UNRBA Falls of the Neuse Reservoir (Falls Lake) Watershed Modeling Report

Final for Submittal to the NC Division of Water Resources for Review and Approval under 15A NCAC 02B .0275

Prepared for
Upper Neuse River Basin Association, NC

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Prepared by

and

Limitations:

This document was prepared solely for UNRBA in accordance with professional standards at the time the services were performed and in accordance with the contract between UNRBA and Brown and Caldwell. This document is governed by the specific scope of work authorized by UNRBA and the UNRBA Modeling Quality Assurance Project Plan.

This document serves the following purposes:

1. Provides documentation that the development of the WARMF Watershed Model followed the UNRBA Modeling Quality Assurance Project Plan (QAPP) approved by the North Carolina Division of Water Resources (DWR) for this modeling effort.

2. Supports the review and approval of this Watershed Analysis Risk Management Framework (WARMF) Watershed model development report by DWR under Falls Lake Rule 15A NCAC 02B .0275.

3. Provides an evaluation of the modeling results relative to the impacts of land use in the watershed, the distribution of nutrient loading, and the implications of those findings for a revised strategy.

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Executive Summary

The Upper Neuse River Basin Association (UNRBA) has developed watershed and lake models to support its reexamination of Stage II of the Falls Lake Nutrient Management Strategy (Falls Lake Rules). The UNRBA undertook this reexamination effort under the adaptive management provision of the Falls Lake Rules. The Association committed itself to a careful, detailed, and science-based process for assessing the current Nutrient Management Strategy. At every step through this process, the UNRBA has sought and received approval from DEQ/DWR as required under the Rules.

Additionally, as a reflection of the UNRBA membership's ongoing support of maintaining and improving the water quality of Falls Lake, the jurisdictions in the UNRBA continue to implement the New Development requirements and the Stage I requirements of the Strategy for existing development and wastewater treatment plants. Because of the uncertainty of the requirements for Stage II and the tremendous technical and economic challenges of these requirements, the UNRBA provided local government funding for a reexamination effort that would provide the necessary, scientific basis to support an updated strategy.

In 2016, the UNRBA initiated the Modeling and Regulatory Support (MRS) project as part of the reexamination of the Falls Lake Nutrient Management Strategy (Falls Lake Rules). The Falls Lake Nutrient Management Strategy developed by DWR and approved by the Environmental Management Commission (EMC) requires very large reductions in lake nutrient loading from wastewater treatment plants, agriculture, and existing development, as well as ongoing control of new development in the watershed. The responsibility for achieving the unprecedented levels of required loading reduction from existing development falls primarily on the local governments in the watershed. DWR's baseline modeling period (2005 to 2007) also represented a historic drought for the area. While the year selected as the basis for the nutrient reduction targets (2006, "the baseline year") had a total annual rainfall near the annual average for the area, more than half of the total was delivered by three large storms including a tropical system. Because the watershed and lake modeling developed by the State and used as the basis of the rules was completed on a compressed schedule with limited data, stakeholders noted there was considerable uncertainty in the required loading targets. DWR and the EMC recognized this concern, so the Rules allow for a "reexamination" of the required nutrient load reductions under Stage II. This adaptive management provision resulted in the UNRBA implementing its reexamination project.

The UNRBA finalized a plan for conducting the reexamination in 2013. This plan included a minimum of three years of water quality monitoring in the watershed and the lake. The UNRBA began collecting water quality data in August 2014 and completed monitoring in October of 2018, providing data from four "growing seasons" in the lake. A main purpose for collecting this data was to support revised and new models as part of the reexamination. However, a tremendous amount of additional types of data and information are also needed to develop the models. The model preparation work is crucial, and an extensive effort has been made to assemble the datasets needed to properly build the modeling tools to support the reexamination.

This report describes the development of the Falls Lake watershed model using the Watershed Analysis Risk Management Framework (WARMF). A separate report describes the lake models.

Report Purpose

This report was developed to carefully document the extensive work performed to develop the UNRBA's Falls Lake Watershed model and for submittal of the model for approval under Falls Lake Rule 15A NCAC .0275. The computer files developed for this watershed model have been provided to the UNRBA member jurisdictions and the NC Division of Water Resources (DWR) for review and evaluation.

The UNRBA's WARMF watershed modeling effort followed the DWR-approved UNRBA Description of the Water Quality Modeling Framework and the UNRBA Modeling Quality Assurance Project Plan (QAPP). Approval of the watershed model is requested under rule 15A NCAC 02B .0275(5)(f), which states that any model submitted must be developed "in accordance with the quality assurance requirements of the Division." The quality assurance requirements for this effort were established in the DWR-approved QAPP. The calibrated and validated WARMF Watershed model developed for the UNRBA is described in detail in this report and is fully referenced to the Modeling QAPP. As the UNRBA has discussed several times with DWR, it was agreed that models developed will be submitted as the work is completed. Other model development reports and documentation will be submitted for review and approval by DWR following finalization of those models.

This report also documents the extensive effort undertaken by the UNRBA to improve the science and understanding of nutrient and carbon loading delivered to Falls Lake. This improved information provides the basis for the revised nutrient management strategy for Falls Lake.

The model development process used data from a host of established sources (described in this report) and watershed data collected under the DWR-approved UNRBA Monitoring Plan. The modeling has resulted in improved understanding regarding the importance of soil chemistry on the transport and retention of nutrients in the watershed. This understanding should be reflected in the revised strategy in a way that reflects the length of time that changes in watershed activities may take to realize changes in delivered loading to Falls Lake and resulting water quality. Similarly, the modeling demonstrates that the significant efforts in the watershed to reduce point and non-point source nutrient loading have had a measurable impact on delivered loads to Falls Lake. Because the majority (75 percent) of the land use in the watershed is unmanaged (forests, unmanaged grasslands/shrublands including land in forest succession, wetlands, etc.), approximately half of the delivered nutrient and carbon load to Falls Lake originates from unmanaged lands. These lands are important to the health of the watershed and the lake, and multiple stakeholders have expressed that conservation is an important component of a revised nutrient management strategy.

Background: Previous UNRBA Efforts to Support the Reexamination

Planning for the reexamination began in 2012 and important progress on the two main components of this effort has been made: the UNRBA Monitoring Program to support the modeling effort was completed in 2018 and key UNRBA Modeling and Regulatory Support (MRS) Project efforts have also been completed. Each project component included plans and quality assurance procedures that were approved by DEQ/DWR before proceeding with the efforts.

In preparation for the development of modeling tools and the actions necessary to complete this component of the reexamination effort in accordance with the Falls Lake Rules, the UNRBA accomplished the following required tasks prior to development of the modeling tools (documents related to these projects are available at www.unrba.org):

Approval by the NC Division of Water Resources (DWR) of all planning documents and quality assurance project plans (QAPP) required by the Falls Lake Nutrient Management Strategy:

- UNRBA Description of the Modeling Framework (2014)
- UNRBA Monitoring Plan (2014) and UNRBA Monitoring QAPP (2014)
- UNRBA Modeling QAPP (2018)

Design, implementation, and successful completion of a four-year monitoring program (50 months total) to support development of lake and watershed models including routine monitoring and several special studies (2014 to 2018).

Evaluation and Selection of Model Packages for the UNRBA Modeling and Regulatory Support Project (2017) for the watershed and lake models following a rigorous screening process

Development of a Conceptual Modeling Plan (2017) describing the watershed model, hydrodynamic/water quality lake models (Watershed Analysis Risk Management Framework (WARMF) and Environmental Fluid Dynamics Code (EFDC)), statistical/Bayesian lake model, and cost benefit analysis

Development of a Data Management Plan (2018)

Completion of a comprehensive monitoring program report that not only looks at the data collected by the UNRBA, but data available on Falls Lake since it was put in service in 1982 (Final UNRBA Monitoring Report (2019) available at www.unrba.org)

Construction of a comprehensive, publicly available UNRBA monitoring database providing essential input information for the Watershed Analysis Risk Management Framework (WARMF) model to support model development available to the public through the UNRBA data portal (2019).

Presentation of modeling development work at publicly available sessions of the UNRBA's Path Forward Committee (PFC), Modeling and Regulatory Support Workgroup (MRSW), numerous additional workgroups, and Board of Directors meetings (ongoing, materials available on the UNRBA Meeting Page).

Coordination of special technical stakeholder meetings, forums, symposia, and presentations at conferences and public meetings to describe the status of the models and receive feedback (ongoing, materials available on the UNRBA Meeting Page)

Development of the UNRBA Decision Framework (2020) to document how the organization incorporates input from internal and external stakeholders, works toward consensus, and formalizes decisions

Development of the watershed model has been a multi-year effort that included gathering data, configuring the model, developing model input files, and calibrating and validating for hydrology and water quality observations. The watershed model calibration was approved by the UNRBA in 2022 and has been used to support development and calibration of two mechanistic lake water quality models. Together, the watershed and lake models have been used to evaluate the impacts of scenarios and management options on lake water quality.

Coordination and Input from Internal and External Stakeholders

Throughout this process, the UNRBA has been and continues to be committed to an open and well vetted model development process. Development of an accurate watershed model for predicting stream flows and pollutant loads requires well-developed input data and characterization of the watershed soils, land uses, wastewater treatment processes, etc.

The UNRBA extends many thanks to these organizations and the dedicated staff that develop and maintain these critical data sources.	Data collection for critical components of the model preparation effort would not have been possible without the cooperation, support, and work of the UNRBA members (Cities of Creedmoor, Durham, and Raleigh; Counties of Durham, Franklin, Granville, Person, Orange, and Wake; Towns of Butner, Hillsborough, Stem, and Wake Forest; and the South Granville Water and Sewer Authority), the Modeling and Regulatory Support Workgroup (MRSW) of the UNRBA, the Path Forward Committee (PFC) of the UNRBA, the NC Department of Agriculture and Consumer Services' (NCDA&CS) Division of Soil and Water Conservation, local Soil and Water Conservation Districts, the NC Farm Bureau Federation, the Falls Lake Watershed Oversight Committee (WOC), the US Forest Service, US Geologic Survey, NC State's Climate Office (SCO), NC's Department of Transportation (DOT), the NC Division of Water Resources (DWR), the NC Wildlife Resources Commission (WRC), and representatives from non-governmental organizations (NGOs).
Throughout the process, the UNRBA has hosted several workshops and forums to communicate the work of the UNRBA and to receive input from internal and external stakeholders regarding the reexamination.	In addition to UNRBA members, representatives from several State agencies (DWR, DOT, WRC, NCDA&CS Division of Soil and Water Conservation), agriculture (Farm Bureau, WOC, NC Horse Council), and NGOs (American Rivers, River Guardian Foundation, WakeUP Wake County, Sound Rivers Upper Neuse Riverkeeper, Ellerbe Creek Watershed Association, Upper Neuse Clean Water Initiative, Triangle Land Conservancy) have participated directly in these workshops and provided input over the entire period of planning and performing the tasks outlined in this report. Meeting materials and presentations for workshops and forums are available at the UNRBA Meeting Page.
The UNRBA has worked closely with researchers funded by the NC Collaboratory to conduct research in Falls Lake and its watershed and to provide "third-party" subject matter expert review of the UNRBA models.	Descriptions of the research studies and review efforts pertaining to the watershed modeling are referenced in the relevant sections of this report (studies pertaining to the lake models are discussed in the UNRBA Lake Modeling Report). Reports on research funded through the NC Collaboratory are available online at nutrients.web.unc.edu/resources/. The researchers summarized their work during three joint symposia held by the NC Collaboratory and the UNRBA. Recordings of the presentations are available online for the three events: May 2021, April 2022, and April 2023. Many of the researchers have also presented their work at MRSW and PFC meetings and copies of these presentations are available on the UNRBA Meeting Page. The UNRBA modeling team has worked closely with these researchers to ensure the data, assumptions, and model simulations and components are consistent with the available research and knowledge about Falls Lake and its watershed.

The UNRBA has also coordinated closely with DWR modeling staff, "third-party" reviewers funded by the NC Collaboratory, and technical subject matter experts on the UNRBA team and from other organizations to evaluate the model and provide input, note concerns, pose questions, or point out issues identified as the model was being developed.

These reviewers were invited to participate in and provide feedback during all the UNRBA's meetings involving status reports or modeling-specific discussions. In instances where questions could not be resolved during routine meetings, special meetings were held to discuss options and review additional analyses. Questions and issues raised by the "third-party" reviewers, subject matter experts, and DWR staff in reference to processing steps, model assumptions, or model calibration were addressed prior to finalizing the models. Following special meetings with reviewers, recommendations for proceeding were presented to the MRSW and PFC, and votes were held to formalize decisions regarding model development. This process is documented throughout this report and appendices. The model development files, and the documentation of this extensive model development process are available to all parties interested in reviewing this work.

Model Characteristics and Development Process

The development of a watershed model requires a solid understanding of the inputs to the modeled area and a well-developed simulation tool for the processes that impact those inputs as they move through the watershed. The WARMF Watershed model is a well-established, tested, used, and accepted tool for the development of realistic and reasonable results for guiding the development of regulatory approaches for addressing lake and reservoir nutrient impacts. The stepwise process of watershed model development begins with a summary of sources that represents the nutrient input to the watershed, followed by the development and calibration of the model, and then a review of the simulated output by source category for land use in the watershed.

The Falls Lake WARMF model employed special features of the model or included improvements to the model code to provide the information needed for supporting revisions to the Falls Lake Nutrient Management Strategy. WARMF is a lumped parameter model, so the land uses and soils for each modeling catchment 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 similar loading rates (pounds per acre per year) from sources across the catchment. Because soil nutrients and how they are impacted by land use is very important in the assessment of watershed sources, this modeling effort included adjustments to the model configuration for the Falls Lake watershed. In order to address this standard modeling characteristic of WARMF and better distinguish the loading by land use, **the Falls watershed WARMF model was configured to isolate soils by land use.** This output provides information that is reflective of the soil conditions in the watershed.

Through support by the NC Collaboratory and funding provided by DWR, **the WARMF model code was also improved for this application to allow the simulation of up to 15 types of onsite wastewater treatment systems rather than the model default (three systems).** DWR assisted with securing grant funding through 319 to fund these model code revisions. The UNRBA worked closely with researchers funded through the NC Collaboratory to develop the model inputs associated with each type of onsite wastewater treatment system.

Unlike empirical models, the WARMF Watershed model simulates the movement of "applied" nutrients over the land surface, through the soil, and through streams and impoundments to the targeted downstream location, i.e., Falls Lake. This represents a dynamic response to land use and management. The variation in loading per unit surface area is based on rates and timing of nutrient application, rainfall and antecedent moisture conditions, vegetation growth and harvesting cycles, and physical/biological/

chemical changes to nutrients as they move through the watershed. This is a much more accurate way to project the variation in loading based on weather and physical conditions compared to prescribing runoff nutrient concentrations or surface area loading rates that are intended to represent an average condition and are often based on studies from different regions or periods that are not representative of local rainfall, soils, and physical watershed conditions. This more complex, process-based model using local data allows for better decision making for the development of an improved nutrient management strategy for Falls Lake. The UNRBA's watershed model for the 2015 to 2018 period represents conditions with above average rainfall, and the model was calibrated to simulate flows and water quality concentrations observed during that period.

During meetings with technical subject matter experts and "third-party" model reviewers, questions were raised about the simulated areal loading rates (mass per area per time, e.g., pounds per acre per year) for different land use types. Some reviewers questioned loading rates for certain land uses like forests as seemingly too high, and comparisons to other published studies were provided for confirmation of the model loading rates. Fortunately, research on forested area in the Falls Watershed are available from the US Forest Service. To ensure the WARMF watershed model was simulating reasonable areal loading rates for various land uses, representative modeling catchments with predominate land use in agriculture, urban development, or forest were evaluated for rainfall conditions that more closely matched those of the monitoring studies or other model publications. For this comparison, the selected modeling catchments were evaluated for a dry year (2007) and an average year (2017). Simulated loading rates by land use under these hydrologic conditions were very comparable to the areal loading rates from the US Forest Service monitoring studies and other model publications. These analyses are documented in Appendix H. Based on these comparisons, the WARMF Watershed model output properly reflects variation in loading resulting from land use and variation in rainfall.

Summary of Nutrients Applied or Released to the System

External sources of nitrogen and phosphorus enter the Falls Lake watershed system on the vegetation or land surface, subsurface, or as discharges to streams and rivers. In addition, nutrients are stored in the watershed soils and lake sediments based on past nutrient inputs, vegetative removal or recycling, and physical, chemical, and biological transformations that occur in the groundwater and the soils. Many processes act on these applied and stored nutrients before they are delivered to Falls Lake. Several of these processes, like crop harvesting and denitrification, remove the nutrients from the system entirely.

Most sources of nutrients that are applied or released to the Falls Lake watershed are represented using model input files including atmospheric deposition, nutrient application to agriculture or urban land, wastewater treatment facilities, sanitary sewer overflows, and onsite wastewater treatment systems. Wastewater treatment facilities, sanitary sewer overflows, and discharging sand filter systems are tracked together in a category called point sources. Inputs applied to the land surface such as nutrient application and atmospheric deposition are tracked by land use type (Figure ES-1). Natural areas only receive external nutrient inputs from atmospheric deposition. This is a critical factor in considering future releases from these lands.

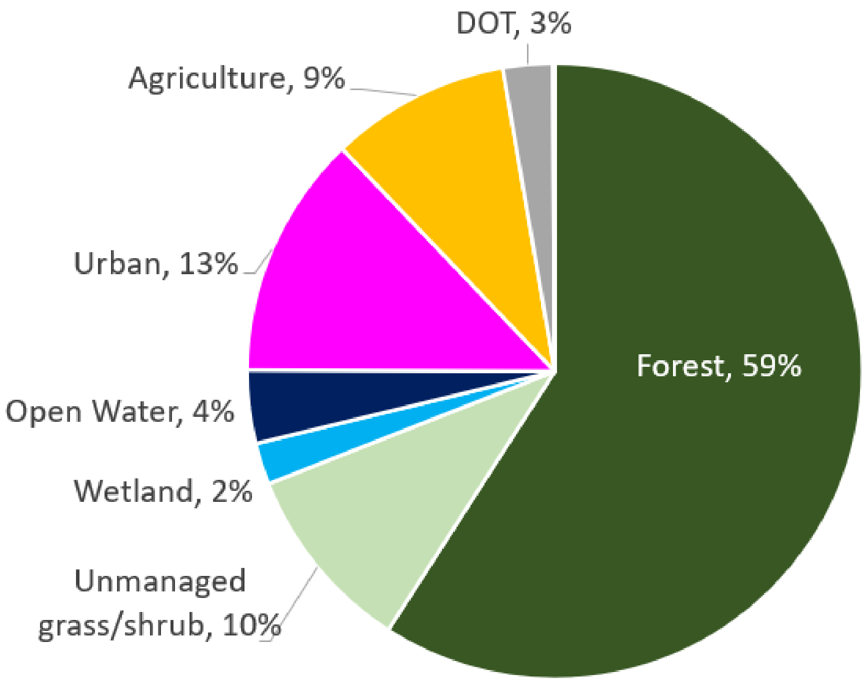
Some sources are internally calculated by the model, like streambank erosion and loading associated with soils, dissolution of nutrients into groundwater, and soil erosion. The model tracks these as sources of loading delivered to Falls Lake, but these are not prescribed in model input files. External nutrient applications to unmanaged areas come only from atmospheric deposition.

The majority of the watershed area is in an unmanaged land use such as forests, wetlands, shrubland/grassland including land in forest succession, or open water. Approximately ten percent of the watershed area is in agriculture: of this, 57 percent is pasture, 12 percent is full season soybeans, 10 percent is hay, 7 percent is double-cropped soybeans, 6 percent is flue-cured tobacco, 6 percent is no-till grain corn, and 2 percent is wheat or other crops. Rights of way managed by the NC Department of Transportation comprise approximately 3 percent of the watershed area. Approximately 13 percent of the watershed is "urban" with 68 percent of this area comprised of developed open space and non-DOT road right of way, 20 percent low intensity existing development, 7 percent medium intensity existing development, and 2.5 percent high intensity existing development. **Only 1.5 percent of the total watershed area is medium or high intensity development.** New development and interim development (City of Durham lands developed with nutrient control requirements between those of existing and new development) comprise approximately 2 percent of the "urban" area.

Nutrients are applied or released to the watershed each year from atmospheric deposition, nutrient application, discharges from wastewater treatment plants, etc.

Some nutrients also originate from internal watershed processes like streambank erosion.

Natural areas only receive external nutrient inputs from atmospheric deposition.



75 percent of the watershed area is in unmanaged land uses: forests, grassland, shrubland, wetlands, or open water.

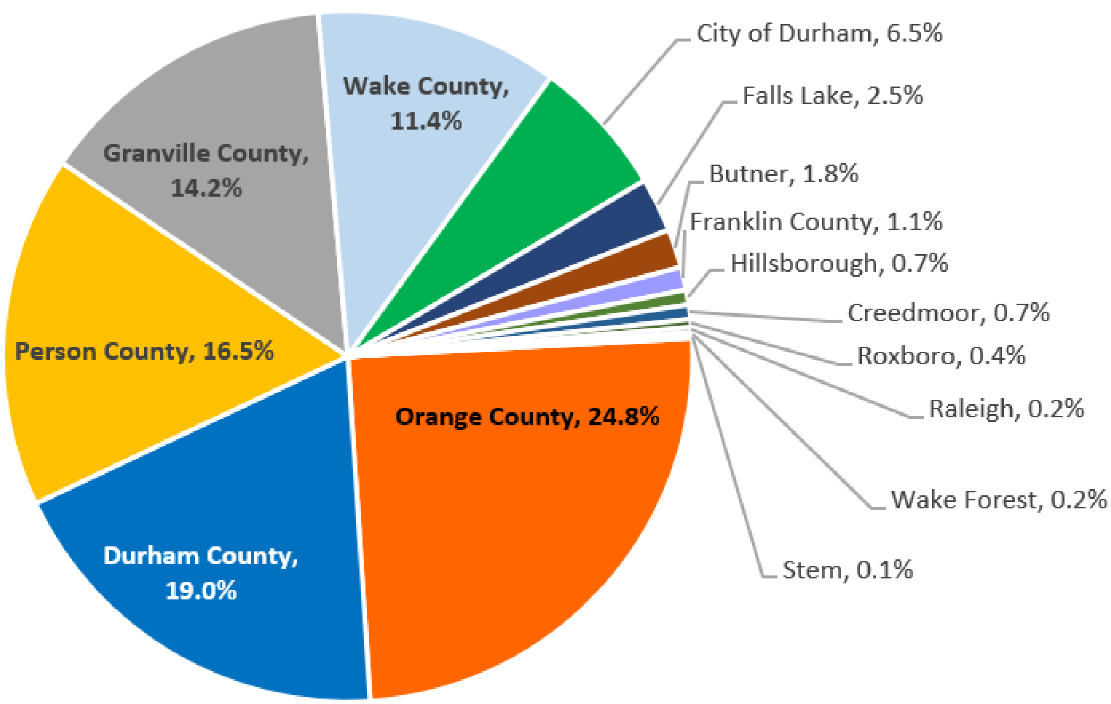


Figure ES-1. Land Use Composition and Percent of Area by Jurisdiction for the Falls Lake Watershed (492,000 acres) for the UNRBA Study Period (2015 to 2018)

Atmospheric deposition and nutrient application to agricultural and developed areas are the largest gross contributors to total nitrogen and total phosphorus in the watershed (Figure ES-2 and Figure ES-3, respectively). Nutrient application to agriculture (before crop harvesting) and atmospheric deposition each contribute approximately 40 percent of the total nitrogen applied to the system. Nutrient application to agriculture (before crop harvesting) and fertilizer application to urban areas contribute approximately 60 percent and 20 percent of the total phosphorus load applied to the system, respectively.

Figure ES-2 and Figure ES-3 summarize the gross inputs to the watershed, not the loading delivered to Falls Lake. These figures are based on the watershed model input files and do not reflect the biogeochemical processes or nutrient removal due to crop harvesting that ultimately reduce the loading delivered to Falls Lake (i.e., watershed processes). The figures also show the model inputs for effluent from centralized wastewater treatment facilities and onsite systems. These amounts represent post-treatment nutrient loads, not raw wastewater.

Based on the calibrated model results, watershed processes including crop harvesting reduce the total nitrogen input by approximately 83 percent prior to delivery to Falls Lake and the total phosphorus input by approximately 88 percent. This 770 square mile system includes several major impoundments and an extensive stream network which reduces nutrients during transport through adsorption to sediment, settling, denitrification, biological uptake, etc. Overland transport also reduces loads by filtering, settling, and plant uptake. The harvesting of crops results in removal of nutrients from the system. These percent reductions in nutrients applied or released to the watershed are conservatively low because 1) they are based on treated wastewater discharges from the facility to the stream, not raw wastewater loads received at the facility, and 2) the delivered loads to the lake also include loading from internal processes like streambank erosion that are not reflected in the loads applied or released to the watershed.

The proportion of delivered load from each major input varies based on the processes that affect it:

- Inputs from nutrient application to agriculture are high relative to other sources; however, much of these nutrients are stored in crops, harvested, and ultimately removed from the system (percentage of delivered load is smaller than percentage of inputs).
- Atmospheric deposition is also a major input which affects all land use types including forests and wetlands which can store and cycle nutrients and carbon; a portion of this input is removed from the system by crop harvest (percentage of delivered load is smaller than percentage of inputs).
- The percent contribution from wastewater (WW) treatment plants is relatively small in terms of inputs to the system partly due to facility upgrades and optimization; these inputs are directly discharged to streams typically downstream of impoundments (percentage of delivered load is larger than percentage of inputs).
- Streambank erosion is a significant source of delivered loading of phosphorus but is not reflected in these watershed input pie charts because it is accounted for internally by the model and is not “applied” to the model as part of the model input files.

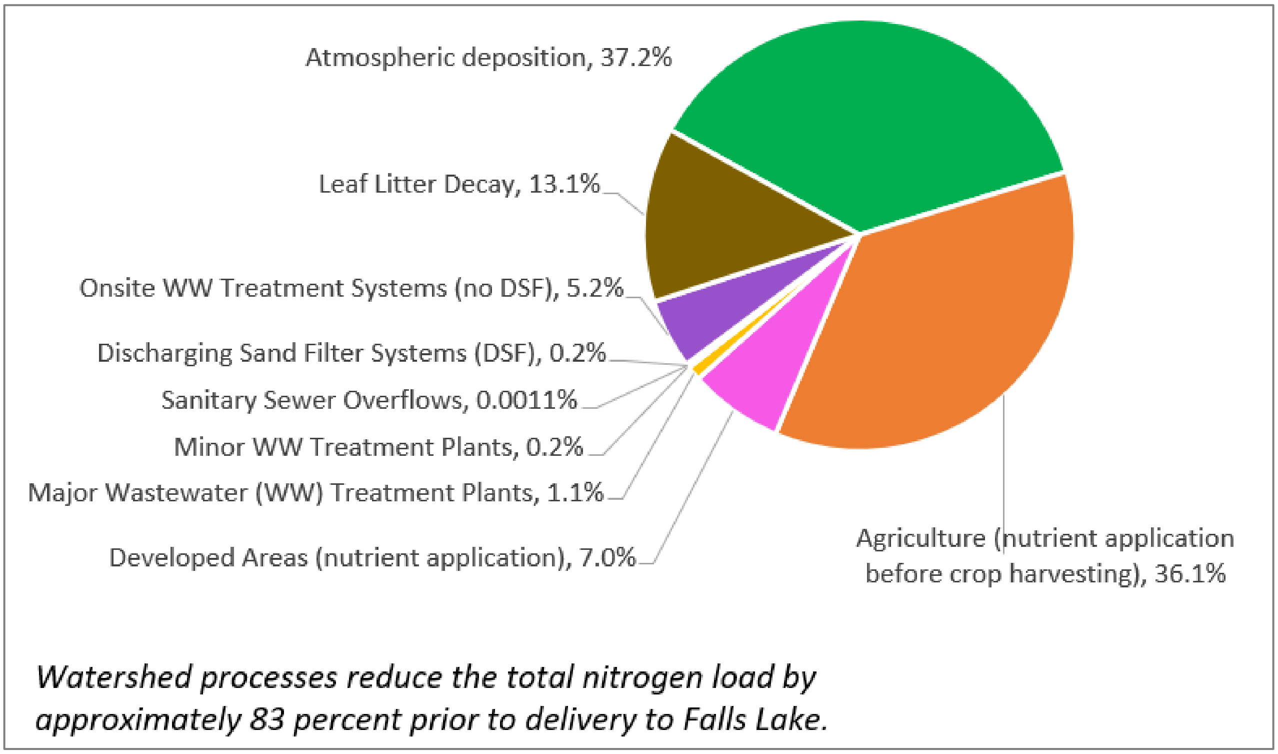


Figure ES-2. Percent Contribution to Gross Inputs of Total Nitrogen (9.9 million pounds per year) Applied or Released in the Falls Lake Watershed for the UNRBA Study Period (2015 to 2018)

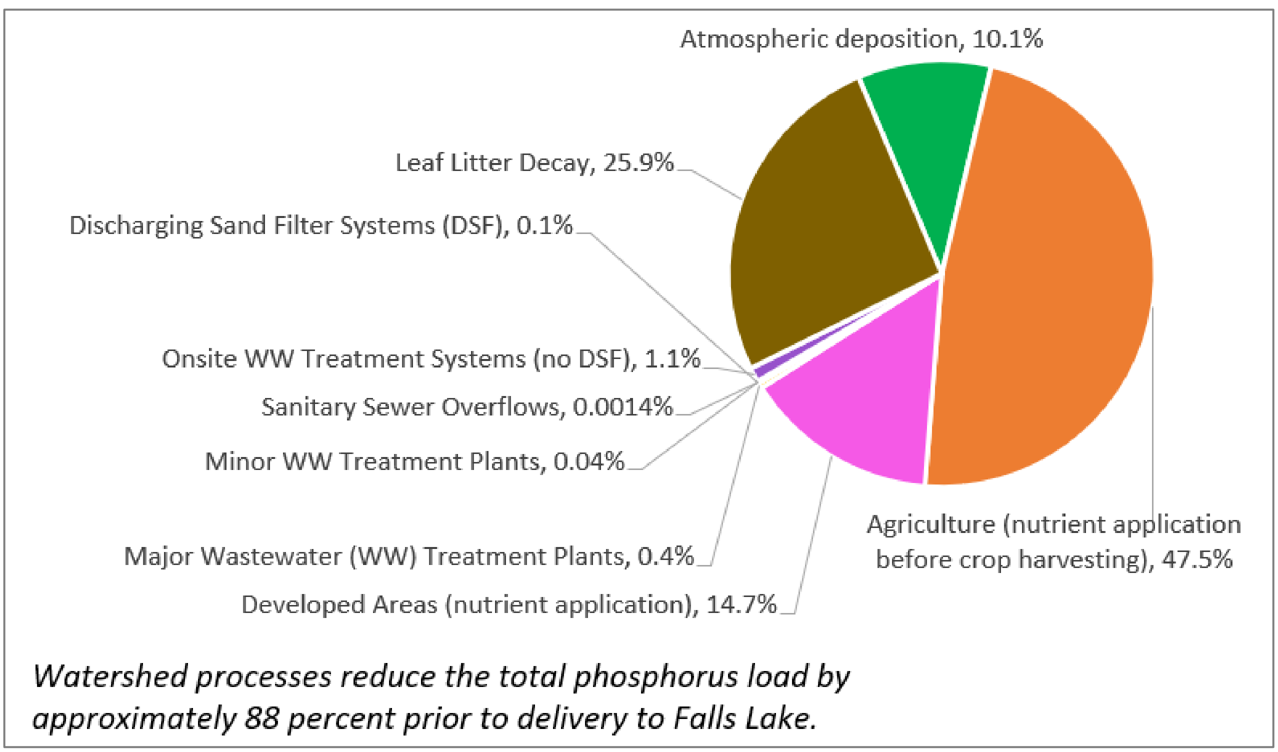


Figure ES-3. Percent Contribution to Gross Inputs of Total Phosphorus (1.5 million pounds per year) Applied or Released in the Falls Lake Watershed for the UNRBA Study Period (2015 to 2018)

Watershed Calibration

The UNRBA and its members have invested a significant amount of time and financial resources into the development of a watershed model for Falls Lake. This included a concentrated effort to gather and respond to input from the UNRBA member representatives, "third-party" reviewers, subject matter experts, DWR, and other stakeholders. Accurate simulation of stream discharge and chemical constituents as they travel through the system is critical to the development of an updated nutrient management strategy. The resultant, calibrated model is an effective, well-vetted, professional, and scientifically developed simulation tool qualified for use in developing and supporting a revised nutrient management strategy.

The UNRBA Modeling QAPP describes how the models should be developed and what criteria must be used to evaluate the model for approval under the Falls Lake Rules (summarized in Section 6.1). Calibration involves adjustment of the model coefficients to achieve the best overall fit across a suite of parameters. As described in the QAPP, model calibration and evaluation of performance focus on the upper five tributaries to Falls Lake that deliver more than 70 percent of the flow to the lake. These five tributaries include Ellerbe Creek, Eno River, Little River, Flat River, and Knap of Reeds Creek.

To evaluate the hydrologic performance of the WARMF watershed model, simulated stream flows were compared to those recorded by the US Geologic Survey (USGS). There are eight USGS gages on these five tributaries which were used to compare to WARMF simulated stream flows.

Based on the performance criteria specified in the QAPP (summarized in Section 6.3), the model performs in the "good" to "very good" range for total simulated stream flows as well as annual, summer, and winter periods at these eight gages. Six of the gages also rank "good" to "very good" for the fall and spring seasons, but Knap of Reeds and Flat River below Lake Michie rank "fair" for these two seasons. For the 50 percent lowest flows, four gages rank "very good," one ranks "fair," and two do not meet the criteria for "fair" where flows are under-predicted relative to the gaged flows. Model inaccuracy at low flows does not significantly impact overall simulated nutrient loading to Falls Lake which is primarily driven by high flows. Also, consistent with USGS description of accuracy, there is more uncertainty in the gaged flow estimates when flows are low (Section 4.3.1). For the 10 percent highest flows, the model ranks good to very good at all gages except Knap of Reeds; this gage is in a swampy area with a large flood plain that is both difficult to simulate and to gage with a high degree of accuracy. Because of the conditions at this gage location, flow accuracy is less dependable.

Calibration of the watershed model for water quality concentrations also focuses on these five tributaries. Observations regarding model performance for the UNRBA study period (2015 to 2018) at the five lake loading stations for these tributaries are provided in Table ES-2. Additional parameters, locations, and results for the calibration and validation periods are described in the main body of this report and its appendices.

Accurate simulation of stream flows, pollutant loading, and sources of delivered load to Falls Lake is critical to the development of an updated nutrient management strategy.

To evaluate the hydrologic performance of the WARMF watershed model, simulated stream flows were compared to those recorded by the US Geologic Survey (USGS). There are eight USGS gages on these five tributaries which were used to compare to WARMF simulated stream flows.

Calibration of the watershed model for water quality concentrations also focuses on these five tributaries.

Table ES-1. Hydrologic Performance Rankings for the UNRBA Study Period (2015-2018)								
Volume	Ellerbe - Club Boulevard (0208675010)	*Ellerbe - Gorman (02086849)	Eno - Hillsborough (02085000)	*Eno - Durham (02085070)	Flat - Bahama (02085500)	*Flat - Dam Near Bahama (02086500)	*Knap Of Reeds - Butner (02086624)	*Little River - Orange Factory (0208521324)
Total	Good	Good	Very Good	Good	Good	Good	Very Good	Good
Annual	Very Good	Very Good	Very Good	Very Good	Very Good	Very Good	Very Good	Very Good
50% lowest flows	Low[1]	Very Good	Very Good	Fair	Very Good	Good	Low	Very Good
10% highest flows	Very Good	Good	Very Good	Very Good	Good	Good	Fair	Very Good
Summer	Good	Very Good	Very Good	Very Good	Good	Good	Very Good	Very Good
Fall	Very Good	Very Good	Very Good	Good	Very Good	Very Good	Fair	Very Good
Winter	Good	Very Good	Very Good	Good	Very Good	Very Good	Very Good	Very Good
Spring	Good	Very Good	Good	Very Good	Good	Fair	Good	Good

[1] *Low indicates that model performance did not meet the requirement to be considered "fair," and flows were underpredicted.*

** Indicates this location is the most downstream stream flow gage on the tributary and represents the best estimate of delivered stream flows to Falls Lake.*

Table ES-2. Water Quality Performance Rankings for the UNRBA Study Period (2015-2018) for the Five Largest Tributaries					
Parameter	Ellerbe	Eno	Flat	Little	Knap
Temperature	Very good	Good	Good	Good	Good
TSS	Low[1]	Fair	Low	Good	Fair
Ammonia	Good	High[2]	Good	Low	Good
Nitrate	Very good	Good	Low	Low	Low
TKN	Fair	Very good	Very good	Very good	Very Good
TN	Good	Very good	Very good	Very good	Good
TP	Very good	Good	Good	Very good	Low
TOC	Very good	Very good	Very good	Very good	Good
Chlorophyll-a	Low	Low	Low	Fair	Low

[1] *"Low" indicates that model performance did not meet the requirement to be considered "fair," and values were underpredicted.*

[2] *"High" indicates that model performance did not meet the requirement to be considered "fair," and values were overpredicted.*

The summary rankings for the water quality performance are described below in terms of the full modeling period (2015 to 2018):

Temperature model performance is "good" to "very good"

THIS MEANS:
A well calibrated model for temperature is important because biological and chemical processes are temperature dependent.

The WARMF model output for total suspended solids (TSS) includes only silt and clay. TSS is generally underpredicted with Eno River, Knap of Reeds Creek, and Little River achieving rankings of good to fair.

THIS MEANS:
While TSS is important because it is associated with other pollutants like total phosphorus that can adsorb to particles and affect delivery to Falls Lake, calibration to this parameter does not impact the overall nutrient balance for this watershed. As noted, watershed model performance for TSS is not as good as other simulated parameters. However, this is not affecting the accuracy of simulated nutrient concentrations in the tributaries or the calibration results for nutrient concentrations delivered to Falls Lake which are good to very good for total nitrogen and total phosphorus.

Ammonia model performance is "very good" at Ellerbe Creek, "good" at Flat River and Knap of Reeds Creek, and just over the criteria for "fair" at Eno River. The model does not meet the requirement for "fair" for simulated ammonia concentrations at Little River where the model underpredicts ammonia concentrations; this calibration location is downstream of Little River Reservoir. Observed ammonia concentrations are relatively low in this tributary (observed mean is 0.08 mg-N/L). Low ammonia concentrations do not greatly affect total nitrogen loading to Falls Lake.

THIS MEANS:
At four of the five largest tributaries, the model is performing well for ammonia. Because ammonia concentrations are generally low, this parameter is not a significant component of total nitrogen. Not meeting the target for ammonia is not affecting the performance of the model for total nitrogen.

Nitrate model performance is "very good" at Ellerbe Creek and "good" at Eno River.

The model does not meet the criterial for fair at Little River, Flat River, and Knap of Reeds Creek where nitrate is underpredicted; these calibration locations are downstream of an impoundment. Also, at Little River and Flat River, the mean measured nitrate concentrations are low, less than 0.2 mg-N/L.

The model underpredicts nitrate at Knap of Reeds due to missing information in the middle of the calibration period; the model is "very good" for nitrate during the validation period.

THIS MEANS:

At two of the five largest tributaries, the model is performing well for nitrate. Where the model under performs, the calibration stations are downstream of an impoundment and nitrate concentrations are relatively low. For Knap of Reeds Creek, the model underpredicts nitrate during the calibration period due to missing information but performs very well during the validation period. The model still performs well for total nitrogen at all five tributaries.

Total Kjeldahl Nitrogen (TKN, comprised of organic nitrogen and ammonia) model performance is "very good" at Eno, Flat, and Little Rivers and at Knap of Reeds Creek. Simulated TKN at Ellerbe Creek is "fair."

THIS MEANS:

In this watershed, TKN is comprised mostly of organic nitrogen and comprises most of the total nitrogen. The model meets the performance criteria for TKN at each of the five largest tributaries.

Total nitrogen model performance is "very good" at Little, Flat, and Eno Rivers and "good" at Ellerbe Creek and Knap of Reeds Creek. At Knap of Reeds Creek for the calibration period, the simulation for TN is "fair" due to missing information during the calibration period (late 2015 to early 2016), but the model is "very good" during the validation period (2017 and 2018).

THIS MEANS:

An accurate characterization of total nitrogen loading to Falls Lake is an important consideration for lake management. While the simulation of the individual nitrogen species summarized above does not always meet the target, the model is predicting total nitrogen well at the five largest tributaries. Transformations from one nitrogen species to another can happen rapidly, so calibration can be challenging particularly when comparing a simulated 6-hour average value to a point in time measurement.

Since total nitrogen is the most referenced parameter for nitrogen management, these results support the use of this tool for management decisions.

Total phosphorus model performance at these five stations is "good" to "very good" except at Knap of Reeds Creek where the model underpredicts phosphorus concentrations during a period in late 2015 and early 2016. A period of high phosphorus concentrations was observed in the creek as part of the UNRBA Monitoring Program at this location. The model performance is "very good" at this location for the validation years (2017 and 2018).

THIS MEANS:

An accurate characterization of total phosphorus loading to Falls Lake is an important consideration for lake management. The model is predicting total phosphorus well at the five largest tributaries. An exception occurs for a brief period in one tributary due to missing information. This exception does not significantly impact the viability of the model for making management decisions.

Total organic carbon model performance is "very good" at these five stations, except for Knap of Reeds Creek where the performance is just outside of the threshold for "very good" range and ranks "good."

THIS MEANS:

Total organic carbon is an important consideration for drinking water supplies like Falls Lake, and understanding the amount originating from the watershed is important for management decisions. The model is predicting total organic carbon well at the five largest tributaries. It should be noted that total organic carbon is not currently addressed through water quality standards or established as a control parameter for water sources for producing drinking water. Water supply providers do monitor and consider total organic carbon as an operational consideration.

Chlorophyll-a in the tributaries to Falls Lake is generally underpredicted by the watershed model compared to observations, and the model does not meet the criteria to be considered "fair" except at Little River. In streams, measured chlorophyll-a is likely due to sloughing of periphyton, not floating algae, and so the species in the tributaries are different than those prevalent in Falls Lake.

The observed mean chlorophyll-a concentrations in the tributaries ranges from 3.5 µg/L to 12.6 µg/L which are lower than the mean concentrations observed in Falls Lake. Underpredicting the concentrations in the tributaries is not anticipated to negatively affect the lake model where growing conditions for algae are better and observed concentrations are usually higher than those measured in the tributaries. This is particularly true when concentrations are low. For example, if the percent bias is -75 percent and the observed mean chlorophyll-a concentration in the tributary is 4.7 µg/L, then the mean concentration predicted by the model is 1.2 µg/L. These differences are not important relative to the regulatory standard of 40 µg/L. However, if the observed mean was 50 µg/L and the model predicted a mean of 12.5 µg/L, that could have more of an impact on the ability of the downstream lake models to simulate chlorophyll-a in Falls Lake relative to the standard.

THIS MEANS:

Chlorophyll-a is the regulatory driver for the Falls Lake Nutrient Management Strategy. Tributary monitoring and watershed modeling confirm the concentrations entering the lake from the tributaries are relatively low compared to concentrations observed in Falls Lake. The simulated chlorophyll-a values in the tributaries to Falls Lake do not significantly affect the lake water quality models because Falls Lake is more conductive to algae growth than the free-flowing tributaries.

The UNRBA WARMF Lake and EFDC lake models were developed to simulate chlorophyll-a concentrations in Falls Lake based on information from the watershed model. While the watershed model underpredicts chlorophyll-a concentrations in the tributaries to Falls Lake, the observed concentrations are so low these differences do not affect the simulation processes in the lake models.

Simulated Delivered Loads to Falls Lake

WARMF tracks delivered loads from sources in the watershed based on the nutrient inputs they receive, the processes that affect each source individually, and transformations that occur in catchments, streams, and impoundments in the watershed during transport. The loads delivered to Falls Lake are a function of tributary stream flow and water quality concentrations. Delivered loads are strongly dependent on rainfall amounts and antecedent (prior) conditions.

Delivered loads are what reach Falls Lake after the nutrient inputs and watershed processes have been accounted for. Delivered loads represent only 20 percent of "applied' nutrients in the watershed.

Forests, non-pasture grassland, wetlands, and other unmanaged lands contribute approximately half of the nutrient load to Falls Lake because they are the majority of the drainage area. These areas are important to the health of the watershed and provide many benefits.

The following sources are tracked in the model output files:

- Individual land uses (e.g., deciduous forest, full-season soybeans, developed open space)
- Individual types of onsite wastewater treatment systems (e.g., conventional functioning systems, conventional malfunctioning systems)
- “General point sources” (includes major and minor dischargers, discharging sand filter systems, and sanitary sewer overflows)
- “General nonpoint sources” (accounts for the initial mass of chemical constituents in the watershed soils, streams, and impoundments)
- Stream bank erosion
- Direct wet and dry deposition to Falls Lake

Figure ES-4 through Figure ES-6 show the percent contribution and the source of the delivered total nitrogen, total phosphorus, and total organic carbon loads to Falls Lake, respectively. These delivered loads account for nutrient removal due to crop harvesting and subsurface, overland, instream, and impoundment processes that reduce loading before it is delivered to the lake (i.e., watershed processing). Near Lake areas also include the surface of Falls Lake which receives direct wet and dry deposition of these parameters from the atmosphere.

With three-quarters of the land area in unmanaged uses (forests, wetlands, unmanaged grassland and shrubland, land in forest succession, and open water), over one-half of the total nitrogen, total phosphorus, and total organic carbon loads delivered to Falls Lake originates from these areas. While these areas contribute loading, particularly during wet conditions, they are important to the health of the watershed by storing and cycling nutrients and carbon, infiltrating and storing rainwater, buffering temperatures, and providing habitat to terrestrial, avian, and aquatic wildlife. Increased loading from forested areas following large rainfall events has been reported by many researchers (Hunt 2023, Paerl et al. 2018, 2019, 2020; Osburn 2016; Timmons 1977; Oyarzún and Hervé-Fernandez 2015). Several of these studies were cited in DWR’s 20-yr status report on the Neuse and Tar Pam Estuaries in reference to increased nutrient loading from forested areas resulting from increased precipitation and climate change (Draft – May 16, 2023).

The remainder of the total nitrogen load and total organic carbon load originates from agriculture, urban areas, and wastewater treatment (centralized facilities and onsite systems). Streambank erosion contributes approximately 14 percent of the total phosphorus load, and the remaining 31 percent is due to urban areas, agriculture, and wastewater treatment (centralized facilities and onsite systems).

Local governments, utilities, and the agricultural community have made significant investments in stormwater nutrient reduction measures, optimized or upgraded processes at wastewater treatment plants, and reduced the amount of nutrients applied in the watershed. These activities have maintained the amount of nutrients delivered to Falls Lake relative to the baseline period even though rainfall amounts, and resultant stream flows, were much higher during the UNRBA study period.

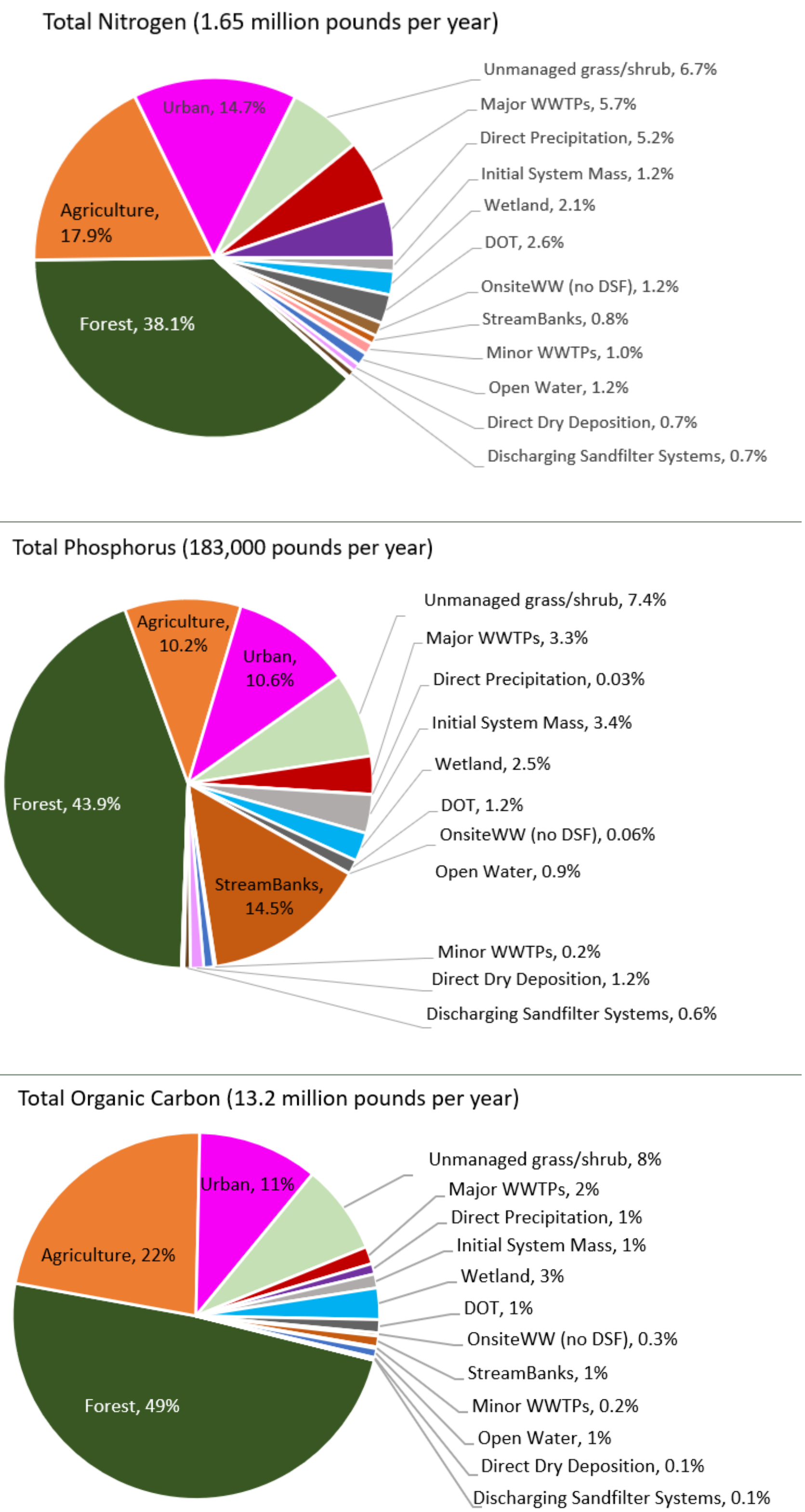


FIGURE NOTES:

Loads from unmanaged lands, including forests, contribute the largest fraction of the load because 75 percent of the watershed is comprised of these areas (Figure ES-1). These areas are important to the health of the watershed.

Loads from wastewater treatment plants (WWTPs) include major and minor discharges as well as sanitary sewer overflows. Loads from WWTPs have been significantly reduced since the baseline year (2006).

Loads from onsite wastewater treatment systems (Onsite WW) are listed separately for discharging sandfilter systems (DSF) and other systems (no DSF).

13% of the watershed is “urban.” 68% of "urban" area is developed open space (mostly non-DOT road right of way) and 20% is existing development, low intensity. Only 1.5% of the watershed is medium or high intensity development. Thus, most of the “urban” land in the watershed is low intensity.

Loads from streambank erosion are listed separately from urban loads.

Only 9 % of the watershed remains in agriculture. 57% of agriculture is pasture, 12% is full season soybeans, 10% is hay, 7% is double-cropped soybeans, 6% is flue-cured tobacco, 6% is no-till grain corn, and 2% is wheat or other crops. These are mostly small family farms.

Atmospheric deposition affects the entire watershed. Direct deposition and direct precipitation are the amounts falling on lake surfaces.

Initial system mass is the amount of pollutant in the streams and impoundments at the start of the model simulation.

Figure ES-4 Source Contributions of the Delivered Loads to Falls Lake for the UNRBA Study Period

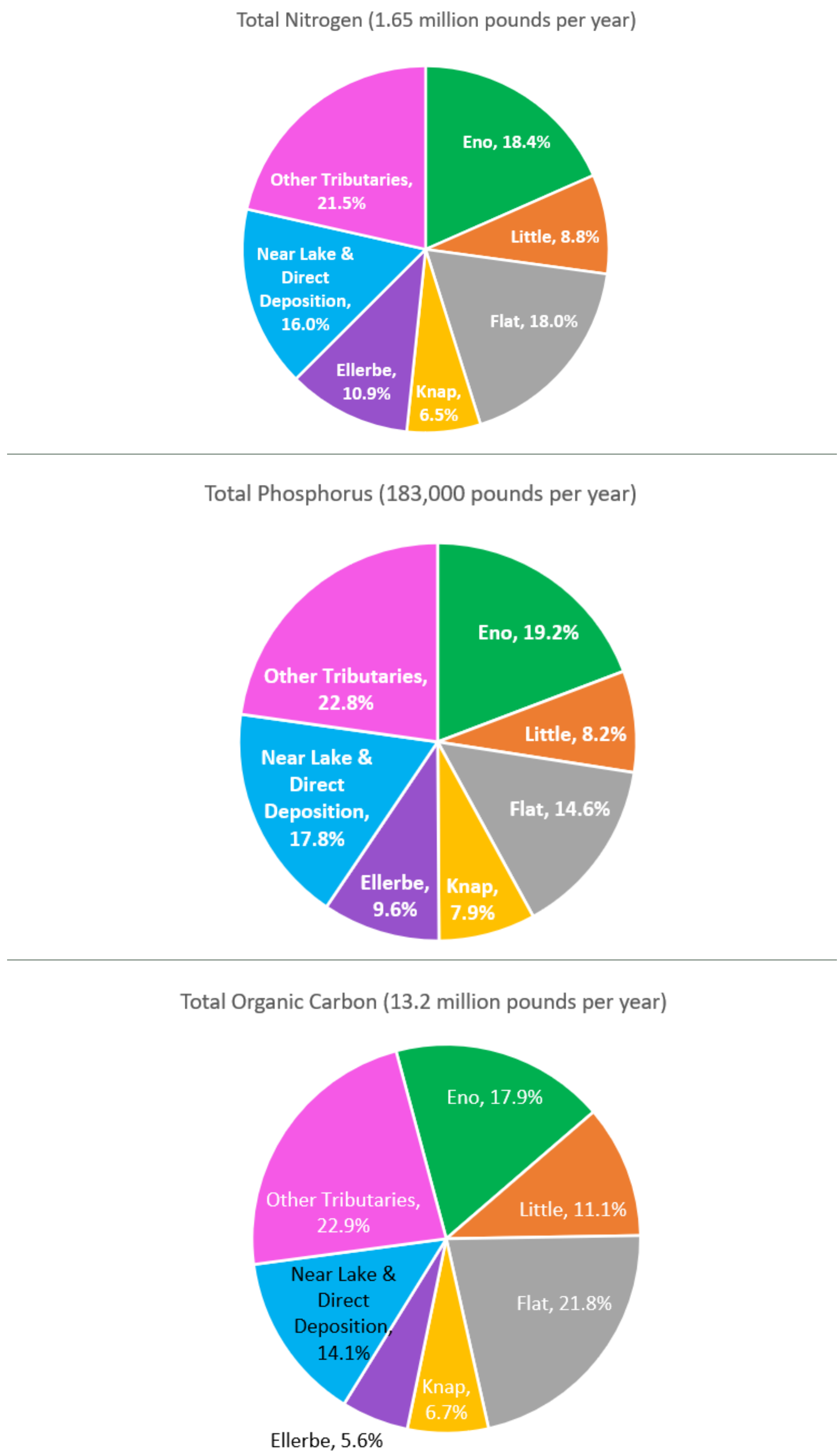


Figure ES-5 Tributary Contributions of the Delivered Loads to Falls Lake for the UNRBA Study Period

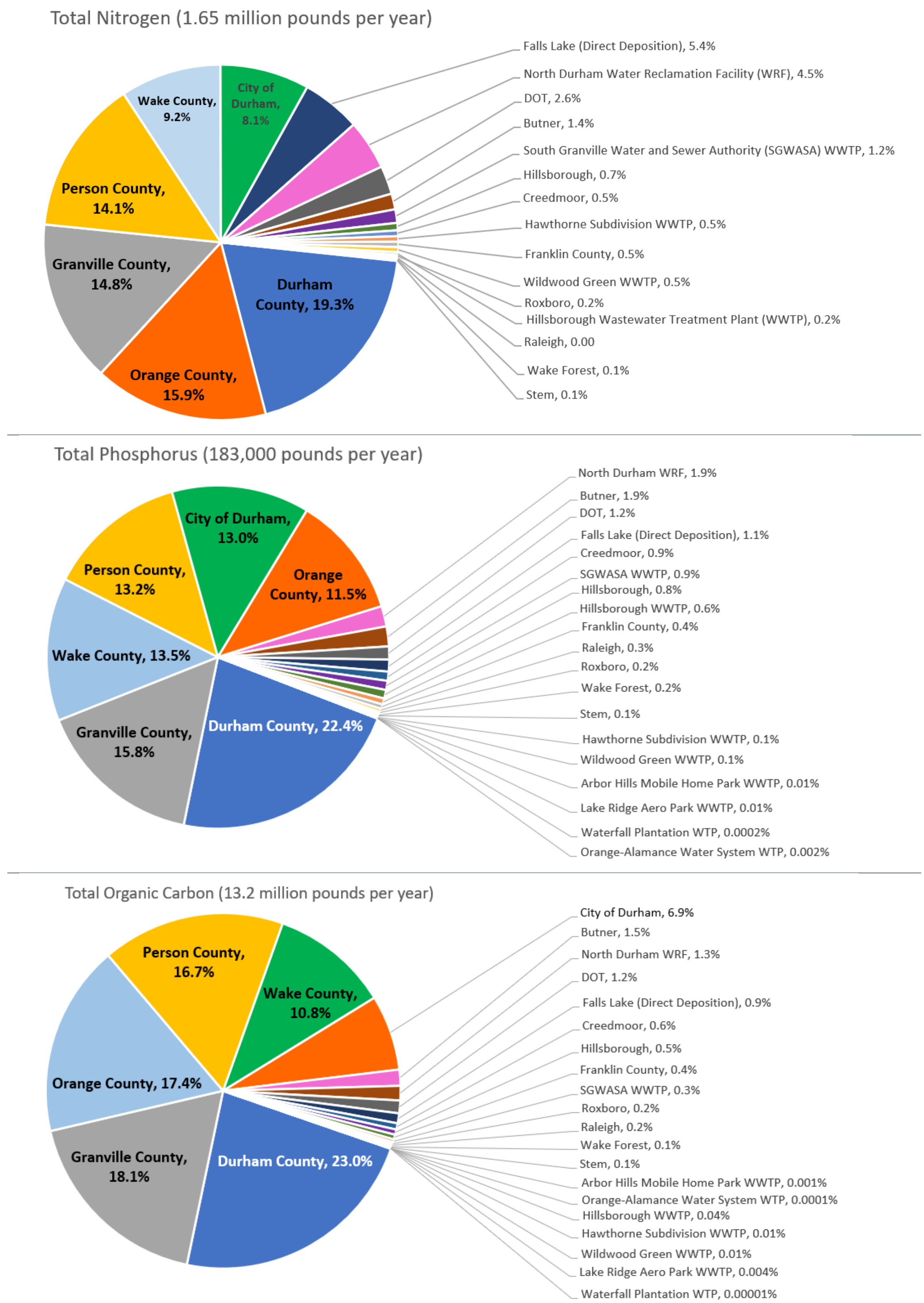


Figure ES-6 Jurisdictional and Permitted Contributions of the Delivered Loads to Falls Lake for the UNRBA Study Period

Summary of the Watershed Modeling Effort and Key Findings

The Falls Lake Nutrient Management Strategy was passed in 2011. In response, some UNRBA members and other regulated entities began early implementation to reduce nutrient loading to Falls Lake including installation of hundreds of stormwater control measures, best management practices, and stream restoration projects. UNRBA members have also provided extensive investments to secure improvements at wastewater treatment plants, reductions to sanitary sewer overflows, implementation of retrofits for existing development, and maintenance and repair programs for onsite wastewater treatment systems. In implementing these efforts, the jurisdictions in the watershed have provided an unprecedented, comprehensive response to the goal of managing nutrients in this watershed and reservoir.

The UNRBA has invested significant financial and management support resources into the development of a watershed model to accurately characterize nutrient and carbon loading to Falls Lake to allow for evaluation of management strategies and future tracking of watershed conditions. A key dataset for calibrating the model and ensuring that simulations in the watershed match observations was the four-year (August 2014 to October 2018) approved water quality monitoring program designed, implemented, and funded by the UNRBA to support the modeling efforts. The UNRBA began allocating resources while the monitoring program was still underway to plan for and begin data collection efforts to support the watershed model development. The UNRBA worked with watershed stakeholders to select the WARMF model to simulate the watershed and Falls Lake (Modeling & Regulatory Support Work Products & Documents | Upper Neuse River Basin Association (unrba.org)). Two additional lake models have also been developed (EFDC and a statistical/Bayesian model).

Several improvements or features of WARMF were used to provide additional information about the sources of nutrient loading to Falls Lake. For example, the WARMF option to isolate soils by land use was applied to better distinguish the loading by land use. In addition, the WARMF model code was improved to allow the simulation of up to 15 types of onsite wastewater treatment systems rather than the model default (three systems). DWR assisted with securing grant funding through 319 to fund these model code revisions. The UNRBA worked closely with researchers funded through the NC Collaboratory to develop the model inputs associated with each type of onsite wastewater treatment system.

Securing all of the data needed to provide the best configuration of the model was a large and important task. The effort would not have been possible without the cooperation of others. Many stakeholders provided data, information, insights, and feedback to support this modeling effort and ensure that all available information was incorporated accurately into the model: local governments and utilities that comprise the UNRBA, state agencies (DWR, NCDA&CS, Department of Transportation, Wildlife Resources Commission, State Climate Office), federal agencies (US Forest Service, US Geologic Survey), researchers funded through the NC Collaboratory, and representatives from the Farm Bureau and American Rivers. All of the information obtained through this process has been identified, reviewed, quality assured, and incorporated into the model. In addition, the NC Collaboratory provided funding for a "third-party" review of the model. This extensive review resulted in refinements and improvements to the model with a focus on source load allocation and simulated areal loading rates.

The results of this extensive, multi-year model development process provide insights on watershed loading of nutrients to Falls Lake.

Because of the extensive data available for this model, the review of the model results, and the features and modifications to the model that were made during this application, this work provides an updated and more extensive understanding of how watershed processes affect nutrients and carbon delivered to Falls Lake:

The amount of agricultural land has decreased in the basin by approximately 44 percent since the baseline period (2005 to 2007), and many of the nutrient application rates for specific crops have also declined over this period. Rates of atmospheric deposition of nitrogen have declined by approximately 20 percent since the baseline period. Nutrient loads from WWTP have declined 38 percent for TN and 81 percent for TP when comparing 2006 to 2018.

THIS MEANS:

The regulated community in the Falls Lake watershed has made significant progress in reducing nutrient loading to Falls Lake. Atmospheric deposition of nutrients has also declined.

The chemistry of the soils in the watershed (based on data from the US Department of Agriculture National Cooperative Soil Survey) results in the retention and slow release of nutrients over time. A change in a watershed model input (land use, nutrient application rate, etc.) takes approximately 25 simulation years for the soils in the watershed to reach equilibrium and simulate a change in delivered load.

THIS MEANS:

Changes in the watershed directed at nutrient management may take decades to have a measurable impact on nutrient loading to Falls Lake. It will be important to consider this timeframe in the development of a revised nutrient management strategy.

Conventional and advanced treatment systems that discharge to the subsurface for onsite wastewater treatment are very effective at removing nutrients, partly due to the soil chemistry in the watershed. This finding from the modeling is supported by recent research funded through the NC Collaboratory. These sources comprise approximately 1.2 percent of the total nitrogen load and 0.06 percent of the total phosphorus load delivered to Falls Lake. These percent contributions account for all on-site systems, functioning and malfunctioning.

Discharging sand filter systems primarily discharge to very small streams or upland drainage channels in this watershed and are simulated as point sources by the model. They comprise approximately 0.6 and 0.7 percent of the total nitrogen load and the total phosphorus load delivered to Falls Lake, respectively.

THIS MEANS:

Onsite wastewater treatment systems including discharging sand filters do not contribute significantly to delivered nutrient loading to Falls Lake (2 percent or less).

Urban areas only comprise 13 percent of the watershed. Most of this area, 68 percent of the 13 overall percent, is developed open space like parks or road rights of ways (not owned by NCDOT). Low intensity existing development is 20 percent of the urban area. Only 12 percent of urban area, or 1.5 percent of the total watershed area, is medium or high intensity development. Local governments in the watershed have installed over 350 existing development retrofit projects to treat stormwater from development.

Agriculture comprises only 9 percent of the watershed area and mostly consists of pastureland. Land-based agriculture in the watershed has decreased by 44% since 2006. Rates of nutrient application on remaining farms have also been optimized over time reducing the application and nutrient release from the lands remaining in production.

NCDOT rights of way comprise 3 percent of the watershed area.

These managed lands (urban, agriculture, and NCDOT) comprise 15, 18, and 3 percent of the total nitrogen load and 11, 10, and 1 percent of the total phosphorus load, respectively, delivered to Falls Lake.

THIS MEANS:

Managed lands in the watershed (developed land, developed open space, agriculture, and NCDOT rights of way) comprise only 25 percent of the total watershed area and contribute approximately 36 percent of the total nitrogen load and 31 percent of the total phosphorus load to Falls Lake. Streambank erosion contributes 14 percent of the total phosphorus load to Falls Lake, and rates of streambank erosion increase with development intensity due to increases in peak stream flows. Streambank erosion cannot be assigned to any particular land use in the watershed. This source of loading is distributed and crosses property ownership lines. This represents an additional management challenge in reducing overall phosphorus loading.

Major WWTPs contribute less than six percent of the delivered total nitrogen load and approximately 3 percent of the delivered total phosphorus load to Falls Lake. These percentages represent actual discharge flow rates at the time of this evaluation and will increase as the facilities approach their design flows. Significant improvements in treatment at the major facilities have reduced total nitrogen loads discharged to streams by approximately 38 percent and total phosphorus loads by 81 percent when comparing 2018 to 2006 (the baseline year). It is anticipated that nutrient treatment efforts will continue to provide reductions in excess of Stage I requirements.

SSOs are relatively infrequent with small volumes reaching surface waters. They comprise a relatively small portion of the delivered load to Falls Lake.

THIS MEANS:

Owners of the three major wastewater treatment plants in this watershed have invested significant resources in facility upgrades and optimization. As a result, delivered nutrient loads from this source contribute less than 6 percent of the nutrient load delivered to Falls Lake during the study period. Sanitary sewer overflows have also been reduced and contribute a relatively small portion of the load to Falls Lake.

Approximately 61 percent of the watershed is comprised of forests. Other unmanaged land uses (wetlands, unmanaged grassland and shrubland including land in forest succession, and open water) comprise approximately 14 percent of the area. These areas provide important wildlife habitat, store rainwater, and store and cycle nutrients and carbon. These areas are also not under any regulatory control program and are not considered appropriate for inclusion in required control.

THIS MEANS:

Most of the land in the watershed (75 percent) is currently unmanaged. This limits the area subject to nutrient management requirements and represents land use with limited to no nutrient reduction potential. It is important to protect these areas as part of the long-term nutrient management strategy for Falls Lake.

The UNRBA study period (2015 to 2018) used to develop and calibrate the watershed model had average to wet precipitation amounts each year. In contrast, DWR's baseline modeling period (2005 to 2007) coincided with a historic drought for the area. As a result, during the baseline period on the Flat River above Lake Michie, the average annual stream flowrate was 82 cubic feet per second while during the UNRBA study period, the average annual stream flowrate at this location was 173 cubic feet per second, over twice as high. Nutrient loads are highly dependent on rainfall amount and resulting stream flows. Thus, the loading potential for the UNRBA study period is much greater than the baseline period.

The pervious areas in the watershed which receive inputs from atmospheric deposition and nutrient application have the ability to store nutrients in the soil matrix during dry periods. During wet periods when the soils become saturated, these nutrients have the potential to be transported to the stream network and Falls Lake. Impervious surfaces also contribute nutrient loading, but they do not have the same potential to accumulate large quantities of nutrients during extended dry periods.

THIS MEANS:

Delivered nutrient loading is a function of rainfall, stream flow, and concentration. Thus, hydrology is the primary driver of variation in nutrient loading to Falls Lake. The level of rainfall is also the main factor impacting areal loading rates from unmanaged areas. Pervious areas like forests and agricultural fields can store nutrients during dry periods and export them during wet periods. The modeling shows that loading from unmanaged areas is not constant but fluctuates based on rainfall conditions. Very large storms can increase delivered nutrient loads by hundreds of times compared to days with little to no rainfall. Storm water control measures are required to treat the first inch of precipitation, and most days have rainfall less than one inch. However, high rainfall events exceed the design flow of these systems and loading from these areas increase.

For the UNRBA study period (2015 to 2018), nearly 9.9 million pounds of total nitrogen were deposited, applied, or discharged to the watershed or lake surface each year. Compared to the baseline period (2005 to 2007), this is a reduction in gross inputs of approximately 34 percent. Approximately 17 percent of the total nitrogen inputs were delivered to Falls Lake during the UNRBA study period. Crop harvesting and denitrification result in nitrogen loss from the system (denitrification is an important process for removing nitrogen from the system as nitrogen gas).

In the UNRBA study period, over 1.5 million pounds of total phosphorus were deposited, applied, or discharged to the watershed or lake surface each year, a reduction of approximately 24 percent compared to the baseline period. Approximately 12 percent of the total phosphorus inputs reach Falls Lake in the UNRBA study period.

THIS MEANS:

Watershed processes including crop harvesting significantly reduce the amount of nutrients that reach Falls Lake compared to the amount that is applied to the system. Gross inputs of nutrients applied or released in the watershed have decreased by approximately 25 percent or more relative to the baseline period. However, these reductions in inputs do not provide a similar magnitude of reduction in delivered loads because only a portion of inputs (approximately 10 to 20 percent) reach the lake. These watershed processes also reduce the reduction benefits in load delivered to the lake from projects implemented in the watershed.

Seventy-five percent of the watershed is unmanaged (forests, wetlands, etc.), and these areas comprise the majority of land surrounding and draining directly to Falls Lake. Almost 50 percent of the total nitrogen load delivered to Falls Lake originates from unmanaged lands. These lands also contribute over 50 percent of the total phosphorus load and over 60 percent of the total organic carbon load delivered to Falls Lake. These areas are important to the storage and cycling of nutrients and carbon in the watershed.

THIS MEANS:

Unmanaged lands contribute approximately one-half of the total nitrogen load and more than one-half of the total phosphorus and total organic carbon loads delivered to Falls Lake. Unless sources like atmospheric deposition continue to decline, it is unlikely that reductions from these areas will occur. Given changing rainfall patterns, storm sizes are likely to increase rather than decrease. Thus, loading from unmanaged areas is likely to increase as well.

Because these are natural lands, it will be extremely difficult to achieve nutrient load reductions from these areas. Regulatory requirements to reduce nutrient loading should not apply to these areas. It is important to protect these areas as part of the long-term nutrient management strategy for Falls Lake.

Summary of Report Contents

This report summarizes the WARMF watershed model configuration, model inputs, and results of the hydrologic and water quality calibration and validation.

The following are further described in this report:

Delineation of the modeling catchments for the watershed model

Comparison of simulated stream/river flows to USGS measurements and simulated water quality to UNRBA monitoring data; comparisons to DWR monitoring data are also included where monitoring locations intersect catchment boundaries

Observations of stream flow (recorded by US Geological Survey (USGS)) and stream water quality (collected by the Upper Neuse River Basin Association and DWR)

Configuration of upstream impoundments in the watershed

Descriptions of calibration parameters for hydrology and water quality

Time series data used to develop model inputs including discharge monitoring data from wastewater treatment plants, withdrawals from impoundments, meteorological data, and air chemistry data

Watershed characterization including soils data, land use, nutrient application rates, and locations and types of onsite wastewater treatment systems

Summaries of nutrient and carbon loading to Falls Lake by source and contributing area

The hydrodynamic and water quality calibration of the WARMF Lake and EFDC models for Falls Lake and the impacts of scenarios on lake water quality are described in a separate modeling report.

The UNRBA is extremely grateful for all the input and feedback provided by both internal and external stakeholders.

The model calibration effort was accompanied by extensive review by the SMEs, MRSW, “third-party” reviewers funded by the NC Collaboratory, and other stakeholders. All calibration decisions were carefully vetted and presented during extensive meetings, and DWR was included in these meetings. The watershed model provides an important linkage between existing land use in the watershed, changes in watershed activities, and delivered loads to streams and ultimately Falls Lake. The watershed model output has been used to develop and calibrate the lake water quality models. Calibrated lake models have been used to evaluate scenarios and their impact on lake water quality to inform development of a revised nutrient management strategy.

For additional details on the model development and calibration, see the main report which starts on the following page. Iterative drafts of this report were reviewed by the MRSW, PFC, subject matter experts, “third-party” model reviewers, and DWR. The report was revised based on these reviews. On December 5, 2023, the PFC approved the final report for submittal to DWR for review and approval under Falls Lake Rule 15A NCAC 02B .0275.

Section 1

Introduction and Background

The Upper Neuse River Basin Association (UNRBA) has invested considerable financial and management support resources in monitoring and modeling efforts to reexamine the Falls Lake Nutrient Management Strategy which requires very high levels of nutrient reduction to Falls Lake. This report summarizes the work of the Association to support this effort overall with a focus on development and calibration of a Falls Lake watershed model.

1.1 Previous UNRBA Efforts to Support the Reexamination

In 2016, the UNRBA initiated the Modeling and Regulatory Support (MRS) project as part of the reexamination of the Falls Lake Nutrient Management Strategy (Falls Lake Rules). Stage II of the Falls Lake Nutrient Management Strategy developed by DWR and approved by the Environmental Management Commission (EMC), as reflected in the adaptative management provisions of the rules, has a significant level of uncertainty and requires very large reductions in lake nutrient loading from wastewater treatment plants, agriculture, and existing development, as well as ongoing control of new development in the watershed. The responsibility for achieving the unprecedented levels of required loading reduction from existing development falls primarily on the local governments in the watershed. Because the watershed and lake modeling developed by the State used as the basis of the rules was completed on a compressed schedule with limited data, there is considerable uncertainty in the projections done to generate required loading targets. Because stakeholders noted this and DWR and the EMC recognized this concern, the rules allow for a “reexamination” of the required nutrient load reductions under Stage II. This adaptive management provision resulted in the UNRBA taking up its reexamination project.

The UNRBA finalized a plan for conducting the reexamination in 2013. This plan included a minimum of four years of water quality monitoring in the watershed and the lake. The UNRBA began collecting water quality data in August 2014 and completed monitoring in October of 2018, providing data from four “growing seasons” in the lake. A main purpose for collecting this data was to support revised and new models as part of the reexamination. However, a tremendous amount of additional types of data and information are also needed to develop the models. The model preparation work is crucial, and an extensive effort has been made to assemble the datasets needed to properly build the modeling tools to support the reexamination. The Executive Summary and the detailed sections below acknowledge the many organizations that were essential in our ability to develop a robust data base for the MRS work.

Planning for the reexamination began in 2012 and, as of the date of this report, important progress on the two main components of this effort has been made: the UNRBA Monitoring Program to support the modeling effort has been completed and key UNRBA Modeling and Regulatory Support (MRS) Project efforts are underway. In preparation for the development of modeling tools and the actions necessary to complete this component of the reexamination effort in accordance with the Falls Lake Rules, the UNRBA accomplished the following required tasks prior to development of the tools (documents related to these projects are available at www.unrba.org):

- Approval by the NC Division of Water Resources (DWR) of all planning documents and quality assurance project plans (QAPP) required by the Falls Lake Nutrient Management Strategy:
  - UNRBA Description of the Modeling Framework,
  - UNRBA Monitoring Plan and UNRBA Monitoring QAPP

  - UNRBA Modeling QAPP
- Design, implementation, and successful completion of a four-year monitoring program (50 months total) to support development of lake and watershed models including routine monitoring and several special studies
- Evaluation and Selection of Model Packages for the UNRBA Modeling and Regulatory Support Project for the watershed and lake models following a rigorous screening process
- Development of a Conceptual Modeling Plan describing the watershed model, hydrodynamic/water quality lake models (Watershed Analysis Risk Management Framework (WARMF) and Environmental Fluid Dynamics Code (EFDC)), statistical/Bayesian lake model, and cost benefit analysis
- Development of a Data Management Plan
- Completion of a comprehensive monitoring program report that not only looks at the data collected by the UNRBA, but data available on Falls Lake since it was put in service in 1982 (Final UNRBA Monitoring Report available at www.unrba.org)
- Construction of a comprehensive UNRBA monitoring database providing essential input information for the WARMF model to support model development available to the public through the UNRBA data portal
- Presentation of modeling development work at publicly available sessions of the UNRBA's Path Forward Committee (PFC), Modeling and Regulatory Support Workgroup (MRSW), numerous additional workgroups, and Board of Directors meetings.
- Coordination of special technical stakeholder meetings, forums, symposia, and presentations at conferences and public meetings to describe the status of the models and receive feedback (materials available on the UNRBA Meeting Page).
- Development of the UNRBA Decision Framework to document how the organization incorporates input from internal and external stakeholders, works toward consensus, and formalizes decisions.

Leading up to FY2022, previous phases of modeling preparation work included gathering data, configuring the watershed and lake models, and developing the model input files. During FY2020, as described in this report, the watershed model was calibrated and validated for hydrology. During FY2021, the focus shifted to calibration and validation of the watershed model for water quality. The watershed model calibration was finalized in FY2022 and is being used to support water quality calibration of two mechanistic lake models.

1.2 Model Selection to Support the Reexamination

In order to provide as complete a picture as possible of how the lake responds to the inputs from the watershed, atmosphere, and lake bottom sediments, the UNRBA selected different types of models to support the reexamination. For the simulation of the watershed, the UNRBA selected the Watershed Analysis and Risk Management Framework (WARMF) with input from external stakeholders. This is a well-established model with many applications throughout the US and abroad. DWR used this model for its effort prior to the adoption of the rules.

The UNRBA WARMF model uses the extensive data available on activities in the watershed to track nutrient generation and movement in the watershed projecting the nutrient loading reaching the lake from various sources and jurisdictions. These loads serve as input to the lake nutrient response models to predict the growth of algae in response to nutrient loads. The level of attention this effort is placing on nutrient generation and movement in the watershed allows the UNRBA's watershed model effort to be directly linked to the lake response models. This is a key aspect of this modeling effort because it allows the evaluation of changes in nutrient generation activities anywhere in the watershed to answer important questions about how potential watershed management actions translate to water quality in Falls Lake. This linkage of the watershed model to the lake response model was not done for the state's modeling effort.

Because the prediction of algal growth in the lake will be used to evaluate the revised nutrient load reductions, the UNRBA has decided to develop multiple lake nutrient response models including the WARMF-Lake model, the Environmental Fluid Dynamics Code model (EFDC), and a statistical lake model. Having multiple models reduces the reliance on a single model and provides corroboration for the results. These models are described further in the Conceptual Modeling Plan developed by the UNRBA. Additional information on these models and the UNRBA's extensive effort to evaluate different modeling approaches before selecting these models is available in the following documents: the UNRBA's Model Selection Criteria and Evaluation and Selection of Model Packages for the UNRBA Modeling and Regulatory Support Project.

This watershed modeling report addresses two periods. The first period, 2005 to 2007, corresponds to the "baseline" modeling period that DWR used to establish the Falls Lake Nutrient Management strategy (only year 2006 which had a total rainfall closer to the annual average was used to set the load reduction requirements). The Association had originally planned to develop a model for the baseline period, but sufficient data were not available to develop a calibrated model for this period. The baseline period may be modeled by the UNRBA as a scenario in the future.

The second period, 2015 to 2018, corresponds to the four years of the UNRBA Monitoring Program. This period is referred to as the UNRBA study period. While the UNRBA also included 2014 in their program, the monitoring did not begin until August. Therefore, 2014 is used to initialize the models and ensure stability in soil moisture, water levels, etc. before the models are calibrated, validated, and used to inform management decisions. The UNRBA study period was used to calibrate and validate the watershed model, and the results of this effort are provided in this report.

Because the UNRBA had initially planned to model the baseline period, model input data were collected to represent this period. This report compares the amount of nutrients applied, deposited, or discharged to the watershed for the baseline period and the UNRBA study period. This comparison provides important context because the baseline period was used to establish the Falls Lake Nutrient Management Strategy developed by DWR.

1.3 Report Purpose

This report was developed to document the extensive work performed to develop the UNRBA's Falls Lake Watershed model and for submittal of the model for approval under Falls Lake Rule 15A NCAC 02B .0275. The computer files developed for this watershed model have been made available to the UNRBA member jurisdictions and the NC Division of Water Resources (DWR) for review and evaluation.

The development process described in this report used data from a host of established sources (as identified in this report) and watershed data collected under the DWR-approved UNRBA Monitoring Plan (referenced below).

The UNRBA's WARMF watershed modeling effort followed the DWR-approved UNRBA Description of the Water Quality Modeling Framework and the UNRBA Modeling Quality Assurance Project Plan (QAPP). Approval of the watershed model is requested under rule 15A NCAC 02B .0275(5)(f), which states in summary that any model submitted must be developed "in accordance with the quality assurance requirements of the Division." In practical terms, the quality assurance requirements for this effort were established in the DWR-approved QAPP. The calibrated and verified WARMF Watershed model developed for the UNRBA is described in detail in this report and is fully referenced to the Modeling QAPP. As the UNRBA has discussed several times with DWR, it was agreed that models developed would be submitted as the work is completed. Other model development reports and documentation will be submitted for review and approval by DWR following finalization of those models.

Section 2 of this report describes the preliminary configuration of the WARMF watershed model and development of the modeling catchments. Section 3 summarizes the soils data and land use data. Time series data compiled to support development of the model is described in Section 4. Section 5 describes the results of the hydrologic and water quality calibration and validation of the watershed model.

1.4 Coordination and Input from Internal and External Stakeholders

The UNRBA is committed to an open and well vetted model development process. Development of an accurate watershed model for predicting stream flows and pollutant loads requires well-developed input data and characterization of the watershed soils, land uses, wastewater treatment processes, etc. Data collection for critical components of the model preparation effort would not have been possible without the cooperation, support, and work of the UNRBA member jurisdictions, the Modeling and Regulatory Support Workgroup (MRSW) of the UNRBA, the Path Forward Committee (PFC) of the UNRBA, the NCDA&CS Division of Soil and Water Conservation, local Soil and Water Conservation Districts, the NC Farm Bureau Federation, the Falls Lake Watershed Oversight Committee (WOC), NC State's Climate Office (SCO), NC's Department of Transportation (DOT), the NC Division of Water Resources (DWR), the NC Wildlife Resources Commission (WRC), and representatives from non-governmental organizations (NGOs). The UNRBA extends many thanks to these organizations and the dedicated staff that develop and maintain these critical data sources.

The UNRBA has hosted several workshops and forums to communicate the work of the UNRBA and to receive input from internal and external stakeholders regarding the reexamination. In addition to UNRBA members, representatives from several State agencies (DWR, DOT, WRC, NCDA&CS Division of Soil and Water Conservation), agriculture (Farm Bureau, WOC, NC Horse Council), and NGOs (American Rivers, River Guardian Foundation, WakeUP Wake County, Sound Rivers Upper Neuse Riverkeeper, Ellerbe Creek Watershed Association, Upper Neuse Clean Water Initiative, Triangle Land Conservancy) have participated directly in these workshops and provided input over the entire period of planning and performing the tasks outlined in this report. Meeting materials and presentations for workshops and forums are available at the UNRBA Meeting Page unless otherwise noted. The following list of activities provides a summary of the formal and informal sessions arranged and conducted to assist with model development and to communicate the work of the UNRBA to stakeholders:

- The September 28, 2016, Technical Stakeholders Workshop described past efforts for water quality monitoring and modeling of Falls Lake and its watershed and described how the UNRBA Monitoring Program was developed to update and improve the models. Stakeholders were asked to relay concerns and questions about the UNRBA's plans for the reexamination.
- The October 25, 2017, Technical Stakeholders Workshop provided an update on the UNRBA Monitoring Program and summarized the results of the UNRBA model selection process for the watershed and lake models. The WARMF watershed model was described in terms of how it operates and the input data requirements. Participants were asked to provide information about relevant input data from their organizations that could be used to support model development.
- The October 24, 2018, Technical Stakeholders Workshop provided an update on the UNRBA Monitoring Program as well as model development. Stakeholders were invited to provide information regarding potential input data and were asked what types of model output would be useful to them and their organization (parameters, spatial and temporal resolution, potential questions to address with the models). This feedback guided decisions about model development.
- In 2019, the UNRBA began to hold MRSW meetings to discuss model development with internal and external stakeholders on a more frequent basis. These meetings continued through 2022 and early 2023 until the models (watershed and lake) were finalized and approved by the MRSW. The MRSW was the initial step in the modeling decision-making process for the UNRBA and presented its recommendations to the PFC which in turn presented its recommendations along with project status

updates to the UNRBA Board of Directors. MRSW decisions regarding watershed model development are noted throughout the body of this report.

- The February 12, 2020, UNRBA Regulatory Forum targeted local leaders and elected officials to raise awareness of the UNRBA efforts among council members, commissioners, and managers. Background information about the Falls Lake Nutrient Management Strategy and the UNRBA's reexamination was provided. Participants were invited to share concerns about the process and request support for future decision making on nutrient management in the Falls Lake watershed. This input helped guide adjustments in our process to complete model development and provide effective tools for the reexamination.
- The first joint symposium with the NC Collaboratory was held on May 19, 2021. The purpose of the symposium was to inform Falls Lake stakeholders of recent NC Collaboratory-funded Falls Lake research and UNRBA efforts to reexamine the Falls Nutrient Management Strategy. Stakeholders provided feedback on potential modeling scenarios and ideas about nutrient management.
- A second joint symposium with the NC Collaboratory was held on April 7, 2022. This symposium provided an update on the key findings of the research and included discussions with stakeholders to hear input on the revised nutrient management strategy.

The UNRBA has worked closely with researchers funded by the NC Collaboratory to conduct research in Falls Lake and its watershed. The NC Collaboratory also funded a "third-party" review of the UNRBA model development process. Descriptions of the research studies and review efforts pertaining to the watershed modeling are referenced in the relevant sections of this report (studies pertaining to the lake models are discussed in a separate report). Reports on the research funded through the NC Collaboratory are available online at https://nutrients.web.unc.edu/resources/. The researchers summarized their work during a joint symposium held in May 2021 by the NC Collaboratory and the UNRBA, and recordings of the presentations are available online at https://nutrients.web.unc.edu/2021-falls-lake-symposium/. Many of the researchers have also presented their work at MRSW and PFC meetings and copies of these presentations are available on the UNRBA meeting page: https://www.unrba.org/meetings. The UNRBA modeling team has worked closely with these researchers to ensure the data, assumptions, and model simulations and components are consistent with the available research and knowledge about Falls Lake and its watershed.

The UNRBA has also coordinated closely with DWR modeling staff, "third-party" reviewers funded by the NC Collaboratory, and technical subject matter experts to evaluate the model and provide input on concerns, questions, or issues identified as the model was being developed. These reviewers were invited to participate in and provide feedback during all of the UNRBA's meetings involving status reports or modeling-specific discussions. In instances where questions could not be resolved during routine meetings, special meetings were held to discuss options and review additional analyses. Questions and issues raised by the "third-party" reviewers, subject matter experts, and DWR staff in reference to processing steps, model assumptions, or model calibration were addressed prior to finalizing the models. Following special meetings with reviewers, recommendations for proceeding were presented to the MRSW and PFC, and votes were held to formalize decisions regarding model development. This process is documented throughout this report and appendices.

The UNRBA began presenting our coordination with the NC Collaboratory-funded "third-party" subject matter expert reviewers to the Board, PFC, and MRSW in September 2019. The Association routinely presented the plan to incorporate the "third-party" review into the model development process rather than receive feedback after the models had been calibrated, scenarios evaluated, and reports written. When the "third-party" review occurs after these steps have been completed, there is often little time or budget remaining to make changes to the models.

While this is not the "standard" after the fact "third-party" review, it is a "third-party" review in a practical and real way. The researchers funded by the NC Collaboratory have no financial or oversight relationship with the UNRBA. They were clearly "independent" to the UNRBA-funded model development process. This integrated, independent review allowed the kind of interactive and responsive action that would never be possible with a "standard third-party" review that occurs after the model is developed. The UNRBA acknowledges this distinction and refers to this as a "third-party" review only to relate the role of the reviewers funded by the NC Collaboratory.

It is also important to note that this intensive review process significantly extended the model development period and resulted in scope and cost expansion for the model development contractor. To fully respond to all input from the "third-party" reviewers, other subject matter experts, DWR, environmental interest stakeholders, and all that participated in this years-long process, the UNRBA provided significant additional funding.

This approach to the "third-party review" was discussed at the monthly meetings of the PFC and MRSW from September 2019 until the models were completed. The UNRBA invited staff from DWR modeling and planning groups to attend these monthly meetings which were usually attended by one or more staff from DWR. The UNRBA anticipates that DWR and potentially EPA Region 4 will review the models following submittal. The model development files, and the documentation of this extensive development process are available to all parties interested in reviewing this work.

Section 2

WARMF Watershed Model Overview and Configuration

The development of a viable watershed model requires a solid understanding of the inputs to the modeled area and a well-developed simulation tool for the processes that impact those inputs as they move through the system. The WARMF Watershed model is a well-established, tested, and accepted tool for the development of realistic and viable results that can effectively guide the development of a regulatory approach to address reservoir nutrient impacts. This report documents the steps followed to build this model, starting with a summary of sources that represents the nutrient inputs to this watershed, followed by the development and calibration of the model, and concluding with a review of the simulated output by source category for each land use and nutrient source in the watershed.

2.1 Model Overview

External sources of nitrogen, phosphorus, and other chemical constituents enter the Falls Lake watershed system via deposition on the vegetation or land surface, subsurface discharge, or as discharges to streams and rivers. In addition, nutrients are stored in the watershed soils and lake sediments based on past inputs, vegetative removal or recycling, and physical, chemical, and biological transformations that occur in the groundwater and the soils. Most sources of nutrient loading to Falls Lake are represented in the model using model input files: atmospheric deposition, nutrient application to agriculture or urban land, wastewater treatment facilities, sanitary sewer overflows, and onsite wastewater treatment systems. Wastewater treatment facilities, sanitary sewer overflows, and discharging sand filter systems are tracked together in a category called point sources. Inputs applied to the land surface such as nutrient application and atmospheric deposition are tracked by land use type (Figure ES-1). Some sources are internally calculated by the model, like streambank erosion and loading associated with soils, dissolution of nutrients into groundwater, and soil erosion; the model tracks these as sources of loading delivered to Falls Lake, but these are not prescribed in model input files.

Unlike empirical models, the WARMF Watershed model simulates the movement of “applied” nutrients over the land surface, through the soil, and through streams and impoundments to the targeted downstream location, i.e., Falls Lake. This represents a dynamic response to the variation in loading per unit surface area based on rates and timing of nutrient application, rainfall and antecedent moisture conditions, vegetation growth and harvesting cycles, and physical/biological/chemical changes to the nutrients as they move through the watershed. This approach is more capable of projecting the variation in loading based on weather and physical conditions than prescribing runoff nutrient concentrations or surface area loading rates that are intended to represent an average condition and are often based on studies from different regions or periods that are not representative of local rainfall, soils, and physical watershed conditions.

The WARMF model code is owned and maintained by Systech Water Resources, and Systech is continually updating the code and adding features to suit the needs of a variety of clients. There have been a number of features added to the WARMF model since DWR built the Falls Lake watershed model to simulate the baseline time period (2005-2007). These changes are related to preprocessing and postprocessing of model inputs and outputs, and do not affect the algorithms that WARMF utilizes to calculate flow or water quality concentrations for the constituents of concern to the UNRBA.

Two model code updates were made during the course of the Falls Lake watershed model development. These updates were made to align model functionality with the goals and objectives of the UNRBA. The UNRBA approved and arranged funding for Systech to make the following changes to the WARMF model code:

1. Simulation of soil processes at the land use scale. WARMF is a lumped parameter model, so the land uses and soils for each modeling catchment 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 similar loading rates (pounds per acre per year) from sources across the catchment. In order to address this standard modeling characteristic of WARMF and better distinguish the loading by land use, the Falls watershed WARMF model was configured to isolate soils by land use. This makes output information reflective of soil conditions in the watershed.
2. Expansion of the capacity of WARMF to simulate septic systems. The WARMF model code was expanded to accommodate the simulation of up to 15 types of onsite wastewater treatment systems rather than the model default (three systems). DWR assisted with securing grant funding through 319 to fund these model code revisions, and the grant report is included as Appendix A of this report. The UNRBA worked closely with researchers funded through the NC Collaboratory to develop the model inputs associated with each type of onsite wastewater treatment system.

Relative to the original Falls Lake watershed WARMF model developed by DWR, the following refinements were made to model configuration for the UNRBA Falls Lake WARMF model:

- Runs on a 6-hour time step as opposed to 24-hour
- Applies radar precipitation data rather than individual monitoring locations

2.2 Model Configuration

The WARMF watershed model requires the delineation of modeling units that divide the 770 square mile watershed into smaller areas. These modeling units are also called catchments, which route runoff and pollutants from land surfaces into receiving waterbodies. Catchments for the Falls Lake watershed modeling were delineated using the USGS StreamStats Program (https://water.usgs.gov/osw/streamstats/ssinfo.html). StreamStats is an accepted and widely used approach for this delineation process and is an online application that uses a GIS program along with a database containing land elevation models, historic weather data, and other data to delineate drainage basins and measure basin characteristics for user-selected sites. The UNRBA MRSW sought input from technical stakeholders during the October 2018 UNRBA Technical Stakeholders Workshop to ensure that the watershed modeling catchments were developed to address stakeholder concerns (e.g., how geologic basins impact nutrient loading). Following input from watershed stakeholders at the Fall 2018 UNRBA Technical Stakeholder Workshop and discussion with the MRSW on March 11, 2019, modeling catchments were delineated using StreamStats based on the following characteristics/guidelines:

The UNRBA MRSW sought input from technical stakeholders during the October 2018 Workshop to ensure that the watershed modeling catchments were developed to address stakeholder concerns (e.g., how geologic basins impact nutrient loading). The MRSW approved the approach and catchment boundaries during their March 2019 meeting.

- **Presence of a UNRBA watershed monitoring station.** Maps and information on UNRBA monitoring locations are available at www.unrba.org/monitoring. Placing modeling catchment pour points at UNRBA monitoring stations allows for direct comparison of simulated water quality concentrations to observed data for the UNRBA monitoring period (August 2014 to October 2018). The monitoring sites are shown in Figure 2-1.
- **Hydrologic network.** Configuration the modeling catchments at the confluences of tributaries allows distinction of simulated loading from different areas of the watershed and routing the flow of water and delivery of pollutants through the watershed to Falls Lake.
- **Geologic basin** (i.e., Carolina Slate Belt, Raleigh Belt, and Triassic Basin). At the Fall 2018 UNRBA Technical Stakeholder Meeting, the stakeholders expressed interest in evaluating the differences in pollutant loading and potential management strategies associated with geologic basins. Delineating the modeling catchments generally along the geologic basins simplifies processing and interpretation of model output to address this concern (Figure 2-1). Additional information regarding soils data is provided in Section 3.1 (see Figure 3.1).
- **Location of impoundments in the watershed** (Section 4.5.3). The WARMF watershed model requires that modeling catchments be delineated upstream and downstream of impoundments. This delineation ensures the proper routing of water through the watershed and allows for simulation of the physical, biological, and chemical processes that occur in impoundments.
- **Consistency with recently revised WARMF modeling conducted by the City of Durham** (Limno Tech 2016 and AECOM 2018). The City of Durham recently revised the WARMF modeling catchments relative to the DWR version of the Falls Lake watershed model. The UNRBA WARMF model includes these City of Durham delineations to provide consistency across models.
- **County Boundaries.** At the March 2019 MRSW meeting, the workgroup requested that delineations at County lines be incorporated into the catchments if the county line crosses a major stream or river, the catchments are relatively large, and the delineation would result in at least a 60/40 split of the original catchment.

Once preliminary drainage basin areas were obtained from StreamStats for each monitoring site, GIS analyses were used to confirm the accuracy of each area. Following this quality assurance (QA) procedure, a series of additional steps were conducted to format the catchment areas for modeling purposes. First, each catchment boundary was modified to ensure there was no overlap between catchment areas and that catchment outlets are co-located with the outlet of impoundments, UNRBA monitoring locations, and USGS stream gaging locations. The land area bordering Falls Lake where there are no UNRBA monitoring locations or stream reaches was then divided into additional catchments to cover the littoral areas draining directly to the lake; these areas are referred to in this report as "Near Lake" areas.

Each catchment with a stream channel is represented by a modeling stream reach. Reach chacteristics were populated using data from the USGS National Hydrography Dataset. Figure 2-1 shows the 264 WARMF watershed modeling catchments and 215 stream reaches in relation to the UNRBA monitoring stations, geologic basin, and location of impoundments in the watershed. These catchments incorporate the recent revised City of Durham catchments for consistency and incorporate county boundaries using the guidelines above. Figure 2-2 displays the catchments located above Interstate 85, and Figure 2-3 focuses on catchments below Interstate 85; these two figures show municipal boundaries relative to the catchments. Appendix B summarizes the catchment characteristics.

There are 28 tributaries that drain to Falls Lake, 18 of which were monitored by the UNRBA. The drainage areas of each tributary and the Near Lake area are provided in Table 2-1. The Near Lake area also includes the surface area of Falls Lake at normal pool (12,410 acres).

Table 2-1. Tributary and Near Lake Drainage Areas to Falls Lake (Sorted from Largest to Smallest)

Tributary	Drainage Area (acres)	Percent of Drainage Area
Flat River	108,708	22%
Eno River	96,558	20%
Little River	67,465	14%
Near Lake Including Falls Lake	64,646	13%
Knap of Reeds Creek	28,726	5.8%
Ellerbe Creek	14,929	3.0%
Ledge Creek	14,100	2.9%
Little Lick Creek	9,569	1.9%
Robertson Creek	9,439	1.9%
Horse Creek	9,226	1.9%
New Light Creek	8,913	1.8%
Beaverdam Creek	8,733	1.8%
Lick Creek	8,430	1.7%
Lower Barton Creek	7,249	1.5%
Smith Creek	6,733	1.4%
Upper Barton Creek	5,491	1.1%
Unnamed Tributary 184	3,504	0.7%
Honeycutt Creek	3,148	0.6%
Panther Creek	2,937	0.6%
Little Ledge Creek	2,443	0.5%
Laurel Creek	2,227	0.5%
Unnamed Tributary 183	2,179	0.4%
Buckhorn Creek	1,980	0.4%
Lowery Creek	1,742	0.4%
Unnamed Tributary 195	1,391	0.3%
Unnamed Tributary 219	1,054	0.2%
Water Fork	569	0.1%
Cedar Creek	179	0.0%
Grand Total	492,267	100%

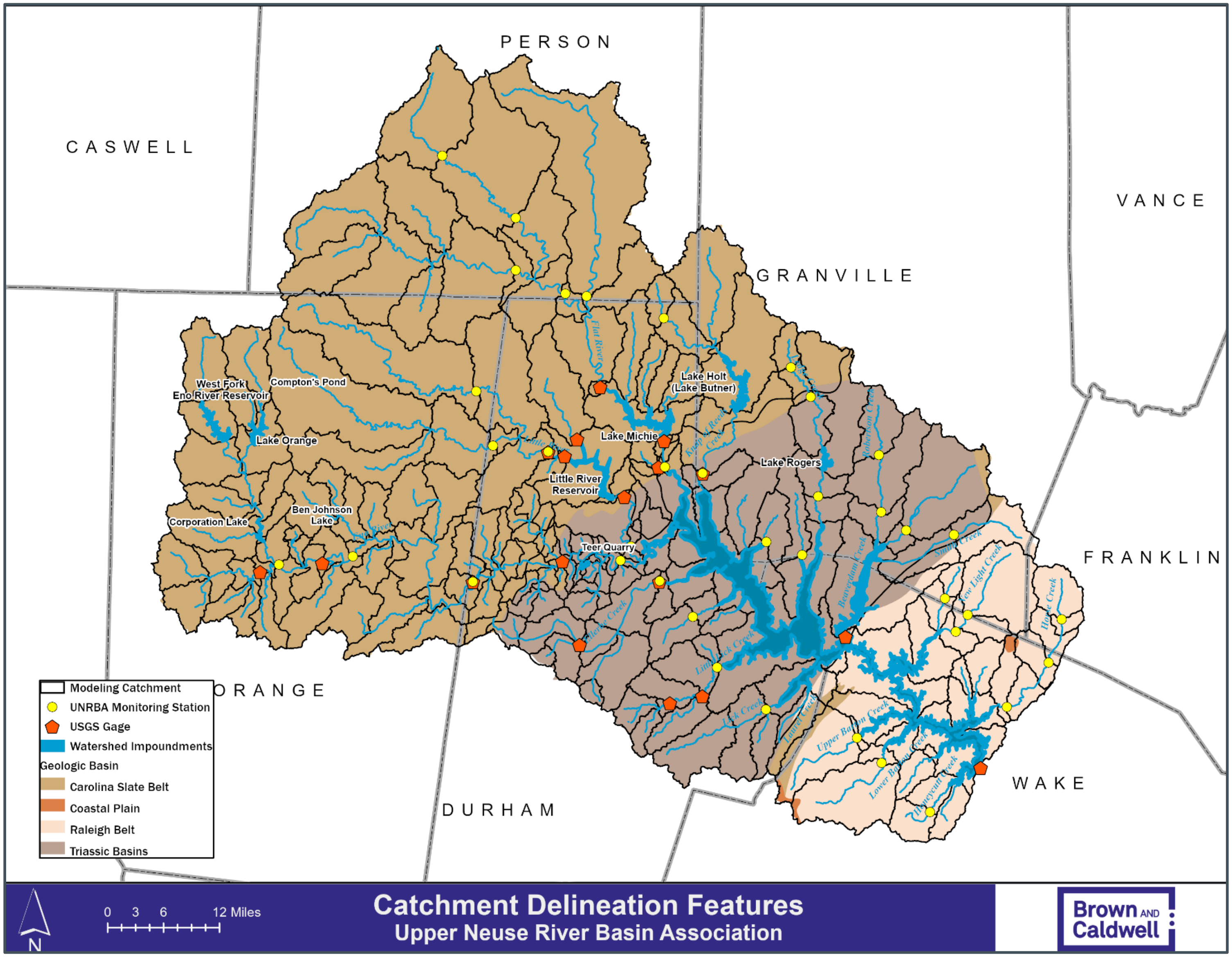


Figure 2-1. Geologic Soil Basin Boundaries, Monitoring Stations, and Impoundments Used to Delineate Modeling Catchments

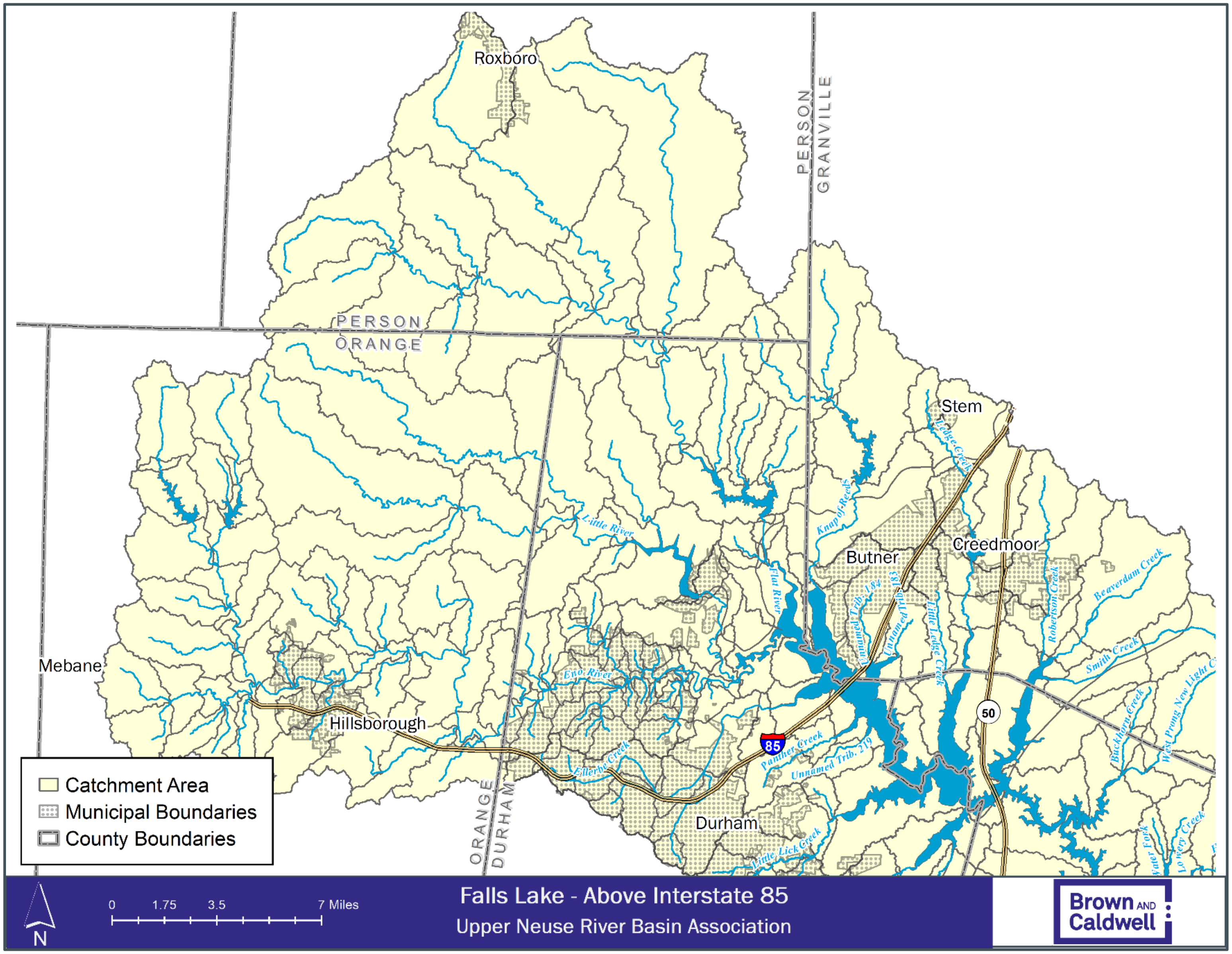


Figure 2-2. Catchment areas within the Falls Lake watershed upstream of Interstate 85

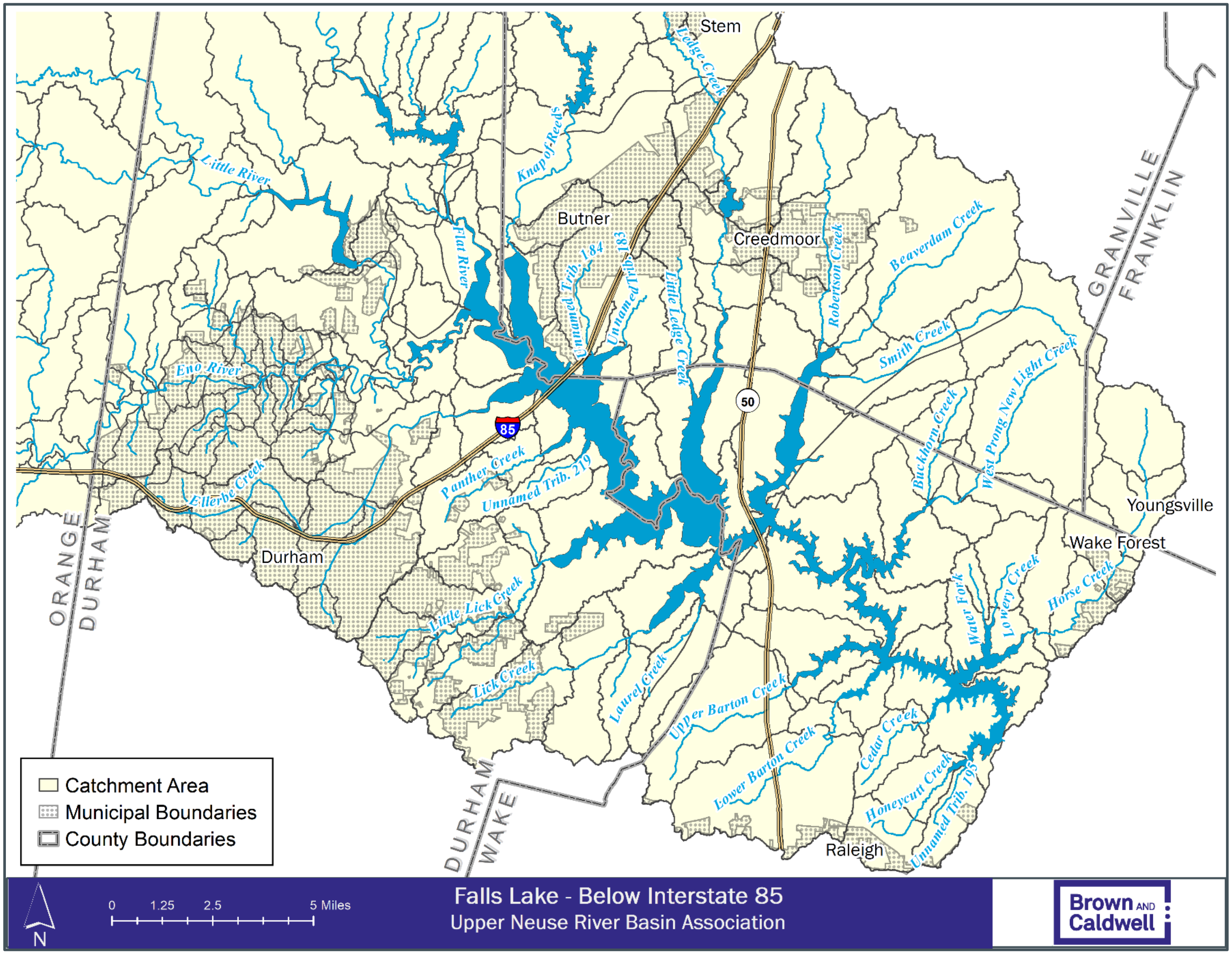


Figure 2-3. Catchment areas within the Falls Lake watershed downstream of Interstate 85

Section 3
Spatial Data

Watershed models rely on several types of spatial data to simulate hydrologic response and pollutant loading. This section describes development of model inputs for soils, land uses, nutrient application rates, onsite wastewater treatment systems, and upstream impoundments in the Falls Lake watershed.

3.1 Soils

Accurate soils data are critical for watershed model development because soil characteristics affect the storage and movement of water through the hydrologic system as well as the capacity for chemical reactions to occur within the soil horizon. To characterize the soils in the Falls Lake watershed for the UNRBA WARMF model, spatial soils data were acquired from the US Department of Agriculture Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO). (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/). The SSURGO data was used to characterize the soil series, parent rock material, soil depths, and characteristics. Figure 3-1 shows the soil series in the watershed based on the SSURGO data. Table 3-4 shows the location of the 20 most prevalent soils in terms of county and geologic basin. For example, Georgeville soils comprise up to 25 percent of the soils in a county and are predominately located in the Carolina Slate Belt.

WARMF is a lumped parameter model, so the land use and soils for each modeling catchment are simulated as a unit. WARMF traditionally keeps track of the nutrient balances associated with land uses in a catchment (nutrient application, crop uptake, etc.), but the soil layers are 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 similar loading from sources across the watershed. In order to better distinguish the loading by source, the WARMF option to isolate soils by land use was applied. However, the initial conditions are assigned to each layer as a catchment average, and not specific to each landuse. Therefore it takes several iterative runs for the soil nutrient balances to “separate” and the model to provide loading information that is distinguishable across land use types.

Initial soil parameters will be assumed the same for the baseline period as the UNRBA study period. This will introduce some uncertainty into the baseline period if selected for evaluation by the UNRBA because soil compaction, infiltration rates, nutrient application rates, and nutrient processing will have changed the conditions between 2005 to 2007 and 2015 to 2018. Because WARMF is being run iteratively five times, the nutrient balances should be representative of the baseline period in terms of application rates, etc if the baseline period is simulated. Vertical and horizontal soil hydraulic conductivity rates are established as catchment-averaged values regardless of land use, and this rate does not change over time in the model.

3.1.1 Hydrologic Characteristics

WARMF uses several soil characteristics that control the water balance in terms of infiltration, storage, and evapotranspiration. Default values for each calibration parameter are embedded in the model simulation code so WARMF users can run a model following initial setup without having to populate each model parameter. These parameter defaults were obtained from the scientific literature and provide a reasonable starting point for most applications. In the Falls Lake WARMF model, soil layer thickness and field capacity were populated by querying the SSURGO soil database. Model defaults were utilized for the other hydrology calibration parameters. The calibration process used to match simulated stream flows to recorded stream flows is described in Section 6.1.

Total soil depth is set to the average depth of soil to a restrictive layer within each catchment based on the SSURGO data. Average values for total depth by catchment range from 120 cm to 201 cm. In reality, soil depth within a catchment can be highly variable as soils are not uniform. While this variability exists, soil depth was not used as a calibration parameter during the hydrology calibration for the model (i.e., the average values based on the SSURGO data were not changed to alter simulation results).

Up to five soil layers were used to simulate the total soil depth in a catchment. The maximum thickness of each individual soil layer is specified in Table 3-1. The soil layers are the depth listed if the total soil depth is great enough to accommodate the maximum layer depth. If the total soil depth is shallower than the maximum layer depth plus the maximum depth of all shallower layers, the depth of the bottom soil layer is reduced. For example, a catchment with an average soil depth of 153 would have soil layer depths of 20, 30, 50, 50, and 3. A catchment with an average soil depth of 127 would have soil layer depths of 20, 30, 50, and 27. Soil survey samples typically do not extend to depths greater 200 cm, and depths greater than that are not relevant for WARMF. So, if soil depth is greater than 200, the five soil layer depths remain 20, 30, 50, 50, and 50.

Table 3-1. WARMF Soil Layers and Associated Maximum Depth

Soil Layer	Maximum Depth (cm)
1	20
2	30
3	50
4	50
5	50

This information is relevant for parameterization of the water quality model because initial concentrations of constituents in pore water, adsorption, and mineral composition are specific to each soil layer.

3.1.2 Chemical Characteristics

Initial soil pore water concentrations of chemical constituents play a critical role in simulated stream water quality. If values are too high, instream concentrations will be simulated too high, particularly in the first few years of the simulation. Instream concentrations will decrease over time as soil concentrations reach equilibrium with chemical inputs from nutrient application and atmospheric deposition that are applied to the land surface. If initial concentration values are too low, instream concentrations will be too low in the first few years and will gradually increase over time. Initial porewater concentrations are often used as a calibration term in the model. Having a reasonable starting point for these concentrations improves the efficiency of model calibration.

The UNRBA monitoring data collected in 2014-2018 were used to estimate the initial (pre-calibration) porewater concentrations for the parameters that were measured under this program. The average concentration measured when stream flows were less than or equal to the median value was calculated for each monitoring station. Stations were averaged by geologic basin (Figure 2-1) to provide initial inputs for the catchments. Monitoring data downstream of an impoundment, wastewater treatment plant, or multiple geologic basins were excluded from the data used to estimate the initial pore water concentrations. Daniels (1984) provided starting points for other parameters not measured by the UNRBA. Model defaults were applied to the remaining WARMF model parameters. Table 3-2 summarizes the initial porewater concentrations for the model as well as the source of the information. These initial porewater concentrations were specified by geologic basin but were adjusted for each catchment during model calibration.

Table 3-2. Initial Porewater Concentrations for the Falls Lake WARMF Watershed Model				
Parameter	Carolina Slate Belt	Raleigh Belt	Triassic Basin	Source
Ammonia Nitrogen as N, mg/l	0.050	0.061	0.102	UNRBA
Dissolved Organic Carbon, mg/l	2.7	2.7	11.0	UNRBA
Dissolved Organic Phosphorus, calculated, mg/l	0.018	0.018	0.028	UNRBA
Nitrate + Nitrite as N, mg/l	0.25	0.40	0.06	UNRBA
Organic N - calculated, mg/l	0.43	0.33	0.93	UNRBA
Particulate Organic Carbon, calculated, mg/l	0.18	0.18	0.57	UNRBA
Particulate Phosphorus, calculated, mg/l	0.012	0.012	0.068	UNRBA
Total N - calculated, mg/l	0.73	0.78	1.09	UNRBA
Total Organic Carbon, mg/l	4.9	2.9	11.4	UNRBA
Total Orthophosphate as P, mg/l	0.021	0.021	0.051	UNRBA
Total Phosphorus as P, mg/l	0.057	0.046	0.124	UNRBA
Total Soluble Phosphorus, mg/l	0.036	0.036	0.061	UNRBA
Total Suspended Solids, mg/l	7.911	6.372	15.925	UNRBA
CBOD5, mg/l	1	1	3	UNRBA
Al (mg/L)	0.002	0.002	0.002	2x model default (0.001)
Ca (mg/L)	20	20	20	Model default
Mg (mg/L)	4	4	4	Model default
K (mg/L)	5	5	5	Daniels 1984
Na (mg/L)	1	1	1	Model default
SO4 (mg/L)	0.5	0.5	0.5	Model default
Cl (mg/L)	10	10	10	Daniels 1984
SiO2 (mg/L)	0.5	0.5	0.5	Model default
Fecal Coliform (#/100 mL)	0	0	0	Model default
DO (mg/L)	8	8	8	Model default

WARMF also requires information on how the simulated chemical constituents interact with soil particles. Base saturation percent for hydrogen (H), ammonium (NH4), aluminum (Al), calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) are required, and should sum to 100. Adsorption isotherms for phosphate (PO4, mg/kg), sulfate (SO4, L/kg), and dissolved organic carbon (DOC, L/kg) are required.

Cation-exchange capacity (CEC) is a measure of how many cations can be retained on soil particle surfaces. Negative charges on the surfaces of soil particles bind positively charged atoms or molecules (cations) but allow these to exchange with other positively charged particles in the surrounding soil water according to their relative affinities. The CEC of the soil is used in conjunction with the cation base saturation percentages to determine quantities of these cations that bind to soil particles. As such, CEC is an important parameter to constrain early in the water quality calibration process. This data is available by soil series and depth in the SSURGO database.

Table 3-3 summarizes the CEC and base saturation percentages by geologic basin based on SSURGO or the USDA National Cooperative Soil Survey (NCSS) data collected in the counties in the Falls Lake Watershed. The depth-specific data are relatively limited but provide a reasonable starting point to initialize the model for the soil layers. Some of the NCSS data are decades old when land use and nutrient application practices were very different. The range of PO4 adsorption isotherms based on the NCSS data was very large and the initial conditions originally selected resulted in underprediction of total phosphorus concentrations across the watershed. Daniel Obenour, "third-party" reviewer for the UNRBA modeling, suggested application of data from USGS (Smith et al., 2013) be used as the starting point. These higher values improved the model simulations of phosphorus. Local information for SO4 and DOC isotherms was not available, so model defaults of 10 L/kg and 100 L/kg were used (add to table if values change by layer). The values in Table 3-3 were used to set the initial estimates but were adjusted during model calibration at the catchment scale.

Table 3-3. Initial Characteristics for Interactions with Soil Particles Based on NCSS Data

Geologic Basin	WARMF Layer (cm)	CEC meq/100g	H%	NH4%	AL%	Ca%	Mg%	Na%	K%	PO4 (mg/kg)
Triassic Basin	0-20	12.9	24.8	0.8	41.0	21.2	9.5	1.3	1.4	135
Triassic Basin	20-50	16.8	9.8	0.8	60.4	15.2	10.6	1.7	1.4	72
Triassic Basin	50-100	25.0	4.1	0.9	76.4	6.9	8.5	2.0	1.2	52
Triassic Basin	100-150	26.5	3.4	0.8	73.5	8.6	10.4	2.4	1.0	33
Triassic Basin	150-200	23.6	2.7	0.7	80.1	6.4	7.4	1.9	0.9	44
Triassic Basin	200+	16.1	2.6	0.8	77.5	6.4	9.4	2.5	0.8	39
Raleigh Belt	0-20	13.4	47.2	1.0	19.0	19.4	9.7	1.5	2.2	286
Raleigh Belt	20-50	6.4	53.4	1.0	19.0	15.6	6.3	3.1	1.6	183
Raleigh Belt	50-100	10.3	45.9	1.0	23.0	17.1	8.6	2.9	1.5	73
Raleigh Belt	100-150	9.8	27.7	1.0	53.0	10.3	4.9	2.1	1.0	54
Raleigh Belt	150-200	7.7	9.2	1.0	82.0	2.6	1.3	2.6	1.3	56
Raleigh Belt	200+	6.8	5.9	1.0	85.8	1.5	1.5	3.0	1.4	59
Carolina Slate Belt	0-20	12.9	26.0	0.8	37.3	22.4	10.9	0.8	1.7	597
Carolina Slate Belt	20-50	16.9	13.0	0.8	42.6	22.5	18.5	1.2	1.3	48
Carolina Slate Belt	50-100	19.3	8.1	0.6	42.6	19.7	23.5	1.2	4.2	35
Carolina Slate Belt	100-150	18.3	6.3	0.8	46.3	19.9	25.4	0.7	0.7	23
Carolina Slate Belt	150-200	15.6	4.9	0.5	84.5	3.4	5.1	0.5	1.0	33
Carolina Slate Belt	200+	10.8	0.7	0.4	92.0	1.5	2.6	1.0	1.9	33

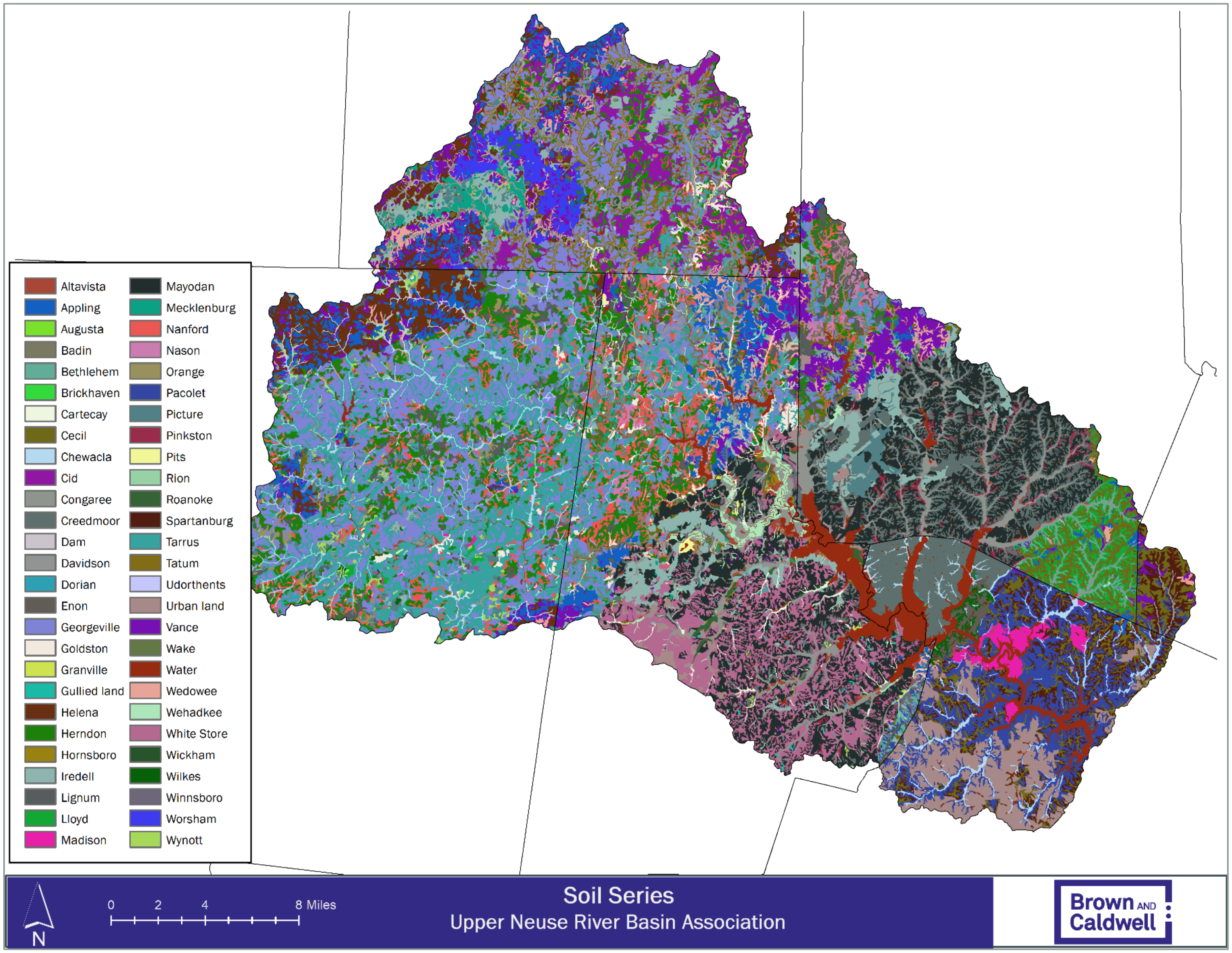


Figure 3-1. SSURGO Soils in the Falls Lake Watershed

Table 3-4. SSURGO Soils in the Falls Lake Watershed by County and Geologic Basin

Soil Series (Top 20)	Granville	Person	Franklin	Orange	Durham	Wake	Carolina Slate Belt	Raleigh Belt	Triassic Basins
Georgeville	1.98%	16.29%	0.00%	25.61%	6.06%	0.00%	99.78%	0.00%	0.22%
Mayodan	23.16%	0.00%	0.00%	0.00%	17.09%	0.00%	4.26%	0.04%	95.70%
Tarrus	1.22%	2.16%	0.00%	23.88%	5.11%	0.00%	99.61%	0.00%	0.39%
Herndon	2.19%	8.66%	0.00%	12.02%	5.42%	0.00%	99.79%	0.00%	0.21%
Creedmoor	17.46%	0.00%	0.00%	0.00%	2.27%	11.46%	2.57%	0.01%	97.41%
White Store	0.00%	0.00%	0.00%	0.00%	15.58%	0.00%	1.70%	0.02%	98.28%
Congaree	8.43%	6.67%	4.92%	0.68%	4.91%	0.00%	42.69%	4.65%	52.66%
Pacolet	0.20%	0.00%	8.41%	0.00%	0.55%	27.66%	6.00%	92.75%	0.69%
Appling	1.29%	6.21%	0.04%	4.20%	4.71%	0.24%	95.31%	3.50%	0.51%
Water	2.94%	0.77%	0.36%	0.84%	5.21%	9.52%	22.69%	19.19%	58.09%
Vance	5.90%	7.08%	9.88%	1.99%	2.38%	0.05%	94.67%	4.27%	1.07%
Iredell	5.62%	5.68%	0.00%	0.84%	4.44%	0.00%	51.54%	0.18%	48.27%
Nanford	0.92%	2.84%	0.00%	5.31%	4.83%	0.00%	99.33%	0.00%	0.67%
Cecil	5.86%	0.80%	37.42%	0.29%	1.22%	8.24%	20.81%	74.48%	4.25%
Helena	0.00%	6.65%	0.89%	6.59%	0.00%	0.94%	95.71%	4.04%	0.00%
Cid	0.00%	12.43%	0.00%	0.01%	0.00%	0.00%	100.00%	0.00%	0.00%
Chewacla	0.02%	0.00%	0.08%	4.78%	0.00%	5.41%	63.82%	28.67%	7.14%
Tatum	1.63%	9.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Lignum	1.85%	0.00%	0.00%	3.66%	1.85%	0.00%	100.00%	0.00%	0.00%
Spartanburg	0.01%	0.27%	35.92%	0.00%	0.00%	10.09%	4.03%	94.94%	0.28%

3.1.3 Third-Party Review of Input Data for Watershed Soils

Soils data was developed using primarily USDA NRCS and NCSS data supplemented with WARMF model inputs, UNRBA monitoring data, and literature. This data was processed spatially for developing model input files for each catchment. Because many of the soil water quality parameters were used as initial conditions that were then adjusted during model calibration or processed by the model in response to external factors (e.g., nutrient application) a comprehensive "third-party" review of the soils data was not conducted. However, during water quality calibration, "third-party" model reviewer Daniel Obenour (funded through the NC Collaboratory) suggested evaluation of USGS soil phosphorus concentration data to increase simulated phosphorus concentrations. Application of this data improved the model performance for total phosphorus, particularly in response to storm events.

3.2 Land Use Land Cover

Land use land cover data is an essential component of watershed models. Characteristics of land cover strongly affect the simulated movement of water and pollutants. For the Falls Lake Watershed, multiple sources of land cover data were used to characterize each modeling catchment for both modeling periods.

3.2.1 US Geologic Survey National Land Cover Database and Simulation of Urban Areas

the US Geologic Survey (USGS) National Land Cover Database (NLCD) is a standard and commonly accepted land use / land cover dataset for building watershed models. The NLCD is a Landsat satellite-based landcover database converted to a 30-meter resolution grid, with several independent data layers, that facilitates a wide variety of applications. The database includes:

- 16 classes of land-cover data derived from the imagery, ancillary data, and derivatives using a decision tree
- Classification rules, confidence estimates, and metadata from the land cover classification

This dataset is currently the best available watershed-wide land use coverage. The NLCD land use scheme was re-classified in WARMF to provide simplified land use categories that are more meaningful in terms of estimating pollutant loading rates. The most recent versions of NLCD data sets (2006, 2011, and 2016) were used to develop the land use data for the baseline period (2005 to 2007) and the UNRBA study period (2015 to 2018). With release of the 2016 data, the USGS and the Federal interagency Multi-Resolution Land Characteristics (MRLC) Consortium released reprocessed NLCD data sets for 2006 and 2011 for more consistent classification of land uses and more accurate comparisons of change across land use categories.

The current Falls Lake Nutrient Management Strategy resulted in new development rules that were implemented across the watershed beginning in 2011 and continuing in 2012. The new development rules require that loading from the site not exceed 2.2 lb-N/ac/yr and 0.33 lb-P/ac/yr. A portion of this requirement can be fulfilled using offsite mitigation. As a result, development in the Falls Lake Watershed before and after implementation of new development rules is different. The 2011 NLCD land use data provides the closest approximation of land use at the time the new development rules went into effect. The NLCD land use data sets were processed to distinguish between development that occurred before and after 2011. Because the City of Durham required more stringent development requirements between 2007 and 2011 (but less stringent than the new development requirements), development that occurred in the City of Durham between 2007 and 2011 was assigned its own land use designation.

The designation of different types of development (existing, new, and City of Durham interim) offers the following benefits to the modeling: 1) it reflects development characteristics in the watershed as required by the Falls Lake Nutrient Management Strategy or City of Durham ordinances, 2) it streamlines modeling efforts by characterizing loading rates from different types of development rather than simulating site-level stormwater control measures for which data acquisition and accounting would be difficult retroactively, and 3) it allows for evaluation of nutrient management strategies for different types of development.

The NLCD data for the watershed for 2006, 2011, and 2016 are shown in Figure 3-2, Figure 3-3, and Figure 3-4, respectively.

The MRSW approved the approach for simulating different types of development in the watershed at the March 2019 MRSW meeting. The group also reviewed the land use data inputs for the baseline and UNRBA study periods to confirm development in their jurisdictions was accurately represented.

The MRSW approved the approach for simulating different types of development in the watershed at the March 2019 MRSW meeting. The group also reviewed the land use data inputs for the baseline and UNRBA study periods to confirm development in their jurisdictions was accurately represented. The NLCD data sets were used as follows:

- The 2006 data were used to define development for the baseline period 2005 to 2007. This development has the characteristics of "existing development." This development also includes institutions, schools/colleges, etc., that may be owned or operated by private or public entities.
- The 2011 data were used to estimate the amount of development that occurred during the period between the baseline year of the Falls Lake Nutrient Management Strategy (2006) and the full implementation of the new development rules (2012).
  - For the City of Durham which had a stricter development ordinance in place in the anticipation of the new development rules, this development is assigned the characteristics of "City of Durham interim development."
  - For other jurisdictions that did not have more strict development ordinances in place, this development is assumed to have the same characteristics as "existing development."
- The 2016 data were used to quantify the total amount of development in the watershed for the modeling period 2014 to 2017. The change in developed area between the 2011 data and the 2016 data was assigned characteristics of "new development," i.e., being covered by the Falls new development Rule, except for the Town of Hillsborough which provided site-specific data for developments that were permitted prior to the implementation of the new development rules and grandfathered in as "existing development." Development data provided for the Town of Butner were used to verify that the 2016 NLCD data accurately identified areas of new development.
- Prior to the new development rules taking effect in 2012 and in anticipation of the coming rules, the City of Durham incorporated the following changes into their local ordinance:
  - 1993: Water Supply Overlay requirements (85% TSS)
  - 2007: 3.6 N limit lb/ac/yr (Neuse Rules)
  - 2010: N limit 2.2 lb/ac/yr and P limit 0.5 lb/ac/yr (voluntary interim limit)
  - 2012: N limit 2.2 lb/ac/yr and P limit 0.33 lb/ac/yr (current Falls Rules)
- The City of Durham had also implemented 348 existing development retrofit projects by December 2015 (Figure 3-5). Most of these were concentrated in the Ellerbe Creek watershed to reduce storm peak flows and reduce nutrient loading to Falls Lake. To reflect these projects, the WARMF modeling catchments in the Ellerbe Creek watershed were assigned appropriate amounts of detention volume

using the best management practice module in the WARMF model. Assigning volumes of detention was necessary for the calibration of the stream flows in this watershed.

Percent impervious values for developed open space, low intensity, medium intensity, and high intensity developments are 20, 20, 50, and 80, respectively. To simulate the effects of stormwater control measures required for new development, the model assumes the first inch of runoff from impervious surfaces on new development is routed to a detention basin. Interim development is assumed partially treated and therefore the model assumes the first ½ inch is routed to a detention basin. Note that the percentages of new development and interim development are very small for the UNRBA study period, and these assumptions about routing a portion of the runoff to a detention basin do not affect the model calibration results because the area is so small. Application or modification of this assumption to affect larger areas could be important when model scenarios are evaluated.

In its simulation of developed areas, WARMF only simulates nutrient application to pervious areas, but atmospheric deposition affects both pervious and impervious areas. 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 infiltrates into the soil where it can interact with soil particles and travel to the stream. 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. Using the BMP features of the model was required to calibrate to observed stream water quality data.

Stream bank erosion is simulated by WARMF separately from the individual land uses (see parameter ranges in Table 6-5 and additional discussion in Appendix H). Stream bank erosion is an average condition for the reach within each river segment and is calculated based on soil erosivity, simulated shear stress, bank and vegetation characteristics, etc. The hydrologic impacts of impervious surfaces on stream bank erosion are not accounted for in the nutrient loads tracked for each land use by the model. This approach is 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 impervious surfaces on stream bank erosion and resulting nutrient loading rates are associated with the land uses in the drainage area. This is an important consideration when communicating to stakeholders the results of the model in terms of the impacts of urban development on nutrient loading.

Stream bank erosion is simulated by WARMF separately from the individual land uses. The hydrologic impacts of impervious surfaces on stream bank erosion are not accounted for in the nutrient loads tracked for each land use by the model.

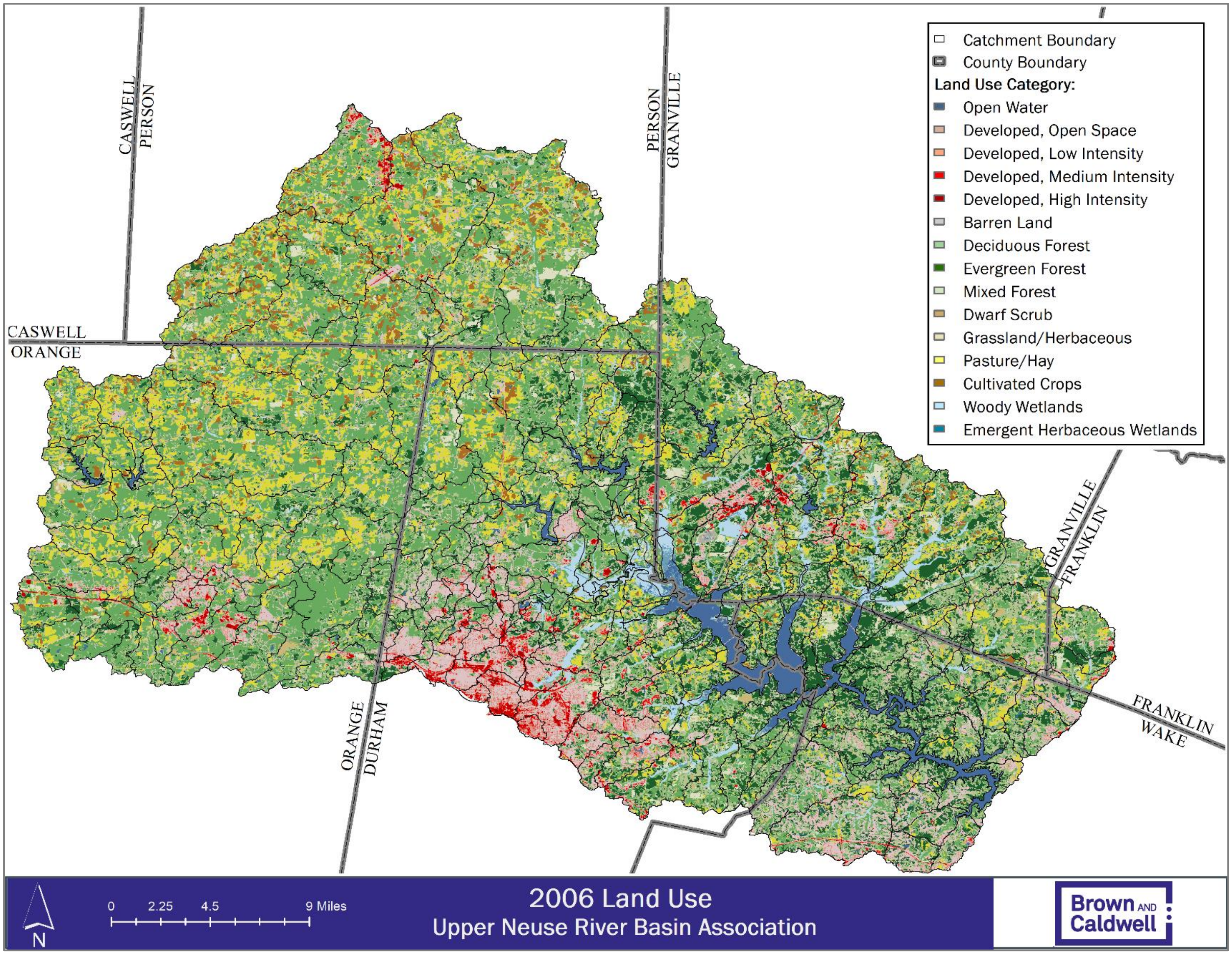


Figure 3-2. USGS NLCD for 2006

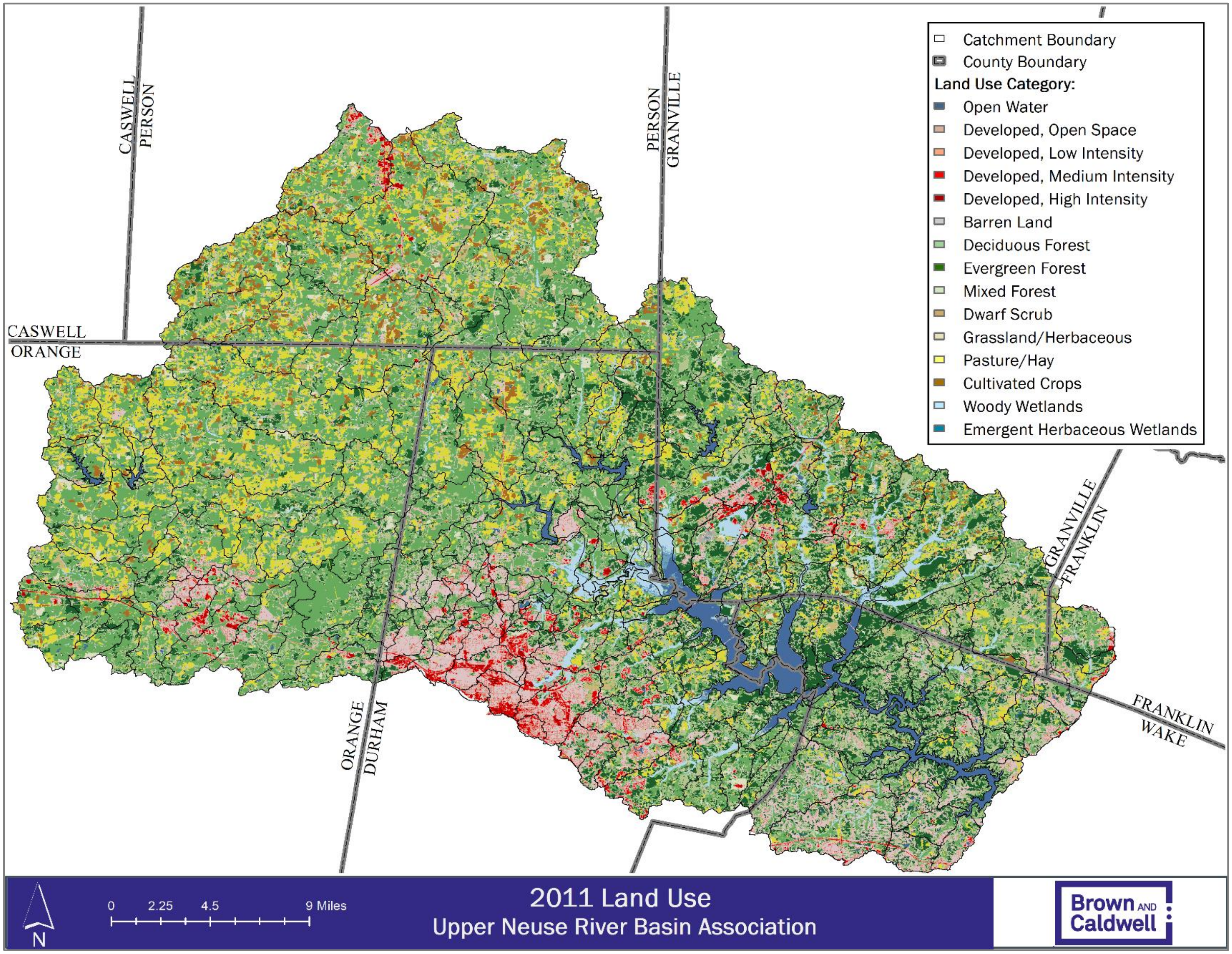


Figure 3-3. USGS NLCD for 2011

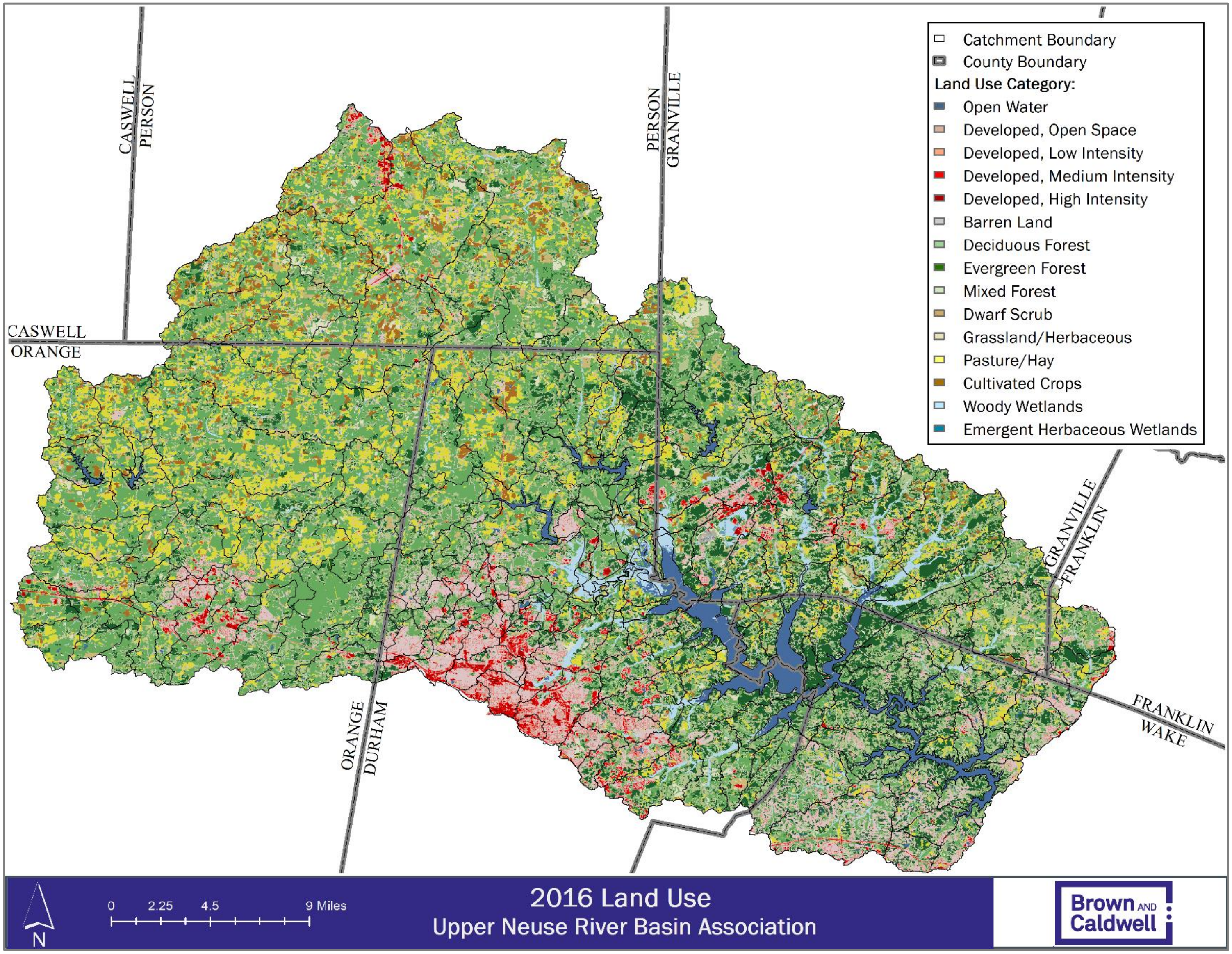


Figure 3-4. USGS NLCD for 2016

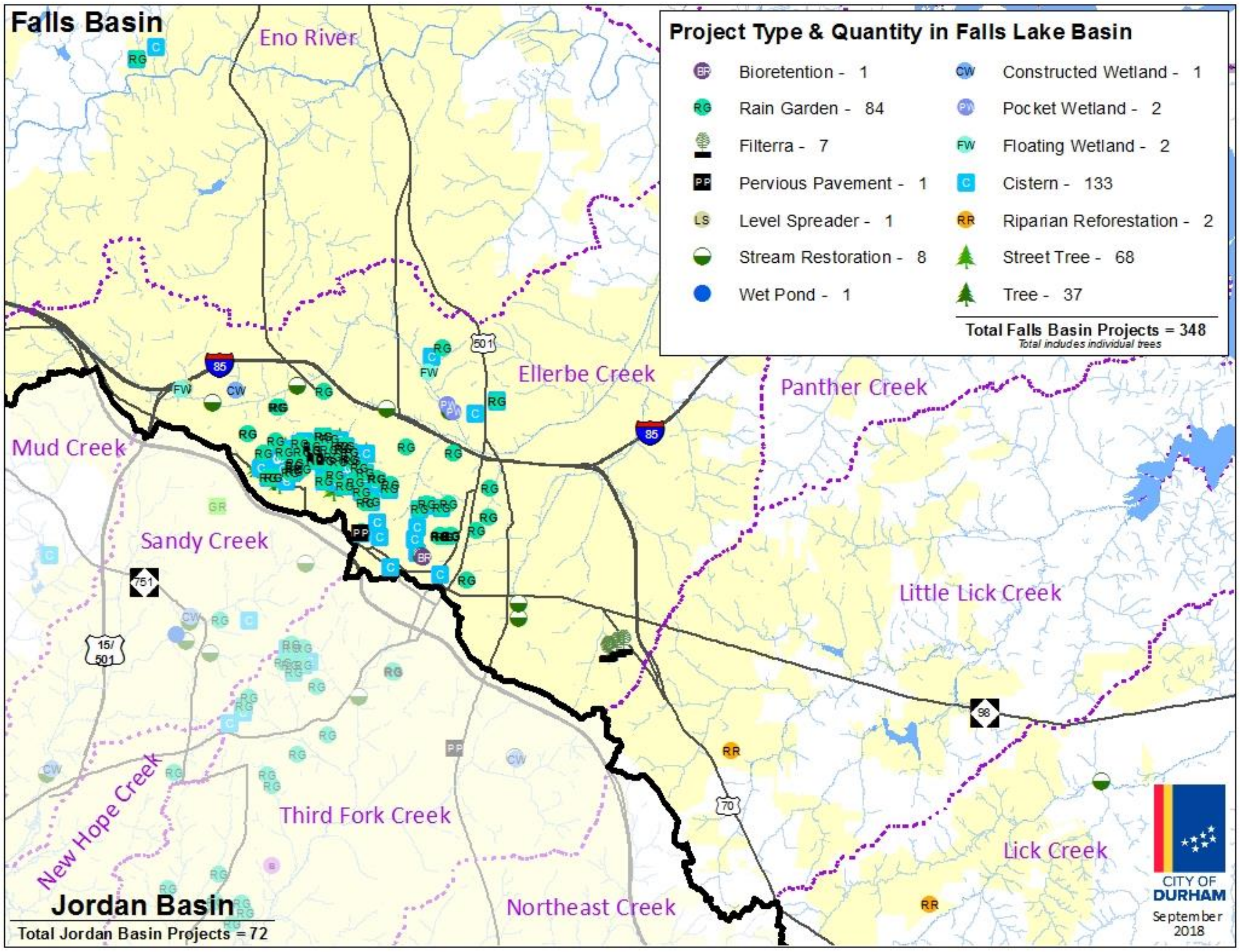


Figure 3-5. Existing Development Retrofits Installed by the City of Durham by December 2015

3.2.2 NCDA&CS Crop and Pasture Data

The passage of the Falls Lake Nutrient Management Strategy resulted in the formation of the Watershed Oversight Committee (WOC) for the Falls Lake Basin. The WOC includes staff from the NCDA&CS Division of Soil and Water Conservation (DSWC), the USDA Natural Resources Conversation Service, North Carolina Cooperative Extension, and the NC Department of Environmental Quality (DEQ), as well as agricultural and environmental interests from within the watershed.

Under the Rules, the WOC is charged with compiling, analyzing, and reporting data related to agricultural production, nutrient loading, and compliance with the Falls Lake Nutrient Management Strategy. Local Advisory Committees (LACs) which are managed at the county level provide their data to the DSWC. The LAC-supplied data includes information from local soil and water conservation districts and agricultural producers. The DSWC generates annual reports from these data which are submitted to the WOC, which then reviews and finalizes the document for submission to DEQ and the EMC. As a result, the DSWC maintains the best available information related to agricultural land use and nutrient management in the watershed and represents a singular point of contact for developing this information to go into the model.

The DSWC land use data represents county-wide acreages of pasture and cropland (soybeans, corn, etc.). The DSWC provided annual, county-level crop data from within the Falls Lake watershed for 2007 and each year from 2011 to 2018. Pasture data are compiled every five years and were provided for 2007 and 2017. To estimate the crop and pasture acreages for the baseline period (2005 to 2007), the 2007 crop and pasture data were used. For the UNRBA study period (2015 to 2018), crop data from 2016 and pasture data from 2017 were applied. The raw data provided by the DSWC is provided in Table 3-5 and Table 3-6 for the baseline and UNRBA study periods, respectively; production acres declined by 44 percent.

DSWC crop and pasture data acreages are provided at the county-level and include specific crop types (e.g., wheat versus oats). The NLCD data are available spatially but only include two agricultural categories (cultivated crops and hay/pasture). While the NLCD includes cultivated crops and hay/pasture, USDA has reported technical difficulties in distinguishing areas considered "pervious" like crops, pasture, urban grass, etc., (https://www.nass.usda.gov/Research_and_Science/Cropland/sarsfaqs2.php). To develop land use model inputs at the catchment scale, the more broadly classified, spatial data included in the NLCD dataset were post-processed to integrate the county-level, crop-specific agricultural data. Due to the difficulties in distinguishing pervious areas in the NLCD data set, the NLCD crop and pasture areas are not sufficient to account for the county-level data provided by DSWC, especially in 2006 when production acres were higher. Therefore, other pervious areas represented in NLCD were assigned to agriculture to ensure sufficient agricultural areas were represented in the model. These areas were then assigned to the DSWC crop categories using the county-level data.

The following assumptions and methods were discussed with the DSWC and used to develop the land use inputs for the model; these were also reviewed by the MRSW:

- To account for crop and pasture acreages, areas were taken first from NLCD cultivated crops and then hay/pasture, grassland/herbaceous, shrub/scrub, and deciduous forest in that order until "available" agricultural land use area was sufficient to assign the DSWC crop and pasture data.
- To ensure that area from grassland/herbaceous, shrub/scrub, and deciduous forest was assigned from a rural catchment, acres were only reclassified in catchments that had some area identified by NLCD as cultivated crops or hay/pasture.
- Double-cropped soybean acres were assumed in rotation with wheat. These acres were subtracted from the wheat acres provided by the DSWC. Acres remaining in wheat after the subtraction were classified as "wheat." If the subtraction resulted in a negative acreage, then "wheat" was set to zero unless additional processing steps added to that category.
- For crops that were not at least one percent of the agricultural area in any county, acreages were collapsed into other crop types
  - Oats, rye, barley, pearl millet, and sorghum were assigned to the "wheat " category
  - Sorghum Sudan (hay) was assigned to fescue (hay)
  - Any remaining hay/pasture in NLCD not needed to account for agricultural acres was assigned to "herbaceous" and simulated in a non-managed state

Staff from the DSWC not only provided the raw data used to develop the land use estimates but also assisted with development of the assumptions and methods needed to integrate this data with the NLCD data as noted in the bullets above. Staff also quality assured the final land use data sets after all post-processing was complete. The UNRBA is extremely grateful for the support of the NCDA&CS Division of Soil and Water Conservation, the WOC, and the LACs in developing the land use dataset for agriculture.

The UNRBA is extremely grateful for the support of the DSWC, the WOC, the LACs, and the NCDA&CS in developing the land use dataset.

Table 3-5. Crop and Pasture Acreages for the Falls Lake Watershed by County for the Baseline Period

Crop	Durham	Franklin	Granville	Orange	Person	Wake	Total
Barley	0	0	0	380	0	0	**380**
Bermudagrass (Hay)	0	0	0	0	0	0	**0**
No-Till Grain Corn	275	0	95	1448	1529	33	**3,380**
Conventional Grain Corn	72	0	95	617	170	33	**987**
No-Till Silage Corn	26	0	203	456	425	0	**1,110**
Conventional Silage Corn	27	0	203	161	0	0	**391**
Fescue (Hay)	1,000	0	4140	3994	9040	448	**18,622**
Oats	46	0	47	367	0	0	**460**
Rye	193	0	0	0	0	0	**193**
Sorghum	0	0	0	113	0	0	**113**
Double-cropped Soybeans	488	188	294	1,755	0	0	**2,725**
Full Season Soybeans	488	0	440	1,755	3,723	1,865	**8,271**
Flue-Cured Tobacco	241	35	351	775	1,611	0	**3,013**
Wheat	478	50	410	2,769	3,874	214	**7,795**
Fescue (Pasture)	5,164	1,500	16,363	9,331	7,958	1,322	**41,638**
Total	**8,498**	**1,773**	**22,641**	**23,921**	**28,330**	**3,915**	**89,078**

Table 3-6. Crop and Pasture Acreages for the Falls Lake Watershed by County for the UNRBA Study Period

Crop	Durham	Franklin	Granville	Orange	Person	Wake	Total
Barley	0	0	0	42	0	0	**42**
Bermudagrass (Hay)	0	0	0	0	0	0	**0**
No-Till Grain Corn	333	0	420	1125	744	30	**2,652**
Conventional Grain Corn	0	0	105	35	0	31	**171**
No-Till Silage Corn	0	0	0	0	0	0	**0**
Conventional Silage Corn	0	0	0	0	0	0	**0**
Fescue (Hay)	750	0	1,000	2,000	546	246	**4,542**
Oats	0	0	14	12	61	27	**114**
Pearl Millet	0	0	4	21	20	0	**45**
Rye	0	0	0	24	20	0	**44**
Sorghum	0	0	19	90	29	0	**138**
Sorghum Sudan (Hay)	0	0	0	68	0	0	**68**
Double-cropped Soybeans	0	176	451	581	1,956	213	**3,377**
Full Season Soybeans	424	0	781	1,241	2,440	1,026	**5,912**
Flue-Cured Tobacco	160	42	518	408	1,632	0	**2,760**
Wheat	449	59	451	581	1,956	213	**3,709**
Fescue (Pasture)	3,060	394	8,327	8,648	5,235	921	**26,585**
Total	**5,176**	**671**	**12,090**	**14,876**	**14,639**	**2,707**	**50,159**

3.2.3 NC Department of Transportation Road Data

The NC Department of Transportation (DOT) owns and maintains roads, rights-of-way and other facilities throughout the Falls Lake Watershed. Through coordination with staff at DOT, consultants for DOT provided spatial datasets for the baseline and UNRBA study periods for integration into the watershed model land use characterization. This data included the extent of the right of way as well as the impervious area within the right of way. Based on this data, the average imperviousness applied to roads maintained by DOT assumed for this modeling is 40 percent; this assumption was reviewed by DOT staff and consultants.

The WARMF model can distinguish roads that are directly connected to waterways and those that are indirectly connected. DOT categorizes these roads by assuming those within an MS4 boundary or within 300 feet of stream were directly connected and others were not. Segments of roads that are simulated as directly connected are assumed to discharge directly to a waterbody and therefore do not experience "trapping" of pollutants that occurs as runoff flows across pervious surfaces.

Roads that are not maintained by DOT are accounted for in the NLCD developed land use classes. Figure 3-6 shows the road classification for those maintained by DOT versus those that are not. These non-DOT roads were left in the urban developed categories and not broken out as separate land uses because 1) literature values for model parameters tend to include roads in the developed categories, 2) often street sweeping occurs beyond roads (e.g., parking lots that would be part of the urban development classes), and

3) impervious surfaces are often connected to roads and there is no benefit to splitting out non-DOT roads from other types of urban development, and 4) WARMF is a lumped parameter model so if these areas are connected then they should be simulated together.

The UNRBA MRSW discussed and approved these methods and assumptions regarding connected/unconnected roads and DOT/other roads during its September 2019 meeting. The approaches employed in this watershed modeling effort to simulate the role of this type of land use are consistent with established and appropriate modeling conventions.

Following integration of the DOT road characterization into the UNRBA WARMF land use input databases for the baseline and modeling periods, consultants for DOT quality assured the processed data to assure it was consistent with the raw data they provided. The UNRBA is grateful to DOT and their consultants for providing this data and review of the model inputs.

The UNRBA is extremely grateful to DOT and their consultants for providing this data and review of the model inputs.

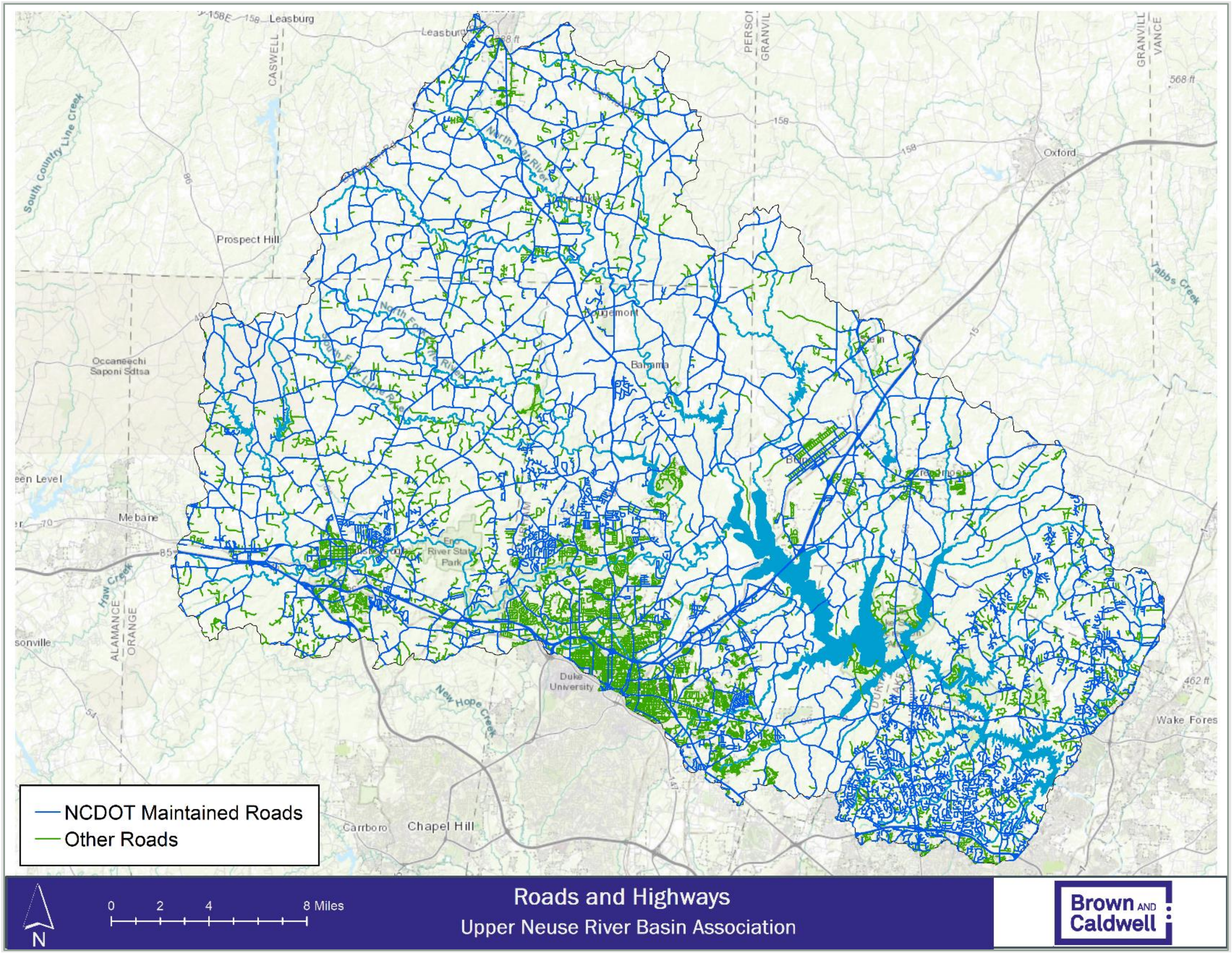


Figure 3-6. Roads and Highways in the Falls Lake Watershed Maintained by NCDOT (blue) and Other Roads (green)

3.2.4 NC Wildlife Resources Commission

Waterfowl impoundment areas within the Falls Lake watershed were identified using spatial data obtained from the North Carolina Wildlife Resources Commission (NCWRC, Figure 3-7). Once identified, these areas were assigned a separate land use designation. To avoid double counting land use acreages, NLCD designated land use areas overlapping with waterfowl impoundment areas were removed. Values for hydrologic model parameters were set equal to the parameter values used for the emergent herbaceous wetlands land cover class. Based on discussions with WRC (personal communication from Christopher Baranski on 11/10/2020), the number and species present at each impoundment is highly variable and there is not a way to estimate populations or nutrient loading. Because these impoundments are inland, they are not used by the same number of birds as coastal impoundments. Thus, the water quality assumptions for waterfowl impoundments in the WARMF model have been set to the same levels as other wetlands. Because waterfowl impoundments comprise only 0.2 percent of the watershed area to Falls Lake, this assumption is not likely to significantly impact the simulated nutrient loading to the lake.

The UNRBA is extremely grateful to NCWRC for providing this data and information regarding the model inputs.

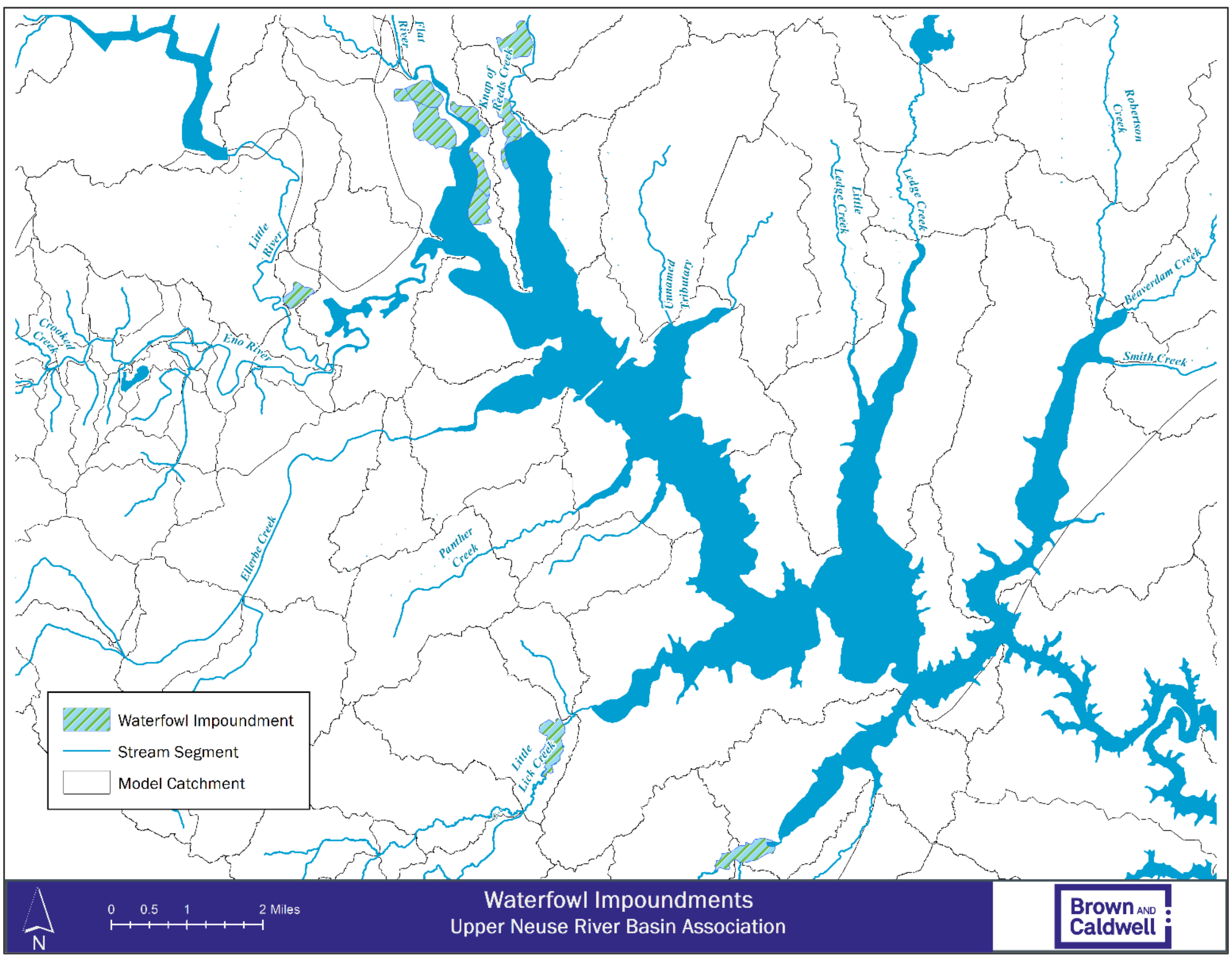


Figure 3-7. Location of Wildlife Impoundments in the Falls Lake Watershed (from NCWRC)

3.2.5 Local Government and Third-Party Review of Processed Land Use Data Sets

As noted in Sections 3.2.1 through 3.2.4, staff from the local governments in the watershed, NCDA&CS, NCDOT, and NCWRC provided the raw data to build the model input files associated with land uses in the Falls Lake Watershed under their purview. Staff from the NCDA&CS and NCDOT also quality-assured the processing of their raw data for building the watershed model input files. Additional processing of NCWRC data was not needed because these were provided spatially and simulated as a single land use class. Staff from local governments in the watershed and the MRSW reviewed the processed land uses as part of model development.

3.2.6 Summary of Land Use Characterization

Land use data are input into the WARMF model as a percentage for each modeling catchment. Appendix B provides the land use percentages for each WARMF modeling catchment. Land use acreages and percentages for the baseline period are summarized in Table 3-7 and Table 3-8, respectively and for the recent period in Table 3-9 and Table 3-10. Percentages for each period are shown graphically in Figure 3-8 and Figure 3-9 for the baseline and UNRBA study period, respectively. Forest is the largest contributing land use at approximately 60 percent of the watershed area. No other land use exceeds ten percent of the watershed area. Unmanaged lands in the watershed (forest, wetlands, open water, and unmanaged grass and shrubland) comprised 68 percent of the watershed in the baseline period and 75 percent in the recent period due partly to reductions in agricultural production acres.

Table 3-7. Land Use Acreages in the Falls Lake Watershed by County for the Baseline Period

Land Use	Durham	Franklin	Granville	Orange	Person	Wake	Total
Barren Land	217	2	179	62	17	22	**500**
Conventional Grain Corn	71	0	94	613	169	33	**980**
Conventional Silage Corn	27	0	201	160	0	0	**388**
Deciduous Forest	32,472	432	11,058	56,367	33,322	9,319	**142,970**
Developed, High Intensity	829	22	218	191	192	17	**1,470**
Developed, Low Intensity	6,894	116	1,555	1,478	953	1,131	**12,127**
Developed, Medium Intensity	2,659	36	524	449	322	154	**4,144**
Developed, Open Space	17,151	588	4,468	7,603	3,970	8,078	**41,859**
Double-cropped Soybeans	483	186	291	1,744	0	0	**2,704**
Emergent Herbaceous Wetlands	285	1	359	16	25	41	**728**
Evergreen Forest	16,580	1,124	18,917	8,145	3,980	15,590	**64,336**
Fescue (Pasture)	5,114	1,485	16,184	9,272	7,902	1,302	**41,260**
Fescue (Hay)	990	0	4,095	3,969	8,977	441	**18,472**
Flue-Cured Tobacco	239	35	347	770	1,600	0	**2,990**
Full Season Soybeans	483	0	435	1,744	3,697	1,837	**8,196**
Herbaceous, not managed	10,348	0	0	8,755	0	772	**19,875**
Mixed Forest	19,096	954	16,638	13,660	9,119	14,479	**73,946**
No-Till Grain Corn	272	0	94	1,439	1,518	33	**3,356**
No-Till Silage Corn	26	0	201	453	422	0	**1,102**
DOT rights of way, not connected	2,109	170	1,052	2,661	1,305	2,062	**9,360**
Open Water[1]	1,987	11	1,277	1,204	540	776	**18,205**
DOT rights of way, connected	1,311	9	612	330	235	244	**2,741**
Shrub, scrub	1,192	0	0	2,008	0	531	**3,731**
Waterfowl Impoundment	681	0	158	0	0	0	**839**
Wheat	237	0	161	1,862	3,847	339	**6,446**
Woody Wetlands	4,248	94	3,690	448	471	594	**9,545**
TOTAL	**126,002**	**5,264**	**82,809**	**125,404**	**82,583**	**57,795**	**492,267**

[1] Falls Lake adds 12,410 acres to the open water category, as reflected in the totals. This acreage represents 2.5 percent of the total watershed area.

Table 3-8. Land Use Percentages in the Falls Lake Watershed by County for the Baseline Period

Land Use	Durham	Franklin	Granville	Orange	Person	Wake	Total
Barren Land	0.0%	0.00%	0.04%	0.01%	0.00%	0.00%	**0.10%**
Conventional Grain Corn	0.0%	0.00%	0.02%	0.12%	0.03%	0.01%	**0.20%**
Conventional Silage Corn	0.0%	0.00%	0.04%	0.03%	0.00%	0.00%	**0.08%**
Deciduous Forest	6.6%	0.09%	2.2%	11.5%	6.8%	1.9%	**29.0%**
Developed, High Intensity	0.2%	0.00%	0.04%	0.04%	0.04%	0.00%	**0.30%**
Developed, Low Intensity	1.4%	0.02%	0.32%	0.30%	0.19%	0.23%	**2.5%**
Developed, Medium Intensity	0.5%	0.01%	0.11%	0.09%	0.07%	0.03%	**0.84%**
Developed, Open Space	3.5%	0.12%	0.91%	1.5%	0.8%	1.6%	**8.5%**
Double-cropped Soybeans	0.1%	0.04%	0.06%	0.35%	0.00%	0.00%	**0.55%**
Emergent Herbaceous Wetlands	0.1%	0.00%	0.07%	0.00%	0.01%	0.01%	**0.15%**
Evergreen Forest	3.4%	0.23%	3.8%	1.7%	0.81%	3.2%	**13.1%**
Fescue (Pasture)	1.0%	0.30%	3.3%	1.9%	1.6%	0.26%	**8.4%**
Fescue (Hay)	0.2%	0.00%	0.83%	0.81%	1.8%	0.09%	**3.8%**
Flue-Cured Tobacco	0.0%	0.01%	0.07%	0.16%	0.32%	0.00%	**0.61%**
Full Season Soybeans	0.1%	0.00%	0.09%	0.35%	0.75%	0.37%	**1.7%**
Herbaceous, not managed	2.1%	0.00%	0.00%	1.8%	0.00%	0.16%	**4.0%**
Mixed Forest	3.9%	0.19%	3.4%	2.8%	1.9%	2.9%	**15.0%**
No-Till Grain Corn	0.1%	0.00%	0.02%	0.29%	0.31%	0.01%	**0.68%**
No-Till Silage Corn	0.0%	0.00%	0.04%	0.09%	0.09%	0.00%	**0.22%**
DOT rights of way, not connected	0.4%	0.03%	0.21%	0.54%	0.27%	0.42%	**1.9%**
Open Water[1]	0.4%	0.00%	0.26%	0.24%	0.11%	0.16%	**3.7%**
DOT rights of way, connected	0.3%	0.00%	0.12%	0.07%	0.05%	0.05%	**0.56%**
Shrub, scrub	0.2%	0.00%	0.00%	0.41%	0.00%	0.11%	**0.76%**
Waterfowl Impoundment	0.1%	0.00%	0.03%	0.00%	0.00%	0.00%	**0.17%**
Wheat	0.0%	0.00%	0.03%	0.38%	0.78%	0.07%	**1.3%**
Woody Wetlands	0.9%	0.02%	0.75%	0.09%	0.10%	0.12%	**1.9%**
TOTAL	**25.6%**	**1.1%**	**16.8%**	**25.5%**	**16.8%**	**11.7%**	**100.0%**

[1] Falls Lake adds 12,410 acres to the open water category, as reflected in the totals. This acreage represents 2.5 percent of the total watershed area.

Table 3-9. Simulated Land Uses Acreages in the Falls Lake Watershed for the UNRBA study Period

Land Use	Durham	Franklin	Granville	Orange	Person	Wake	**Total**
Barren Land	212	1	174	47	18	19	**471**
Conventional Grain Corn	2	0	96	32	2	37	**169**
Deciduous Forest	34,169	972	16,420	52,569	32,925	9,531	**146,587**
Developed, Open Space	17,131	458	4,654	7,772	4,064	8,902	**42,981**
DOT Roads (Connected)	1,382	11	626	354	240	275	**2,888**
DOT Roads (Not Connected)	2,237	169	1,094	2,718	1,325	2,432	**9,976**
Double-Cropped Soybeans	35	126	499	553	1,897	241	**3,350**
Emergent Herbaceous Wetlands	128	2	234	12	13	17	**406**
Evergreen Forest	17,310	1,126	18,983	8,658	4,867	17,558	**68,503**
Fescue (Hay)	782	0	937	1,892	648	305	**4,564**
Fescue (Pasture)	3,267	282	7,864	7,946	5,523	1,442	**26,324**
Flue Cured Tobacco	180	30	519	391	1,581	34	**2,736**
Full Season Soybeans	462	1	782	1,160	2,402	1,054	**5,861**
Herbaceous (Not Managed)	10,988	64	2,356	14,492	11,972	1,612	**41,484**
High Intensity Existing Development	815	25	269	211	205	28	**1,554**
High Intensity Interim Development[1]	63	-	-	1	-	-	**64**
High Intensity New Development	29	0	30	5	2	7	**72**
Low Intensity Existing Development	6,764	121	1,751	1,592	989	1,393	**12,610**
Low Intensity Interim Development[1]	250	-	-	2	-	-	**252**
Low Intensity New Development	172	5	43	10	9	99	**339**
Medium Intensity Existing Development	2,608	50	673	542	347	228	**4,449**
Medium Intensity Interim Development[1]	327	-	-	3	-	-	**330**
Medium Intensity New Development	194	2	38	21	4	40	**298**
Mixed Forest	19,671	894	16,253	13,626	9,525	15,948	**75,917**
No-Till Grain Corn	356	0	404	1,034	777	56	**2,627**
Open Water[2]	2,287	8	1,390	1,207	570	1,061	**18,933**
Shrub/Scrub	1,259	47	1,289	1,837	2,533	403	**7,368**
Waterfowl Impoundment	661	-	178	-	-	-	**839**
Wheat	431	0	42	174	143	29	**820**
Woody Wetlands	4,180	110	3,456	439	492	818	**9,495**
Total	**128,352**	**4,504**	**81,055**	**119,302**	**83,074**	**63,570**	**492,267**

[1] *Interim development is simulated only in the City of Durham*

[2] *Falls Lake adds 12,410 acres to the open water category, as reflected in the totals. This acreage represents 2.5 percent of the total watershed area.*

Table 3-10. Simulated Land Uses Percentages in the Falls Lake Watershed for the UNRBA study Period

Land Use	Durham	Franklin	Granville	Orange	Person	Wake	Total
Barren Land	0.04%	0.00%	0.04%	0.01%	0.00%	0.00%	0.10%
Conventional Grain Corn	0.00%	0.00%	0.02%	0.01%	0.00%	0.01%	0.03%
Deciduous Forest	6.9%	0.2%	3.3%	10.7%	6.7%	1.9%	29.8%
Developed, Open Space	3.5%	0.1%	0.9%	1.6%	0.8%	1.8%	**8.7%**
DOT Roads (Connected)	0.28%	0.00%	0.13%	0.07%	0.05%	0.06%	**0.59%**
DOT Roads (Not Connected)	0.45%	0.03%	0.22%	0.55%	0.27%	0.49%	**2.0%**
Double-Cropped Soybeans	0.01%	0.03%	0.10%	0.11%	0.39%	0.05%	**0.68%**
Emergent Herbaceous Wetlands	0.03%	0.00%	0.05%	0.00%	0.00%	0.00%	**0.08%**
Evergreen Forest	3.5%	0.23%	3.9%	1.8%	1.0%	3.6%	**13.9%**
Fescue (Hay)	0.16%	0.00%	0.19%	0.38%	0.13%	0.06%	**0.93%**
Fescue (Pasture)	0.66%	0.06%	1.6%	1.6%	1.1%	0.29%	**5.3%**
Flue Cured Tobacco	0.04%	0.01%	0.11%	0.08%	0.32%	0.01%	**0.56%**
Full Season Soybeans	0.09%	0.00%	0.16%	0.24%	0.49%	0.21%	**1.2%**
Herbaceous (Not Managed)	2.2%	0.01%	0.48%	2.9%	2.4%	0.33%	**8.4%**
High Intensity Existing Development	0.17%	0.01%	0.05%	0.04%	0.04%	0.01%	**0.32%**
High Intensity Interim Development[1]	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.01%**
High Intensity New Development	0.01%	0.00%	0.01%	0.00%	0.00%	0.00%	**0.01%**
Low Intensity Existing Development	1.4%	0.02%	0.4%	0.32%	0.20%	0.28%	**2.6%**
Low Intensity Interim Development[1]	0.05%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.05%**
Low Intensity New Development	0.03%	0.00%	0.01%	0.00%	0.00%	0.02%	**0.07%**
Medium Intensity Existing Development	0.53%	0.01%	0.14%	0.11%	0.07%	0.05%	**0.90%**
Medium Intensity Interim Development[1]	0.07%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.07%**
Medium Intensity New Development	0.04%	0.00%	0.01%	0.00%	0.00%	0.01%	**0.06%**
Mixed Forest	4.0%	0.18%	3.3%	2.8%	1.9%	3.2%	**15.4%**
No-Till Grain Corn	0.07%	0.00%	0.08%	0.21%	0.16%	0.01%	**0.53%**
Open Water[2]	0.46%	0.00%	0.28%	0.25%	0.12%	0.22%	**3.8%**
Shrub/Scrub	0.26%	0.01%	0.26%	0.37%	0.51%	0.08%	**1.5%**
Waterfowl Impoundment	0.13%	0.00%	0.04%	0.00%	0.00%	0.00%	**0.17%**
Wheat	0.09%	0.00%	0.01%	0.04%	0.03%	0.01%	**0.17%**
Woody Wetlands	0.85%	0.02%	0.70%	0.09%	0.10%	0.17%	**1.9%**
Total	**26.1%**	**0.9%**	**16.5%**	**24.2%**	**16.9%**	**12.9%**	**100%**

[1] *Interim development is simulated only in the City of Durham*

[2] *Falls Lake adds 12,410 acres to the open water category, as reflected in the totals. This acreage represents 2.5 percent of the total watershed area.*

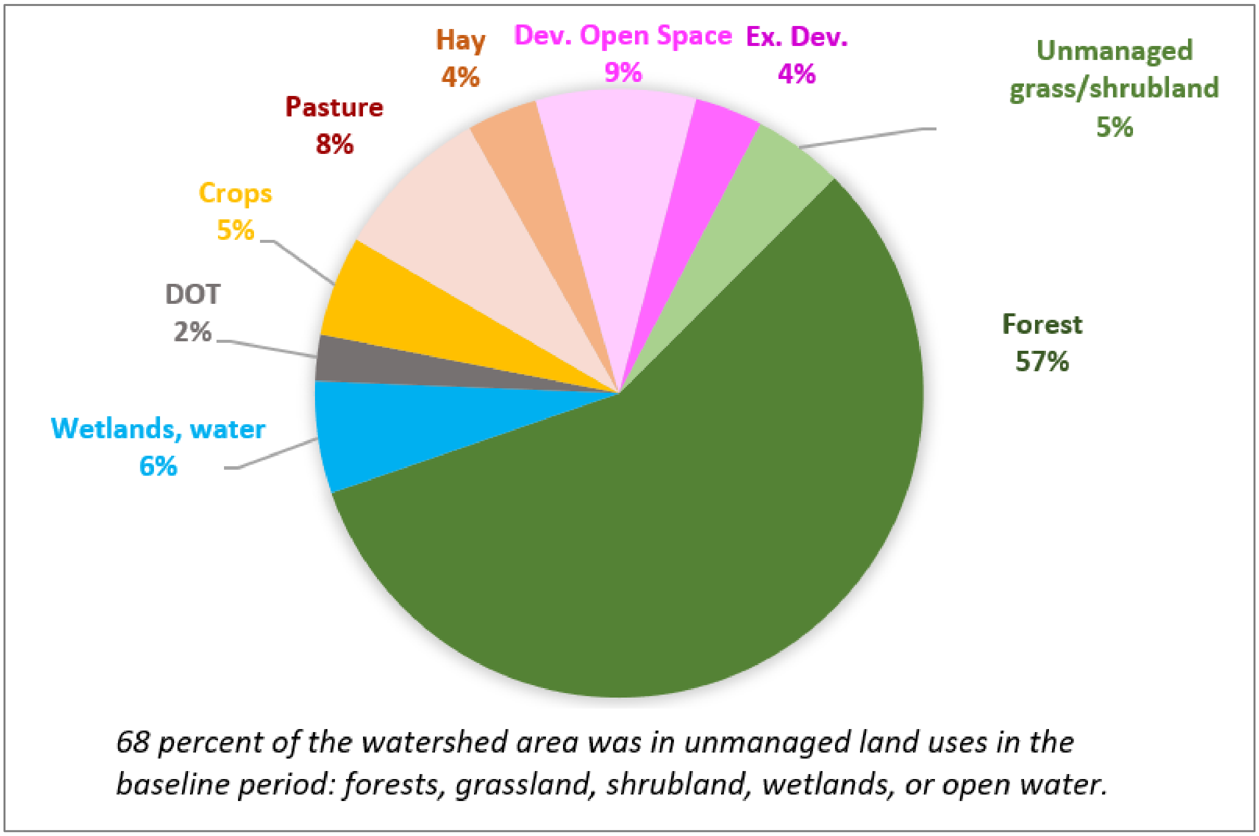


Figure 3-8. Percent Land Use Area in the Falls Lake Watershed for the Baseline Period

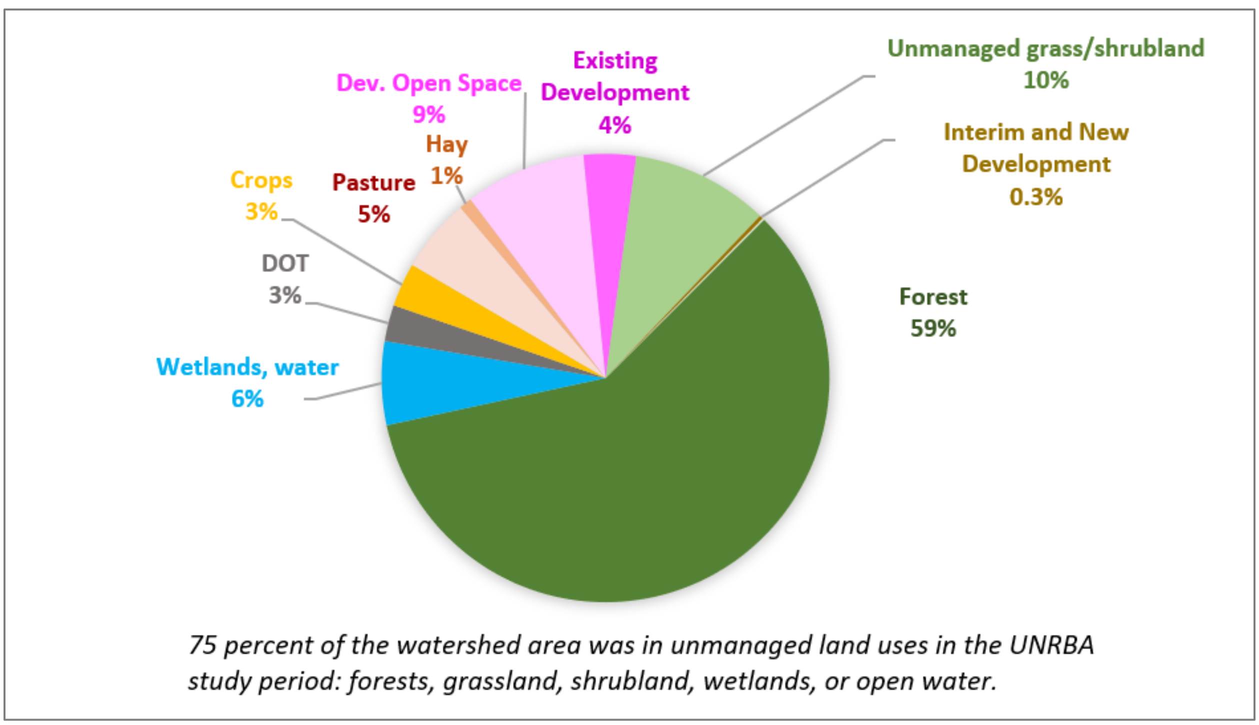


Figure 3-9. Percent Land Use Area in the Falls Lake Watershed for the UNRBA Study Period

3.3 Nutrient Application, Planting Dates, and Harvest Dates

The WARMF model specifies monthly nutrient and mineral application rates for each land use classification represented in the model. The model developer defines the spatial resolution for this input based on available information and designation of land use classes. For example, the model can assign general cropland nutrient application rates or specific rates for more defined crop types (corn, soybean, etc.). In the Falls Lake Watershed, the information varies by sector, such that nutrient application to agricultural areas is better quantified than developed areas. Data and assumptions by sector are described below.

3.3.1 Agriculture

Each year since the Falls Lake Nutrient Management Strategy went into effect in 2011, the WOC provides annual status reports to DEQ that summarize agricultural activities in the Falls Lake Watershed. In addition to the acreages of pasture and crops at the county level, the WOC compiles and summarizes data on nitrogen application rates. The DSWC has compiled total nitrogen application rates for pasture and for crops grown in the watershed. This information was provided to the UNRBA in spreadsheet format for years 2007 and 2011 through 2018. In addition to nitrogen application rates, the approximate timing (by month) for planting, applications, and harvest were also provided by DSWC. Assumptions regarding potassium and phosphorus application rates were obtained from the report "Delineating Agriculture in the Neuse River Basin" (Osmond and Neas 2011).

Table 3-11 and Table 3-12 summarize the total nitrogen, total phosphorus, and potassium application rates and timing for agriculture in the Falls Lake watershed before nutrient removal due to crop harvesting. Nitrogen application rate data were available for a representative year in the baseline period (2007) and for the UNRBA study period (2014 to 2018; 2014 was included in the averaging for the recent period since it was the year used to initialize the soil conditions). For crops, the Falls Lake WARMF model assumes that one-third of the nitrogen application is in the nitrate form and two-thirds is in the ammonia form (assumption reviewed by staff at DSWC and the NC State University College of Agriculture and Life Sciences Department of Crop and Soil Sciences via email on August 7, 2020). For pasture, staff at DSWC provided average nitrogen deposition rates by county that reflect the direct deposition of manure minus volatilization plus inorganic supplement normalized by each pastured animal type (estimates provided by staff at DSWC via email on August 20, 2020. In an email dated March 12, 2021, staff at DSWC indicated that approximately ½ of nitrogen application to pasture would occur in inorganic form in April, with the remaining nitrogen application applied evenly over the other months as organic matter. The total organic carbon application associated with agriculture comes from the organic matter deposited on pastureland.

For phosphorus and potassium application, data were obtained from a report published in 2011 which is near the middle of the two modeling periods. For the baseline and UNRBA study periods, the application rates for these two parameters are assumed the same. The exception to this approach is Person County where total phosphorus concentrations simulated in the Flat River were too high relative to observations. Given the age of the Neuse River Basin report and the fact that the Person County phosphorus application rates were higher for each crop relative to the other counties, the phosphorus application rates reported for Orange County in 2011 were used for the UNRBA study period for catchments in Person County. The rates as provided in the report were used for the baseline period.

The application rates are total inputs that include application of commercial fertilizer, biosolids, and animal manure (poultry, horses, sheep, goats, and cattle). Thus, for agricultural areas, the modelers did not need to explicitly simulate small or large animal operations including horse farms or application of biosolids. These rates were included in the total amounts (the WARMF model does not require specification of the source of nutrients).

Nutrients are consumed from the soil as plants grow and are removed from the system during harvesting. Table 3-13 summarizes the typical planting and harvest schedules provided by DSWC. The modeling team worked closely with staff at the DSWC and the NC State University College of Agriculture and Life Sciences Department of Crop and Soil Sciences to develop the inputs and assumptions associated with agricultural land uses in the Falls Lake watershed. These staff provided data when available and guidance on reasonable assumptions when data were not available. The UNRBA is very fortunate to have had access to the level of information provided by local agricultural experts in the development of the watershed model. The nutrient content of the harvested materials was based on the Soil and Water Assessment Tool crop model database.

The UNRBA is very fortunate to have had access to the level of information provided by local agricultural experts in the development of the watershed model.

Table 3-11. Simulated Application Rates for the Baseline and UNRBA Study Periods for Agricultural Land Uses (Before Nutrient Removal Due To Crop Harvesting)

County and Agricultural Land Use	Baseline Nitrogen (lb/ac/yr)	Recent Nitrogen (lb/ac/yr)	Baseline and Recent Phosphorus (lb/ac /yr)	Baseline and Recent Potassium (lb/ac /yr)
Durham County				
Conventional Grain Corn	150	NA	42.34	65.84
No-Till Grain Corn	150	131	42.34	65.84
Fescue (Hay)	60	70	17	17
Fescue (Pasture)	83	96	4.8	44.7
Double-Cropped Soybeans	0	NA	0	0
Full Season Soybeans	0	0.4	0	0
Flue-Cured Tobacco	89	85	81	167.76
Wheat	110	100	37.5	37.5
Franklin County				
Fescue (Pasture)	79	87	28.3	28.3
Double-Cropped Soybeans	0	0	0	0
Flue-Cured Tobacco	90	80	82	234.3
Wheat	105	110	2.2	6.7
Granville County				
Conventional Grain Corn	140	125	47.1	77.5
No-Till Grain Corn	140	125	47.1	77.5
Fescue (Hay)	100	46	0	0
Fescue (Pasture)	73	82	0	0
Double-Cropped Soybeans	0	0	0	0
Full Season Soybeans	0	0	0	0
Flue-Cured Tobacco	78	74.6	78.5	151.5
Wheat	100	89.2	0	0
Orange County				
Conventional Grain Corn	110	150	50	54
No-Till Grain Corn	110	150	50	54
Fescue (Hay)	150	60	15.1	6.2
Fescue (Pasture)	126	86	11.8	11.8

Table 3-11. Simulated Application Rates for the Baseline and UNRBA Study Periods for Agricultural Land Uses (Before Nutrient Removal Due To Crop Harvesting)

County and Agricultural Land Use	Baseline Nitrogen (lb/ac/yr)	Recent Nitrogen (lb/ac/yr)	Baseline and Recent Phosphorus (lb/ac /yr)	Baseline and Recent Potassium (lb/ac /yr)
Double-Cropped Soybeans	0	0	7.8	7.8
Full Season Soybeans	0	2	7.8	7.8
Flue-Cured Tobacco	80	70	79.3	149.3
Wheat	80	100	13.8	14.4
Person County				
Conventional Grain Corn	140	NA	50	51.5
No-Till Grain Corn	140	148	50	51.5
Fescue (Hay)	80	54	15.1	14
Fescue (Pasture)	100	91	11.8	18.7
Double-Cropped Soybeans	0	0	7.8	14.2
Full Season Soybeans	0	2	7.8	14.2
Flue-Cured Tobacco	76	64	79.3	137.8
Wheat	110	96	13.8	26
Wake County				
Conventional Grain Corn	140	120	25.8	65.8
No-Till Grain Corn	140	127.5	25.8	65.8
Fescue (Hay)	150	60	0	9.3
Fescue (Pasture)	79	77	4.7	66.2
Double-Cropped Soybeans	0	0	0.5	2.7
Full Season Soybeans	0	1.6	0.5	2.7
Flue-Cured Tobacco	NA	NA	64.5	165.9
Wheat	105	100	3.1	22.3

Table 3-12. Simulated Fraction Applied by Month for the Baseline and UNRBA Study Periods

Agricultural Land Use	February	March	April	May	June	July	August	September	October	November, December, January
Conventional and No-Till Grain Corn	0	0	0.3	0	0.7	0	0	0	0	0
Fescue (Hay)	0	0	0.25	0.25	0	0	0	0.25	0.25	0
Fescue (Pasture)	0.045	0.045	0.5	0.045	0.045	0.045	0.5	0.045	0.045	0.045
Double-Cropped Soybeans	0	0	0	0	0	0	0	0	0	0
Full Season Soybeans	0	0	0	0	1	0	0	0	0	0
Flue-Cured Tobacco	0	0	0	0.25	0	0.75	0	0	0	0
Wheat	0	0.7	0	0	0	0	0	0	0.3	0

Table 3-13. Typical Planting and Harvest Schedules Assumed for the Baseline and UNRBA Study Periods		
Agricultural Land Use	**Planting**	**Harvesting**
Conventional and No-Till Grain Corn	March - May	August - October
Fescue (Hay)	September	April - November (2-3 cuttings)
Fescue (Pasture)	Growth Ongoing	None
Double-Cropped Soybeans	May 20 - June 30	November - December
Full Season Soybeans	May 20 - June 30	November - December
Flue-Cured Tobacco	April - May	August - September
Wheat	September - November	June

3.3.2 Developed Land

Pervious surfaces such as lawns within developed land use classes also receive nutrient application to support plant growth. Less information is available to develop the modeling assumptions for these areas because the owner types and individual preferences and practices vary widely (homeowners, institutions, parks, etc.). Fortunately, two publications that included local homeowner surveys are available to provide a reasonable starting point for model development for these types of areas.

The local communities surveyed for homeowner practices related to fertilization are Durham County (Fleming 2013) and Cary (Osmond and Hardy 2004). While Cary is not in the watershed, it is nearby and provides additional insight into homeowner practices within the general area. Both publications indicate that approximately one-half of homeowners do not apply fertilizer, one-fourth apply it themselves, and one-fourth use a contractor. Fleming (2013) also included an evaluation of fertilizer use by lot size and report that smaller lots tend to over apply fertilizer and larger lots apply less.

Fleming (2013) also indicates that cool season grasses like fescue are generally fertilized at the correct time of year but warm season grasses are not. Osmond and Hardy (2004) found neither to be timed correctly. The correct time for cool season grasses according to Osmond and Hardy (2004) is September, November, and February, but homeowners often apply in February, March, and April, and often the full annual application during a single application. Warm season grasses should receive fertilizer in May, June, July, and August, but they tend to be fertilized in March, April, September, October, and November. Based on these publications, the Falls Lake watershed model was developed with initial assumptions that applications to developed land uses occur in February, March, April, September, October, and November. Ten percent of the application was assumed applied in November with the other five months each receiving 18 percent of the annual application.

Of those that apply fertilizer, Fleming (2013) found that lot size was a good predictor of application rates. WARMF model inputs for existing development were adjusted within the ranges provided by Fleming (2013). Because new development rules went into effect in 2012 that require stormwater treatment (e.g., wet ponds, bioretention, etc.), the nutrient application rates to new development were scaled down to generate areal loading rates similar to those required by the Falls Lake Rules (2.2 pounds of nitrogen per year and 0.33 pounds of phosphorus per year). The WARMF model cannot simulate individual stormwater control measures by land use category, so the fertilizer application rates were adjusted to account for the net effect of all loading sources and stormwater control measures that are required. For nitrogen, because of the contribution from atmospheric deposition, homeowner application rates had to be set to zero to simulate the effects of the stormwater control measures. For phosphorus, application rates to new development were set to one-half those of existing development. Nutrient application rates for interim development were based on the averages of existing development and new development. There are approximately 700 acres of new development in watershed based on the timing of construction and number of grandfathered developments present in the 2015 to 2018 modeling period. Interim development comprises approximately 650 acres in the watershed. These are very small areas relative to the 770 square mile watershed, so the assumptions for fertilizer application to new development and interim development do not significantly impact model calibration.

Osmond and Hardy (2004) also reported typical nitrogen application rates for DOT rights of way; average rates are relatively low because not all right of ways are fertilized. For DOT rights of way, potassium and phosphorus application rates were estimated using ratios of nitrogen, phosphorus, and potassium provided by Fleming (2013) for low intensity development.

Rates applied to developed open space are highly uncertain as some areas likely apply high rates (like golf courses) and others apply little to none. There are approximately 43,000 acres of developed open space in the watershed.

Table 3-14 summarizes the annual application rates to pervious acreages of each land use class. No distinction is made between the baseline and UNRBA study periods for the developed land uses rather the rates vary between existing, interim, and new development land use classes.

Table 3-14. Simulated Average Application Rates to Pervious Areas for Developed Land Uses in the Falls Lake Watershed

Developed Land Use	Nitrogen (lb/ac/yr)	Phosphorus (lb/ac /yr)	Potassium (lb/ac /yr)
High Intensity Existing Development[1]	61.8	21.9	8.7
Medium Intensity Existing Development[1]	41.8	18	7.6
Low Intensity Existing Development[1]	20.9	14	6.5
High Intensity Interim Development[2]	15.4	16.4	8.7
Medium Intensity Interim Development[2]	13.2	13.5	7.6
Low Intensity Interim Development[2]	10.5	10.5	6.5
High Intensity New Development[3]	0	11.0	8.7
Medium Intensity New Development[3]	0	9.0	7.6
Low Intensity New Development[3]	0	7.0	6.5
Developed Open Space[4]	2.1	0.4	6.5
DOT Right of Way[5]	8	1.4	2.5

1. *Rates for existing development are based on local homeowner surveys (Osmond and Hardy 2004, Fleming 2013). There are 18,600 acres of existing development in the model.*
2. *Rates for interim development are the average of those assumed for existing development and new development; there are 650 acres of interim development in the model.*
3. *New development loading rates were reduced to simulate the net effect of stormwater control measures and result in loading rates similar to those required by the Falls Lake Nutrient Management Strategy. There are 700 acres of new development in the model.*
4. *Rates applied to developed open space are highly uncertain as some areas likely apply high rates (like golf courses) and others apply little to none. There are approximately 43,000 acres of developed open space in the watershed.*
5. *Osmond and Hardy (2004) also reported typical nitrogen application rates for DOT rights of way; average rates are relatively low because not all right of ways are fertilized. For DOT rights of way, potassium and phosphorus application rates were estimated using ratios of nitrogen, phosphorus, and potassium provided by Fleming (2013) for low intensity development. There are approximately 13,000 acres of DOT right of way in the model.*

3.3.3 Summary of Nutrient Application Model Inputs

The acreages of agriculture and development at the county level were multiplied by the nutrient application rates reported for the baseline period (2005 to 2007) and UNRBA study period (2015 to 2018).

These estimates indicate that application of nitrogen to agricultural areas has decreased from 7.5 million pounds per year in the baseline period to 3.6 million pounds per year in the recent period. Phosphorus application to agricultural areas has decreased from 1.2 million pounds per year in the baseline period to 0.7 million pounds per year in the recent period. These reductions in nutrients applied to agricultural areas are due to 1) decreases in production acres (from approximately 89 thousand acres to approximately 50 thousand acres) and 2) reductions per acre of nutrient applied for several crops. Nutrient application rates to agricultural areas were provided by the NCDA&CS and are applied based on the nutrient uptake needs of each crop. Crops are then harvested and the nutrients contained within the harvested crops are removed from the system.

The acreage of developed areas has not changed as significantly as the acreage for agriculture. Under the baseline period, there were approximately 72 thousand acres of developed areas with approximately 53 thousand of these assumed pervious. For the UNRBA study period, there were approximately 76 thousand acres of developed areas with approximately 56 thousand of these assumed pervious. Simulated nutrient application to developed areas apply only to the pervious acreages. Simulated total nitrogen application rates to developed areas increased from approximately 660 thousand pounds per year to approximately 700 thousand pounds per year from the baseline period to UNRBA study period. Simulated total phosphorus application rates to developed areas increased from approximately 200 thousand pounds per year to approximately 220 thousand pounds per year.

3.4 Onsite Wastewater Treatment Systems

The WARMF model simulates loading from onsite wastewater treatment systems as a discharge from the treatment system (septic tank and drainfield if applicable) to either the subsurface, the land surface, or a stream. To simulate onsite systems in the Falls Lake watershed, estimates of system type, location, and failure rates are required to build the model input files.

3.4.1 Data to Assign System Types and Counts

The Falls Lake Nutrient Management Strategy required local governments to develop inventories (counts and types) and to characterize the load reduction potential for the onsite disposal of wastewater. These inventories were due by January 2013 and included information on the system types, level of functionality, and average failure rate in the watershed for each county. The UNRBA Modeling Team used these 2013 inventories to assign the failure rates by system type for the modeling except for Wake County which provided updated information. While efforts across the watershed have been made to address failures, the 2013 inventories are the most recent from which to estimate failure in most of the counties.

In addition to these inventories, the local governments maintain current records of parcel-level system locations and types, repairs and maintenance, connections to centralized wastewater treatment systems, etc. These records exist in a variety of formats with differing levels of historic data and system type data. Some counties maintain spatial databases and others track them in tax records. The Modeling Team used the local records provided from each county to estimate the locations and system types in each modeling catchment. In counties where spatial data were not available, researchers at the NC Collaboratory provided estimates of location by overlaying the residential parcels with the area not served by sewer. Where system type was not recorded, the ratio of system types listed in the 2013 inventories for that county was applied.

DWR also assisted with the simulations of onsite wastewater treatment in two ways. First, DWR provided a spatial database of State-permitted discharging sand filter systems and a list of non-permitted discharging sand filter systems that have received notices of violation for lack of permit. These data were used to account for discharging sand filter systems in terms of location and counts. The Modeling Team coordinated with county staff to ensure that these systems were not double counted as some counties included these State-permitted systems in their database and others did not. Second, DWR assisted the UNRBA with approval of an EPA 319 grant to modify the WARMF model code so that several types of onsite wastewater treatment systems could be simulated with varying effluent concentrations and discharge layers (subsurface, land surface, or discharge to stream). This work is described in the 319 Project Final Report (Appendix B).

The UNRBA extends its thanks to staff at each jurisdiction, DWR, and the researchers funded through the NC Collaboratory who helped develop the model inputs associated with onsite wastewater treatment.

The UNRBA extends its thanks to staff at each jurisdiction, DWR, and the researchers funded through the NC Collaboratory who helped develop the model inputs associated with onsite wastewater treatment.

A brief description of the data available by county, supplemented by DWR, is provided below and summarized in Table 3-15. Figure 3-10 shows the approximate location of the systems in the watershed permitted by either the counties or the state. Table 3-16 summarizes the failure rate assumptions and sources of information by system type and county.

- Wake County provided a spatial database at the parcel level of onsite wastewater treatment systems and types that includes systems permitted by the county as well as by the State (discharging sand filter systems) through August 2020. Failure rate estimates were provided by the County in email communication with the Modeling Team (personal communication to Alix Matos from Nancy Daly, December 23, 2020).
- Durham County provided a spatial database at the parcel level of onsite wastewater treatment systems and types that includes systems permitted by the county as well as by the State (discharging sand filter systems) through 2014. Durham County staff provided updated spreadsheets for new operational permits for years 2015 to 2018 to align with other counties. Failure rates by system type were provided in the 2013 Durham County inventory.
- Orange County provided a spatial database at the parcel level of onsite wastewater treatment systems and types that includes systems permitted by the county from 1986 to June 2018. Spatial data provided by the State for the State-permitted discharging sand filter systems were added to the county data to capture State-permitted systems. Researchers at the NC Collaboratory provided the locations of systems based on overlaying residential parcels with sewer service areas. This data was used to determine the locations of older systems that are not included in the County's database, and these older systems were assumed conventional type systems as suggested in the 2013 Orange County Inventory. Failure rates by system type were also provided in the 2013 Orange County inventory.
- Person County provided a spatial database at the parcel level of onsite wastewater treatment systems that represents the total number of systems in the watershed through July 2019. Information about system type is not included in this database, so the State's database on permitted systems was used to estimate the location of discharging sand filter systems. Other systems in Person County were assumed conventional systems, and the total number of systems was kept constant at the county-provided estimates (i.e., the types were adjusted but the total counts were not). Failure rates by type were applied from the Person County 2013 inventory for onsite wastewater treatment systems. Person County maintains spatial records of system repairs as part of a county grant program, and these were factored into the catchment level estimates of failing systems as an update to the 2013 inventory. In order to apply the failure rates by type for conventional systems (either gravity-based or pressure-dosed),

estimates of these types were generated by applying the ratios of these two system types to the total number of conventional systems using data from the 2013 inventory.

Person County's inventory also included failure rate data by system age with systems less than 30-years old having an average failure rate (weighted by number of systems) of 3.3 percent and systems older than 30 years having a weighted average failure rate of 23.4 percent. While the Modeling Team does not have data regarding system age to apply these failure rates across the watershed, this does suggest that repair programs targeting older systems may provide the most benefit to improve water quality.

- Granville County maintains information regarding presence of onsite wastewater treatment systems in the tax records, but not in a format that allowed for efficient extraction by the Modeling Team. Through his work under the NC Collaboratory, Guy Iverson at East Carolina University developed a parcel level database using 2020 parcel data and information on sewer service area to estimate which parcels are served by onsite systems. This database of total onsite systems was then compared to the State's database of permitted discharging sand filter systems to determine the number of systems that are either conventional or discharging sand filters. To estimate the number of conventional systems that are either gravity-based or pressure-dosed for the purpose of applying the 2013 Granville County failure rates by type, the ratios of these two system types reported in the 2013 inventory were applied to the number of conventional systems.
- Franklin County maintains a database of onsite systems installed since 2004. Because the watershed model needs to include all active onsite wastewater treatment systems, the spatial estimates developed by Guy Iverson at East Carolina University were used. This database of total onsite systems was then compared to the State's database of permitted, discharging sand filter systems, to determine the number of systems that are either conventional or discharging sand filters. The Franklin County 2013 inventory did not include information about gravity-based versus pressure-dosed systems, so all conventional systems were assumed gravity-based. The Franklin County 2013 inventory indicated that no malfunctions were detected in their survey of 61 onsite systems, but three deficiencies were noted. The assumed malfunction rate for Franklin County was estimated at 4.9 percent (3/61) to provide a comparable estimate to the failure rates applied to the other counties.

Table 3-15. Summary of Data Sources Regarding Location and Types of Onsite Wastewater Treatment Systems in the Falls Lake Watershed

Type of information	Wake	Durham	Orange	Person	Granville	Franklin
Parcel-level location data	County provided both county and state permitted systems		County provided county permitted systems since 1986. State database was used to locate state-permitted systems. Locations of systems installed prior to 1986 were based on estimates from NC Collaboratory researchers	County provided all parcels served by onsite systems	NC Collaboratory researcher provided	
System type	County provided		County and State provided	State databased was used to identify discharging sand filter systems; all others were assumed conventional which were divided into gravity or pressure-dosed using ratio of systems reported in 2013 county inventory		State databased was used to identify discharging sand filter systems; all others were assumed conventional, gravity-based systems
Failure rate by system type	County provided updated values	2013 county inventories were used				

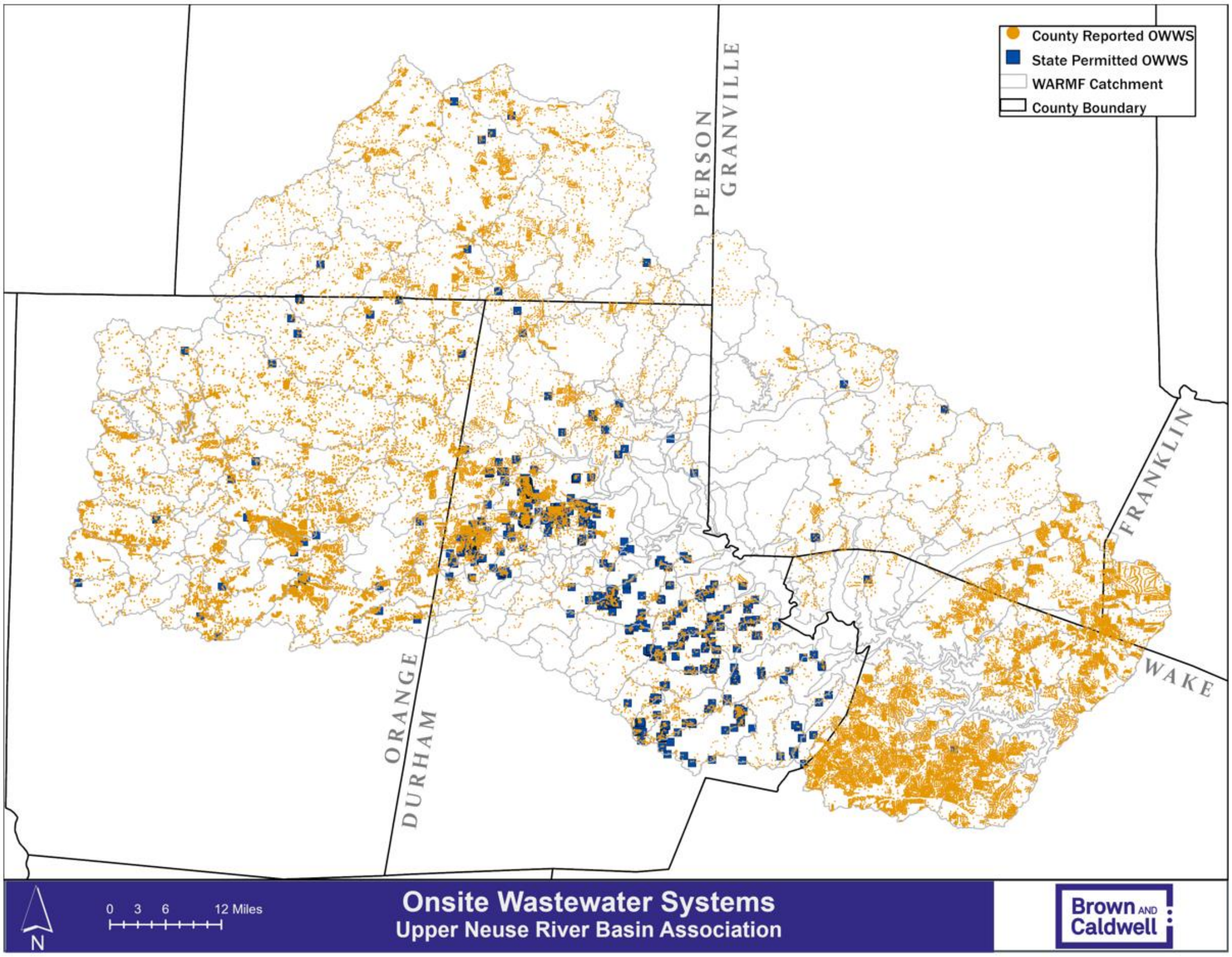


Figure 3-10. Location of Onsite Wastewater Treatment Systems in the Falls Lake Watershed for the UNRBA Study Period

Table 3-16. Summary of Failure Rates for Onsite Wastewater Treatment Systems in the Falls Lake Watershed as Reported in 2013 County Inventories with Updated Values Provided by Wake County

Category[1]	Durham	Orange	Person	Granville	Franklin	Wake
Type II	9.5%	6.2%[2]	10.7%[4]	6.2%[5]	4.9%[6]	7.0%
Type III	6.1%	6.2%[3]	5.6%	6.2%[5]	Not applicable	7.0%
Type IV	15.8%	5.7%	Not applicable	Not applicable	Not applicable	7.0%
Type V	0%	8.7%	0	Not applicable	Not applicable	7.0%

[1] Other system types not included in this table do not have separate modeling categories for functioning and malfunctioning systems. Type II systems are conventional, gravity-based systems. Type III are conventional, pump systems which require inspection at least every five years. Type IV are advanced treatment systems with pressure dispersal systems which require inspection at least every three years. Type V are advanced treatment systems with a sand filter pretreatment step which require inspection at least every 12 months. Descriptions and requirements for these types are provided in the Sanitation Rules 18A.1900 (North Carolina Onsite Wastewater Rules (ncpublichealth.com)).

[2] Not reported; assumed 6.2% based on reporting for all reported system types combined.

[3] Weighted average failure rate reported for Type III-B and Type III-G systems.

[4] Weighted average failure rate reported for Type II and Unknown systems.

[5] Weighted average failure rate reported for all systems.

[6] Zero failures were reported; estimated failure rate based on number of deficiencies reported and total systems inspected.

3.4.2 Development and Summary of Model Inputs

After the raw data was processed to determine the locations, types, and status of systems (malfunctioning or not), the types were aggregated into modeling categories. For example, a functioning Type II or Type III conventional system is assumed to discharge to the subsurface with the same effluent water quality (i.e., presence of a pump in a Type III system does not affect the discharge concentrations). While the failure rates for Type II and Type III systems may differ, once the system is categorized as functioning or malfunctioning, it can be grouped with other conventional systems of similar status. Researchers at the NC Collaboratory provided input on these categories as part of their 319 project to support the UNRBA in development of model inputs associated with onsite wastewater treatment. The following modeling categories for onsite wastewater treatment systems were assigned:

- Privy – all Type I systems were assigned to this category. There are very few in the watershed, and there is no designation of functionality. These systems assume raw wastewater discharged to the subsurface.
- Conventional, functioning, subsurface discharge systems – includes all functioning Type II, Type III, and those listed in county databases as "unknown" or "suspected septic systems"
- Conventional, malfunctioning, subsurface discharge systems – includes malfunctioning Type II, Type III, unknown, and suspected septic systems (estimated based on failure rates).
- Advanced treatment, functioning, subsurface discharge systems, single family – includes functioning Type IV and V systems. In the Falls Lake watershed, 95 percent of the advanced systems are Type IV which must meet the requirements for TS-II systems specified in 15A NCAC 18A .1970. These types of systems are inspected and monitored for performance annually by certified operators; if issues are detected they are repaired as soon as possible. Based on input from the NC Collaboratory Researchers and their review of available monitoring studies, advanced systems improve nitrogen concentrations but have little impact on phosphorus concentrations (personal communication, Charlie Humphrey, November 23, 2020), so these were set the same as conventional, functioning systems.
- Advanced treatment, malfunctioning, subsurface discharge systems, single family – includes malfunctioning Type IV and V systems estimated from county failure rates for these system types. Failures for these types of systems vary and can result in effluent concentrations ranging from

functioning to malfunctioning conventional systems depending on what part of the system fails and where it is in the treatment process. For the purposes of modeling, the values assumed for conventional failing systems are applied to this category.

- Advanced treatment, functioning, subsurface discharge systems, greater than 3,000 gallons per day – includes Type VI systems. These systems have a larger capacity but are assumed to have the same effluent concentrations and ranges as the single-family, functioning advanced systems. These systems are required to be inspected by County staff at least every 6 months (15A NCAC 18A .1970.) and there are few in the watershed; all are assumed functioning and meeting regulatory requirements because of the frequency of inspections.
- Single pass, sand filter discharging to land surface – includes Type VII systems. These are simulated in WARMF as point source discharges to land surface.
- Single pass, sand filter discharging to stream – includes systems listed in county databases as "DWQ," "suspected sand filter," "sand filter," Type VIII, or those permitted under NCG550000. These are simulated in WARMF as point source discharges to streams.
- Recirculating sand filter discharging to stream – includes those permitted under NCG570000 (only two are currently permitted in the watershed). Based on input from the NC Collaboratory Researchers and their review of available monitoring studies, recirculating systems improve nitrogen concentrations but have little impact on phosphorus concentrations (personal communication, Charlie Humphrey, December 7, 2020). These are simulated in WARMF as point source discharges to streams.

To estimate the number of systems present for the baseline period, the data provided by each county were used to "subtract out" systems with operational permits issued after 2007. Systems without a date were assumed present prior to the baseline period as record keeping has improved. For counties without spatial data, the number of systems simulated by DWR during development of their WARMF watershed model were used. Table 3-17 summarizes the counts by county for each category for the baseline period (2005 to 2007), and Table 3-18 summarizes this information for the UNRBA study period (2015 to 2018).

Researchers at the NC Collaboratory also provided input on system flow and median effluent concentrations based on past and current studies in Falls Lake watershed including the NC Collaboratory Year 1 Report (O'Driscoll et al., 2020), and other NC studies reported in the literature (Beavers and Tulley 2005, Bushman 1996, Christopherson et al. 2005, Gill et al. 2011, Gill et al. 2009, Harrison et al. 2000, Hu and Gagnon 2006, Humphrey et al. 2016, Humphrey et al. 2010, Iverson et al. 2018, Laaksonen et al. 2017, Lancellotti et al. 2017, Lowe et al. 2009, Mahoney 2016, O'Driscoll et al. 2020, O'Driscoll et al. 2019), and the USEPA (2002) report for onsite wastewater systems. The NC Collaboratory researchers received 319 grant funding to support the UNRBA's model development. The researchers (Guy Iverson, Charles Humphrey, and Mike O'Driscoll) met virtually with the modeling team on November 23, 2020, to review the available information and assign the median effluent concentrations associated with each modeling category (Table 3-19). Per capita water use for all single-family system types is 55.2 gallons/person/day, and median household size is assumed 2.5 people per home based on the 2019 US Census ((O'Driscoll et al., 2020)). Type VI systems by regulation have at least 3000 gallons per day discharged, and this flow rate was assumed for the modeling. Based on their review of monitoring studies, nitrogen speciation varies by system type as described in Table 3-19; total phosphorus is assumed 90 percent phosphate regardless of system type based on input from the NC Collaboratory researchers and available monitoring data.

The NC Collaboratory also funded a research study to evaluate treatment efficiencies and nutrient loading from onsite wastewater treatment systems to Falls Lake (O'Driscoll et al. 2020, Iverson et al. 2022 and 2023). Depending on the system type, system density, underlying soils, and surrounding land uses, the researchers found that the median N transport to the streams from the systems was 1.07 kg-N/person/yr (or 2.3 lb-N/person/yr), and the median attenuation rate for nitrogen between the system and the stream is approximately 76 percent with a range of 39 to 100 percent. For phosphate, there was greater attenuation between the onsite systems and the streams. It was estimated that the median per capita loading was 0.015 kg-PO4-P/person/yr (or 0.033 lb-P/person/yr) and an attenuation rate of approximately 99 percent, with a range of 68-100%. Additional attenuation would occur during transport in the stream and through impoundments and wetlands, and these processes are accounted for in the WARMF watershed model as is the attenuation in the soils between the system and stream.

Table 3-17. Summary of Counts by Modeling Category for Onsite Wastewater Treatment Systems in the Falls Lake Watershed for the Baseline Period

Category	Durham	Orange	Person	Granville	Franklin	Wake	Total
Privy	1	6	0	0	0	1	**8**
Conventional, functioning, subsurface discharge	3,157	11,484	2,778	5,207	339	11,464	**34,429**
Conventional, malfunctioning, subsurface or discharge	321	756	334	341	17	859	**2,628**
Advanced treatment, functioning subsurface discharge, single family	103	237	0	0	0	144	**484**
Advanced treatment, malfunctioning subsurface discharge, single family	19	12	0	0	0	10	**41**
Advanced treatment, subsurface discharge, >3000 gallons per day	0	0	0	0	0	1	**1**
Single pass, sand filter discharging to land surface	0	26	0	0	0	0	**26**
Single pass, sand filter discharging to stream	695	29	0	0	0	0	**724**
Recirculating sand filter discharging to stream	0	0	0	0	0	0	**0**
Total	**4,296**	**12,550**	**3,112**	**5,548**	**356**	**12,477**	**38,339**

Table 3-18. Summary of Counts by Modeling Category for Onsite Wastewater Treatment Systems in the Falls Lake Watershed for the UNRBA Study Period

Category	Durham	Orange	Person	Granville	Franklin	Wake	Total
Privy	1	7	0	0	0	1	**9**
Conventional, functioning, subsurface discharge	7,102	11,585	5,671	4,181	1,790	14,094	**44,423**
Conventional, malfunctioning, subsurface or discharge	708	763	634	278	93	1,057	**3,533**
Advanced treatment, functioning subsurface discharge, single family	631	235	0	0	0	163	**1,029**
Advanced treatment, malfunctioning subsurface discharge, single family	114	14	0	0	0	12	**140**
Advanced treatment, subsurface discharge, >3000 gallons per day	4	0	0	0	0	2	**6**
Single pass, sand filter discharging to land surface	0	26	0	0	0	0	**26**
Single pass, sand filter discharging to stream	996	60	8	4	0	2	**1,070**
Recirculating sand filter discharging to stream	2	0	0	0	0	0	**2**
Total	**9,558**	**12,690**	**6,313**	**4,463**	**1,883**	**15,331**	**50,238**

Table 3-19. Median Effluent Concentrations and Nutrient Speciation by Modeling Category for Onsite Wastewater Treatment Systems in the Falls Lake Watershed Developed with Input from the NC Collaboratory Researchers

Category	Total Nitrogen (mg-N/L)	Nitrogen Speciation	Total Phosphorus (mg-P/L) with 90% assumed PO4-P	Total Organic Carbon (mg-C/L)[1]
Privy/wastewater with no treatment	57.5	75% organic 25% ammonia	9.8	185
Conventional, functioning, subsurface discharge (accounting for attenuation in the soil treatment unit)	23.6	87% nitrate 7% organic 6% ammonia	0.29	18.4
Conventional, malfunctioning, subsurface discharge	42.6	61% ammonia 39% organic	6.86	185
Advanced treatment, functioning, subsurface discharge	16.2	77% nitrate 15% organic 8% ammonia	0.29	27.1
Advanced treatment, malfunctioning, subsurface discharge	42.6	61% ammonia 39% organic	6.86	185
Single pass, sand filter discharging to land surface	32.8	5% ammonia 89% nitrate 6% organic	4.31	22
Single pass, sand filter discharging to stream	32.8	5% ammonia 89% nitrate 6% organic	4.31	22
Recirculating sand filter discharging to stream	29.3	80% nitrate 10% organic 10% ammonia	4.31	22

[1] *Total organic carbon concentrations were estimated by scaling up the organic nitrogen concentration by 11.15 based on stoichiometric assumptions in the WARMF model regarding the composition of organic material.*

3.4.3 Local Government and Third-Party Review of Input Data

As noted in Sections 3.4.1 and 3.4.2, inventories of systems and failure rates were provided by the counties and State. Once the systems were assigned spatially to modeling categories, the data were aggregated to the county level and provided back to the counties for additional review. This process occurred iteratively with each county until the types and numbers matched the counties records. Researchers funded through the NC Collaboratory established the effluent concentrations associated with the system types, and these were used as model inputs.

3.4.4 Summary of WARMF Model Nutrient Inputs from Onsite Wastewater Treatment Systems

The WARMF model simulates onsite wastewater treatment systems in the Falls Lake Watershed as either point sources or one of several types of “septic” systems. Discharging sand filters and recirculating sand filters are simulated as point sources to either land surfaces or streams, depending on their type. In the baseline period, there were 750 sand filter systems in the watershed, and for the UNRBA study period there were 1,098 systems. Based on the number of systems, assumed people per household, and assumed discharging flow rates and effluent concentrations described in Section 3.4.2, the total nitrogen load discharged from these systems in the baseline period was 10,340 lb-N/yr and in the UNRBA study period was 15,134 lb-N/yr (46.4 percent increase). Total phosphorus loads from discharging sand filter systems increased from 1,359 lb-P/yr to 1,989 lb-P/yr (46.4 percent increase).

Other types of onsite wastewater treatment systems are simulated as one of several types of “septic” systems in WARMF ranging from privies to conventional to advanced treatment systems and including those assumed functioning or malfunctioning. In the baseline period there were 37,589 non-discharging systems and in the recent period there were 49,140 systems. The total nitrogen load released to the watershed from these systems in the baseline period was 392,933 lb-N/yr, and in the UNRBA study period was 514,518 lb-N/yr (30.9 percent increase). Total phosphorus loads released to the watershed from non-discharging systems increased from 11,987 lb-P/yr to 16,184 lb-P/yr (35.0 percent increase).

3.5 Watershed Impoundments

The Falls Lake watershed includes several impoundments situated along tributaries to Falls Lake (Figure 3-11). These impoundments affect the storage and hydrologic response of the watershed. These impoundments also can have significant impacts on water quality parameters. Some impoundments are used as water supplies. It is important to account for storage, flow routing, and withdrawals from impoundments as part of model development and calibration. Sources of information regarding bathymetry, withdrawals, and releases are summarized in Table 3-20. Appendix C provides the stage-area and stage-release curves used in the UNRBA WARMF Model for Falls Lake Watershed.

All but one impoundment in the watershed simulated releases using a stage-discharge curve. This simplifies the comparison of model scenarios that affect hydrology. However, the complexity of the operations at Little River Reservoir could not be accurately simulated in the model, so a time series of releases was developed using observed flows at the USGS gage downstream.

In addition to impacting storage and release of water, these impoundments also affect water quality through the physical and biogeochemical processes. Unfortunately, very little water quality data has been collected in the impoundments located upstream of Falls Lake. These impoundments likely exert a significant influence on both hydrology and water quality, though specifics are unknown due to the paucity of observational data. Model parameters were adjusted during model calibration based on observations at the next downstream water quality station monitored by the UNRBA and quarterly sampling conducted by USGS during the recent model period in Lake Michie, West Fork Eno Reservoir, and Little River Reservoir. The parameters used to calibrate the model include nitrification, denitrification, organic carbon decay, algae kinetics (growth, respiration, death, settling, decay), adsorption, water column diffusion, and sediment diffusion (further description in Section 6.4).

Table 3-20. Sources of Data Used to Characterize and Simulate Impoundments in the Falls Lake Watershed

Impoundment	Bathymetry Data (Stage-Area)	Water Supply Withdrawal Data	Simulation of Releases
Falls Lake	UNRBA bathymetric survey by Water Cube	City of Raleigh	In progress
Lake Butner (Lake Holt)	SGWASA provided data from a 1986 water supply capacity study	SGWASA	UNRBA WARMF Model Stage-Release Curve
Lake Michie	City of Durham Revised WARMF modeling files and lake operation manual	City of Durham	UNRBA WARMF Model Stage-Release Curve
Little River Reservoir	City of Durham Revised WARMF modeling files and lake operation manual	City of Durham	Specified as a time series based on USGS measurements observed downstream of the dam
Lake Orange	City of Durham Eno River watershed plan model	No withdrawals	Minimum releases specified as a time series plus UNRBA WARMF Model Stage-Release Curve for additional flows
Compton's Pond	Simulated as river reach	No withdrawals	Simulated as river reach
West Fork Eno River	City of Durham Eno River watershed plan model	No withdrawals	Minimum releases specified as a time series based on USGS measurements plus UNRBA WARMF Model Stage-Release Curve for additional flows
Lake Ben Johnson	Simulated as river reach	Town of Hillsborough	Simulated as river reach
Lake Rogers	Simulated as river reach	1997 withdrawals rates were scaled by population data reported by the US Census for 2000 and 2010.[1]	Simulated as river reach
Corporation Lake	Simulated as river reach	NC DEQ	Simulated as river reach
Teer Quarry	Offline impoundment	Offline impoundment[2]	Offline impoundment

1. *The 2003 Water Supply Plan for Lake Rogers (The Wooten Company, 2003) includes monthly withdrawals for 1997. These values were scaled by population to estimate monthly withdrawals for 2005, 2006, and 2007 assuming linear population growth between the 2000 and 2010 census data. Lake Rogers ceased use as a water supply in 2012 when SGWASA began to provide water to Creedmoor (Plewah and Richardson 2018).*
2. *Teer Quarry is an offline impoundment used as a source of water supply during emergency droughts. The quarry was used over a 59-d period during the 2007 to 2008 drought, but specific dates and volumes withdrawn are not available (AECOM 2018).*

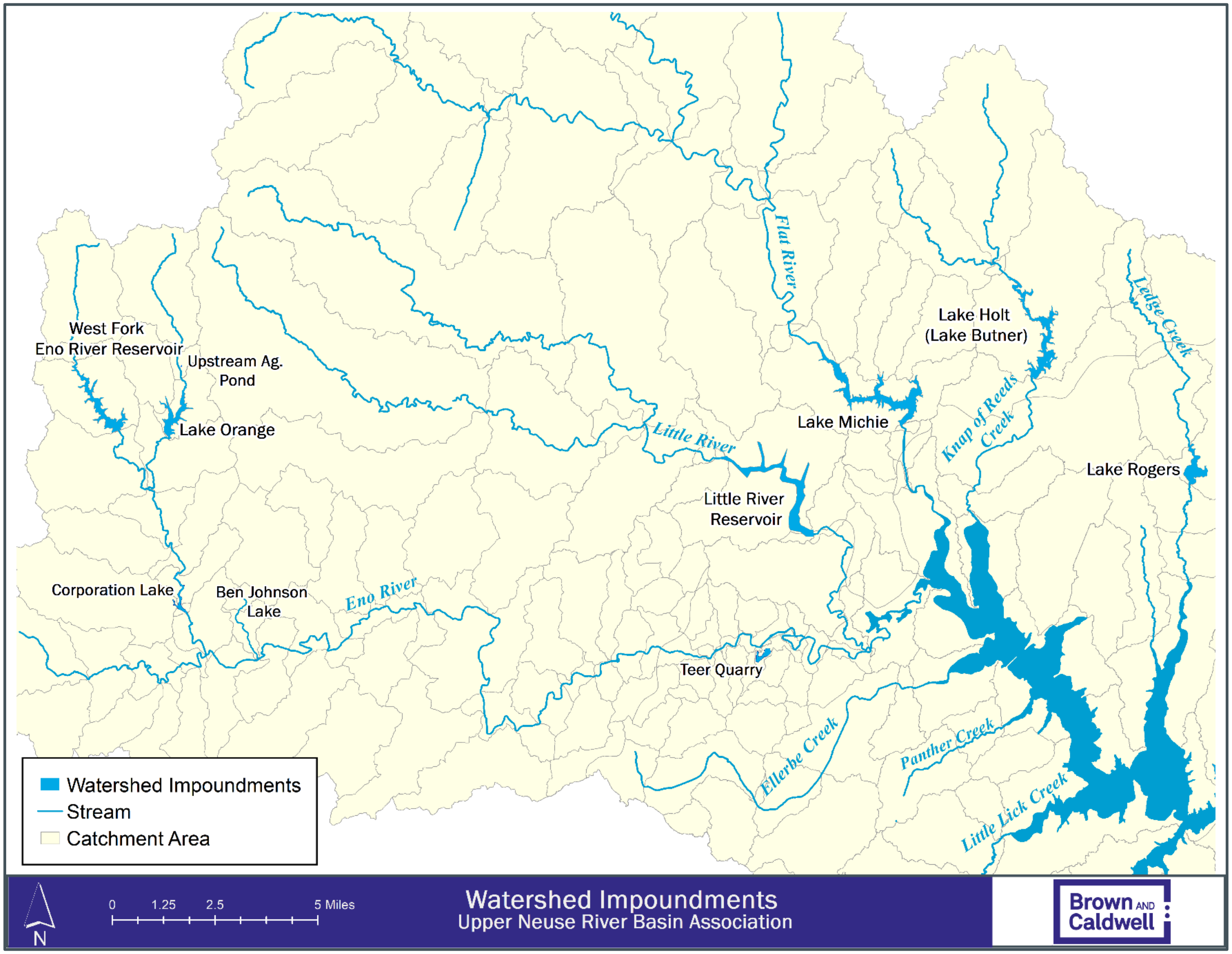


Figure 3-11. Impoundments within the Falls Lake watershed

Section 4

Time Series Model Inputs or Calibration Data

Once the model is configured and the watershed is characterized in terms of soils and land use, time series input files are used to either drive the simulations or to provide observations for comparison to model output. Time series model inputs include meteorological data, air quality data, discharges from wastewater treatment plants, sanitary sewer overflows, discharges from sand filter systems, and withdrawals and releases from impoundments. Stream discharge data from gaged sites are reported by the USGS, and this data is used to compare simulated stream flows to observations to calibrate the model and evaluate model performance. Calibration involves the adjustment of model parameters until simulated values match observations relatively well. The performance criteria for model calibration are specified in the UNRBA Modeling QAPP.

4.1 Meteorological Data

As described in the 2019 UNRBA Monitoring Program Report (BC 2019), nutrient loading to Falls Lake from the watershed is driven by flow in rivers and streams. Accurate meteorology inputs across the watershed, particularly precipitation, are needed to develop and calibrate accurate models to simulate pollutant loading to the reservoir.

Weather patterns are highly spatially variable. This variability is particularly impacted by watershed size and variation in topographic conditions within the watershed. Therefore, accurate simulation of natural hydrology and water quality starts with accurate and spatially representative meteorology inputs. Simulation results are improved by good weather station coverage across the watershed. Common sources of the meteorology data required by WARMF (precipitation, minimum temperature, maximum temperature, cloud cover, dew point, atmospheric pressure, and wind speed) are discussed in the following paragraphs.

Accurate weather inputs across the watershed, particularly precipitation, are needed to develop and calibrate accurate models to simulate pollutant loading to the reservoir.

4.1.1 Discrete Weather Measurements

Sources of discrete weather measurements include the NC Climate Retrieval and Observations Network of the Southeast (CRONOS) and Environment and Climate Observing Network (ECONet) Databases (both developed by the State Climate Office of North Carolina), USGS, NOAA, and the Western Regional Climate Center (WRCC). NOAA data (including NEXRAD radar data and Integrated Surface Hourly Data) is obtained through the National Climatic Data Center (NCDC). The NCDC is a clearinghouse for weather measurements that are collected at discrete locations by a variety of organizations across the United States.

Figure 4-1 shows the locations of each weather monitoring station in the watershed. Table 4-1 summarizes the parameters measured at each site and the period of record. Few stations include all of the required WARMF meteorology inputs, and many parts of the watershed do not have any weather stations. To provide better spatial coverage of meteorology inputs, additional sources of information (described in Sections 4.1.2 and 4.1.3) were evaluated and used to develop the model inputs. For the precipitation estimates during the baseline period, there were several missing records in the database. Discrete measurements were used to fill in these records as described in Section 4.1.4.

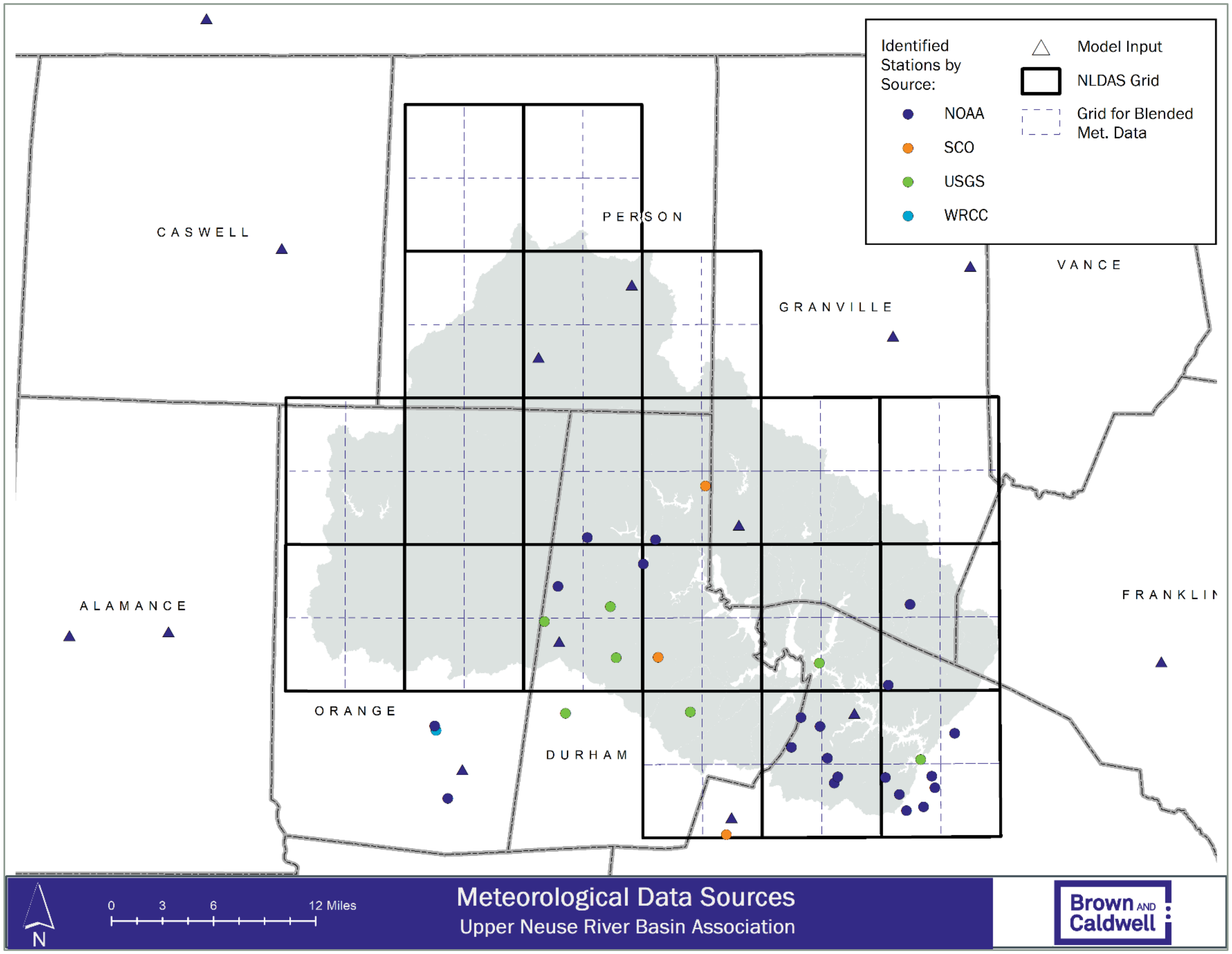


Figure 4-1. Locations of meteorological data sources

Table 4-1. Meteorological Stations in or around the Falls Lake Watershed

WARMF Model Inputs Observed	Source	Station Name	Station ID	Frequency	Years Included	Latitude	Longitude
Precipitation	USGS	FALLS LAKE ABOVE DAM NR FALLS, NC	02087182	Daily, Sub-hourly	1997-2018 2010-2018	35.9411	-78.5833
		BEAVERDAM CREEK AT DAM NEAR CREEDMOOR, NC	0208706575	Daily, Sub-hourly	2006-2018 2007-2018	36.0236	-78.6892
		RAINGAGE AT MAUREEN JOY CHARTER SCHOOL NR DURHAM	0355852078572045	Daily, Sub-hourly	2008-2018 2008-2018	35.9813	-78.956
		RAINGAGE AT LTL LICK CR AT NC HWY 98 OAK GROVE, NC	0355856078492945	Daily, Sub-hourly	2008-2018 2008-2018	35.9823	-78.8248
		RAINGAGE AT WEST MURRAY AVENUE AT DURHAM, NC	0360143078540945	Daily, Sub-hourly	2008-2018 2008-2018	36.0287	-78.9026
		RAINGAGE AT ENO RIVER NEAR HUCKLEBERRY SPRING, NC	0360334078584145	Daily, Sub-hourly	2008-2018 2008-2018	36.0594	-78.9780
		RAINGAGE AT ENO RIVER NEAR DURHAM, NC	0360419078543145	Daily, Sub-hourly	2008-2018 2008-2018	36.0721	-78.9087
	GHCN	DURHAM 9.1 NNE, NC US	US1NCDH0018	Daily	2010-2015	36.1085	-78.874
		DURHAM 10.7 NNE, NC US	US1NCDH0035	Daily	2014-2018	36.1292	-78.8611
		WAKE FOREST 8.2 NNW, NC US	US1NCGV0013	Daily	2017-2018	36.0734	-78.5939
		RALEIGH 10.3 N, NC US	US1NCWK0001	Daily	2007-2018	35.9696	-78.6887
		RALEIGH 6.8 NNE, NC US	US1NCWK0009	Daily	2007-2016	35.9114	-78.6058
		RALEIGH 7.2 N, NC US	US1NCWK0011	Daily	2007-2008, 2011-2012	35.9266	-78.6703
		WAKE FOREST 4.6 SW, NC US	US1NCWK0021	Daily	2007-2014	35.917	-78.5685
		WAKE FOREST 1.6 WSW, NC US	US1NCWK0025	Daily	2008-2013	35.9633	-78.5475
		RALEIGH 7.5 NNE, NC US	US1NCWK0036	Daily	2007-2014	35.926	-78.6205
		WAKE FOREST 4.2 SW, NC US	US1NCWK0037	Daily	2007-2016	35.9268	-78.5717
		RALEIGH 7.0 NE, NC US	US1NCWK0197	Daily	2015-2018	35.9007	-78.5805
		RALEIGH 6.2 NNE, NC US	US1NCWK0249	Daily	2017	35.8977	-78.5984

Table 4-1. Meteorological Stations in or around the Falls Lake Watershed							
WARMF Model Inputs Observed	Source	Station Name	Station ID	Frequency	Years Included	Latitude	Longitude
Precipitation, Temperature	GHCN	WAKE FOREST 5.9 WNW, NC US	US1NCWK0252	Daily	2017-2018	36.0047	-78.617
		GORMAN 7.2 SE, NC US	US1NCWK0255	Daily	2017-2018	35.9773	-78.7087
		BUTNER FILTER PLANT, NC US	USC00311285	Daily	2005-2017	36.1414	-78.7736
		GORMAN 9.3 NW, NC US	US1NCDH0013	Daily	2008-2009	36.131	-78.9329
		RALEIGH 8.4 N, NC US	US1NCWK0061	Daily	2008-2018	35.9425	-78.6812
		RALEIGH 6.9 N, NC US	US1NCWK0100	Daily	2011-2018	35.9214	-78.6741
		RALEIGH 9.6 NNW, NC US	US1NCWK0180	Daily	2014-2015	35.9519	-78.7189
		CHAPEL HILL 2 W, NC US	USC00311677	Daily	2005-2018	35.9086	-79.0794
		DURHAM, NC US	USC00312515	Daily	2005-2013	36.0425	-78.9625
		DURHAM 3 W, NC US	USC00312518	Daily	2005-2006	36.0894	-78.9636
		FALLS LAKE, NC US	USC00312993	Daily	2005-2018	35.9808	-78.6529
Precipitation, Wind Speed Temperature	LCD	RALEIGH AIRPORT, NC US	USW00013722	Daily	2005-2018	35.8923	-78.7819
		DURHAM 11 W NC US	WBAN:03758	Hourly, Daily, Monthly	2007-2018	35.9705	-79.0931
Precipitation, Temperature, Wind Speed, Wind Direction, Station Pressure, Dew Point Temperature,	LCD	ROXBORO_PERSON_CO_AIRPORT	WBAN:03722	Hourly, Daily	2006-2018	36.28472	-78.98417
		LOUISBURG FRANKLIN CO AIRPORT NC US	WBAN:03731	Hourly, Daily	2006-2018	36.02333	-78.33028
		CHAPEL HILL WILLIAMS AIRPORT NC US	WBAN:93785	Hourly, Daily, Monthly	2006-2018	35.93333	-79.06417
		RALEIGH AIRPORT NC US	WBAN:13722	Hourly, Daily	2005-2018	35.8923	-78.7819
Precipitation, Temperature, Wind Speed, Wind Direction, Relative Humidity, Pressure	WRCC	DUKE FOREST	NESS 326E9622	Daily	2000-2018	35.966667	-79.09167
	SCO	BUTNER CATTLE LABORATORY	BAHA	Hourly	2018	36.17492	-78.8086
		N. DURHAM RECLAMATION FACILITY	DURH	Hourly	2014-2018	36.02896	-78.85851
		REEDY CREEK FIELD LABORATORY	REED	Hourly	2004-2007, 2014-2018	35.80712	-78.74412
Above plus Level 1 through Level 3 Clouds	SCO	RALEIGH-DURHAM AIRPORT	KRDU	Hourly	2004-2007, 2014-2018	35.87764	-78.78747

U.S. Local Climatological Data (LCD); Western Regional Climate Center (WRCC); State Climate Office (SCO); Global Historical Climatology Network Daily (GHCND)

4.1.2 National Land Data Assimilation System (NLDAS) Data

Compared to the limited availability of discrete measurements described in Section 4.1.1, higher resolution data are available through the North American Land Data Assimilation System (NLDAS). The stated goal of the NLDAS is to, "construct quality-controlled, and spatially and temporally consistent, land-surface model (LSM) datasets from the best available observations and model output to support modeling activities. Specifically, this system is intended to reduce the errors in the stores of soil moisture and energy which are often present in numerical weather prediction models, and which degrade the accuracy of forecasts." (https://ldas.gsfc.nasa.gov/nldas/).

Because the coverage of weather parameters and locations in the Falls Lake Watershed is sparse in some areas, remote sensing data from the National Land Data Assimilation System (NLDAS) was downloaded to provide better spatial coverage. The NLDAS provides estimates of the meteorology parameters required by WARMF across a 1/8th-degree (approximately 8.6 miles) grid over central North America at hourly intervals. This data provides good coverage of the watershed.

In addition to providing high resolution data on an hourly basis, the NLDAS has the added benefit of providing estimates of other meteorological inputs that are not always monitored at NCDC weather monitoring stations including solar radiation and cloud cover. Section 4.1.4 summarizes the time series weather inputs used in the WARMF model for the two modeling periods based on the NLDAS: 2005 to 2007 and 2015 to 2018.

During their March 2018 meeting, the MRSW approved application of the NLDAS data to provide better spatial coverage of the necessary meteorological inputs for the WARMF model. The modelers confirmed that NLDAS provides accurate data for most weather parameters, but precipitation data required an alternative data source.

During their March 2018 meeting, the MRSW approved application of the NLDAS data to provide better spatial coverage of the necessary meteorological inputs for the WARMF model. The modelers confirmed that NLDAS provides accurate data for most weather parameters, but precipitation data required an alternative data source.

To determine the accuracy of NLDAS weather predictions and the applicability for developing the Falls Lake Watershed WARMF model, the air temperature and precipitation estimates generated by the NLDAS were compared to observations at NOAA weather monitoring stations. For this analysis, each NOAA weather station was paired with the closest NLDAS grid cell (Figure 4-1). Weather observations from NOAA were plotted against estimates from the NLDAS and a linear regression analysis was conducted. The R^2 values included in Table 4-2 indicate that the NLDAS predicts temperature on a daily basis well, with diurnal variability indicated by daily minimum and daily maximum values with R^2 values of 0.90 and 0.86 respectively. The NLDAS model does not appear to accurately predict daily precipitation. While substituting daily values with weekly or monthly averages improves the fit for precipitation, the accuracy is still relatively limited and other sources of spatially prevalent precipitation data were sought (Section 4.1.3).

Table 4-2. Comparison Of Simulated And Observed Temperature And Precipitation Values using NLDAS

Parameter	Basis	Season	R2
Min Temperature	Daily	Annual	0.90
Max Temperature	Daily	Annual	0.86
Precipitation	Daily	Annual	0.15

Table 4-2. Comparison Of Simulated And Observed Temperature And Precipitation Values using NLDAS

Parameter	Basis	Season	R2
Precipitation	Weekly	Annual	0.42
Precipitation	Weekly	Fall	0.61
Precipitation	Weekly	Spring	0.62
Precipitation	Weekly	Summer	0.56
Precipitation	Weekly	Winter	0.16
Precipitation	Monthly	Annual	0.67
Precipitation	Monthly	Fall	0.81
Precipitation	Monthly	Spring	0.53
Precipitation	Monthly	Summer	0.48
Precipitation	Monthly	Winter	0.76

4.1.3 NEXRAD (Next Generation Weather Radar) Precipitation Data

Based on comparisons to data collected at weather stations, the NLDAS generates good predictions of temperature that can be used in the WARMF model (Section 4.1.2). Because NLDAS is less accurate when it comes to estimating precipitation (see relatively low R^2 values listed in Table 4-2), an alternative source of precipitation data was used.

The NOAA operates the Next Generation Weather Radar (NEXRAD) system which is comprised of 160 regional-radar sites in the US. This radar data can be used (when processed for input) to generate precipitation estimates for specific locations at a finer spatial resolution than available through either the individual weather monitoring stations or the NLDAS.

The State Climate Office (SCO) of North Carolina uses the NEXRAD data to generate quality-assured estimates of precipitation at 6-hr increments. The spatial coverages of 6-hr precipitation and SCO-algorithms can be used to develop time series of precipitation anywhere in the watershed. The SCO uses these algorithms to support the NC DOT in their facility inspection program that requires inspections following rain events of certain amounts. During the Fall 2018 UNRBA Technical Stakeholder Workshop, staff at DOT offered to coordinate with the SCO on behalf of the UNRBA to use this approach to develop time series of precipitation for input to the WARMF model. The SCO provided the 6-hr precipitation data for both modeling periods at 78 locations in the watershed. These locations provide coverage at grid-cells that are approximately 2 miles by 2 miles. This approach provides a high degree of spatial resolution for use in watershed modeling.

The UNRBA MRSW approved the use of the 6-hr NEXRAD precipitation data at their March 2019 meeting. This data establishes the model time step for the UNRBA watershed and lake models. The UNRBA and their Modeling Team are grateful to the NC State Climate Office and NC Department of Transportation for supporting development of the watershed model with this high quality, spatially refined precipitation data.

The NEXRAD data were complete (except for one missing record) for the UNRBA study period (2015 to 2018), but there were 115 missing values in 2006 and 16 missing values in 2007. Figure 4-2 compares the NEXRAD annual precipitation totals at the 78 stations to observations based at Global Historical Climatology Network daily (GHCND) locations. The 2005 NEXRAD annual precipitation totals are generally less than the discrete measurements, even though no records are missing that year. The other years show better overlap with the top of the bars relative to the distribution of the discrete measurements (some locations are higher and some lower than the series of bars).

The UNRBA MRSW approved the use of the 6-hr NEXRAD precipitation data at their March 2019 meeting. This data establishes the model time step for the UNRBA watershed and lake models. The UNRBA and their Modeling Team are grateful to the NC State Climate Office and NC Department of Transportation for supporting development of the watershed model with this high quality, spatially refined precipitation data.

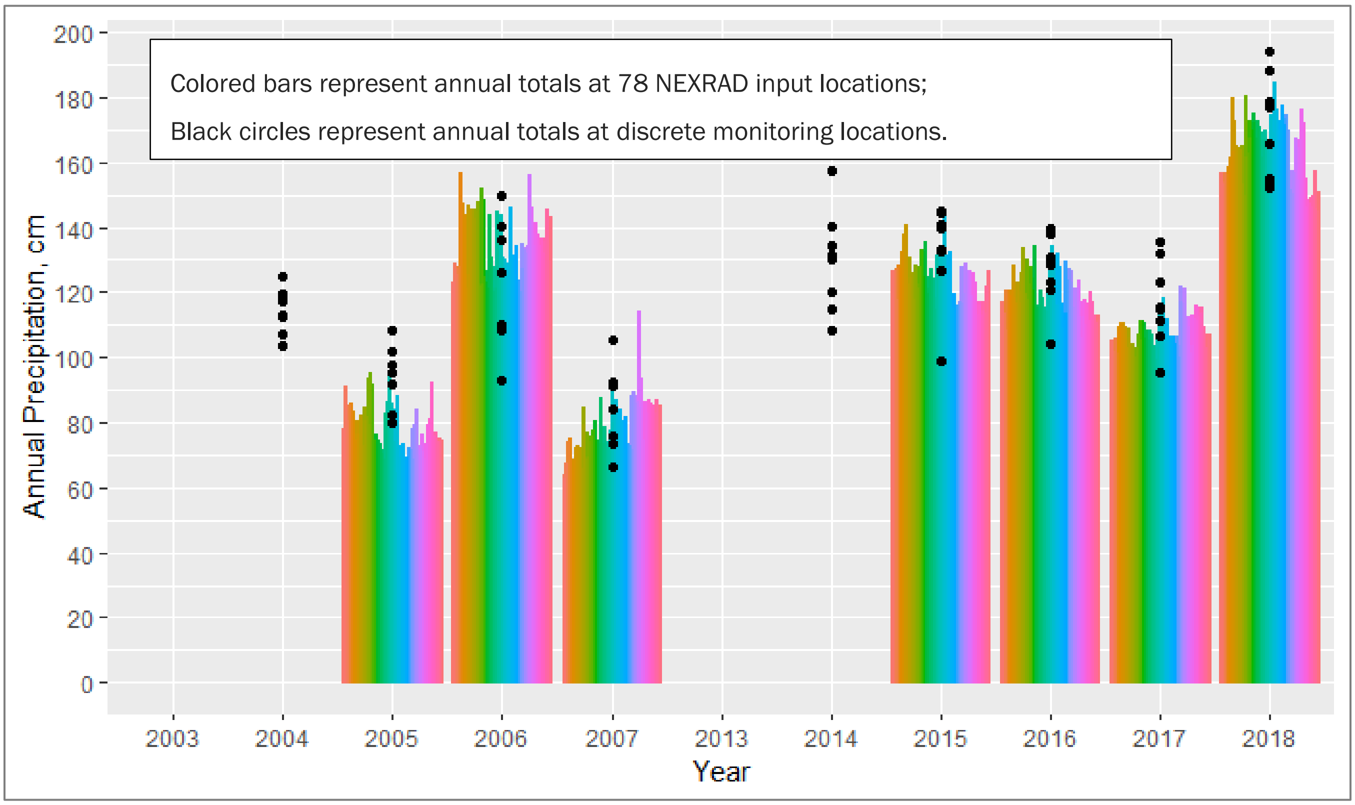


Figure 4-2. Comparison of Annual Totals at 78 NEXRAD Locations (colored bars) compared to GHCND Discrete Observations (black dots)

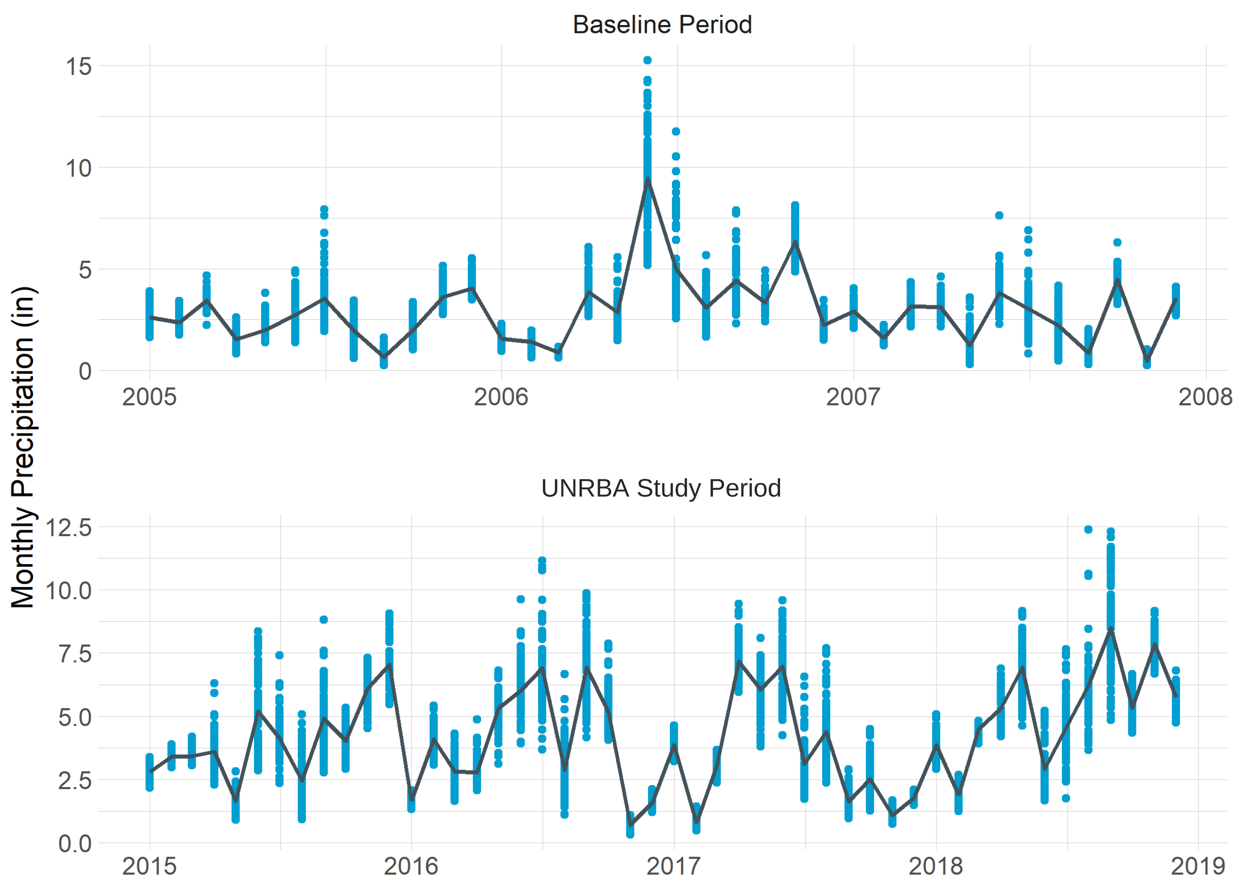


Figure 4-3. Comparison of Monthly Totals at 78 NEXRAD Locations (colored points) with the Monthly Average (black line).

Several of the months with relatively high precipitation totals included large storms such as hurricanes and tropic storms. Table 4-3 (from the UNRBA 2019 Annual Monitoring Report) provides a list of large storms that occurred in 2005 to 2007 (10 storms) and August 2014 to October 2018 (36 storms).

Table 4-3. NOAA Storm Summary for Counties around Falls Lake for 2005 to 2007 and August 2014 to October 2018

Month	Year	Type (Name or Rain Amount if Provided)[1]	Month	Year	Type (Name or Rain Amount if Provided)[1]
Jan	2005	Winter Storm	Sep	2016	Tropical Storm (Hermine, 3 to 5 inches)
Jun	2005	Flash Flood	Oct	2016	Flash Flood (Matthew, ~ 7 inches)
Jun	2006	Flash Flood (Alberto, ~7 inches at RDU)	Jan	2017	Winter Storm
Jul	2006	Flash Flood	Apr	2017	Flash Flood
Aug	2006	Flash Flood	Jun	2017	Flash Flood
Sep	2006	Tropical Storm	Jun	2017	Flash Flood
Nov	2006	Flash Flood	Sep	2017	Flash Flood

Table 4-3. NOAA Storm Summary for Counties around Falls Lake for 2005 to 2007 and August 2014 to October 2018

Month	Year	Type (Name or Rain Amount if Provided)[1]	Month	Year	Type (Name or Rain Amount if Provided)[1]
Nov	2006	Heavy Rain (2 to 4 inches)	Dec	2017	Winter Storm
Mar	2007	Flash Flood	Jan	2018	Winter Storm
Jul	2007	Flash Flood	Mar	2018	Winter Storm
Aug	2014	Flash Flood	Mar	2018	Winter Storm
Feb	2015	Winter Storm	Apr	2018	Flash Flood
Feb	2015	Winter Storm	May	2018	Flash Flood (3 to 5 inches)
Apr	2015	Flash Flood	Jul	2018	Flash Flood
Jun	2015	Flash Flood	Jul	2018	Flash Flood
Dec	2015	Flash Flood (up to 3 inches)	Jul	2018	Flash Flood (2 to 3 inches)
Dec	2015	Flash Flood	Aug	2018	Flash Flood
Jan	2016	Winter Storm (3 to 5 inches)	Aug	2018	Flash Flood (3 to 5 inches)
Feb	2016	Winter Storm	Sep	2018	Tropical Storm (Florence, 6 to 15 inches)
Jul	2016	Flash Flood	Sep	2018	Flash Flood
Jul	2016	Flood	Sep	2018	Flood
Jul	2016	Flash Flood	Oct	2018	Tropical Storm (Michael, 3 to 6 inches)
Aug	2016	Flash Flood	Oct	2018	Flash Flood

[1] *Amounts do not include snowfall.*

4.1.4 WARMF Model Meteorological Input File Development

Several processing steps were required to develop and format the meteorology input files using the available sources of data. The UNRBA Modeling QAPP (BC et al., 2018) specifies the following modeling periods for comparison to observed flows and water quality: historic comparison (2005 to 2007), calibration (2015 to 2016), and validation (2017 to 2018). For these seven years, the NEXRAD data provided by the SCO provide the precipitation inputs (with some filling of missing records required during the 2005-2007 time period) and the NLDAS data provide the other meteorological inputs (air pressure, dew point, temperature, etc.). A common practice for model development is to provide an initialization period (aka “spin-up”, “warm start”, etc.) that precedes the modeling years during which comparisons between simulated and observed data will be made. This initialization allows the model to reach equilibrium in terms of soil moisture content, lake water levels, etc., before simulating the focus period. For the two initializations years, 2004 and 2014, watershed-wide, 6-hr precipitation estimates were developed using the available GHCND stations. Additional details are provided below regarding the development of the meteorology input files for WARMF. These files end with the extension ".MET."

Blending NEXRAD and NLDAS - The 6-hr resolution of the NEXRAD data defines the magnitude of the time step for the WARMF watershed model being developed by the UNRBA. The SCO could not provide quality assured data at a smaller increment (e.g., hourly), and the MRSW and modeling team prefer to use quality-assured data when available. In order to develop meteorology input files across the watershed, the NEXRAD data (precipitation only) and NLDAS data (other required inputs) were blended to develop input files for 78 locations in the watershed.

Consistency of timestamps - The WARMF model uses time stamps associated with the starting time of each model time step. The NEXRAD data were provided with a time stamp associated with the end of the data interval. To match the WARMF convention, the length of the data interval (6-hours) was subtracted from each time stamp in the SCO data files to obtain a time stamp for the start of the data interval. When running on 6-hr time steps, WARMF uses fixed time-intervals starting at midnight (0:00), 6:00, 12:00, and 18:00. Precipitation provided by the SCO was aggregated to 6-hour time intervals beginning at 1:00, 7:00, 13:00, and 19:00. Meteorological parameters obtained from the hourly NLDAS data set and USGS stream discharge values were also aggregated to match the NEXRAD time steps of 1:00, 7:00, 13:00, and 19:00 so that all meteorological and hydrologic inputs are temporally aligned. To match the model input files to the fixed WARMF time intervals, the time stamps in the data files were shifted back 1 hour: the first time step of the day in WARMF (representative of midnight to 6:00 a.m.) actually corresponds to meteorological and hydrological data from 1:00 a.m. to 7:00 a.m. Without this one-hour shift, the WARMF model would compare simulated output from one 6-hr period to the next 6-hour period of observations. This one-hour discrepancy in the data provided by the SCO compared to the assumptions for the WARMF model is not expected to introduce significant uncertainty in the modeling since the hydrologic outputs are also compared to the same 6-hr average observations of flow.

Filling missing records - Input files for the non-precipitation parameters had no missing records for either the baseline or UNRBA study period because they are based on regional climate model output provided by the NLDAS. The NEXRAD precipitation dataset was complete for the UNRBA study period, but there were 115 missing values in 2006 and 16 missing values in 2007. Missing values were estimated using a spatially explicit interpolation of available precipitation gage data as described below.

Sub-daily precipitation data were downloaded for seven stations in and surrounding the upper Neuse River basin from the U.S. Local Climatological Data (LCD) dataset (https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00684).

For the Roxboro Person Co Airport location, precipitation values in the database for these years are stored with incorrect units and were appropriately transformed prior to using. (Precipitation reported in the records as hundredths of an inch are actually millimeters for this location; records from this station for the more recent period of 2014-2019 are correct and do not need to be transformed).

Precipitation data from these LCD stations were binned to six-hour intervals to match the aggregated NEXRAD data periods beginning at 1:00, 7:00, 13:00, and 19:00 daily.

Daily precipitation totals were obtained for an additional 7 locations in and surrounding the basin using the GHCND dataset. These seven stations report daily total precipitation starting and ending at 7:00 AM each day. Two other GHCND stations near but outside of the basin were excluded because their daily totals began and ended at 8:00 AM and were therefore difficult to match to both the stations with 7AM start times and the aggregated NEXRAD data which use 7:00 AM as one of their 6-hr breakpoints.

Precipitation at the daily stations was disaggregated to (i.e., divided into) the necessary 6-hour time steps using precipitation patterns observed at nearby stations with hourly data (using a spatially explicit inverse distance weighted interpolation of the proportion of daily rainfall that was received in each of the four sub-daily six-hour intervals for the seven stations with hourly estimates ("LCD stations")).

Finally, data for missing NEXRAD intervals (6-hour) were filled in as follows. For periods where all precipitation gages in the region reported zero rainfall, the missing values were filled in with zeros and commented in the WARMF .MET files using the tag “#zeroFill”. For missing periods when rainfall was recorded at one or more of the stations, missing values were estimated using precipitation patterns observed at nearby stations with hourly data (using a spatially explicit inverse distance weighted interpolation of the 6-hourly precipitation using data from all 14 stations (Figure 4-1)) and estimated values were commented in the WARMF .MET files using the tag “#IDW-LCD-GHCND” (meaning inverse distance weighted using data from the LCD and GHCND stations).

Developing inputs for initialization years - In addition to the model years specified in the QAPP, each period is preceded by one year to initialize the model. To generate precipitation inputs for 2004 and 2014, precipitation was estimated using daily totals derived from spatially weighted average precipitation from available daily gages in/around the basin from the GHCND (Figure 4-4). Seven gages were available to generate the 2004 precipitation record and nine were available for the 2014 record. The daily precipitation for these two initialization years was partitioned to 6-hr periods based on ratio of total daily precipitation received in each period at the Raleigh-Durham airport (closest station with a complete hourly dataset). If daily average precipitation was positive for the basin based on the spatially averaged measurements, but no precipitation was recorded at RDU, the daily total was spread evenly throughout the day. [Values in the *.MET files derived using this approach are indicated with the end-of-line comment "#GHCND-estimate."]

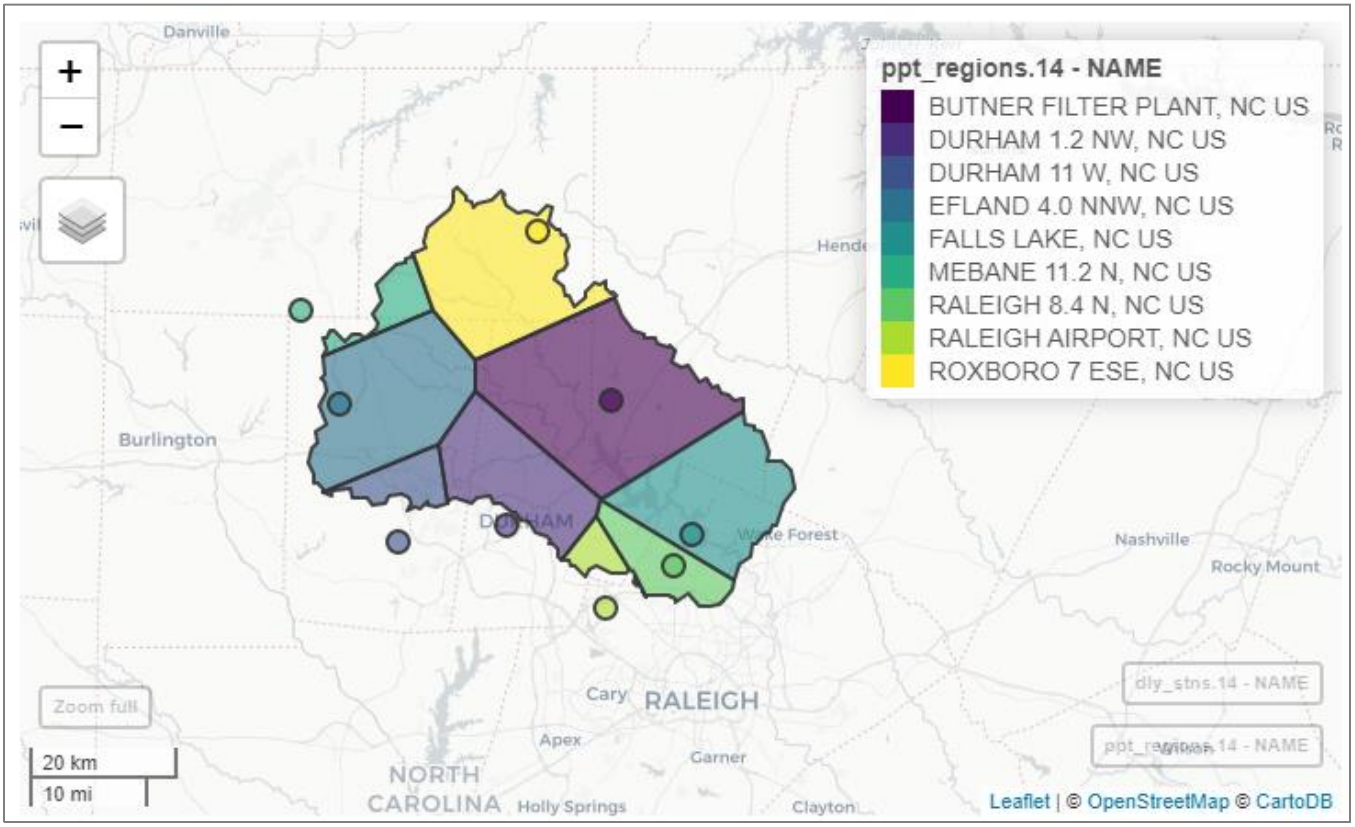


Figure 4-4. Spatial Averaging of GHCND Precipitation Stations to Develop Inputs for Model Spin-up Years (2004 and 2014)

4.1.5 Third-Party Review of Input Data

In late 2019, draft meteorological input files and notes regarding the processing steps were provided to Nathan Hall, a "third-party" reviewer of the UNRBA watershed modeling funded through the NC Collaboratory. Dr. Hall reviewed both the baseline and UNRBA study period meteorological input files with a focus on precipitation and large events exceeding 5 inches of rainfall in an 18-hour period in the NEXRAD data that have the potential to significantly impact nutrient loading to Falls Lake. Fifteen of the baseline rainfall events and forty-one of the recent period events were evaluated by comparing cloud cover data and rainfall data measured at the KRDU weather station downloaded from MesoWest. Following this review, Dr.

Hall noted uncertainty around the following large storm events; the other storms evaluated were consistent with cloud cover data and the rainfall gage at KRDU:

- Baseline period (2005 to 2007) to be potentially evaluated as a scenario and not to evaluate model performance:
  - June 15, 2006- The timing of the storm event associated with Hurricane Alberto occurs mostly on June 15, 2006, in the NEXRAD files but occurred on June 14th based on the rainfall gage at KRDU. The range of precipitation depth across the watershed was 0 to approximately 9 inches in the NEXRAD data and the depth measured at RDU was ~7 inches. This was a storm of long duration and the timing issue could be a result of when the rainfall bands affected the airport as opposed to other areas of the watershed. Nutrient loading to Falls Lake will likely not be significantly affected, but the timing of delivery could be.
  - July 5, 2006 –Average cloud cover based on the NLDAS input files was 0% and precipitation depth at RDU was 0.01 inches. This storm affects 9 out of 78 NEXRAD data files with the highest precipitation approximately 8 inches.
- UNRBA study period (2015 to 2018) used to calibration and validate the watershed model
  - June 19, 2017 – this storm affects 53 of the 78 NEXRAD data files with an average rainfall depth of 6.5 inches for the 78 files. No extreme weather events were reported by the NWS office in Raleigh and the measured rainfall at KRDU was approximately 0.1 inch. While most of the NEXRAD data across the watershed show a significant rainfall event, the NEXRAD location close to KRDU shows a negligible amount of rainfall.
  - July 21, 2018 - this storm affects 5 of the 78 NEXRAD data files with an average rainfall depth of approximately 1 inch for the 78 files and a maximum depth over 6 inches. No extreme weather events were reported by the NWS office in Raleigh and the measured rainfall at KRDU was approximately 0.01 inch. The NEXRAD location close to KRDU shows a negligible amount of rainfall.
  - August 2, 2018 - this storm affects 11 of the 78 NEXRAD data files with an average rainfall depth of 2.2 inches for the 78 files. No extreme weather events were reported by the NWS office in Raleigh and the measured rainfall at KRDU was approximately 0.26 inch. The NEXRAD location close to KRDU shows rainfall depth of approximately 8 inches.
  - August 19, 2018 – one NEXRAD file has a total precipitation over 10 inches within a 6-hour period. No extreme weather events were reported by the NWS office in Raleigh. Gaged precipitation at RDU for the 18 h period that spanned the 6 h NEXRAD accumulation period was 0.001 inches. The average NEXRAD estimate for the 78 data files for this period was 0.39 inches. This single NEXRAD file does not likely affect the watershed model significantly but could cause localized impacts in the simulation.
  - September 17, 2018 – this storm was not flagged as suspect by Dr. Hall but is included in this list of potential anomalies due to operation of the impoundments in the watershed. This extreme weather event was reported by the NWS office in Raleigh as rainfall from Hurricane Florence and gaged precipitation at KRDU 1.8 inches. The average NEXRAD estimate for the 78 data files for this period was 4.72 inches and rainfall greater than 2 inches was estimated in the vicinity of the KRDU gage. Average cloud cover for the period was 48%. In response to this storm, operators of impoundments were instructed to decrease water levels in the impoundments by 12 inches per day, and this led to very high stream flows. As the lake releases were operational in nature, and several of the impoundments in the watershed model are represented by stage-release curves, the stream flow peaks will be difficult to simulate accurately with the model.

The model input files for rainfall were not altered due to these uncertainties but these reviews help provide context about the model's ability to simulate stream flow when rainfall data is uncertain. There are also periods where the model underpredicts stream flows and storm hydrographs are not captured. This is likely due to the NEXRAD underpredicting rainfall or small "pop-up" storms that NEXRAD did not capture. Thus, sometimes NEXRAD likely underpredicts storms and sometimes it likely overpredicts storms. This may affect model performance in terms of predicting stream flows and water quality concentrations at specific points in time.

4.1.6 Summary of WARMF Model Inputs for Precipitation and Air Temperature

Precipitation and temperature are key drivers of watershed processes in terms of runoff response and biogeochemical reactions. These inputs were processed at 6-hr intervals consistent with the WARMF model time step. While 6-hr air temperature is relatively consistent across the watershed, precipitation can be highly variable. To summarize these 6-hr model inputs, Figure 4-5 displays the range of total monthly precipitation values using data from the 78 NEXRAD stations. In general, storms in the baseline period (2005 to 2007) were smaller and less frequent than those in the UNRBA study period (2015 to 2018) with the exception of June 2006 which included Tropical Storm Alberto.

Figure 4-6 presents daily temperature trends generated using data from the 40 NLDAS locations. Because average air temperature values are variable from day-to-day, identifying year-to-year trends can be difficult. To address this issue, locally estimated scatterplot smoothing (LOESS) was applied to the average NLDAS temperature values to help identify year-to-year temperature variability more easily during the baseline and modeling periods. In general, air temperature is more variable year-to-year during the winter and more consistent in the Spring, Summer, and Fall. However, it appears that an overall cooler summer was observed in 2004.

Appendix H includes additional information about the frequency of storms by size class and the resulting effects on delivered nutrient and carbon loads.

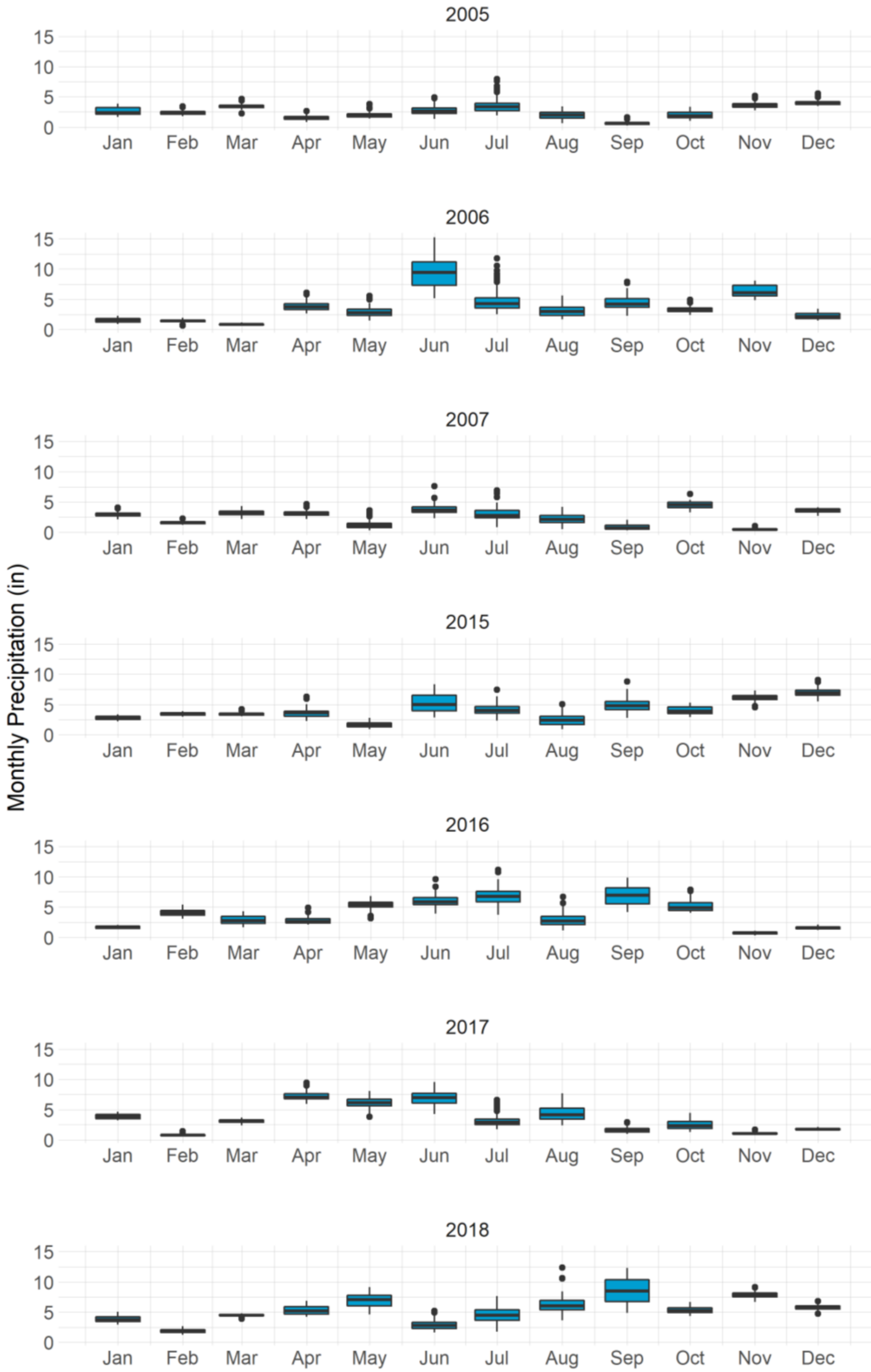


Figure 4-5. Boxplots Showing Distribution of Monthly Precipitation Totals at 78 NEXRAD Locations.

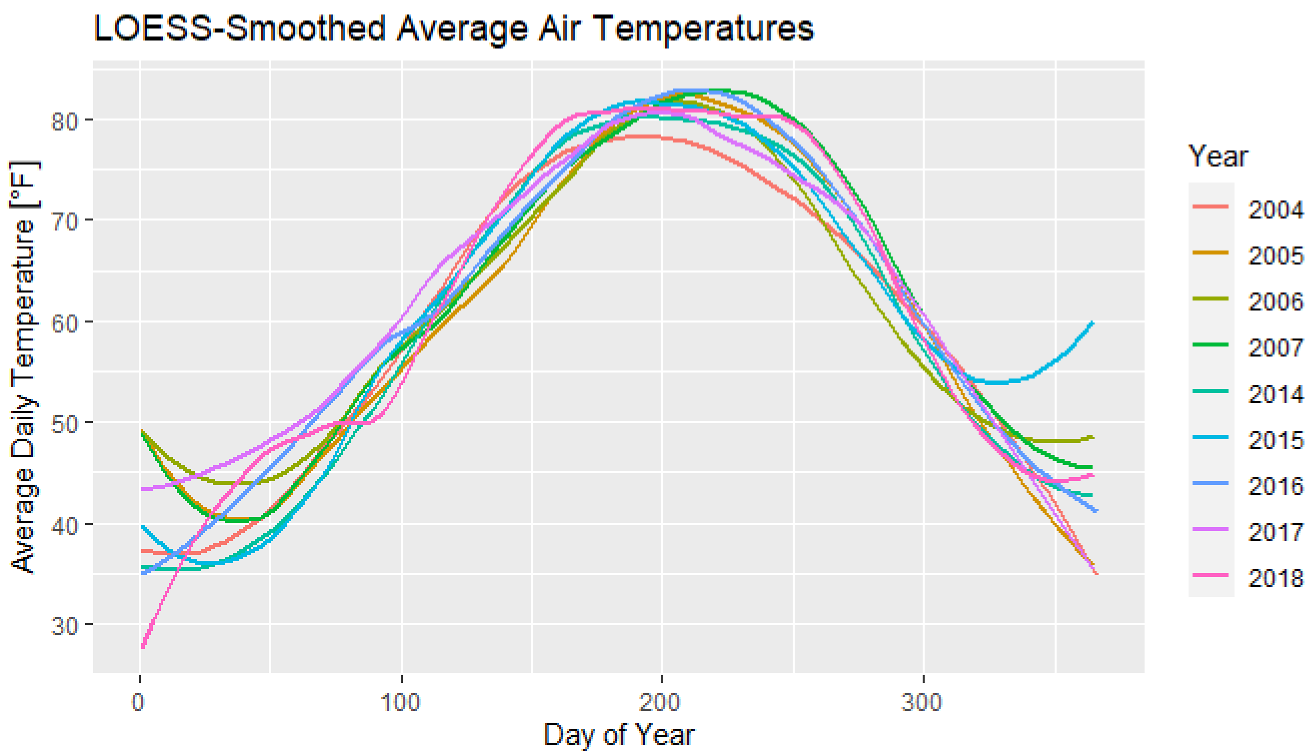


Figure 4-6. Comparison of the Average Daily Air Temperature Variation Across the Years Displayed LOESS Smoothed Trendlines.

4.2 Precipitation Chemistry and Air Chemistry

The air quality (dry deposition) and precipitation chemistry (wet deposition) data required by WARMF includes the concentrations of main constituents in the air (in µg/m³) and in rainwater (in mg/L). The dry and wet deposition data are typically available as mean weekly concentrations of calcium, magnesium, potassium, sodium, ammonium, nitrate, chlorine, sulfate, and phosphate. Dry deposition data sources also provide information on particulate nitrogen and sulfur oxides in addition to nitrate and sulfate.

4.2.1 Monitoring Data

USEPA Clean Air Status and Trends Network (CASTNET) measures the dry deposition of particles at 90+ site locations across the United States (http://www.epa.gov/castnet/data.html). Three of these stations are relevant to this modeling effort: Duke Forest (DUK008), Research Triangle Park (RTP101), and Candor (CND 125). Figure 4-7 illustrates the location of each of these CASTNET stations. The Candor site is the farthest away from the Falls Lake watershed, but it is the only one of the three sites that has remained active throughout the periods of interest (2005-2007, 2014-2018). RTP101 was discontinued in October 2008, and DUK008 did not begin collecting data until April 2017. Thus, the Candor site was used to simulate dry deposition for the Falls Lake watershed.

The National Atmospheric Deposition Program's National Trends Network (NADP-NTN) collects data for 263 sites in the United States, Puerto Rico, and the Virgin Islands. The Finley Farm NADP site (NC-41) serves as the source of wet deposition data for the WARMF model precipitation chemistry input. NC-41 is located roughly 20 miles south of the Falls Lake State Recreation Area, near the North Carolina State University campus. The site has been collecting weekly mean precipitation chemistry data since 1978, and therefore covers both modeling periods.

The CASTNet and NADP-NTN networks have been specifically designed to collect data to provide reliable measurements of air quality and precipitation chemistry across the United States. Dry and wet deposition rates are highly variable, however, and can be influenced significantly by local sources. Therefore, the national network's station locations have been specifically selected to estimate background atmospheric pollution concentrations, and do not provide details about how urban areas can affect the deposition of pollutants from local sources. Neither of the national networks measure the deposition of organic nitrogen, which can be a significant source of nitrogen in localized areas.

The City of Durham, NC recently investigated atmospheric deposition in the Falls Lake watershed to determine how local deposition rates may differ from estimates provided by the national networks and to evaluate the contribution of organic nitrogen to the total nitrogen load from atmospheric sources. The study revealed that dry deposition rates in the watershed are higher than the estimates provided by the national networks and that organic nitrogen comprised approximately 6 percent of the total nitrogen deposition (AMEC, 2012). The study also found that deposition rates are dependent on the amount of precipitation. The findings are based on approximately eighteen months atmospheric deposition data that was collected at multiple locations within the watershed.

Organic carbon in the atmosphere comes from anthropogenic and natural sources. Anthropogenic sources include fossil fuel combustion, biomass burning, domestic heating and cooking, tire and asphalt wear, solvent use, emissions from agriculture (such as pesticides), and natural gas exploration. While these sources are significant, the majority of atmospheric organic carbon comes from isoprene and monoterpene emissions from vegetation. Organic carbon data is not collected at the NADP or CastNET sites that were used to build the WARMF model of the Falls Lake watershed. However, it is necessary to include this parameter in the deposition inputs so that in-stream organic carbon numbers are reasonable - if deposition inputs are not considered, in-stream concentrations cannot be adequately calibrated. A monitoring study in Duke Forest near Chapel Hill, NC focused on organic nitrogen in atmospheric deposition as well as organic carbon deposition (Lin et al. 2010). This study conducted measurements in January and June 2007. Of the nitrogen concentration in PM2.5, organic compounds contributed approximately 33 percent. Concentrations of organic nitrogen were relatively low with an average of 0.16 microgram per cubic meter ($\mu g/m^3$), and concentrations of organic carbon 2.94 $\mu g/m^3$. For the WARMF model input, organic carbon deposition was estimated using measured nitrogen deposition with a scaling factor to account for the quantity of nitrogen produced by organic carbon decay in WARMF.

This assumption resulted in a simulated organic carbon concentration in dry deposition of 1.6 $\mu g/m^3$ which is less than that measured in Duke Forest in January and June 2007 (2.94 $\mu g/m^3$). A similar approach was taken for estimating the concentration of organic carbon in wet deposition (average of 0.9 mg/L); no monitoring data for wet deposition are available for comparison.

Phosphorus is not typically measured in wet or dry deposition chemistry data. The City of Durham monitoring study did not detect phosphorus in wet deposition and monitoring in dry deposition was beyond the scope of the study. Neither NAPD nor CASTNET data include phosphorus monitoring. A literature review by Tipping et al (2014) reported that a small amount of phosphorus in dry deposition occurs based on global data collected at 250 sites with 82 percent of the locations in Europe and North America. For the WARMF model, a constant phosphate air concentration of 0.424 $\mu g/m^3$ and depositional velocities from CASTNET were applied to estimate the rates of deposition to the watershed.

Figure 4-7 shows the locations of the CASTNET, NADP, and City of Durham monitoring locations that were used to develop the input files for WARMF. NCDEQ also monitors a few locations in the watershed for nitrate; this data was not used directly to build the model input files because other sources of nitrate data were available in combination with additional parameters, but it was used to verify the seasonal trends associated with atmospheric deposition. It also provided information regarding the high variability of nitrate in the air depending on proximity to roads and upwind sources.

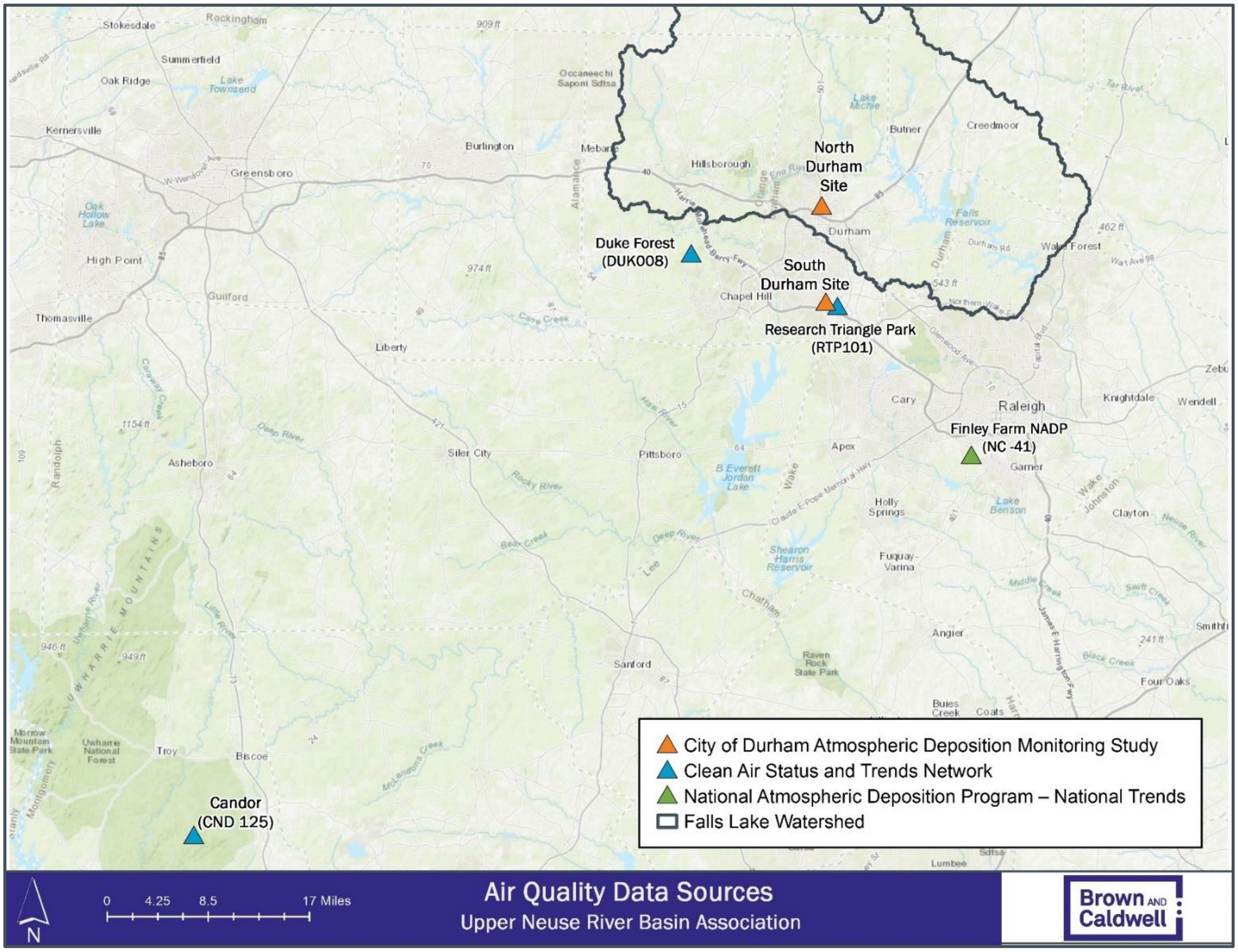


Figure 4-7. Air and Precipitation Monitoring Stations Used to Develop Input Files for the Falls Lake Watershed

4.2.2 Third-Party Reviews of Input Data

Dr. Nathan Hall was funded through the NC Collaboratory to provide "third-party" review of the UNRBA watershed model. His review included comparison of the raw data from CASTNET and NADP to the processed input files for WARMF. The purpose of this review was to establish that the nutrient concentration data gathered from the two monitoring programs was downloaded, reformatted, recalculated in units expected by the WARMF model, and interpolated correctly. Based on this review, a small degree of apparently random error for air nutrient concentrations during both modeling periods was detected. It was not clear what caused these small errors, but Dr. Hall concluded they were "very unlikely to result in any significant effects on model performance." Dr. Hall also noted that during mid-December 2005, the precipitation chemistry data were not available at weekly intervals, and that project documentation should note that the average of the nearest two values was used to create the daily input files, rather than the linear interpolation used on the weekly measurements.

Dr. Daniel Obenour was also funded through the NC Collaboratory to provide "third-party" review of the UNRBA models. To aid in his review of the atmospheric deposition inputs to the model, he and his graduate student, Kimia Karimi, compiled available information on nitrogen and phosphorus deposition rates for comparison. This compilation is useful for context and ensuring the WARMF simulations are reasonable. The values listed below should not be expected to match the WARMF model results for Falls Lake specifically because the references in Appendix D are from earlier periods and broader areas. The general findings are consistent with the WARMF model results. These reviews are provided in Appendix D with brief summaries below [text in brackets are additional notes based on the information provided]:

- Based on published maps, most of the atmospheric deposition of nitrogen in the Falls Lake watershed is of the oxidized form (e.g., nitrate), and rates of nitrogen deposition are approximately twice as high in urban areas as rural areas.
- Dry deposition of nitrogen comprises approximately 60 percent of the total deposition, and dry deposition rates of nitrogen have declined significantly since 2000 due to reductions in the oxidized components. Wet deposition of nitrogen is driven by precipitation amounts and tends to be higher in the spring and summer.
- Spatial models of nitrogen deposition are available for 2002 to 2014, and these show a high degree of spatial variability with the northern, rural parts of the watershed receiving 8-8.5 lb-N/ac/yr and the southern, urban parts of the watershed receiving 9.6-11.3 lb-N/ac/yr. [As these models are not available for the UNRBA study period used to calibrate and validate the UNRBA WARMF watershed model, spatially uniform rates of deposition were assumed across the watershed.]
- The median total, wet, and dry deposition of nitrogen are 10.9, 4.4, and 6.5 lb-N/ac/yr, respectively. [The total deposition and relative contribution from wet and dry deposition varies based on many factors including precipitation amount.]
- Phosphorus deposition is generally assumed to be minor relative to other sources and is usually not monitored by national studies like NADP.
- Phosphorus deposition is highly correlated to the amount of precipitation, and most phosphorus deposition occurs in wet form.
- Total phosphorus deposition studies across the US from the 1970s to the 2010s typically report values ranging from 0.045 to 0.45 lb-P/ac/yr. A 2012 study reported total phosphorus deposition in the Falls Lake Basin of 0.07 lb-P/ac/yr.

4.2.3 Summary of WARMF Model Inputs for Deposition of Nutrients

To build the model input files for WARMF, the weekly concentration data reported by CASTENT and NADP were directly converted to the WARMF file format without transformation for the baseline (2005 to 2007) and recent (2015 to 2018) modeling periods. In mid-December 2005, measurements were not at weekly intervals, and the nearest data points were averaged to fill in the input file. Assumptions for organic nitrogen and phosphate were based on data summarized by Lin et al. (2010) and Tipping et al (2014) as described in Section 4.2.1. The average deposition inputs to the watershed and Falls Lake are summarized in Table 4-4. A model for the baseline period has not been fully developed, so simulated loads from atmospheric deposition for that period are not yet processed; these can be reported later if the UNRBA chooses those years as a scenario to evaluate.

Table 4-4. Summary of Average Annual Total Deposition Rates to Falls Lake and its Watershed for the UNRBA study Period

Constituent	UNRBA study Period (2015 to 2018) (lb/yr)
Ammonia as N	2,142,686
Nitrate as N	1,088,936
Organic Nitrogen as N	451,391

Table 4-4. Summary of Average Annual Total Deposition Rates to Falls Lake and its Watershed for the UNRBA study Period	
Constituent	UNRBA study Period (2015 to 2018) (lb/yr)
Total Nitrogen	3,683,014
Phosphate as P	150,592
Organic Phosphorus as P	2,507
Total Phosphorus	150,592
Total Organic Carbon	5,036,502

4.3 Recorded Stream Flows for Hydrologic Calibration

4.3.1 US Geologic Survey (USGS) Data

The Falls Lake watershed includes 10 USGS stream gages that record instantaneous discharge (flow) in tributaries to Falls Lake. The model catchments include delineations to these gages for direct comparison to recorded stream flows for the purposes of calibrating the simulated hydrology. An additional stream gage located along the Neuse River below Falls Lake measures water level and flow as water is released from the dam. Table 4-5 and Figure 4-8 contain information about the amounts of and type of information each gage records as well as the location of each gage within the watershed.

Table 4-5. Active USGS Stream Flow Gages

Gage Number	Waterbody	Drainage Area (mi2)	Gage Name	Upstream Reservoir	Upstream Major WWTP	Earliest Available Daily Flow Data	Earliest Available Sub-Hourly Flow Data
02086849	Ellerbe Creek	21.9	Ellerbe Creek near Gorman, NC	No	Yes	1985-10-01	1985-10-01
0208675010	Ellerbe Creek	6.01	Ellerbe Creek near Durham, NC	No	No	2008-08-01	2008-08-01
02085000	Eno River	66	Eno River at Hillsborough, NC	Yes	No	1927-10-01	1985-10-01
02085070	Eno River	141	Eno River near Durham, NC	Yes	Yes	1963-09-01	2007-10-01
02086500	Flat River	168	Flat River at Dam near Bahama, NC	Yes	No	1927-09-01	1985-10-01
02085500	Flat River	149	Flat River at Bahama, NC	No	No	1925-08-01	2007-10-01
02086624	Knap of Reeds Creek	43	Knap of Reeds Creek near Butner, NC	Yes	Yes	1982-10-01	1985-10-01
0208521324	Little River	78.2	Little River at SR1461 near Orange Factory, NC	No	No	1987-09-30	1987-10-01
0208524975	Little River	98.9	Little River at Fairntosh, NC	Yes	No	1995-10-24	1995-10-24
0208524090	Mountain Creek	7.97	Mountain Creek near Bahama, NC	No	No	1994-10-01	1994-10-07
02087183	Neuse River	771	Neuse River near Falls, NC	Yes	Yes	1970-06-26	1985-10-01

It is important to note that the majority of reported USGS streamflow measurements are not made directly. Rather, a series of field measurements of stream flow and stream stage are made and used to define the relationship between stream discharge and water elevation (stage). This stage-discharge relationship is unique for each station and is used by USGS personnel to estimate discharge based on stage measurements which are recorded automatically. As USGS develops this stage-discharge relationship, they have to develop a line on the plot of stage vs. discharge that best describes (or fits) the relationship between the two parameters. There is data scatter around this line that highlights the fact that even with a stage-discharge curve, there is some variation around the “true” value of discharge at a certain stage. However, this is the established and accepted method for developing flow data at a gaged site. Based on literature including evaluations conducted by USGS staff (Westerberg 2016, Coxon 2015, Kiang 2018, Domeneghetti et al., 2012, and McMillan 2015 and 2017), uncertainty in stream discharge estimates is greatest in the extremes of the flow regime (both high and low), uncertainty can be considerable, and the magnitude of the uncertainty is related to site characteristics and the stability and consistency of these conditions (algae growth, erosion/deposition zones, cross-section characteristics, etc.) as well as general measurement errors. Figure 4-9 shows the field measurements from the past 20 years and the USGS flow rating curves for four example gages in the watershed. Ratings curves for the other gages are provided in Appendix E. There is a great deal of uncertainty with the estimated flows during low water levels, and field measurements of flow sometimes vary by an order or magnitude or more for very small changes in water level.

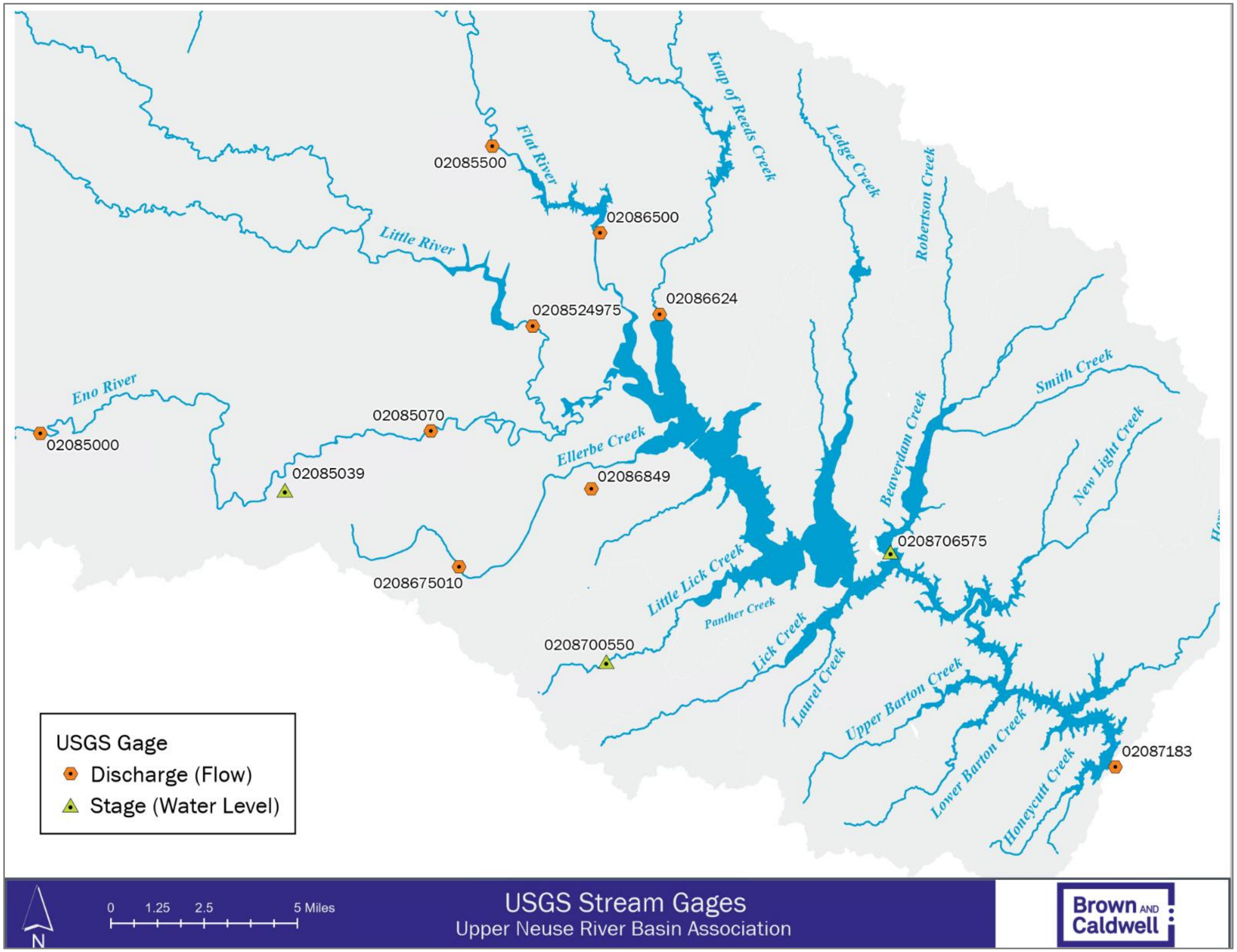


Figure 4-8. Locations of USGS Stream Flow Gages

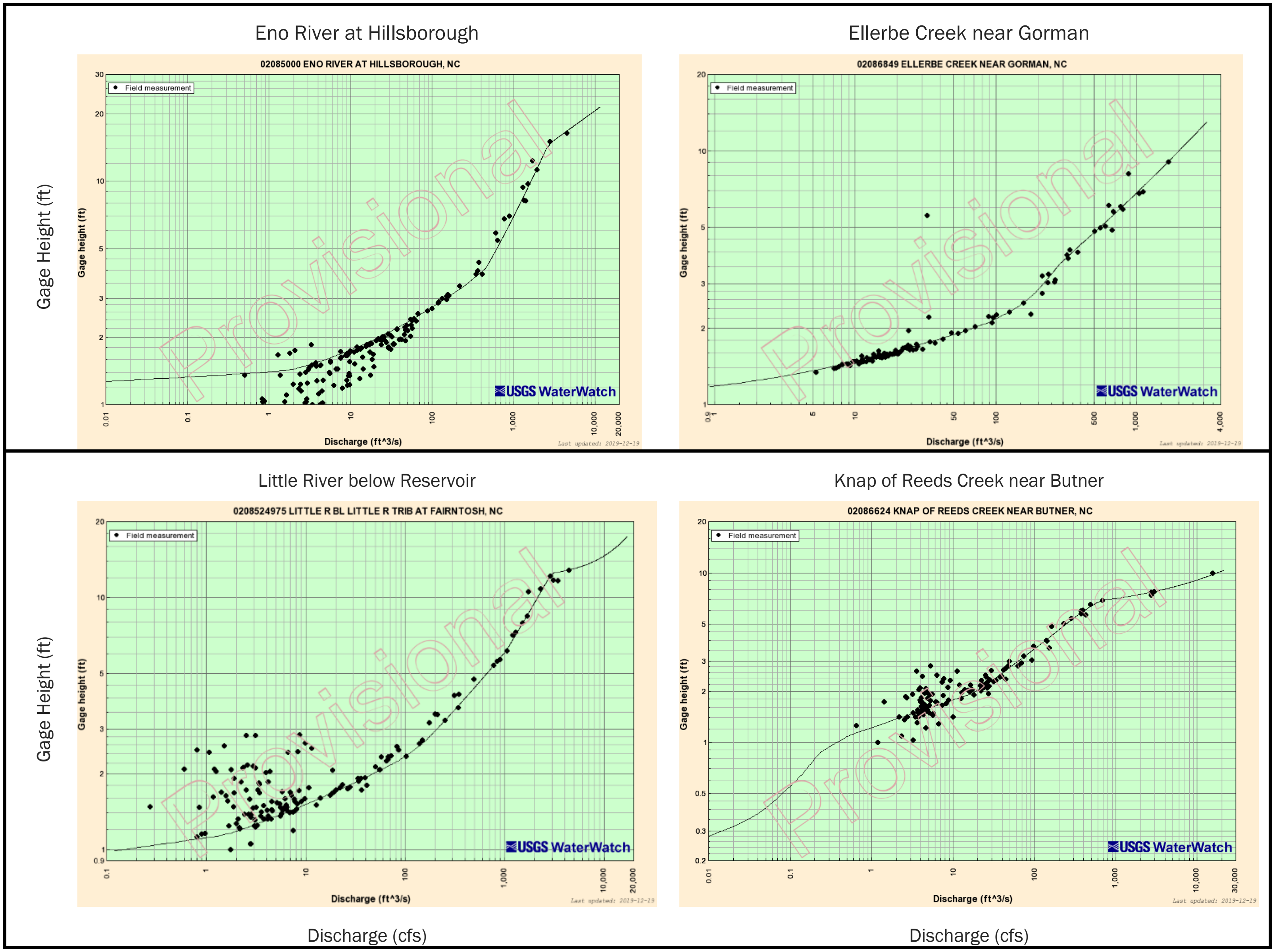


Figure 4-9. Rating Curves and Field Measurements for Several Gages in the Falls Lake Watershed; Figures downloaded from the USGS Data Portal

4.3.2 Flow Estimates for Ungaged Streams

The UNRBA Modeling QAPP specifies that performance criteria be evaluated for locations in the watershed with gaged stream flow estimates provided by the USGS. These gages are available in five drainages to Falls Lake (Eno River, Flat River, Ellerbe Creek, Little River, and Knap of Reeds Creek). There are 12 additional tributaries that flow directly into Falls Lake for which USGS gages are not available.

Previous statistical modeling was used to evaluate different methods of predicting flow to generate estimates at ungaged locations in the Falls Lake watershed (Cardno ENTRIX 2014 available at https://www.unrba.org/sites/default/files/news-files/FlowEstimationTM_March28_Final.pdf). Based on these analyses, basin proration provides relatively accurate estimates of flow if donor gages exclude those with upstream wastewater treatment plants or impoundments. This method scales a set of donor gages' flows based on the drainage area ratios among locations. Donor gages include Flat River above Lake Michie, Eno River at Hillsborough, Eno River near Durham, Little River above Reservoir, Mountain Creek, and Tar River near Tar River (USGS Gage 02081500).

The UNRBA Modeling Team compared simulated flows at the 12 ungaged tributaries to flow estimates using these donor gages to ensure that simulated flows were reasonable. While no performance thresholds were specified for these ungaged tributaries, the comparison indicates that 10 of the ungaged tributaries have simulated total volumes, peak flows, and high flows within +-25% of the estimates.

The two tributaries that are not within +-25% of the flow estimates are Lick and Little Lick Creeks. These two are more similar to the Ellerbe Creek watershed than the donor gages. They are within the Triassic Basin and include more urban development than the donor gages. The WARMF model predicts higher flows than the basin proration method which is based on gages located in less developed areas across various geologic basins. When an alternate gage on Ellerbe Creek above the wastewater treatment plant is used as the donor gage, then the WARMF model simulates lower flows than those estimated. However, the portion of the Ellerbe Creek watershed upstream of this gage is part of the most intensely developed area in the watershed, and storm flows are expected to be higher here. The WARMF model estimates are predicting flows between these two basin proration estimations.

Though there is not a direct comparison to recorded stream flows, the comparisons of WARMF simulated flows with basin proration estimates at each ungaged tributary confirms that the WARMF model is behaving as expected and simulating reasonable stream flows.

4.3.3 Third-Party Review of Calibration Data

Accurate processing of gaged stream flow data is critical to the watershed model calibration because it provides the basis for evaluating the hydrologic calibration. Dr. Nathan Hall was funded as a "third-party" reviewer of the watershed model by the NC Collaboratory. Dr. Hall evaluated the 6-hour processed stream flow calibration files based on raw data from the USGS gaged recorded in the baseline and UNRBA study period. His review noted errors on time stamps when flows were very large due to a failed "find and replace" operation that occurred when flows were sufficiently high to cause the flow value to touch the date value. His review also detected revisions to provisional data by USGS that occurred between the time the original model input files were developed and review occurred. Both of these items were corrected before the model files were finalized. Dr. Hall also noted some discrepancies between the processed flows during very low periods that were attributed to rounding differences between the processing methods used to either develop the model input files or review them. These differences were considered nonconsequential as they occurred during periods of low stream flows.

4.3.4 WARMF Model Flow Data

Figure 4-10 and Figure 4-11 display the average 6-hr stream flow at USGS gages in the watershed. These gages collected data approximately every fifteen minutes for the UNRBA study period. Six-hour averages are displayed rather than the 15-min data to improve readability and to correlate to the time step of WARMF modeling. The 6-hr stream flows were used to calibrate the watershed model for hydrology. Calibration includes the adjustment of hydrologic and hydrodynamic model parameters within acceptable ranges to result in simulated values similar to those measured.

For the 2005-2007 baseline period, daily average flows were often recorded by USGS. The discrepancy in model time step (6 hours), the resolution of the USGS flow data during this period (daily), and the substantial amount of missing precipitation data in the baseline period limited the ability to calibrate the model for the baseline period. Therefore, model performance was only evaluated for the UNRBA study period. Simulation of the baseline period will only be used as a scenario if selected by the UNRBA to compare to historic modeling and to provide a relative comparison between baseline and UNRBA study periods. This approach is consistent with the UNRBA Modeling QAPP which stated the baseline period would be used for historic comparison.

Model performance was only evaluated for the UNRBA study period. Simulation of the baseline period will only be used as a scenario if selected by the UNRBA to compare to historic modeling and to provide a relative comparison between baseline and UNRBA study periods. This approach is consistent with the UNRBA Modeling QAPP.

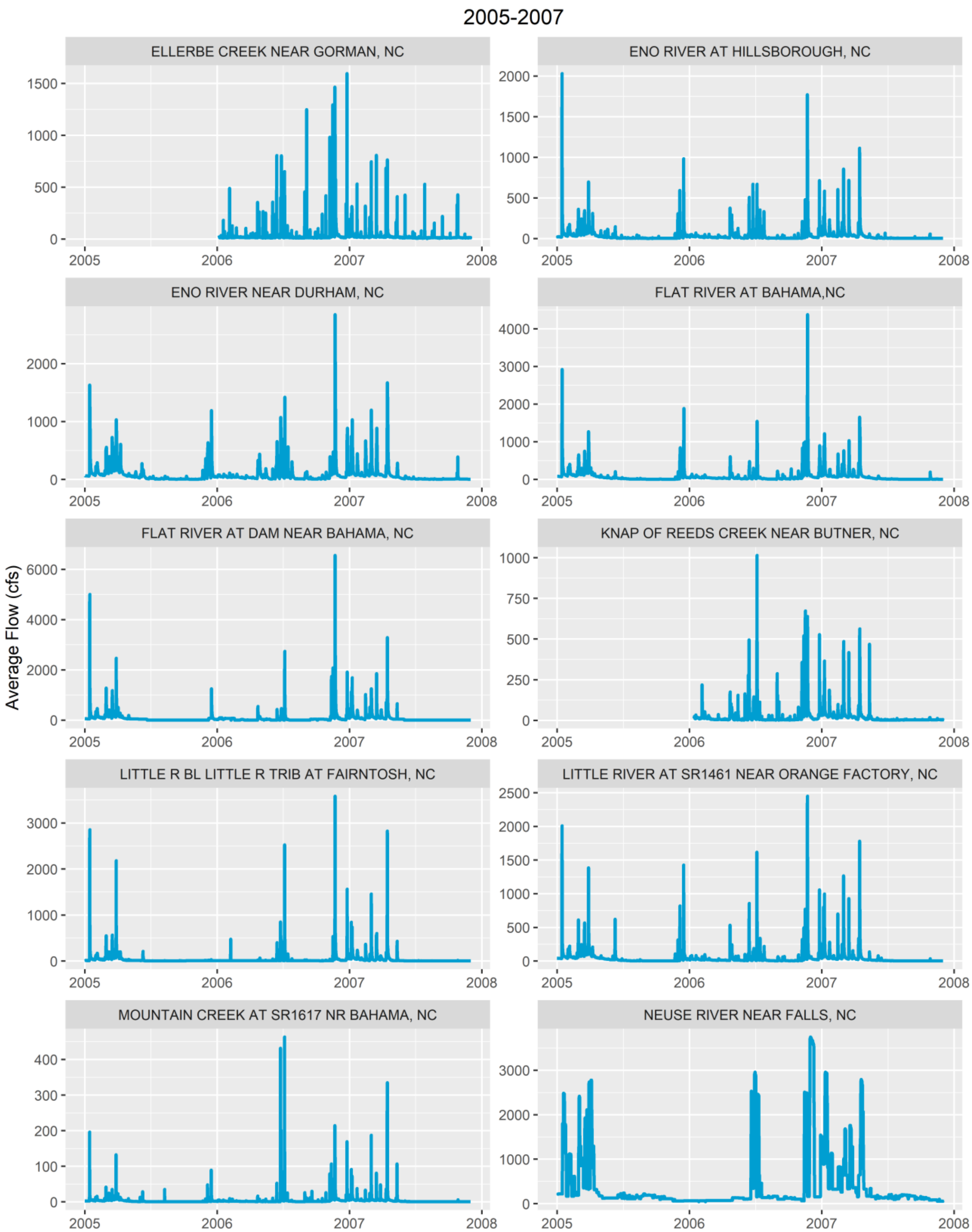


Figure 4-10. Average 6-hr stream flows for 2005 through 2007

Figure 4-11. Average 6-hr stream flows for 2014 through 2018

4.4 Water Quality Data to Support Model Calibration

Water quality monitoring locations in the watershed are shown in Figure 4-12, and the WARMF watershed modeling catchments were defined to include outputs at these locations for comparison to monitoring data. The UNRBA 2019 Annual Monitoring Report available at https://www.unrba.org/monitoring-program summarizes the data collection efforts associated with this program. The water quality calibration results for the WARMF watershed model provided in Section 6.4 display this data for comparison to WARMF simulated parameters. It should be noted that laboratory measurements are themselves uncertain and reported concentrations should not be assumed exact.

The 2019 UNRBA Monitoring Report provides water quality data for the parameters analyzed under the program. Table 4-6 lists all the parameters collected as part of the UNRBA monitoring program along with their associated reporting limits, the number of field blanks (using deionized water) analyzed between 2014 and 2018, and the percentage of those samples with results above the nominal reporting limit. It also lists the 95th percentile of all field blank results which for ammonia and total phosphorus is higher than the reporting limit. These elevated values increase the likelihood that values reported below 0.03 mg/L (phosphorus) and 0.04 mg/L (ammonia) may not actually have phosphorus or ammonia present. However, at these low concentrations, the uncertainty associated with measurements would not likely affect nutrient loading to Falls Lake significantly.

Laboratory measurements are themselves uncertain, and reported concentrations should not be assumed exact

Table 4-6. Field Blank Concentrations Greater than the Reporting Limit

Parameter	N (Blanks)	N > RL	% > RL	95th Percentile Blank Concentration	Nominal Reporting Limit
Dissolved Organic Carbon, mg/L	46	-	0	< 1.0	1.0
Soluble Orthophosphate as P, mg/L	350	-	0	< 0.01	0.01
Total Organic Carbon, mg/L	169	-	0	< 1.0	1.0
Total Orthophosphate as P, mg/L	102	-	0	< 0.01	0.01
Volatile Suspended Residue, mg/L	79	-	0	< 2.5	2.5
Total Suspended Residue, mg/L	205	2	1	< 2.5	2.5
Chlorophyll-A, µg/L	99	1	1	< 1.0	1.0
Nitrate-Nitrite as N, mg/L	258	4	2	< 0.01	0.01
Total Kjeldahl Nitrogen as N, mg/L	258	4	2	< 0.2	0.2
Total Phosphorus as P, mg/L	253	30	12	0.03	0.02
Ammonia Nitrogen as N, mg/L	254	85	33	0.04	0.01

In addition to field blanks, the UNRBA Monitoring Program also evaluated field duplicates where two samples were collected at the same day and time on a fraction of the samples included in the program. From these duplicates, a confidence interval for each parameter can be calculated. Table 4-7 lists the 95th percentile confidence interval for the parameters evaluated under the UNRBA Monitoring Program as described in the 2019 UNRBA Monitoring Report. Ammonia and total phosphorus have the largest confidence intervals, particularly at lower concentrations. Using a measured ammonia concentration of 0.05 mg/L as an example, we are 95 percent confident that the true concentration in the sample is 0.05 +/- 69 percent, or falls between 0.016 mg/L and 0.084 mg/L. The time series figures that show WARMF simulated concentrations compared to water quality observations include bars to visualize the uncertainty associated with the water quality observations; the length of the bars corresponds to the 95th confidence intervals calculated for the entire UNRBA monitoring data set and do not reflect the specific confidence with individual measurements or data collected by other organizations.

Table 4-7. The Uncertainty and Expanded Uncertainty (95% Confidence Interval) Associated with the Collection of Field Duplicate Samples

Parameter	Measurement Range	Standard Uncertainty, u	Expanded Uncertainty, U (95% confidence level)
Chlorophyll-a, µg/l	1 - 20	10%	± 19%
	20 - 200	5%	± 9%
Dissolved Organic Carbon, mg/L	1.5 - 21	2%	± 3%
Total Organic Carbon, mg/L	1.6 - 21	2%	± 4%
Absorbance at 440nm, /cm	0.005 - 0.08	9%	± 18%
Absorbance at UV 254nm, /cm	0.07 - 0.9	4%	± 7%
Color (Apparent), CU	25 - 300	11%	± 21%
Ammonia Nitrogen as N, mg/L	0.01 - 0.06	35%	± 69%
	0.06 - 0.33	27%	± 54%
Nitrate-Nitrite as N, mg/L	0.01 - 0.2	9%	± 18%
	0.2 - 3.3	4%	± 8%
Total Kjeldahl Nitrogen as N, mg/L	0.2 - 0.8	13%	± 27%
	0.8 - 2.8	12%	± 23%
Total Orthophosphate as P, mg/L	0.01 - 0.25	7%	± 15%
Total Phosphorus as P, mg/L	0.02 - 0.31	22%	± 44%
CBOD5, mg/L	2 - 11	5%	± 10%
Total Suspended Solids, mg/L	2.5 - 190	17%	± 33%
Volatile Suspended Solids, mg/L	2.5 - 26	10%	± 21%

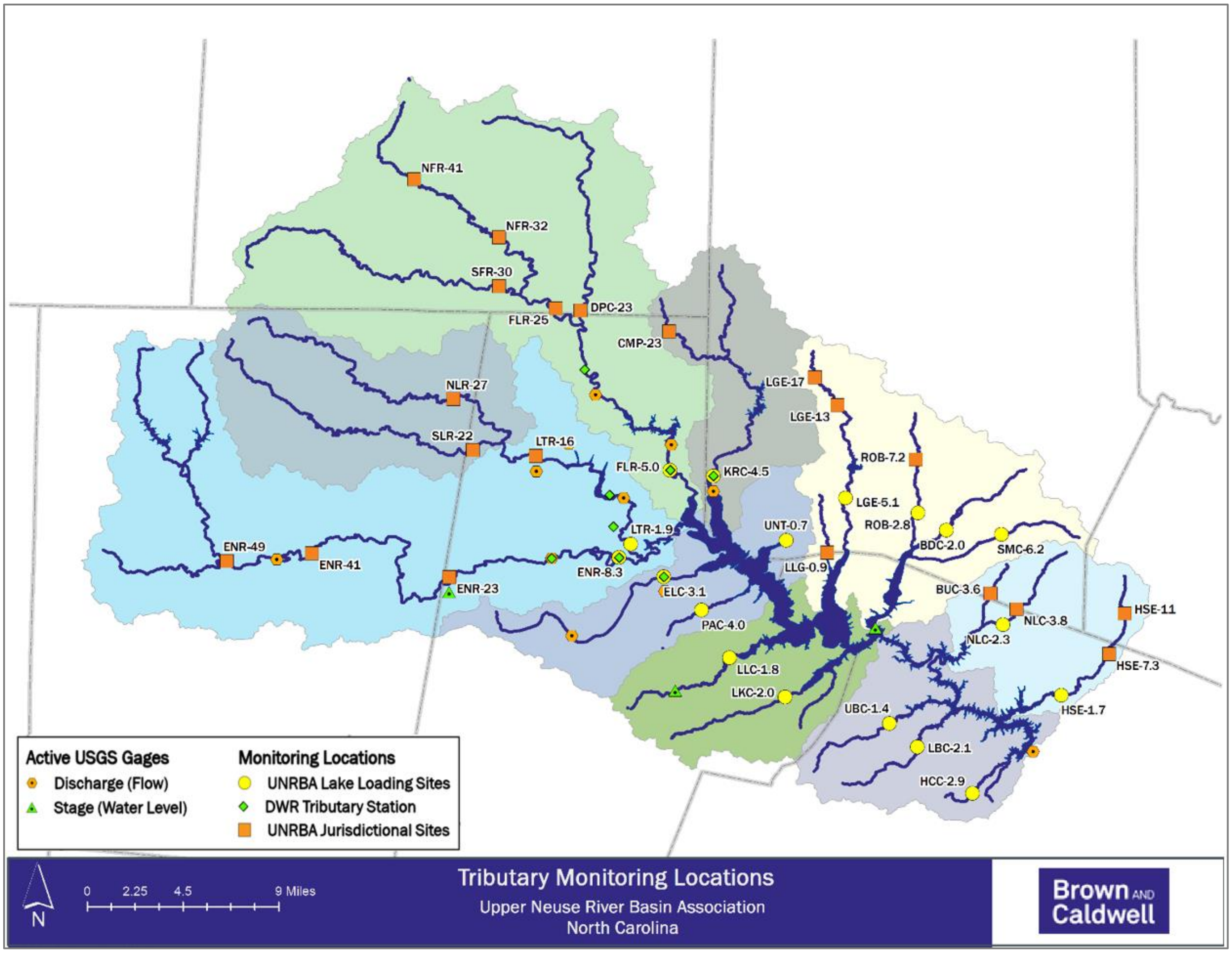
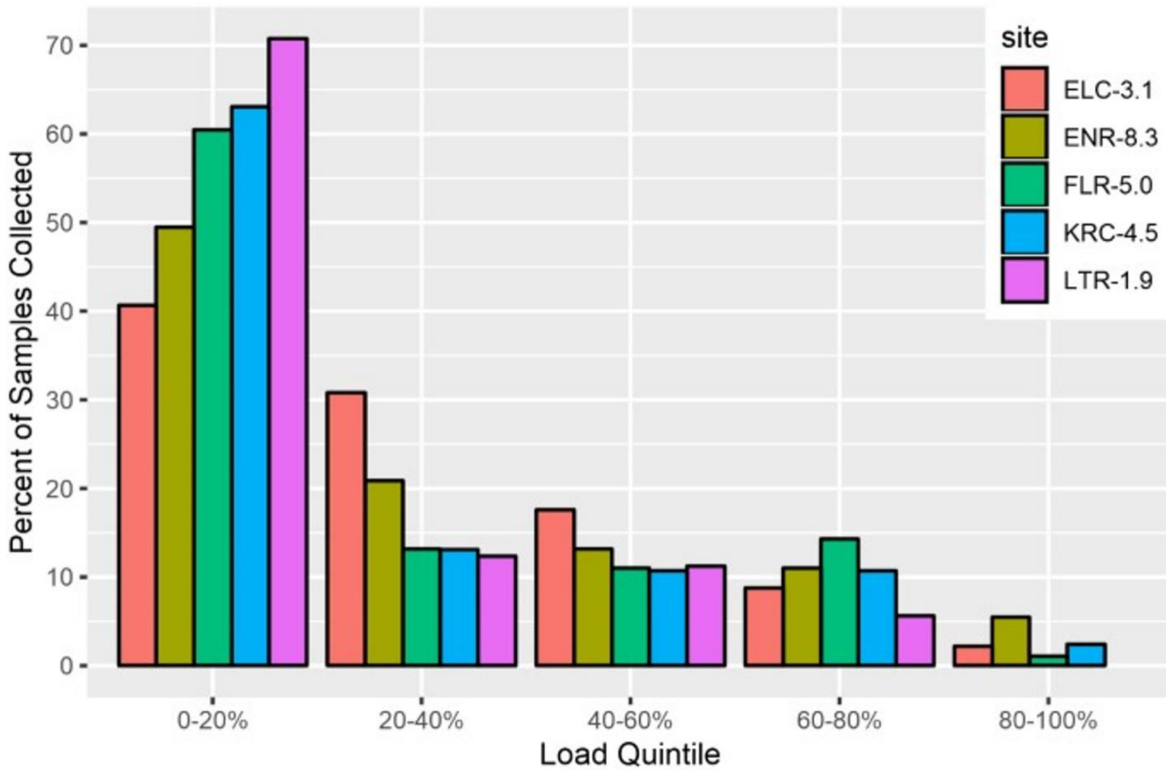


Figure 4-12. Locations of sources of water quality data within the Falls Lake watershed

The UNRBA 2019 Annual Monitoring Report also summarizes the flow regimes during which most of the water quality samples were collected for each of the top five flow contributors to Falls Lake. To assess the percentage of samples collected during different flow conditions, flows were distributed among five equal groups (quintiles) based on the range of all flow values observed during the monitoring period. The percentage of samples collected from each quintile was then calculated for all five streams (Figure 4-13). The UNRBA Monitoring Program was designed to include sampling (either as grab samples or using automated samplers) during higher flow periods. This sampling approach resulted in samples collected across all flow regimes which improved development and calibration of the model during high-flow events. However, the majority of samples collected at each station (40 to 70 percent) were collected when flows were in the lowest quintile.



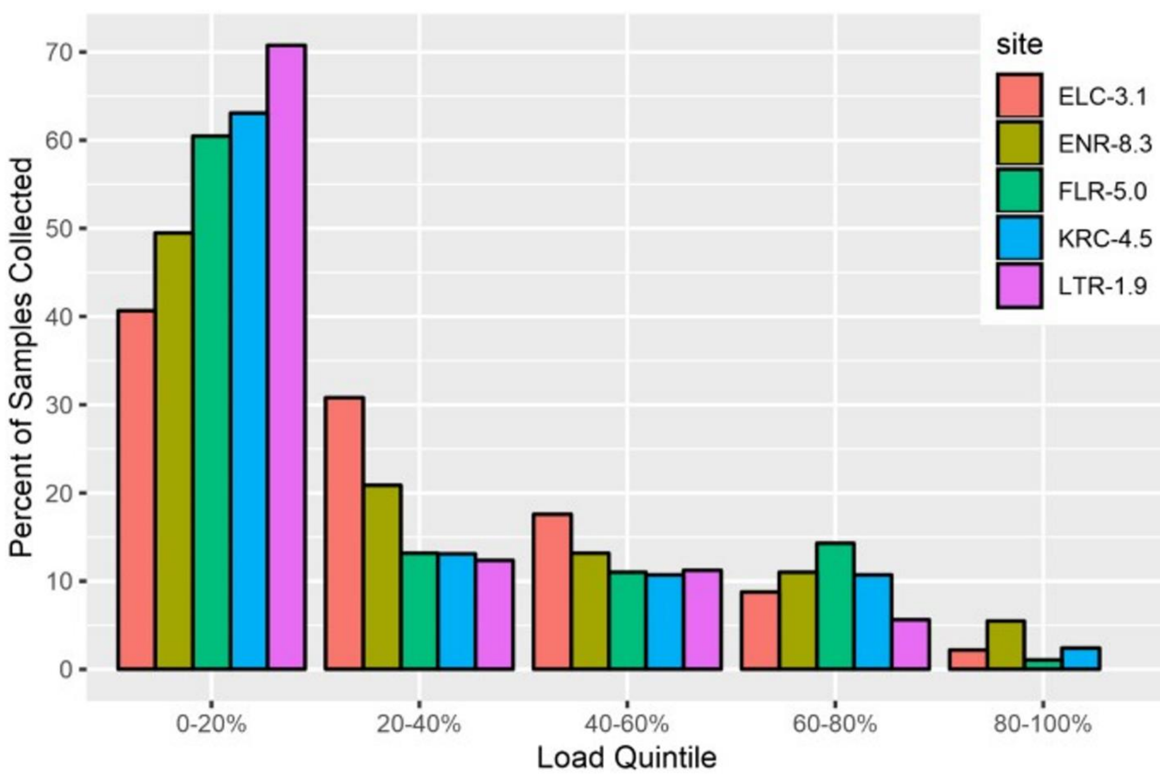


Figure 4-13. Percentage of Samples Collected during Different Loading Quintiles for The Five Largest Flow Contributors to Falls Lake Collected during the UNRBA Monitoring Period (2014 to 2018)

4.5 Wastewater Treatment Facilities

WARMF requires discharge flow and water quality data from wastewater treatment plants with discharges in the watershed. This section summarizes the flow and water quality data provided for each facility.

4.5.1 Major Point Sources

There are three major wastewater treatment facilities (discharging more than 1 million gallons per day (MGD)) in the Falls Lake Watershed (Table 4-8, Figure 4-14).

Table 4-8. Major Wastewater Treatment Facilities in the Watershed

Permit Number	Facility Name	Type	Permitted Flow (MGD)	Receiving Stream
NC0023841	North Durham Water Reclamation Facility (NDWRF)	Municipal Wastewater Discharge, Large	20	Ellerbe Creek
NC0026433	Hillsborough Wastewater Treatment Plant (WWTP)	Municipal Wastewater Discharge, Large	3.0	Eno River
NC0026824	South Granville Water and Sewer Authority (SGWASA) WWTP	Municipal Wastewater Discharge, Large	5.5	Knap of Reeds Creek

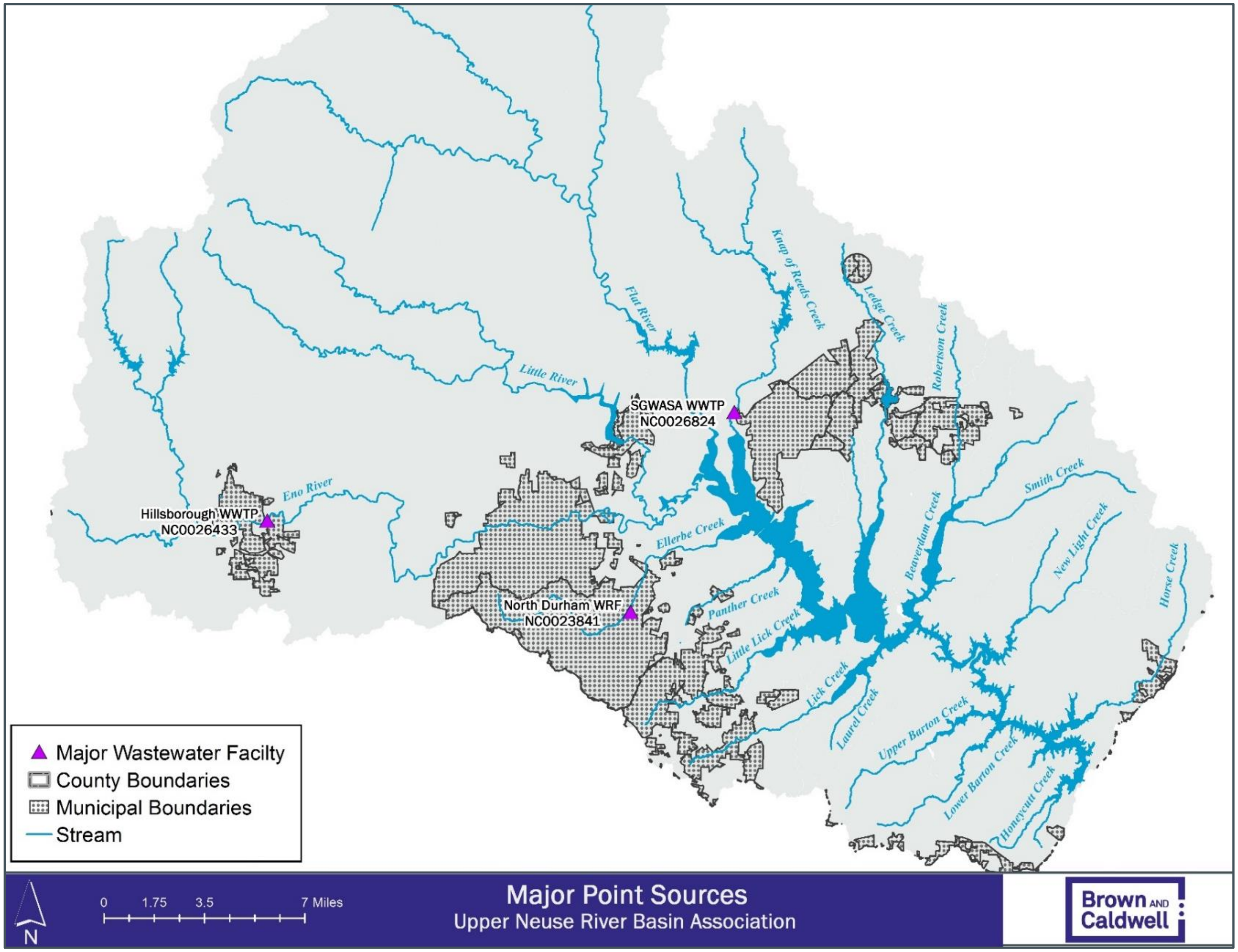


Figure 4-14. Major wastewater treatment facilities in the watershed

Table 4-9 summarizes the effluent data provided by each organization that operate these facilities. These data were used to develop time series inputs for the WARMF watershed model that account for the flows and concentrations discharged to streams from these facilities. The data summary is relevant to the two modeling periods (2005 to 2007 and 2014 to 2018). The WARMF model defaults to a step-function time series (the concentration for a given parameter is repeated until the next entry). For observations recorded as less than the reporting limit (RL), concentrations were calculated as 0.5 * RL.

Table 4-9. Summary of Effluent Data Provided by the Three Major Facilities in the Watershed[1]

Owner:	SGWASA			NDWRF	Hillsborough		
Permit Number:	NC0026824			NC0023841	NC0026433		
Date Range:	Jan-Mar 2006, Sep-Dec 2007	Apr 2006-Aug 2007	2014-2018	2014-2018	2006-2010	Jan 2011-Aug 2013	Sept 2013-Dec 2018
Flow (MGD)	D	D	D	D	D	D	D
Temperature (°C)	5/W	D	5/W		5/W	5/W	5/W
pH	5/W	D	5/W		5/W	5/W	5/W
Dissolved Oxygen (mg/l)	5/W	D	5/W		5/W	5/W	5/W
Conductivity (UMHOS/cm)	3/W	3/W	5/W				
BOD5 (20°C) (mg/l)	5/W	5/W	5/W		5/W	5/W	2/W
Total Suspended Residue (mg/l)	5/W	D	5/W		5/W	5/W	2/W
Ammonia Nitrogen (mg/l)	5/W	5/W	5/W		5/W	5/W	2/W
Nitrate plus nitrite (mg/l)	W	W	W	W	W	W	W
Total Kjeldahl Nitrogen (mg/l)	W	W	W	W	W	W	W
Total Nitrogen (mg/l)	W	W	W	W	W	W	W
Total Phosphorus (mg/l)	W	W	W	W	2/W	W	W

[1] Frequency of measurements is listed as daily (D), weekly (W), or number per week (#/W).

The referenced wastewater treatment plants are designed for biological treatment of wastewater. As such, the plants generate biosolids during the normal operation of their treatment process. These biosolids contain nutrients and other components of the wastewater and are monitored and regulated under federal and state requirements. A widely accepted approach for the proper management of these treated solids is the application of the solids to agricultural land at agronomic rates. All three major wastewater treatment facilities have provided biosolids to area farms that use the material as a source of nutrients and organic materials (personal email communications from Lindsay Mize (SGWASA) received 5/8/2018, John Dodson (NDWRF) received 5/8/2018, and Heather Fisher (Hillsborough) 7/9/2018 to Alix Matos. However, the Town of Hillsborough stopped land application of biosolids in 2013 (personal email communications from Terry Hackett (Hillsborough) received 7/29/2022). All sources of nutrients applied to agricultural land, including biosolids, are accounted for in nutrient loading information developed by the DSWC. This accounting is related to the agricultural land use data development process discussed in Section 3.2.2 of this report. Thus, biosolids application does not need to be accounted for separately for these facilities as this would double count the nutrient application. Nutrient application, including biosolids, is summarized in Section 3.3.

To support the watershed modeling, the three organizations that operate these wastewater treatment plants provided effluent monitoring data relevant to the two modeling periods (2005 to 2007 and 2014 to 2018).

Based on personal communication with Howard Fleming at Orange County, a portion of the flow to the Town of Hillsborough WWTP has been diverted to the Town of Mebane WWTP (which is located outside of the Falls Lake watershed): "On 12/12/18, the Efland sewage flow to the Town of Hillsborough was diverted to the City of Mebane. This was Orange County's small sewer system serving approximately 325 active services, which has now been transferred to the City of Mebane as part of a long-planned Orange County capital improvement project known as the Efland Sewer to Mebane, Phase 2 Extension project." This change is reflected in the flow and effluent quality data provided by the Town of Hillsborough that was used to develop the UNRBA watershed model through the end of 2018. No other flow adjustment for the model would be needed.

4.5.2 Minor Water and Wastewater Treatment Facilities

Minor facilities in the watershed discharge less than 1 MGD to receiving waters. Typically, less information is available to develop time series inputs for minor point sources. Table 4-10 summarizes the permit information for the minor discharges in the Falls Lake watershed. Locations are shown in Figure 4-15. The Compliance and Expedited Permitting Unit of DWR provided flow and nutrient data for these facilities. The frequency and type of data provided are summarized in Table 4-10.

Table 4-10. Minor Water or Wastewater Treatment Facilities

Permit Number	Facility Name	Type	Permitted Flow (MGD)	Receiving Stream
NC0037869	Arbor Hills Mobile Home Park WWTP	Discharging 100% Domestic < 1MGD	0.0060	Stony Creek
NC0049662	Hawthorne Subdivision WWTP	Discharging 100% Domestic < 1MGD	0.2500	Upper Barton Creek
NC0082759	Orange-Alamance Water System Water Treatment Plant	Water Plants and Water Conditioning Discharge	0.3000	Eno River
NC0059099	Lake Ridge Aero Park WWTP	Discharging 100% Domestic < 1MGD	0.016	Panther Creek
NC0063614	Wildwood Green WWTP	Discharging 100% Domestic < 1MGD	0.1	Lower Barton Creek
NC0085111	Heather Glen Water Treatment Plant	Water Plants and Water Conditioning Discharge	not limited	Sevenmile Creek
NC0085863	Waterfall Plantation Water Treatment Plant	Water Plants and Water Conditioning Discharge	0.0050	Horse Creek

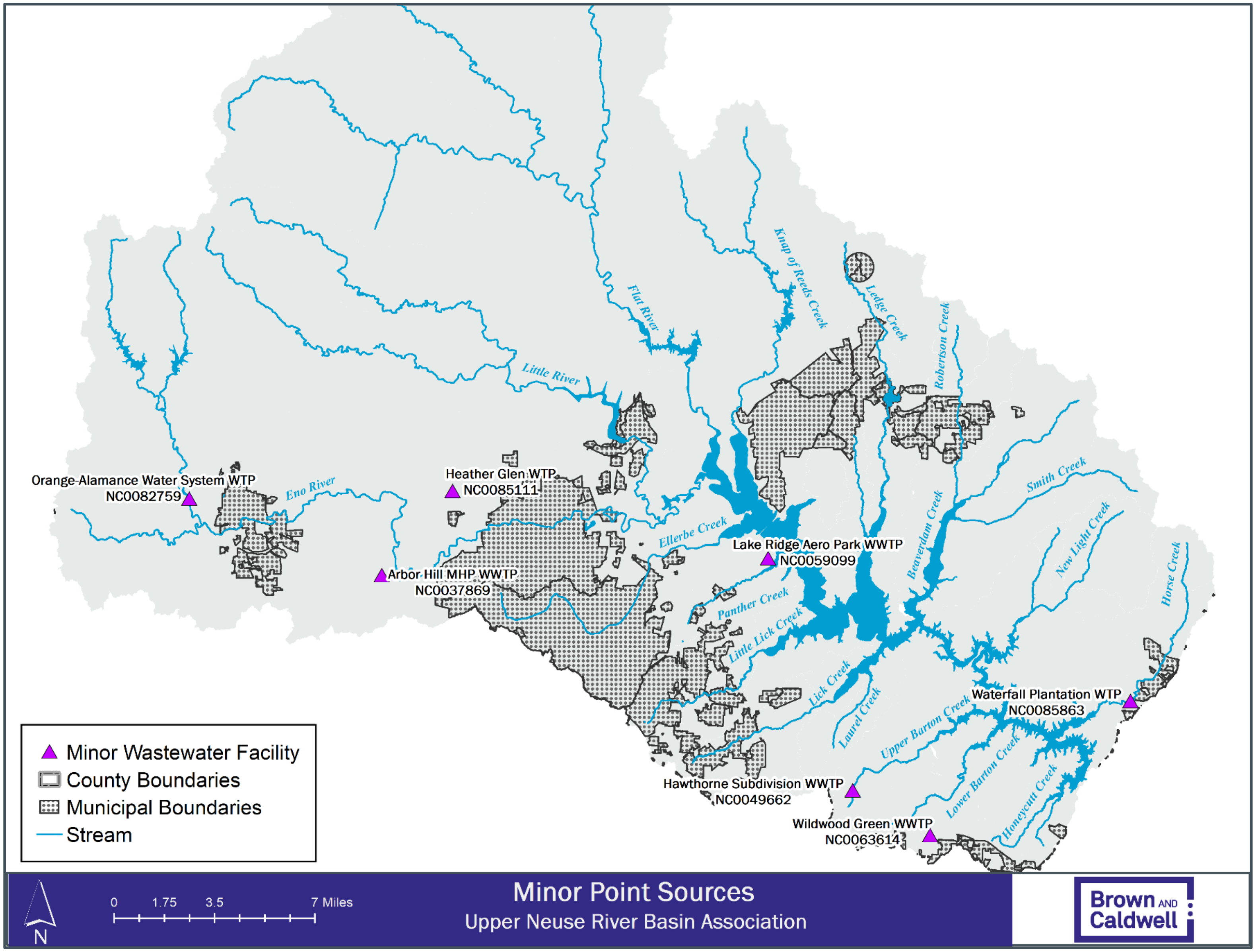


Figure 4-15. Minor wastewater point sources within the watershed

Table 4-11. Summary of Effluent Data Provided By Minor Facilities in the Watershed[1]

Facility:	Arbor Hills MHP		Hawthorne Subdivision		Lake Ridge Aero Park		Wildwood Green		Orange-Alamance Water System		Heather Glen		Waterfall Plantation	
Permit number:	NC0037869		NC0049662		NC0059099		NC0063614		NC0082759		NC0085111		NC0085863	
Date Range:	Apr '05– Dec '07	Jan '14 – Dec '18	Apr '05 – Dec '07	Jan '14 – Dec '18	Jan '05 – Dec '07	Jan '14 – Dec '18	Jan '05 – Dec '07	Jan '14 – Dec '18	May '05 – Dec '07	Jan '14 – Dec '18	Apr '05 – Dec '07	Jan '14 – Dec '18	Apr '05 – Dec '07	Jan '14 – Dec '18
Flow (MGD)	W	W	D	D	D	D	D	D	D	D	10 obs.		2-3/W	D
Total Flow (MGD)						M		M						M
Temperature (°C)	5/W	5/W	5/W	5/W	5/W	5/W - W	5/W	5/W		3/W				
Dissolved Oxygen (mg/l)	W	W	W	3/W	5/W	W	5/W - W	W						
Total Nitrogen (mg/l)	W	Alt-W or M	M	D or Alt-W	M	D, Alt-W, or M	M	Alt-W	M- 3/W	2/W	7 obs.		6 obs.	110 obs.
Ammonia Nitrogen (mg/l)	W	W	W	W	W	W	W	W		2/W				
Total Kjeldahl Nitrogen (mg/l)	W	Alt-W or M	alt-W or M	Alt-W	M		Alt-W or M	Alt-W	M- 3/W	2/W	7 obs.	No data available[2]	6 obs.	
Nitrate plus nitrite (mg/l)	W	Alt-W or M	alt-W or M	Alt-W	M		M	Alt-W	M- 3/W	2/W	7 obs.		6 obs.	
Total Phosphorus (mg/l)	Alt-W	Alt-W or M	W	Alt-W	W	M	W	W	M- 3/W	2-3/W	7 obs.		6 obs.	10 obs.
Total Nitrogen (calculated) (lb/yr)		M		M				M						
Total Nitrogen (calculated) (lb/month)		Alt-W or M		Alt-W or M				Alt-W or M						1 obs.

[1] Frequency of measurements is listed as daily (D), weekly (W), monthly (M), number per week (/W), every other week (Alt-W), or number per month (/M). For nonroutine frequencies, the number of observations within the period is listed (obs)

.[2] From DEQ: no data available; per the most recent permit renewal (completed 2015), the NPDES permit is for emergency discharge only. Assume intermittent discharge for the 2005 to 2007 modeling period as well.

4.5.3 Local Government Review of Major WWTP Input Data

Development of the input files associated with discharges from WWTPs requires processing daily effluent flow measurements and approximately weekly water quality measurements into model input files for WARMF. To review the processing of this data, operators of the three major WWTPs in the Falls Lake watershed were provided monthly and annual summaries of total nitrogen and total phosphorus loading from their facilities for the baseline (2005 to 2007) and recent (2015 to 2018) modeling periods. No concerns with the loading summaries were raised during this review.

4.5.4 Summary of WARMF Model Inputs for Wastewater Treatment Plants

Wastewater treatment plant effluent flow and water quality data are input the WARMF model as time series data. Discharge flow rates for the three major WWTPs and the flows from the combined minor facilities are shown in Figure 4-16. Data to the left of the dashed vertical line represent discharges in the baseline period and to the right represent the UNRBA study period. For the baseline period, some WWTPs were only able to provide monthly average flowrates; for the recent period, daily discharge flow rates were available for the three major WWTPs. Discharges have increased for the three major facilities over this time and have stayed relatively similar for the combined minor facilities. The relative flow rates from the minor facilities and Hillsborough WWTP are low and difficult to view on this figure.

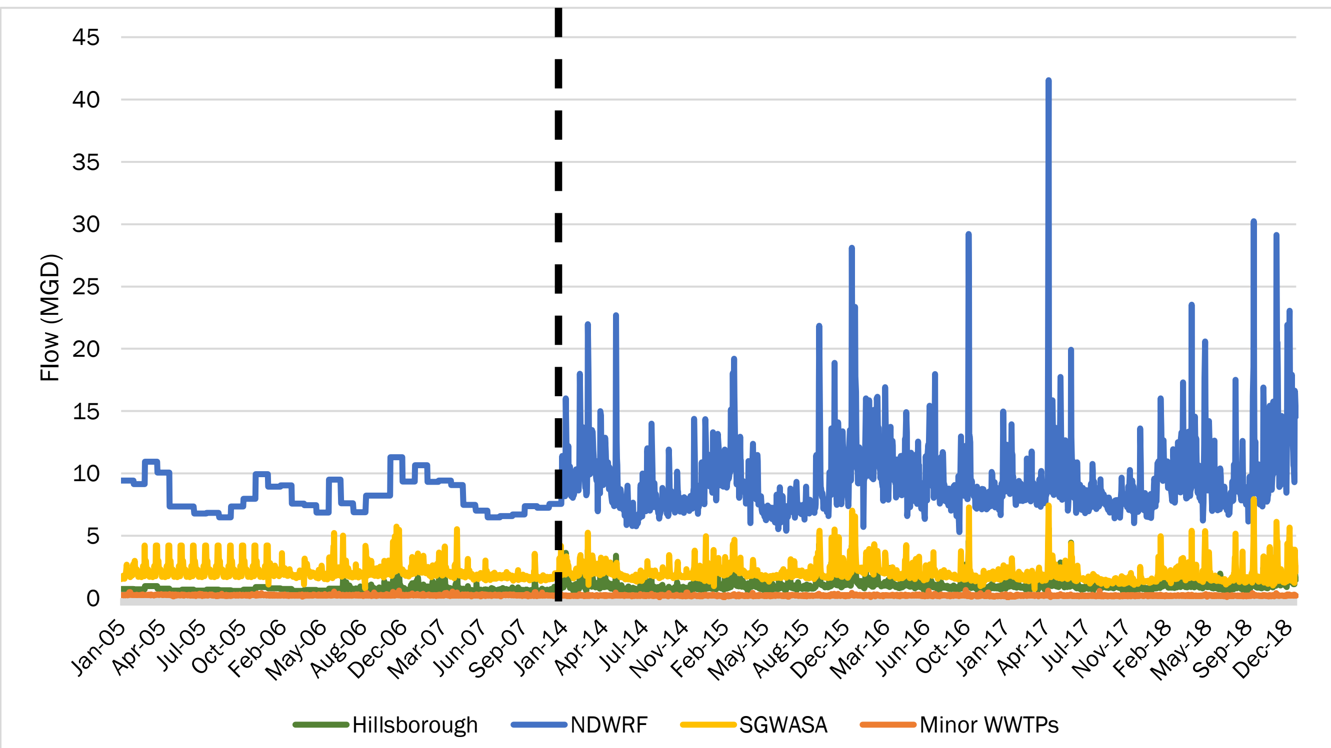


Figure 4-16. Time Series of WWTP Discharge Flow Rates for the Baseline (left) and Recent (right) Modeling Periods

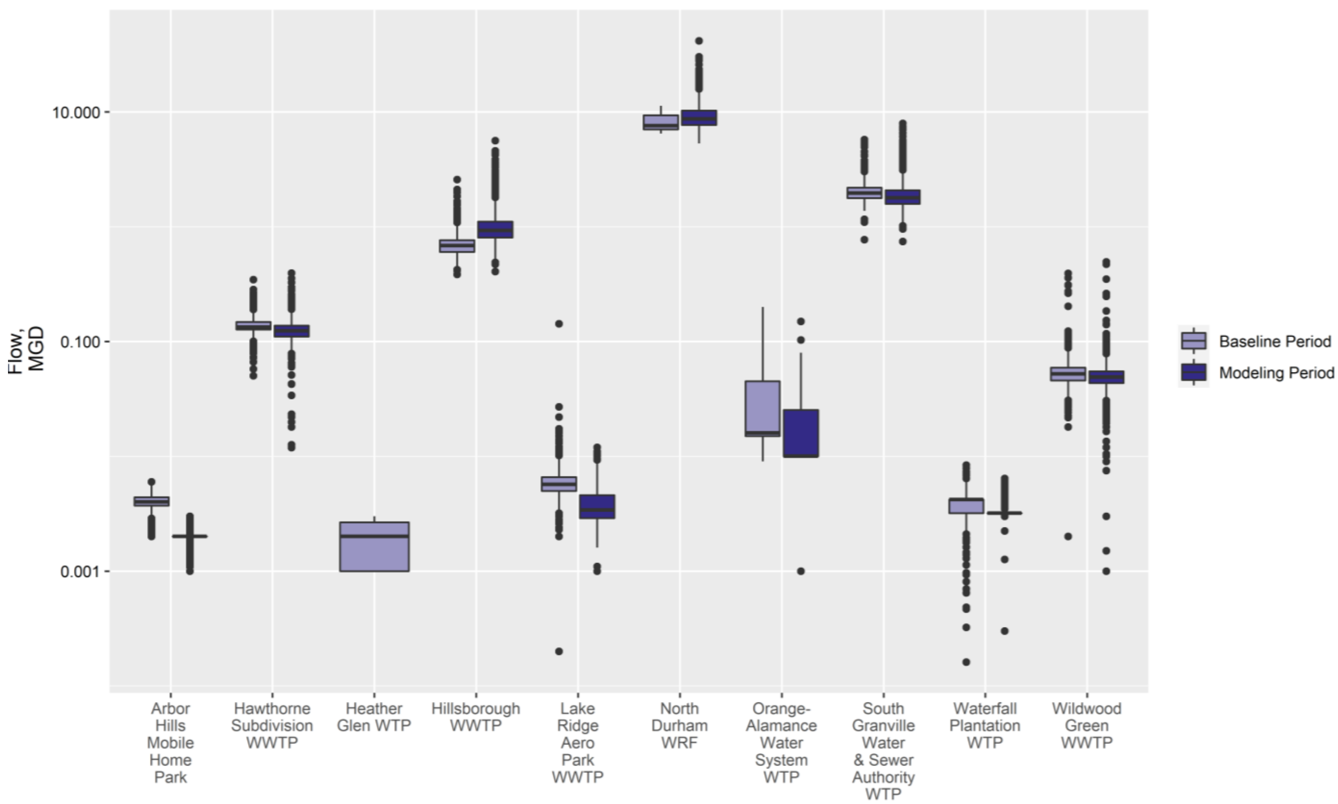


Figure 4-17. Distribution of WWTP Daily Discharge Flow Rates for each Facility for the Baseline and UNRBA study Periods (log scale)

Figure 4-18, Figure 4-19, and Figure 4-20 show the distribution (log-scale) of daily ammonia, nitrate, and total phosphorus loads from each major or minor WWTP during the baseline period and UNRBA study period. As expected, the three major facilities discharge the highest loads of these three parameters. Nutrient loading from the minor facilities sometimes exceeded that of the Hillsborough WWTP by as much as 15 percent. Loading from each of the three major facilities decreased from the baseline period (2005 to 2007) to the UNRBA study period (2015 to 2018). Some of the minor facilities had decreases in nutrient loading and others had increases when comparing these two periods.

Table 4-12 and Table 4-13 show the annual simulated nutrient load for each facility for total nitrogen and total phosphorus, respectively. Across all major and minor facilities, the nitrogen load decreased from 159,548 lb-N/yr in the baseline period to 120,842 lb-N/yr for the recent period. If 2015 (when two of the major facilities were undergoing significant renovations) is excluded from the analysis, then the average total nitrogen load is 106, 689 lb-N/yr. For total phosphorus, discharges from all facilities decreased from 21,237 lb-P/yr to 6,628 lb-P/yr (or 5,314 lb-P/yr if 2015 is excluded from the analysis). Excluding 2015, total nitrogen loads from minor and major wastewater treatment plants have been reduced by 33 percent and total phosphorus loads have been reduced by 75 percent. However, loading from minor facilities as a subset of discharges has increased by 35 percent for nitrogen and decreased by 40 percent for phosphorus.

Total organic carbon concentrations are not typically measured in the effluent of wastewater treatment facilities. An average total organic carbon concentration of 5.5 mg/L was assumed for the modeling based on data provided by Yang et al. (2014).

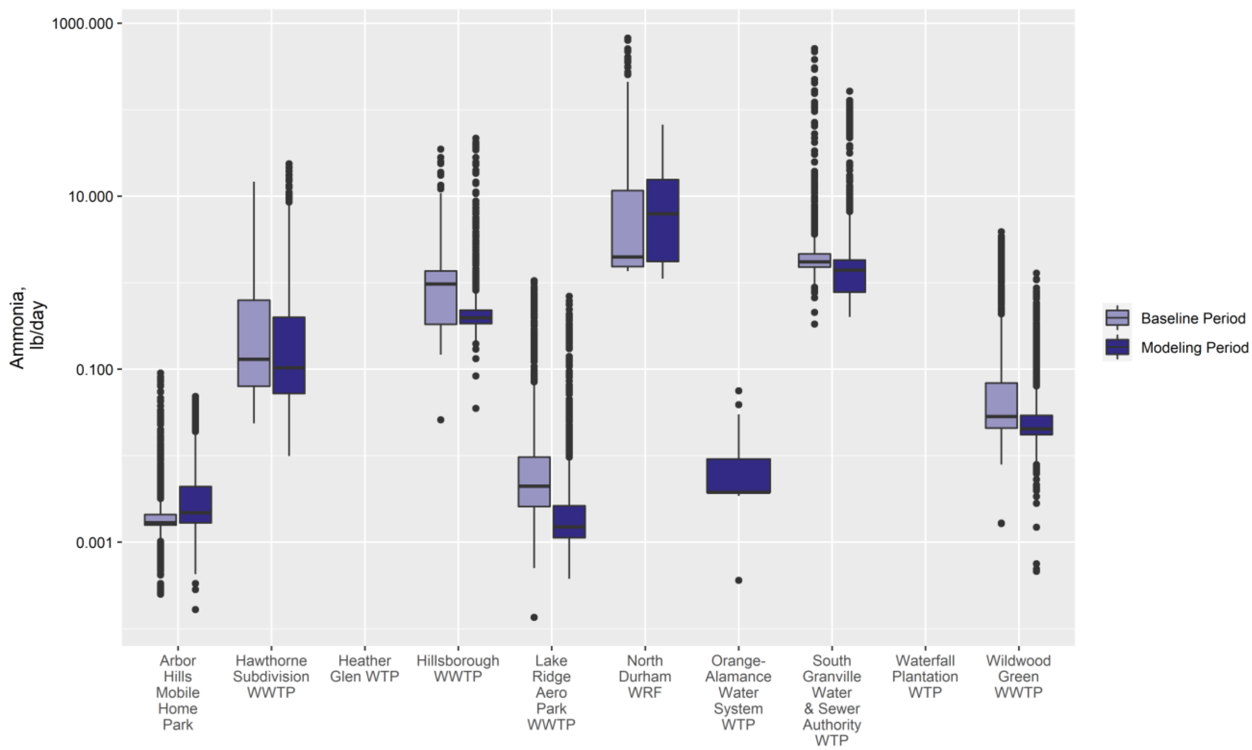


Figure 4-18. Distribution of Daily WWTP Discharge Ammonia Loads for each Facility for the Baseline and UNRBA study Periods (log scale)

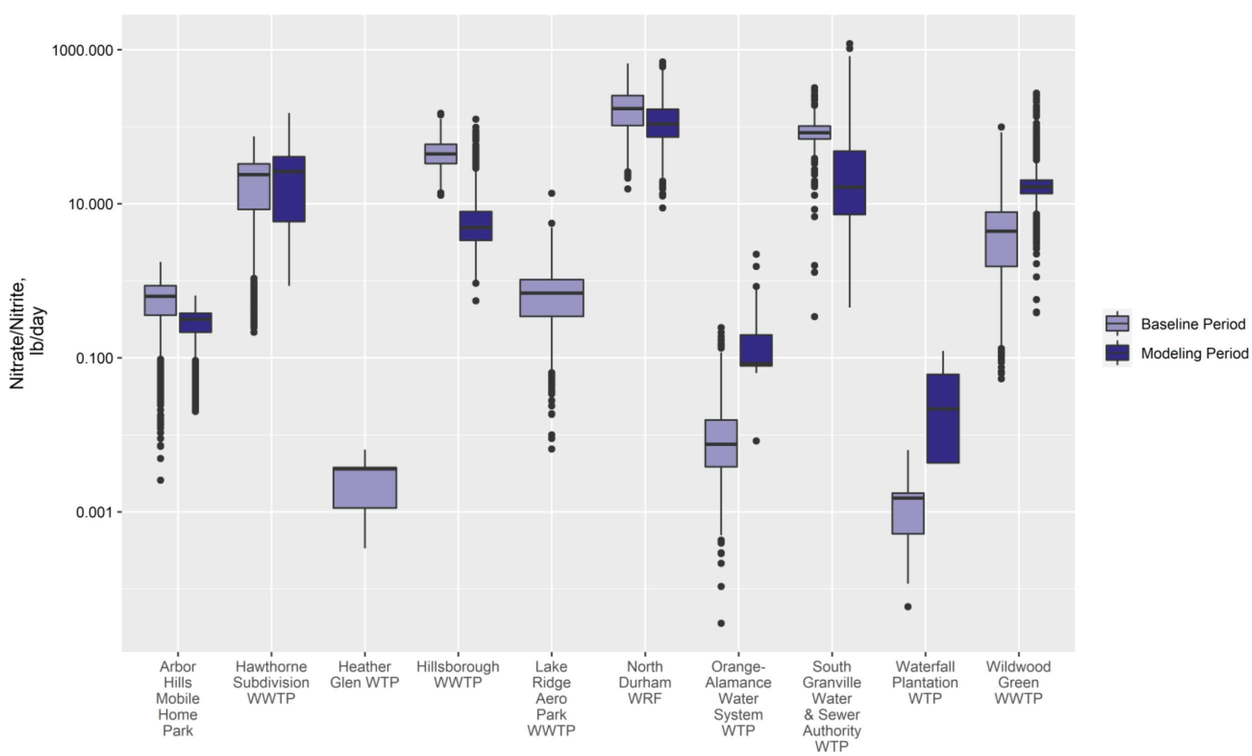


Figure 4-19. Distribution of Daily WWTP Discharge Nitrate Loads for each Facility for the Baseline and UNRBA study Periods (log scale)

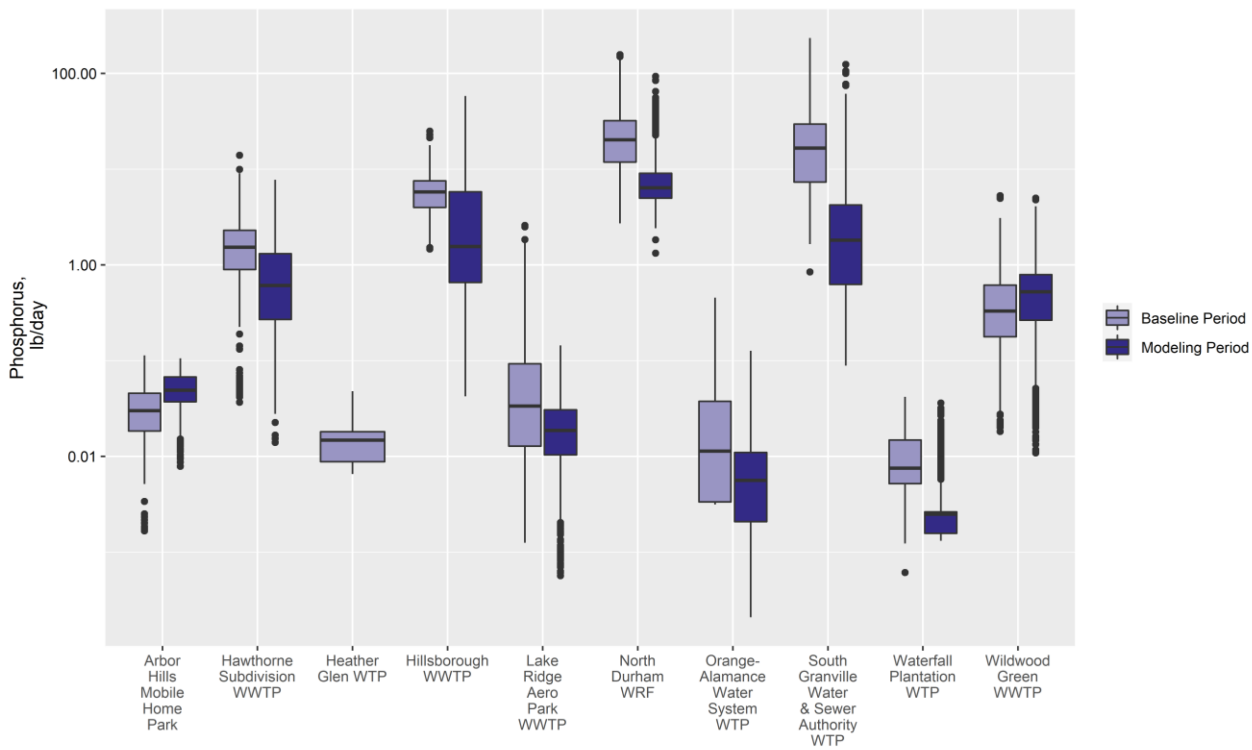


Figure 4-20. Distribution of Daily WWTP Discharge Phosphorus Loads for each Facility for the Baseline and UNRBA study Periods (log scale)

Table 4-12. Annual Total Nitrogen Loads (pounds per year) for Model Simulation Years

Permit Number	Facility Name	2005	2006	2007	2015	2016	2017	2018
NC0023841	North Durham Water Reclamation Facility (WRF)	54,006	92,343	109,115	82,210	75,839	61,457	83,337
NC0026433	Hillsborough Wastewater Treatment Plant (WWTP)	24,746	28,409	18,197	6,675	4,641	5,593	6,586
NC0026824	South Granville Water and Sewer Authority (SGWASA) WWTP	34,319	41,668	40,846	53,395	14,573	14,387	11,747
NC0037869	Arbor Hills Mobile Home Park WWTP	392	306	176	155	116	93	136
NC0049662	Hawthorne Subdivision WWTP	3,292	11,248	11,452	14,444	11,179	4,289	1,772
NC0059099	Lake Ridge Aero Park WWTP	239	327	344	21	48	203	664
NC0063614	Wildwood Green WWTP	1,264	3,486	2,313	6,347	6,989	11,101	5,244
NC0082759	Orange-Alamance Water System Water Treatment Plant	31.2	55.3	50.5	24.0	19.7	23.4	21.4
NC0085111	Heather Glen Water Treatment Plant1	2.7	5.5	3.0	0.0	0.0	0.0	0.0

Table 4-12. Annual Total Nitrogen Loads (pounds per year) for Model Simulation Years								
Permit Number	Facility Name	2005	2006	2007	2015	2016	2017	2018
NC0085863	Waterfall Plantation Water Treatment Plant2	2.8	3.2	0.6	33.2	3.1	3.0	1.1
	Total Major and Minor	118,295	177,851	182,497	163,304	113,408	97,149	109,509
	Average for Period Major and Minor	159,548			120,842 (24% reduction from baseline)			
	Average for Period Excluding 2015	Not applicable			excluded	106,689 (33% reduction from baseline)		

Table 4-13. Annual Total Phosphorus Loads (pounds per year) for Model Simulation Years								
Permit Number	Facility Name	2005	2006	2007	2015	2016	2017	2018
NC0023841	North Durham Water Reclamation Facility (WRF)	11,419	10,015	9,437	2,764	2,520	3,152	3,066
NC0026433	Hillsborough Wastewater Treatment Plant (WWTP)	1,992	2,444	2,267	2,722	887	855	648
NC0026824	South Granville Water and Sewer Authority (SGWASA) WWTP	2,863	11,868	8,577	4,265	2,072	661	645
NC0037869	Arbor Hills Mobile Home Park WWTP	11	16	12	25	14	19	23
NC0049662	Hawthorne Subdivision WWTP	546	735	832	550	405	253	62
NC0059099	Lake Ridge Aero Park WWTP	51	25	24	3	8	15	9
NC0063614	Wildwood Green WWTP	97	208	212	238	231	266	112
NC0082759	Orange-Alamance Water System Water Treatment Plant	10.4	3.5	16.1	1.8	6.8	6.2	3.9
NC0085111	Heather Glen Water Treatment Plant1	6.1	8.8	3.3	0.0	0.0	0.0	0.0
NC0085863	Waterfall Plantation Water Treatment Plant	3.5	3.8	3.6	0.7	0.5	0.8	1.0
	Total Major and Minor	16,999	25,327	21,384	10,570	6,144	5,228	4,570
	Average for Period	21,237			6,628 (69% reduction from baseline)			
	Average for Period Excluding 2015	Not applicable			excluded	5,314 (75% reduction from baseline)		

4.6 Sanitary Sewer Overflows

For the UNRBA study period (2015 to 2018), the locations, durations, volumes reaching surface water, and type (wet or dry) of sanitary sewer overflows (SSOs) were provided by the operators of the three major WWTPs in the watershed as well as staff at NCDEQ. These data were combined and cross referenced to ensure that all reported events were captured in the model, and that none were double counted when the databases were combined. For events where wet or dry conditions were not noted in the database, the

UNRBA modeling team reviewed the weather files to determine the likely condition. Figure 4-21 shows the location of the SSOs simulated for the UNRBA study period.

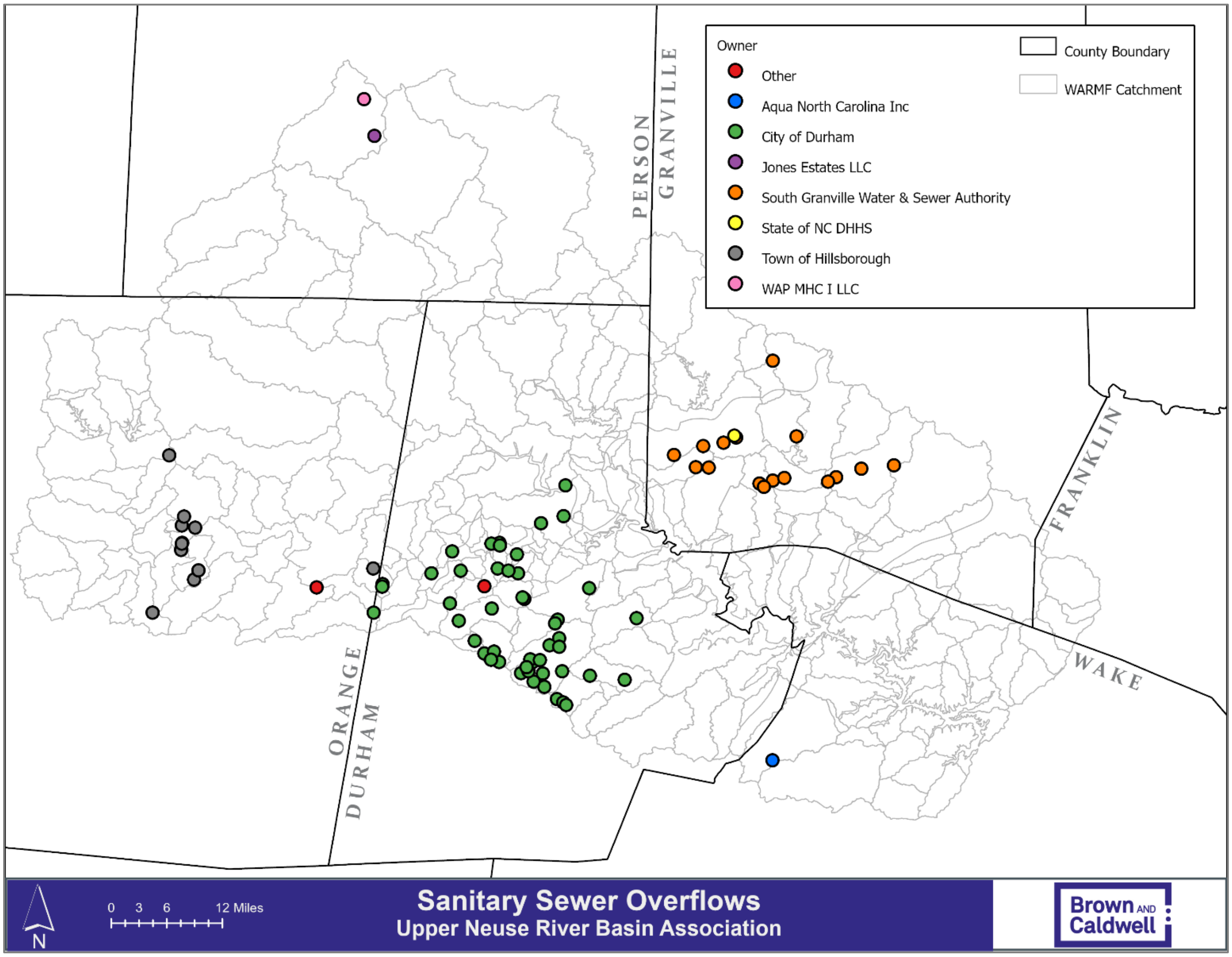


Figure 4-21. Location of Sanitary Sewer Overflows (SSOs) by Owner for the UNRBA study Period

For the baseline period (2005 to 2007), less information was available to characterize SSOs. As DWR developed that model using their available data, and the DWR WARMF model files include estimates of volumes and nutrient loads associated with those discharges, the DWR WARMF model files for the baseline period were used to estimate flows and pollutant loads from SSOs in the baseline period. These events assumed concentrations of ammonia of 25 mg-N/L and total phosphorus of 8 mg-P/L. These files include a relatively large release in late March 2005 that included approximately 134 thousand gallons likely released from a lagoon that has since been decommissioned.

Spatial data included in the databases were used to assign these events as point source discharges occurring over specific, often short, durations in specific modeling catchments. Based on the NCDEQ crediting document for illicit discharges developed by the UNRBA, the following concentrations of nitrogen and phosphorus were assumed for wet and dry weather events for the UNRBA study period (2015 to 2018). Total organic carbon concentrations are not specified in the crediting document. Since dry weather SSOs are mostly wastewater, the total organic carbon concentration was selected from the list of onsite wastewater treatment systems that had a total nitrogen concentration closest to the value specified in the DWR crediting document.

- Dry weather SSO's assume total nitrogen = 33 mg-N/L, total phosphorus = 6.0 mg-P/L, and total organic carbon = 22 mg/L (these are assumed mostly comprised of wastewater)
- Wet weather SSO's assume that one-third of the volume is wastewater (33 mg-N/L and 6.0 mg-P/L) and two-thirds is stormwater (1.4 mg-N/L and 0.27 mg-P/L). Total nitrogen concentration = 12 mg-N/L and total phosphorus = 2.2 mg-P/L. The ratio of dry weather SSO TN to wet weather SSO TN was used to estimate the wet weather SSO concentration of TOC (8 mg/L).

Table 4-14 summarizes the total nitrogen and phosphorus loads for the baseline period (2005 to 2007) and the UNRBA study period (2015 to 2018).

Table 4-14. Annual Nutrient Loads from SSOs (pounds per year) for Baseline and Recent Period Model Simulation Years

Year	Total Nitrogen (lb-N/yr)	Total Phosphorus (lb-P/yr)
2005	89	29
2006	105	34
2007	81	26
2015	177.0	32.2
2016	21.6	3.9
2017	12.0	2.2
2018	234.4	42.6

Section 5

Nutrient and Carbon Inputs

External sources of nitrogen, phosphorus, and organic carbon enter the Falls Lake watershed system on the land surface, subsurface, or as discharges to streams and rivers as described in Section 3 and Section 4. In addition, nutrients and carbon are stored in the watershed and lake and river sediments based on past inputs. Nutrients and carbon cycle through the modeled system via vegetative growth, harvest, litter fall, and decay as well as physical, chemical, and biological transformations that occur in the surface water, groundwater, and the soils.

Most sources of nutrient and carbon inputs to the Falls Lake watershed are represented using model input files: atmospheric deposition, application to agriculture or urban land, wastewater treatment facilities, sanitary sewer overflows, and onsite wastewater treatment systems. However, these sources are not tracked separately as delivered loads to Falls Lake except for onsite wastewater treatment systems that discharge subsurface. Wastewater treatment facilities, sanitary sewer overflows, and discharging sandfilter systems are tracked together in a category called point sources. Inputs applied to the land surface such as nutrient application and atmospheric deposition are tracked by land use. Some sources are internally calculated by the model like streambank erosion and loading associated with soils, dissolution of nutrients into groundwater, and soil erosion; the model tracks these as sources of loading delivered to Falls Lake, but these are not prescribed with model input files.

The average annual inputs to the system for the baseline (2005 to 2007) and UNRBA study periods (2015 to 2018) are summarized in Figure 5-1 and Table 5-1 for total nitrogen and Figure 5-2 and Table 5-2 for total phosphorus. Figure 5-3 shows the inputs for the system for total organic carbon for the study period. The watershed model for the baseline period has not been developed, but the data needed to represent the nitrogen and phosphorus inputs had previously been collected and is available for comparison. The total organic carbon inputs for the baseline period have not been compiled completely.

These are gross inputs based on model input files for the baseline and UNRBA study periods and do not reflect the biogeochemical processes or nutrient removal due to crop harvesting that ultimately reduce the loading to Falls Lake. Model inputs for effluent from centralized wastewater treatment facilities and onsite systems represent post-treatment concentrations; these inputs do not represent raw wastewater. If raw wastewater inputs were used to calculate the percent reduction of the watershed as a system, then the reductions would be higher than those presented in these figures. Sources associated with internal processes such as stream bank erosion or soil chemistry are not included in the model input files, but they are simulated by the model and reflected in the total delivered loads to Falls Lake that were used to calculate the percent reductions of inputs to delivered loads. If loads associated with background sediments and stream bank erosion were not accounted for in the delivered loads to Falls Lake, then the percent reductions of watershed inputs would be higher than those presented in these figures (i.e., these loads are only accounted for on one side the equation).

Based on the calibrated model, watershed processes reduce the total nitrogen input by approximately 83 percent, the total phosphorus input by approximately 88 percent, and total organic carbon input by 62 percent prior delivery to Falls Lake. This 770 square mile system includes several major impoundments and an extensive stream network which reduces nutrients during transport through adsorption to sediment, settling, denitrification, biological uptake, etc. Overland transport also reduces loads thru filtering, settling, and plant uptake. The harvesting of crops results in removal of nutrients from the system. The proportion of delivered load from each major input varies based on the processes that affect each input:

- Inputs from nutrient application to agriculture are high relative to other sources; however, much of these nutrients are stored in crops, harvested, and ultimately removed from the system (the relative contribution to the delivered load is smaller than the relative contribution to the system inputs).
- Atmospheric deposition is also a major input which affects all land use types including forests and wetlands which can store and cycle nutrients and carbon. A portion of this input is removed with crops (the relative contribution to the delivered load is smaller than the relative contribution to the system inputs).
- The percent contribution from wastewater (WW) treatment plants is relatively small in terms of inputs to the system partly due to facility upgrades and optimization; these inputs are directly discharged to streams typically downstream of impoundments (the relative contribution to the delivered load is larger than the relative contribution to the system inputs).
- Streambank erosion is a significant source of delivered loading of phosphorus (approximately 14 percent) but is not reflected in these pie charts because it is calculated internally by the model.
- Leaf litter decay is also an important source of total nitrogen, total phosphorus, and total organic carbon, particularly since 60 percent of the watershed is forested. This source is accounted for by the model through processing and cycling within forests, wetlands, and other vegetated areas. In WARMF, the process of organic matter decay proceeds from coarse litter to fine litter, to humus, to organic carbon. During each step, individual ions (NO3, NH4, PO4, etc.) are also produced. The estimated inputs from leaf litter decay are shown on the gross inputs figure for context, but the loads generated from organic matter production and decay are not prescribed in model input files like the other watershed inputs shown on these figures; i.e., they are processes internal to the model like streambank erosion. For the comparison of baseline period to study period gross inputs, the leaf litter decay amounts were assumed the same for both periods. A baseline period model was not developed to simulate inputs from leaf litter decay for that period.

Sanitary sewer overflows (SSOs) do not appear in the pie charts, but these inputs are included in the model as point source files based on data provided by plant operators and DWR. These inputs comprise less than 0.002 percent of the total nitrogen or total phosphorus that is applied or released in the watershed. Other potential inputs that are not explicitly simulated by the model are pet waste, wildlife droppings, and sewer exfiltration. The potential impact of pet waste and wildlife droppings could be tested using sensitivity analyses that adjust monthly nutrient application rates based on assumed animal density, mass deposited, and nutrient and carbon content of waste. As these inputs would be simulated as applied to the land surface, they would be subject to similar types of watershed processes as other land-based inputs. Sewer exfiltration could also be tested using sensitivity analyses with a distribution of subsurface inputs using a new category of “onsite wastewater treatment systems” as the vehicle to account for this loading in the model. Effluent concentrations from these “systems” could be set at higher concentrations than that leaving a septic system drainfield, and the layer receiving the discharge could be modified as well. As these loads would be discharged subsurface, they would be subject to the similar types of processes that affect loading from onsite wastewater treatment systems.

Estimates in the reduction of inputs from atmospheric deposition are based a dry deposition monitoring station that is 75 miles from the watershed and a wet deposition monitoring station that 20 miles from the watershed. As described in Section 4.2.1, these locations were selected because they report weekly measurements of the inputs required by the WARMF model. Due to their distance from the watershed, there is more uncertainty associated with the inputs from this source compared to other sources where local data are available. Sensitivity analyses that scale the inputs from this source could be used to evaluate the impacts of the uncertainty. These analyses may be informed by regional modeling and tested by scaling the load uniformly through time. The MRSW discussed potential sensitivity analyses to evaluate on August 2, 2022. Sensitivity analyses are further discussed in Section 6.6.

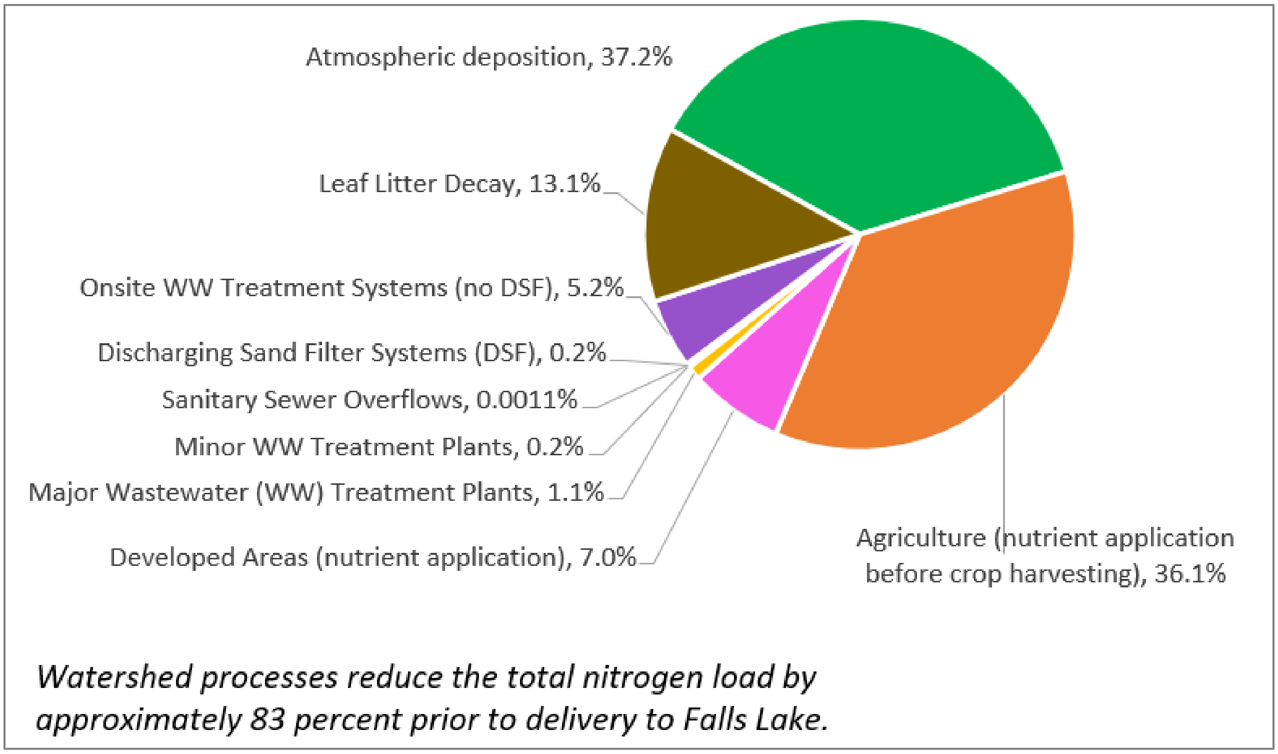


Figure 5-1. Percent Contribution to Gross Inputs of Total Nitrogen (9.9 million pounds per year) Applied or Released in the Falls Lake Watershed during the UNRBA Study Period

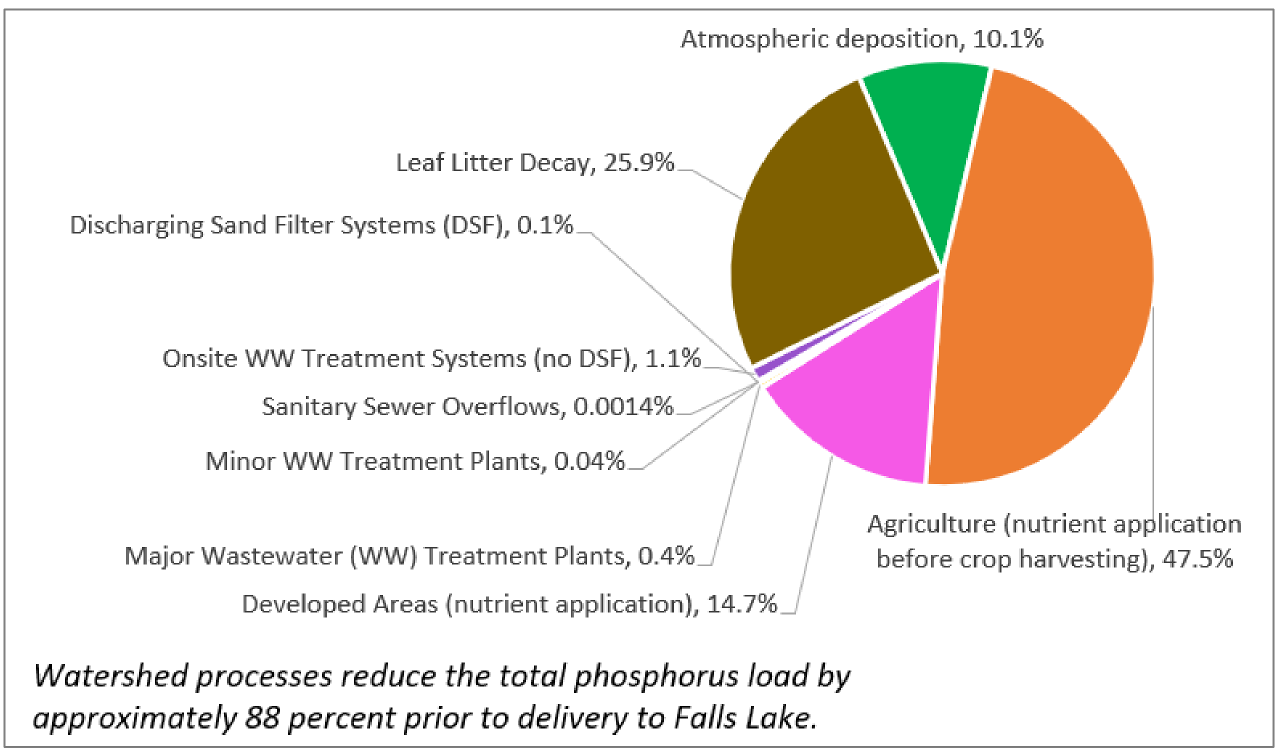


Figure 5-2. Percent Contribution to Gross Inputs of Total Phosphorus (1.5 million pounds per year) Applied or Released in the Falls Lake Watershed during the UNRBA Study Period

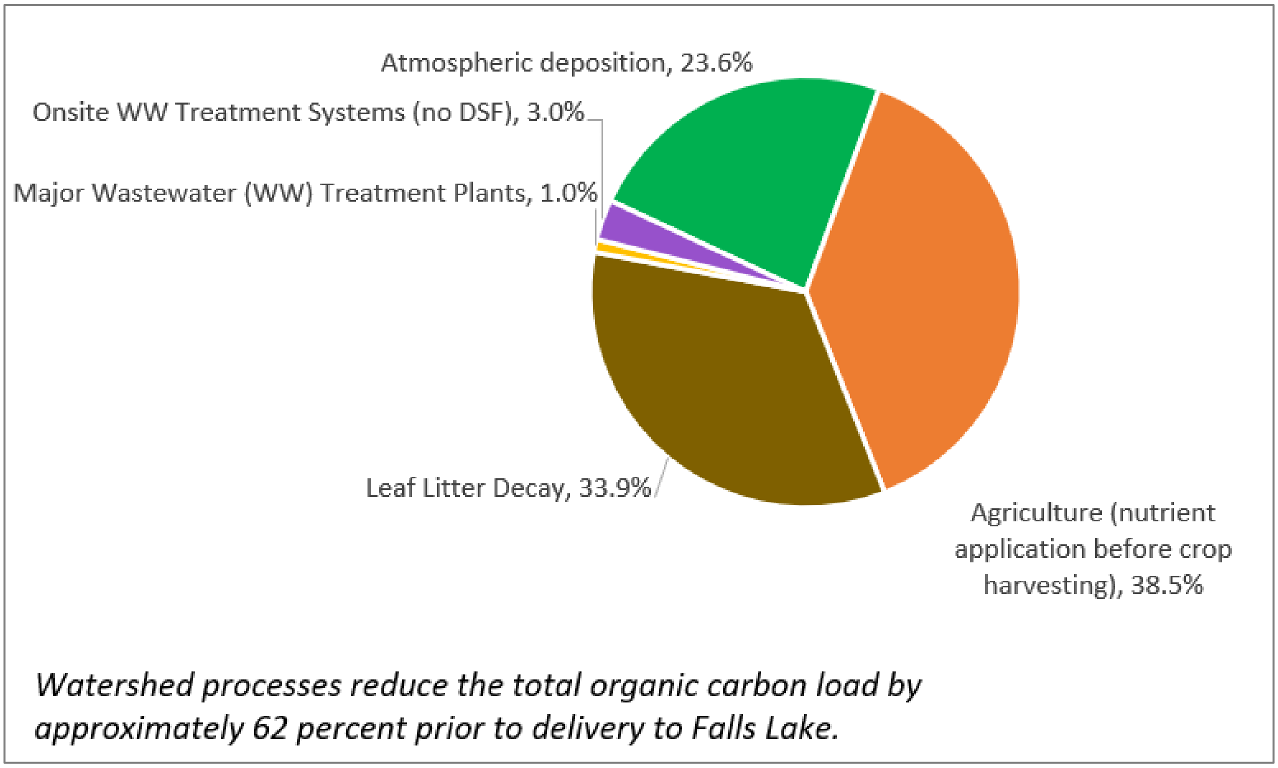


Figure 5-3. Percent Contribution to Gross Inputs of Total Organic Carbon (21.3 million pounds per year) Applied or Released in the Falls Lake Watershed during the UNRBA Study Period

Relative to the baseline period (2005 to 2007), the inputs of nitrogen and phosphorus to the watershed have decreased significantly. The average input of nitrogen has decreased from 15.0 million pounds per year to 9.9 million pounds per year, a 34 percent reduction since baseline. The average input of phosphorus has decreased from 1.95 million pounds per year to 1.49 million pounds per year, a 24 percent reduction. These reductions are due to a decline in agricultural production acres (44 percent), reduced rates of nutrient application in response to market drivers and improved crop science, improvements at major wastewater treatment facilities, and reductions in nutrient deposition to the watershed from the atmosphere.

In addition to these reductions in inputs, hundreds of stormwater control measures, best management practices, and stream restoration projects have been implemented in the watershed since the passage of the Falls Lake Nutrient Management Strategy.

Table 5-1. Annual Average Model Inputs of Nitrogen to the Watershed for the Baseline and UNRBA Study Periods and Total Delivered Load to Falls Lake (values are calculated from model input and output files and do not denote significance in terms of accuracy)

Source	Gross Inputs for the Baseline Period (2005 to 2007) (lb/yr)	Gross Inputs for the Study Period (2015 to 2018) Load (lb/vr)	Percent Change in Gross Inputs from Baseline Period
Atmospheric deposition to watershed (indirect) and lake surface (direct)[1]	4,972,069 (based on scaling deposition rates simulated by CASTNET)	3,683,014	25.9% reduction
Agriculture (nutrient application before nutrient removal due to crop harvesting)	7,531,278	3,566,291	52.6% decrease
Developed Areas (nutrient application)	661,476	696,739	5.3% increase
Leaf litter decay (internal model process) [2]	1,292,878	1,292,878	Assume baseline same as study period
Treated Effluent from Major Wastewater (WW) Treatment Plants[3]	147,883	105,110	28.9% decrease
Treated Effluent from Minor WW Treatment Plants	11,665	15,732	34.9% increase
Sanitary Sewer Overflows	91.7	111.2	21.4% increase
Treated WW from Discharging Sand Filter Systems (DSF)	10,340	15,134	46.4% increase
Treated WW from Onsite WW Treatment Systems (no DSF)	392,934	514,518	30.9% increase
Total Gross Input	**15,020,615**	**9,889,528**	**34.2% decrease**
Total Simulated Load Delivered to Falls Lake After Reductions in Watershed	Baseline model not evaluated	**1,656,361**	Baseline model not evaluated
Percent of Gross Input Reaching Falls Lake (after WW treatment)	Baseline model not evaluated	**16.8%**	Baseline model not evaluated
Percent Reduction of Nutrient Inputs (after WW treatment)	Baseline model has not been evaluated	**83.2%**	Baseline model has not been evaluated

1. *The WARMF watershed model for the baseline period has not been developed from which to simulate wet and dry deposition. For nitrogen, the average annual rate for total nitrogen deposition simulated by CASTNET at the Candor site for the baseline period (2005 to 2007) was divided by the rate for the UNRBA study period (2015 to 2018). This ratio (1.35) was used to scale up the average deposition rates simulated by WARMF for the recent period and approximate inputs for the baseline period for comparison to other sources listed in the table.*

2. *Nutrients released from leaf litter decay are calculated by the model based on leaf composition, not input by the user. To provide an estimate for the baseline period, the input from this source was assumed the same as the UNRBA study period.*

3. *Two of the three major wastewater treatment plants were undergoing facility upgrades or optimization efforts in 2015. If 2015 is excluded, the average annual nitrogen load from 2016 to 2018 is 92,720 lb-N/yr. Loading by facility and year are provided in Section 4.5.4.*

Table 5-2. Annual Average Model Inputs of Phosphorus to the Watershed for the Baseline and UNRBA study Periods and Total Delivered Load to Falls Lake (values are calculated from model input and output files and do not denote significance in terms of accuracy)

Source	Gross Inputs for the Baseline Period (2005 to 2007) (lb/yr)	Gross Inputs for the Recent Period (2015 to 2018) (lb/yr)	Percent Change in Gross Input
Atmospheric deposition[1]	121,980 (based on ratio of precipitation amounts between the two periods)	150,592	23.4% increase
Agriculture (nutrient application before nutrient removal due to crop harvesting)	1,205,991	706,803	41.4% decrease
Developed Areas (nutrient application)	201,671	219,103	8.6% increase
Leaf litter decay (internal model process) [2]	385,588	385,588	Assume baseline same as study period
Treated Effluent from Major Wastewater (WW) Treatment Plants[3]	20,294	6,064	70.1% decrease
Treated Effluent from Minor WW Treatment Plants	943	564	40.2% decrease
Sanitary Sewer Overflows	29.7	20.2	31.8% decrease
Treated WW from Discharging Sand Filter Systems (DSF)	1,359	1,989	46.4% increase
Treated WW from Onsite WW Treatment Systems (no DSF)	11,987	16,183	35.0% increase
Total Gross Input	**1,949,842**	**1,486,906**	**23.7% decrease**
Total Simulated Load Delivered to Falls Lake After Reductions in Watershed	Baseline model has not been evaluated	**183,717**	Baseline model has not been evaluated
Percent of Gross Input Reaching Falls Lake (after WW treatment)	Baseline model has not been evaluated	**12.4%**	Baseline model has not been evaluated
Percent Reduction of Nutrient Inputs (after WW treatment)	Baseline model has not been evaluated	**87.6%**	Baseline model has not been evaluated

1. *The WARMF watershed model for the baseline period has not been developed from which to simulate wet and dry deposition. Based on a literature review conducted by Dr. Daniel Obenour funded by the NC Collaboratory, phosphorus deposition is highly corrected to precipitation amounts. Phosphorus is not subject to the same air quality controls as nitrogen. For phosphorus, the average annual precipitation amount recorded by CASTNET at the Candor site for the baseline period (2005 to 2007) was divided by the precipitation rate for the UNRBA study period (2015 to 2018). This ratio (0.81) was used to scale the average deposition rates simulated by WARMF for the recent period and approximate inputs in the baseline period for comparison to other sources listed in the table.*
2. *Nutrients released from leaf litter decay are calculated by the model based on leaf composition, not input by the user. To provide an estimate for the baseline period, the input from this source was assumed the same as the UNRBA study period.*
3. *Two of the three major wastewater treatment plants were undergoing facility upgrades or optimization efforts in 2015. If 2015 is excluded, the average annual load from 2016 to 2018 is 4,835 lb-P/yr. Loading by facility and year are provided in Section 4.5.4.*

Section 6

Watershed Model Calibration and Comparison to Other Estimates of Loading to Falls Lake

After preliminary model setup and initialization, the modeler calibrates, or adjusts, the model coefficients so that simulated values represent the observations in terms of magnitudes and trends (seasonal, hydrological, etc.). This process uses reasoned revisions of model coefficients to obtain a “fit” to the data that minimizes differences relative to the set of observations. As described in Section 4.4, the observations themselves have some inherent uncertainty and variability, and sometimes more than one observation is available for a given location and time step. Typically, undetermined or unmeasured variables in the model are set based on default model coefficients and then are adjusted during calibration based on similar studies, literature, research, or input provided by subject matter experts.

For the UNRBA modeling, model performance is evaluated relative to criteria described in the UNRBA Modeling QAPP. WARMF has a scenario manager that can create scenarios for alternative evaluations, and the scenario manager can be used to aid the calibration of coefficients. A scenario in WARMF contains a set of model input coefficients and the corresponding simulation results. At the beginning of calibration, the model is first run with default model coefficients. This default case is copied to create a test scenario, which is then modified to test different coefficients values, and the test scenario is run through the WARMF menu. WARMF can display the simulated results for the default case, the test scenario, and the observed data on a graph. The results for the default case and test scenario are shown in different colors and overlaid with black circles for the observed data. The simulation results can be compared to the observed data visually or by examining error statistics to determine which set of model coefficients produces a better match with the observations. Figure 6-1 illustrates an example comparison between two scenarios and measured ammonia concentration data in the Little River watershed. The soil nitrification rate was decreased in catchments upstream of the water quality monitoring location to produce the difference between the two scenarios. If an improvement is made by increasing/decreasing a coefficients value, it can be increased/decreased some more to determine if additional change is helpful. If the results get worse, the change can be made in the reverse direction. The procedure can be repeated until an adequate calibration is achieved. To continue the calibration for the next coefficients, the modeler can copy the test scenario to a new scenario. The new scenario is then modified so that its simulation results match the observed data more closely than the previous test scenario.

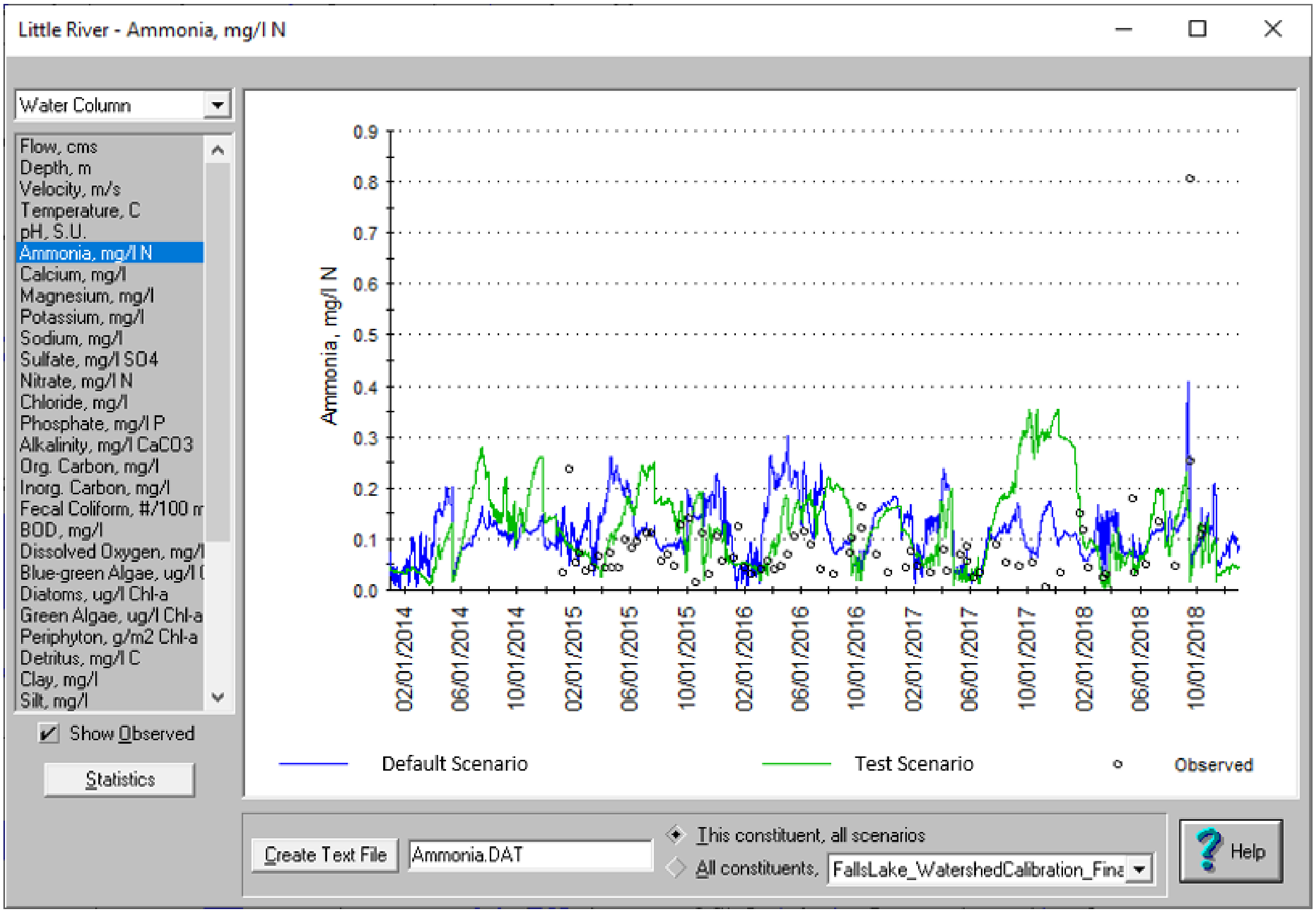


Figure 6-1. Example of Default and Test Scenarios Compared to Observations in the WARMF Menu

Section 6.1 summarizes the model performance criteria from the UNRBA Modeling QAPP and describes the coefficients that were adjusted to calibrate the model. Section 6.2 summarizes the hydrologic calibration and performance of the model, and Section 6.4 summarizes the water quality calibration and performance.

6.1 Model Calibration and Performance Criteria

The Falls Lake WARMF model has been developed and calibrated to simulate stream flows (hydrology) and water quality concentrations observed in the watershed. Model calibration is the adjustment of model coefficients so that simulated stream flows and water quality provide a good representation of the processes occurring in the watershed. To evaluate the model calibration, simulated values are compared to observations, and adjustments to model coefficients are made until a relatively close fit is achieved. Adjustments to coefficients should conform to physical, chemical and biological realities to best represent the system.

There are tradeoffs in calibration in which the modeler may prioritize different parts of the flow regime or water quality constituents. For example, achieving a better match for one flow regime may result in a poorer match for another. Or, improving the fit on simulated ammonia concentrations may result in poorer fit on nitrate concentrations. The

Adjustments to coefficients should conform to physical, chemical and biological realities to best represent the system.

emphasis of the calibration should be dictated by the purpose of the modeling. If the primary concern is concentration of pollutants at low flow (e.g., simulating concentrations for a permitting analysis for low flow conditions) then calibrating the hydrologic baseflow should be the priority. Conversely, if the primary concern is pollutant loading to a downstream waterbody, the focus of hydrologic calibration may shift to the accurate simulation of high flow events. Similarly, if ammonia concentrations are much lower than nitrate concentrations and therefore contribute less to nitrogen loading, then achieving a good fit on ammonia concentrations would be less of a priority compared to nitrate concentrations.

Water quality calibration follows hydrologic calibration and includes concentrations of sediments, nutrients, carbon, and algae transported in streams to Falls Lake. The modeling catchments of the UNRBA WARMF watershed model were established to coincide with UNRBA monitoring stations and the UNRBA study period (2015 to 2018) corresponds to the monitoring program conducted by the Association. As specified in the UNRBA Modeling QAPP, water quality calibration focuses on the largest five tributaries that drain to Falls Lake above Interstate 85. These five tributaries deliver over 70 percent of the water to Falls Lake and the majority of the loading. These tributaries are also gaged by USGS and were evaluated for hydrologic performance as well.

The primary hydrologic and water quality performance criteria described in the UNRBA Modeling QAPP are summarized in Section 6.1 with performance results summarized in Sections 6.2 and 6.4. Appendix F provides additional performance statistics listed in the UNRBA Modeling QAPP as well as scatter plots for simulated parameters. Overall, the model performs in the very good, good, or fair ranges of performance, but some stations and parameters are under or overpredicted in terms of simulated concentrations. Some of the challenges associated with model calibration are described in Section 6.2 along with a discussion of implications for developing the lake models which receive output from the watershed model. Evaluation of loading to Falls Lake and comparison to other loading estimates are provided in Section 7.

The UNRBA Modeling QAPP lists the statistical measures of goodness of fit between measured and simulated flow that were used to support the calibration effort and evaluate the model performance (e.g., percent bias, R^2, RMSE, etc.). At the locations where continuous streamflow is measured, criteria based on Lumb, et al. (1994) and Donigian (2002) were used as targets for hydrology calibration in this study. These criteria use the percent bias in aggregated flow characteristics between simulated and observed. The percent bias is a measure of model error relative to the observed mean and is calculated as follows:

Percent Bias:

$$\%Bias = \frac{\sum P - O}{\sum O} \times 100$$

Where,

O is the observed measurement (or aggregate of the observed)

P is the predicted model result (or aggregate of the predictions)

Target ranges are identified for very good, good or fair performance for multiple model error components as shown in Table 6-1. These percent bias performance criteria were used to guide the hydrology calibration for the UNRBA Falls Lake WARMF model.

Table 6-1. Hydrology Calibration Percent Bias Performance Criteria			
Prediction Error	Very Good	Good	Fair
Error in total volume	≤ 5%	5-10%	10-15%
Error in annual volumes[1]	≤ 10%	10-15%	15-25%
Error in volume of 50% lowest flows	≤ 10%	10-15%	15-25%
Error in volume of 10% highest flows	≤ 10%	10-15%	15-25%
Seasonal volume error – Summer	≤ 15%	15-30%	30-50%
Seasonal volume error – Fall	≤ 15%	15-30%	30-50%
Seasonal volume error – Winter	≤ 15%	15-30%	30-50%
Seasonal volume error – Spring	≤ 15%	15-30%	30-50%

[1] This statistic was listed in the UNRBA Modeling QAPP as a monthly statistic. The modeling team discussed with DWR modeling staff who approved a correction to an annual statistic via personal communication from Pamela Behm to Forrest Westall on April 6, 2020.

Additional statistics that are commonly used to evaluate streamflow simulations were also calculated to further guide the hydrology calibration process at gaged locations. These values are defined in the UNRBA Modeling QAPP.

For water quality variables, a similar 3-tiered system of categorizing statistical performance developed by Donigian (2002) was used for calibration guidance at the locations where statistical water quality calibration was performed. The system is based on the percent bias measure (defined above) with the categorized values shown in Table 6-2. As described previously, these statistical measures are used to supplement graphical evaluation of the model results and aid in determining the endpoints of model calibration.

Table 6-2. General Watershed Model Calibration Guidance			
Parameter	% Bias Criteria		
	Very Good	Good	Fair
Sediment	< ± 20	± 20-30	± 30-45
Water Temperature	< ± 7	± 8-12	± 13-18
Nutrients/chlorophyll-a	< ± 15	± 15-25	± 25-35

6.2 Calibration Challenges, Third-Party Review, and Model Approval by UNRBA

Watershed models aim to simulate many processes that impact hydrology and pollutant loading. Accurate characterization of the watershed, meteorology, and nutrient inputs impact how well the model performs. Accuracy of the stream flow data and water quality observations also impact performance. Limitations associated with the input data sets were described in Section 3 and Section 4.

The UNRBA Modeling QAPP describes the visual evaluations and statistical criteria used to gage the watershed model performance. While the goal is to achieve the best fit across as many parameters and locations as possible, there are constraints not only on model inputs but also on time and model development resources. As the watershed model provides crucial input to the WARMF Lake and EFDC models of Falls Lake, its timely completion is important to meet the schedule of the reexamination.

The following challenges were discussed during MRSW and PFC meetings as the model was developed in addition to those associated with watershed characterization and input data sets:

- **Model limitations for river reaches** – The WARMF watershed model has been developed to simulate the transport of flow and material primarily through river reaches (impoundments can be simulated as well). When the simulated flow in a river reach goes to zero, the model does not output a simulated concentration. Because river reaches are generally flowing, growth of algae in the simulation is difficult to achieve. To overcome these limitations and allow some growth of algae to occur prior to discharge to Falls Lake, some storage in the downstream reaches was assumed. These storage areas affect other water quality parameters as well, and the calibration aimed to fit as many parameters as possible. River reaches are also assumed fully mixed across the water column which impacts the water temperature and dissolved oxygen concentrations simulated by the model. These parameters are important drivers of many reaction rates.
- **Hydrologic response** – some of the streams in the Falls Lake watershed have a “flashy” hydrologic response where the stream flows rise and fall relatively quickly in response to storm events. To simulate these patterns, the vertical hydraulic conductivities in these modeling catchments (e.g., Ellerbe Creek) were decreased relative to other catchments in the Triassic Basin. Triassic Basin soils already have lower vertical hydraulic conductivities compared to Carolina Slate Belt and Raleigh Belt soils. Decreasing the vertical hydraulic conductivities has the effect of lowering the baseflow contribution to the streams and limiting the amount of interaction with the subsurface soil layers in these catchments. Adjustments of vertical hydraulic conductivities were applied to catchments draining to a USGS stream flow gage, or to the catchments between two gages if applicable. Vertical hydraulic conductivities for ungaged tributaries were set based on those applied to gaged catchments in close proximity.
- **Low observed concentrations** - When observed concentrations are very low on average, it can be difficult to meet the performance criteria which are based on percentages. Low concentrations of some parameters may not greatly affect loading to the lake especially if they occur during low flows. For parameters that are linked in terms of reaction rates or other factors, the modeler may prioritize improving the model fit for the parameter that is a more substantial part of the load. For example, if the average ammonia concentration is 0.1 mg-N /L, a 50 percent bias could represent an average concentration of 0.05 mg-N /L or 0.15 mg-N /L. A difference in concentration of 0.05 mg-N/L does not significantly affect overall nitrogen loading to Falls Lake (0.05 mg-N/L in 100 L of water is 5 mg-N). Alternatively, if the average nitrate concentration is 1 mg-N/L, a 50 percent bias could be 0.5 mg-N /L or 1.5 mg-N /L. These higher concentrations have a greater potential to impact loading to the lake (0.5 mg-N/L in 100 L of water = 50 mg-N).
- **Model input limitations** - The model can only be as good as its inputs. While this watershed model represents more data and information than is usually available, some localized events may not be captured by the input data. For example, nitrate observations in Knap of Reeds Creek at the lake loading station (KRC-4.5) indicate relatively high concentrations for a period in late 2015 and early 2016 (Figure 6-2). These could be due to variations at the WWTP that were not captured by the composite sampling conducted during that period, sanitary sewer overflow(s) that were not identified, or some other illicit discharge. The model does not perform well at this location during this period because the input files do not accurately reflect nutrient inputs to the stream. This negatively impacts the performance criteria at Knap of Reeds Creek for the calibration period, but the statistics improve during the validation period when the higher concentrations are no longer present. The only way to improve this situation would be to adjust the model input files until the simulated concentrations match those observed, which would not be considered good modeling practice.
- **Upstream impoundments** - The presence of upstream impoundments in the watershed also complicates the calibration. Frequent water quality measurements in these waterbodies are not available, so it is difficult to evaluate how well the model is simulating their processes. It is also difficult to pinpoint the

best adjustments to model coefficients because these impoundments are less studied than Falls Lake. At the suggestion of the MRSW, the modeling team reviewed quarterly USGS measurements where available. This data guided revisions to simulated processes in Little River Reservoir and nitrogen simulations downstream at LTR-1.9 improved as a result. Further improving simulation of these impoundments could take a significant amount of effort given lack of information. Without extensive data, there is no reasonable way to develop appropriate lake behavior. For these reasons, the model calibration at stations downstream of these impoundments was deemed sufficient by the MRSW and PFC.

- **Inconsistencies with simulated time steps and point-in-time observations** - Time presents another challenge to the model calibration. Water quality observations are collected at specific points in time and represent instantaneous conditions. The WARMF model time step is 6-hours, so each model output represents a 6-hour average, not a specific moment in time. Water quality sampling represents a specific point in time, not an average condition. Water quality concentrations can change quickly, especially in response to storm events.

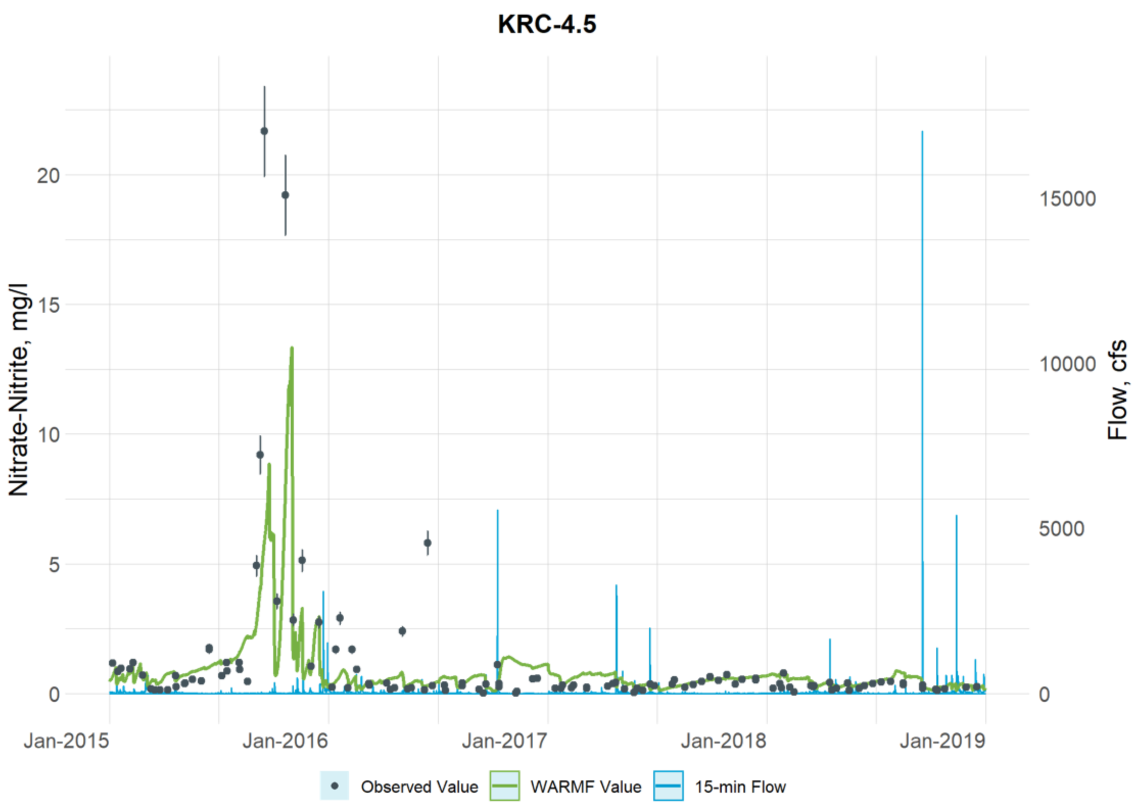


Figure 6-2. Simulated Versus Observed Nitrate Concentrations at Knap of Reeds Creek (2015 to 2018) (vertical bars are used to illustrate the uncertainty with laboratory analyses and are based on the 95th percentile confidence interval calculated from the UNRBA data for each parameter)

As part of the review of the model calibration and performance, the modeling team described the challenges with further improvements to performance criteria and model fit at a special meeting of the MRSW on August 27, 2021. The MRSW reviewed this information and considered the adequacy of the model in light of the intended uses of the watershed model. The MRSW approved the model calibration and its use for developing the lake models during the special meeting, and the PFC approved the model at its meeting on September 7, 2021. Following these approvals, the lake modelers began preliminary water quality calibration of the lake models, and the subject matter experts and "third-party" reviewers began their review of the watershed modeling results including source load allocations and areal loading rates by land use. This review resulted in modifications to the nitrogen simulation and running the model iteratively five times rather than three. Refined performance results were presented to and re-approved by the MRSW on January 4, 2022, and the PFC on February 1, 2022. The model results presented in this report reflect these refinements.

6.3 Hydrologic Calibration and Performance

Water quality and algal response in Falls Lake is related to both the quantity and timing of nutrient loading to the lake from the upstream watershed, in addition to other factors like residence time and light availability. Nutrient loading and residence time in Falls Lake are primarily driven by hydrology, so accurate simulation of flow is important to understanding nutrient loading and lake response. Loading is the combination of concentration and flow to provide a "mass" of pollutant moving through the streams. Therefore, hydrologic calibration of the UNRBA Falls Lake WARMF model prioritized accurately predicting the water volume transported to Falls Lake over annual and seasonal time frames, during high flow events and during baseflow conditions. Water quality simulations are evaluated for performance over the UNRBA study period for the calibration years (2015 and 2016), the validation years (2017 and 2018), and the full simulation period (2015 to 2018).

Model coefficients are adjusted during the calibration process to minimize the differences between model simulations and observations. Table 6-3 summarizes the WARMF coefficients to which the hydrologic calibration is generally most sensitive, as described in the WARMF user's guide (Herr et al., 2001) and at http://www.warmf.com. Catchment, soil layer, and reach-level coefficients are provided in Appendix B. Systemwide coefficients are global and have the same value for every catchment in the watershed; these are calibrated prior to the catchment, river, and lake coefficients. For example, the impervious fraction varies by land use but applies everywhere each land use occurs. The other model coefficients are set uniquely for individual catchments, river segments, or reservoirs. Local data may constrain some of these coefficients, but most can be adjusted within reasonable ranges. Default values serve as a starting point, and adjustments, within a reasonable range, are made to improve the match between simulated and measured hydrology. Each coefficient has a unique effect on different aspects of the water balance: long-term flow balance, seasonal variation, and the shape of the hydrograph when driven by precipitation and/or snowmelt events.

Table 6-3. Hydrologic Calibration Coefficients for the UNRBA Falls Lake WARMF Model			
Coefficient	Type	Effect on Hydrograph	Range
Evaporation magnitude (scaling factor, unitless)	Systemwide	Long-term	0.6 - 1.4
Evaporation skewness (scaling factor, unitless)	Systemwide	Seasonal	0.6 - 1.4
Impervious fraction (developed land uses)	Systemwide by land use	Event hydrograph	0.1-0.8
Precipitation weighting factor (scaling factor, unitless)	Catchment and lake/reservoir	Long-term, event hydrograph	0.9-1.026
Soil layer thickness (cm)	Catchment, soil layer	Seasonal, event hydrograph	1-51
Soil initial moisture (fraction, by volume)	Catchment, soil layer	Seasonal, event hydrograph	0.16-0.48
Soil field capacity (fraction, by volume)	Catchment, soil layer	Seasonal, event hydrograph	0.14-0.48
Soil saturation moisture (fraction, by volume)	Catchment, soil layer	Seasonal, event hydrograph	0.28-0.55
Soil hydraulic conductivity, horizontal (cm/day)	Catchment, soil layer	Seasonal, event hydrograph	5-245,000
Soil hydraulic conductivity, vertical (cm/day)	Catchment, soil layer	Seasonal, event hydrograph	2-25
Soil root distribution (fraction of total)	Catchment, soil layer	Seasonal, event hydrograph	0-0.8
Surface Manning's n factor (unitless)	Catchment	Event hydrograph	0.1-0.8
Detention storage (percent of surface water which is not available for surface runoff)	Catchment	Event hydrograph	0-10
Stream Channel Manning's n factor (unitless)	River	Event hydrograph	0.02 – 0.045
Wind speed multiplier (scaling factor, unitless)	Lake/reservoir	Long-term	1-1.2

The long-term flow volume is a function of the amounts of precipitation, evaporation, and transpiration. When meteorological data are imported into WARMF, precipitation weighting factors are automatically calculated for each catchment to approximate precipitation in catchments without a direct measurement. Since there are more catchments than meteorology stations, the precipitation in a catchment is approximated by multiplying the precipitation of the station used by the catchment by a constant factor so there is a linear spatial gradient in average precipitation among catchments between stations. The precipitation weighting factor can be adjusted manually by the modeler if a linear spatial gradient in precipitation does not fit the local circumstance.

Evapotranspiration is calculated by WARMF as a function of sun angle, temperature, humidity, and soil moisture. There are two model coefficients to calibrate the overall magnitude and seasonal skewness of evapotranspiration.

The seasonal flow balance and shape of the storm hydrograph depend largely on how water is stored in and released from the soil and snowpack. The thickness of the soil and the amount of void space controls how much storage is available for precipitation and snowmelt without producing overland flow. The hydrograph of a watershed with thin soils has a high ratio of peak flow to baseflow, whereas thicker soils capture water and release it more slowly. In addition to soil layer thickness, the shape of the simulated storm hydrograph depends on a combination of soil thickness, field capacity, saturation moisture, and the hydraulic conductivity of the soil layers.

The calibration period for the UNRBA Falls Lake models is 2015 and 2016. A separate validation period (2017 to 2018) was also run to verify that the model performs relatively well for an independent period. Table 6-4 shows the performance of the calibrated model relative to observations at USGS flow gages in the watershed. The table is color-coded such that values ranked "very good" are dark green, "good" are light green, "fair" are yellow, and values that are not at least "fair" are orange. Negative values indicate the model is simulating less flow than recorded, and positive values indicate the model simulated more flow than was recorded. Gages closest to Falls Lake on the five largest tributaries were prioritized for calibration. The most downstream gages on the five largest tributaries are denoted in the table with a "*" preceding their name. Because of the complexities associated with the operation of Little River Reservoir, USGS recorded flows downstream of the impoundment were assigned as a times series to prescribe outflow from this reservoir. If the model underpredicted flow during one period (calibration or validation) and overpredicted in the other, further adjustments were not attempted as the statistic would improve in one period but likely worsen in the other. There is some uncertainty with the gaged flows particularly during flow extremes as described in Section 4.3.1. While the NEXRAD precipitation data provides good coverage of rainfall patterns, some storms are missed or over-predicted. Simulated flows from upstream impoundments with little flow release data also introduced challenges for calibration. Despite these challenges, based on the performance criteria listed in the UNRBA Modeling QAPP, the model generally performs in the "good" to "very good" range for total stream flows as well as annual, summer, and winter periods at these eight gages. Six of the gages also rank "good" to "very good" for the fall and spring seasons, but Knap of Reeds and Flat River below Lake Michie rank "fair" for these two seasons. For the 10 percent highest flows, the model ranks "good" to "very good" at all gages except Knap of Reeds Creek; this gage is located in a swampy area with a large flood plain that is both difficult to simulate and to gage with a high degree of accuracy. The model ranks "fair" to "low" at three of the gages for the 50 percent lowest flows. Model inaccuracy at low flows does not significantly impact overall simulated nutrient loading to Falls Lake which is primarily driven by high flows and there is more uncertainty in the gaged flow estimates when flows are low (Section 4.3.1). For most of the seasons and locations, the seasonal simulations are in the "good" to "very good" range.

In addition to the performance statistics included in Table 6-4, the MRSW requested scatter plots of simulated and observed values as well as time series comparisons. Figure 6-3 shows the scatter plot and R^2 values for each gage which generally range from 0.5 to 0.7. R^2 values are calculated from individual observations and simulation values and were not assigned criteria in the UNRBA Modeling QAPP. R^2 values are affected by the timing of the hydrologic response, so if the model predicts that the storm peak occurs during a time step different than that observed, the R^2 value will be lower. The model was calibrated with a focus on minimizing percent bias as described in Section 6.1 as this is less affected by the timing of specific storms.

Figure 6-4 and Figure 6-5 present the comparisons between simulated and observed values as time series for the calibration (2015 and 2016) and validation periods (2017 and 2018), respectively. Figure 6-6 shows the comparison across the four-year period (2015 to 2018). Individual time series figures for each gage are provided in Appendix G.

Table 6-4. Hydrologic Percent Bias for Calibration (2015-2016), Validation (2017-2018), and Full Period (2015-2018)

Volume	Period	Ellerbe - Club Boulevard (0208675010)	*Ellerbe - Gorman (02086849)	Eno - Hillsborough (02085000)	*Eno - Durham (02085070)	Flat - Bahama (02085500)	*Flat - Dam Near Bahama (02086500)	*Knap Of Reeds - Butner (02086624)	Little River - Orange Factory (0208521324)
Total	2015-2016	15	4	8	10	-4	-1	-9	15
	2017-2018	2	9	-9	6	-10	-11	7	2
	2015-2018	8	7	-1	8	-8	-7	0	8
Annual	2015-2016	15	4	8	10	-4	-1	-9	15
	2017-2018	2	9	-9	6	-10	-11	7	2
	2015-2018	8	7	-1	8	-8	-7	0	8
50% lowest flows	2015-2016	-54	-10	-14	-5	-1	27	-29	12
	2017-2018	-2	-3	4	-26	-10	-10	-28	-11
	2015-2018	-27	-7	-5	-16	-3	14	-26	0
10% highest flows	2015-2016	16	12	9	0	-15	-13	9	-7
	2017-2018	1	16	-13	7	-15	-13	23	-7
	2015-2018	7	14	-4	4	-15	-13	18	-6
Summer	2015-2016	-34	-17	-6	-12	15	26	-38	6
	2017-2018	-3	-2	-12	-4	23	31	46	6
	2015-2018	-21	-11	-10	-7	19	29	11	6
Fall	2015-2016	52	42	31	28	-18	-3	68	13
	2017-2018	-10	9	0	20	-6	-9	15	3

Table 6-4. Hydrologic Percent Bias for Calibration (2015-2016), Validation (2017-2018), and Full Period (2015-2018)

Volume	Period	Ellerbe - Club Boulevard (0208675010)	*Ellerbe - Gorman (02086849)	Eno - Hillsborough (02085000)	*Eno - Durham (02085070)	Flat - Bahama (02085500)	*Flat - Dam Near Bahama (02086500)	*Knap Of Reeds - Butner (02086624)	Little River - Orange Factory (0208521324)
	2015-2018	13	23	14	23	-11	-7	31	8
Winter	2015-2016	29	3	23	22	18	11	-14	11
	2017-2018	3	26	0	18	3	11	-11	5
	2015-2018	16	13	13	21	12	11	-13	9
Spring	2015-2016	3	-10	-30	-19	-30	-34	-56	-28
	2017-2018	19	5	-22	-9	-29	-31	-4	-25
	2015-2018	13	-1	-25	-13	-29	-32	-24	-26

The most downstream gages on the five largest tributaries are denoted in the table with a "" preceding their name.*

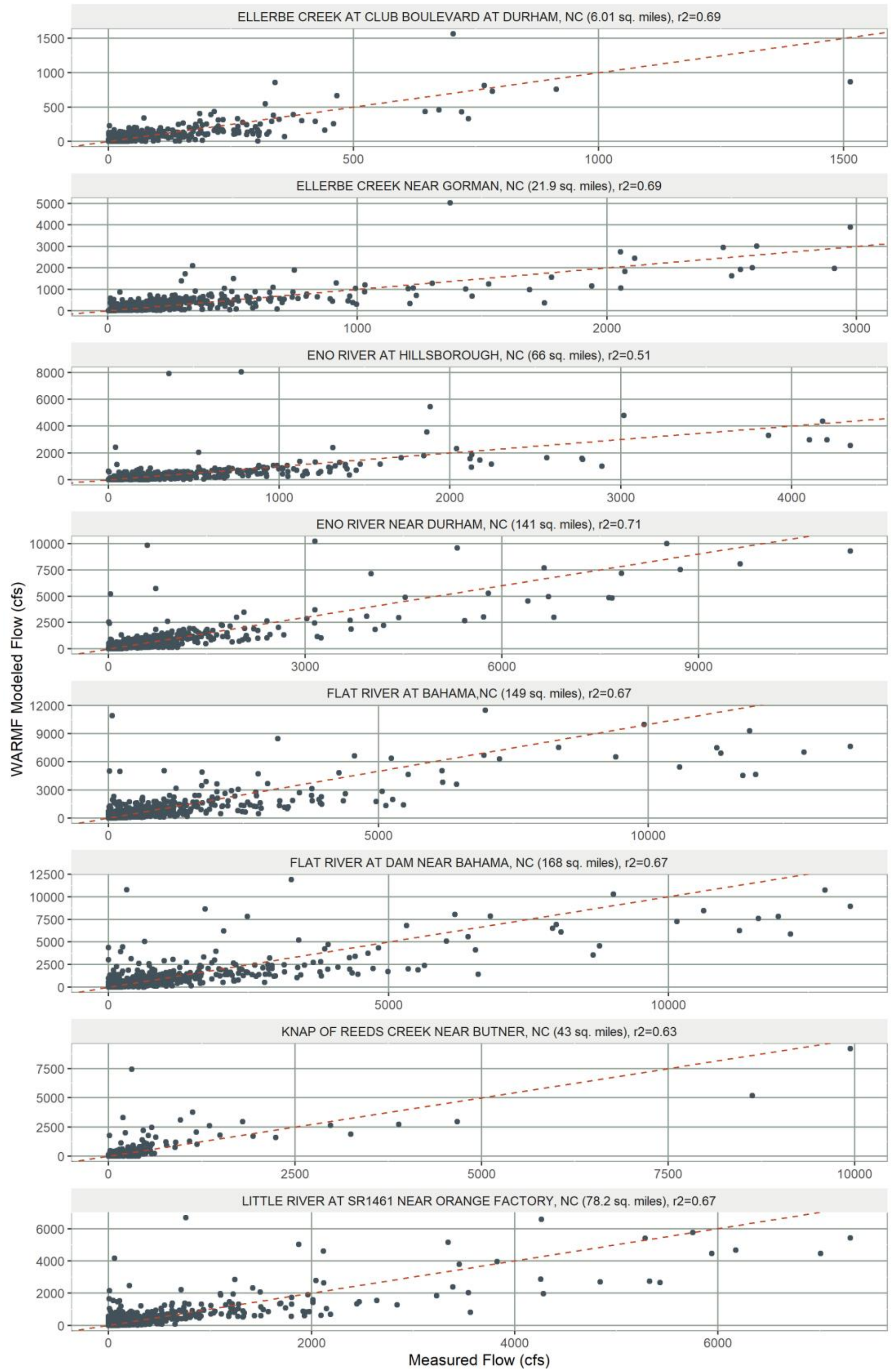


Figure 6-3. Scatter Plot of Simulated and Observed Stream Flows (2015 to 2018)

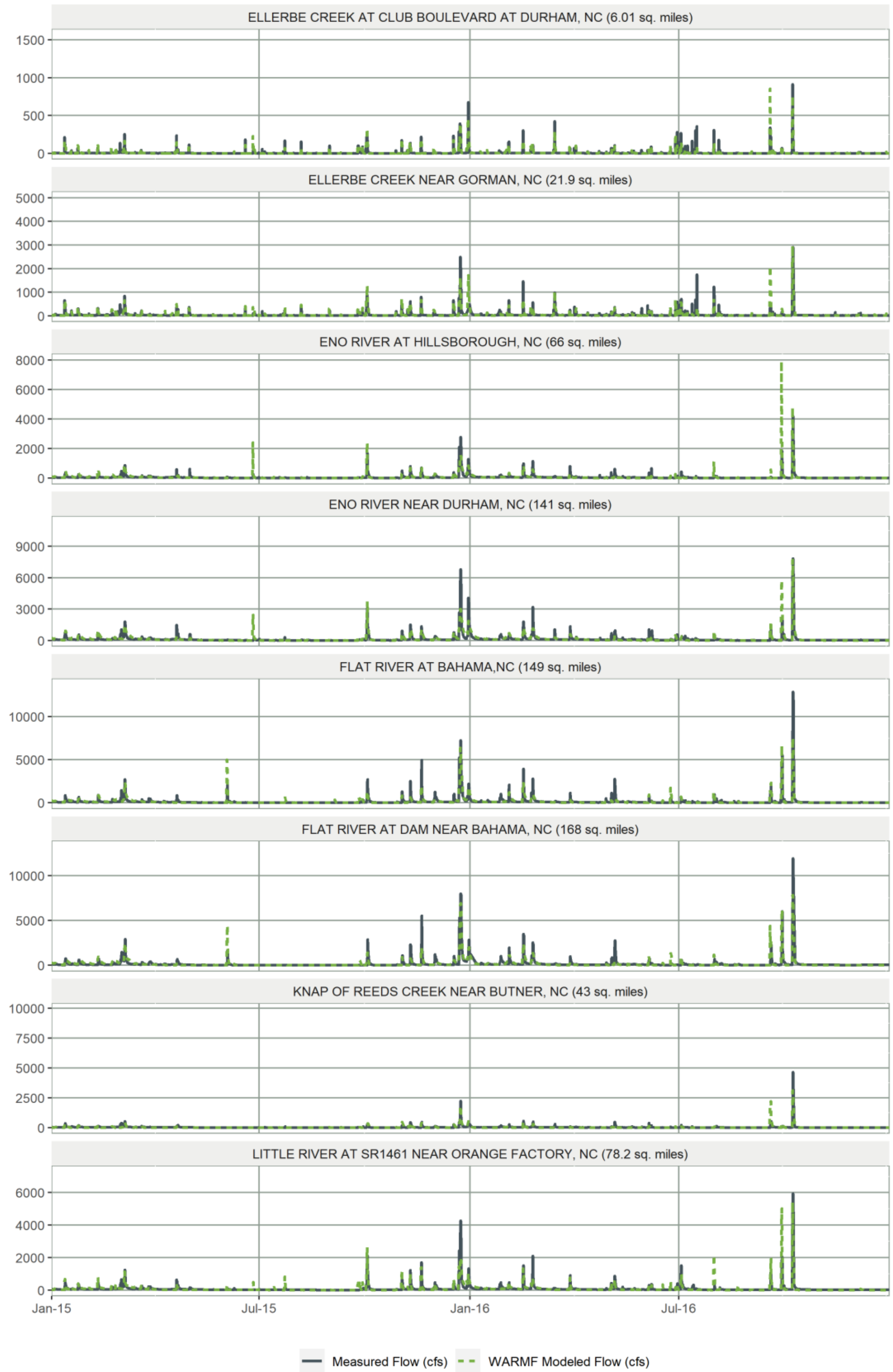


Figure 6-4. Time Series of Simulated and Observed Stream Flows for the Calibration Period (2015 to 2016)

Figure 6-5. Time Series of Simulated and Observed Stream Flows for the Validation Period (2017 to 2018)

Figure 6-6. Time Series of Simulated and Observed Stream Flows for the Recent Model Period (2015 to 2018)

6.4 Water Quality Calibration and Performance

As specified in the UNRBA Modeling QAPP, water quality performance is evaluated for a minimum of seven locations in the watershed on tributaries with gaged streamflow. The selected sites for calibration include the lake loading stations on the largest five tributaries draining to Falls Lake (ELC-3.1, ENR-8.3, LTR-1.9, FLR-5.0, and KRC-4.5), stations upstream of Lake Michie on Flat River (FLR-25) and Little River Reservoir on Little River (LTR-16), and a station approximately halfway up Eno River (ENR-23) for a total of eight calibration stations (Figure 4-12). Similar to the hydrologic performance summary in Section 6.2, water quality performance is summarized for the calibration (2015 to 2016), validation (2017 to 2018), and full modeling period (2015 to 2018) using the percent bias rankings described in the UNRBA Modeling QAPP. Downstream stations on these tributaries were prioritized for calibration because they represent pollutant loading to Falls Lake. Stations upstream of impoundments were selected to demonstrate the complexities of simulating impoundments when little is known about their operations and internal processes. Figure 4-12 shows the locations of these stations in the watershed.

WARMF water quality calibration is most efficiently conducted by following a specific order, reflecting the influence of individual constituents on others. Temperature is calibrated first, followed by total suspended sediment, conservative substances, nutrients, algae, and dissolved oxygen. In the Falls Lake WARMF model, conservative substances (e.g., sodium, potassium, calcium, etc.) were briefly addressed to ensure that sufficient concentrations of these parameters exist throughout the model domain so as not to limit the reactions of constituents that are the focus of this investigation. The model may be adequately calibrated at a location after one pass through the constituents of concern, or the modeler may have to iterate through the constituents, as changes made to constituents may affect the calibration of constituents that have already been addressed. For example, algae concentrations impact the penetration of solar radiation in a water body, which can in turn alter the simulated temperature of the water body. So additional changes to the temperature calibration may be required following the calibration of algae. The degree to which iteration through calibration constituents is required is influenced by watershed characteristics and is situationally dependent (e.g., if algae concentrations are low, algae simulation is unlikely to affect temperature). Once all constituents of interest have been adequately calibrated at a location, the process is repeated at the next downstream station.

The catchments, river reaches, and sub-impoundments in the Falls Lake watershed are spatially variable due to land use patterns, soil characteristics, stream morphometry, etc. The watershed model was calibrated to the UNRBA monitoring stations. Catchments upstream of a water quality monitoring station often have a common set of model coefficients unless there were data to indicate otherwise. A common set of model coefficients was not applied to every catchment and river reach across the watershed as this approach would not have met the performance criteria listed in the QAPP and would not represent the varying hydrologic and chemical properties of the soils and streams in the watershed.

For example, nitrification rates in river reaches range from 0.01/d to 0.2/d in the model. Nitrification is a biological process that converts ammonia to nitrate. There are 215 river reaches in the model. Most of the reaches (203) have a nitrification rate of 0.01/d. The remaining thirteen have nitrification rates of 0.1/d or 0.2/d. These reaches are either in Ellerbe Creek or downstream of the confluence of the Eno and Little Rivers. Increased nitrification rates were needed to convert simulated ammonia into nitrate at a faster rate that simulated with 0.01/d. These adjustments were made to better match observed ammonia and nitrate concentrations.

Another biological process simulated by the WARMF model is denitrification which simulates the conversion of nitrate to nitrogen gas. The nitrogen gas is lost from the system to the atmosphere. This process occurs under low oxygen conditions with sufficient organic material like wetland areas with saturated soils. In the WARMF model, each of the 264 catchments are assigned a soil denitrification rate. If soil layers within the catchment are simulated as saturated for an extended period of time, low dissolved oxygen conditions in the soils will be simulated. However, if saturated soils only occur in specific areas of a catchment, like along stream banks or in wetlands, and the model does not simulate saturated conditions across the entire catchment, denitrification in the soil layers will not be simulated. To overcome this model limitation, soil denitrification rates were increased in some catchments to better match the total nitrogen observed at the UNRBA monitoring stations. Soil denitrification rates in the model range from 0.001/d to 0.2/d. Most of the catchments (156 out of 264) have a denitrification rate of 0.001/d. These catchments are within the Carolina Slate Belt and represent the five largest tributary drainage areas. Carolina Slate Belt soils drain relatively quickly compared to other soils in the watershed like the Triassic Basin. Forty-eight of the catchments in the Lick Creek, Lower Barton, Smith Creek, Horse Creek, New Light Creek, Honeycutt Creek, and near lake drainages around these streams have a denitrification rate of 0.01/d; most of these catchments are in the Raleigh Belt with some in the Triassic Basin and a few in a small sliver of Carolina Slate Belt located between the Raleigh Belt and Triassic Basin on the south side of the lake. Fifty catchments in the Ledge Creek, Beaverdam Creek, Panther Creek, Upper Barton Creek, lower part of Little River, and the near lake drainages around these streams have a denitrification rate of 0.1/d; these catchments are predominantly in the Triassic Basin with a few in the Raleigh Belt. Ten catchments in the Little Lick Creek drainage have a denitrification rate of 0.2/d which is entirely in the Triassic Basin. Triassic Basin soils drain relatively slowly and the wetlands in the watershed are more commonly found in this geologic formation.

Diatom growth rates in stream reaches are another example where the UNRBA monitoring data were used to inform adjustment of model coefficients. Diatoms tend to be the dominate algae growing during cooler months. Diatom growth rates were used to calibrate the model to observed chlorophyll-a concentrations observed during winter months at the 17 UNRBA lake loading stations. Chlorophyll-a data were only collected at the mouths of the tributaries, not at upstream monitoring locations. Diatom growth rates in the river reaches range from 0.57/d to 4/d. The majority of the river reaches (190 out of 215) have diatom growth rates ranging from 1/d to 2/d. The highest diatom growth rates (3.5/d to 4/d) were assigned to reaches in Robertson Creek, Beaverdam Creek, and an unnamed tributary which saw the largest distributions of chlorophyll-a concentrations based on the UNRBA monitoring data (Figure 3-25 of the UNRBA 2019 Annual Monitoring Report). These reaches have stagnant sections where algae are more likely to grow. However, stream reaches in the WARMF model are assigned reach-averaged characteristics based on the National Hydrography Dataset. Increasing the diatom growth rate allows for more algal growth in the winter in these reaches. The lowest diatom growth rate assigned, 0.57/d, was applied to the river reaches in the Horse Creek drainage to better simulate the relatively low chlorophyll-a concentrations observed in this tributary. Leaving this reach at the higher growth rates resulted in over-prediction of chlorophyll-a at the mouth of this tributary.

Table 6-5 summarizes the water quality calibration coefficients that were used to calibrate the WARMF model in the Falls Lake watershed. Catchment, soil layer, and reach-level coefficients are provided in Appendix B. These coefficients include initial concentrations of minerals and chemical constituents in the soil profile; factors influencing heat transfer; rates governing chemical reactions, decomposition/decay of materials, biological processes; the diffusion of chemical inputs in water; and adsorption isotherms which control the balance between constituents bound to sediment and dissolved in solution.

Table 6-5. Water Quality Calibration Coefficients for the UNRBA Falls Lake WARMF Model			
Coefficient	Type	Effect on Water Quality Simulation	Range
Convective heat factor	Rivers	Effects stream temperature and the diurnal temperature cycle	2E-07 to 1E-05
Percent stream shading	Rivers	Effects stream temperature and the diurnal temperature cycle	25 to 100
Reaeration rate multiplication factor	Rivers	Effects the rate of oxygen exchange between the atmosphere and the river water column	0.1 to 1.25
Wind speed factor	Reservoirs	Effect the evaporative loss from water bodies, and the heating/cooling of reservoir surface waters	1 to 1.2
Depth of radiation fraction	Reservoirs	Effect the evaporative loss from water bodies, and the heating/cooling of reservoir surface waters	0.5
Fraction of radiation absorbed in top layer	Reservoirs	Effect the evaporative loss from water bodies, and the heating/cooling of reservoir surface waters	0.5
Sediment detachment velocity multiplier	Rivers	Effects sediment transport and streambank erosion	5E-8 to 8E-6
Sediment detachment velocity exponent	Rivers	Effects sediment transport and streambank erosion	1.3-2.0
Vegetation stability factor	Rivers	Effects sediment transport and streambank erosion	0
Bank stability factor	Rivers	Effects sediment transport and streambank erosion	5E-8 to 0.001
Nitrification (1/d)	Catchments, Rivers, and Reservoirs	Effects the rate at which ammonia is converted to nitrate	0.005 to 0.2
Denitrification (1/d)	Catchments, Rivers, and Reservoirs	Effects the rate at which nitrate is converted to N2 gas, reaction is restricted to low simulated dissolved oxygen conditions (<2 mg/L)	0.001 to 0.5
Wetland Denitrification (1/d)	Catchments, Rivers, and Reservoirs	Same effect as Denitrification, but without the anoxic requirement (necessary to simulate process when modeling unit (e.g., reach) is not simulated as anoxic)	0 to 0.4
Organic Carbon Decay (1/d)	Catchments, Rivers, and Reservoirs	Effects the rate at which organic carbon breaks down into its constituent components	0 to 0.1
Algae Growth Rate (1/d)	Rivers and Reservoirs	Algae kinetics effect the concentration of nutrients and organic carbon	0.57 to 2.5
Algae Respiration Rate (1/d)	Rivers and Reservoirs	Algae kinetics effect the concentration of nutrients and organic carbon	0.01 to 0.15
Algae Death Rate (1/d)	Rivers and Reservoirs	Algae kinetics effect the concentration of nutrients and organic carbon	0.01 to 0.1
Algae Settling Rate (m/d)	Rivers and Reservoirs	Algae kinetics effect the concentration of nutrients and organic carbon	0 to 1
Water Column Ammonia Adsorption (L/kg)	Rivers and Reservoirs	Effects the affinity of ammonia to bind to suspended sediment particles, thereby changing transport pathways	6,233
Water Column Phosphate Adsorption (L/kg)	Rivers and Reservoirs	Effects the affinity of phosphate to bind to suspended sediment particles, thereby changing transport pathways	10,000 to 15,000
Sediment/Soil Ammonia Adsorption (L/kg)	Catchments, Rivers, and Reservoirs	Effects the affinity of ammonia to bind to sediment in the soil (in catchments) and river/reservoir bed	15 to 6,233

Table 6-5. Water Quality Calibration Coefficients for the UNRBA Falls Lake WARMF Model

Coefficient	Type	Effect on Water Quality Simulation	Range
Sediment/Soil Phosphate Adsorption (L/kg)	Catchments, Rivers, and Reservoirs	Effects the affinity of phosphate to bind to sediment in the soil (in catchments) and river/reservoir bed	300 to 15,000
Minimum Water Column Diffusion (m^2/d)	Reservoirs	Effects the minimum rate at which chemical constituents disperse throughout the water column	0.005
Sediment Diffusion (m^2/d)	Reservoirs	Effects the rate at which chemical constituents move from the reservoir bed to the water column and vice versa	8E-06 to 3E-05
Initial Concentrations (mg/L)	Catchment, River, and Reservoir Coefficients	Initial concentrations of chemical constituents in catchment soils have a big impact on simulation results over the first several years of the simulation. Rivers and reservoirs flush out more quickly.	See Table 3-2 and Table 3-3
Percent Mineral Composition	Catchments	Mineral content in soil layers provide a source of ions in the soil.	1-15
Mineral Weathering (1/year)	Catchments	The weathering rate dictates how fast the minerals break down into their constituent components	0.002-0.02

It is important to note that there are many other coefficients in the WARMF model that have a direct impact on the water quality simulation. For example, coefficients adjusted during the hydrology calibration will also affect water quality because they impact residence times, flow pathways, and flow velocities. Table 6-5 has been constrained to include only those coefficients that were adjusted specifically for the purpose of altering the water quality simulation.

Table 6-6 summarizes the observed mean concentrations for each parameter and the percent bias statistics for the water quality calibration (2015 to 2016) and validation (2017 to 2018) periods as well as the full period (2015 to 2018). The table is color-coded such that values ranked “very good” are dark green, “good” are light green, “fair” are yellow, and values that are not at least “fair” are orange. Negative values indicate the model is simulating lower concentrations on average than those observed, and positive values indicate the model simulated higher concentrations on average than those observed. Monitoring stations closest to Falls Lake on the five largest tributaries were prioritized for calibration. If the model underpredicted concentrations during one period (calibration or validation) and overpredicted in the other, further adjustments were not attempted as the statistic would improve in one period but likely worsen in the other.

The summary rankings for the water quality performance are described below in terms of the full modeling period for the most downstream station on each tributary included in Table 6-6:

- Temperature performance is “good” to “very good”
- The WARMF model output for total suspended solids (TSS) includes only silt and clay. Laboratory measurements include all suspended particles greater than a specified size. The UNRBA monitoring program also collected measurements of volatile suspended solids (VSS) at the lake loading stations. Simulated concentrations of TSS are compared to measured TSS minus measured VSS in the evaluation of model performance to eliminate the portion of TSS that is organic material. TSS measurements without a paired VSS measurement were excluded from the performance evaluation. TSS is generally underpredicted with Eno River, Knap of Reeds Creek, and Little River achieving rankings of good to fair.
- Ammonia performance is “very good” at Ellerbe Creek, “good” at Flat River and Knap of Reeds Creek, and just over the criteria for “fair” at Eno River. The model does not meet the requirement for “fair” for simulated ammonia concentrations at Little River where the model underpredicts ammonia concentrations. Observed ammonia concentrations are relatively low in this tributary (observed mean is 0.08 mg-N/L). Low ammonia concentrations do not greatly affect total nitrogen loading to Falls Lake.
- Nitrate performance is “very good” Ellerbe Creek and “good” at Eno River. The model does not meet the criterial for fair at Little River, Flat River, and Knap of Reeds Creek where nitrate is underpredicted. At Little River and Flat River, the mean observed nitrate concentration is less than 0.2 mg-N/L. The model underpredicts nitrate at Knap of Reeds due to missing information in the middle of the calibration period; the model is “very good” for nitrate during the validation period.
- Total Kjeldahl Nitrogen (comprised of organic nitrogen and ammonia) is “very good” at Eno, Flat, and Little Rivers and at Knap of Reeds Creek. Simulated TKN at Ellerbe Creek is “fair.”
- Total nitrogen performance is “very good” at Little, Flat, and Eno Rivers and “good” at Ellerbe Creek and Knap of Reeds Creek. At Knap of Reeds Creek for the calibration period, the simulation for TN is “fair” due to missing information (Section 6.2) during the calibration period (late 2015 to early 2016), but the model is “very good” during the validation period (2017 and 2018). While the simulation of the individual nitrogen species summarized in the preceding bullets (ammonia, nitrate, Total Kjeldahl Nitrogen) is sometimes less than “fair”, the model performs “good” to “very good” at these five stations for total nitrogen for the full model period.
- Total phosphorus performance at these five stations is “good” to “very good” except at Knap of Reeds Creek where the model underpredicts phosphorus concentrations during a period in late 2015 and early 2016. A period of high phosphorus concentrations was observed in the creek as part of the UNRBA

Monitoring Program at this location. The model performance is "very good" at this location for the validation years (2017 and 2018).

- Total organic carbon performance is "very good" at these five stations except at Knap of Reeds Creek where the performance is just outside of the threshold for "very good" and ranks "good."
- Chlorophyll-a in the tributaries to Falls Lake is generally underpredicted by the watershed model compared to observations, and the model does not meet the criteria to be considered "fair" except at Little River. In streams, measured chlorophyll-a is likely due to sloughing of periphyton, not floating algae, and so the species in the tributaries are different than those prevalent in Falls Lake. The observed mean chlorophyll-a concentrations in the tributaries ranges from 3.5 µg/L to 12.6 µg/L which are lower than the mean concentrations observed in Falls Lake. Underpredicting the concentrations in the tributaries is not anticipated to negatively affect the lake model where growing conditions for algae are better and observed concentrations are usually higher than those measured in the tributaries. This is particularly true when concentrations are low. For example, if the percent bias is -75 percent and the observed mean chlorophyll-a concentration in the tributary is 4.7 µg/L, then the mean concentration predicted by the model is 1.2 µg/L. These differences are not important relative to the regulatory standard of 40 µg/L. However, if the observed mean was 50 µg/L and the model predicted a mean of 12.5 µg/L, that could have more of an impact on the ability of the downstream lake models to simulate chlorophyll-a in Falls Lake. Previous lake models assumed that tributary input chlorophyll-a concentrations were comparable to those observed in Falls Lake and generally higher than those observed in the UNRBA tributary monitoring. The UNRBA WARMF Lake and EFDC lake models are being developed to simulate chlorophyll-a concentrations in Falls Lake based on information from the watershed model. While the watershed model may slightly underpredict chlorophyll-a concentrations in the tributaries to Falls Lake, the observed concentrations are so low these differences are not expected to affect the simulation processes in the lake models.

Time series comparisons to observed water quality data for these eight calibration stations for ammonia, nitrate, Total Kjeldahl Nitrogen, total nitrogen, total phosphorus, total minus volatile suspended solids, total organic carbon, and chlorophyll-a are provided in Appendix G. As noted in Section 4.4, these time series figures include bars to indicate the 95th confidence interval associated with the water quality observations. Figure 6-7 through Figure 6-11 provide three-pane figures for total nitrogen, total phosphorus, and total organic carbon for the lake loading stations at the largest five tributaries.

Table 6-6. Water Quality Mean Observed Concentration (Mean Obs.) and Percent Bias (pBias) for Calibration (2015-2016), Validation (2017-2018), and Full Period (2015-2018) with Observed Means for the Full Period

Statistic / Parameter	Mean Obs. ELC-3.1	pBias ELC-3.1	Mean Obs. ENR-23	pBias ENR-23	Mean Obs. ENR-8.3	pBias ENR-8.3	Mean Obs. FLR-25	pBias FLR-25	Mean Obs. FLR-5.0	pBias FLR-5.0	Mean Obs. KRC-4.5	pBias KRC-4.5	Mean Obs. LTR-1.9	pBias LTR-1.9	Mean Obs. LTR-16	pBias LTR-16
Water Temperature, C																
Full	18.6	4.4	17.1	7.3	16.8	7.2	16.8	0.2	15.1	8.9	17.8	7.8	16.8	-8.8	16.0	8.1
Calibration	18.6	4.4	17.0	5.4	16.7	7.9	16.7	-2.7	14.9	9.2	17.7	9.1	16.3	-7.5	16.2	7.7
Validation	18.6	4.3	17.2	9.4	16.8	6.1	17.0	3.4	15.3	8.5	18.0	6.0	17.9	-11.3	15.7	8.5
Ammonia Nitrogen, mg/L																
Full	0.12	-0.7	0.04	13.7	0.05	35.5	0.06	59.4	0.08	-22.1	0.19	-19.6	0.08	-48.4	0.03	62.3
Calibration	0.15	-18.4	0.04	37.7	0.05	41.9	0.06	39.5	0.08	-11.3	0.18	-36.2	0.08	-43.1	0.03	51.6
Validation	0.09	35.2	0.05	-8.5	0.05	28.6	0.06	80.0	0.09	-34.9	0.21	-2.4	0.10	-54.7	0.03	74.0
Nitrate-Nitrite, mg/L																
Full	1.5	-11.5	0.3	17.1	0.2	23.4	0.4	-52.4	0.2	-72.3	1.1	-40.0	0.2	-61.7	0.3	3.8
Calibration	1.7	-15.2	0.3	17.6	0.2	40.8	0.4	-59.8	0.2	-75.2	1.7	-46.0	0.2	-67.8	0.3	0.2
Validation	1.2	-5.4	0.2	16.4	0.2	4.5	0.3	-43.1	0.2	-68.4	0.3	-3.3	0.2	-52.4	0.3	8.7
Total Kjeldahl Nitrogen, mg/L																
Full	1.1	-33.8	0.4	22.1	0.6	0.34	0.6	29.6	0.7	6.3	1.0	-2.4	0.6	6.4	0.5	26.7
Calibration	1.1	-35.2	0.4	22.2	0.5	12.2	0.6	25.1	0.7	7.5	1.0	-8.1	0.6	7.4	0.5	3.9
Validation	1.1	-32.3	0.4	21.9	0.7	--11.1	0.6	33.8	0.7	4.5	1.0	5.1	0.7	5.2	0.4	57.6
Total Nitrogen, mg/L																
Full	2.5	-21.6	0.7	20.3	0.8	4.7	0.9	-2.5	0.9	-9.7	2.2	-23.8	0.8	-9.6	0.8	12.7
Calibration	2.7	-24.3	0.7	20.5	0.8	19.4	1.0	-10.8	0.9	-9.9	3.0	-33.1	0.8	-11.7	0.9	-9.9
Validation	2.2	-17.7	0.7	20.	1.0	-10.4	0.9	6.3	0.9	-9.3	1.3	2.8	0.8	-6.9	0.7	45.2
Total Organic Carbon, mg/L																
Full	7.6	-12.5	4.5	12.9	5.8	4.1	5.6	21.0	7.8	-4.7	8.3	15.4	7.0	-5.5	4.9	12.5
Calibration	7.4	-14.4	4.7	13.1	5.3	11.1	5.8	18.4	8.0	-4.7	8.2	15.1	6.7	-7.7	5.1	4.7
Validation	7.9	-10.2	4.2	12.7	6.5	-3.22	5.2	28.1	7.7	-4.8	8.4	15.8	7.3	-2.7	4.3	35.7

Table 6-6. Water Quality Mean Observed Concentration (Mean Obs.) and Percent Bias (pBias) for Calibration (2015-2016), Validation (2017-2018), and Full Period (2015-2018) with Observed Means for the Full Period

Total Ortho-Phosphate, mg/L																
Full	0.053	120.8	NA	NA	0.016	283.3	NA	NA	0.012	458.5	0.506	-54.9	0.015	277.4	NA	NA
Calibration	0.053	118.2	NA	NA	0.018	265.9	NA	NA	0.013	435.3	0.717	-60.3	0.017	252.6	NA	NA
Validation	0.053	125.8	NA	NA	0.013	334.0	NA	NA	0.008	542.7	0.092	26.9	0.012	353.6	NA	NA
Total Phosphorus, mg/L																
Full	0.13	10.1	0.05	51.8	0.08	-2.5	0.08	-5.6	0.06	19.0	0.44	-50.5	0.07	10.3	0.05	40.6
Calibration	0.10	28.2	0.06	47.6	0.06	19.3	0.07	-7.0	0.06	34.6	0.70	-59.0	0.05	36.1	0.06	34.6
Validation	0.16	-3.2	0.04	57.1	0.10	-19.4	0.09	-4.7	0.07	1.9	0.14	-3.8	0.09	-11.2	0.05	47.8
Total Solids (sand+silt+clay), mg/L																
Full	33.7	-58.2	10.2	-22.9	41.7	-39.5	10.2	-57.8	13.0	-52.2	21.0	-37.1	19.1	-28.3	23.5	-48.6
Calibration	17.2	-55.1	15.3	-43.2	28.2	-66.3	9.0	-68.1	10.8	-58.2	10.6	-39.9	12.9	-55.9	39.5	-65.1
Validation	53.4	-59.4	4.8	48.0	59.3	-22.8	11.5	-49.0	16.2	-46.5	33.8	-36.0	27.5	-10.7	6.1	67.0
Total Suspended Solids (silt+clay), mg/L																
Full	33.7	-58.2	10.2	-26.4	41.7	-39.5	10.2	-80.5	13.0	-52.2	21.0	-37.1	19.1	-28.3	23.5	-67.9
Calibration	17.2	-55.1	15.3	-47.3	28.2	-66.3	9.0	-83.6	10.8	-58.2	10.6	-39.9	12.9	-55.9	39.5	-76.2
Validation	53.4	-59.4	4.8	46.7	59.3	-22.8	11.5	-77.9	16.2	-46.5	33.8	-36.0	27.5	-10.7	6.1	-10.0
Chlorophyll-a, ug/L																
Full	3.6	-66.1	NA	NA	5.1	-52.0	NA	NA	12.6	-48.3	3.7	-73.3	9.9	-33.4	NA	NA
Calibration	2.6	-63.5	NA	NA	4.2	-42.0	NA	NA	10.7	-41.7	2.8	-70.0	6.5	0.1	NA	NA
Validation	4.7	-67.7	NA	NA	6.3	-61.1	NA	NA	15.4	-54.7	4.7	-75.7	14.5	-53.6	NA	NA

NA: not applicable; chlorophyll-a and ortho-phosphate data were only collected at lake loading stations.

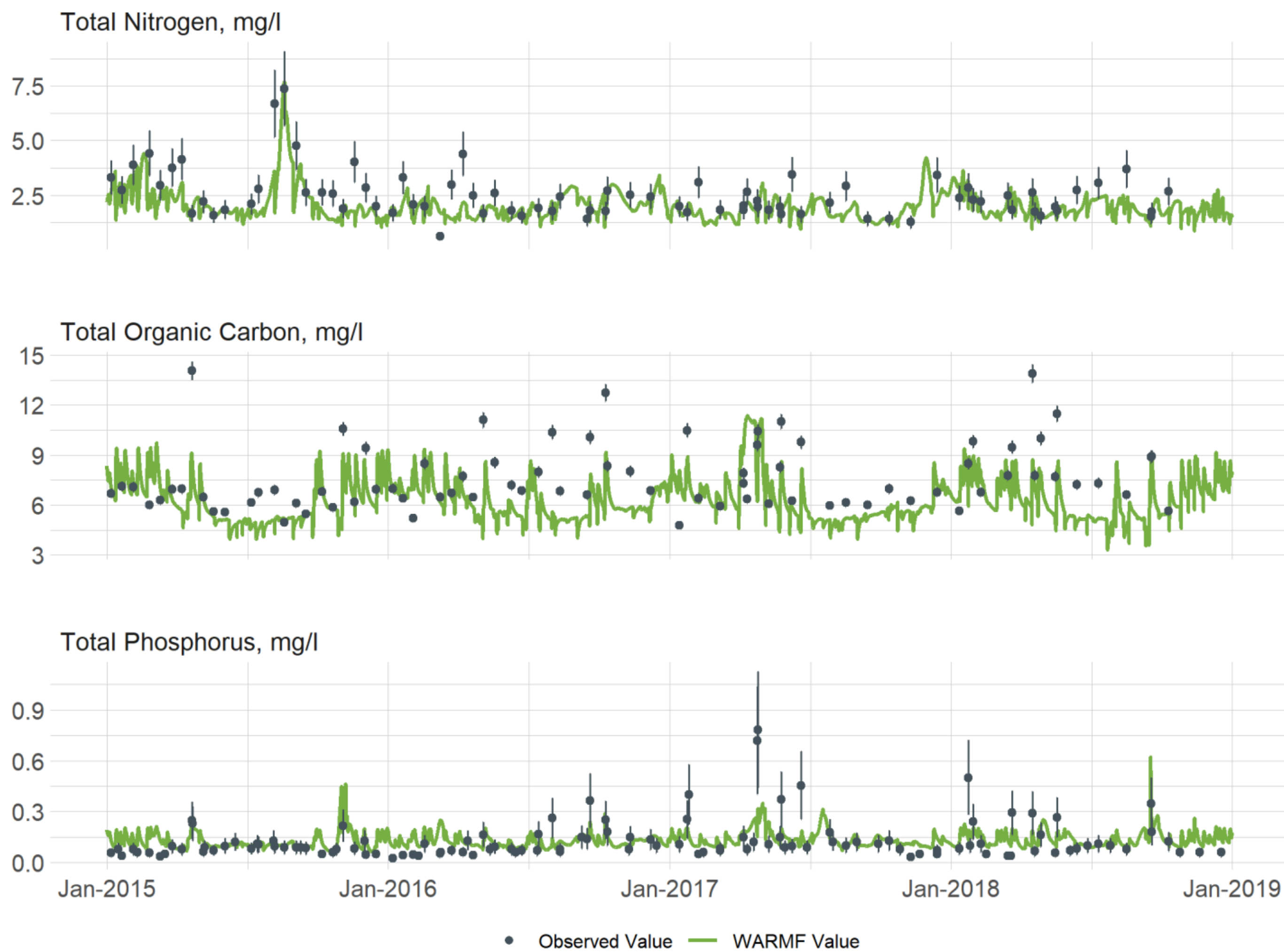


Figure 6-7. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Ellerbe Creek (vertical bars are used to illustrate the uncertainty with laboratory analyses and are based on the 95th percentile confidence interval calculated from the UNRBA data set for each parameter)

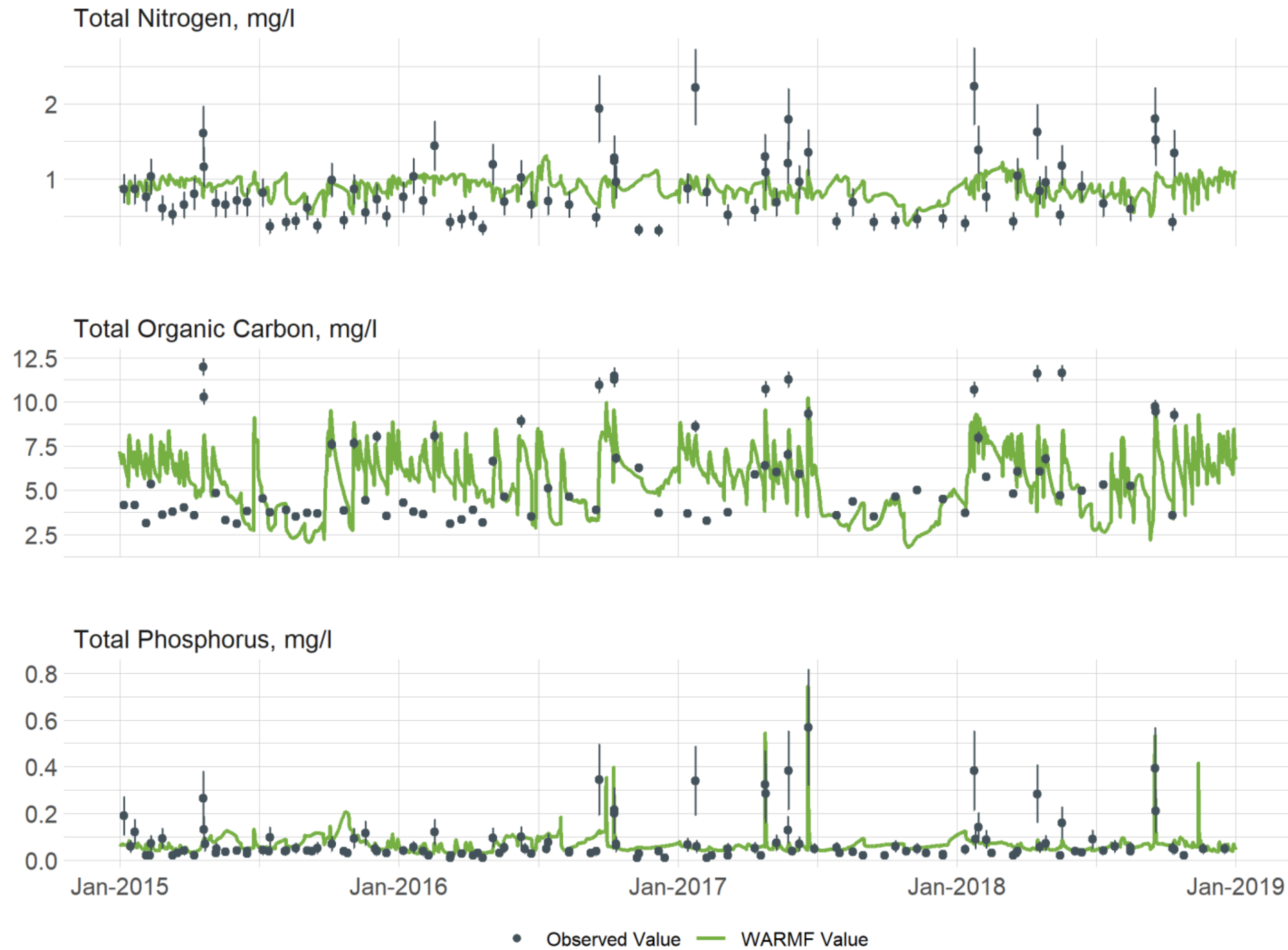


Figure 6-8. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Eno River (vertical bars are used to illustrate the uncertainty with laboratory analyses and are based on the 95th percentile confidence interval calculated from the UNRBA data set for each parameter)

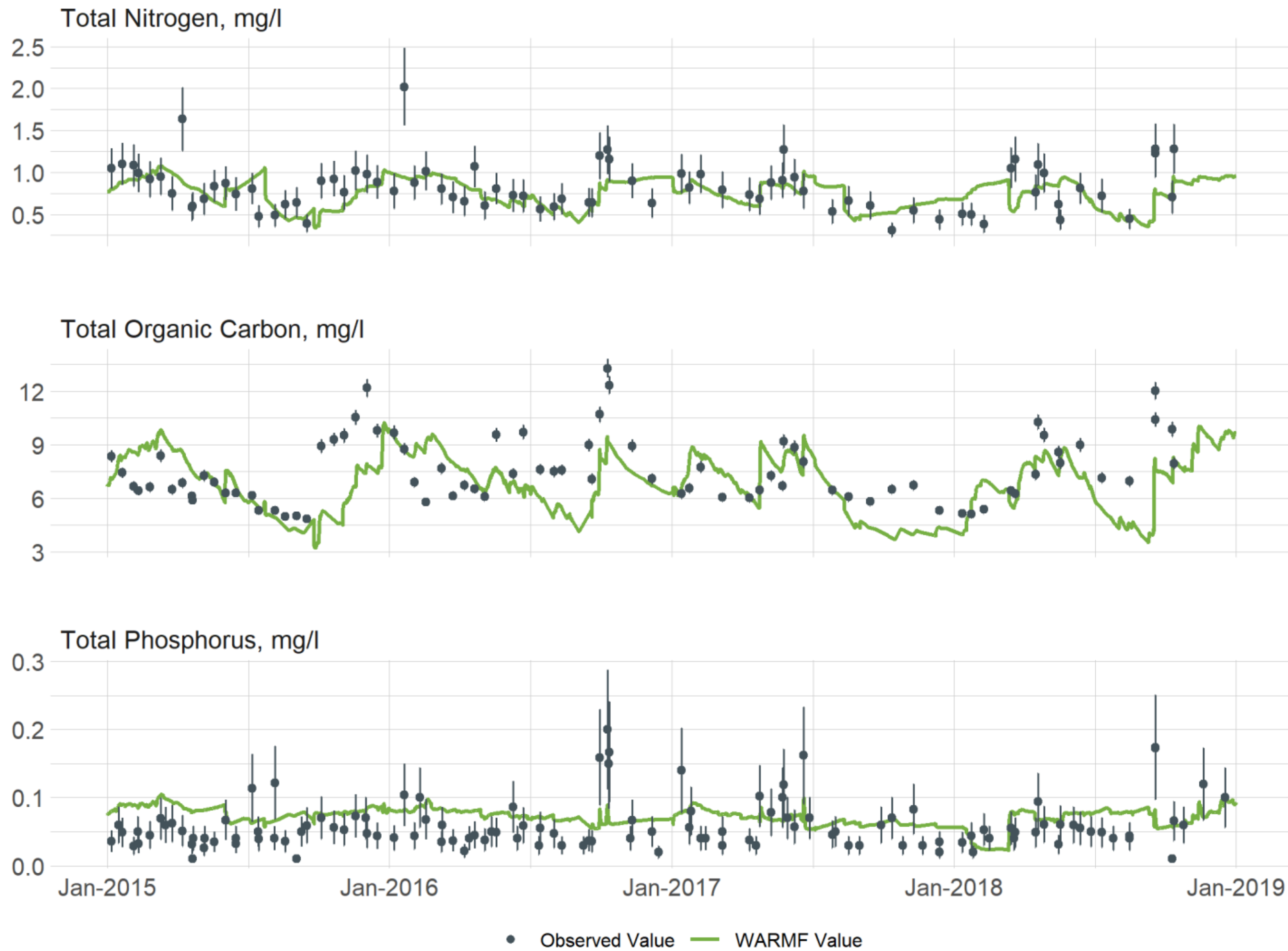


Figure 6-9. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Flat River (vertical bars are used to illustrate the uncertainty with laboratory analyses and are based on the 95th percentile confidence interval calculated from the UNRBA data set for each parameter)

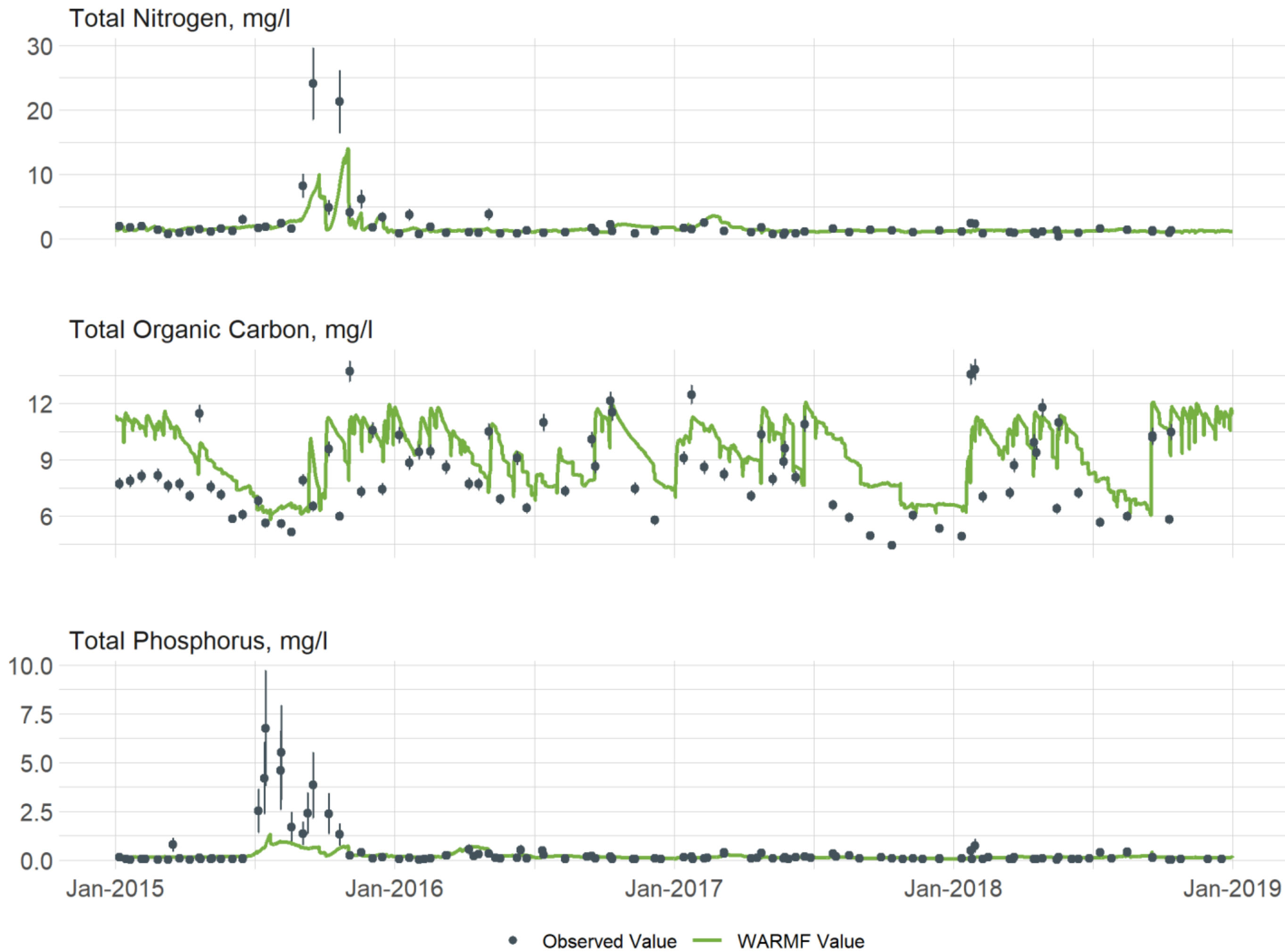


Figure 6-10. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Knap of Reeds Creek (vertical bars are used to illustrate the uncertainty with laboratory analyses and are based on the 95th percentile confidence interval calculated from the UNRBA data set for each parameter)

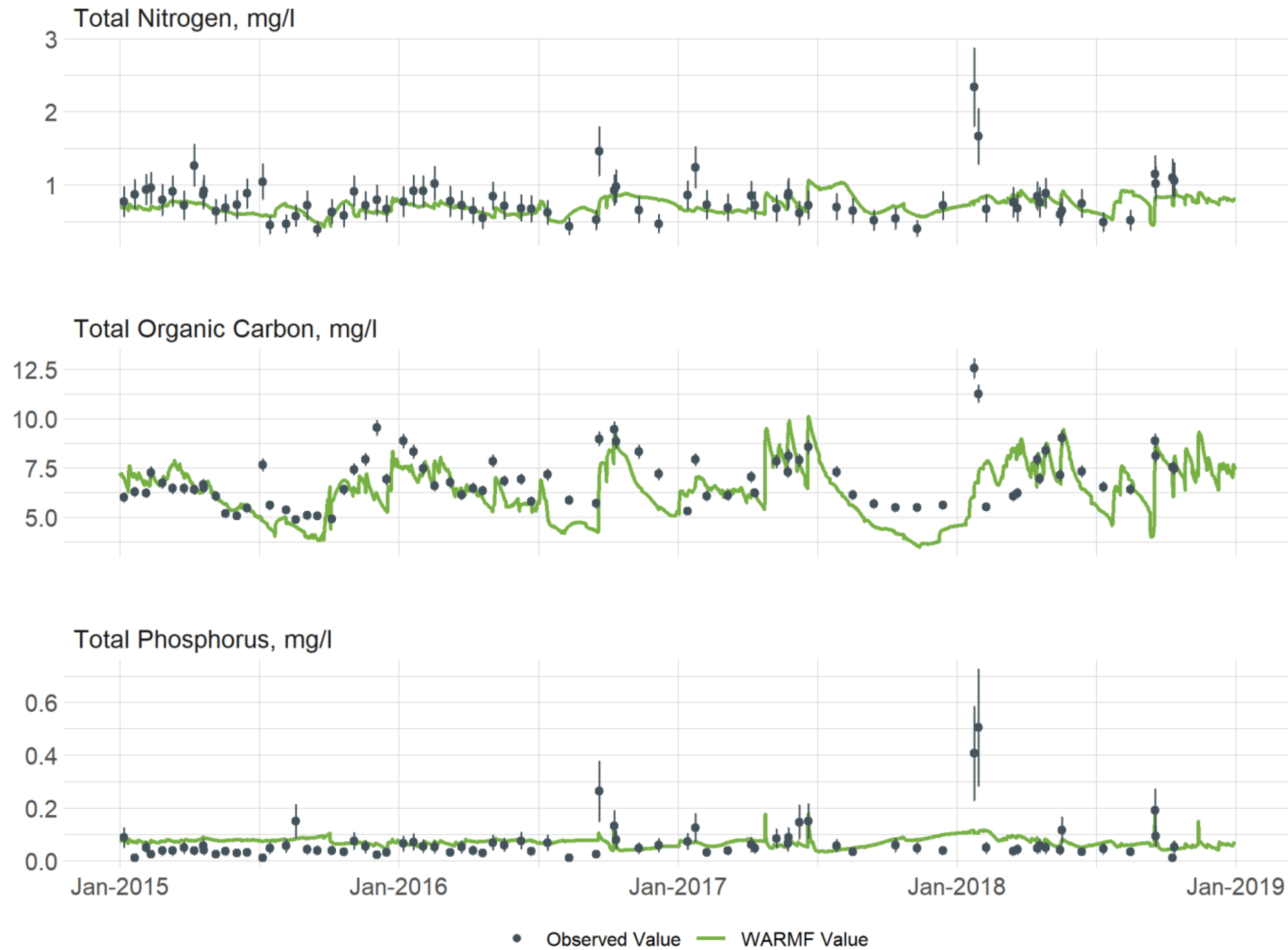


Figure 6-11. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Little River (vertical bars are used to illustrate the uncertainty with laboratory analyses and are based on the 95th percentile confidence interval calculated from the UNRBA data set for each parameter)

6.5 Comparison of WARMF Simulated Loads to Other Loading Estimates

As described above, loading is the combination of concentration and flow to provide a "mass" of pollutant moving through the streams over time. The calibration of the watershed model and evaluation of performance focused on simulated flows and concentrations separately. Because concentrations and flows have complex interactions that may vary under different hydrologic and seasonal conditions, it is important to also consider loading estimates and ensure they are reasonable.

The UNRBA Modeling QAPP does not specify loading comparisons in the evaluation of model performance, in part because the methods available to calculate loads are themselves estimates. However, the comparison of two estimates, neither of which is exact, can be used to ensure reasonable predictions and model behavior. These evaluations focus on the lake loading stations on the five largest tributaries as these represent the majority of the loading to Falls Lake and each include a USGS gaging location and a UNRBA monitoring station. Loading comparisons are made for total nitrogen, total phosphorus, and total organic carbon.

6.5.1 Comparison to Ranges of Daily Load Estimates

Two scales of loading estimates were developed for comparison to the WARMF predictions. Daily load comparisons are fairly limited in number because they use the UNRBA and DWR observed concentrations (~12 samples per year) combined with daily average estimated flows As described in Section 4.4, the majority of water quality samples were collected during periods where flows were at or below the 20th percentile and the concentrations themselves are not exact measurements. During baseflow conditions, flows are fairly steady over the course of a day, but during and following storm events, flows can vary widely in a 24-hour period. For example, the UNRBA monitoring program collected a water quality sample at Ellerbe Creek (ELC-3.1) on April 24, 2017, at 1:25 PM when stream flow was approximately 800 cfs. Gaged flows ranged from 50 cfs to 2,300 cfs on this day; a sample collected when flow was 800 cfs may not provide a good basis from which to estimate the daily load when the hydrologic condition varied so significantly.

At each site and for each parameter, the WARMF simulated daily loads follow a similar pattern and range as those estimated from USGS flow data and UNRBA monitoring data, indicating that WARMF is simulating reasonable flows, concentrations, and resultant loads of nitrogen, phosphorus, and carbon.

To provide a comparison to daily load estimates, the WARMF simulated daily loads (a sum of the 6-hour simulations) on the sampling days were compared to a range of daily load estimates for the sampling day. The low end of the daily load estimate was calculated from the minimum 15-minute flowrate recorded by USGS on the sampling day multiplied by the lower 95th percentile range of concentration based on the UNRBA data. The high end of the range used the maximum 15-minute flowrate recorded on the sampling day and the upper 95th percentile range of concentration based on the UNRBA data. These ranges are for illustrative purposes to account for the range of flows reported by USGS on the sampling day, the uncertainty in pairing the water quality sample to a daily flow value, and the uncertainty associated with laboratory data. These ranges bracket the potential daily load and are not themselves 95th percentile confidence intervals. Figure 6-7 through Figure 6-21 provide three-pane figures for total nitrogen, total phosphorus, and total organic carbon for the lake loading stations at the largest five tributaries. For each of the five lake loading stations, the figure is provided using an arithmetic scale followed by a log scale. At each site and for each parameter, the WARMF simulated daily loads follow a similar pattern and range as those estimated from USGS flow data and UNRBA monitoring data, indicating that WARMF is simulating reasonable flows, concentrations, and resultant loads of nitrogen, phosphorus, and carbon.

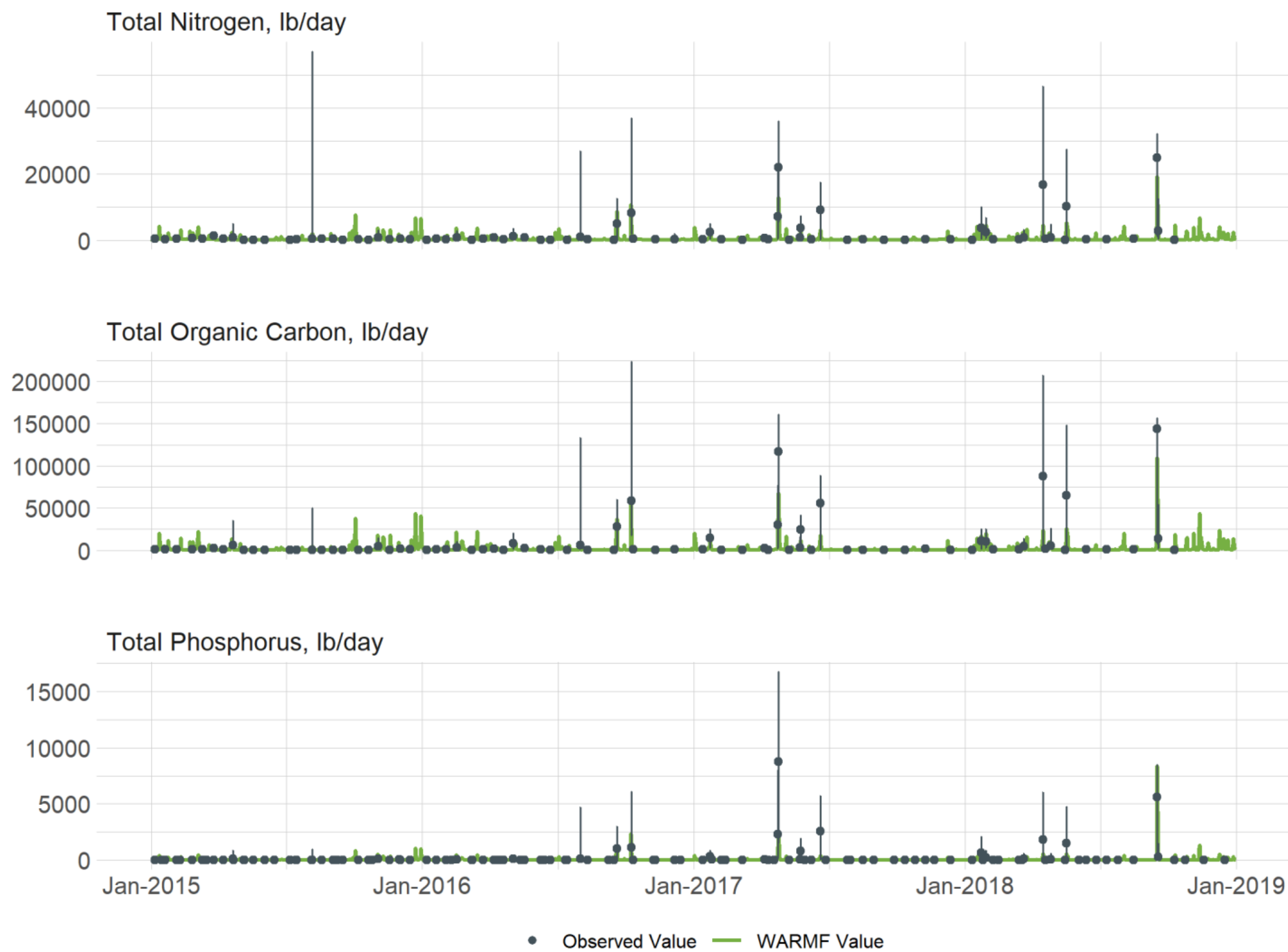


Figure 6-12. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Ellerbe Creek (vertical bars bracket the potential load for the sampling day)

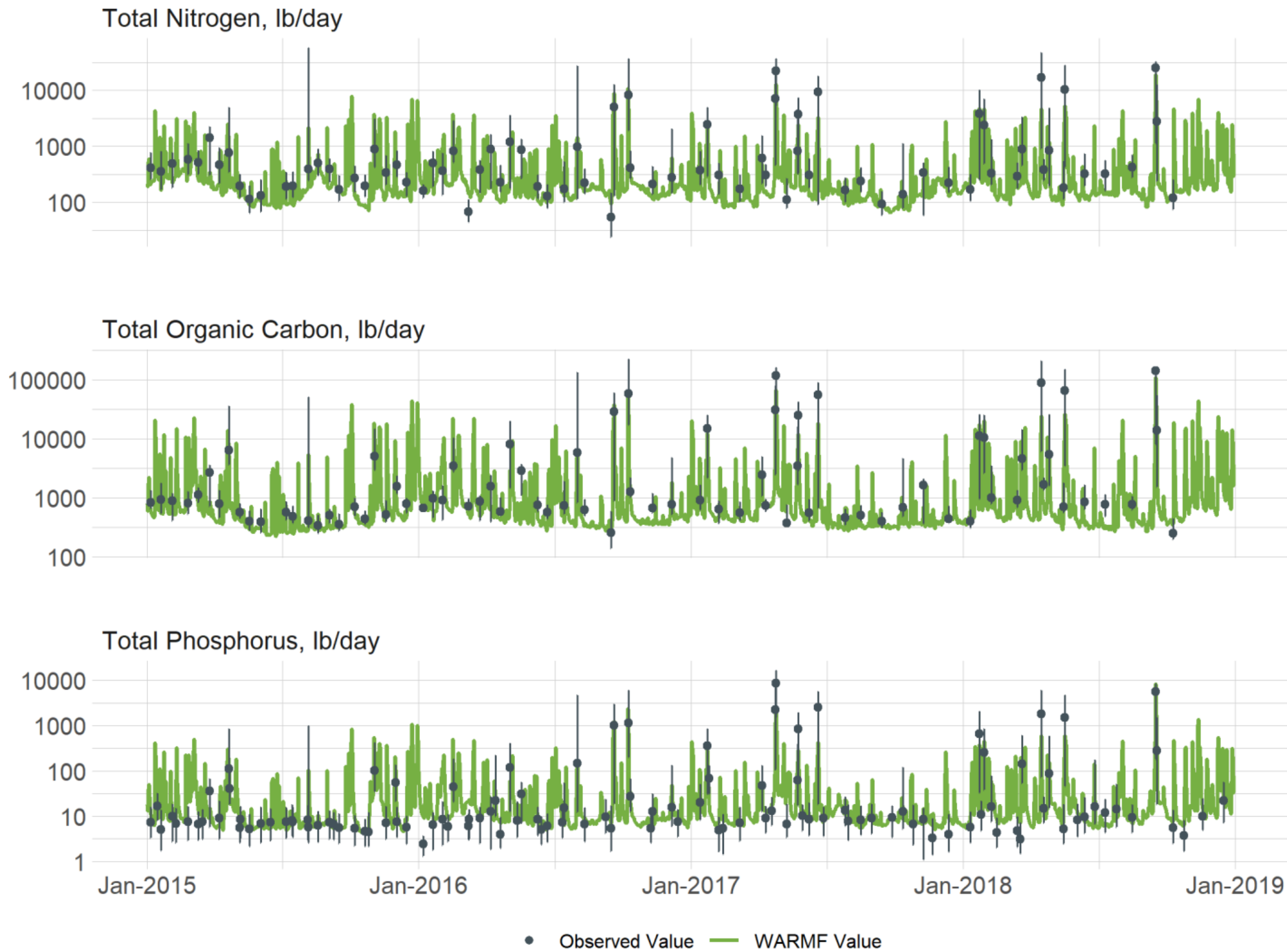


Figure 6-13. Log-Scale Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Ellerbe Creek (vertical bars bracket the potential load for the sampling day)

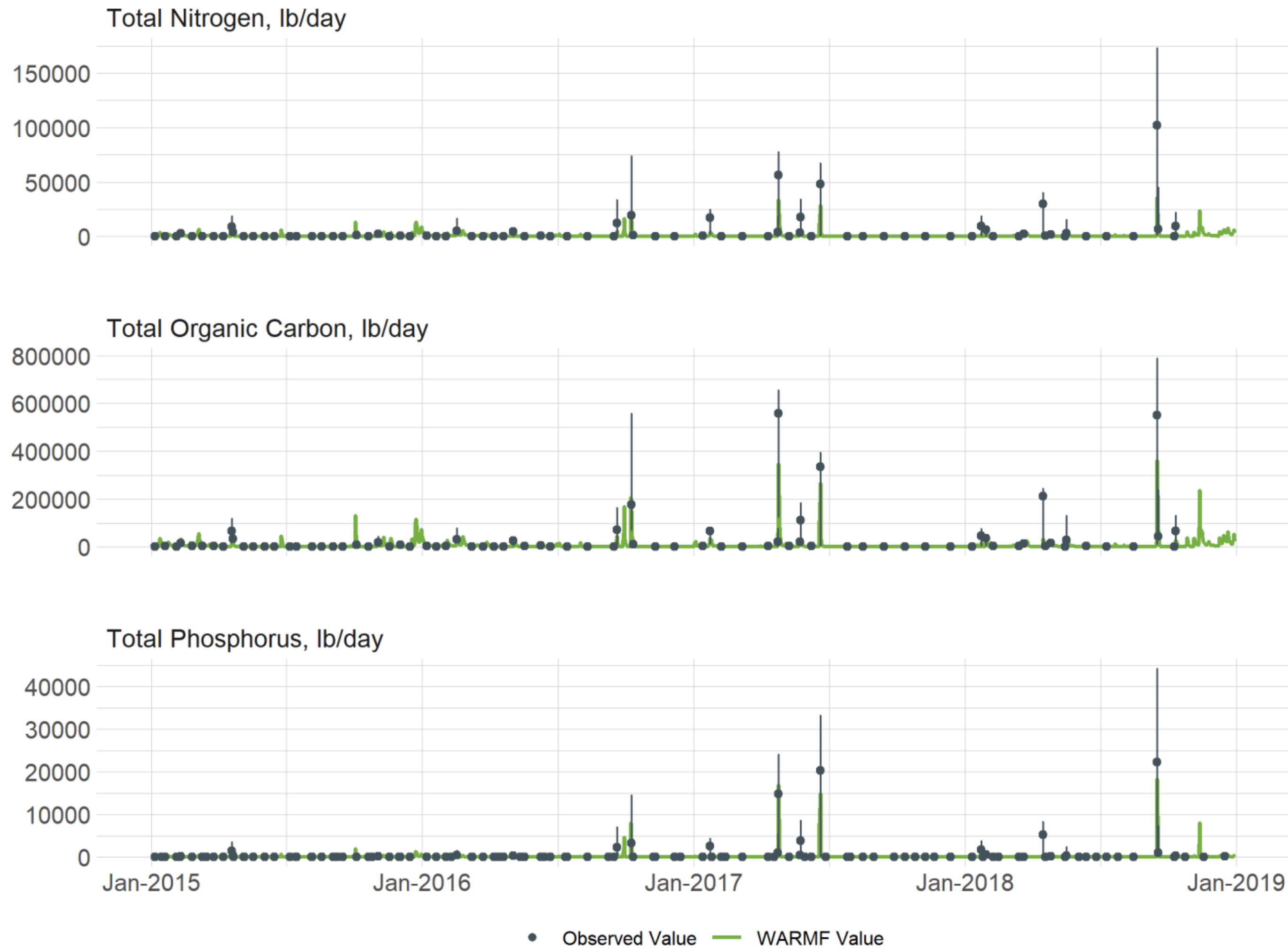


Figure 6-14. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Eno River (vertical bars bracket the potential load for the sampling day)

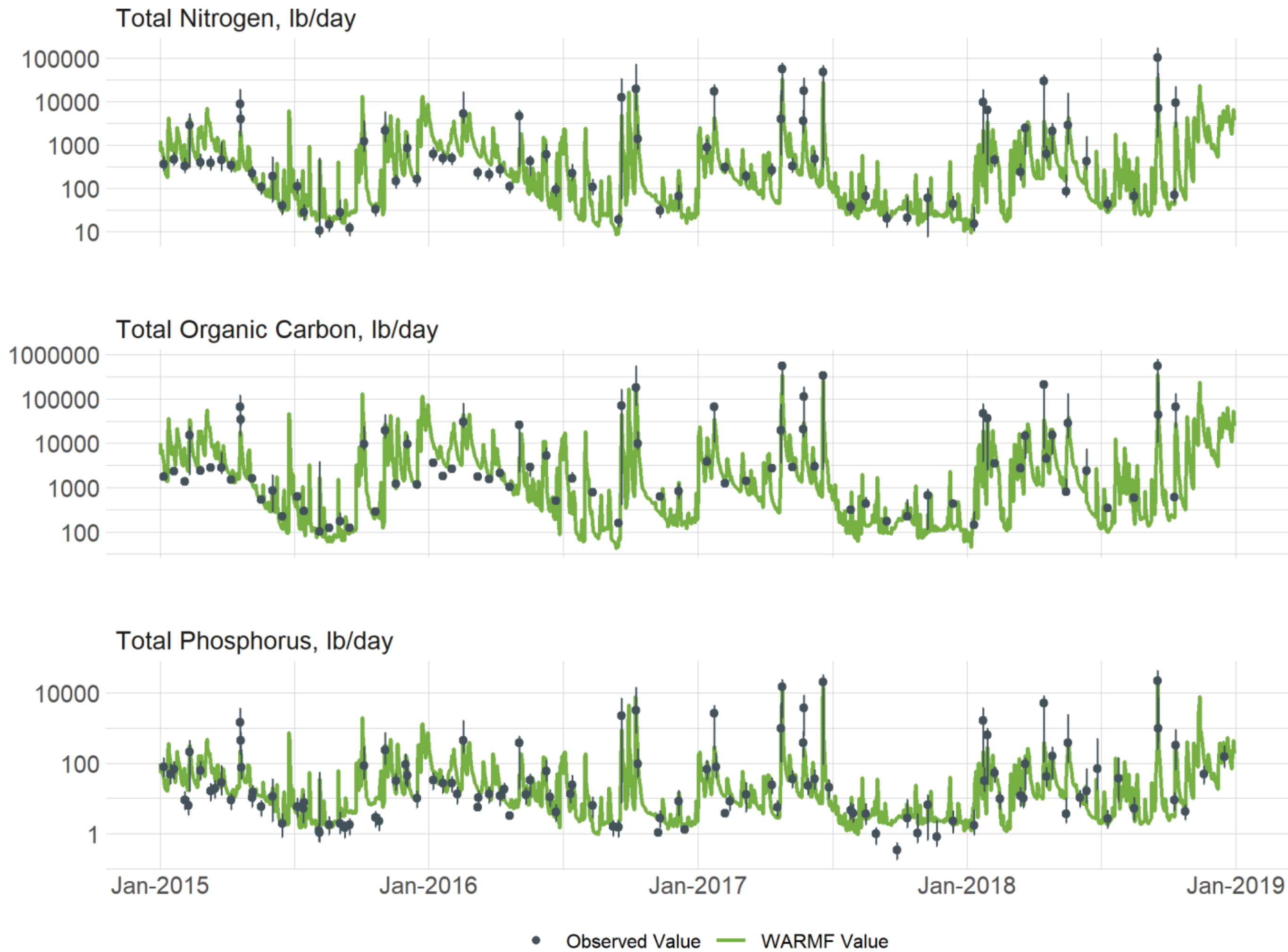


Figure 6-15. Log-Scale Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Eno River (vertical bars bracket the potential load for the sampling day)

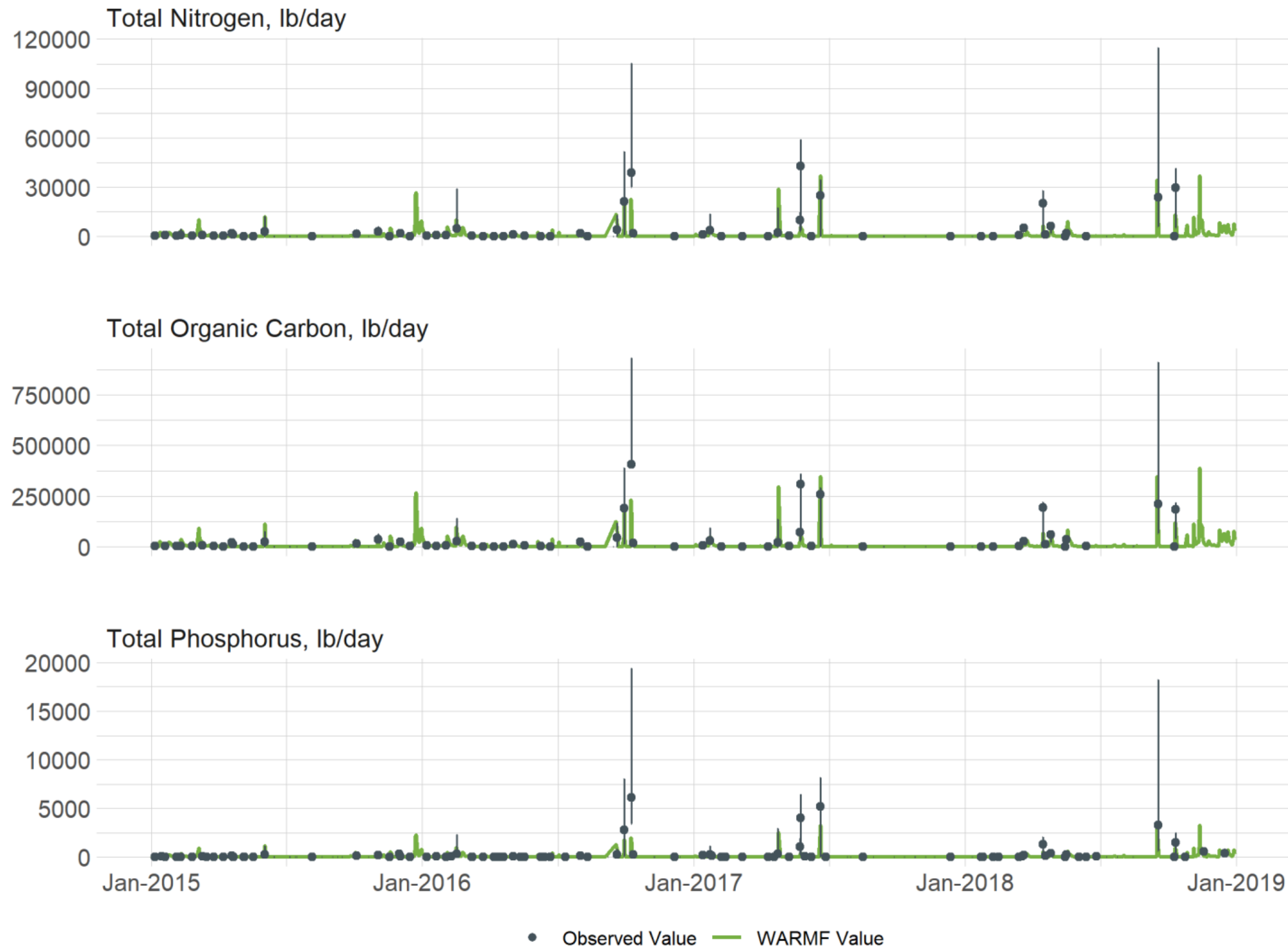


Figure 6-16. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Flat River (vertical bars bracket the potential load for the sampling day)

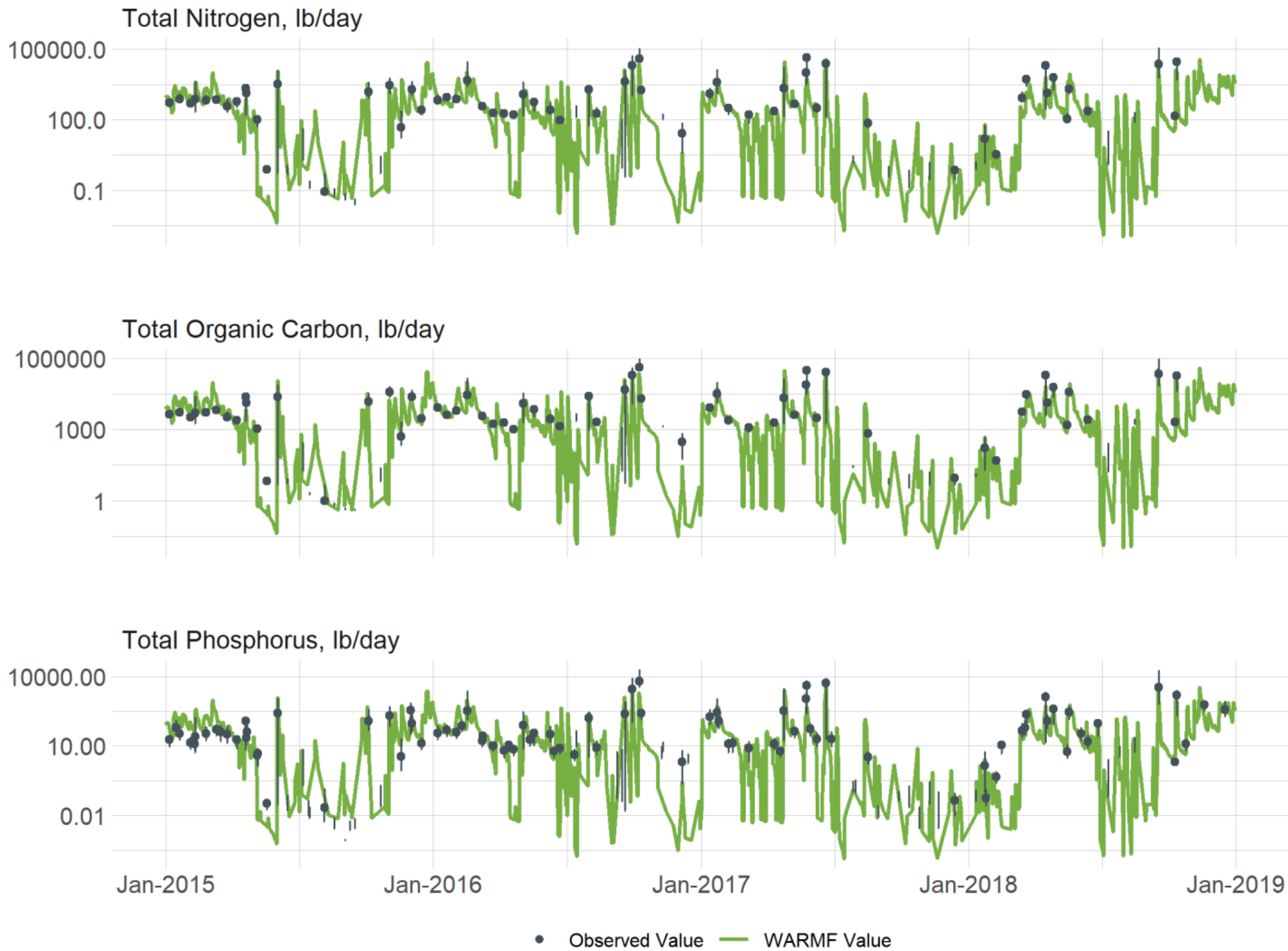


Figure 6-17. Log-Scale Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Flat River (vertical bars bracket the potential load for the sampling day)

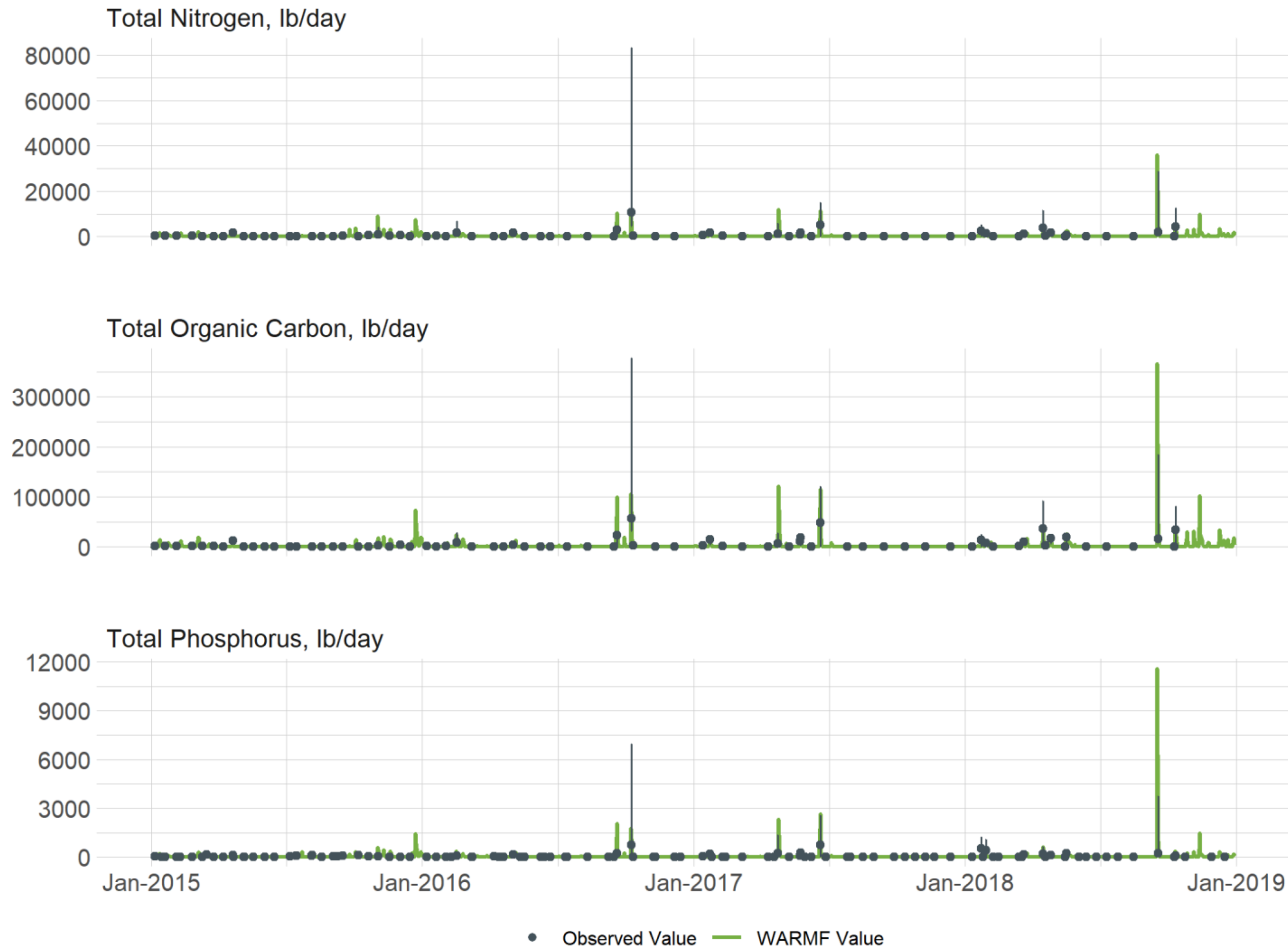


Figure 6-18. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Knap of Reeds Creek (vertical bars bracket the potential load for the sampling day)

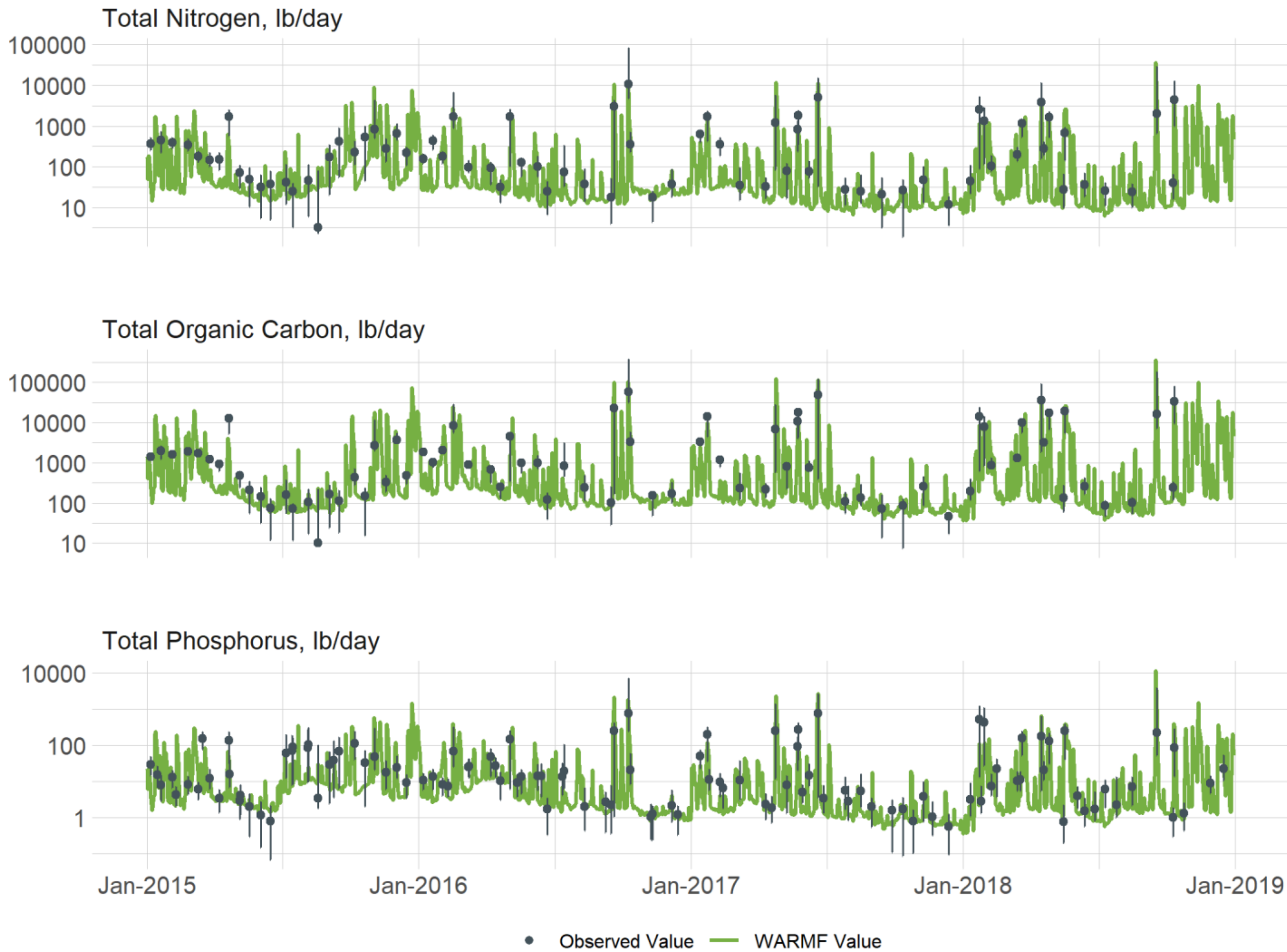


Figure 6-19. Log-Scale Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Knap of Reeds Creek (vertical bars bracket the potential load for the sampling day)

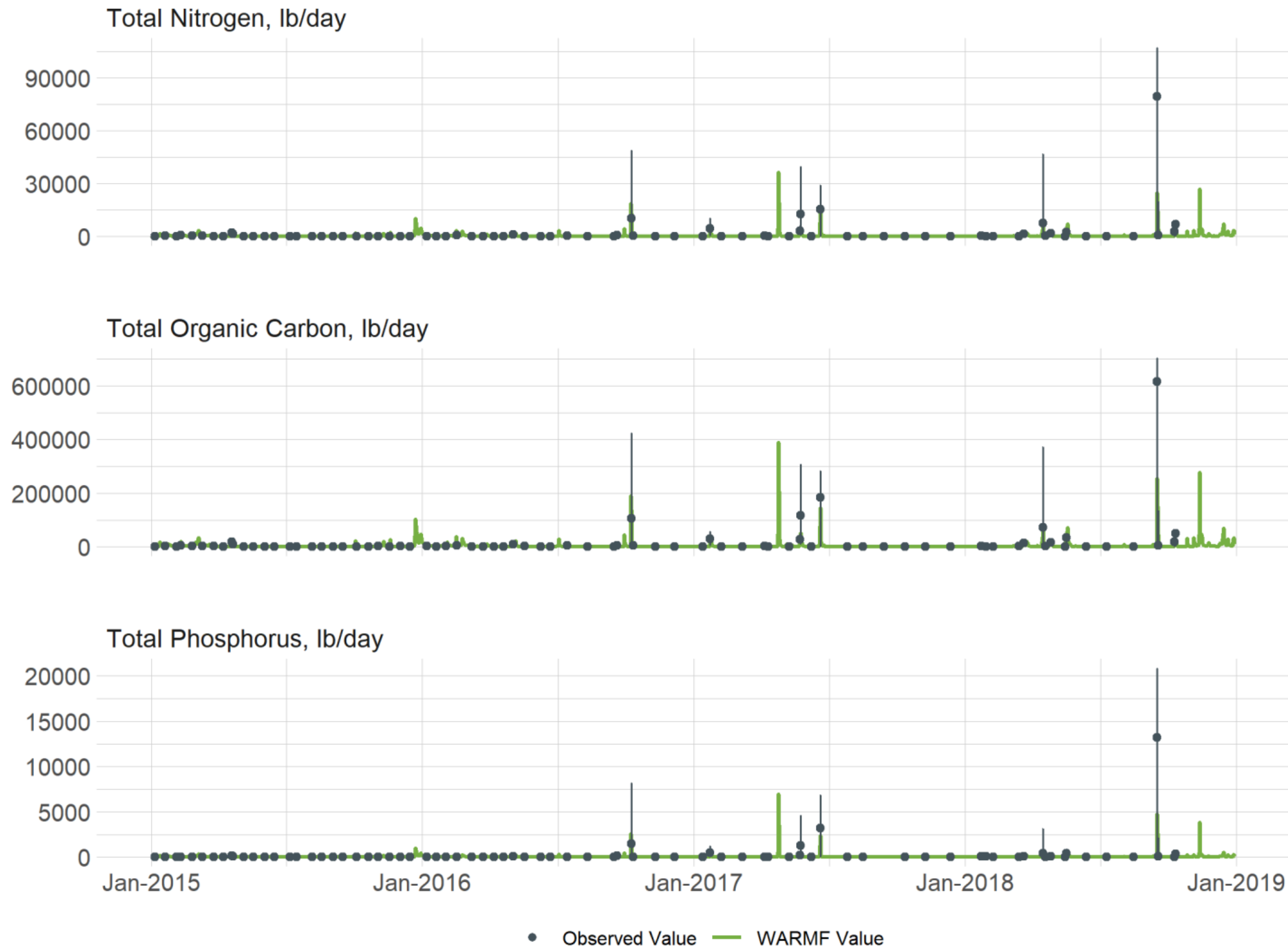


Figure 6-20. Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Little River (vertical bars bracket the potential load for the sampling day)

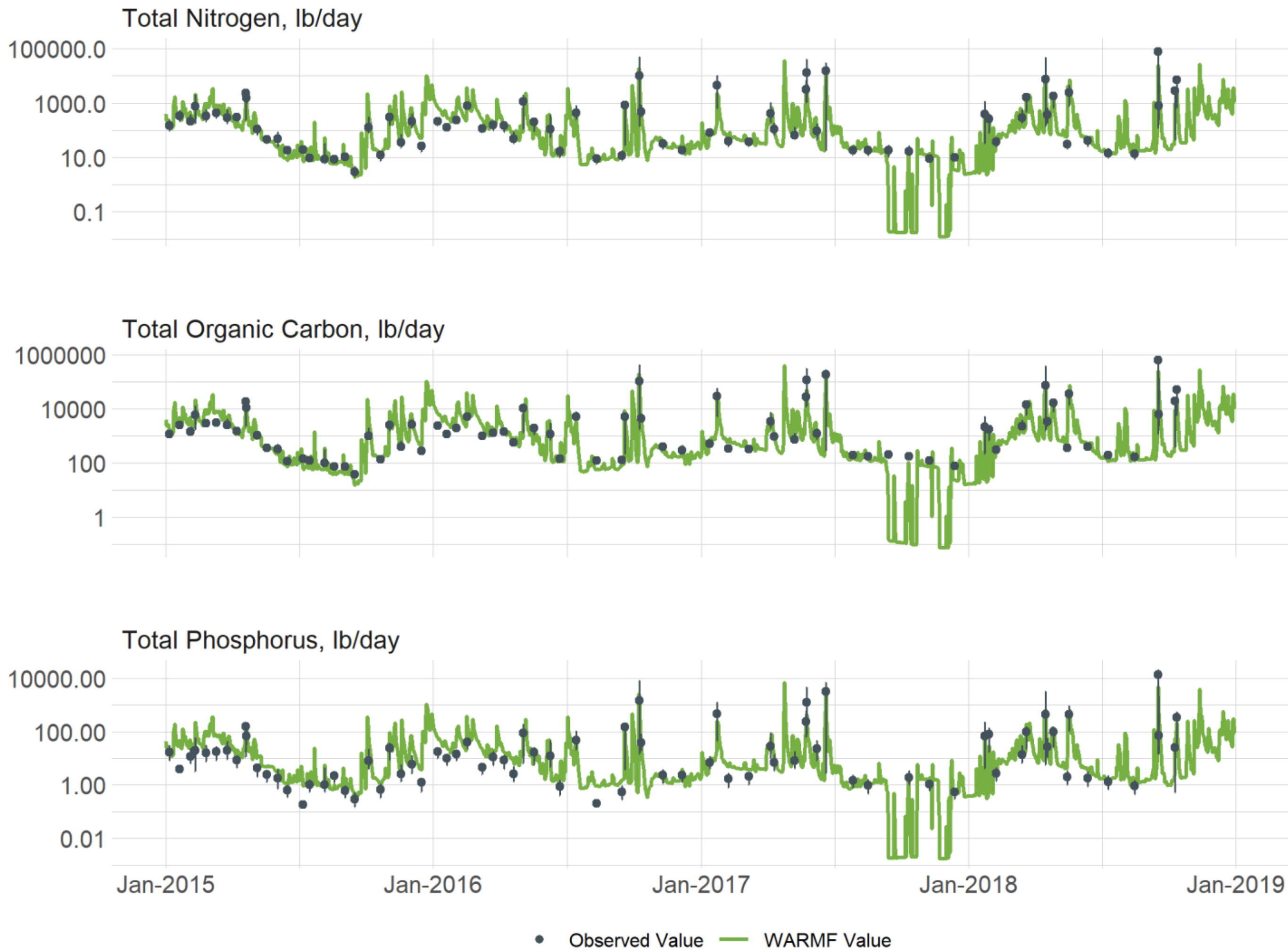


Figure 6-21. Log-Scale Comparison of Simulated Total Nitrogen, Total Phosphorus, and Total Organic Carbon to Observations Collected at Little River (vertical bars bracket the potential load for the sampling day)

6.5.2 Comparison to Ranges of Annual Load Estimates

Annual load comparisons were conducted using LOADEST models previously developed for the UNRBA and described in the UNRBA 2019 Monitoring Report. The LOADEST models are regression equations based on pairings of observed water quality and gaged flows. Because they are regression equations, loads can be estimated across a wide range of flow conditions for each day simulated by WARMF (i.e., these estimates are not limited to sampling days). There is some uncertainty with this approach as well, especially at very high flows where streams cannot be safely sampled and the regression curve must be extrapolated.

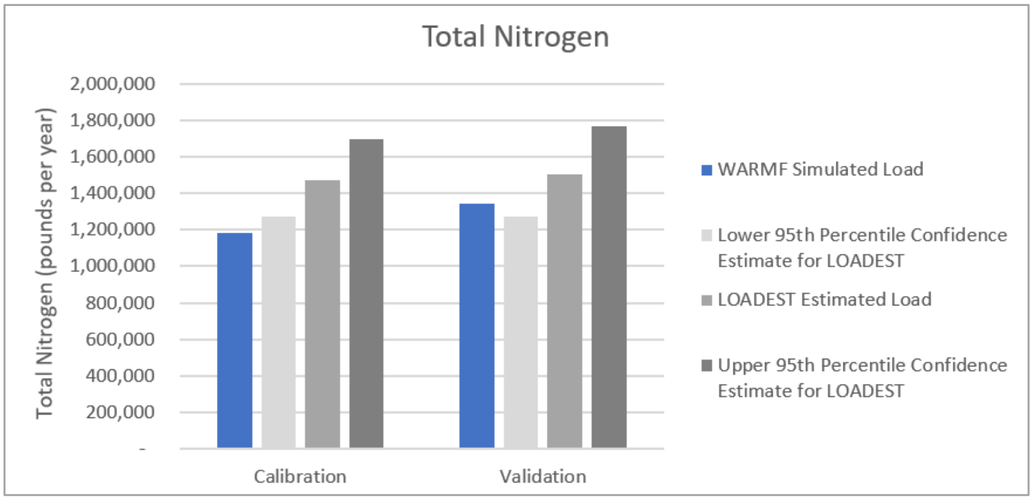
In response to a request from DWR modeling staff, the LOADEST models were rerun to specify that LOADEST output 95th percentile confidence intervals. This required filling in missing flow data at the Flat and Little River gages. The WARMF simulated delivered loads to the lake loading stations are toward the lower end of those predicted by LOADEST. However, the bias statistics for LOADEST (LOADEST model regression compared to load calculated from observed flow and water quality data on sampling days) indicate that model is likely over-predicting loads for some parameters and tributaries (Table 6-7). There is also more uncertainty with the LOADEST predictions during extreme high flow events as water quality sampling cannot be conducted safely when flooding occurs. Both WARMF and LOADEST are models and neither can be assumed 100 percent accurate. WARMF, however, is constrained in how much load can be simulated during high flow events based on the model inputs and processes. LOADEST requires extrapolation of stream water quality during high flow events that may be inaccurate. The two loading estimates for total nitrogen, total phosphorus, and total organic carbon are within 25 percent of each other for the calibration and validation periods. This comparison provides another point of reference to ensure the WARMF model is simulating reasonable loads to Falls Lake given observed flows and water quality.

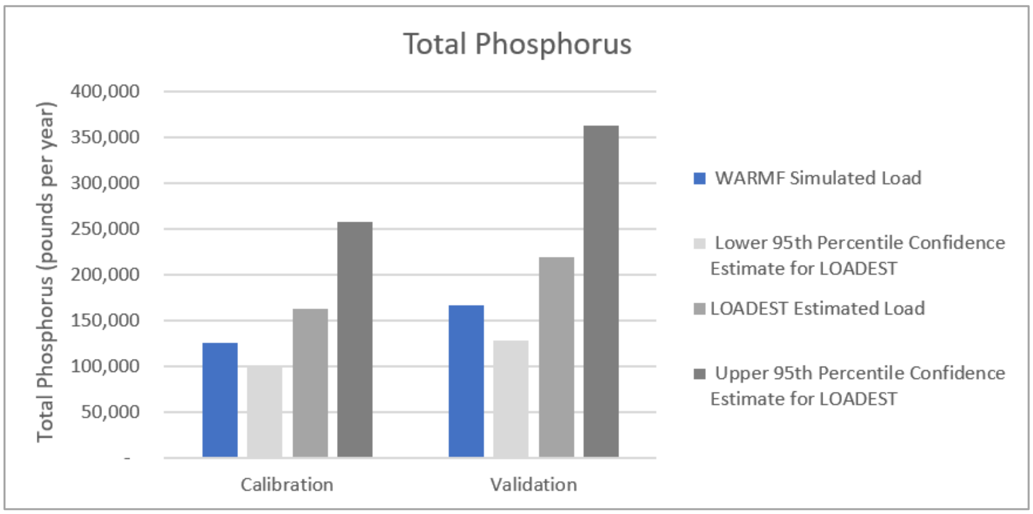
Table 6-7. LOADEST Model Percent Bias (based on Comparison of Observed Data to LOADEST Model Regression)

Tributary	Total Nitrogen	Total Organic Carbon	Total Phosphorous
Ellerbe Creek	2.6	3.1	29.4
Eno River	17.2	18.0	58.9
Flat River	-3.5	-7.7	-12.1
Little River	-3.6	-1.8	-10.4
Knap of Reeds Creek	12.8	2.3	55.8
Beaverdam Creek	9.9	3.1	-8.7
Honeycutt Creek	-7.3	-1.4	10.7
Horse Creek	1.5	3.3	30.5
Ledge Creek	11.6	0.0	-15.3
Lick Creek	5.4	7.5	-17.6
Little Lick Creek	8.8	7.4	-9.1
Lower Barton Creek	-3.2	7.8	25.6
New Light Creek	2.4	23.6	62.3
Panther Creek	4.1	10.1	-11.9
Robertson Creek	13.7	-5.8	-4.6
Smith Creek	7.7	31.5	-0.8
Unnamed Tributary	8.3	-3.1	-6.0
Upper Barton Creek	-4.4	8.4	12.3
Percent Bias for All Tributaries Weighted by Mean Load	5.8	3.4	24.0

Figure 6-22 compares the annual WARMF loading estimates to the 95th percentile confidence intervals estimated by LOADEST for the tributaries to Falls Lake. There are approximately 129 square miles of drainage area downstream of the UNRBA Monitoring Stations that contribute loading to Falls Lake. This area is 75 percent forested. Thus, total delivered loads elsewhere in this report are higher than those reflected in the figure which are loads at the furthest downstream monitoring locations.

This comparison between WARMF and LOADEST provides another point of reference to ensure the WARMF model is simulating reasonable loads to Falls Lake given observed flows and water quality.





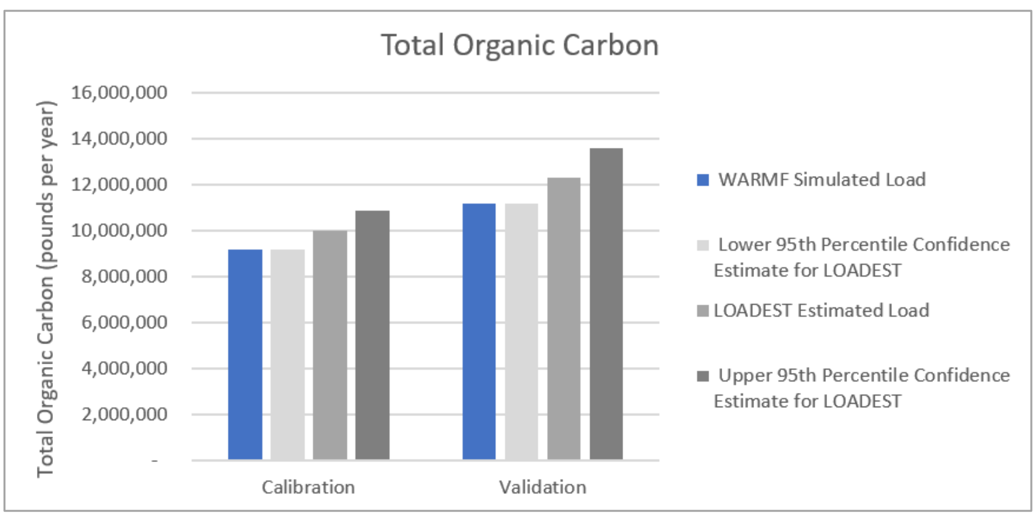


Figure 6-22. WARMF Simulated Total Nitrogen (top), Total Phosphorus (middle), and Total Organic Carbon Loads Delivered to Falls Lake Compared to the 95th Percentile Confidence Interval from the LOADEST Model

6.6 Sensitivity Analyses and Comparisons to Other Models

Following calibration of the watershed model, sensitivity analyses were conducted on a subset of global model parameters or inputs to evaluate the impact of variability or uncertainty on the degree of calibration of the model and on its results and conclusions. The modeling team worked with the MRSW, "third-party" model reviewers, and DWR to determine the parameters and ranges for sensitivity analyses evaluation. As the regulatory driver for the project is chlorophyll-a, this output parameter in Falls Lake will be the focus of the sensitivity analyses for the lake models. For the watershed model, the output of interest is nutrient loading to Falls Lake.

As part of the subject matter expert and "third-party" review of the watershed model described in Section 6.2, model sensitivity to hydrologic conditions and implementation of best management practices and stormwater control measures in urban areas were evaluated. These analyses were conducted to provide a comparison of the WARMF watershed model output to other modeling or monitoring studies that were conducted during dry to average conditions. These analyses are described in Appendix H. A summary of findings is provided here:

- Average loading rates simulated by the Falls Lake WARMF watershed model as delivered to Falls Lake are within the ranges published in the literature for other models across all land use categories.
- Loading rates from agriculture are generally higher than existing development which is higher than forests and unmanaged grasslands.
- Precipitation is the primary driver of variability in loading rates for the land uses
    - Simulated loading rates for forested catchments are similar to the Forest Service monitoring studies when precipitation is similar (dry to average). Other monitoring and modeling studies show that loading rates from forested areas increase during wet hydrologic periods like the UNRBA modeling shows (Hunt 2023; DWR 2021; Paerl et al. 2018, 2019, 2020; Osburn 2016; Timmons 1977; Oyarzún and Hervé-Fernandez 2015).
    - Variability in the nutrient loading to Falls Lake is highly dependent on precipitation, antecedent conditions, and resulting stream flows
- Delivered loads to Falls Lake by land use are each subject to transformations in overland flow, streams, and impoundments.
- Each catchment is unique in terms of its rainfall, slope, catchment width (which affects overland transport), stream length (which affects instream processing), soils, and current and past land uses and precipitation amounts (78 rainfall stations across the watershed). In addition to the catchment characteristics, catchment-scale output shows more variation in areal loading rates because the stream and impoundment processing is not accounted for at the catchment scale.
- Water and associated water quality constituents originating in the headwaters has a longer residence time in the watershed (more time for reactions/transformations) while water originating closer to Falls Lake (mostly forested land), has less time for reaction/transformation.
- The watershed average delivered loading rates for forests are affected by the proximity of the Near Lake drainage area, which is comprised mostly of forests (75%).
- Simulated best management practices (BMPs) and stormwater control measures (SCMs) in urban areas significantly reduce the land use loading rate of phosphorus from urban areas compared to a scenario where these practices are removed. Nitrogen is less affected by this scenario because nitrogen from developed areas is primarily in the dissolved form and less subject to adsorption and settling than phosphorus. BMPs and SCMs included in the calibrated model include street sweeping, stream buffers, and stormwater detention. 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. By December 2015, the City of Durham had installed approximately 350 practices in the watershed in addition to implementing a street sweeping program. As described in Section 3.2.1, for the stormwater practices, nutrient removal efficiencies are not simulated for individual practices, rather catchment-scale detention volumes were assigned to treat the volume associated with the first inch of runoff from impervious surfaces. For new development, fertilizer application rates were decreased to result in simulated loading rates similar to those required by the new development rules through the implementation of SCMs. As described in Appendix H, these BMPs and SCMs had to be accounted for in the calibrated model to meet the hydrologic and water quality model performance criteria, particularly in the Ellerbe Creek watershed where development is concentrated.

- The result is somewhat similar average delivered loading rates 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. Land use loading rates include the surface runoff and shallow interflow components. Stream bank erosion is tracked as a separate loading category from land uses because stream flows result from all upstream land uses. Rates of bank erosion and nutrient loading from streambank erosion are higher in catchments with more impervious area.
- Three catchments dominated by specific land uses have been evaluated in terms of areal loading rates for comparison to other modeling studies or Forest Service monitoring studies.
    - Simulated concentrations compare well to water quality observations at these locations, even for those catchments that were not the focus of the water quality calibration (i.e., model coefficients were not adjusted to improve the model fit at these specific locations).
    - Each of these three catchments yields varying land use loading rates, and all three predict the magnitude and patterns of observed total nitrogen, total phosphorus, and total organic carbon observed at the UNRBA monitoring stations.
    - When a catchment is dominated by a land use type, the model cannot be calibrated if the areal (per-acre) loading rates from the dominate land uses are not reasonable.
    - Other areas in the watershed where land use patterns are more mixed also have simulated concentrations and flows that match the observations; the modeling methods are the same in terms of underlying datasets and approach

A sensitivity analysis on atmospheric deposition rates was also conducted (Appendix H). Deposition rates of nitrogen species, total phosphorus, and total organic carbon were adjusted by +-25 percent. Total nitrogen delivered loads were the most affected by this analysis. Lowering the rates of atmospheric deposition of nitrogen reduced the delivered total nitrogen load to Falls Lake by 5 percent; raising the rates of atmospheric deposition of nitrogen increased the delivered total nitrogen load to Falls Lake by 5 percent. Approximately 10 to 20 percent of nutrients applied or deposited to the lands in the watershed are delivered to Falls Lake on average due to crop harvesting, denitrification, settling, etc. This watershed processing is why this sensitivity analysis has a relatively small impact on delivered loading (25 percent times 20 percent equals 5 percent).

A sensitivity analysis on rainfall amount for the entire watershed was also conducted. Simulating the current watershed conditions with 20 percent less rainfall than occurred in 2015 to 2018 reduced the total nitrogen load delivered to Falls Lake by 35 percent and the total phosphorus load by 42 percent. Simulating the current watershed conditions with 20 percent more rainfall than occurred in 2015 to 2018 increased the total nitrogen load delivered to Falls Lake by 36 percent and the total phosphorus load by 60 percent. This multi-year sensitivity analysis is similar to load estimates reported by DWR in the 5-yr status report for Falls Lake (2021). DWR generated annual loading estimates for 2006 to 2019 using the USGS LOADEST package. The estimated tributary loading from the five largest tributaries in the watershed is based on USGS-gaged river flows and DWR water quality concentrations. In 2017, DWR reports that total nitrogen load delivered to Falls Lake from the five largest tributaries was 1.06 million pounds of total nitrogen per year. In 2018, DWR reports that the total nitrogen load from the five largest tributaries to Falls Lake was 1.81 million pounds of total nitrogen per year. **Based on DWR's estimates, the total nitrogen load in 2018 was 70 percent higher than 2017.** In 2019, the total nitrogen load decreased to 1.31 million pounds of total nitrogen per year when rainfall became more typical for the area but followed a very wet year. DWR reports that total phosphorus load delivered to Falls Lake in 2017 from these five tributaries was 150,788 pounds of total phosphorus per year and that in 2018, the total phosphorus load delivered to Falls Lake was 243,621 pounds of total phosphorus per year. **Based on DWR's estimates, the total phosphorus load in 2018 was 62 percent higher than 2017.** In 2019, total phosphorus loads based on LOADEST decreased to 143,732 pounds of total phosphorus per year. There were not widespread changes in the watershed that lead to these fluctuations in delivered loading between 2017 and 2019. Rainfall and antecedent soil moisture conditions are the reasons for the fluctuations during these years.

Additional information regarding sensitivity analyses and model scenarios is provided in Section 8.

6.7 Model Uncertainty

Several sections of the report as well as its appendices address uncertainty associated with model inputs, calibration data sets, and model configurations and calculations. This section summarizes that information.

WARMF is a lumped parameter model that assumes each of the 264 modeling catchments has uniformity in soil layers and characteristics. One improvement to the model to address this uncertainty separates the soils under each land use and runs the model for 25 years to achieve equilibrium from the initial catchment-wide soil characterization with the land use specific nutrient application and uptake rates. This improvement to the model allows for the chemical properties of the soils to stabilize depending on land use activities. It does not address hydrologic properties like vertical hydraulic conductivity which remain uniform across the catchment.

WARMF simulates one stream reach per modeling catchment. Additional feeder tributaries may be present, and the model does not explicitly account for the processes that occur in these streams. The model is calibrated, however, to represent the net effect of upstream processes and simulate reasonable stream flows and loads to Falls Lake.

Some of the data used to set the chemical characteristics of the soils for initial conditions is decades old. Running the model for 25 years to achieve equilibrium with nutrient application rates helps address this uncertainty as the soils achieve equilibrium.

Land use land cover data is based on satellite imagery from a specific year, and the model period covers five years. Localized land use changes or year-to-year changes in crop types may not be accurately reflected.

Nutrient application rates for agricultural lands are specified at the county level and may not represent field-scale differences in application. There is more uncertainty with the amount of fertilizer applied to urban areas, and the assumptions were based on two published studies that were applied to the entire watershed (i.e., not specified at the county level). Homeowner fertilizer application practices vary from not applying fertilizer to over applying. We assume the midpoint of the ranges reported as an approximation.

Median effluent concentrations from onsite wastewater treatment systems were provided by NC Collaboratory researchers. Different concentrations were assumed for different types of systems and functionality. Failure rates are based on county-wide averages and are spaced evenly throughout the county. The model may not represent localized conditions if high failure rates are concentrated in specific areas. However, loading from this source to Falls Lake is less than 2 percent for total nitrogen and total phosphorus, so uncertainty with the application of median concentrations by type and function is not expected to significantly affect simulated loading to Falls Lake.

The model time step is 6-hours and precipitation depths are summed over each 6-hr increment. Intense storms that occurred over a shorter period may not be accurately simulated by the model in terms of peak stream flows and concentrations. The total load would be accounted for but spread over the 6-hour simulation period.

Water quality monitoring in the tributaries to Falls Lake represents specific points in time. The model simulates average concentrations over each 6-hour time step. General trends and total loads are accounted for by the model, but specific data points are sometimes missed.

Precipitation and air chemistry data are collected at a limited number of stations that are 20 to 70 miles from the watershed. Deposition models indicate higher rates of nitrogen deposition near urban areas compared to rural areas. The Falls Lake watershed model assumes the same amount of deposition occurs across the watershed (varies in time based on weekly measurements but in space the rates are constant). The average annual total nitrogen deposition rate simulated by the WARMF model for the UNRBA study period is 8.4 kg/ha/yr. The online EPA EnviroAtlas reports 2016 estimated deposition rates ranging from 8.1 kg/ha/yr in Granville and Person Counties up to 9.4 kg/ha/yr in Wake County. To address the uncertainty with atmospheric deposition, sensitivity analyses have been conducted on these inputs and are discussed in Appendix H. Future updates to the model may include evaluation of EPA's recently developed, spatially variable models of nitrogen deposition.

To calibrate the simulated stream flows, comparison are made to gaged stream flows reported by USGS. Eight of the ten USGS stream flow gages are located in the Carolina Slate Belt and drain relatively rural areas. Two of the gages are located in the most developed subwatershed, Ellerbe Creek, which is located in the Triassic Basin. These gaged flows are based on water level readings and a regression equation to estimate flows. Thus, the model is not being calibrated to actual measurements of stream flow but rather estimates of stream flows. There is more uncertainty in the USGS gaged stream flows at the extremes (very low flows or very high flows). Uncertainty in gaged or simulated flows during very low flow conditions does not significantly affect total loading delivered to Falls Lake, but uncertainty during high flow conditions can affect the simulated loading. The model is constrained by the amount of loading that can be simulated by the model inputs for precipitation, soil chemistry and hydrologic characteristics, nutrient inputs, etc.

Much less data is available from the impoundments in the watershed compared to Falls Lake including bathymetric, water quality, and sediment flux data. There is more uncertainty about the chemical, biological, and physical processes occurring these lakes compared to Falls Lake. Fortunately, water quality monitoring locations and stream flow gages are active downstream of most of these impoundments, and the model performs relatively well at these sites for total nitrogen, total phosphorus, and total organic carbon. The speciation of nitrogen is affected by the processes within each lake, and model performance is not as good at the species level.

Laboratory analyses are also uncertainty and reported values should not be considered exact measurements. Comparisons of simulated water quality concentrations to observed data are shown with the 95th percentile confidence interval based on the UNRBA data set for each parameter. These intervals are used to visualize the uncertainty but are not used to calculate model performance.

Section 7, Appendix H, and Appendix I of this report summarize the delivered nutrient and carbon loads to Falls Lake. Loads are presented to the single pound so that comparisons by tributary, source, jurisdiction, etc. all sum to the same totals. Rounding the delivered loads is not possible because some sources contribute orders of magnitude less than others. While the model generates very refined estimates loading, reporting of these values should not be inferred as a statement of certainty in the model results down to the single pound.

Section 7

Summary of Loading to Falls Lake

WARMF simulates the individual physical, chemical, and biological processes within each catchment, stream reach, and impoundment. Characterization of the watershed includes soil chemistry data which affects how nutrients are bound to particles, soil hydrologic properties which affect water movement through soil layers, land use data, nutrient application data (rates and timing by crop and county), crop planting and harvesting dates, estimates of atmospheric deposition, discharges from wastewater treatment plants, and onsite wastewater treatment systems. The WARMF model conserves mass in its accounting, and the user does not specify runoff concentrations, soil nutrient concentrations, or groundwater concentrations. The model calculates these at each time step based on the information input to the model.

WARMF model outputs include stream flow, concentrations of all constituents contained within that flow, and constituent loading by area and by source. Loading output by source represents the average mass/day or mass/area/year over the simulation period. This model was developed specifically for the Falls Lake watershed and the local land use intensity, soil characteristics, and nutrient reduction achievements must be considered when comparing WARMF simulated results to other studies or regions.

The UNRBA collected tributary monitoring data at 38 locations across the watershed (Figure 4-12) each month from August 2014 to October 2018. These water quality monitoring stations are located across the watershed and drain areas comprised of varying types of land uses (Figure 3-4). Some of these areas are intensely developed, some are mostly unmanaged, and some include up to 25 percent agricultural lands. This level of monitoring coverage is exceptional and provides an excellent basis for confirming model simulations throughout the watershed. Appendix H includes several catchment-scale model results for catchments that are predominantly unmanaged, predominately urban, or have relatively high percentages of agricultural land uses. These catchments were evaluated for dry to average hydrologic conditions in addition to the UNRBA study period which was hydrologically average to wet. These catchments were used to test that the model responds as expected to increased rainfall. Loading rates from the mostly unmanaged catchments were compared to monitoring studies conducted by the US Forest Service in the Falls Lake watershed. The US Forest Service studies were conducted during years of dry to average hydrologic conditions. When the UNRBA watershed model is evaluated with similar hydrologic conditions, the simulated loading rates from forests are similar to the monitoring studies. When simulated rainfall is higher, the loading rates from forests are higher. This also occurs in catchments with relatively high percentages of agriculture. During dry periods, both forests and agricultural lands can accumulate organics and nutrients. Under wet hydrological conditions, these areas can release loads. Impervious surfaces do not behave in this manner because they cannot store and accumulate material the way that pervious areas can.

For the UNRBA study period, the model simulates approximately 1,650,000 pounds per year of total nitrogen; 183,000 pounds per year of total phosphorus; and 13,100,000 pounds per year of total organic carbon delivered to Falls Lake. With three-quarters of the land area in unmanaged uses (forests, wetlands, unmanaged grassland and shrubland, and open water), nearly one-half of the total nitrogen and over one-half of the total phosphorus and total organic carbon loads delivered to Falls Lake originate from these areas. While these areas contribute loading to the lake, particularly during wet conditions, they are important to the health of the watershed by storing and cycling nutrients and carbon, infiltrating and storing rainwater, buffering temperatures, and providing habitat to terrestrial, avian, and aquatic wildlife.

WARMF simulated loads and per-acre loading rates from forests and other unmanaged areas were a considerable focus of the model review efforts by subject matter experts and “third-party” reviewers funded by the NC Collaboratory. Appendix H documents these discussions and model testing to confirm reasonable loads and per-acre loading rates are being simulated. As demonstrated by the model sensitivity to rainfall, loading rates from forest increase under wet hydrologic conditions. When a dry to average hydrologic condition is simulated with the model, the per-acre forest loading rates are similar to those observed by the USFS which conducted monitoring studies during dry to average hydrologic conditions (2008 to 2013).

DWR's 5-year status report for Falls Lake also demonstrates the effects of rainfall on nutrient loading to Falls Lake (DWR 2021). As noted throughout this report, 2017 was an average rainfall year (45 inches) and 2018 was a very wet year (60 inches). DWR's 5-yr status report provides estimated tributary loading from the five largest tributaries in the watershed. Based on DWR's application of the USGS LOADEST model (also referenced in Section 6.6), total nitrogen loads delivered to Falls Lake from the five largest tributaries was 70 percent higher in 2018 compared to 2017. Total phosphorus loads delivered to Falls Lake from these five tributaries was 62 percent higher. These increases from 2017 to 2018 were not the result of extensive land use changes, removal of stormwater control measures, failures at wastewater treatment plants, etc. This increase in load is due to an additional 15 inches of rain that fell in 2018.

Increased loading from forested areas following large rainfall events and during wet hydrologic conditions has been documented by many researchers (Hunt 2023, Paerl et al. 2018, 2019, 2020; Osburn 2016; Timmons 1977; Oyarzún and Hervé-Fernandez 2015). Several of these studies were cited in DWR's 20-yr status report on the Neuse and Tar Pam Estuaries in reference to increased nutrient loading from forested areas resulting from increased precipitation and climate change (Draft – May 16, 2023). Below are quotations the DWR draft report:

Increased loading from forested areas following large rainfall events and generally wet hydrologic conditions has been documented by many researchers.

- "Analyses of nitrogen loading to the two estuaries have clearly documented a substantial decadal or longer rise in organic nitrogen delivery to both beginning around 2000, accompanied by strong evidence of the same phenomenon occurring in the Albemarle Sound as well, suggesting a broader pattern. This increase has offset the nitrogen loading gains made by point sources. An interinstitutional team of researchers has now established **compelling evidence** that since the late 1990's, distinct **increases have occurred in coastal NC rainfall and flooding** from intensified tropical cyclone activity and these storms have, among other effects, **mobilized large amounts of previously stored dissolved organic carbon from freshwater wetlands, and have substantially increased nutrient loading from the watershed, including dissolved organic nitrogen,** to the estuaries along with driving increased productivity in and carbon release from the estuaries and sound. The authors conclude that "we appear to have entered a new climatic regime characterized by more frequent extreme precipitation events, with major ramifications for hydrology, cycling of C, N and P, water quality and habitat conditions in estuarine and coastal waters" (Paerl et al, 2020)."
- "As these trends have emerged, Paerl and colleagues have built a compelling case (Paerl et al, 2020; Paerl et al, 2019; Paerl et al, 2018) that distinct increases have occurred in coastal NC **rainfall and flooding** from intensified tropical cyclone activity since the late 1990's, and they have, among other things, **mobilized large amounts dissolved organic carbon from freshwater wetlands, and increased N and P loading, including dissolved organic nitrogen, and have delivered them to the estuaries."**
- "Large amounts of mobilized, previously accumulated, terrigenous carbon (C) was determined through fluorescence tracking to originate from flooded freshwater wetlands. Floodwaters contained

extremely high loads of organic matter, dominated by dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) as well as other nutrients. **Major storms caused up to a doubling of annual nitrogen and tripling of phosphorus loading** compared to non-storm years."

- "The study [Osburn 2016] found that while **>70% of DON [dissolved organic nitrogen] was attributed to natural background sources**, nonpoint sources, such as soil and poultry litter leachates and street runoff, accounted for the remaining 30%."
- "They [Lebo et al. 2012] found that decreases in nitrate-nitrite (NO3–N) concentrations occurred throughout the basin and were largest just downstream of the Raleigh metropolitan area. Conversely, **concentrations of total Kjeldahl N (TKN) increased at many stations, particularly under high flow conditions. This indicates a relative increase in organic N (Org-N) inputs since the mid-1990s. Basically, nitrate-nitrate concentrations, most likely from Raleigh urban areas, are decreasing in the upper reaches, likely due to TMDL implementation** in upper estuary. The concentrations are not progressing in the lower reaches likely because settled particle bound N may be remineralized when they are deposited from high river flows (i.e., more precipitation or storms). TKN, organic N, concentrations are getting worse."
- "Results from the extreme weather event flooding showed that land and wetland derived dissolved organic carbon flushed into receiving waters can have persistent effects on carbon cycling processes, which linger for months afterward. **Non-tidal wetlands were confirmed as the predominant source of labile, dissolved organic carbon to the estuary… In 2016, Hurricane Matthew accounted for 25% of the annual riverine C loading to the Neuse River Estuary Pamlico Sound."**
- "This study [Rudolph et al. 2020] provided evidence that flooded wetlands contribute to dissolved organic matter (DOM) export in the Neuse River Estuary-Pamlico Sound. The authors used a geographic information system (GIS) based flood model, validated with a Bayesian Monte Carlo mixing model, and data primarily collected through ModMon (https://paerllab.web.unc.edu/projects/modmon/). This study, similar to Pearl et al., 2018, Paerl et al., 2019, Paerl et al., 2020, **emphasizes the importance of considering large storms (or extreme weather events) in nutrient and carbon cycling dynamics** – the authors looked at DOM exports related to Hurricane Matthew. Results were consistent with prior studies in this system, and other coastal ecosystems, that attributed a high reactivity of DOM as the underlying reason for large CO2 releases following extreme weather events."

The remaining half of the total nitrogen and total organic carbon loads are due to a combination of agriculture, urban areas, and wastewater treatment (centralized facilities and onsite systems). The remaining total phosphorus load is due to those sources as well as streambank erosion. Loads from agriculture, urban areas, and wastewater treatment facilities have generally declined since baseline due to implementation of nutrient reduction measures, land use changes, and declining rates of atmospheric deposition.

Agriculture in the Falls Lake watershed is mostly small, family farms and less intensive than other parts of the state or country. The UNRBA WARMF model integrated 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

The local characteristics of the land use intensity and soil chemistry result in per acre loading rates for agriculture that are lower than other regions where agriculture is more intensive and more commonly studied.

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. Nutrient application rates for crops and pasture were provided by the NCDA&CS and include inputs from animal manure, biosolids, and commercial fertilizer. The local characteristics of the land use intensity and soil chemistry result in per acre loading rates for agriculture that are lower than other regions where agriculture is more intensive and more commonly studied:

- Of the 50,000 acres in the watershed remaining in agricultural production, more than one-half is pasture (26,600 acres). Simulated per acre nitrogen loading rates from pasture are higher than any other land use in the watershed and four times the simulated loading rates for forests (Appendix H). 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.**
- The second largest type of agriculture remaining in the watershed is soybeans (5,900 acres full season and 3,400 acres double-cropped). **Soybeans 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.
- Hay is the third largest type of agricultural land in this watershed (~4,500 acres). Two-thirds of the hay production acres are in counties that reduced their per acre nitrogen application rates by **more than one-half since the baseline period** (Table 3-11). Hay in this watershed also has per acre nitrogen loading rates to Falls Lake are similar to forests areas under a wet hydrologic condition.

Lands classified as “urban” in the model comprise 76,000 acres of the 492,000 acres in the watershed. Most of the urban land is low intensity existing development, developed open space, or non-DOT road rights of way (69,000 acres). **Medium and high intensity development (at least 50 percent impervious surface) make up only 1.5 percent of the entire watershed area (7,380 acres).**

The high degree of focus on relative loading rates from land uses simulated by the Falls Lake WARMF watershed model are not unique. In response to questions from DWR about why the simulated loading rates for forest in the High Rock Lake watershed were high relative to other modeling studies, Tetra Tech (2012) offered the following explanations:

> “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."

Table 7-1 summarizes the loads by individual source and source group; colors correspond to those used elsewhere in the report for source groups. Conversion of these loads and areas to areal loading rates (pounds per acre per year) and comparison to other modeling studies is provided in Appendix H. Spatial loading summaries by tributary and jurisdiction are provided in Appendix I.

Table 7-1. Load Delivered to Falls Lake and Percent Contribution by Individual Source (All Contributing Areas)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN %Load	TP lb/yr	TP %Load	TOC lb/yr	TOC %Load
Conventional Grain Corn	169	Agriculture	610	0.04%	120	0.1%	3,749	0.0%
Double-cropped Soybeans	3,350	Agriculture	6,694	0.4%	1,137	0.6%	64,807	0.5%
Fescue (Pasture)	6,324	Agriculture	239,013	14.5%	10,719	5.8%	2,550,168	19.4%
Fescue (Hay)	4,564	Agriculture	11,500	0.7%	1,442	0.8%	94,243	0.7%
Flue-Cured Tobacco	2,736	Agriculture	16,592	1.0%	1,710	0.9%	54,250	0.4%
Full Season Soybeans	5,861	Agriculture	12,335	0.7%	2,203	1.2%	120,206	0.9%
No-Till Grain Corn	2,627	Agriculture	6,508	0.4%	996	0.5%	51,895	0.4%
Wheat	820	Agriculture	2,787	0.2%	351	0.2%	17,163	0.1%
DOT Roads, Connected	2,888	DOT	13,889	0.8%	760	0.4%	47,076	0.4%
DOT Roads, Unconnected	9,976	DOT	28,876	1.7%	1,498	0.8%	105,540	0.8%
Existing Development (ExDev), High Intensity	1,554	Urban	7,111	0.4%	169	0.1%	12,029	0.1%
ExDev, Medium Intensity	4,449	Urban	25,283	1.5%	1,072	0.6%	71,209	0.5%
ExDev, Low Intensity	12,610	Urban	65,954	4.0%	5,760	3.1%	322,378	2.5%
Developed Open Space	42,981	Urban	140,445	8.5%	12,051	6.6%	965,267	7.3%
Interim Development (IntDev), High Intensity	64	Urban	239	0.0%	9	0.005%	599	0.00%
IntDev, Medium Intensity	330	Urban	1,159	0.1%	75	0.04%	5,240	0.04%
IntDev, Low Intensity	252	Urban	898	0.1%	87	0.05%	5,816	0.04%
New Development (NewDev), High Intensity	72	Urban	177	0.0%	8	0.004%	586	0.00%
NewDev, Medium Intensity	298	Urban	732	0.0%	60	0.03%	4,642	0.04%
NewDev, Low Intensity	339	Urban	840	0.1%	117	0.1%	6,974	0.1%
Deciduous Forest	146,587	Forest	302,024	18.3%	31,475	17.2%	3,052,303	23.2%
Coniferous Forest	68,503	Forest	164,242	9.9%	26,525	14.5%	1,692,401	12.9%
Mixed Forest	75,917	Forest	163,788	9.9%	22,518	12.3%	1,694,157	12.9%
Shrub / Scrub	7,368	Unmanaged grass/shrub	15,971	1.0%	1,976	1.1%	156,785	1.2%
Unmanaged Grassland	41,484	Unmanaged grass/shrub	94,950	5.7%	11,625	6.3%	885,116	6.7%
Barren	471	Barren	2,684	0.2%	356	0.2%	13,179	0.1%

Table 7-1. Load Delivered to Falls Lake and Percent Contribution by Individual Source (All Contributing Areas)

Source	Drainage Area (ac)	Source Group	TN lb/yr	TN %Load	TP lb/yr	TP %Load	TOC lb/yr	TOC %Load
Emergent Herbaceous Wetland	406	Wetland	1,152	0.1%	169	0.1%	11,802	0.1%
Woody Wetland	9,495	Wetland	31,759	1.9%	4,170	2.3%	330,139	2.5%
Waterfowl Impoundment	839	Wetland	2,225	0.1%	268	0.1%	23,157	0.2%
Water	4,455	Open Water	19,343	1.2%	1,602	0.9%	104,017	0.8%
General Nonpoint Sources	NA	Initial System Mass	19,650	1.2%	6,180	3.4%	160,936	1.2%
Stream Bank Erosion	NA	Stream Banks	12,996	0.8%	26,519	14.5%	125,217	1.0%
Direct Precipitation	NA	Direct Precipitation	85,585	5.2%	59	0.03%	122,138	0.9%
Direct Dry Deposition	NA	Direct Dry Deposition	11,376	0.7%	2,130	1.2%	8,271	0.1%
Privy	NA	Onsite WW (no DSF)	2	0.0001%	0	0.000%	11	0.000%
Conventional Functioning	NA	Onsite WW (no DSF)	16,917	1.02%	2	0.001%	2,268	0.017%
Conventional Malfunctioning	NA	Onsite WW (no DSF)	3,285	0.20%	104	0.057%	33,100	0.252%
Advanced Treatment, Functioning	NA	Onsite WW (no DSF)	295	0.02%	0	0.000%	117	0.001%
Advanced Treatment, Malfunctioning	NA	Onsite WW (no DSF)	104	0.01%	3	0.002%	1,121	0.009%
Advanced Treatment, Functioning >3000gpd	NA	Onsite WW (no DSF)	1	0.00003%	0	0.000%	0	0.000%
Major WWTPs	NA	Major WWTPs	93,793	5.7%	6,103	3.3%	201,628	1.5%
Minor WWTPs	NA	Minor WWTPs	17,002	1.0%	295	0.2%	19,747	0.2%
Discharging Sandfilter Systems	NA	Discharging Sandfilter Systems	10,976	0.66%	1,015	0.55%	8,991	0.1%
Sanitary Sewer Overflows	NA	Sanitary Sewer Overflows	52	0.0031%	7	0.004%	60	0.0005%
Total			1,651,813	100%	183,444	100%	13,150,496	100%

The sections below summarize the delivered loads for these three parameters by contributing area and source groups.

7.1 Total Nitrogen

Total nitrogen is comprised of ammonia, nitrate plus nitrite, and organic nitrogen. Inputs to the system are primarily nutrient application, atmospheric deposition, and wastewater from centralized systems and onsite systems. Losses from the system are primarily nutrient removal due to crop harvesting, denitrification, and settling of adsorbed fractions in impoundments and streams.

Figure 7-1 through Figure 7-3 display the sources, contributing areas, jurisdictions, and permittees contributing total nitrogen to Falls Lake. The underlying data for the source/tributary figures is provided in Table 7-2 which shows the amount and percent contribution to the lake. Similar data for the source/jurisdictions is provided in Appendix I. Areal loading rates (pounds per acre per year) are provided in Appendix H.

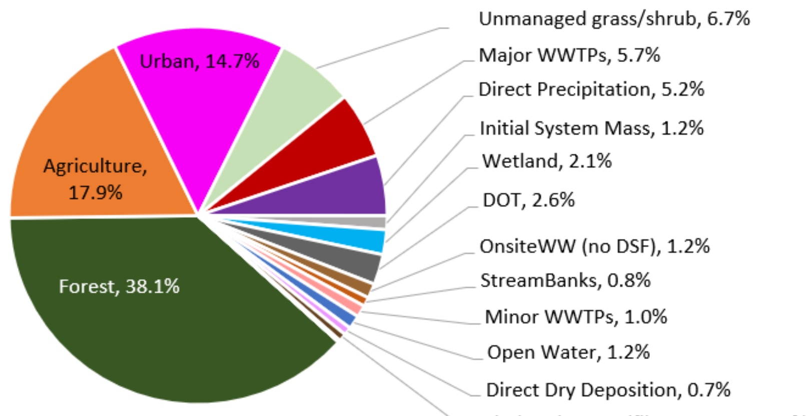
The largest source of total nitrogen delivered to Falls Lake comes from forested areas which comprise approximately 60 percent of the total watershed area and 75 percent of the Near Lake area. These areas are important to the health of the watershed as they store and cycle nutrients and carbon. Loading from these areas increases with higher precipitation depths as the storage capacity of the soil becomes saturated and runoff occurs. The second and third largest contributors are agriculture and urban areas, respectively. In this watershed, developed open space, which is mostly non-DOT right of ways, comprises the majority (68 percent) of the urban source group. Over one-half of the agriculture in the basin is pasture.

The delivered loads represent an approximately 83 percent reduction relative to the gross inputs due to watershed processes, crop harvesting, etc.

Appendix H provides comparison of the WARMF simulations for the Falls Lake watershed to other modeling studies. One of these studies (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., natural, background sources), 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 percent 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.”

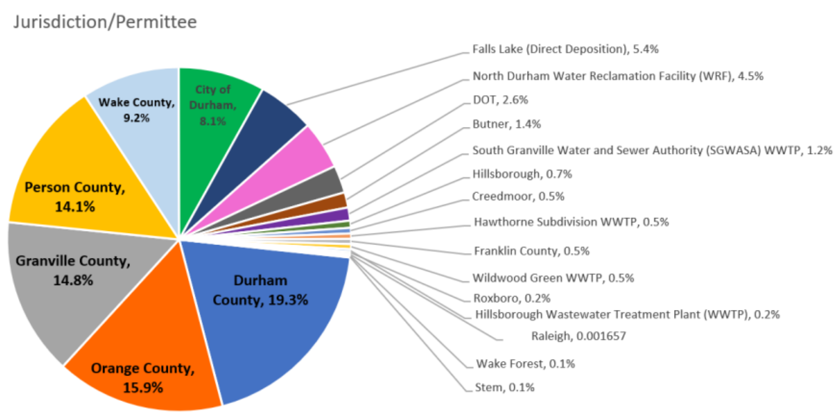
Osburn et al. (2016) found that on average, 72 to 85 percent of organic nitrogen loading matched the fluorescence signatures of reference streams that were classified as Outstanding Resource Waters. The sampled reference streams had no discharges from wastewater treatment facilities, street or storm water runoff over paved surfaces, or poultry or swine operations in their watersheds and were “used to quantify a natural background source” of organic nitrogen. In the Falls Lake watershed, the organic component of nitrogen represents half or more of the total nitrogen load to the lake.



Loads from unmanaged lands contribute the largest fraction of the load because 75 percent of the watershed is comprised of these areas.

57% of "agriculture" is pasture, 12% is full season soybeans, 10% is hay, 7% is double-cropped soybeans, 6% is flue-cured tobacco, 6% is no-till grain corn, and 2% is wheat or other crops.

68% of "urban" area is developed open space (mostly non-DOT road right of way) and 20% is existing development, low intensity.



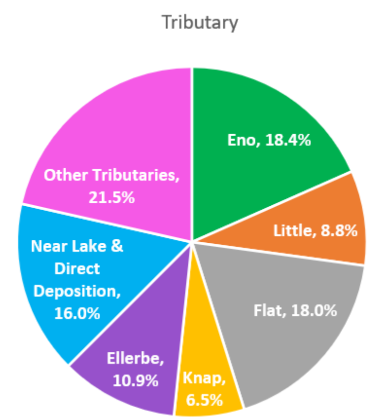


Figure 7-1. Sources (top) and Contributing Areas (bottom) of Total Nitrogen Delivered to Falls Lake (1.65 million pounds per year)

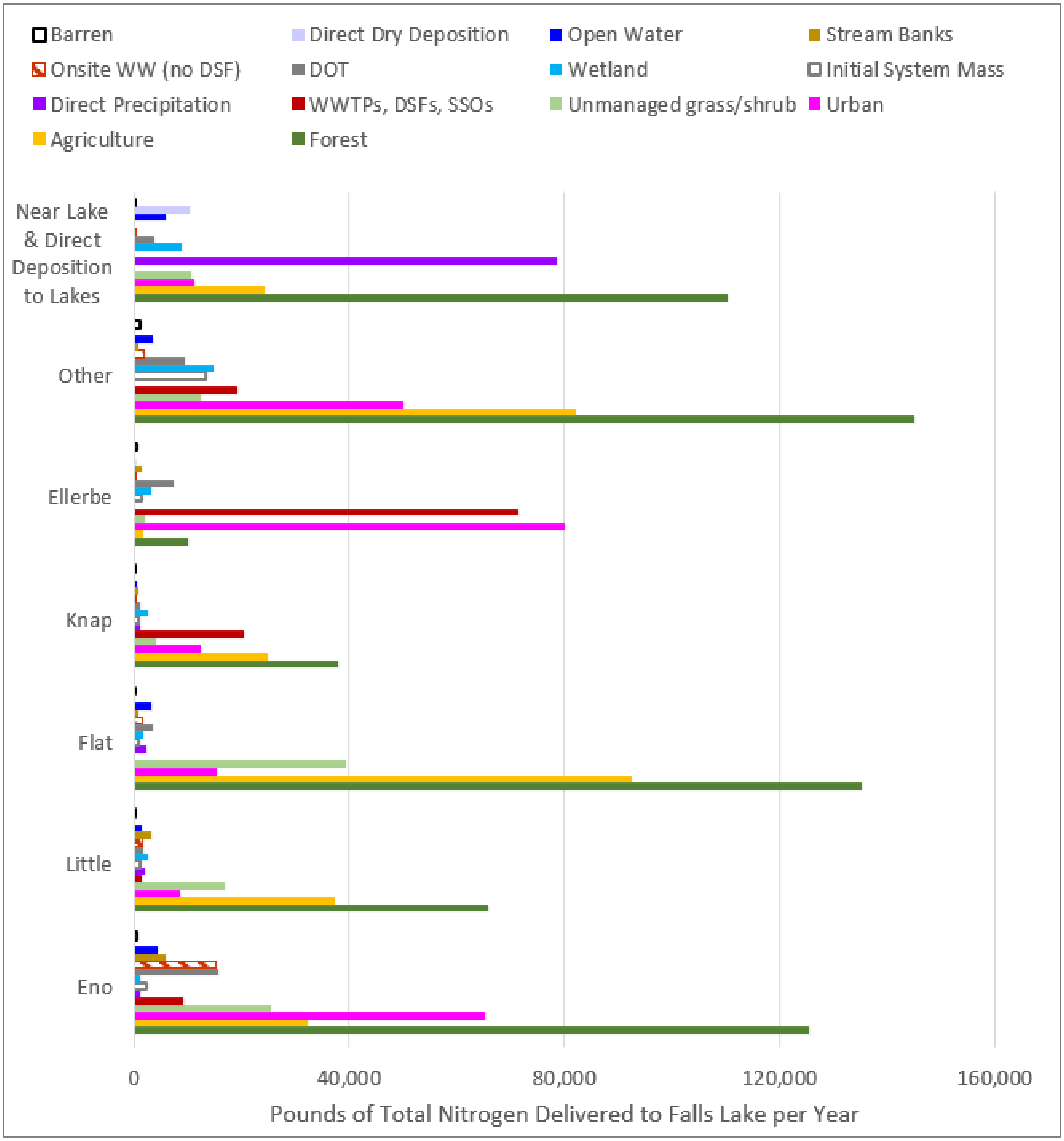


Figure 7-2. Total Nitrogen Load Delivered to Falls Lake by Source and Contributing Area

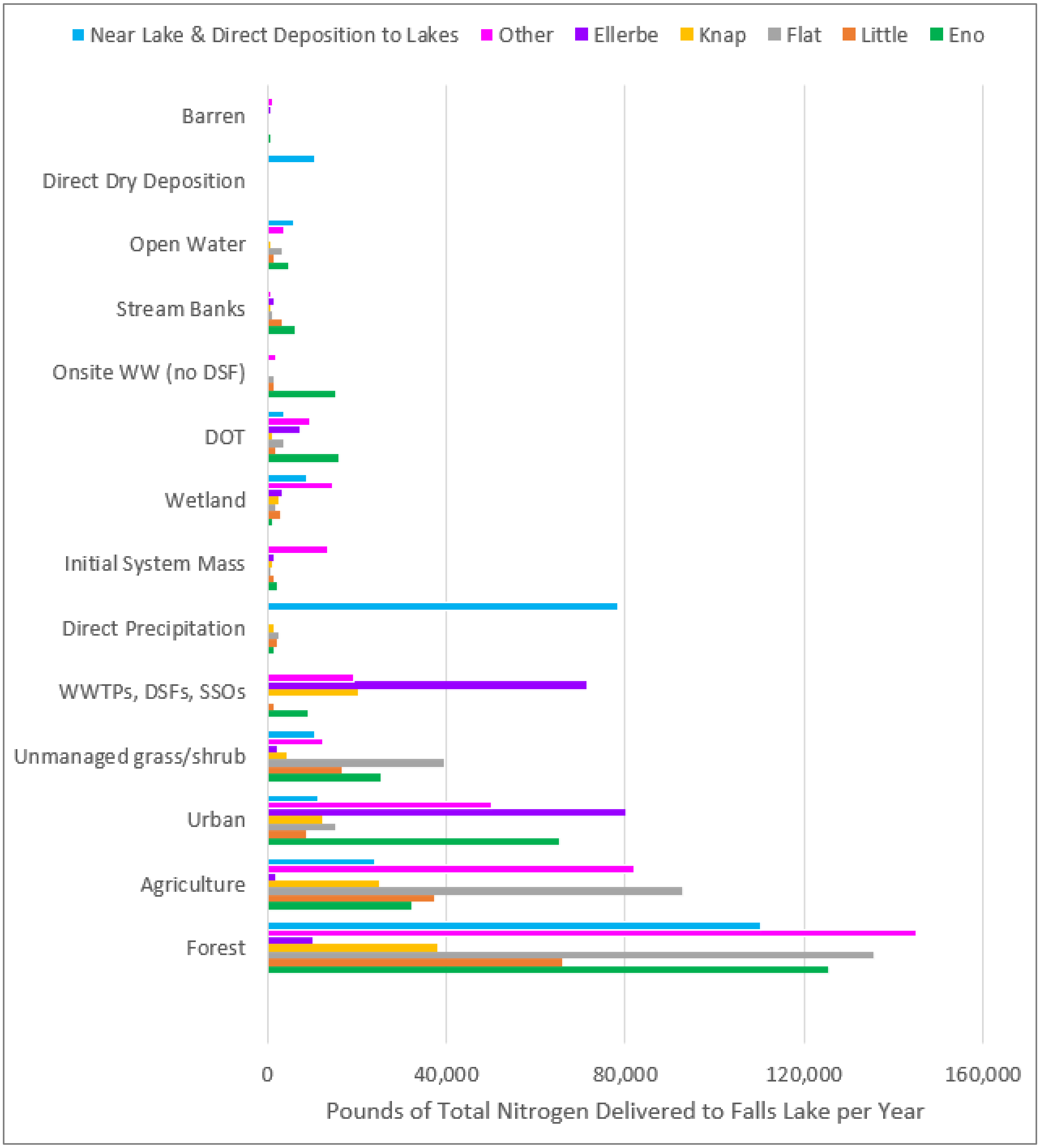


Figure 7-3. Total Nitrogen Load Delivered to Falls Lake by Contributing Area and Source

Table 7-2. Total Nitrogen Load Delivered to Falls Lake by Source Group and Contributing Areas (loads top, percentages bottom)

Source Group	Eno	Little	Flat	Knap	Ellerbe	Other Tributaries	Near Lake & Direct Deposition to Lakes	Total
Forest	125,435	65,818	135,374	37,978	9,928	145,195	110,327	630,054
Agriculture	32,313	37,435	92,580	25,014	1,660	82,839	24,198	296,039
Urban	65,245	8,703	15,247	12,273	80,143	50,052	11,176	242,839
Unmanaged grass/shrub	25,402	16,724	39,549	4,216	2,017	12,437	10,575	110,920
WWTPs, DSFs, SSOs	9,016	1,528	237	20,379	71,352	19,307	2	121,822
Direct Precipitation	1,274	2,130	2,398	1,274	0	0	78,509	85,585
Initial System Mass	2,200	1,218	812	856	1,334	13,230	0	19,650
Wetland	1,006	2,705	1,844	2,536	3,340	14,754	8,951	35,135
DOT	15,785	1,756	3,551	1,149	7,267	9,467	3,792	42,765
Onsite WW (no DSF)	15,092	1,546	1,504	37	100	1,939	385	20,604
Stream Banks	5,942	3,234	830	732	1,478	779	0	12,996
Open Water	4,472	1,496	3,092	617	309	3,589	5,769	19,343
Direct Dry Deposition	163	262	301	167	0	0	10,482	11,376
Barren	494	121	85	35	599	1,166	185	2,684
Total	303,839	144,676	297,403	107,263	179,528	354,753	264,351	1,651,813
Source Group	Eno	Little	Flat	Knap	Ellerbe	Other Tributaries	Near Lake & Direct Deposition to Lakes	Total
Forest	7.59%	3.98%	8.20%	2.30%	0.60%	8.79%	6.68%	38.14%
Agriculture	1.96%	2.27%	5.60%	1.51%	0.10%	5.02%	1.46%	17.92%
Urban	3.95%	0.53%	0.92%	0.74%	4.85%	3.03%	0.68%	14.70%
Unmanaged grass/shrub	1.54%	1.01%	2.39%	0.26%	0.12%	0.75%	0.64%	6.72%
WWTPs, DSFs, SSOs	0.55%	0.09%	0.01%	1.23%	4.32%	1.17%	0.00%	7.38%
Direct Precipitation	0.08%	0.13%	0.15%	0.08%	0.00%	0.00%	4.75%	5.18%
Initial System Mass	0.13%	0.07%	0.05%	0.05%	0.08%	0.80%	0.00%	1.19%
Wetland	0.06%	0.16%	0.11%	0.15%	0.20%	0.89%	0.54%	2.13%
DOT	0.96%	0.11%	0.21%	0.07%	0.44%	0.57%	0.23%	2.59%
Onsite WW (no DSF)	0.91%	0.09%	0.09%	0.00%	0.01%	0.12%	0.02%	1.25%
Stream Banks	0.36%	0.20%	0.05%	0.04%	0.09%	0.05%	0.00%	0.79%
Open Water	0.27%	0.09%	0.19%	0.04%	0.02%	0.22%	0.35%	1.17%
Direct Dry Deposition	0.01%	0.02%	0.02%	0.01%	0.00%	0.00%	0.63%	0.69%
Barren	0.03%	0.01%	0.01%	0.00%	0.04%	0.07%	0.01%	0.16%
Total	18.39%	8.76%	18.00%	6.49%	10.87%	21.48%	16.00%	100.00%

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.

7.2 Total Phosphorus

Total phosphorus inputs to the system are primarily nutrient application and atmospheric deposition. Losses from the system are primarily nutrient removal due to crop harvesting, adsorption to soils, and settling of the adsorbed fraction in impoundments and streams.

Figure 7-4 through Figure 7-6 display the sources, contributing areas, jurisdictions, and permittees contributing total phosphorus to Falls Lake. The underlying data for the source/tributary figures is provided in Table 7-3 which shows the amount and percent contribution to the lake. Similar data for the source/jurisdictions is provided in Appendix I.

The largest source of total phosphorus delivered to Falls Lake (44 percent of the load) comes from forested areas which comprise approximately 60 percent of the total watershed area and 75 percent of the Near Lake area. These areas 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. The second largest contributor is stream bank erosion. Urban areas and agriculture are similar and have the next highest loads. In this watershed, developed open space, which is mostly non-DOT right of ways, comprises the majority of the urban source group. Over one-half of the agriculture in the basin is pasture..

With three-quarters of the land area in unmanaged uses (forests, wetlands, unmanaged grassland and shrubland, and open water), 55 percent of the total phosphorus load delivered to Falls Lake originates from these areas. Streambank erosion contributes approximately 14 of the loading and remaining 31 percent is due to urban areas, agriculture, and wastewater treatment (centralized facilities and onsite systems).

The delivered loads represent an approximately 84 percent reduction relative to the gross inputs applied, deposited, or released to the watershed. The reduction in phosphorus load is greater than the nitrogen reduction largely due to the adsorption properties of phosphorus.

The findings from the WARMF model for the Falls Lake Watershed are consistent with other modeling studies (Appendix H). For example, the SPARROW model developed by USGS predicts that over 40 percent of the phosphorus load to streams in the Southeast 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 includes 75 percent unmanaged lands 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. Appendix H also provides comparison of the WARMF-simulated areal loading rates of total phosphorus from forested areas to monitoring studies conducted by the US Forest Service. When the model is evaluated for a dry to average rainfall condition, similar to what occurred during the monitoring studies, the areal loading rates are similar.

Note that the UNRBA study period had average to high precipitation relative to long-term averages. Loading rates from forested areas simulated by the model are higher than loading rates simulated under dry to average hydrologic conditions. WARMF-simulated loads for the dry to average hydrologic condition are similar to those measured by the US Forest Service monitoring studies which were conducted during dry to average hydrologic conditions (Appendix H).

When comparing nutrient loading rates from forests to urban areas, the following considerations are important to note:

- The UNRBA Falls Lake watershed model tracks loading from streambank erosion separately, so urban export rates, particularly for phosphorus, are generally lower than those reported in the literature that account for both surface runoff and stream bank erosion.
- The UNRBA study period had average to wet rainfall (up to 60 inches per year in 2018) which results in saturation of pervious areas including forests and agricultural fields and exporting nutrients

downstream. Loading rates from these areas are lower during lower rainfall conditions when the soils are not saturated. Urban areas with compacted soils and impervious surfaces are not able to store as much precipitation compared to other land uses.

- Approximately 90 percent of “urban” land in the Falls Lake watershed is categorized by the USGS NLCD as developed open space or low intensity development (both have an assumed percent imperviousness of 20 percent based on NLCD categorization). To comply with the Falls Lake Rules, the local governments have installed over 350 existing development retrofit projects. Thus, “urban” areas in the Falls Lake watershed may be very different than those in other published studies.

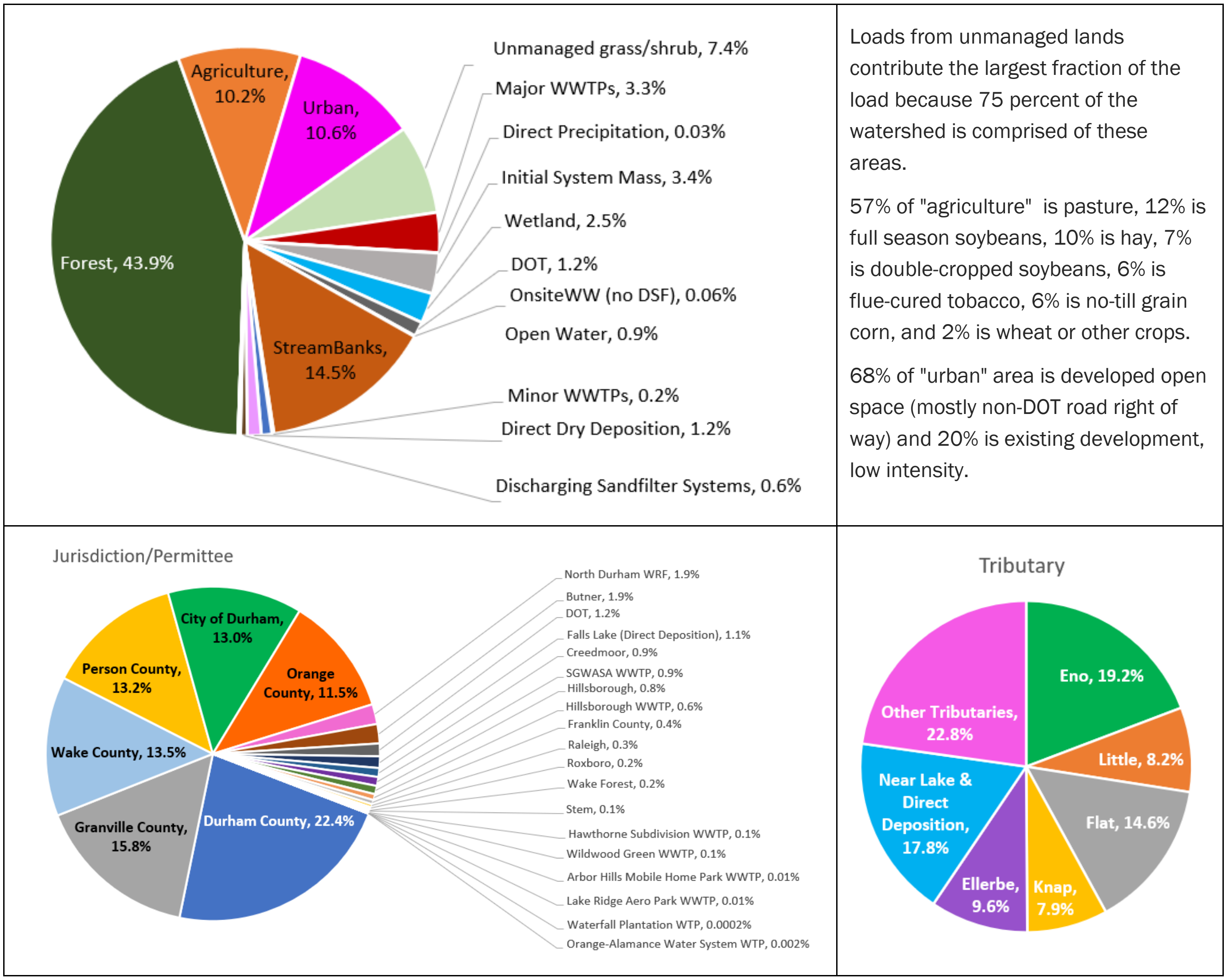


Figure 7-4. Sources (top) and Contributing Areas (bottom) of Total Phosphorus Delivered to Falls Lake (183,000 pounds per year)

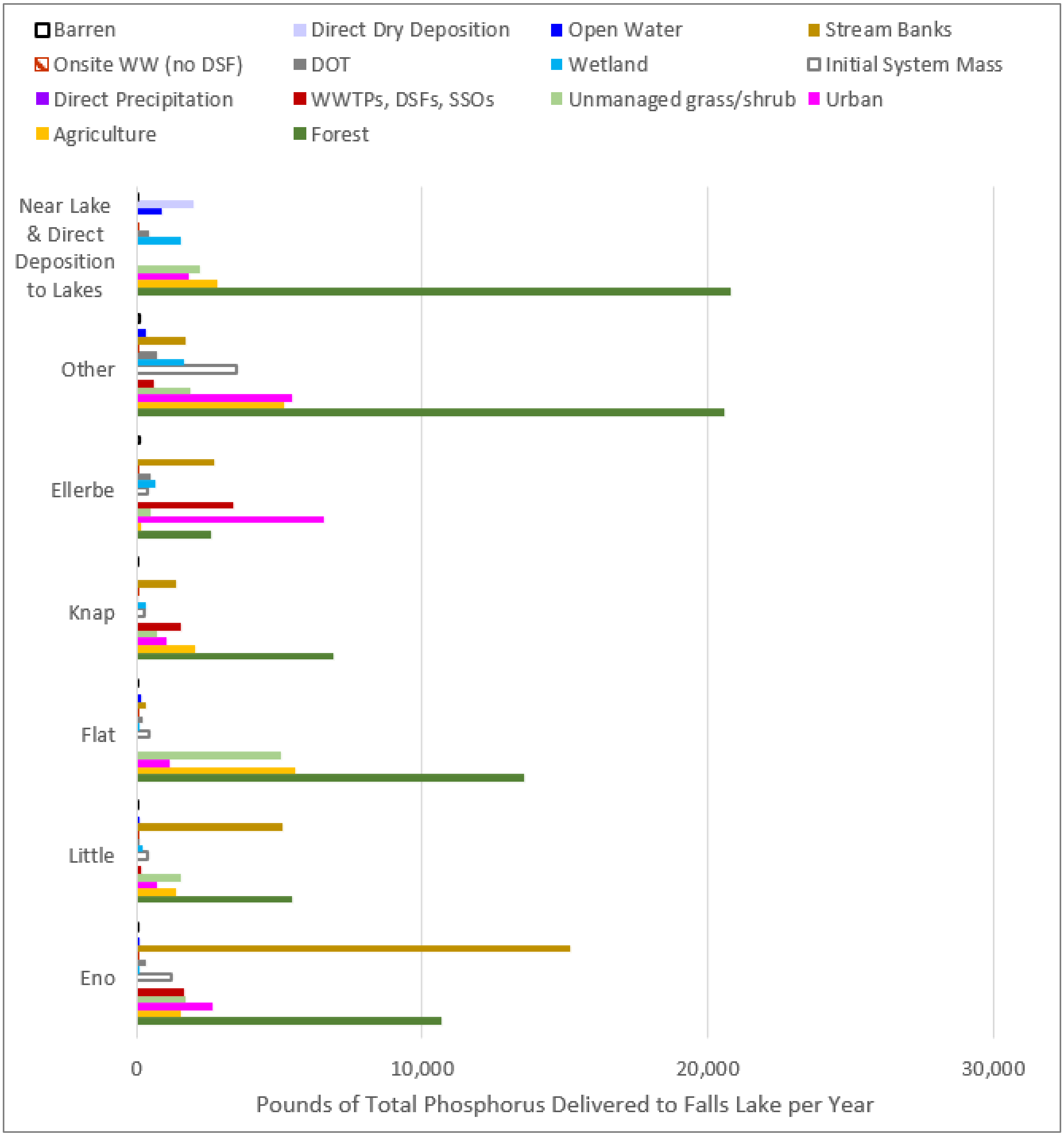


Figure 7-5. Total Phosphorus Load Delivered to Falls Lake by Source and Contributing Area

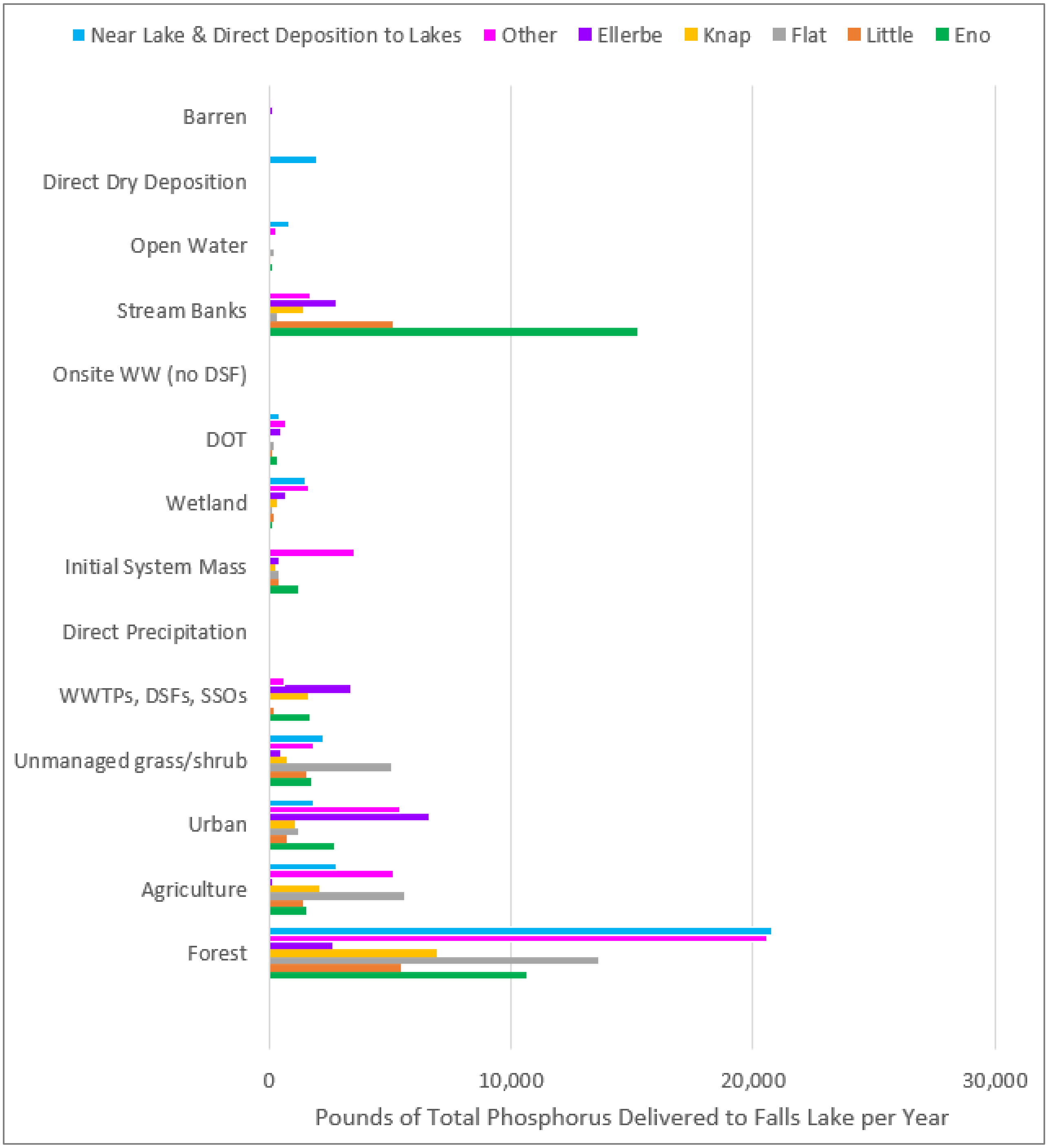


Figure 7-6. Total Phosphorus Load Delivered to Falls Lake by Contributing Area and Source

Table 7-3. Total Phosphorus Load Delivered to Falls Lake by Source Group and Contributing Areas (loads top, percentages bottom)

Source Group	Eno	Little	Flat	Knap	Ellerbe	Other Tributaries	Near Lake & Direct Deposition to Lakes	Total
Forest	10,665	5,431	13,574	6,901	2,580	20,579	20,789	80,518
Agriculture	1,540	1,389	5,558	2,050	140	5,189	2,810	18,677
Urban	2,668	697	1,180	1,034	6,577	5,439	1,811	19,407
Unmanaged grass/shrub	1,717	1,526	5,047	736	471	1,860	2,245	13,601
WWTPs, DSFs, SSOs	1,649	173	24	1,575	3,379	620	1	7,420
Direct Precipitation	1	1	1	1	0	0	56	59
Initial System Mass	1,223	372	420	285	396	3,483	0	6,180
Wetland	102	203	127	326	657	1,661	1,531	4,607
DOT	300	97	195	66	468	712	419	2,258
Onsite WW (no DSF)	6	4	11	0	2	46	40	109
Stream Banks	15,204	5,107	326	1,383	2,724	1,774	0	26,519
Open Water	107	77	172	51	36	303	857	1,602
Direct Dry Deposition	21	33	50	25	0	0	2,000	2,130
Barren	62	14	12	8	100	120	41	356
Total	35,264	15,124	26,698	14,440	17,532	41,785	32,601	183,444
Source Group	Eno	Little	Flat	Knap	Ellerbe	Other Tributaries	Near Lake & Direct Deposition to Lakes	Total
Forest	5.81%	2.96%	7.40%	3.76%	1.41%	11.22%	11.33%	43.89%
Agriculture	0.84%	0.76%	3.03%	1.12%	0.08%	2.83%	1.53%	10.18%
Urban	1.45%	0.38%	0.64%	0.56%	3.59%	2.97%	0.99%	10.58%
Unmanaged grass/shrub	0.94%	0.83%	2.75%	0.40%	0.26%	1.01%	1.22%	7.41%
WWTPs, DSFs, SSOs	0.90%	0.09%	0.01%	0.86%	1.84%	0.34%	0.00%	4.05%
Direct Precipitation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	0.03%
Initial System Mass	0.67%	0.20%	0.23%	0.16%	0.22%	1.90%	0.00%	3.37%
Wetland	0.06%	0.11%	0.07%	0.18%	0.36%	0.91%	0.83%	2.51%
DOT	0.16%	0.05%	0.11%	0.04%	0.26%	0.39%	0.23%	1.23%
Onsite WW (no DSF)	0.00%	0.00%	0.01%	0.00%	0.00%	0.03%	0.02%	0.06%
Stream Banks	8.29%	2.78%	0.18%	0.75%	1.48%	0.97%	0.00%	14.46%
Open Water	0.06%	0.04%	0.09%	0.03%	0.02%	0.16%	0.47%	0.87%
Direct Dry Deposition	0.01%	0.02%	0.03%	0.01%	0.00%	0.00%	1.09%	1.16%
Barren	0.03%	0.01%	0.01%	0.00%	0.05%	0.07%	0.02%	0.19%
Total	19.22%	8.24%	14.55%	7.87%	9.56%	22.78%	17.77%	100.00%

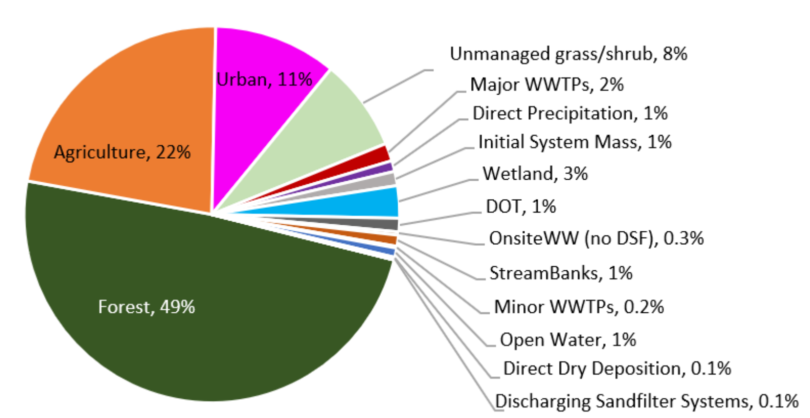
Loads are presented to the single pound for comparisons across the model report and appendices that present the data in various categories. This reporting is not to infer precision in the modeling results.

7.3 Total Organic Carbon

Total organic carbon is primarily associated with forested areas in the watershed but is also deposited by the atmosphere. Pasture lands also receive inputs of organic material. Figure 7-7 through Figure 7-9 display the sources, contributing areas, jurisdictions, and permittees contributing total organic carbon to Falls Lake. The underlying data for the source/tributary figures is provided in Table 7-4 which shows the amount and percent contribution to the lake. Similar data for the source/jurisdictions is provided in Appendix I.

The largest source of total organic carbon delivered to Falls Lake comes from forested areas which comprise approximately 60 percent of the total watershed area and 75 percent of the Near Lake area. These areas 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. The second and third largest contributors are agriculture and urban areas, respectively. In this watershed, developed open space, which is mostly non-DOT right of ways, comprises the majority of the urban source group. Agriculture is comprised mostly of pasture.

Research in the Falls Lake watershed (McKee 2020) states that "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." Additional comparisons of the WARMF watershed model simulations are provided in Appendix H.



Loads from unmanaged lands contribute the largest fraction of the load because 75 percent of the watershed is comprised of these areas.

57% of "agriculture" is pasture, 12% is full season soybeans, 10% is hay, 7% is double-cropped soybeans, 6% is flue-cured tobacco, 6% is no-till grain corn, and 2% is wheat or other crops.

68% of "urban" area is developed open space (mostly non-DOT road right of way) and 20% is existing development, low intensity.

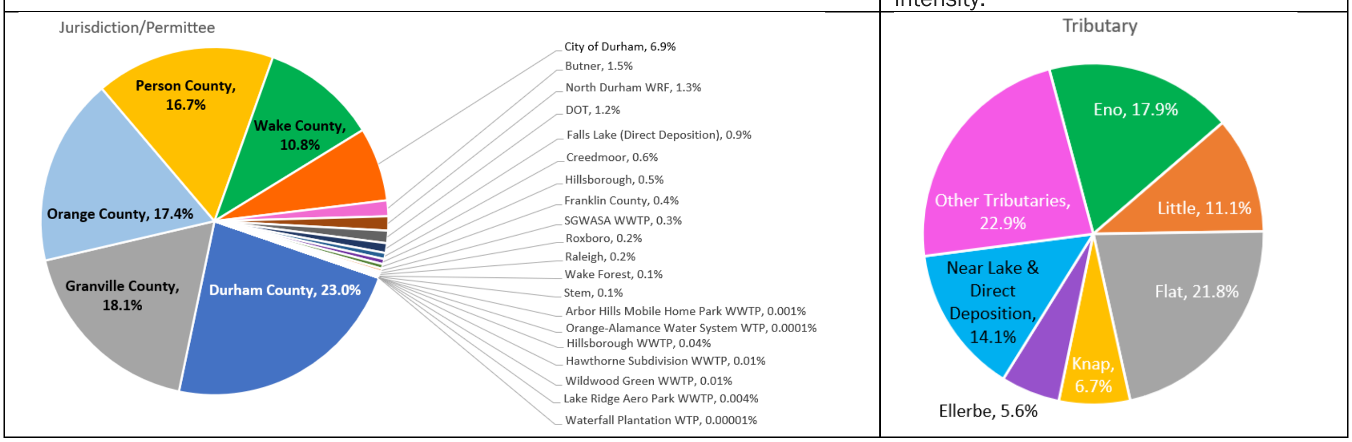


Figure 7-7. Sources (top) and Contributing Areas (bottom) of Total Organic Carbon Delivered to Falls Lake (13.2 million pounds per year)

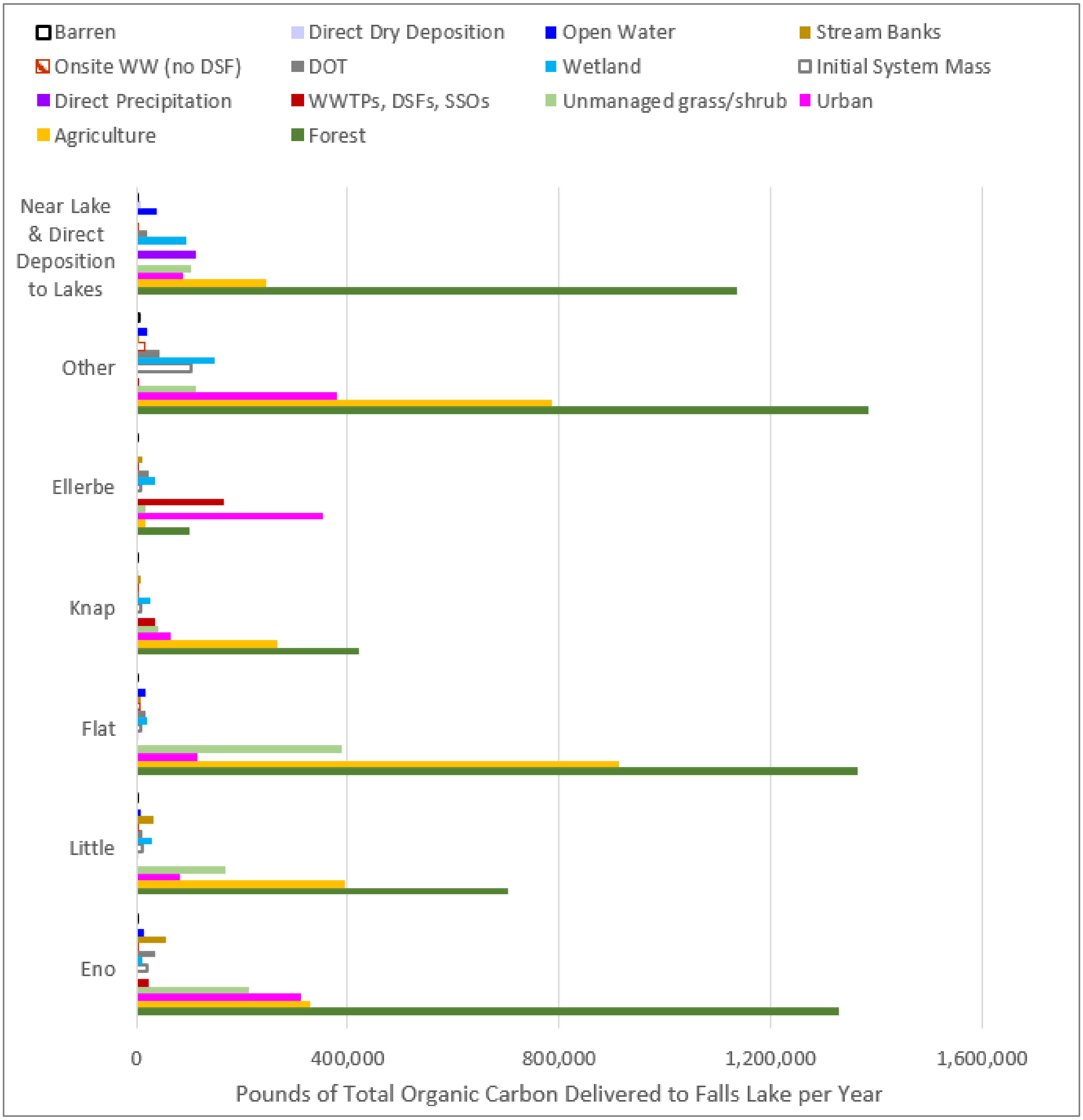


Figure 7-8. Total Organic Carbon Load Delivered to Falls Lake by Source and Contributing Area

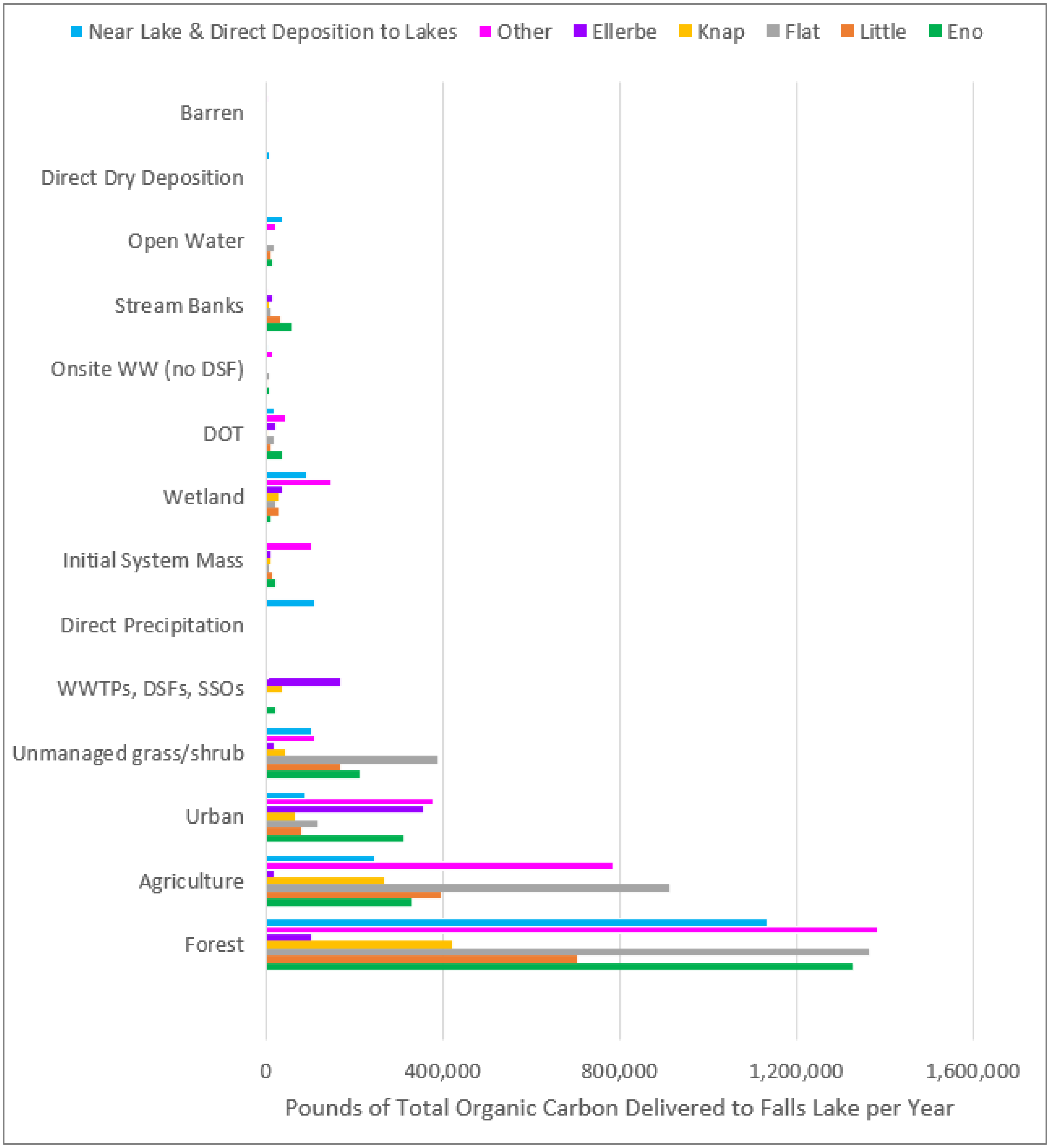


Figure 7-9. Total Organic Carbon Load Delivered to Falls Lake by Contributing Area and Source

Table 7-4. Total Organic Carbon Load Delivered to Falls Lake by Source Group and Contributing Areas (loads top, percentages bottom)

Source Group	Eno	Little	Flat	Knap	Ellerbe	Other Tributaries	Near Lake & Direct Deposition to Lakes	Total
Forest	1,327,768	703,113	1,364,698	422,312	100,679	1,385,033	1,135,258	6,438,861
Agriculture	329,574	395,196	913,220	266,884	15,985	790,297	245,324	2,956,480
Urban	311,221	81,572	116,131	63,776	353,938	379,372	88,731	1,394,740
Unmanaged grass/shrub	211,814	169,380	386,873	42,007	16,714	112,955	102,158	1,041,901
WWTPs, DSFs, SSOs	22,234	1,643	151	35,685	166,557	4,141	15	230,425
Direct Precipitation	1,953	3,122	3,418	1,960	0	0	111,685	122,138
Initial System Mass	20,056	12,903	7,570	9,498	8,537	102,373	0	160,936
Wetland	10,937	29,579	19,538	27,527	34,989	148,650	93,877	365,098
DOT	35,006	10,295	16,559	4,112	21,940	44,578	20,127	152,617
Onsite WW (no DSF)	5,104	3,705	7,231	265	593	15,678	4,041	36,617
Stream Banks	56,699	33,160	8,817	7,348	12,271	6,921	0	125,217
Open Water	13,461	8,949	16,601	3,349	1,379	21,348	38,930	104,017
Direct Dry Deposition	127	196	219	131	0	0	7,598	8,271
Barren	1,753	743	472	191	2,530	6,248	1,242	13,179
Total	2,347,707	1,453,555	2,861,499	885,044	736,112	3,017,593	1,848,986	13,150,496
Source Group	Eno	Little	Flat	Knap	Ellerbe	Other Tributaries	Near Lake & Direct Deposition to Lakes	Total
Forest	10.10%	5.35%	10.38%	3.21%	0.77%	10.53%	8.63%	48.96%
Agriculture	2.51%	3.01%	6.94%	2.03%	0.12%	6.01%	1.87%	22.48%
Urban	2.37%	0.62%	0.88%	0.48%	2.69%	2.88%	0.67%	10.61%
Unmanaged grass/shrub	1.61%	1.29%	2.94%	0.32%	0.13%	0.86%	0.78%	7.92%
WWTPs, DSFs, SSOs	0.17%	0.01%	0.00%	0.27%	1.27%	0.03%	0.00%	1.75%
Direct Precipitation	0.01%	0.02%	0.03%	0.01%	0.00%	0.00%	0.85%	0.93%
Initial System Mass	0.15%	0.10%	0.06%	0.07%	0.06%	0.78%	0.00%	1.22%
Wetland	0.08%	0.22%	0.15%	0.21%	0.27%	1.13%	0.71%	2.78%
DOT	0.27%	0.08%	0.13%	0.03%	0.17%	0.34%	0.15%	1.16%
Onsite WW (no DSF)	0.04%	0.03%	0.05%	0.00%	0.00%	0.12%	0.03%	0.28%
Stream Banks	0.43%	0.25%	0.07%	0.06%	0.09%	0.05%	0.00%	0.95%
Open Water	0.10%	0.07%	0.13%	0.03%	0.01%	0.16%	0.30%	0.79%
Direct Dry Deposition	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.06%	0.06%
Barren	0.01%	0.01%	0.00%	0.00%	0.02%	0.05%	0.01%	0.10%
Total	17.85%	11.05%	21.76%	6.73%	5.60%	22.95%	14.06%	100.00%

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.

Section 8

Model Scenarios and Sensitivity Analyses

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.

The allowable loads and the baseline loads from the Falls Lake Rules are also 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 (an estimate of delivered loads to Falls Lake for this period) were based on gaged flows and tributary water quality data from the five largest tributaries in the watershed. 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 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 simulated as 2015 to 2018 average conditions, 2005 to 2007 average conditions, or the “all forests and wetlands” condition
- **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 “all forests and wetlands” condition
- 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 land conversion to all forest scenario. These conductivities had been reduced during model calibration to better reflect the flashiness of the watershed. Vertical hydraulic conductivities were increased to match other catchments in the Triassic Basin with more rural land use composition.

Table 8-1 and Table 8-2 compare the delivered total flow and total nutrient loads to Falls Lake for total nitrogen and total phosphorus, respectively, for the entire watershed. 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 (“20 percent lower rainfall” scenario), the total nitrogen delivered load decreases by 35 percent and the total phosphorus delivered load decreases by 42 percent. 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 (“all forest, study period rainfall”), the total nitrogen delivered load only decreases by 25 percent and the total phosphorus delivered load only decreases by 3 percent. If the hypothetical land use/no onsite and centralized wastewater treatment systems and nutrient application 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. 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. These scenarios further support that hydrologic condition and rainfall are the primary drivers of loading to Falls Lake.

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. Changing the last 25 percent of watershed area does not have a huge effect on delivered loads when rainfall amounts are relatively high. 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 when rainfall is simulated at or below the annual average because the soils do not become saturated as frequently under this condition. 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. 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 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.

Table 8-1. 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	1,651,813 (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)

Table 8-1. 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)
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 and 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 except for the "all forest, increase vertical hydraulic conductivities (VHCs) in Ellerbe Creek watershed which increases those rates to other rural catchments in the Triassic Basin.

Table 8-2. 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	183,444 (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 (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 and 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 except for the "all forest, increase vertical hydraulic conductivities (VHCs) in Ellerbe Creek watershed which increases those rates to other rural catchments in the Triassic Basin.

Table 8-3 and Table 8-4 compare the delivered total nitrogen and delivered 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 ("UNRBA study period") is similar to the baseline loads prescribed in the Rules based on 2006. Therefore, even though rainfall and stream flows increased, delivered nutrient loads did not. This is a result of changes in the watershed including upgrades at wastewater treatment plants, a 44 percent decline in the acreage of agriculture, and 20 percent less atmospheric deposition of nitrogen. The relative percent reductions across the scenarios and sensitivity analyses are similar to those shown in Table 8-1 and Table 8-2 in terms of the impacts of rainfall condition, changes to rates of atmospheric deposition, and simulation of hypothetical watershed conditions.

Table 8-3 shows that current watershed conditions with "20 percent less rainfall" are achieving the Stage II total nitrogen allocations prescribed by the Falls Lake Rules. In other words, when the improvements in the watershed are considered and a hydrologic condition comparable to the baseline period is evaluated, the Stage II total nitrogen allocations have been met or are close to being met. However, Table 8-4 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.

When the improvements in the watershed are considered and a hydrologic condition comparable to the baseline period is evaluated, the Stage II total nitrogen allocations have been met or are close to being met. However, there is no feasible way to meet the Stage II total phosphorus allocation (35,000 pounds per year).

Table 8-3. 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 (40% 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 (59% lower)
Baseline Loads	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 Land Conversion to All Forest ("All Forest") scenario removes onsite and centralized wastewater treatment systems and 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.

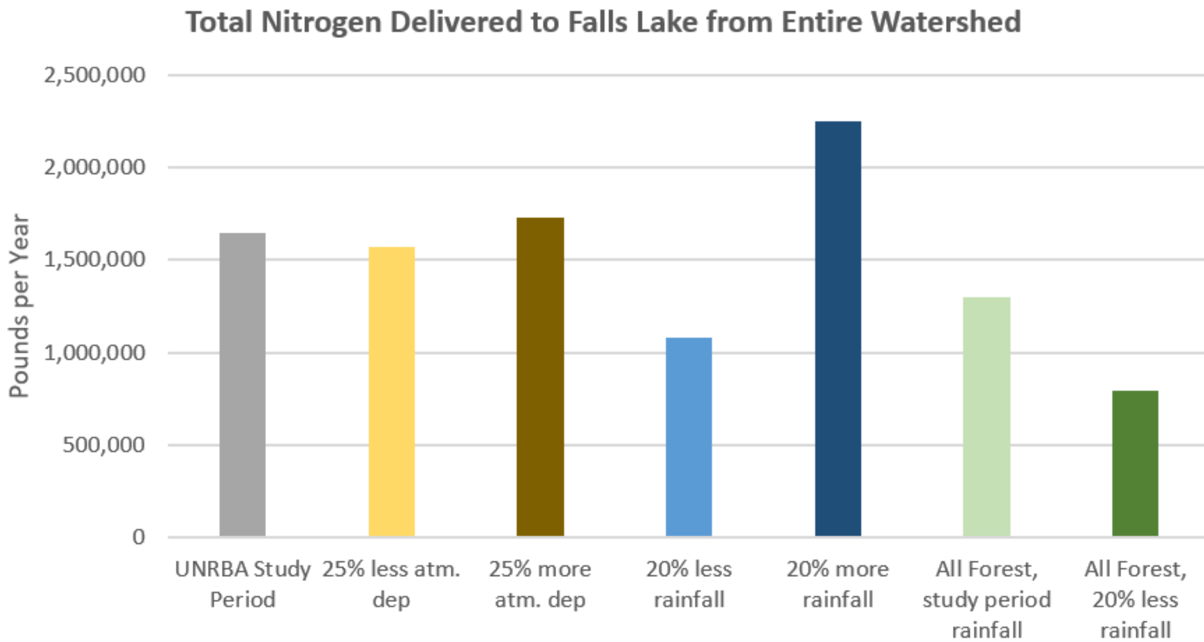
Table 8-4. Total Phosphorus (TP) Delivered Loads from Only the Upper Five Tributaries

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	52,036 (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 Land Conversion to All Forest ("All Forest") scenario removes onsite and centralized wastewater treatment systems and 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 8-1 and Figure 8-2 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. The Land Conversion to All Forest ("All Forest") scenario removes onsite and centralized wastewater treatment systems and 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.



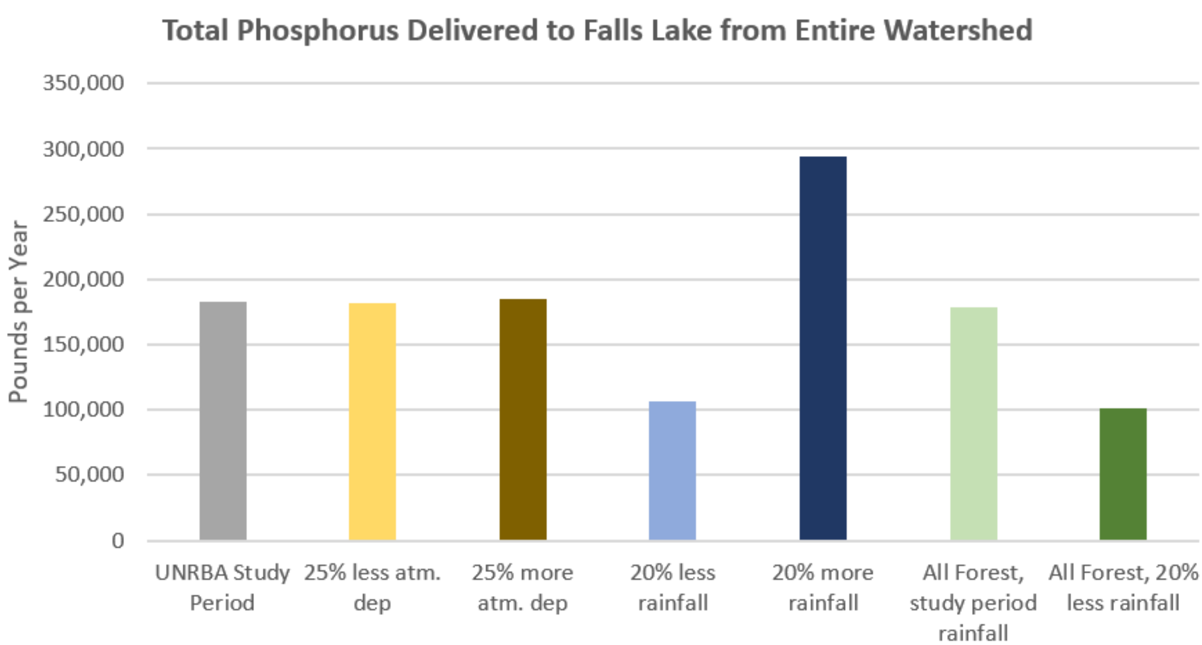
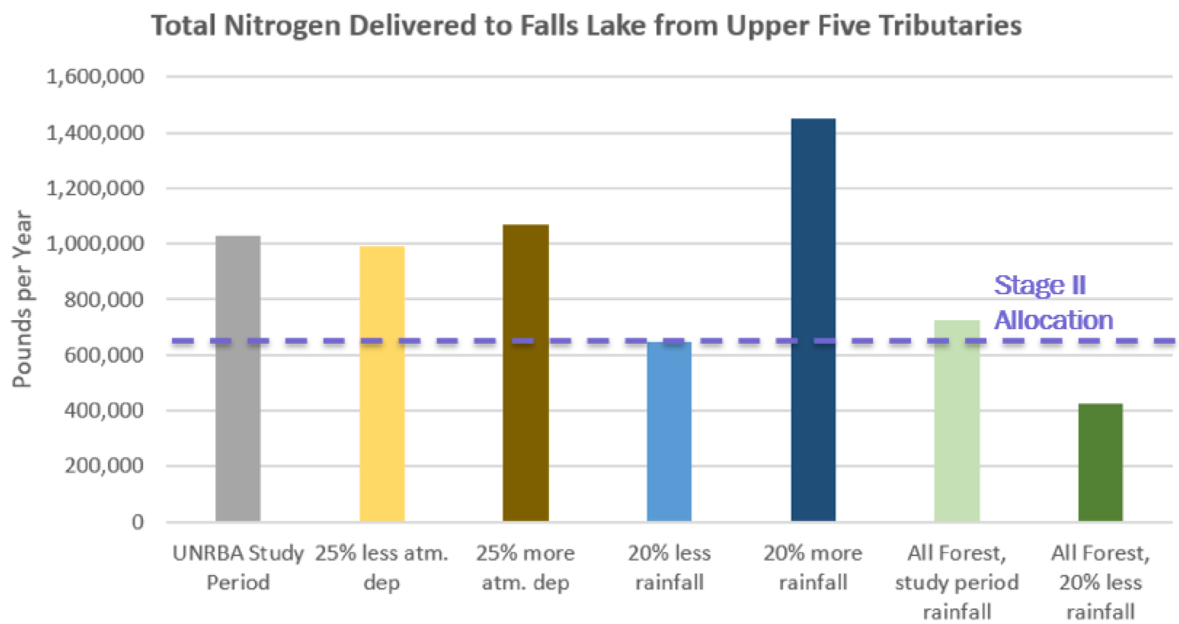


Figure 8-1. Comparison of Delivered Total Nitrogen Loads (top) and Delivered Total Phosphorus Loads (bottom) from the Entire Watershed

The Land Conversion to All Forest (:All Forest") scenario removes onsite and centralized wastewater treatment systems and 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.



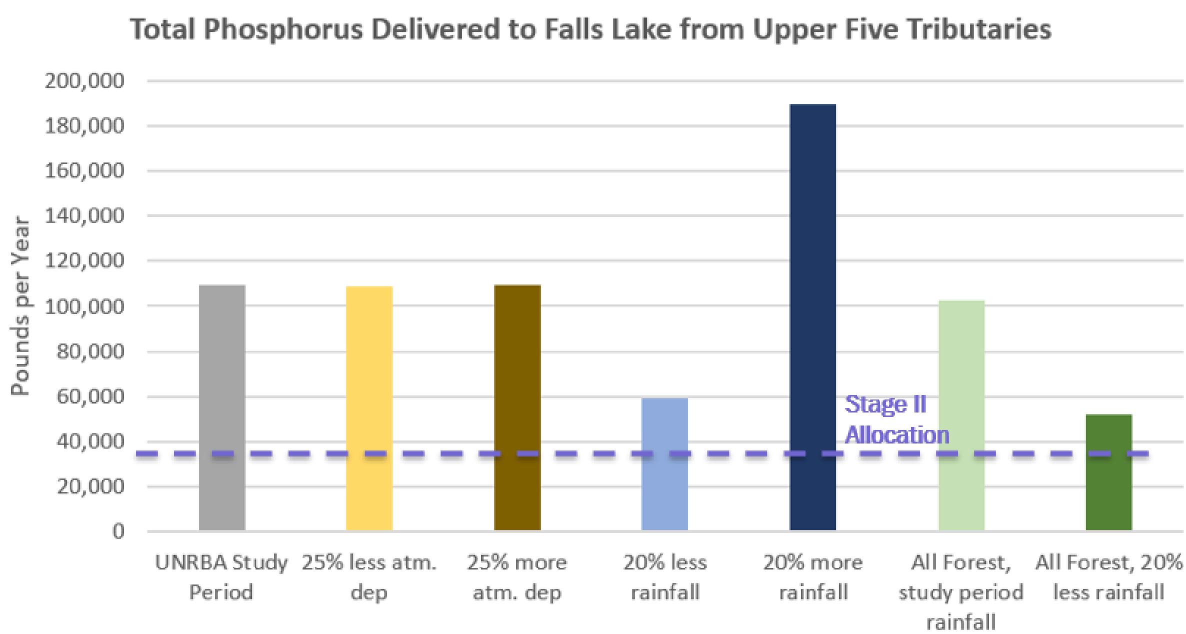


Figure 8-2. Comparison of Delivered Total Nitrogen Loads (top) and Delivered Total Phosphorus Loads (bottom) from the Upper Five Tributaries Compared to the Stage II Allowable Loads

The Land Conversion to All Forest (:All Forest") scenario removes onsite and centralized wastewater treatment systems and 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.

Section 9

Conclusions

The UNRBA WARMF watershed model development process has been comprehensive and transparent. Stakeholders within and outside of the UNRBA have had multiple opportunities to review and have input on the model as it was being developed. The NC Collaboratory funded a “third-party” review of the model, and those reviewers have been engaged throughout the development process. The input and consideration of that input is well documented in this report and its appendices. All quality assurance requirements as described in the approved QAPP for the modeling effort have been followed and applied in developing this model. The Fall Lake WARMF watershed model represents an effective tool for developing management approaches and providing appropriate input data for the two lake mechanistic models (WARMF Lake and EFDC).

The Falls Lake Nutrient Management Strategy was passed in 2011. In response, some UNRBA member governments began early implementation to reduce nutrient loading to Falls Lake including installation of hundreds of stormwater control measures, best management practices, and stream restoration projects. UNRBA members have also invested a large amount of resources for improvements at wastewater treatment plants, reductions to sanitary sewer overflows, implementation of retrofits for existing development, and maintenance and repair programs for onsite wastewater treatment systems. The amount of agricultural land has decreased in the basin by approximately 44 percent since the baseline period (2005 to 2007), and many of the nutrient application rates for specific crops have also declined over this period. Rates of atmospheric deposition of nitrogen have declined by approximately 20 percent since the baseline period.

The UNRBA has invested significant financial and management support resources into the development of a watershed model to accurately characterize nutrient and carbon loading to Falls Lake to allow for evaluation of management strategies and future tracking of watershed conditions. A key dataset for calibrating the model and ensuring that simulations in the watershed match observations was the four-year (August 2014 to October 2018) water quality monitoring program that was designed, implemented, and funded by the UNRBA to support the modeling efforts. The UNRBA began allocating resources towards the end of the monitoring program to plan for and begin data collection to support the watershed model development. The UNRBA worked with watershed stakeholders to select the WARMF model to simulate the watershed and Falls Lake. Two additional lake models are also being developed (EFDC and a statistical/Bayesian model).

WARMF is a lumped parameter model, so the land uses and soils for each modeling catchment 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 similar loading rates (pounds per acre per year) from land uses in the catchment. To better distinguish the loading by land use, the WARMF option to isolate soils by land use was applied. The WARMF model code was also improved for this application to allow the simulation of up to 15 types of onsite wastewater treatment systems rather than the model default (three systems). DWR assisted with securing grant funding through 319 to fund these model code revisions. The UNRBA worked closely with researchers funded through the NC Collaboratory to develop the model inputs associated with each type of onsite wastewater treatment system.

Securing the data needed to provide the best configuration of the model was a large and important task. The effort would not have been possible without the cooperation of others. Many stakeholders provided data, information, insights, and feedback to support this modeling effort and ensure that all available information was incorporated accurately into the model: local governments and utilities that comprise the UNRBA, state agencies (DWR, NCDA&CS, Department of Transportation, Wildlife Resources Commission, State Climate Office), federal agencies (US Forest Service and US Geologic Survey), researchers funded through the NC Collaboratory, and representatives from the Farm Bureau and American Rivers. All of the information obtained through this process has been identified, reviewed, quality assured, and incorporated into the model. In addition, the NC Collaboratory provided funding for a "third-party" review of the model. This extensive review resulted in refinements and improvements to the model with a focus on source load allocation and simulated areal loading rates. The UNRBA applied consistent assumptions and underlying data sets to describe soil characteristics, plant growth and plant nutrient content, and rates of atmospheric deposition. Agricultural and urban lands receive nutrient application in the model, but unmanaged lands do not.

Models are representations of systems and are implicitly uncertain. No model is exact, but the watershed model could not be calibrated to stream flow and water quality observations if its representation of nutrient loading unmanaged lands was not reasonable accurate. As noted, seventy-five percent of the Falls Lake watershed is unmanaged (369,000 acres). There are only 50,000 acres remaining in agricultural production. There are 76,000 acres that are "urban" and only 7,400 that are medium or high intensity development. Nutrient loads from wastewater treatment plants in 2018 were 38 percent lower for total nitrogen and 81 percent lower for total phosphorus compared to 2006. Large storm events result in increased loading from all land uses in the watershed, including forested areas and other unmanaged lands which make up the vast majority of the watershed. Rainfall is the single most important factor in watershed loading to Falls Lake and other waterbodies where land use is dominated by unmanaged areas. This model was developed specifically for the Falls Lake watershed and the local land use intensity, soil characteristics, and nutrient reduction achievements must be considered when comparing WARMF simulated results to other studies or regions.

The results of this extensive, multi-year process yield insights on the watershed loading to Falls Lake. Because of the extensive data available for this model, the review of the model results, and the features and modifications to the model that were made during this application, updated and more extensive information is available on how the watershed processes nutrients and carbon and delivers these nutrients to Falls Lake:

- The chemistry of the soils in the watershed (based on data from the US Department of Agriculture National Cooperative Soil Survey) results in the retention and slow release of nutrients over time. A change in a watershed model input (land use, nutrient application rate, etc.) takes approximately 25 simulation years for the soils in the watershed to reach equilibrium and simulate a change in delivered load. Simulated changes to onsite wastewater treatment systems may take longer to fully stabilize, but this source is reasonably well accounted for and is a relatively small percentage of the total load to Falls Lake. This characteristic of long stabilization does not introduce significant error in the model. However, it is important to take into consideration this timeframe because it will be important to consider in the development of a revised nutrient management strategy for Falls Lake. Similar evaluations for changes to lake sediment quality and internal loading of nutrients have been performed with the lake models. Falls Lake sediments are relatively stable with the continued input and processing of nutrients to the system.
- Approximately 61 percent of the watershed is comprised of forests. Other generally unmanaged land uses comprise approximately 14 percent of the area. Thus, approximately 75 percent of the watershed area is unmanaged. No other land use comprises more than 10 percent of the area in the UNRBA study period (2015 to 2018).
- Many of the catchments in the watershed model are dominated by unmanaged lands. During dry periods, nutrients from atmospheric deposition, litter fall and decay, and other model processes build up on unmanaged lands. Following heavy rains, the accumulated nutrients and organic material are

flushed out (Hunt 2023, Paerl et al. 2018, 2019, 2020; Osburn 2016; Timmons 1977; Oyarzún and Hervé-Fernandez 2015).

- Forests are an important component of watershed health and vital to the ecological integrity of the watershed. Because forests comprise the majority of the watershed (60 percent), forests contribute the highest overall percentage of the nitrogen load to Falls Lake from any single source (38 percent of the total nitrogen load). The only simulated application of nutrients to forested areas is associated with atmospheric deposition to the land surface as either wet or dry deposition. Monitoring and modeling have shown that loading from forests increases during wet periods when nutrients stored in the forest areas are released. During dryer conditions more of the rainwater is stored and used by plants.
- Three-quarters of the watershed area is an unmanaged land use (forests, wetlands, unmanaged grassland and shrubland, land in forest succession, and open water). Over one-half of the total nitrogen load delivered to Falls Lake originates from these areas. The other half of the total nitrogen load is due to agriculture, urban areas, and wastewater treatment (centralized facilities and onsite systems).
- Forests are also the highest contributor of phosphorus loading to Falls Lake (44 percent of the total phosphorus load). Nevertheless, the presence of this extensive forest land in this watershed is a significant reason that lake conditions have been significantly better than projected prior to completion of the dam and filling of the reservoir.
- Unmanaged land uses contribute 55 percent of the total phosphorus load delivered to Falls Lake. Streambank erosion contributes approximately 14 of the loading and remaining 31 percent is due to urban areas, agriculture, and wastewater treatment (centralized facilities and onsite systems).
- Forests also contribute the largest percentage of the total organic carbon load to Falls Lake (49 percent). The second largest source is agriculture (22 percent) followed by urban areas (11 percent).
- The Near Lake areas that drain directly to Falls Lake are mostly forests (75 percent); these areas contribute loading directly to Falls Lake with only some trapping occurring during lateral soil and overland flow. These areas do not have the benefit of stream or impoundment transformations that provide reductions in loading from other areas (and sources) in the watershed. Conserving unmanaged lands near waterways is a priority of several land conservation organizations in the watershed and the UNRBA.
- For the UNRBA study period (2015 to 2018), nearly 9.9 million pounds of total nitrogen are deposited, applied, or discharged to the watershed or lake surface on average each year. These represent gross inputs to the watershed and reflect a reduction of approximately 34 percent compared to the gross inputs estimated for the baseline period (2005 to 2007) which were 15.0 million pounds per year. The watershed modeling shows that only 17 percent of the total nitrogen applied/released in the watershed reaches Falls Lake in the recent period due to crop harvesting, processing in streams and impoundments, etc. Thus, the modeling demonstrates that watershed processes and activities in the watershed effectively reduce the loading applied/released in the watershed by 83 percent.
- Stage II of the Falls Lake Nutrient Management Strategy requires reductions in total nitrogen loading to the lake of 40 percent from agriculture, wastewater, and existing development relative to the baseline period. This level of load reduction has already or nearly been achieved by agriculture (44 reduction in production acres and reductions in nutrient application rates) and wastewater treatment plants (38 percent relative to 2006). Based on research conducted by NC State (Hunt et al. 2012), installing all potential retrofits in the Ellerbe watershed would only reduce nitrogen loads by approximately 10 percent. Wastewater treatment plants would require use of reverse osmosis to achieve additional significant reductions in nutrients, and these facilities currently discharge approximately 6 percent of the load to Falls Lake. Even reducing their load by another 50 percent would only result in a 3 percent decrease in total load to Falls Lake. Agricultural production in the watershed is likely to decline further. Reducing delivered loads from agriculture by one-half from current levels would only reduce nitrogen

loading to Falls Lake by approximately 9 percent because so little area remains. Even though these inputs to nutrients applied, discharged, or deposited on the watershed have been achieved, nutrient loading to Falls Lake during the UNRBA study period was similar to the baseline period. However, rainfall and resulting stream flows were much higher in the UNRBA study period. The fact that nutrient loading did not increase under a wetter hydrologic condition is a demonstration of the successes achieved in the watershed. This evaluation demonstrates that efforts in the watershed have improved loading to the lake, but that the hydrologic condition needs to be considered when allocating loads. The lake models will evaluate the impact of watershed nutrient reductions.

- In the UNRBA study period, over 1.5 million pounds of total phosphorus are deposited, applied, or discharged to the watershed or lake surface on average each year. This amount represents an estimated reduction of approximately 24 percent compared to the total phosphorus applied/released during the baseline period (1.9 million pounds of total phosphorus). The model indicates that only 12 percent of the total phosphorus inputs to the watershed reach Falls Lake in the UNRBA study period due to crop harvesting, soil adsorption, process in streams and impoundments, etc. Thus, watershed processes and activities in the watershed effectively reduce inputs by 88 percent.
- Stage II of the Falls Lake Nutrient Management Strategy requires a 77 percent reduction in total phosphorus load delivered to the lake from agriculture, wastewater, and existing development relative to the baseline period. Wastewater treatment plants in the watershed have reduced their loads by approximately 80 percent (comparing 2006 discharges to 2018). Delivered loads from agriculture have declined by approximately 40 percent due to a reduction in production acres. Staff at the NC DA&CS were asked if additional best management practices could be implemented to further reduce nutrient loading from agriculture. They responded that agriculture has implemented the majority of practices and that further reductions from operating fields would be minor. Further reductions in loading from agriculture to achieve the Stage II goals would require all production to cease in the watershed. Many watershed stakeholders have expressed their desire to keep the watershed in a rural state. NC State's research in the Ellerbe Creek watershed (Hunt et al. 2012) indicates that installing all potential retrofits would only reduce total phosphorus loads by approximately 25 percent, far short of the required 77 percent. Wastewater treatment plants would require use of reverse osmosis to achieve additional significant reductions in nutrients, and these facilities currently discharge approximately 3 percent of the load to Falls Lake. Even reducing their load by another 50 percent would only result in a 1.5 percent decrease in total load to Falls Lake. Agricultural production in the watershed is likely to decline further. Reducing delivered loads from agriculture by one-half from current levels would only reduce nitrogen loading to Falls Lake by approximately 5 percent because so little area remains. Reducing loading to Falls Lake from the land uses by 77 percent represents a level of management that is unachievable. The watershed model shows that almost 75 percent of phosphorus comes from unmanaged land areas in the watershed, stream bank erosion, and initial system mass. The modeling shows that changing the phosphorus loading to the lake at the level envisioned by the Falls Lake Rules is not possible.
- Hydrologic condition is the primary driver of variability in nutrient loads for land uses in the Falls Lake watershed. The UNRBA monitoring period (2015 to 2018) that was used to develop and calibrate the watershed model had average to wet precipitation each year. This program included water quality monitoring stations in primarily forested catchments. In contrast, DWR's baseline modeling period for the Rules (2005 to 2007) coincided with a historic drought for the area (only year 2006 which had a total rainfall closer to the annual average was used to set the load reduction requirements; the preceding year was very dry). The antecedent condition and precipitation amount and timing dictate the volume of runoff that reaches streams and ultimately Falls Lake. USGS gaged stream flows provide a comparison of the hydrologic condition for these periods and their potential to deliver nutrient loads to the lake. For example, during the baseline period on the Flat River above Lake Michie, the average annual stream flowrate was 82 cubic feet per second. For the recent period (2015 to 2018), the average annual stream flowrate at this location was 173 cubic feet per second, over twice as high.

Thus, the loading potential for the recent period is much greater than the baseline period when less water reached the streams.

- The pervious areas in the watershed which receive inputs from atmospheric deposition and nutrient application have the ability to store nutrients in the soil matrix during dry periods. During wet periods when the soils become saturated, these nutrients have the potential to be transported to the stream network and Falls Lake. Impervious surfaces also contribute nutrient loading, but they do not have the same potential to accumulate large quantities of nutrients during extended dry periods.
- The UNRBA's watershed model for the 2015 to 2018 period represents conditions with above average rainfall, and the model was calibrated to simulate flows and water quality concentrations observed during that period. As a result of the "third-party" review and meetings with technical subject matter experts and "third-party" reviewers, questions were raised about the simulated areal loading rates (mass per area per time; e.g., pounds per acre per year) for different land use types. Specifically, the reviewers questioned loading rates for certain land uses like forests. They believed these simulated rates may be too high, and comparisons to other published studies were provided for consideration. To ensure the WARMF watershed model was simulating reasonable areal loading rates for various land uses, representative modeling catchments with predominate land use in agriculture, urban, and forest were evaluated for lower rainfall periods including a dry year (2007) and an average year (2017). Simulated loading rates by land use under these hydrologic conditions were very comparable to the areal loading rates from the other published studies including a monitoring study for forested catchments in the Falls Lake watershed conducted by the US Forest Service. These analyses are documented in Appendix H. Based on these comparisons, the WARMF Watershed model output properly reflects variation in loading as caused by variation in rainfall.
- Large storm events, exceeding 1 inch of precipitation depth, occur relatively infrequently (approximately 4 percent of days during the UNRBA study period). However, depending on the storm size, preceding hydrologic condition, and parameter evaluated, daily loads entering the lake following large storms can be tens to hundreds of times higher than those delivered during baseflow conditions.
- Denitrification is an important process in the watershed for removing nitrogen from the system as nitrogen gas. This process occurs more frequently in wet areas like wetlands and riparian areas where sufficient carbon is also present. The importance of this process is part of a research effort funded by the NC Collaboratory.
- Conventional and advanced treatment systems that discharge to the subsurface for onsite wastewater treatment are very effective at removing nutrients, partly due to the soil chemistry in the watershed. This finding from the modeling is supported by recent research funded through the NC Collaboratory. These sources comprise approximately 1.4 percent of the total nitrogen load and 0.02 percent of the total phosphorus load delivered to Falls Lake. These percent contributions account for functioning and malfunctioning systems.
- Discharging sand filter systems primarily discharge to streams in this watershed and are simulated as point sources by the model. They comprise approximately 0.6 percent of both the total nitrogen load and the total phosphorus load delivered to Falls Lake.
- Major WWTPs contribute less than six percent of the delivered total nitrogen load and less than four percent of the delivered total phosphorus load to Falls Lake. Significant improvements in treatment at the major facilities have reduced average annual total nitrogen loads discharged to streams by approximately 33 percent and average annual total phosphorus loads by 77 percent relative to the baseline period when 2015 is excluded from the comparison (two of the three major wastewater treatment plants were undergoing facility upgrades or optimization efforts in 2015).
- SSOs are relatively infrequent with small volumes reaching surface waters. They comprise a relatively small portion of the delivered load to Falls Lake.

The UNRBA is extremely grateful for the input and feedback provided by both internal and external stakeholders. The watershed model output has been used to develop and calibrate the lake water quality models. The watershed model provides an important linkage between existing land use in the watershed, changes in watershed activities, and delivered loads to streams and ultimately Falls Lake. The watershed model output has been used to develop and calibrate the lake water quality models. The suite of models developed by the UNRBA have been used to evaluate scenarios and their impact on lake water quality to inform development of a revised nutrient management strategy. Modeling reports and UNRBA recommendations for the revised strategy are available online at https://unrba.org/reexamination.

Section 10

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Appendix A: WARMF Model Code Revisions to Simulate Several Types of Onsite Wastewater Treatment Systems

Appendix A is available online at https://unrba.org/reexamination.

Appendix B: Model Coefficients and Characteristics of WARMF Modeling Catchments for the UNRBA Falls Lake Watershed Model

Appendix B is available online at https://unrba.org/reexamination.

Appendix C: Stage-Area and Stage-Release Curves for the UNRBA Falls Lake Watershed Model

Appendix C is available online at https://unrba.org/reexamination.

Appendix D: Compilation of Available Information on Atmospheric Deposition Rates Compiled by NC Collaboratory Third-Party Reviewers

Appendix D is available online at https://unrba.org/reexamination.

Appendix E: USGS Field Measurements and Stream Flow Rating Curves for Gages in the Falls Lake Watershed

Appendix E is available online at https://unrba.org/reexamination.

Appendix F: Additional Comparisons of Observed and Simulated Concentrations and Estimated Daily Loads

Appendix F is available online at https://unrba.org/reexamination.

Appendix G: Time Series Comparisons for Streamflow Gages and Water Quality Monitoring Stations in the Falls Lake Watershed Compared to WARMF Simulated Values for the Calibration (2015 and 2016) and Validation (2017 and 2018) Periods

Appendix G is available online at https://unrba.org/reexamination.

Appendix H: Subject Matter Expert and Third-Party Review of Areal Loading Rates and Comparison to Other Modeling Studies

Appendix H is available online at https://unrba.org/reexamination.

Appendix I: Source Loads by Area

Appendix I is available online at https://unrba.org/reexamination.