and 20 percent less atmospheric deposition of nitrogen resulted in delivered loads that did not increase despite heavier rainfall.

The relative percent reductions across the scenarios and sensitivity analyses are similar to those shown in Table H-22 and Table H-23 in terms of the impacts of rainfall condition, changes to rates of atmospheric deposition, and simulation of hypothetical watershed conditions.

Table H-24 shows that current watershed conditions with "20 percent less rainfall" are projected to achieve the Stage II total nitrogen allocations prescribed by the Falls Lake Rules. In other words, when the improvements in the watershed seen between 2006 and recent conditions are considered under a hydrologic condition comparable to the baseline period of the Rules, the loading to the lake would be at or near the Stage II total nitrogen allocations. However, Table H-25 shows there is no feasible way to meet the Stage II total phosphorus allocations even if dry to average rainfall is simulated. The Stage II allowable total phosphorus load of 35,000 pounds per year divided by the drainage area of the upper five tributaries results in an areal loading rate of 0.11 lb-P/ac/yr. None of the forested headwater catchments monitored by the US Forest Service met a loading rate of 0.11 lb-P/ac/yr each year of the 6-yr monitoring study (Figure H-28). Therefore, the Stage II Rules for phosphorus are not feasible even under the hypothetical scenario of removing onsite and centralized wastewater treatment systems, ceasing nutrient application, and instantaneously converting all lands except wetlands to forests.

When the improvements in the watershed are considered and a hydrologic condition comparable to the baseline period is evaluated, it is projected that loading to the lake from the upper tributaries would meet or come close to the Stage II total nitrogen allocations. However, there is no feasible way to meet the Stage II total phosphorus allocation (35,000 pounds per year).

Table H-24. Total Nitrogen (TN) Delivered Loads from Only the Upper Five Tributaries

Short Name	Land use	Rainfall	Onsite and Centralized Wastewater Treatment Systems and Nutrient Application	Atmospheric Deposition	TN lb/yr (change relative to recent load)
UNRBA Study Period	2015-18	Average to wet	2015-18	2015-18	1,032,709 (recent load)
20% less rainfall	2015-18	Dry to average	2015-18	2015-18	646,000 (37% lower)
20% more rainfall	2015-18	Very wet	2015-18	2015-18	1,450,659 (4041% higher)
25% less atm. dep	2015-18	Average to wet	2015-18	-25%	996,496 (3.5% lower)
25% more atm. dep	2015-18	Average to wet	2015-18	+25%	1,070,801 (3.7% higher)
All Forest, study period rainfall	Forest	Average to wet	None	2015-18	777,083 (25% lower)
All Forest, 20% less rainfall	Forest	Dry to average	None	2015-18	426,985 426,100 (59% lower)
Baseline Loads (2006)	2006	2006	2006	2006	1,096,700
Stage II Allowable Loads	2006	Not stated	2006	2006	658,000

Loads are presented to the single pound for comparisons across the model report and appendices that present the data for various analyses. This reporting is not to infer precision in the modeling results.

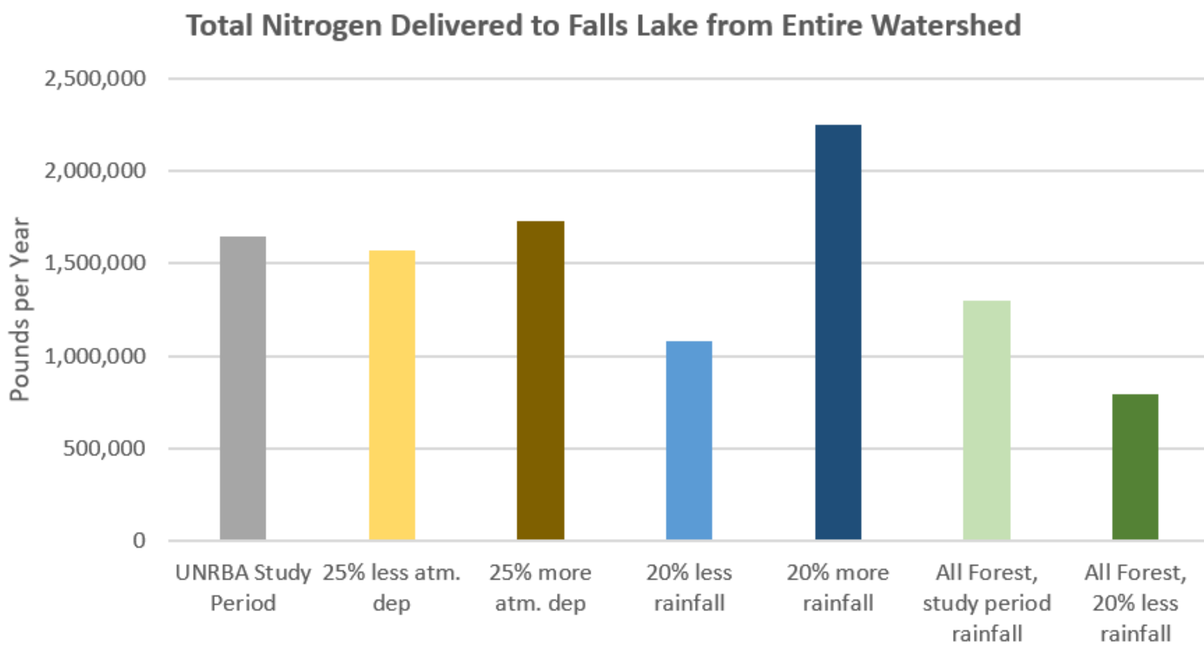
The All Forest scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantaneously converts all lands except wetlands to forests. This scenario does not alter soil chemistry or soil hydrologic properties relative to the calibrated watershed model.

Table H-25. Total Phosphorus (TP) Delivered Loads from Only the Upper Five Tributaries					
Short Name	Land use	Rainfall	Onsite and Centralized Wastewater Treatment Systems and Nutrient Application	Atmospheric Deposition	TP lb/yr (change relative to recent load)
UNRBA Study Period	2015-18	Average to wet	2015-18	2015-18	109,058 (recent load)
20% less rainfall	2015-18	Dry to average	2015-18	2015-18	59,000 (46% lower)
20% more rainfall	2015-18	Very wet	2015-18	2015-18	190,049 (74% higher)
25% less atm. dep	2015-18	Average to wet	2015-18	-25%	108,793 (0.2% lower)
25% more atm. dep	2015-18	Average to wet	2015-18	+25%	109,254 (0.2% higher)
All Forest, study period rainfall	Forest	Average to wet	None	2015-18	102,044 (6% lower)
All Forest, 20% less rainfall	Forest	Dry to average	None	2015-18	52,036000 (52% lower)
Baseline Loads	2006	2006	2006	2006	106,000
Stage II Allowable Loads	2006	Not stated	2006	2006	35,000

Loads are presented to the single pound for comparisons across the model report and appendices that present the data for various analyses. This reporting is not to infer precision in the modeling results.

The All Forest scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantaneously converts all lands except wetlands to forests. This scenario does not alter soil chemistry or soil hydrologic properties relative to the calibrated watershed model.

Figure H-38 and Figure H-39 compare the total nitrogen and total phosphorus loads delivered to Falls Lake for the modeling scenarios and sensitivity analyses from either the entire watershed or the upper five tributaries. Assessment of the impact of the improved loading changes are assessed in the lake modeling component of the UNRBA reexamination and summarized in the UNRBA Lake Modeling Report.



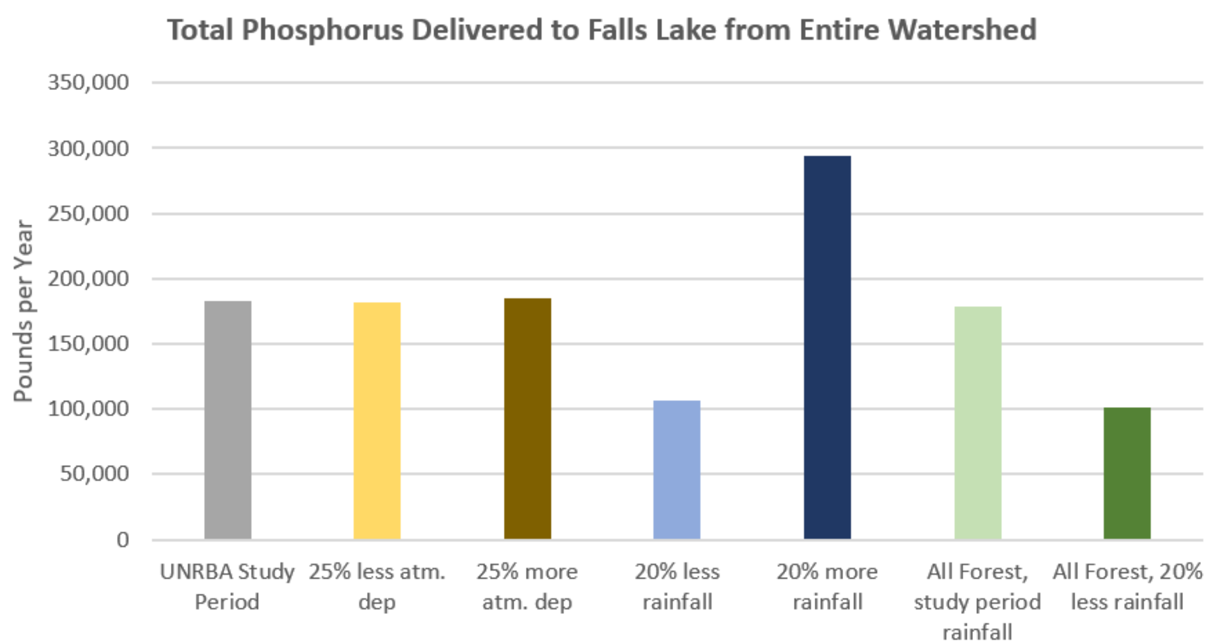
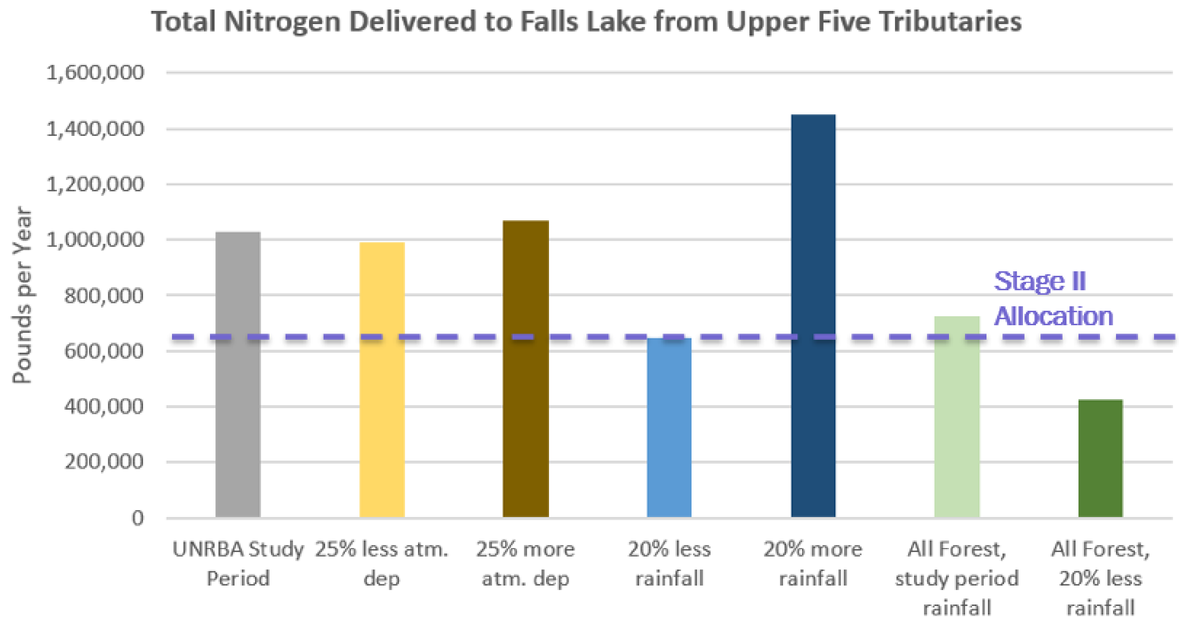


Figure H-38 Comparison of Delivered Total Nitrogen Loads (top) and Delivered Total Phosphorus Loads (bottom) from the Entire Watershed

The "All Forest" scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantaneously converts all lands, except wetlands, to forests. This scenario does not alter soil chemistry or soil hydrologic properties relative to the calibrated watershed model.



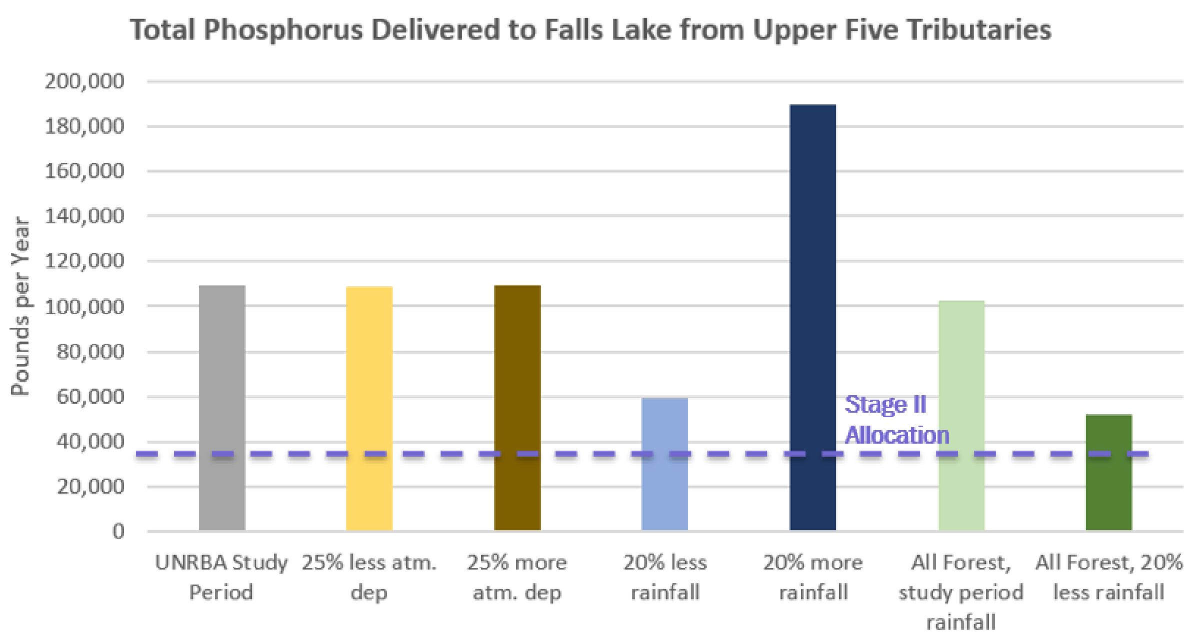


Figure H-39 Comparison of Delivered Total Nitrogen Loads (top) and Delivered Total Phosphorus Loads (bottom) from the Upper Five Tributaries Compared to the Stage II Allowable Loads

The "All Forest" scenario removes onsite and centralized wastewater treatment systems, ceases nutrient application, and instantaneously converts all lands, except wetlands, to forests. This scenario does not alter soil chemistry or soil hydrologic properties relative to the calibrated watershed model.

Comparison of WARMF-Simulated Nutrient Loading Rates to Other Modeling Studies

This section helps address the following question:

- *How do simulated urban loading rates compare to other modeling studies?*

During their review of the WARMF-simulated load allocations to Falls Lake, the SMEs suggested that the modeling team compare the WARMF simulated areal loading rates to those of other modeling studies, or literature reviews summarizing modeling studies, dating back to an EPA National Estuary Program study of the Albemarle Pamlico Estuary and as recent as the Jordan Lake modeling studies funded by the Collaboratory. They provided a list of references to include in this comparison. These and other studies are summarized in this section. Additional detail on these studies as well as excerpts from the studies are provided at the end of this document.

It is important to note that some of these studies are decades old, and nutrient application practices and deposition from the atmosphere over the recent decades results in lower loading rates than previously estimated. The nearest modeling study was conducted in the Jordan Lake basin, and that model was based on meteorology developed for 1996 to 2012. Nine of these seventeen simulation years had precipitation at RDU less than the average of 45 inches. The UNRBA modeling study of the Falls Lake watershed covers the period 2014 to 2018 when precipitation ranged from 45.6 to 60.3 inches. As noted in the sections above, hydrologic conditions are the key driver of loading from the watershed.

Past literature reviews, modeling, and evaluations of areal loading rates of nutrients provide a check on the simulated loading rates for the WARMF watershed model developed for Falls Lake. The WARMF modeling is based on land use, nutrient application, and atmospheric deposition for the years 2014 to 2018 as well as soil chemistry data obtained from USDA. Table H-26 (TN) and Table H-27 (TP) summarize the ranges reported across several modeling studies. Within a land use category, the values are sorted from lowest to highest. Each of the studies provide relatively wide ranges of loading, and the WARMF simulated rates fall within those reported by others. Additional details regarding each of the individual studies is provided at the end of the document. Only the Forest Service's research referenced in this appendix is based on monitoring data: the others are modeling studies.

The WARMF simulated loading rates are within the ranges reported by others. There is more variation in the WARMF loading rates when precipitation conditions are compared. Variability in the nutrient loading rates across catchments and among land uses is highly dependent on precipitation, antecedent conditions, and resulting stream flows. Hydrologic conditions can result in a given land use and catchment having areal loading rates that vary by an order of magnitude.

When comparing the delivered loading rates to Falls Lake for the UNRBA study period (2014 to 2018) to those reported in the literature, WARMF simulated loading rates are within the ranges reported in other modeling studies. The example catchment-scale loading rates presented above are also within these published rates. The following statements compare the average annual <u>delivered loading rates</u> to Falls Lake for 2014 to 2018 by land use to the ranges reported in the studies evaluated:

- The WARMF simulated delivered total nitrogen loading rates from forest and unmanaged grassland/shrubland range 1.3 to 1.6 kg-N/ha/yr for the dry to average simulation to 2.3 to 2.7 kg-N/ha/yr for the average to wet period. This is within the range reported by other studies 0.1 to 6.7 kg-N/ha/yr which reflects a range of model types, modeling periods, hydrologic conditions, and geologic basins including the Tetra Tech (2012) simulated rates of 3.9 kg-N/ha/yr to 4.5 kg-N/ha/yr.

- The WARMF simulated delivered phosphorus loading rates from forest and unmanaged grassland/shrubland ranges from 0.14 to 0.26 kg-P/ha/yr for the dry to average simulation to 0.22 to 0.43 kg-P/ha/yr for the average to wet period. The other studies report a range of 0 to 1.0 kg-P/ha/yr with loading rates for the High Rock Lake watershed simulated at 0.9 kg-P/ha/yr to 1.0 kg-P/ha/yr.
- WARMF simulated delivered nitrogen loading rates for existing development (low, medium, and high intensity) range from 4.2 to 5.0 kg-N/ha/yr for the dry to average simulation to 5.1 to 6.4 kg-N/ha/y for the average to wet simulation period. These rates are two to three times higher than those simulated for forested areas. Local governments in the Falls Lake watershed have been implementing stormwater retrofits for existing development since before the rules went into effect and these practices have been accounted for in the modeling using small detention volumes in each catchment. New development loading rates are approximately 1.9 kg-N/ha/yr for the dry to average period and 2.8 kg/ha/yr for the average to wet period; the New Development Rules that went into effect in 2011 require implementation of stormwater control measures to reduce loading from new development to 2.5 kg-N/ha/yr (2.2 lb-N/yr). WARMF is not a site-scale model and the load from new development may be overestimated in the model. There is not a large amount of new development present in the UNRBA study period, so this potential overestimate should not cause a larger error in the lake modeling. These loading rates do not account for stream bank erosion which is simulated separately by the model. The loading rates are within the ranges reported by other modeling studies 0.7 to 38.5 kg-N/ha/yr.
- WARMF simulated delivered phosphorus loading rates for existing development range from 0.09 to 0.32 kg-P/ha/yr for the dry to average condition to 0.12 to 0.51 kg-P/ha/yr for the average to wet condition. **These WARMF-simulated land-use loading rates do not account for streambank erosion which is tracked separately by the model (not by land use category). Simulated rates of streambank erosion are much higher in catchments with higher percentages of impervious surface.** For phosphorus stream bank erosion contributes approximately 15 percent of the total load to Falls Lake (more than all of the developed land use classes combined). Stream bank phosphorus-loading rates are higher in catchments with higher percentages of urban area. The phosphorus loads associated with urban land are also mitigated by early implementation of existing development retrofits (350 in the City of Durham which has the highest density of development). New development loading rates range from 0.09 to 0.23 for the dry to average condition to 0.12 to 0.39 kg-P/ha/yr for the average to wet condition. These rates do not account for stream bank erosion, and for phosphorus stream bank erosion contributes approximately 15 percent of the total load to Falls Lake (more than all of the developed land use classes combined). These simulated loading rates are within the ranges reported by other modeling studies (0.03 to 6.2 kg- P/ha/yr). While WARMF generates loading rates toward the low end of the range from other studies, the other studies account for the loading from stream bank erosion as part of the land use loading rates.
- WARMF simulated delivered crop and pasture loading rates range from 1.2 to 5.7 kg-N/ha/yr for the dry to average condition to 2.2 to 10.2 kg-N/ha/yr for the average to wet conditions by 2014 to 2018). These rates are within the ranges reported by other modeling studies (0.4 to 79.6 kg-N/ha/yr).
- WARMF simulated delivered crop and pasture phosphorus loading rates 0.2 to 0.46 kg-P/ha/yr for the dry to average condition to 0.35 to 0.79 kg-P/ha/yr for the average to wet conditions.

These rates do not account for stream bank erosion (calculated separately). These are within the ranges reported by other modeling studies (0.1 to 18.6 kg-P/ha/yr).

Table H-26. Compilation of Total Nitrogen Areal Loading Rates from Other Modeling Studies

Modeling Study	Loading Rate lb-N/ac/yr	Loading Rate kg-N/ha/yr
AGRICULTURE (CROPLAND AND PASTURE)		
Tetra Tech (2014) low end of the literature range for cropland	0.4	0.4
Lin (2004) low end of range for pasture	1.3	1.5
Tetra Tech (2014) low end of the modeled range for pasture/grassland	1.8	2.0
Lin (2004) low end of range for cropland	1.9	2.1
Miller et al. (2019) low end of range for pasture and cropland	2.0	2.3
Harden et al (2013) low intensity agriculture	2.1	2.4
Tetra Tech (2014) low end of the modeled range for cropland	2.2	2.5
Tetra Tech (2014) low end of the literature range for pasture/grassland	2.9	3.2
Harden et al (2013) high intensity agriculture	3.4	3.8
Dodd (1992) low end of range for pasture and cropland	4.5	5
Miller et al. (2019) high end of range for pasture and cropland	5.1	5.7
Tetra Tech (2014) high end of the modeled range for pasture/grassland	5.1	5.7
Tetra Tech (2014) high end of the modeled range for cropland	10.3	11.5
Tetra Tech (2014) high end of the literature range for pasture/grassland	12.5	14.0
Dodd (1992) high end of range for pasture and cropland	12.7	14.3
Chesapeake Bay CASTNET Phase 6 for pasture/hay	14.9	16.7
Lin (2004) high end of range for pasture	27.4	30.8
Tetra Tech (2014) high end of the literature range for cropland	44	49.3
Chesapeake Bay Program (2020) CASTNET Phase 6 for cropland	47.5	53.4
Lin (2004) high end of range for cropland	70.8	79.6
URBAN/DEVELOPED		
Miller et al. (2019) low end of range, post 80s	0.6	0.7
Hoos and Roland (2019), low end of range, with delivery accounted for	1.2	1.3
Lin (2004) low end of range	1.3	1.5
Tetra Tech (2014) low end of the literature range for high density dev.	1.6	1.8
Tetra Tech (2014) low end of the simulated range for low-medium density development	2.1	2.4
Hoos and Roland (2019), high end of range, with delivery accounted for	2.2	2.5
Tetra Tech (2014) low end of the literature range for low-medium density development	2.6	2.9
Harden et al (2013) low intensity urban	2.7	3.0

Table H-26. Compilation of Total Nitrogen Areal Loading Rates from Other Modeling Studies		
Modeling Study	Loading Rate lb-N/ac/yr	Loading Rate kg-N/ha/yr
Harden et al (2013) high intensity urban	3.7	4.1
Dodd (1992) low end of range	4.5	5
Tetra Tech (2014) low end of the simulated range for high density development	5.1	5.7
Tetra Tech (2014) high end of the simulated range for low-medium density development	5.8	6.5
Miller et al. (2019) high end of range, post 80s	6.5	7.3
Miller et al. (2019) low end of range, pre80s	6.6	7.4
Tetra Tech (2014) high end of the literature range for low-medium density development	8	9.0
Tetra Tech (2014) high end of the simulated range for high density development	8.2	9.2
Dodd (1992) high end of range	8.7	9.72
Miller et al. (2019) high end of range, pre 80s	10.1	11.4
Tetra Tech (2014) high end of the literature range, high density dev.	11	12.3
Chesapeake Bay Program (2020) CASTNET Phase 6 for developed	16.8	18.9
Lin (2004) high end of range	34.3	38.5
FOREST		
Miller et al. (2019) low end of range	0.1	0.1
Boggs et al. (2012) extended[1], low end of the monitored range	0.3	0.34
Dodd (1992) low end of range	0.6	0.69
Tetra Tech (2014) low end of the simulated range	1.0	1.1
Tetra Tech (2014) low end of the literature range	1.0	1.1
Lin (2004) low end of range	1.2	1.4
Harden et al (2013) undeveloped	1.2	1.4
Miller et al. (2019) high end of range	1.3	1.5
Dodd (1992) high end of range	3.4	3.8
Tetra Tech (2014) high end of the simulated range	3.4	3.8
Tetra Tech (2012) simulated forest rates on Hydrologic Group B soils, High Rock Lake Watershed	3.5	3.9
Tetra Tech (2012) simulated forest rates on Hydrologic Group C soils, High Rock Lake Watershed	4.0	4.5
Boggs et al. (2012) extended[1], high end of the monitored range (includes a site affected by agricultural land use)	4.1	4.6
Chesapeake Bay Program (2020) CASTNET Phase 6 for natural areas	4.2	4.7
Lin (2004) high end of range	5.6	6.3
Tetra Tech (2014) high end of the literature range	6.0	6.7

[1] *Only the Boggs et al. (2012) extended includes monitoring data. The other studies are modeling studies or literature reviews based on modeling studies.*

Table H-27. Compilation of Total Phosphorus Areal Loading Rates from Other Modeling Studies		
Modeling Study	Loading Rate lb-P/ac/yr	Loading Rate kg-P/ha/yr
AGRICULTURE (CROPLAND AND PASTURE)		
Tetra Tech (2014) low end of the literature range for cropland	0.09	0.10
Tetra Tech (2014) low end of the simulated range for pasture/grassland	0.09	0.10
Lin (2004) low end of range for pasture	0.12	0.14
Tetra Tech (2014) low end of the simulated range for cropland	0.16	0.18
Harden et al (2013) low intensity agriculture	0.22	0.24
Lin (2004) low end of range for cropland	0.23	0.26
Tetra Tech (2014) high end of the simulated range for pasture/grassland	0.26	0.29
Harden et al (2013) high intensity agriculture	0.31	0.35
Miller et al. (2019) low end of range for pasture and cropland	0.36	0.4
Tetra Tech (2014) low end of the literature range for pasture/grassland	0.45	0.50
Dodd 1992 low end of range for pasture and cropland	0.49	0.55
Miller et al. (2019) high end of range for pasture and cropland	0.71	0.8
Dodd (1992) high end of range for pasture and cropland	0.88	0.99
Tetra Tech (2014) high end of the simulated range for cropland	1.22	1.37
Chesapeake Bay CASTNET Phase 6 for pasture/hay	1.5	1.7
Chesapeake Bay CASTNET Phase 6 for cropland	2.2	2.5
Lin (2004) high end of range for pasture	4.4	4.9
Tetra Tech (2014) high end of the literature range for pasture/grassland	4.7	5.26
Tetra Tech (2014) high end of the literature range for cropland	5.8	6.50
Lin (2004) high end of range for cropland	16.55	18.6
URBAN/DEVELOPED		
Miller et al. (2019) low, post 80s	0.03	0.03
Tetra Tech (2014) low end of the literature range for high density development	0.1	0.11
Lin (2004) low end of range	0.17	0.19
Hoos and Roland (2019), low, with delivery accounted for	0.19	0.21
Tetra Tech (2014) low end of the simulated range for low-medium density development	0.23	0.26
Hoos and Roland (2019), high, with delivery accounted for	0.30	0.34
Harden et al (2013) low intensity urban	0.31	0.35
Tetra Tech (2014) low end of the literature range for low-medium density development	0.34	0.38
Dodd (1992)	0.40	0.45

Table H-27. Compilation of Total Phosphorus Areal Loading Rates from Other Modeling Studies		
Modeling Study	Loading Rate lb-P/ac/yr	Loading Rate kg-P/ha/yr
Harden et al (2013) high intensity urban	0.62	0.70
Tetra Tech (2014) high end of the simulated range for low-medium density development	0.79	0.88
Tetra Tech (2014) low end of the simulated range for high density development	0.79	0.88
Miller et al. (2019) low, pre80s	1.0	1.1
Miller et al. (2019) high, post 80s	1.2	1.4
Chesapeake Bay Program (2020) CASTNET Phase 6 for developed	1.2	1.4
Dodd (1992)	1.3	1.5
Tetra Tech (2014) high end of the simulated range for high density development	1.4	1.5
Tetra Tech (2014) high end of the literature range for low-medium density development	1.4	1.6
Miller et al. (2019) high, pre 80s	1.6	1.8
Tetra Tech (2014) high end of the literature range for high density development	3.0	3.4
Lin (2004) high end of range	5.5	6.2
FOREST		
Miller et al. (2019) low	0	0
Tetra Tech (2014) low end of the literature range	0.01	0.01
Lin (2004) low end of range for forest	0.02	0.02
Boggs et al. (2012) extended[1], low end of the monitored range	0.04	0.04
Tetra Tech (2014) low end of the simulated range	0.05	0.06
Harden et al (2013) undeveloped	0.06	0.07
Dodd (1992) low	0.08	0.09
Miller et al. (2019) high	0.12	0.13
Chesapeake Bay Program (2020) CASTNET Phase 6 for natural	0.12	0.13
Dodd 1992 high	0.19	0.21
Tetra Tech (2014) high end of the simulated range	0.2	0.22
Boggs et al. (2012) extended[1], high end of the monitored range	0.40	0.45
Lin (2004) high end of range	0.74	0.83
Tetra Tech (2014) high end of the literature range	0.80	0.90
Tetra Tech (2012) simulated forest rates on Hydrologic Group B soils, High Rock Lake Watershed	0.8	0.9
Tetra Tech (2012) simulated forest rates on Hydrologic Group C soils, High Rock Lake Watershed	0.9	1.0

[1] Only the Boggs et al. (2012) extended includes monitoring data. The other studies are modeling studies or literature reviews based on modeling studies.

Summary

Average loading rates simulated by the Falls Lake WARMF model, as delivered to Falls Lake, are within the ranges published in the literature across all land use categories. Loading rates from agriculture are generally higher than existing development which is generally higher than forests and unmanaged grasslands. Precipitation is the primary driver of loading rates for these land uses. Simulated loading rates for forested catchments are similar to the Forest Service monitoring studies when precipitation is similar. Variability in the nutrient loading to Falls Lake is highly dependent on precipitation, antecedent conditions, and resulting stream flows.

Delivered loads by land use are each subject to transformations in subsurface and overland flow, streams, and impoundments. Loads generated from catchments that are farther from the lake have more time in streams and impoundments to be transformed while loads generated from catchments adjacent to the lake, which are mostly forested, have less reaction time. The watershed average delivered loading rates for forests are affected by the proximity of the 129 square-mile, near-lake drainage area (almost 17 percent of the entire watershed area), which is comprised mostly of forests (75 percent). These areas are subject only to overland flow and do not have the benefit of stream or impoundment processing. Simulated BMPs and SCMs in urban areas implemented to comply with the Falls Lake Nutrient Management Strategy significantly reduce the loading rate of phosphorus from urban areas, and phosphorus is more readily reduced during transport to the lake compared to nitrogen. Nitrogen is also attenuated by denitrification processes within streams and particularly in the lake arms (as established by Piehler, Collaboratory research), and ammonia and nitrate are more closely tied to this reaction than organic nitrogen. This is why pasture loading rates are less attenuated than row crop nitrogen loading rates because approximately 55 percent of the nutrients applied to pasture are likely in the organic form (i.e., from animals and crop residuals). These factors result in loading rates more similar than one might expect when comparing across the land use categories, particularly for phosphorus which may be bound to sediment and settle out in streams and impoundments, regardless of contributing source. Additionally, the stream bank erosion component of the loading from developed areas is accounted for separately in the model, and not included as part of the land use loading rate. Simulated nutrient loading rates from streambanks are higher in catchments with more impervious surface.

Catchment scale output shows more variation in areal loading rates because the stream and impoundment processing has not yet occurred. Each catchment is unique in terms of its slope, catchment width (which affects overland transport), stream length and depth (which affects instream processing), soils, current and past land uses, and precipitation amounts. For agriculture, the nutrient application rates vary by crop and county based on data provided by the NC Department of Agriculture.

Three headwater catchments with specific land uses have been evaluated in terms of areal loading rates. Simulated concentrations compare well to observed water quality observations at these locations even though they were not calibration stations (i.e., model coefficients were not adjusted to improve the model fit at these locations). Each of these three catchments yields varying areal loading rates, and all three predict the magnitude and patterns of observed total nitrogen, total phosphorus, and total organic carbon. When a catchment is dominated by a land use type, the model cannot be calibrated if the areal loading rates from the dominate land uses are not reasonable. For example, catchment #14 is 80 percent undisturbed (62 percent forest, 18 percent unmanaged grass and shrubland), and the forest loading rate for TN is approximately 2.9 kg/ha/yr for the average to wet condition. Catchment #42 is approximately 60 percent forest, and the forest loading rate for TN is 3.4 kg/ha/yr for the average to wet condition. The nitrogen loading rates from forests in both of these catchments are different, and both are higher than the average delivered loading rate for forested areas to Falls Lake partly because transformations in streams and impoundments between the reaches and Falls Lake are not reflected in the catchment-scale loading rates. Even though these catchments have different loading rates simulated for forests, both catchments drain to water quality monitoring stations, and both provide a reasonable calibration (neither of these catchments was formally calibrated as they are headwater catchments that do not drain directly to Falls Lake). Other areas in the watershed where land use patterns are more mixed also have simulated concentrations and flows that match those observed; the modeling methods are the same in terms of underlying datasets and approach.

The sensitivity analyses and scenarios that were applied to the entire watershed yield similar findings showing again the importance of rainfall on delivered nutrient loading to Falls Lake. These analyses also demonstrate the extent of improvements that have occurred in the watershed since 2005-2007. These include reductions in loads discharged from wastewater treatment plants, rates of nutrient application and atmospheric deposition, and retrofitting of existing development in the watershed. Similar findings are reported by DWR (2021) in the Falls Lake five-year status report which indicates that the flow-normalized nitrate load delivered to Falls Lake has declined by 37 percent, total nitrogen load has declined by 20 percent, and total phosphorus load has declined by 52 percent when comparing 2006 to 2019.

For both total nitrogen and total phosphorus, the delivered loads from the upper five tributaries under an average to wet rainfall condition are similar to the baseline load described in the Rules for year 2006. Thus, even under a higher rainfall condition, delivered nutrient loads did not increase. When current conditions are simulated under dry to average rainfall conditions, the projected total loading from the upper five tributaries meet or approach the Stage II nitrogen allocations in the rules, but the Stage II phosphorus reductions are not feasible under any of the rainfall conditions evaluated. Even under a hypothetical scenario where all human inputs are removed and all land in the watershed (not already forest) is converted to forest, the Stage II phosphorus allocation is not met.

When current conditions are simulated under dry to average rainfall conditions, the projected total loading from the upper five tributaries meet or approach the Stage II nitrogen allocations in the rules, but the Stage II phosphorus reductions are not feasible under any of the rainfall conditions evaluated. Even under a hypothetical scenario where all human inputs are removed and all land in the watershed (not already forest) is converted to forest, the Stage II phosphorus allocation is not met.

Supplemental Information - Study Details

This section includes additional information regarding the studies summarized in Table H-26 and Table H-27. Some of this information was copied directly from the respective publications.

1992 ApNEP Study

Dodd et al (1992) estimated annual nutrient budgets for land uses, atmospheric deposition, and WWTPs to the Albemarle Pamlico Estuary. Atmospheric deposition monitoring data and discharge monitoring reports for WWTPs were used to approximate annual loads from these sources to the estuary. Export coefficients for land uses were based on a literature review with a range of coefficients reported: low (25^{th} percentile from the literature), median (50^{th} percentile), and high (75^{th} percentile).

Table H-28 is screen-captured from the report (Dodd et al. 1992) and summarizes the reported areal loading rates.

It is important to note when reviewing this study that rates of nutrient application to agricultural areas have generally declined due to nutrient management planning and atmospheric deposition of nitrogen has been reduced by more than one-half since the time of this publication (Figure 40). While the WARMF simulated loading rates are not always within these ranges by land use type, they are not drastically different either, especially given the amount of time that has passed and the literature-based approach used to develop the ApNEP estimates.

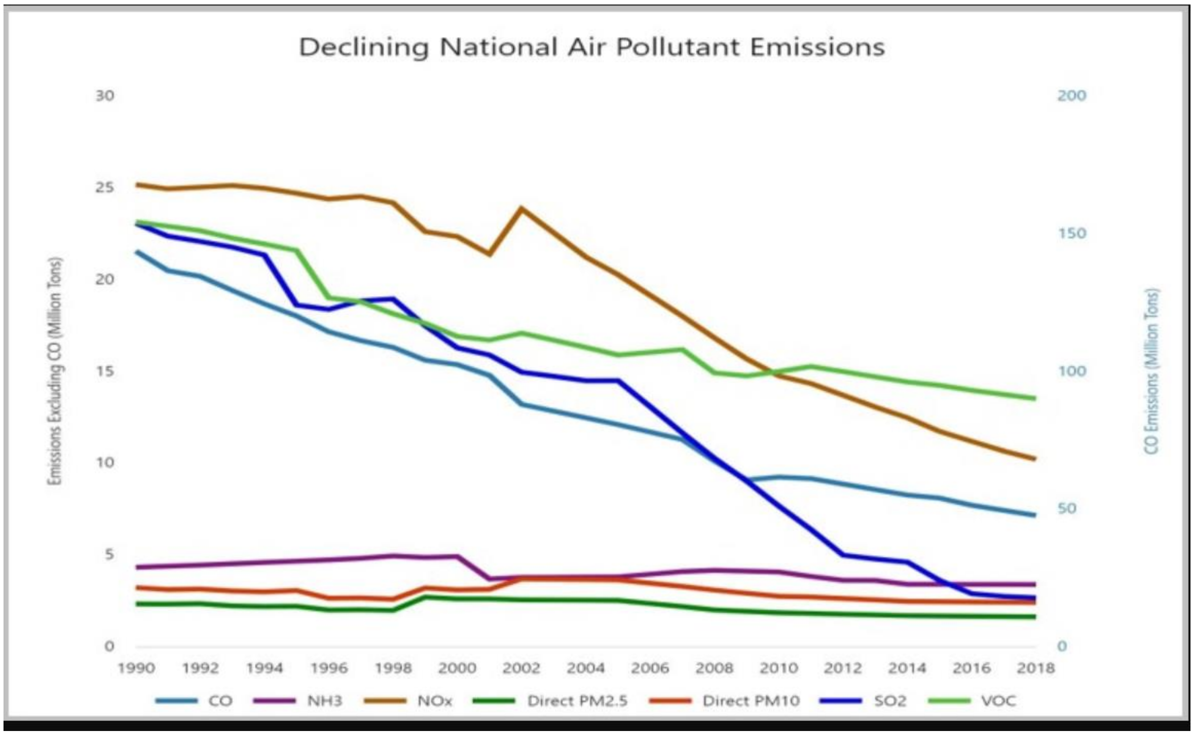


Figure H-40. Total Deposition of Pollutants by Year Reported by EPA from 1990 to 2018
(https://www.epa.gov/clean-air-act-overview)

Table H-28. Export Coefficients by Land Use Reported by Dodd (1992)

Export Coefficients Literature Review
(Kg/ha * y)

	Agriculture	Forest/Wetland	Developed	Atmospheric
Total Phosphorus				
Low (25%)	0.55	0.09	0.45	0.25
Median	0.99	0.13	1.06	0.65
High (75%)	2.03	0.21	1.5	0.69
Total Nitrogen				
Low (25%)	5	0.69	5	8.7
Median	9.8	2.33	7.5	12.4
High (75%)	14.3	3.8	9.72	24
Number of Studies	77	36	78	6

Review of Published Export Coefficient and Event Mean Concentration (EMC) Data for the Wetlands Regulatory Assistance Program

The Wetlands Regulatory Assistance Program published a review of published export coefficient and event mean concentration (EMC) data based on studies located across the US and Canada (Lin 2004). Table H-29 is a screen capture of the mean export coefficients summarized in the report. The average delivered nitrogen and phosphorus loads simulated by the WARMF model are within the reported ranges for forest, row crops, pasture, and urban areas.

Table H-29. Mean Export Coefficient Summarized by Lin (2004)

Land Use	TP and TN Export Coefficients (kg/ha/yr)					
	Mean		Range		Sample Size	
	TP	TN	TP	TN	TP	TN
Forested	.236	2.86	.019 - .830	1.38 - 6.26	26	11
Row Crops	4.46	16.09	.26 - 18.6	2.1 - 79.6	26	26
Non Row Crops	1.08	5.19	.10 - 2.90	.97 - 7.82	13	10
Pasture	1.50	8.65	.14 - 4.90	1.48 - 30.85	14	13
Feedlot/Manure Storage	300.7	3110.7	21.28 – 795.20	680.5 - 7,979.9	13	7
Mixed Agriculture	1.134	16.53	.08 - 3.25	2.82 - 41.50	20	21
Urban	1.91	9.97	.19 - 6.23	1.48 - 38.47	23	19

2014 Jordan Lake Watershed Model

In 2014, Tetra Tech developed a watershed model for Jordan Lake using the Loading Simulation Program in C++ (LSPC) model. The model was developed based on meteorology from 1996 to 2012 using two land use conditions (baseline scenario using 2001 land use and existing using 2010 land use). Nine of the seventeen (approximately one-half) of the simulation years had precipitation at RDU less than the average of 45 inches with some of these years occurring during a historic drought.

Similar to the Falls Lake watershed, approximately 59 percent of the land in the Jordan Lake watershed is forested. Pasture and grassland were simulated as a single land use class in the LSPC model based on available land use data while the UNRBA WARMF model was able to separate these. Nutrient application rates and acreages by county for pasture were provided by NC Department of Agriculture estimates for the Falls Basin. Thus, direct comparison of the LSPC loading rates for pasture and grassland combined compared to the WARMF loading rates where they are separate is challenging.

For the “existing” modeling scenario (2010), the total nitrogen load delivered to Jordan Lake was due to point sources (~33 percent), forest (~25 percent), row crops (~12), pasture/grassland (~7 percent), impervious areas (~14 percent), developed open space (~7 percent), onsite wastewater treatment systems (~1 percent) and direct atmospheric deposition to the lake surface (~1.5 percent). For total phosphorus load, the contributions were from point sources (~22 percent), forested areas (~19 percent), row crops (~21 percent), pasture/grassland (~4 percent), impervious areas ~26 percent, developed open space ~6.6 percent, and onsite wastewater treatment systems (~0.4 percent). Ignoring the point sources, direct deposition, and onsite wastewater treatment systems and just evaluating the contributing from upland sources, forested areas contributed approximately 39 percent of the total nitrogen load and 25 percent of the total phosphorus load. The UNRBA WARMF model, which represents a wetter condition, estimates that forests contribute 39 percent of the total nitrogen load and 44 percent of the phosphorus load.

The Jordan Lake report compared simulated areal loading rates to those reported in the literature.

Table H-30 provides the screen capture from the model report for the nitrogen loading rates, and Table H-31 provides the information for phosphorus. The WARMF-simulated, average delivered total nitrogen loading rate to Falls Lake by land use are within the ranges simulated for the Jordan Lake Watershed using the LSPC modeling. For total phosphorus load delivered to Falls Lake, the WARMF simulated rates for urban land uses are toward the lower end of the range or below the Jordan Lake LSPC model ranges, likely because the WARMF estimates account for loading from streambank erosion separately. For forested areas, the WARMF phosphorus loading rates were higher than the LSPC-simulated rates, but within the rates Tetra Tech (2014) provided for the literature comparison. For row crops, the WARMF simulated loading rates are within those estimated by the LSPC modeling. A comparison between pasture loading rates cannot be made between these two models as noted above.

Table H-30. Comparison of Jordan Lake Watershed LSPC Areal Loading Rates to Literature as Provided by Tetra Tech (2014)

Land Use	Model Range (lb/ac/yr)	Literature Range (lb/ac/yr)	Source
Total Nitrogen Load			
Low-Medium Density Residential [1]	2.1 – 5.8	4 - 8 2.6 – 6.2	*General*: Novotny & Olem, 1994, tables 8-2, 8-3; Hartigan et al., 1983 *NC Piedmont*: Line, 2013; Bales et al., 1999
High Density Residential, Commercial [2]	5.1 – 8.2	1.6 – 11.0	*General*: Novotny & Olem, 1994, tables 8-2, 8-3, Lin, 2004
Forest	1.0 – 3.4	1 – 6 1.1 – 3.6	*General*: Lin, 2004; Chapra, 1997, Table 28.2 *NC Piedmont*: Swartley et al., 2010; Harned, 1995; Line, 2013.
Row Crops	2.2 – 10.3	0.4 – 44 11 - 14	*General*: Chapra, 1997, Table 28.2 *NC Piedmont*: Harned, 1995
Pasture/Grassland	1.8 – 5.1	2.9 – 12.5 5.2 – 7.5	*General*: Lin, 2004 *NC Piedmont*: Line and Osmond, 2010

1. Low-Medium Density assumed impervious area ranging from 10 percent to 30 percent
2. High Density-Commercial assumed impervious area ranging from 50 percent to 80 percent

Table H-31. Comparison of Jordan Lake Watershed LSPC Areal Total Phosphorus Loading Rates to Literature as Provided by Tetra Tech (2014)

Total Phosphorus Load			
Low-Medium Density Residential [1]	0.23 – 0.79	0.4 – 1.4 0.34 – 0.81	*General*: Novotny & Olem, 1994, tables 8-2, 8-3; Hartigan et al., 1983 *NC Piedmont*: Line, 2013; Bales et al., 1999.
High Density Residential, Commercial [2]	0.79 – 1.38	0.1 - 3	*General*: Novotny & Olem, 1994, tables 8-2, 8-3, Lin, 2004
Forest	0.05 – 0.20	0.01 – 0.8 0.14 – 0.32	*General*: Lin, 2004; Chapra, 1997, Table 28.2 *NC Piedmont:* Swartley et al., 2010
Row Crops	0.16 – 1.22	0.09 - 4 3.5 – 5.8	*General*: Chapra, 1997, Table 28.2 *NC Piedmont*: Harned, 1995; Line and Osmond, 2010
Pasture/Grassland	0.09 – 0.26	0.45 – 0.54 2.5 – 4.7	*General*: Lin, 2004 *NC Piedmont*: Line and Osmond, 2010

1. Low-Medium Density assumed impervious area ranging from 10 percent to 30 percent
2. High Density-Commercial assumed impervious area ranging from 50 percent to 80 percent

NC Collaboratory Funded Studies

Miller et al. (2019 and 2021) applied a Bayesian modeling approach to estimate nutrient export factors for land uses in the Jordan Lake and Falls Lake watersheds. Bayesian models use prior estimates to initialize the analysis, and for this evaluation those were based on the Dodd (1992) report summarized above.

The parameter estimates developed by Miller et al. for TN and TP were lower than the Dodd values for agriculture (pasture and crop land) which may be due to decreases in nutrient application rates. The Falls WARMF model (WARMF model) simulated areal loading rates for agriculture were within the range to higher than those estimated by Miller et al.; the phosphorus rates for agriculture were nearly identical.

For forests, the WARMF model predicts higher loading rates for both nitrogen and phosphorus than Miller et al. However, both the low and high ends of the range reported by Miller et al. are the lowest of the ranges reported for forests in Table H-25 and Table H-26 compared to the other studies evaluated (i.e., the low is the lowest of the reported lows and high is the lowest of the reported highs).

For development, Miller et al. generated different rates for the periods before 1980 (called ur1) and after 1980 (called ur2). Their estimates across these two periods for TP were similar to the range reported by Dodd (1992) with lower rates reported for post 1980s development compared to pre 1980s development. For TN, Miller et al. provide a broader range to encompass the pre- and post-1980s development, but both ranges overlap that summarized by Dodd. The WARMF nitrogen loading rates for existing development are toward the high end of the range reported by Miller et al. for post-1980s development and for interim and new development closer to the midpoint of the range. For phosphorus, the WARMF loading rates for development are within the lower half of the range reported for post 1980s development. This is likely due to WARMF accounting for streambank erosion separately in the modeling. Table H- is screen-captured from the Miller et al report (export coefficients are in kg/ha/yr).

Table H-32 also provides precipitation impact coefficients to indicate the variation of the loading rate with respect to land use. Similar to the WARMF modeling, agriculture is most affected followed by forests followed by urban areas.

Table H-32. Mean Parameter Estimates for the TN and TP models (kg/ha/yr) along with 95% Credible Intervals (CI)

Export coefficients and retention rates

	TN		TP	
Parameter	Mean	95% CI	Mean	95% CI
$\beta_{,ag}$	4.0	2.3-5.7	0.6	0.4-0.8
$\beta_{,ur1}$	9.5	7.4-11.4	1.5	1.1-1.8
$\beta_{,ur2}$	3.9	0.7-7.3	0.6	0.03-1.4
$\beta_{,und}$	0.7	0.1-1.5	0.05	0-0.13
$\beta_{,ch}$	0.01	0-0.02	0.004	0-0.009
$\beta_{,h}$	0.04	0.01-0.07	0.02	0-0.04
$\beta_{,cw}$	0.5	0.1-1.0	0.16	0-0.55
$\beta_{,ps}$	0.83	0.75-0.91	0.87	0.70-1.03
d_s	0.04	0.01-0.07	0.03	0-0.07
ρ_r	11.2	8.7-13.6	25.9	17.7-34.8
σ_ε	0.07	0.07-0.08	0.16	0.14-0.17
σ_{LMS}	1.3	0.9-1.9	1.8	0.8-3.9

Precipitation Impact Coefficients

	TN		TP	
Parameter	Mean	95% CI	Mean	95% CI
$\gamma_{,ag}$	4.1	2.9-5.0	4.0	2.9-5.1
$\gamma_{,ur1}$	1.2	0.7-1.7	1.8	1.1-2.5
$\gamma_{,ur2}$	2.1	0.4-4.0	2.0	0.2-3.9
$\gamma_{,und}$	2.8	0.6-5.2	2.4	0.5-4.5
$\gamma_{,ch}$	1.9	0.3-3.8	2.4	0.5-4.8
$\gamma_{,h}$	1.8	0.3-3.7	2.0	0.3-4.1
$\gamma_{,cw}$	1.8	0.3-3.7	2.3	0.4-4.4
$\gamma_{,ret}$	0.07	0.01-0.17	0.09	0 -0.22
μ_γ	1.6	1.1-2.0	1.9	1.1-2.7
σ_γ	1.2	0.8-1.6	1.0	0.5-1.6

Delasantro (2019) monitored 25 small catchments in the Jordan Lake watershed to determine export coefficients from developed land. Measurements of flow and water quality and analyses of low flow loading from forests were also made. Because the forest loading estimates only included baseflows, they were much lower than any of the other studies referenced in this document. Nitrate loading rates from developed areas were reported including baseflow and stormflows and ranged from 0.4 to 2 lb/ac/yr, which is less than the 2.5 to 5.7 lb/ac/yr simulated by WARMF for average delivered total nitrogen from urban areas. Because Delasantro reported only the nitrate component and the WARMF estimates reflect the total nitrogen load, it is not surprising that the WARMF estimates are higher.

USGS SPARROW Models for the Southeast

The USGS has developed Spatially Referenced Regression on Watershed attributes (SPARROW) models to estimate mean-annual streamfow and transport of total nitrogen, total phosphorus, and suspended-sediment in streams in the Southeastern United States. These statistical models are based land use data, atmospheric deposition estimates, point source discharges, and databases describing parent rock material. Management practices are also accounted for in the model. The models account for these sources using varying metrics, and the urban land is the only one whose nutrient coefficient is provided as mass per area per time for comparison to the other areal loading rates described above. The source coefficients are listed separately from the model coefficients that describe losses or additions that may occur in the watershed (overland flow, stream losses, etc.).

The Southeast SPARROW is an empirical model that uses long-term average monitoring data and the characteristics of the watersheds that draining to streamflow and water quality monitoring stations to fit equations describing the relative importance of watershed characteristics on long-term average delivered loads. All terms must be considered in the estimation of delivered loading to streams and waterbodies.

The 2012 Southeast models (Hoos and Roland, 2019) indicate that the largest driver of nitrogen load to streams is atmospheric deposition and that 60 to 70 percent of the TN load originates from this source with the range depending on the significance of other sources in the watershed. The next most significant driver of TN load is the amount of agricultural nutrient application followed by municipal wastewater discharges, application of manure from livestock, and area of urban land. Variability in nitrogen delivery rates to streams was due mostly to climate, soil texture, and vegetative cover. Source loading rates (not accounting for losses during overland flow or within waterbodies) predicted by the SPARROW model for urban land averaged 2.92 kg/ha/yr and ranged from 2.0-3.8 kg/ha/yr. The WARMF catchment-scale loading rates for existing development in the Ellerbe Creek watershed ranged from 10.3 to 12.3 kg/ha/yr for the calibrated model (2014 to 2018) and 7.2 to 9.1 kg/ha/yr for the dry period (represented by 2007). Average annual delivered loading rates to Falls Lake for the entire watershed from 2014 to 2018 ranged from 5.1 to 6.4 kg/ha/yr. Thus, even the delivered loading rates simulated by WARMF are higher than the catchment-scale (to stream) SPARROW estimates. These average delivered loading rates from WARMF do account for transport and ultimate delivery to Falls Lake where the SPARROW loading rates reported do not.

Thus, even the delivered loading rates simulated by WARMF for existing development are higher than the catchment-scale (to stream) SPARROW estimates.

For phosphorus, the SPARROW model indicates that the largest source of delivered load was parent-rock minerals followed by the area of urban land, application rates of manure from livestock, municipal wastewater discharges, application of agricultural fertilizer, and extent of phosphate mining with spatial variability driven by climate, soil erodibility, depth to water table, and the extent of conservation tillage practices in the watershed models (Hoos and Roland, 2019). Across the Southeast, forested areas comprise approximately 40 percent of the area. Nutrient losses in streams, lakes, and impoundments are also accounted for in the modeling using separate terms.

Source loading rates of phosphorus from urban land in the Southeast (not accounting for losses occurring during overland flow or within streams or impoundments) averaged 0.49 kg/ha/yr and ranged from 0.37-0.61 kg/ha/yr. The existing development catchment-scale loading rates from the WARMF model range from 0.37 to 1.8 kg/ha/yr which is higher than the SPARROW model catchment-scale rates. The average annual delivered loading predicts by WARMF range from 0.12 to 0.51 kg/ha/yr; the delivered loading rates are expected to be lower than the catchment-scale rates due to instream and impoundment processing.

The existing development catchment-scale loading rates from the WARMF model range from 0.37 to 1.8 kg/ha/yr which is higher than the SPARROW model catchment-scale rates.

For the Southeast, the SPARROW model predicts that over 40 percent of the phosphorus load to streams is due to background parent rock material and that **areas with little other sources** this load could comprise 60 percent of the total load models (Hoos and Roland, 2019). The Falls Lake WARMF model which is 60 percent forested (75 percent unmanaged) estimates that 44 percent of the phosphorus load to the lake is from forested areas; there are no specific inputs of phosphorus to forested areas other than a minor load from atmospheric deposition. In an earlier publication (García et al. 2011), the mean export rate of phosphorus associated with parent rock material was two times higher than associated with the area of urban development. This earlier paper summarizes the delivered load to waterbodies (accounting for stream and impoundment processes) in the southeast as originating from background phosphorus in soil-parent rock (31%), agricultural land (22%), wastewater discharges (18%), urban land (14%), manure application (9%), and mined lands (6%).

The SPARROW model estimates that 35, 44, and 65 percent of the total nitrogen, total phosphorus, and suspended sediment loads are lost during transport in streams and impoundments. Denitrification is the primary loss pathway for nitrogen in streams and phosphorus removal in streams is primarily due to trapping in bed sediments or settling in impoundments.

Relation of Watershed Setting and Stream Nutrient Yields at Selected Sites in Central and Eastern North Carolina, 1997–2008

This USGS study (Harden et al. 2013) used data collected between 1997 and 2008 at 48 stream sites in NC to identify environmental variables in watersheds that influence nutrient export. Data were compiled from all 48 sites to determine the best predictor variables for the median annual nutrient loads. Median annual streamflow was highly correlated to median annual nutrient loads: total nitrogen R2=0.96, nitrate R2=0.88, total phosphorus R2=0.94 (Figure 12 pasted from report below). Mean annual flow rate at Flat River above Lake Michie for 1997 to 2008 was 132 cfs; during the UNRBA study period (2014-18) was 170 cfs.

Harden et al. (2013) report that total nitrogen yields for low intensity urban and high intensity urban were 2.2 times higher and 2.9 times higher, respectively, than undeveloped areas; total phosphorus yields were 5 times higher and 10 times higher, respectively. The WARMF model generates similar results for nitrogen, and the average annual loads delivered to Falls Lake from existing development is 2 to 3 times higher than forests. The phosphorus load from existing development is similar to that of forests in the WARMF model because the WARMF model does not include the load from streambank erosion in its loading rates for existing development. Streambank erosion results in more phosphorus delivered to Falls Lake than all of the urban categories combined. The Harden et al. model accounts for streambank erosion as part of the land use loading estimates.

Statements from the reported are pasted below for reference:

- Compiled environmental data (including variables for land cover, hydrologic soil groups, base-flow index, streamflows, wastewater treatment facilities, and confined animal feeding operations) were used to characterize the watershed settings for the study sites.
- Data evaluations included an examination of median annual nutrient yields based on a watershed land-use classification scheme developed as part of the study.
- Stream nutrient loads for the study sites are largely contingent on the amounts of streamflow within each of the watersheds. Although various factors influence streamflows (such as basin size and slope, land cover, geology, and water supply use), streamflow amounts are determined primarily by the amount of precipitation that occurs throughout each watershed basin.

- Relations between environmental variables and median annual nutrient (nitrate, total N, and total P) yields were modeled using regression tree analysis (R package "rpart;" Therneau and Atkinson, 2010). Regression tree-based modeling is an exploratory technique for uncovering structure in the data."

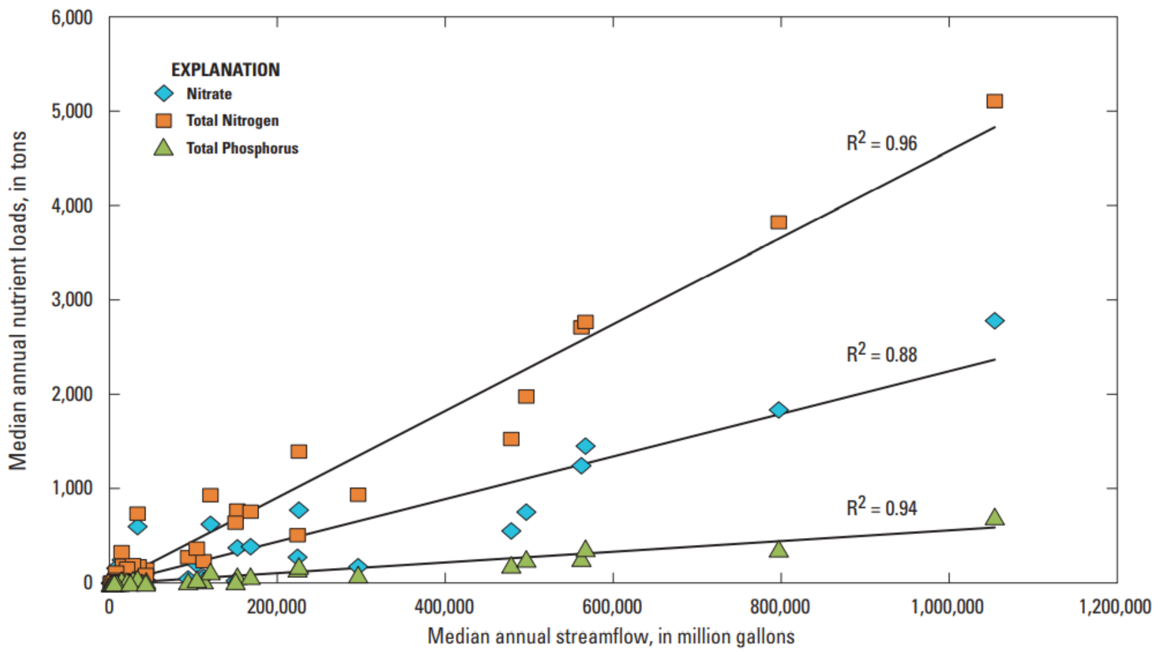


Figure 9. Relation between median annual streamflow and median annual nutrient loads for the study sites, 1997–2008.

Figure above copied from reference.

Table 6. Summary of number of sites and median drainage area, annual nutrient yields, and land-cover class percentages by land-use category. (Land-use categories are described in tables 4 and 5.)

[mi^2, square miles; N, nitrogen; P, phosphorus]

Land-use category (code)	Number of sites	Median drainage area (mi^2)	Median annual nutrient yield			Median land-cover class percentage			
			Nitrate yield (ton/mi^2)	Total N yield (ton/mi^2)	Total P yield (ton/mi^2)	Developed	Agriculture	Forested	Wet-lands
Undeveloped (UN)	4	59.6	0.12	0.40	0.02	5.2	3.8	60.0	10.7
Low agricultural (LAG)	14	166.5	0.24	0.67	0.07	5.6	24.6	60.2	0.9
High agricultural (HAG)	8	122.2	0.54	1.08	0.10	7.7	36.6	36.8	16.2
Low urban (LUR)	2	186.7	0.31	0.87	0.10	19.1	12.1	48.9	10.5
High urban (HUR)	4	27.4	0.40	1.18	0.20	68.0	4.1	21.0	0.6
Mixed (MIX)	10	1,835	0.37	0.81	0.10	15.5	23.7	49.4	1.9
High point-source flow (HPS)	6	58.7	3.93	3.60	0.33	47.4	6.5	38.2	1.0

Table above copied from reference.

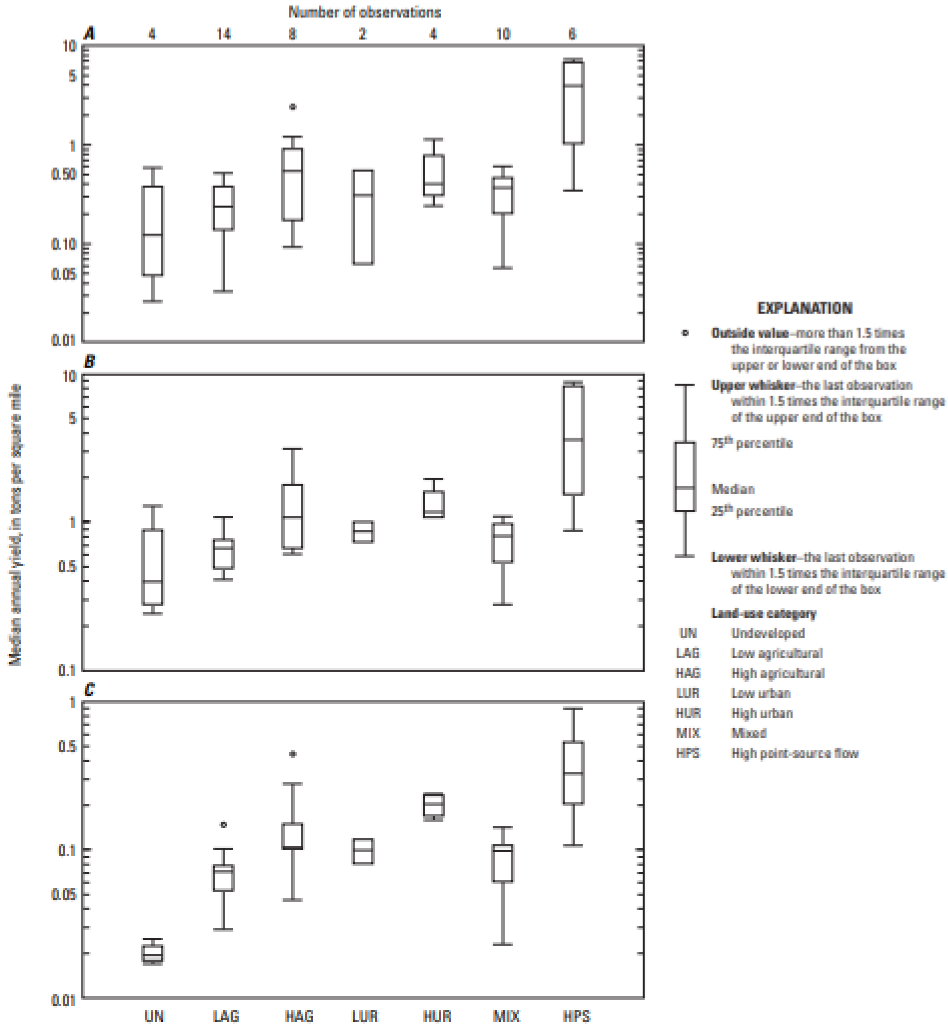


Figure 12. Distributions of median annual yields for (*A*) nitrate, (*B*) total nitrogen, and (*C*) total phosphorus for study sites based on land-use category.

Chesapeake Bay CASTNET Model

The Chesapeake Bay Program (2020) CASTNET Model is a modeling framework that combines multiple models and multiple line of evidence in each of the simulated processes. Average loading rates to small streams are calculated for each land use using the average of several fully calibrated models.

The CASTNET model applies a "No BMP" total nitrogen loading rate for developed areas that is approximately 4 times higher than that of natural areas; the total phosphorus loading rate assuming "No BMPs" is approximately 10 times higher than for natural areas. These are similar to the relative rates reported by Harden et al. (2013).

<u>The following are excerpts from Section 2 of the Phase 6 report:</u>

Average Loads are loads per acre per year for each land use averaged across the entire Chesapeake Bay watershed. Average loads are not true edge-of-field loads, but average for what would reach a small stream. Next, Stream Delivery factors are applied to account for nutrient and sediment processes in streams with average flow less than 100 cfs. These are attenuation factors that act to decrease nutrient delivery in small streams as the loads move to the boundary of the larger modeled river reaches. River Delivery factors account for nutrient attenuation processes in the larger rivers as loads move to the estuary. Streams and rivers are modeled separately because different sources of information are used to estimate their delivery coefficients.

The Phase 6 structure accommodates the scientific community's recommendations by allowing for deliberate use of multiple models and multiple line of evidence in each of the processes. The CBP has used multiple models and multiple lines of evidence wherever possible to estimate the coefficients. For example, average loads are calculated using the average of several fully calibrated models. Table 1-3 (copied from the reference) shows some of the models that are used in the calculation of the coefficients for Phase 6.

A land use average load is defined in the Chesapeake Bay Program's (CBP) Phase 6 Watershed Model (Phase 6) as the spatially averaged and temporally averaged nutrient loading export rate to a stream or other waterbody for a given land use. The loading rate is typically expressed in pounds per acre per year. Average loads are developed at the Chesapeake Watershed scale with the assumption of no management practices, and are independent of local nutrient application rates, location within the watershed, and physical characteristics. For example, the average load for forest nitrogen export to streams is 1.68 pounds per acre per year averaged over the simulation period of 1985-2014 and over the entire Chesapeake Bay watershed. Tables 2-5 through 2-8 (copied directly from the reference) show the areal loading rates assumed by the Phase 6 model.

Table 1-3: Models incorporated in the Phase 6 Watershed Model

Model	Use in Phase 6 Model
CBP Phase 5.3.2 Watershed Model	Average loads Nitrogen sensitivity
USGS SPARROW regression model	Average loads Nitrogen sensitivity Land-to-water Stream delivery
USDA CEAP/APEX Chesapeake model	Average loads Nitrogen sensitivity
APLE	Phosphorus sensitivity
RUSLE	Sediment edge-of-field loads
rSAS	Lag time
UNEC	Lag time
Modflow	Lag Time

Table 2-5: Total nitrogen land class loads and average loading rates above RIM stations

Land class	Crop	Pasture/Hay	Developed	Natural
Acres in millions above the RIM stations	2.6	4.5	2.7	21.5
P532 No BMP Loading Rate (pounds per acre per year)	47.51	14.95	16.80	4.21
CEAP Loading Rate (pounds per acre per year)	42.52	10.19	Not used	1.61
SPARROW Loading Rate with BMP effects removed (pounds per acre per year)	22.35	7.30	8.35	0.40
Average Ratio to Cropland Rate	1.00	0.29	0.36	0.05
Average Land class Loading Rate (pounds per acre per year)	38.22	11.22	13.90	1.84
Total Land class Load (million pounds per year)	100.16	50.88	37.39	39.45

Table 2-6: Total phosphorus land class loads and average loading rates above RIM stations

Land class	Crop	Pasture/Hay	Developed	Natural
Acres in millions above the RIM stations	2.6	4.5	2.7	21.5
P532 Loading Rate (pounds per acre per year)	2.23	1.48	1.22	0.12
CEAP Loading Rate (pounds per acre per year)	3.12	1.29	Not used	0.10
SPARROW Loading Rate with BMP effects removed (pounds per acre per year)	0.94	0.22	0.34	0.06
Average Ratio to Crop Rate	1.00	0.44	0.46	0.05
Average Land class Loading Rate (phosphorus pounds per acre per year)	1.87	0.81	0.85	0.09
Total Land class Load (million pounds per year)	4.89	3.69	2.38	1.98

Table 2-7: Total nitrogen land use acres, relative rates, and average loading rate

Land class	Land Use	Acres	Loading Rate Ratio	Loading Rate (pounds per acre per year)
Cropland	Double Cropped Land	165,396	0.79	30.87
	Full Season Soybeans	282,456	0.71	27.74
	Grain with Manure	389,811	1.4	54.7
	Grain without Manure: Reference land use	451,318	1.00	39.07
	Other Agronomic Crops	417,838	0.45	17.58
	Silage with Manure	392,156	1.62	63.30
	Silage without Manure	69,204	1.16	45.33
	Small Grains and Grains	291,677	0.84	32.82
	Specialty Crop High	35,525	1.34	52.36
	Specialty Crop Low	125,509	0.31	12.11

Developed	CSS Buildings and Other	39,580	0.81	18.08
	CSS Construction	1,516	1.19	26.80
	CSS Roads	10,849	1.02	22.87
	CSS Tree Canopy over Impervious	4,466	0.91	20.49
	CSS Tree Canopy over Turfgrass	15,934	0.38	8.53
	CSS Turf Grass	29,800	0.50	11.19
	MS4 Buildings and Other	164,843	0.81	18.08
	MS4 Construction	65,955	1.19	26.80
	MS4 Roads	59,965	1.02	22.87
	MS4 Tree Canopy over Impervious	24,896	0.91	20.49
	MS4 Tree Canopy over Turfgrass	102,715	0.38	8.53
	MS4 Turf Grass	311,048	0.50	11.19
	Non-Regulated Buildings and Other	295,033	0.81	18.08
	Non-Regulated Roads: Reference Land Use	211,292	1.02	22.45
	Non-Regulated Tree Canopy over Impervious	78,512	0.91	20.49
	Non-Regulated Tree Canopy over Turfgrass	255,214	0.38	8.53
	Non-Regulated Turf Grass	1,121,002	0.50	11.19

	[illegible]	[illegible]	[illegible]	[illegible]
Natural	CSS Forest	25,062	1.00	1.68
	CSS Mixed Open	11,193	1.46	2.45
	Harvested Forest	264,474	7.07	11.88
	Headwater or Isolated Wetland	350,820	1.00	1.68
	Mixed Open	895,240	1.46	2.45
	Non-tidal Floodplain Wetland	397,778	1.00	1.68
	True Forest: Reference Land Use	19,550,675	1.00	1.68
Pasture	Ag Open Space	140,316	0.43	5.07
	Legume Hay	728,148	0.74	8.72
	Other Hay	1,294,306	1.04	12.26
	Pasture: Reference Land Use	2,372,549	1.00	11.78

Table 2-8: Total phosphorus land use acres, relative rates, and average loading rate

Land class	Land Use	Acres	Loading Rate Ratio	Loading Rate (pounds per acre per year)
Cropland	Double Cropped Land	165,396	1*	1.87*
	Full Season Soybeans	282,456		
	Grain with Manure	389,811		
	Grain without Manure	451,318		
	Other Agronomic Crops	417,838		
	Silage with Manure	392,156		
	Silage without Manure	69,204		
	Small Grains and Grains	291,677		
	Specialty Crop High	35,525		
	Specialty Crop Low	125,509		

Developed	CSS Buildings and Other	39,580	0.83	0.69
	CSS Construction	1,516	3.89	3.21
	CSS Roads	10,849	1.04	0.86
	CSS Tree Canopy over Impervious	4,466	0.91	0.75
	CSS Tree Canopy over Turfgrass	15,934	0.79	0.65
	CSS Turf Grass	29,800	1.04	0.86
	MS4 Buildings and Other	164,843	0.83	0.69
	MS4 Construction	65,955	3.89	3.21
	MS4 Roads	59,965	1.04	0.86
	MS4 Tree Canopy over Impervious	24,896	0.91	0.75
	MS4 Tree Canopy over Turfgrass	102,715	0.79	0.65
	MS4 Turf Grass	311,048	1.04	0.86
	Non-Regulated Buildings and Other	295,033	0.83	0.69
	Non-Regulated Roads	211,292	1.04	0.83
	Non-Regulated Tree Canopy over Impervious	78,512	0.91	0.75
	Non-Regulated Tree Canopy over Turfgrass	255,214	0.79	0.65
	Non-Regulated Turf Grass	1,121,002	1.04	0.86
Natural	CSS Forest	25,062	1	0.08
	CSS Mixed Open	11,193	5.69	0.43
	Harvested Forest	264,474	3.12	0.24
	Headwater or Isolated Wetland	350,820	1	0.08
	Mixed Open	895,240	5.69	0.43
	Non-tidal Floodplain Wetland	397,778	1	0.08
	True Forest	19,550,675	1	0.08
Pasture	Ag Open Space	140,316	1*	.81*

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	Legume Hay	728,148		
	Other Hay	1,294,306		
	Pasture	2,372,549		

** At the direction of the Agriculture Land Use Loading Rate Subgroup, the entire crop category was treated as a single unit. The weighted average of all crop types is 1.87 lbs/acre. They are differentiated by inputs and sensitivities as described in Sections 3 and 4. Similarly, pasture is treated as a single unit with a weighted average of 0.81 lbs/acre.*

Predicting Sources of Dissolved Organic Nitrogen to an Estuary from an Agro-Urban Coastal Watershed

Osburn et al. (2016) used fluorescence measurements and statistical modeling to understand the sources of dissolved organic nitrogen in the Lower Neuse River Basin. Data were collected from representative sources to develop their fluorescence signature: reference areas (i.e., forested, undisturbed), septic systems, wastewater treatment plants, stormwater runoff, soils, cropland, swine, or poultry.

Monthly sampling by the Lower Neuse Basin Association (LNBA) was utilized to collect surface water samples at thirteen locations on the Neuse River or its tributaries. The fluorescence signatures of these samples were compared to those of the representative sources to predict the percentage contributions by source. Source categories were defined as follows: "Developed cover was the sum of developed open space, low-, medium-, and high-intensities, and barren land. Forest cover was the sum of deciduous forest, evergreen forest, mixed forest, shrub/scrub, and herbaceous classifications. Cropland cover was the sum of cultivated crops and hay and pasture. Wetlands cover was the sum of woody wetland and emergent herbaceous wetlands."

Osburn et al. (2016) found that on average, 72 to 85 percent of organic nitrogen loading matched the fluorescence signatures of reference streams that were classified as Outstanding Resource Waters. The sampled reference streams had no discharges from wastewater treatment facilities, street or storm water runoff over paved surfaces, or poultry or swine operations in their watersheds. This finding is similar to research in the Falls Lake watershed (McKee 2020) which states "With the exception of Ellerbe Creek, the most likely sources of organic matter discharged into Falls Lake come from soil organic matter. Ellerbe Creek, which has a large proportion of urban environments within its watershed, has lower carbon to nitrogen values which indicate the influence of human inputs such as fertilizer, septic, sewage."

The table below (Table S5) was copied directly from the reference.

Table S5. Percentages of DON in the Neuse River Basin tributaries and main-stem sites predicted by FluorMod from Aug 2011- May 2013. REF = Reference; EFF = Effluent; INF = Influent; PLT = Poultry; SWI = Swine; SEP = Septic; STR = Street runoff; Urban = urban sources (sum of EFF + INF + SEP + STR); Agriculture = animal waste sources (sum of PLT + SWI). Gray shaded values indicate model runs in which a particular source was excluded due to land use analysis. N is the number of stream or river observations modeled.

	Discrete sources								**Grouped sources**	
Stream	**REF**	**EFF**	**INF**	**PLT**	**SWI**	**SEP**	**STR**	**SOI**	**Urban**	**Agriculture**
Crabtree Creek (N = 24)										
mean	77%	1%	3%	0%	0%	7%	5%	7%	16%	0%
max	83%	2%	10%	0%	0%	15%	8%	12%	35%	0%
min	65%	0%	0%	0%	0%	3%	3%	4%	7%	0%
Middle Creek (N=47)										
mean	72%	2%	3%	8%	0%	3%	2%	11%	9%	8%
max	82%	15%	5%	14%	2%	6%	4%	23%	30%	16%
min	69%	0%	0%	0%	0%	0%	0%	3%	0%	0%
Neuse-Clayton (N=13)										
mean	71%	2%	7%	0%	0%	9%	3%	7%	22%	0%
max	80%	8%	15%	0%	0%	17%	5%	20%	45%	0%
min	55%	0%	1%	0%	0%	4%	1%	3%	6%	0%
Neuse-Kinston (N=96)										
mean	78%	0%	2%	5%	0%	1%	2%	11%	6%	5%
max	88%	4%	20%	16%	2%	18%	6%	28%	48%	18%
min	50%	0%	0%	1%	0%	0%	1%	2%	1%	1%
Neuse-Ft. Barnwell (N=90)										
mean	79%	0%	1%	4%	0%	1%	1%	11%	4%	4%
max	86%	14%	30%	12%	1%	20%	3%	21%	67%	13%
min	24%	0%	0%	1%	0%	0%	0%	8%	0%	1%
Trent River (N=78)										
mean	81%	0%	0%	2%	0%	1%	1%	15%	81%	0%
max	87%	10%	5%	12%	0%	15%	4%	31%	87%	10%
min	46%	0%	0%	0%	0%	0%	0%	8%	46%	0%

References

AMEC. 2012. Atmospheric Deposition Study for the City of Durham, North Carolina Eight Month Data Report. Prepared for the City of Durham. April 2012.

BC. 2019. Final UNRBA Monitoring Report for Supporting the Re-Examination of the Falls Lake Nutrient Management Strategy Prepared for Upper Neuse River Basin Association, NC. June 2019.

Boggs, Johnny, Ge Sun, David Jones, and Steven G. McNulty, 2012. Effect of Soils on Water Quantity and Quality in Piedmont Forested Headwater Watersheds of North Carolina. Journal of the American Water Resources Association (JAWRA) 49(1): 132-150. DOI: 10.1111/jawr.12001

Boggs, Johnny, Ge Sun, David Jones, Steven G. McNulty, David Jones, William Swartley, and Tom Gerow 2013. Effectiveness of Forestry Best Management Practices for Water Quality Protection in Headwater Catchments in the Falls Lake Watershed. Presentation at the 2013 Water Resources Research Institute Annual Conference.

Cardno ENTRIX. 2013. Task 3: Estimation of Nutrient Loading to Falls Lake Support of Long Term Planning and Regulatory Nutrient Activities in the Falls Lake Watershed. Prepared for the Upper Neuse River Basin Association.

Chesapeake Bay Program, 2020. Chesapeake Assessment and Scenario Tool (CAST) Version 2019. Chesapeake Bay Program Office.

Delasantro, Joseph. (2019). Jordan Lake Nutrient Study.

Dodd, R.C, McMahon, G., Stichter, S. 1992. Watershed Planning in the Albemarle-Pamlico Estuarine System, Report 1 – Annual Average Nutrient Budgets. Report No. 92-10, August 1992.

Fleming, M. 2013, Durham County Homeowner Fertilizer Behaviors Survey: Summary and Analysis of Results for Drew Cummings, Assistant County Manager, October 14, 2013.

García, Ana María, Anne B. Hoos, and Silvia Terziotti, 2011. A Regional Modeling Framework of Phosphorus Sources and Transport in Streams of the Southeastern United States. Journal of the American Water Resources Association (JAWRA) 47(5):991-1010. DOI: 10.1111/j.1752-1688.2010.00517.x

Harden, S.L., Cuffney, T.F., Terziotti, Silvia, and Kolb, K.R., 2013, Relation of watershed setting and stream nutrient yields at selected sites in central and eastern North Carolina, 1997–2008: U.S. Geological Survey Scientific Investigations Report 2013–5007, 47 p., http://pubs.usgs.gov/sir/2013/5007

Hoos, A.B., and Roland, V.L. II, 2019, Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in the Southeastern United States: U.S. Geological Survey Scientific Investigations Report 2019–5135, 87 p., https://doi.org/10.3133/sir20195135.

Hopkins, Kristina G, Sean A. Woznicki, Brianna M. Williams, Charles C. Stillwell, Eric Naibert, Marina J. Metes, Daniel K. Jones, Dianna M. Hogan, Natalie C. Hall, Rosemary M. Fanelli, and Aditi S. Bhaskar. 2022. Lessons learned from 20 y of monitoring suburban development with distributed stormwater management in Clarksburg, Maryland, USA. *Freshwater Science*, Volume 41, Number 3, September2022.

Lin, J.P. 2004. Review of Published Export Coefficient and Event Mean Concentration (EMC) Data. Wetlands Regulatory Assistance Program. ERDC report TN-WRAP-04-03. September 2004.

McKee, Brent, Sherif Ghobrial and Alyson Burch. 2022. The importance of lake and impoundment ecosystems to global organic carbon cycling and climate change Falls Lakes, NC. Department of Marine Sciences, University of North Carolina at Chapel Hill. September 2020.

Miller, J., Karima, K., Arumugam, S., Obenour, D. 2019. Jordan Lake Watershed Model Report, Prepared for North Carolina Policy Collaboratory. December 2019.

Miller, J. W., Karimi, K., Sankarasubramanian, A., & Obenour, D. R. (2021). Assessing interannual variability in nitrogen sourcing and retention through hybrid Bayesian watershed modeling. Hydrology and Earth System Sciences, 25(5), 2789-2804.

NC Division of Water Resources (DWR). 2009. Falls Lake Watershed Analysis Risk Management Framework (WARMF) Development. Final Report. Prepared by N.C. Department of Environment and Natural Resources Division of Water Quality Planning Section Modeling/TMDL Unit October 2009.

Osburn, C. L., Handsel, L.T., Peierls, B.L., and Paerl, H.W. 2016. Predicting Sources of Dissolved Organic Nitrogen to an Estuary from an Agro-Urban Coastal Watershed, Supporting Information. *Environmental Science & Technology* 2016 50 (16), 8473-8484. DOI: 10.1021/acs.est.6b00053

Osmond, D.L., Hardy, D.H. 2004. Turf Practices in Five North Carolina Communities, Characterization of Turf Practices in Five North Carolina Communities, J. Environ. Qual., Vol. 33, March–April 2004.

Osmond, D., Neas, K. 2011. Final Report for the Sampling Analysis: Delineating Agriculture in the Neuse River Basin, Submitted October 5, 2011, to the NC Department of Environment and Natural Resources (NCDENR), Division of Water Quality.

Smith, D.B., Cannon, W.F., Woodruff, L.G., Solano, Federico, Kilburn, J.E., and Fey, D.L., 2013, Geochemical and mineralogical data for soils of the conterminous United States: U.S. Geological Survey Data Series 801, 19 p., https://pubs.usgs.gov/ds/801/.

Tetra Tech. 2012. High Rock Lake Watershed Model and High Rock Lake Technical Advisory Committee Watershed Model Review Comments and Responses. Prepared for United States Environmental Protection Agency, Region 4, Contract Number: EP-C-08-004, Task Order: 036.

Tetra Tech. 2014. Lake B. Everett Jordan Watershed Model Report. Prepared for North Carolina Nutrient Science Advisory Board, North Carolina Division of Water Resources, and Triangle J Council of Governments. July 2014.