Final UNRBA Monitoring Report for Supporting the Re-Examination of the Falls Lake Nutrient Management Strategy

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Executive Summary

Falls Lake was constructed by the U.S. Army Corps of Engineers (USACE) in the late 1970s. The designated uses of Falls Lake are drinking water supply, recreation, fishing, aquatic life, and wildlife. In 2010, the North Carolina Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy (the Strategy) to reduce chlorophyll-a concentrations in the lake which exceed the criterion of 40 micrograms per liter (µg/L) in some locations. The Strategy requires two stages of nutrient reductions for Falls Lake. The goal of Stage I is to achieve compliance with the chlorophyll-a standard in the lower half of the reservoir (below Highway 50). The goal of Stage II is to comply with the chlorophyll-a standard everywhere in the reservoir. The Strategy dictates load reduction requirements for local governments and other entities, which were based on a lake nutrient response model developed by the North Carolina Division of Water Resources (DWR).

The two Stages of nutrient load reductions are designed to reduce nutrient loading to Falls Lake from various sources, including stormwater runoff from new and existing development, wastewater treatment plants, and agriculture. Based on DWR's fiscal analysis (NCDWQ 2010), the cost of Stage I is expected to exceed $500 million for the parties affected by the Rules (agriculture, local governments, state and federal agencies). The estimated cost of Stage II is over $1 billion.

Local governments and other entities are working towards compliance with Stage I of the Falls Lake Nutrient Management Strategy, however the reduction goals for Stage II are infeasible and beyond the limits of technology. For example, Stage II requires that each square foot of existing development be treated by two stormwater control measures (SCMs). Given site constraints like drainage characteristics and buildout conditions, it is not possible to treat all existing development with even a single SCM.

The Rules recognize there is uncertainty associated with the water quality modeling performed by DWR used to establish the Stage II requirements. As specified in Section 5(f) of the Rules, the Rules allow for a re-examination of the Stage II nutrient load reduction requirements after additional data collection and other procedural steps are followed.

In 2011, the Upper Neuse River Basin Association (UNRBA) began a re-examination process of the regulatory framework for Stage II of the Rules. Full implementation of the nutrient reduction strategy, which is more stringent than any other nutrient strategy implemented in the State, will require extremely costly actions on the part of UNRBA member governments and other regulated parties. In addition, the practical ability to achieve the mandated reductions is uncertain. In light of the financial impact of the Rules and the regional importance of Falls Lake, the UNRBA began examining the technical bases and regulatory framework of Stage II requirements.

At the time the original Falls Lake modeling effort was conducted in 2009, the data available to develop and calibrate the models was limited, and DWR did not have the resources or the time to conduct studies that would address key data gaps. The UNRBA Monitoring Program was specifically designed to reduce the uncertainty and to re-examine the scientific assessment and modeling predictions used by DWR to support the Rules.

The UNRBA re-examination planning process included design of a Monitoring Program to fill data gaps and reduce the uncertainties associated with the DWR models of Falls Lake and its watershed. The Monitoring Program (2014 to 2018) was designed to support three main goals, as prioritized by the UNRBA:

1. Revise lake response modeling
2. Support alternative regulatory options as needed
3. Allocate loads to sources and jurisdictions (i.e., support watershed modeling)

Local governments within the UNRBA agree that protecting Falls Lake as a water supply and public resource is paramount. The members want to ensure that the rules applied to the watershed sufficiently reflect the lake's beneficial uses. Control requirements should be reasonable, fiscally responsible, and should effectively improve the water quality of the resource. Given the high cost of implementing Stage II and the uncertainty of achieving the current chlorophyll-a water quality standard, the scientific re-examination process relies on additional data collection and new modeling efforts to support evaluation of alternative nutrient management strategies and various regulatory options.

Report Overview

This water quality monitoring report will assist the UNRBA's re-examination of the regulatory framework for the Falls Lake Rules. This report summarizes new data and studies that were designed to address previous key data gaps and uncertainties. Consistent with the objectives, this information will be used in modeling efforts to characterize water quality in Falls Lake and its watershed. The water quality monitoring data generated and compiled by the UNRBA is a valuable resource for the region and represents a level of knowledge of the Falls Lake system that far exceeds what is typically available for other reservoirs in NC and the region. The magnitude of this new data and special studies will support robust analyses and inform important decision-making for the development of a revised management approach for Falls Lake and its watershed.

This final UNRBA Monitoring Report is divided into 8 sections, including one devoted to References. The first three sections of the report are similar to previous UNRBA Annual Monitoring Reports (2015 to

2018), where the purpose of the program is summarized (Section 1), the methodology for data acquisition is presented (Section 2), and results of recent monitoring efforts are presented and summarized (Section 3).

Sections 4 and 5, however, provide extensive additional analyses, discussion, observations, and interpretations not previously offered. This report is a comprehensive review of all of the data collected over the UNRBA re-examination monitoring period (2014 to 2018). It also includes historic data that provides an important point of reference for how water quality in the lake has varied since it was filled more than 35 years ago. Examples of information in this report include the following summaries:

- Review of the expected water quality conditions in Falls Lake prior to construction
- Discussion of the characteristics of river impoundments (reservoirs) and primary factors that affect their water quality
- Comparison of results from the UNRBA monitoring period (2014 to 2018) with prior evaluation periods
- Examination of the comparability of results reported by different entities monitoring the same locations
- Estimation of internal nutrient loading from sediments based on studies conducted by the UNRBA
- Nutrient loading patterns from the watershed including evaluation of changes in loading over time
- Nutrient loading patterns from the wastewater treatment facilities in the basin
- Information reflecting the recreational use value of Falls Lake

This report provides context, both from a historical perspective and with respect to the complex interacting water quality factors, that describes the current conditions in the reservoir. The report also provides context for deriving an understanding of the degree to which altered management actions may affect the lake. This report does not offer a re-examination strategy as substantial work remains to be done. The UNRBA will continue to develop the re-examination strategy through a water quality modeling effort and a detailed policy and regulatory evaluation.

> *Although there are frequent references to “Falls Lake”, the water body is a man-made reservoir, created by the impoundment of the Neuse River. Thus, it cannot be expected to behave like a natural lake.*

Section 1. Background and Objectives of UNRBA Monitoring Program

The UNRBA has been collecting and analyzing water quality data in Falls Lake and its watershed since August 2014. Documents that govern the UNRBA Monitoring Program are available online in the UNRBA resource library. These include the UNRBA Monitoring Plan and the UNRBA Monitoring Quality Assurance Project Plan (QAPP). Both documents have been approved by DWR. The program also included nine unique Special Studies to fill data gaps and explore facets of Falls Lake not addressed through the Routine Monitoring, with study plans and reports also available online.

Section 1 of this report outlines the basis for the UNRBA Monitoring Program, summarizing the general framework and schedule of the program, the regulatory history and basis for creating it, and the program's objectives. Results from the UNRBA monitoring efforts will be used to develop new lake response and watershed models. The revised models will be used to project impacts from nutrient loading from sources and jurisdictions, simulate the growth of algae in the lake, evaluate alternate nutrient management strategies. They may also be used to support the development of a range of potential regulatory options for consideration by the UNRBA and for submittal to the EMC for consideration under the Rules. The following models are included in the re-examination process as described in the DWR-approved UNRBA Modeling QAPP:

- The Watershed Analysis Risk Management Framework (WARMF) includes both a watershed model and a lake model.
- The Environmental Fluid Dynamics Code (EFDC) includes a hydrodynamic, water quality lake model, and a sediment diagenesis module.
- A statistical model of Falls Lake applying both empirical and Bayesian techniques will be developed to predict lake water quality and provide linkages to designated uses.

The UNRBA's Monitoring Program to support the re-examination has generated or compiled a very large, high-quality database including multi-year information on reservoir and tributary water quality, precipitation patterns, lake levels, inflows, outflows, and algal abundance and taxonomy. The UNRBA has also collected, compiled, analyzed, and referenced information on nutrient loading, bathymetry, sediment quality and quantity, historic water quality conditions, recreational uses, and other topics related to characterizing water quality conditions in Falls Lake. In addition to providing a broad variety of insights into the status and condition of the reservoir as presented in this report, this information provides an excellent data foundation for the UNRBA's modeling and analytical efforts.

Additional data were also compiled from a number of other sources. In November 2018, the UNRBA reduced its monitoring efforts to a "Transition Monitoring" program that continues to obtain a smaller amount of data, while relying on monitoring efforts by other entities.

Section 2. UNRBA Monitoring Program Protocol

Section 2 summarizes the components and data acquisition protocol of the UNRBA Monitoring Program, which focused around an intensive, multi-year Routine Monitoring effort. The Routine Monitoring obtained data on 20 water quality parameters from 38 tributary stations in the watershed on a monthly basis from August 2014 through October 2018 (51 months of data).

The UNRBA also sponsored a series of individual Special Studies to examine facets of the Falls Lake system that had not been sufficiently explored previously. In addition, the UNRBA compiled monitoring data from many other sources including DWR, the City of Durham, and the NC State University Center for Applied Aquatic Ecology (CAAE).

Additional information about the Routine Monitoring and Special Studies methodologies is provided in the UNRBA Monitoring Plan, the DWR-approved UNRBA Monitoring QAPP, and in the Plan of Study for each Special Study available in the UNRBA resource library.

Data collected by the UNRBA are available online through the data portal available in the UNRBA resource library:

Section 3. UNRBA Monitoring Program Results

Section 3 summarizes the data collected and compiled by the UNRBA Monitoring Program, which includes data generated by the UNRBA and several other monitoring entities. Graphics and summary information in this section offer an overview of the data obtained during the UNRBA monitoring period (August 2014 to October 2018). Section 3 also provides a brief synopsis of the results of each UNRBA Special Study.

Hydrologic Conditions

Annual precipitation patterns since the program began in August 2014 have been normal to wet compared to the 30-year average. For the UNRBA monitoring period (2014 to 2018), the annual average rainfall total was 4 to 11 percent higher than the 30-year average. While the majority of the UNRBA monitoring period exhibited conditions within the "normal" range, the period was also punctuated by a few large flood events and a somewhat dry period for the second half of 2017. This range of rainfall conditions provided the opportunity to collect data representative of a wide range of hydrologic conditions. In contract, the baseline monitoring period used by DWR in their modeling (2005 to 2007) was 13 to 57 percent lower than the 30-year average. The UNRBA watershed and lake models will simulate both of these periods, and thus a wide range of hydrologic conditions will be evaluated. More information about the hydrologic conditions of both monitoring periods are provided in Section 3.

The watershed and lake models being developed by the UNRBA will include comparisons to both the DWR baseline monitoring period and the UNRBA monitoring period. These two periods collectively include seven years that represent a range of hydrologic conditions including severe droughts and record high flows. This range in simulated hydrologic conditions will provide a more complete record on which to base a revised nutrient management strategy.

Of the 18 tributaries to Falls Lake that are monitored by the UNRBA, the flow from five of these tributaries represents on average 78 percent of the water entering the lake: Flat River, Eno River, Little River, Knap of Reeds Creek, and Ellerbe Creek. Just the Flat and Eno Rivers together account for 52 percent of the inflows. This means that flow and loading contributions from these five tributaries have a greater potential to affect overall water quality in the lake than the remaining streams. Aside from these five tributaries, no other tributary delivers more than 3 percent of the annual inflow to the reservoir. This is an important consideration for the modeling and re-examination process that will result in a revised nutrient management strategy. However, the contributions from the other tributaries are important from an overall assessment standpoint in terms of evaluating potential hot spots of loading and providing a strong basis to estimate load contributions. Thus, the monitoring and consideration of these inputs provide important information for reaching conclusions about the impacts of all portions of the watershed.

While tributary flow provides most of the water entering the lake (inflow), the USACE controls the rate at which water exits the lake (outflow). Management of the dam outflow to the Neuse River has a substantial effect on water levels and the amount of time that water is retained in the reservoir. This is discussed in more detail in Section 5.

Five tributaries to Falls Lake contribute 78 percent of the stream flow to the lake.

Routine Monitoring

Water quality summary data from 2014 through 2018 are presented in an extensive series of graphics in Section 3. These data summaries include lake data collected by DWR and other organizations and tributary data collected by the UNRBA. Many of the graphics portray the range of measured values with respect to their relative locations in the watershed and the reservoir. Most parameters tend to be more variable both within and among the tributary stations than in the lake itself where the mass of water tends to dampen variability.

Data from in-lake stations in 2018 show conditions largely consistent with prior years of the UNRBA Monitoring Program with the exception of 2017. In 2017 chlorophyll-a levels in the reservoir were higher than other recent years. Hydrologic conditions in the watershed and the lake were also different in 2017 which resulted in different nutrient loading patterns. For example, total nitrogen and total phosphorus loads to the lake were 46 percent and 52 percent lower, respectively, in 2017 compared to 2018.

While water delivery to the lake and thus nutrient loading was lower in 2017, the residence time in the lake was longer and growth of algae was therefore higher. The impact of hydrology and the timing of flow is critical in projecting algal growth in the lake.

Of more than 20 monitored parameters, four parameters are of particular interest to the UNRBA: the nutrients (nitrogen and phosphorus) because of their known linkage to the growth of algae in surface waters, chlorophyll-a because it represents algal biomass and the parameter is included in NC's Water Quality Standards (40 µg/L), and organic carbon because of its potential impact on potable water treatment and the creation of disinfection by-products in drinking water.

It is important to understand that the Falls Lake Nutrient Management Strategy as reflected in the current Rules, and thereby the re-examination process, is based upon the determination that portions of Falls Lake do not always attain the 40 µg/L chlorophyll-a criterion. The DWR determination that the reservoir is not meeting the chlorophyll-a water quality criterion is the regulatory driver for the nutrient reductions prescribed in the Rules. Figure ES-1 depicts a summary of the chlorophyll-a data collected within Falls Lake during the UNRBA monitoring period. The left side of the graphic shows tributary data, while the right side shows levels measured in the reservoir. The vertical size of each box reflects the general range of data values, while its horizontal position represents its general location. For the tributaries, the ordering represents upstream (left) to downstream (right). For the reservoir, the ordering represents the top of the reservoir (left) to the dam (right). The chlorophyll-a levels from the top of the reservoir to the dam show both a reduction in average chlorophyll-a concentration and a reduction in variability. The large majority of the data from within the lake fall below the horizontal green line that represents the 40 µg/L criterion.

In addition to chlorophyll-a, total nitrogen, total phosphorus, specific conductance, total suspended solids, and color each show a distinct gradient of decreasing from the upper reservoir to the dam. Such longitudinal trends were predicted prior to the construction of Falls Reservoir. Contrary to this decreasing gradient, organic carbon maintains a relatively constant concentration throughout the reservoir.

> *Chlorophyll-a and other parameters show a distinct gradient of decreasing from the upper end of the reservoir to the dam. Contrary to this decreasing gradient, organic carbon maintains a relatively constant concentration throughout the reservoir. This observation suggests that the processing of organic carbon in Falls Lake is refractory and likely comprised of other materials in addition to algae.*

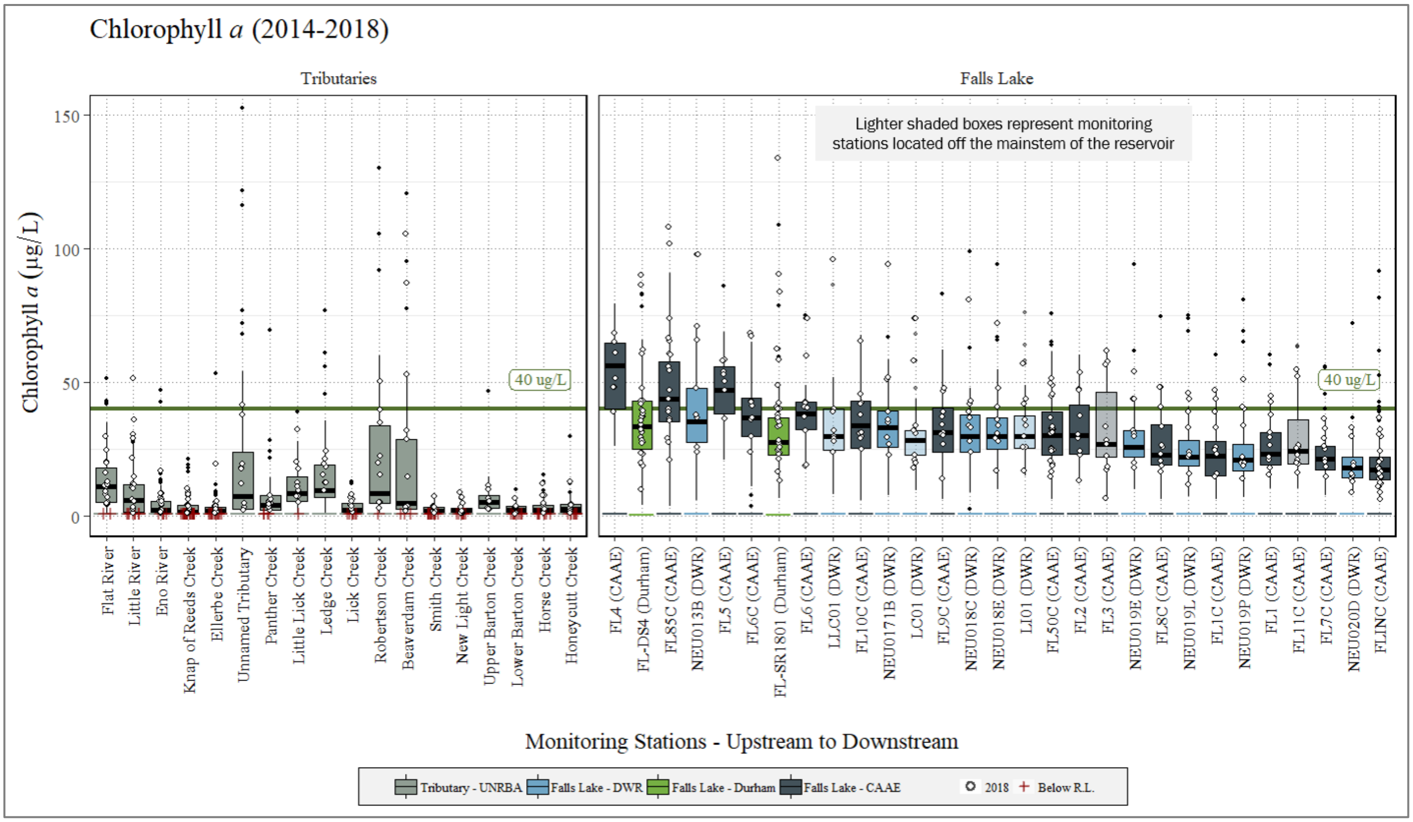

Figure ES-1. Chlorophyll-a in Lake Loading Tributary and Lake Samples from August 2014 to October 2018

Routine Monitoring data indicate that tributary stations in relatively stagnant areas or within wetland complexes tend to have higher concentrations of total phosphorus, TOC, and chlorophyll-a and lower concentrations of dissolved oxygen. For example, Robertson, Beaverdam, and unnamed tributary have the highest chlorophyll-a concentrations for the tributaries (Figure ES-1), and each of these monitoring stations are in stagnant, wetland areas. While the concentrations are sometimes high in these tributaries, the total stream flow is low relative to some other tributaries. They also represent very small volumes of water relative to storm event flows that carry much larger volumes of water to the lake from areas in the watershed that have better water quality. Therefore, these areas do not significantly influence water quality within the lake.

One of the data gaps associated with the DWR monitoring period was a lack of chlorophyll-a data in the tributaries that discharge to Falls Lake. The UNRBA Monitoring Program included monthly monitoring of this parameter at each of the 18 lake loading stations as well as sampling as part of the High Flow Special Study. The tributary chlorophyll-a data collected by the UNRBA indicate that concentrations of chlorophyll-a are usually lower in the tributaries compared to Falls Lake (Figure ES-1). When DWR developed their Falls Lake model, this data was not available, and they were required to make an assumption for this model input. DWR assumed that the tributary concentrations were the same as the closest lake monitoring station. Because in-lake chlorophyll-a is often much higher than tributary chlorophyll-a, the DWR model assumed large loads of chlorophyll-a were discharged to the lake. The UNRBA has the benefit of this additional data on which to develop and calibrate the lake model. This improvement to the model will be important when scenarios representing different nutrient management strategies are evaluated for the lake's response in terms of algal growth and chlorophyll-a.

The DWR model assumed that tributary concentrations were the same as the closest lake station because very little chlorophyll-a monitoring data was available from the tributaries. Because concentrations in the lake are generally higher than the tributaries, this assumption affected how the DWR model responds to reductions in nutrient loading in terms of algal growth. The UNRBA Monitoring Program was designed to reduce the uncertainty associated with this model input and will better characterize the existing levels of chlorophyll-a in the tributaries and in the lake as well as the expected changes resulting from nutrient reductions.

Organic nitrogen comprises the majority of the total nitrogen in the lake. Most organic nitrogen is likely sequestered within algal cells (phytoplankton) or other organisms and detritus suspended in the water column. Similarly, much of the total phosphorus measured in lake samples has likely been attached to sediments or assimilated within planktonic organisms, rather than dissolved in the lake water. These and other monitored water quality parameters are addressed in detail in Section 3.3 of the report.

DWR analyzes samples from three of its in-lake stations for phytoplankton content. Section 3.3.2 summarizes phytoplankton data from 2014-2018 which indicates the high variability in algal biovolume (i.e., the fraction of a water sample occupied by algae cells) within eight major taxonomic groups. Bluegreen algae show the strongest annual pattern, generally peaking in the latter half of the year and declining to low levels in the winter. Other algal groups either show less consistent patterns from year-to-year (e.g., diatoms) or relatively consistent low levels of biomass (e.g., green algae).

Special Studies

Table ES-1 summarizes the new Special Studies sponsored by the UNRBA to address previous data gaps or to provide additional insight for new modeling applications. These are discussed in more detail in Section 3.4. Further interpretation of several of the studies is found in Section 5. Study plans or previous reports for many of the Special Studies are also available in the UNRBA resource library.

Table ES-1 Summary of UNRBA Special Studies

Monitoring Program Component	Purpose
High Flow Sampling (Completed study - concluded in October 2018)	Obtained additional water quality grab samples when there is elevated flow at select Lake Loading stations. These data are being used to determine how water quality in these areas is different when flows are elevated and thus conveying more water and loading to the lake. These data will be used to ensure that loading estimates from these tributaries are representative of delivered loads and will support development of the watershed model.
Lake Bathymetry and Sediment Mapping (Completed study - concluded in Fiscal Year 2017)	Obtained underwater topographic data for Falls Lake to improve representation by lake models. Collected data to estimate the depth of unconsolidated sediments to aid in the interpretation of the lake sediment samples collected during Fiscal Year 2015 and to aid in development of the sediment diagenesis module of the EFDC model.
Falls Lake Constriction Point Flux Assessment (Completed study - initiated in Fiscal Year 2016 and concluded in Fiscal Year 2017)	Obtained water quality and velocity measurements through primary constriction points within Falls Lake to 1) provide data at a finer temporal scale than the routine DWR monitoring, 2) quantify how material moves from one lake segment to the next, and 3) provide data for lake model calibration to ensure that the model is accurately representing changing conditions at time steps that match short-term lake response.
Falls Lake Sediment Evaluation (Completed study – to be concluded in Fiscal Year 2018)	Evaluated nutrient concentrations in Falls Lake sediments to improve estimates of internal loading of nutrients from the lake sediments to aid in development of the sediment diagenesis module of the EFDC model.
Storm Event Sampling (Completed study - initiated in Fiscal Year 2015 and concluded in Fiscal Year 2016)	Obtained water quality data with automated samplers throughout the elevated flow period associated with storms to improve loading estimates to Falls Lake. These data were used in the development of empirical loading estimates summarized in Section 5 and will also be used to help develop and calibrate the watershed model.
Light Extinction Data Collection (Completed study - initiated and concluded in Fiscal Year 2016)	Evaluated historic light extinction data collected in Falls Lake to determine the relationship between actual light extinction measurements and Secchi depth. Light penetration is an important parameter for estimating algal production and this evaluation will aid in the development and calibration of the lake models.
Basic Evaluation of Model Performance (Completed study - initiated and concluded in Fiscal Year 2016)	Use the existing models (EFDC, BATHUB, and the Falls Lake Framework Tool) and the conceptual empirical/probabilistic model to support the ongoing evaluation of and potential adaptations to the Monitoring Program by helping to ensure that data collected through the Program is appropriate and sufficient for future modeling efforts. The Model Performance Evaluation technical memorandum summarizes the study results available online in the UNRBA resource library.
Recreational Use Assessment (Completed study - initiated and concluded in Fiscal Year 2016)	Compiled available recreational data for Falls Lake and conduct background research on recreational use evaluations on other lakes and reservoirs in the Southeastern U.S. and elsewhere to 1) assess the current status of the recreational use of Falls Lake and 2) support discussions with NCDWR and EPA on the need for additional recreational studies.

Table ES-1 Summary of UNRBA Special Studies

Monitoring Program Component	Purpose
Support Development of Alternative Regulatory Options (Funded in Fiscal Year 2015. Continuing activities are expected to be part of the Modeling and Regulatory Support efforts.)	Meetings with regulators (NCDEQ and EPA) to discuss alternative regulatory strategies for Stage II of the Falls Lake Nutrient Management Strategy. These meetings will be used to identify their study expectations for support of alternate regulatory approaches and to be sure the UNRBA monitoring program collects or has access to this information.

An example Special Study is the High Flow Sampling that occurred from August 2014 to June 2018. This Special Study was used to obtain supplementary water quality grab samples from select tributaries to Falls Lake under high flow conditions which are typically under-represented by routine monitoring. High flow conditions are periods when stream flow increases markedly above normal flows in response to a rain event. This supplemental effort helped to ensure that water quality data were obtained when hydraulic loading to the lake was high. Data from this study helps to inform the development of the watershed and lake models for Falls Lake.

Figure ES-2 shows the relationship between the proportion of water quality samples collected and the overall inflows to Falls Lake from its five largest tributaries (Ellerbe Creek ELC-3.1, Eno River ENR-8.3, Flat River FLR-5.0, Knap of Reeds KRC-4.5, and Little River LTR-1.9). Because of the intentional focus on high flow sampling, the UNRBA database now contains results across nearly the entire spectrum of inflows, even though the higher flows only occur during a very small fraction of the time. This sampling approach will improve development and calibration of the watershed model during high-flow, high-loading events, and provide more accurate timing information on loading for the lake response models.

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 will improve development and calibration of the model during high-flow events. The DWR ambient monitoring program did not specifically target high flow conditions and this data was not available at the time their models were developed.

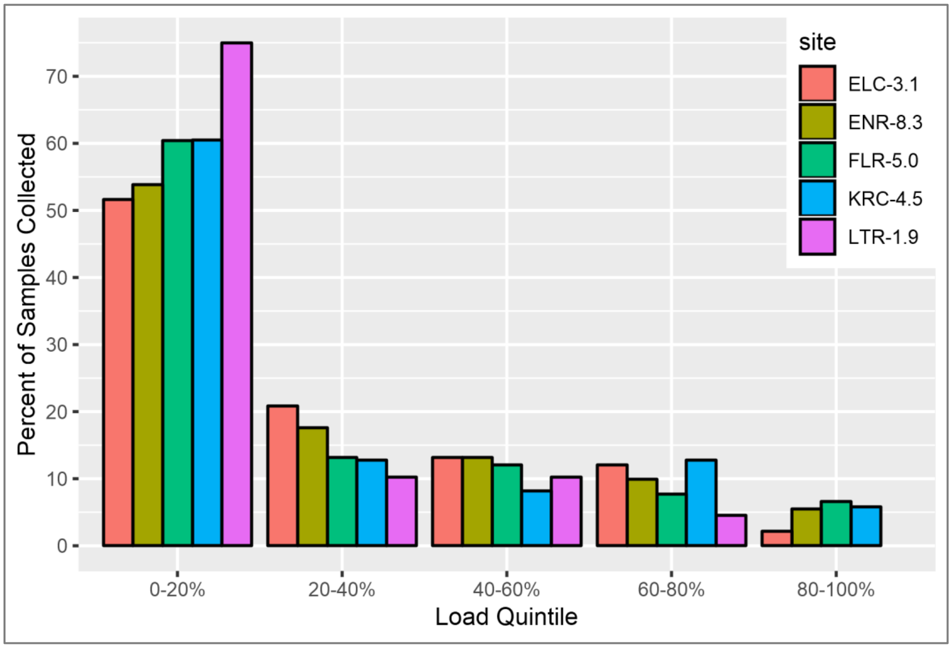

Figure ES-2. Percentage of Samples Collected during Different Loading Quintiles for the Five Largest Flow Contributors to Falls Lake

Section 4. Additional Studies and Information on Falls Lake and Other Reservoirs

Section 4 provides a historical perspective on Falls Lake by examining several studies developed as the impoundment was being planned and designed. By taking a reflective view of this historical perspective, the reader is offered an opportunity to compare current Falls Lake water quality measurements with those anticipated by the government agencies that funded and authorized construction of this reservoir. The reader is also offered the opportunity to compare improvements or declines in water quality over a number of decades since Falls Lake was constructed.

A comprehensive Environmental Statement was prepared by the USACE prior to the construction of the reservoir, as well as forward-looking evaluations of water quality by the State of North Carolina. Each study predicted nutrient and chlorophyll levels very consistent with what has been observed through the nearly 40 years since the impoundment was filled. And in each case, the studies noted that such conditions should not prevent the reservoir from meeting its intended uses. This historic perspective is important since a key consideration in making management decisions is the relative stability of trends in lake water quality over time.

Section 4 also presents a brief review of technical literature published during the past 30 years on the characteristics of reservoir impoundments, including important ways that they differ from natural lakes. Some of the more important differences include the following:

- Reservoirs exhibit hydrodynamic behaviors that derive from their nature as impounded river systems, meaning they can experience significantly more flushing and water movement than natural lakes.
- Water levels and volumes in reservoirs are often actively managed for a variety of reasons, and such management has the capacity to substantially affect water quality. Most natural lakes experience a far more constant water level, or at least more gradual changes in level as a result of inflows and outflows.
- Sedimentation patterns in reservoirs can be markedly different than in natural lakes (again, due to their location within a riverine system. Water quality, including nutrient cycling, can be affected by these patterns.

These differences are important because much of the science developed on water quality in lakes was originally based on observations and measurements from natural lakes (and primarily lakes located in northern latitudes). Since reservoirs have distinct morphological and hydrologic differences from natural lakes, it is necessary to draw from the most appropriate literature when developing models or otherwise attempting to understand or predict patterns and responses in reservoirs.

Falls Lake Chlorophyll-a is well below levels predicted by the North Carolina Division of Environmental Management (1983):

Source	June-September Average Chlorophyll-a (µg/L)		
	Upper Reservoir	Lower Reservoir	Lake-Wide
NCDEM 1983 Model Prediction	110	42	75
DWR Monitoring (Aug 2014-Oct 2018)	41	20	33

Section 5. Extended Analysis and Discussion

Section 5 provides the results of supplemental analyses of selected portions of the data presented in Section 3. Topics include spatial water quality patterns, relationships between watershed characteristics and water quality, nutrient loading estimates and patterns, reservoir bathymetry and morphology, sediment characteristics, hydraulic residence time, nutrient limitation, algal toxins, and recreational use evaluation. These evaluations support the three UNRBA Monitoring Program objectives: revise lake response modeling, allocate loads to sources and jurisdictions (i.e., support watershed modeling), and support alternative regulatory options as needed.

Water Quality

Spatial Patterns

Several monitored parameters showed distinct spatial trends. Total nitrogen, organic nitrogen, total phosphorus, chlorophyll-a, turbidity, and specific conductance all decreased from the upper end of the reservoir to the dam. This gradient pattern is consistent with observations from other reservoirs, where nutrient inputs and primary productivity (algal growth) are highest at the top of the impoundment and decline toward the dam. The pre-impoundment studies of Falls Lake also predicted this gradient pattern.

Relationship between Parameters

As the primary parameter of concern, chlorophyll-a was examined relative to other parameters that could either strongly influence its concentration or be influenced by it. These parameter relationships with chlorophyll-a were individually examined and none of the observed relationships were particularly strong. Total nitrogen, organic nitrogen, and total phosphorus showed positive correlations with chlorophyll-a. In contrast, total organic carbon (TOC) showed no meaningful correlation with chlorophyll-a, suggesting that organic carbon in the water column is primarily from sources other than phytoplankton. Modeling and other future analyses may identify more meaningful linkages, particularly by examining the interactions of multiple parameters to affect chlorophyll-a.

Total organic carbon in the reservoir does not vary with chlorophyll-a levels to any significant degree, even on a station-by-station or growing-season-only basis.

Comparison of Results from Monitoring Entities

Several potential differences were noted in data generated by different entities monitoring the same locations in Falls Lake. In some cases, these differences could be resolved by restricting the comparison of data between entities to time periods when both entities were sampling and using the same methodology. The basis for substantial differences between chlorophyll-a levels reported by the Center for Applied Aquatic Ecology (CAAE) and the City of Durham for lake samples was not readily apparent. The variance between these two datasets and potential bias will be considered as these data are used in modeling, other lake response analyses, and in making important regulatory recommendations. Tributary monitoring results within similar flow conditions reported by DWR were in close agreement with results generated by the UNRBA.

Comparison of UNRBA Monitoring Period Results with Those of Prior Monitoring

Previous UNRBA Annual Reports (2015 through 2018) included limited historical information. There is however, a substantial data set from the years immediately following the filling of the impoundment. The USACE commissioned a four-year water quality study to evaluate conditions in the new reservoir. That study shares several characteristics with the UNRBA data compilation effort (e.g., duration of study, parameters evaluated, general location of stations). Figure ES-3 compares levels of chlorophyll-a, phosphorus, and nitrogen reported during the four years immediately following the filling of Falls Lake (left side of figure) with levels reported by DWR in the most recent years (2014 through 2018). The generally shorter columns on the right side of the figure indicate lower levels of all three parameters in recent years than during the early years of the reservoir. Section 5.1.5 presents a similar comparison of nitrogen and phosphorus loading rates to the reservoir which also show lower loading rates in recent years than in the first years following impoundment.

Figure ES-3 shows that average chlorophyll-a levels during the warmer months were substantially lower during the recent years than in years just after the reservoir was filled. Year-round (annual) total phosphorus and total nitrogen levels (as reflected by the overall height of the columns) have been markedly lower in recent years than in the early years which are typical of a new reservoir.

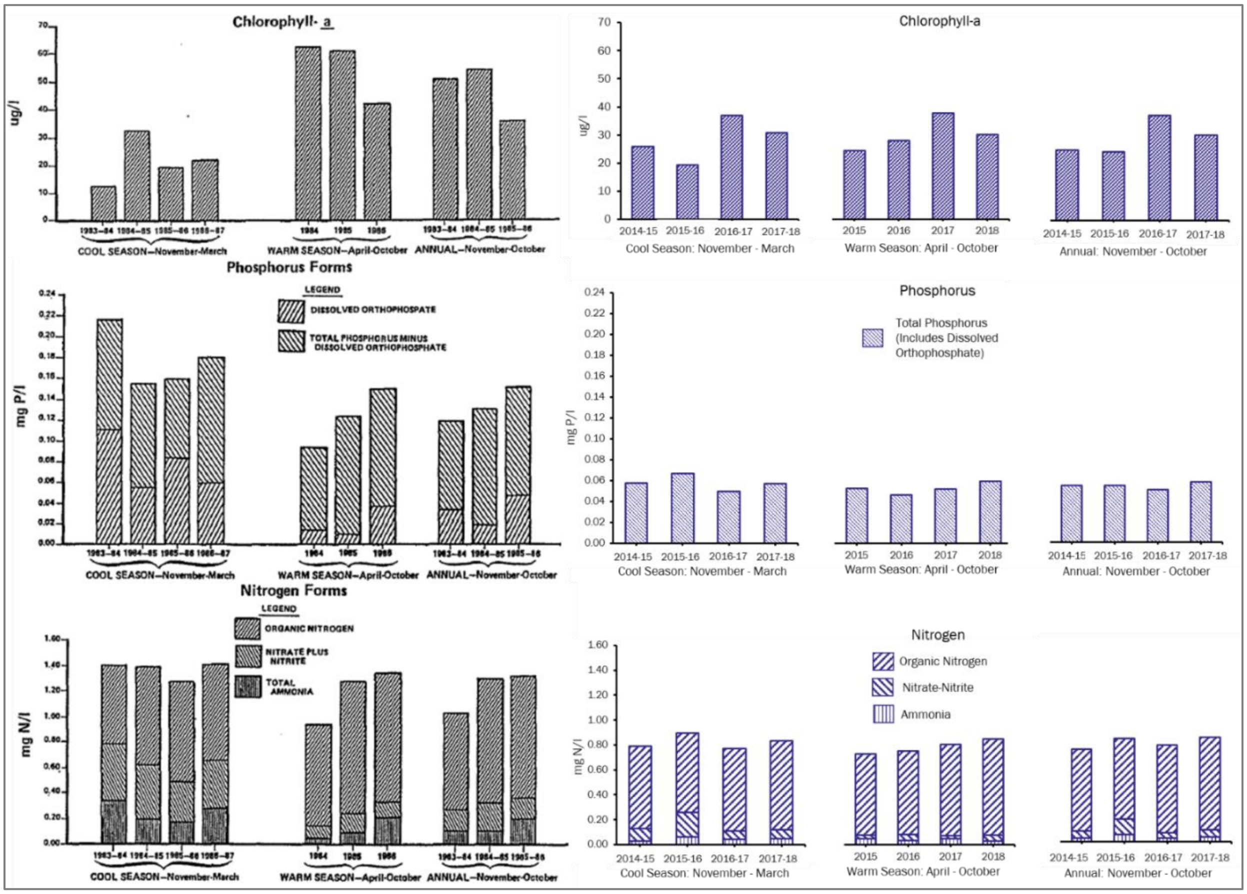

Figure ES-3. Comparison of Lake-Wide Cool Season, Warm Season and Annual Mean Concentrations of Chlorophyll-a, Total Phosphorus and Total Nitrogen from 1983-1987 (Left) and 2014-2018 (Right)

Graphics on the left are from WAR (1988); graphics on the right are based on mainstem DWR samples.

In addition to the comparisons to post-impoundment data, comparisons between the UNRBA monitoring period and the baseline period of the current Falls Lake Nutrient Management Strategy (2005 through 2007) were explored. Since that time, stakeholders in the watershed have implemented the new development requirements under the Strategy, reduced nutrient loading from wastewater treatment plants, and the acreage of agricultural land in the basin has declined. Figure ES-4 compares data for the growing season average (left) and annual average (right) for the recent monitoring period and the baseline period. These comparisons only include data collected by DWR along the thalweg of Falls Lake, and the averages include all of the stations. For the baseline period, only one year (2006) had a complete year of monitoring, so the comparisons of annual averages only include 2006. Similarly, 2018 is excluded from the annual comparisons because this report does not include data past October 2018. For both total phosphorus and total nitrogen, the annual average concentrations in Falls Lake for the recent monitoring period are similar to those from the baseline period. For chlorophyll-a, the annual averages for 2014 through 2016 show a decreasing trend and were each less than 2006; the annual average in 2017 was higher than 2006. As described previously, 2017 was a relatively dry year. While water delivery and pollutant loading to the lake was low in 2017 relative to the other recent monitoring years, the chlorophyll-a concentrations were higher. This result is expected as dryer years tend to have greater residence times and higher rates of algal growth. For the growing season averages, the recent monitoring period generally has lower total nitrogen and total phosphorus concentrations compared to the baseline period. Chlorophyll-a concentrations for three recent growing seasons were lower than baseline; two growing seasons had average concentrations that were similar to baseline. Thus, there is a strong indication that recent nutrient concentrations and loading rates, and algal levels in Falls Lake, are similar to, or lower than, conditions observed during the baseline period.

Monitoring data from 2014-2018 suggests nutrient and chlorophyll-a levels in Falls Lake are similar to, or lower than, conditions observed during the 2005-2007 baseline monitoring period. Given that flows into the lake were higher during the UNRBA monitoring period, the fact that the loads were not higher may be attributable to implementation of new development rules in 2011 that limit nutrient loading from new development, improvements at WWTPs, reductions in atmospheric deposition of nitrogen, changes to farming practices, and overall reductions in agricultural land in the basin.

Figure ES-4. Lake-wide Annual Average Chlorophyll-a and Nutrient Concentrations for Both the Baseline (2005 to 2007) and UNRBA (2014 to 2018) Monitoring Periods

Evaluation of Monitoring Results with Regulatory Criteria

North Carolina uses numeric criteria to assess waters for Clean Water Act purposes in the state. Related to eutrophication, these parameters include pH, dissolved oxygen, and chlorophyll-a. A small proportion of the pH, dissolved oxygen, and chlorophyll-a values reported by the UNRBA from tributaries to Falls Lake exceeded North Carolina surface water criteria. In the vast majority of instances, the exceedances were from tributary monitoring locations characterized by slow-moving water with abundant decaying organic (plant) matter. These kinds of tributaries can commonly experience low oxygen and pH levels and elevated chlorophyll-a concentrations. The application of the water quality standards' numeric criteria to these areas should carefully consider 15A NCAC 02B .0205 where natural waters may on occasion, or temporarily, have characteristics outside of the normal range established by the standards for regulatory decisions.

Relationships between water quality and land uses, soil types, and the presence of wastewater treatment plants are of value in developing and/or interpreting the watershed model.

Consistent with previous observations, monitoring data clearly indicate that the upper portion of the lake experiences higher chlorophyll-a levels than the lower lake. Chlorophyll-a concentrations reported for in-lake stations by DWR, CAAE, and City of Durham included exceedances of the 40 µg/L criterion at many stations. For the UNRBA monitoring period (August 2014 to October 2018), the frequency of exceedance ranges from 0 percent (near the dam) to 80 percent (upper end of the reservoir) depending on the sampling location and year. Overall, the arithmetic average of chlorophyll-a concentration for all station-years was 29 µg/L, with stations above Highway 50 averaging 34 µg/L and stations below Highway 50 averaging 24 µg/L. In addition to annual arithmetic means, geometric means and growing season means were evaluated:

- The annual mean for stations above Highway 50 was about 10 µg/L higher on the average than the mean for stations below Highway 50 (34 versus 24 µg/L), while the average of the growing season means differed by 17 µg/L between the two groups (40 versus 23 µg/L).
- For all station-years taken together, the difference between the average of annual means and annual geometric means was only about 3 µg/L. The same magnitude of difference is seen between growing season means and growing season geometric means.
- Annual geometric means averaged about 3 µg/L lower than annual means for stations above Highway 50 (31 versus 34 µg/L) and differed by a similar margin (2 µg/L) for stations below Highway 50. A similar pattern is seen for growing season geometric means relative to growing season means, but with even smaller differences between the averages (about 2 µg/L and 3 µg/L respectively).

Table ES-2 presents the chlorophyll-a summary data for the entire reservoir, and for the upper and lower segments using arithmetic means and geometric means for the growing season or annual periods.

Table ES-2 Chlorophyll-a (µg/L) Summary Metrics for Falls Lake Based on Data Collected by DWR (August 2014 to October 2018)

Location	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
Average of All Station-years	29	31	26	28
Average of Station-years above Hwy 50	34	40	31	37
Average of Station-years below Hwy 50	24	23	22	21

Hydrologic Soil Group Patterns

Sub-basins with soils having very low infiltration rates (a characteristic of wetlands) tend to show higher total phosphorus, organic nitrogen, TOC, and chlorophyll-a, and lower levels of nitrate plus nitrite in their streams. This is important information for watershed model development and for understanding opportunities and limitations for nutrient management actions.

Nutrient Loading Analysis

There are different sources of nutrient loading to Falls Lake from the watershed (external) and from the lake itself (internal). Stormwater runoff is an external loading source that carries naturally-occurring and human-caused nutrients from urban, suburban, agricultural, and natural areas. Atmospheric deposition contributes nutrients across the watershed and onto the lake surface itself. Wastewater treatment plants release treated water into several tributaries to the lake. Groundwater inflows can convey nutrients from natural sources, fertilized landscapes, and onsite septic systems to the streams, as well as directly to the lake (although it should be noted that migration through soil can remove nutrients from water as well).

The load from most of these external sources, and the biogeochemical processes that affect how they are transported to the lake, are reflected in the water quality samples collected at the UNRBA Lake Loading stations. Two exceptions are the nutrients deposited directly onto the lake from the atmosphere, and runoff and groundwater contributions occurring in the portion of the watershed that is downstream of Lake Loading stations.

Internal loading is the recycling of nutrients that previously entered the reservoir and became entrained within the sediments through various processes. Some of those nutrients can be released back to the water column under certain conditions. Fortunately, the relatively short residence time of Falls Lake should reduce the length of time required to reduce the stores of nutrients in the lake sediments compared to a natural lake. Under the hypothetical condition that all external sources of loading to the lake were eliminated, preliminary estimates indicate that it would take 20 to 40 years to deplete the nitrogen stores in the sediments.

The UNRBA Modeling and Regulatory Support Project is developing a watershed model using the Watershed Analysis Risk Management Framework (WARMF). This model will use available data and model simulations to estimate the loading from each of these watershed sources to Falls Lake. WARMF also includes a lake model that simulates lake response as average conditions over a segment of the lake The Environmental Fluid Dynamics Code (EFDC) lake model operates on a much more refined model grid. EFDC will also simulate nutrient releases from the lake sediments using its sediment diagenesis module. While these models are under development, data collected in the lake and watershed were used to evaluate sources of loading.

Wastewater Treatment Plants

Permitted point source discharges can be a significant source of pollutant loading in a watershed depending on their size and type. Wastewater treatment plants discharge treated effluent and are regulated by National Pollutant Discharge Elimination System (NPDES) permits. Wastewater treatment plants that are considered “major” for permitting purposes discharge more than 1 million gallons per day (MGD) of treated effluent. There are three major wastewater treatment plants that discharge to tributaries in the Falls Lake watershed. All three of these tributaries enter Falls Lake upstream of Interstate 85.

Water quality samples from tributary stations downstream of wastewater treatment facilities, including those below several small package plants, tend to show higher levels of specific conductance, nitrogen, and phosphorus. However, organic carbon does not appear to be influenced by the presence of an upstream treatment facility. Chlorophyll-a concentrations are usually lower in streams with major treatment facilities. Nitrogen and phosphorus levels in Knap of Reeds Creek were substantially elevated in some 2015 samples due to operational issues at the upstream wastewater treatment facility which have since been addressed (based on personal communications with Lindsay Mize, Executive Director of SGWASA, during the monitoring period). Data from 2016 to 2018 in Knap of Reeds Creek did not show similarly elevated levels.

This report summarizes the loads from the three major wastewater treatment plants (WWTPs). The WARMF watershed model will also include discharges and loads from "minor" WWTPs that discharge less than 1 MGD of treated effluent.

Annual loads from major WWTPs discharged in 2017 are much lower than those discharged in 2006 (the baseline year of the Falls Lake Rules).

Total phosphorus loads have been reduced by 81 percent (approximately 19,500 pounds).

Total nitrogen loads have been reduced by 54 percent (approximately 88,000 pounds).

Relative to the total loading to Falls Lake estimated for 2006, these improvements result in overall reductions in loading of 12 percent and 5 percent for total phosphorus and total nitrogen, respectively.

Atmospheric Deposition

Atmospheric deposition of pollutants occurs as both dry deposition (i.e., the settling of particulates) and wet deposition (associated with precipitation). Deposition that occurs on the watershed may be taken up by plants, infiltrated into the soil, or washed off surfaces by stormwater runoff. The net effects of atmospheric deposition in the watershed are accounted for in tributary water quality sampling which accounts for pollutants from all sources that are delivered to the sampling location.

Since the baseline year of 2006, total inorganic nitrogen deposition to the lake surface has decreased by approximately 38,500 pounds of nitrogen per year (2 percent of the 2006 total nitrogen load to the lake from all sources).

Tributary Loading

The figures presented in Section 3 of this report display water quality observations in terms of concentrations. However, these values are not indicative of the total amount of a substance that is actually moving downstream and entering the lake. It is important to quantify the total load of each constituent (i.e., mass delivered) which depends on both the concentration and the volume of water delivered by each tributary to Falls Lake.

Two statistical models were developed to estimate tributary loading to Falls Lake. One uses the USGS LOADEST model which was developed to compare loading during the baseline period (2005 to 2007) to the UNRBA monitoring period (2014 to 2018). LOADEST relied solely on the data obtained during these periods. Another model, the generalized additive model (GAM), used the entire dataset back to the 1980s to allow for comparison of the post-impoundment loading to the recent monitoring period. Three tributaries (Eno River, Ellerbe Creek, and Knap of Reeds Creek) have data that can be used to estimate tributary nutrient loading at the time the reservoir was filled. Comparing the post-impoundment loading estimates to recent years, loads of both nitrogen and phosphorus have decreased since the lake was filled. Between the early 1980s and 2018, total nitrogen loads from these three tributaries decreased by approximately 60 percent and total phosphorus loads decreased by approximately 90 percent. The total discharge from these three tributaries was approximately 50 percent higher in 2018 compared to 1983.

Compared to the baseline period (2005 to 2007), reductions in total loading at Knap of Reeds and Ellerbe Creeks are driven by improvements at WWTPs (stream flow was higher in the recent period, but loading was lower). For the Flat and Eno Rivers, increased loading between baseline and the UNRBA monitoring period is predominately the result of higher stream flows.

While total tributary loading estimates are available through 2018, 2017 was the latest year (at the time this report was developed) for which loading estimates from specific sources across the watershed were available, including discharges from WWTPs and atmospheric deposition.
Figure ES-5 compares the total loads in 2006 to 2017 as well as the source contributions from each source.

From 2006 to 2017, total nitrogen and total phosphorus loads to Falls Lake have decreased by 13 percent and 15 percent, respectively.

Of this reduction, WWTPs contributed approximately 40 percent of the nitrogen load reduction and 80 percent of the phosphorus load reduction.

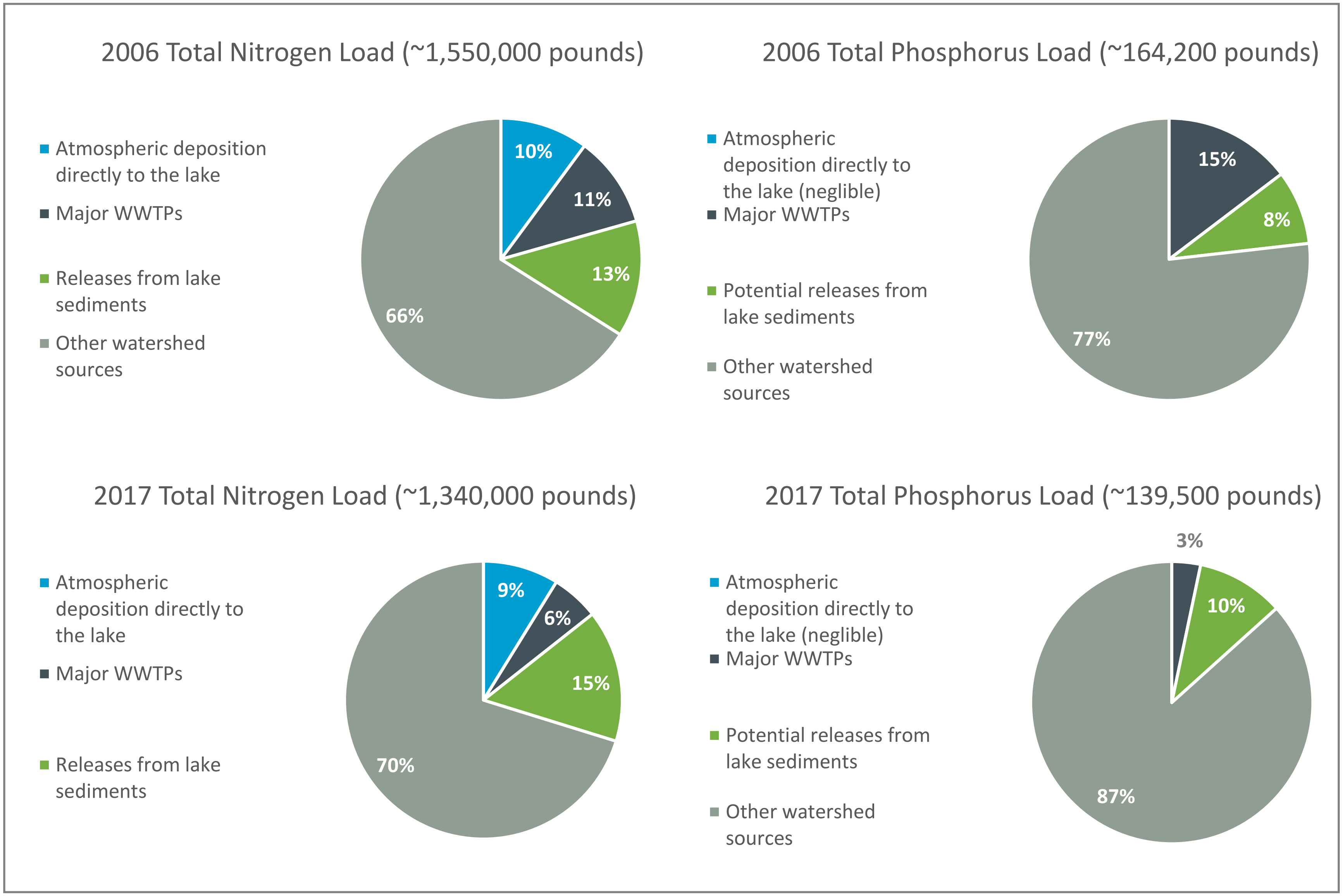

Figure ES-5. Comparison of Total Loads and Source Contributions of Nitrogen (left) and Phosphorus (right) in 2006 (top) and 2017 (bottom)

Reservoir Bathymetry and Sediment Mapping

Underwater topography (bathymetry) influences the retention and movement of water and thus partially controls the biological processing of nutrients that can affect the growth of algae. An accurate representation of bathymetry and flow restrictions is an essential element in understanding the volume of water within each segmented portion of Falls Lake. The UNRBA sponsored a bathymetric survey and sediment mapping study of Falls Lake in Fiscal Year 2017. The survey used dual-sonar frequency technology across much of the lake. Before this UNRBA study, there was little information on the bathymetry of Falls Lake other than pre-reservoir USGS topographic maps and 17 widely-spaced transects collected by DWR to support their modeling. This study has provided a much more detailed understanding of the lake bottom, and with the sediment nutrient flux data, this information provides an exceptionally strong understanding of the role of bottom sediments on nutrient levels in Falls Lake.

Data produced by this mapping effort is being used by the UNRBA modeling team to refine the grid for the hydrodynamic model. The bathymetric data show that Falls Lake at its normal elevation contains very similar water volumes above and below Highway 50 (upper and lower lake), with broad, shallow areas above Highway 50, and narrow, deep areas in the lower lake. A second goal of this study was to generate data on the thickness of the sediment layer throughout Falls Lake. The sediment evaluation saw significant variability in sediment thickness, with substantial areas of the lake bottom having little to no accumulated sediment. The sediment mapping effort showed that sediment accumulation in the upper portion of the lake is much less than in the lower half of the lake. The combination of the Sediment Evaluation and the Sediment Mapping provides the ability to estimate sediment nutrient flux throughout the lake, based on an empirical flux model. This information will support the lake response model by providing initial conditions for the sediment quality and providing an independent estimate for comparison to the fluxes predicted by the sediment diagenesis model (part of the EFDC lake response model). Although not a primary goal of the mapping effort, the sediment survey results can also provide a point of comparison with past and future surveys to estimate sedimentation rates. The USACE has shown a keen interest in this data.

Sediment Quality and Internal Nutrient Loading

A UNRBA Special Study led by Dr. Marc Alperin of the University of North Carolina’s Marine Science Department was initiated in 2015 to evaluate sediments in Falls Lake. The study looked at sediment cores collected from more than 20 locations along the lake which were analyzed for a suite of parameters. This data provides information on the characteristics of the lake sediments which will help better define the role of bottom sediments on lake water quality and support the UNRBA modeling effort. Lake sediments include both historic deposition and legacy nutrients in the deeper layers as well as “younger” sediments near the surface.

An important observation from the sediment core samples was the variability in the thickness of the unconsolidated sediment layer (i.e., muck) among the locations. In general, the river and tributary channels had substantial amounts of accumulated sediment, but areas along the historic floodplain typically had much less sediment. In fact, some shelf areas had little to no sediment, where the core collection device simply contacted hard clay, sand, or gravel. Dr. Alperin developed a model to estimate nutrient flux from the sediment. Some of his modeled estimates of ammonia flux from the sediment are similar to those used by DWR in its modeling of Falls Lake (ammonia is a preferred form of nitrogen for algae). However, his work showed much greater variability among sampled locations, ranging over at least an order of magnitude. For example, on the average, ammonia fluxes from cores collected within the historic river channel were more than three times higher than cores collected nearby, but outside of the channel. For the full set of cores collected within Falls Lake, the best predictor of nitrogen flux was the sediment thickness. Such findings are important because the UNRBA's lake modeling can now include spatial consideration of sediment nutrient flux variability. This level of data was not available when DWR developed their models.

Internal loading from lake sediments comprises over 200,000 pounds per year (14 percent) of the total nitrogen loading to the lake and up to 14,000 pounds per year (9 percent) of the total phosphorus load to the lake.

In June 2018, the U.S. EPA conducted a Sediment Oxygen Demand and Nutrient Flux evaluation of Falls Lake (EPA 2018). This study used in-situ chambers placed at three locations that were near where Dr. Alperin sampled. The rates for NH_3 flux are quite similar between the two studies, particularly given that the two field efforts were conducted three years apart and did not attempt to use the same specific sampling locations or methods. Both studies reflect the relatively low potential for phosphorus release from the sediments in Falls Lake. The general comparability of the two sediment studies, as well as the agreement between the Alperin results and the earlier DWR sediment work at two locations in the lake, increases the level of confidence in using the flux estimates for developing the lake response model.

Loading from lake sediments is difficult to control in a large reservoir like Falls Lake which has a surface area of more than 12,000 acres. Dr. Alperin's study indicated that current stores of nitrogen in the lake sediments are sufficient to release nitrogen for decades even if no additional nitrogen loads enter the lake. Some nutrient loading will continue to enter Falls Lake from the watershed and the atmosphere even with a revised nutrient management strategy. These internal loads of nutrients will never be completely removed as a source.

Falls Lake Segmentation

There is substantial spatial variability associated with the Falls Lake reservoir across many metrics including morphometry and bathymetry, water and sediment quality, watershed characteristics and inputs, etc. The Falls Lake Rules include reference to several geographic breakpoints along the reservoir in addressing timeframes for attaining compliance with the management strategy (e.g., Highway 98 crossing, Highway 50 crossing, Interstate 85 crossing). Locations like causeway crossings are convenient because they are clearly recognizable, permanent features. Such crossings may even have a physical influence on the reservoir's behavior by altering or restricting the movement of water, as was investigated by the UNRBA Constriction Point Special Study. The development and implementation of a nutrient management strategy for Falls Lake will consider its spatial and temporal characteristics.

Reservoir Residence Time

The timing and amount of inputs of water to Falls Lake Reservoir are largely controlled by rainfall patterns in the watershed. In contrast, release of water from Falls Lake to the Neuse River is controlled by the USACE to mitigate flooding downstream and preserve downstream ecological systems. The dynamic interaction of these two processes results in substantial abrupt changes to the lake's residence time (i.e., the number of days an average molecule of water stays in the lake). Residence time varies from as short as about 20 days (when the dam is operated to drop the lake level quickly) to theoretically several hundred days (when the release at the dam is very small to retain water in the reservoir). During large storm events, the USACE's primary goal is to reduce flooding downstream by holding water in Falls Lake and minimizing releases through the dam. Since the USACE actively regulates reservoir discharges (and therefore residence time), any water quality parameter that is affected by residence time (such as chlorophyll-a) is subject to reservoir management decisions generally outside of the influence of the regulated community. These operations must be considered when exploring nutrient management alternatives for the reservoir.

Nutrient Limitation

Like many reservoirs in the Southeastern U.S., Falls Lake is considered eutrophic, meaning it is relatively nutrient rich and can support an abundant fish and algal community. Limiting excessive algal growth in reservoirs by reducing either nitrogen or phosphorus, or both, is a common management objective. Information compiled by the UNRBA suggests that phosphorus is often the limiting nutrient in the lower portion of the lake, but algae in the upper lake are often limited by nitrogen or co-limited by both nutrients. Previous lake modeling conducted by DWR indicate the upper part of the lake is limited by nitrogen approximately 80 percent of the time while the lower part of the lake is limited by nitrogen 40 percent to 50 percent of the time (DWR 2009). From a practical perspective, this means that nutrient management of the lake likely needs to include consideration of both nitrogen and phosphorus. This is a question that will need to be evaluated further as the UNRBA moves through its evaluation of a revised nutrient management strategy and in considering any potential alternative regulatory approaches.

Algal Toxins

Some species of blue-green algae produce toxic substances under environmental and physiological conditions that are not well-understood. Studies across the nation have shown that the species able to produce these toxins are common in both natural lakes and man-made reservoirs. The City of Raleigh conducts monthly monitoring at multiple locations in the reservoir for several algal toxins in association with its water intake from Falls Lake. Data from recent years reflects that, even though algal toxins are reported in a small proportion of samples collected from Falls Lake, they have not been reported at levels above the World Health Organization or U.S. EPA guidelines.

Recreational Use Assessment

Another designated use of Falls Lake is recreation. Prior data compiled by the UNRBA included review of information on recreational uses of Falls Lake. This information found no linkage between counts of visitors to the lake and water quality conditions. To expand on the previous evaluation, a diverse and abundant volume of social media and related information on Falls Lake was examined. Large numbers of recreational users have posted information to various public websites, including quantitative rankings of user experiences. For example, more than 230 reviews on Falls Lake have been posted to the TripAdvisor website and over 90 percent of reviewers ranked their experience as “Excellent” or “Very Good” across a broad range of recreational activities, while less than one percent of the reviewers noted something negative about the lake. Several websites devoted to fishing enthusiasts contain hundreds of records of fishing success on Falls Lake, and the reservoir is the site for numerous fishing tournaments each year, including some events with large sponsorships, media coverage, and substantial purses paid to winning anglers. Such information is valuable as an indicator of the nature and breadth of recreational uses provided by Falls Lake, which may not be evident when only water quality is examined.

According to the USACE (2013), all types of recreational uses for Falls Lake are being met. Limitations on the number of visits are due to the carrying capacity of Falls Lake and its facilities, not water quality.

Section 6. Quality Assurance

Section 6 addresses the confidence and reliability associated with data generated through the UNRBA Monitoring Program. Quality assurance and quality control (QAQC) are primary considerations for the UNRBA Monitoring Program. All analytical data collected through the program (both from Routine Monitoring and from Special Studies) are evaluated for compliance with the quality objectives outlined in the UNRBA Monitoring QAPP. Data accuracy, precision, and completeness reviews are performed following each monitoring event, and reviews of field and laboratory practices are performed on a routine basis. Data collection efforts associated with Special Studies are subject to the same general QAQC considerations and scrutiny as for the Routine Monitoring. Section 6 does not address data collected by other entities, however, only water quality data obtained under a state-approved QAPP are included in the analyses and interpretations in this report.

Data accuracy, precision, and completeness reviews are performed following each monitoring event. Reviews of field and laboratory practices are performed on a routine basis. Since the beginning of the UNRBA Monitoring Program, more than 98 percent of all planned sampling events in which the sampling location had flowing water were completed as planned. Through the end of 2018, there have been no cases of samples where results for Laboratory Control Sample (samples of known concentration analyzed along with field samples) associated with UNRBA data were out of compliance with method criteria.

The UNRBA program calls for relatively low laboratory reporting limits for some parameters (e.g., nutrients). Low reporting limits can increase the risk of having analytical results fall within the range of uncertainty for some methods. Total phosphorus and ammonia each saw more than five percent of field blanks (sample vessels filled in the field with water presumed to have none of the target analyte present) with results above the reporting limit. This means there is an increased chance that some stream samples with levels near or below the reporting limit may have less than the concentration reported. However, most stream samples showed concentrations well above the reporting limits, so the error associated with very low levels is not meaningful in the modeling and related analytical efforts. The QAQC section provides confidence levels for the analyzed parameters. This type of information allows users of the data to estimate the degree of uncertainty associated with laboratory values.

Section 7. Conclusions, Recommendations, and Next Steps

The UNRBA initiated the Transition Monitoring in November 2018 to continue monitoring water quality in selected tributaries to Falls Lake. This scaled-back program provides continuity that will allow the UNRBA to track water quality in the watershed and aid adaptive management of the watershed and the lake. When anomalous conditions occur (like the relatively high in-lake chlorophyll-a concentrations observed in 2017), having water quality data to estimate loading and evaluate patterns of lake response is important to understand the causes. Transition Monitoring can be used to understand how weather events (large storms, drought periods) affect loading and lake response. As the regulated community implements the revised nutrient management strategy, having a continuous dataset will assist with program evaluations and modifications. Continuation of the program during the 2020 fiscal year is recommended, but the program should be looked at each year to determine if continuation is appropriate.

In addition to continuing the Transition Monitoring as it is currently being implemented, it is recommended that the UNRBA request that DWR add a tributary monitoring station on Little River. During the design of the Transition Monitoring, one of the UNRBA's lake loading stations was assumed to be also monitored by DWR. The UNRBA should request that DWR add monitoring of the Little River at Old Oxford Highway to the set of other stations it monitors at the upper end of the Falls Lake reservoir (Latitude: 36.081667, Longitude: -78.854722). This will ensure that each of the largest tributaries delivering water to Falls Lake are monitored.

Coordination Among Entities

As the UNRBA continues the Modeling and Regulatory Support Project, continued coordination with other entities is important to ensure that all sources of data and information are being considered as the re-examination proceeds. The following interactions are planned:

- The UNRBA Monitoring Team leaders will coordinate with the Modeling Team to ensure they have all raw data and other materials developed through the UNRBA Monitoring Program
- The UNRBA Monitoring Team members will be available to respond to Modeling Team inquiries about this report, the underlying data, etc.
- The UNRBA should continue to obtain and review results from DWR, City of Durham, and CAAE ongoing monitoring programs

- The UNRBA is communicating with the UNC Collaboratory regarding potential opportunities for collecting additional data that will support the re-examination and modeling effort.
- The UNRBA will continue to work with North Carolina Department of Environmental Quality regarding appropriate assessment units for Falls Lake that are consistent with the functionality of the lake, the processing of nutrient loads that enter the upper part of the lake, and continued protection of designated uses

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Section 1 Background and Objectives of UNRBA Monitoring Program

Falls Lake was constructed by the US Army Corps of Engineers in the late 1970s. The designated uses of Falls Lake are drinking water supply, recreation, fishing, aquatic life, and wildlife. In 2010, the Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy (the Strategy) to reduce chlorophyll-a concentrations in the lake which exceed the criterion of 40 µg/L in some locations. The Strategy requires two stages of nutrient reductions for Falls Lake. The goal of Stage I is to achieve compliance with the chlorophyll-a standard in the lower half of the reservoir (below Highway 50). The goal of Stage II is to comply with the chlorophyll-a standard everywhere in the reservoir. The Strategy dictates load reduction requirements for local governments and other entities, which were based on a lake nutrient response model developed by the North Carolina Division of Water Resources (DWR).

The two Stages of nutrient load reductions are designed to reduce nutrient loading to Falls Lake from various sources, including stormwater runoff from new and existing development, wastewater treatment plants, and agriculture. Based on DWR's fiscal analysis, the cost of Stage I is expected to exceed $500 million for the parties affected by the rules (agriculture, local governments, state and federal agencies). The estimated cost of Stage II is over $1 billion.

This section describes the Upper Neuse River Basin Association (UNRBA) Monitoring Program, introducing the general organization and purpose of the program. The first three sections of this report are substantially similar to Annual Reports prepared for the UNRBA during each year of the Monitoring Program (2015 to 2018). The purpose of the program is summarized in Section 1, the methodology for data acquisition is presented in Section 2, and results of recent monitoring efforts are presented and summarized in Section 3.

Sections 4 and 5 of this report offers more in-depth discussion than previous annual monitoring reports. Key examples of the new information include the following:

- Discussion of the characteristics of reservoir impoundments and primary factors that determine their water quality
- Examination of the comparability of results reported by different entities monitoring the same lake and tributary locations
- Comparisons of results from the UNRBA monitoring period (2014 to 2018) with prior evaluation periods
- Estimation of internal nutrient loading from sediments based on studies conducted by the UNRBA
- Consideration of nutrient loading patterns from the watershed including evaluation of changes in loading over time and as a result of upgrades to wastewater treatment facilities in the basin
- Examination of web-based information reflecting the recreational use value of Falls Lake.

This information will enhance the understanding of the water quality conditions in Falls Lake supporting the re-examination process. This information will also provide context, both from a historical perspective and with respect to interpreting the complex, interacting factors that collectively control the existing conditions in the reservoir. Understanding this complexity and the controlling conditions in the reservoir will assist the re-examination process and the development of new or revised management actions. Substantial UNRBA work remains to be done. Including the development of several models and the testing of various scenarios with the new modeling tools. This report with its observations and analytical findings constitutes beneficial additions to the re-examination process and the pursuit of an improved management strategy for Falls Lake.

While all substantial elements of the Monitoring Program are addressed in this report, additional details and more thorough discussion of some topics (e.g., Special Studies) are included in prior Annual Reports and other documents available in Monitoring Data and Reports section of the UNRBA resource library. Unless otherwise noted, statistical summaries and graphics presented in this report are "cumulative" through the period (August 2014-October 2018) and thus supersede similar analyses and graphics – and any associated discussion or interpretation – presented in earlier reports.

Although there are frequent references to "Falls Lake", Falls Reservoir, or simply "the lake," the water body is a man-made reservoir impoundment. Most reservoirs are referred to as lakes, but Section 4.2 below provides a discussion of the substantial differences between natural lakes and reservoirs. References to Falls Lake as a "lake" are for convenience only. Falls of the Neuse Reservoir is a man-made impoundment and should not be expected to have the same technical characteristics as a natural lake.

1.1 UNRBA Monitoring Program Overview

The UNRBA Monitoring Program is primarily composed of two categories of water quality monitoring. The first category is Routine Monitoring, which is the repeated testing of water quality variables at fixed locations over many months. Routine Monitoring provides insight into the seasonal and annual variation of nitrogen, phosphorus, chlorophyll-a, and other parameters over time. UNRBA Routine Monitoring began in August 2014. The second category, Special Studies, are focused evaluations conducted within a limited timeframe. Most Special Studies are intended to inform water quality modeling development and calibration so that baseline and management scenarios can be more accurately simulated. Special Studies are also used to assist the UNRBA in its efforts to explore and examine water quality and nutrient management programs, policies and regulations.

In 2014, the UNRBA initiated the Monitoring Plan that described the locations, parameters, frequencies, and other program elements (Cardno 2014b; http://www.unrba.org/monitoring-program). The Monitoring Plan is maintained and updated by the UNRBA monitoring service provider to reflect changes in the program over time. As established in Section 5 (f) of the Falls Lake Nutrient Management Strategy (https://www.deq.nc.gov/about/divisions/water-resources/water-planning/nonpoint-source-planning/falls-lake-nutrient-strategy), the UNRBA Monitoring Plan was initially approved by North Carolina Division of Water Resources (DWR) on July 16, 2014. The UNRBA Monitoring Quality Assurance Project Plan (QAPP) was developed specifically for the program to ensure that data are reliable and suitable for consideration for regulatory purposes. The QAPP describes the protocols and methodologies to be followed by field and laboratory staff to ensure data precision and accuracy. The QAPP was initially approved by the North Carolina Division of Water Resources (DWR) on July 30, 2014 and again on January 18, 2017.

1.2 Regulatory Background

Falls Lake Reservoir was created by the U.S. Army Corps of Engineers (USACE) when a dam was completed at the Falls of the Neuse River in 1981. The North Carolina Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy ("the Rules"), requiring two stages of nutrient reductions within the Falls of the Neuse Reservoir watershed (N.C. Rules Review Commission 2010). The Rules establish a Nutrient Management Strategy to be implemented in two stages: Stage I is described in 15NCAC 02B .0275 (4) (a), and Stage II is described in 15NCAC 02B .0275 (4) (b). The Rules recognize there is uncertainty associated with the water quality modeling performed by DWR used to establish the Stage II requirements, and therefore, allow for re-examination of the Stage II nutrient loading reduction requirements after additional data collection, as specified in Section 5(f) of the Rules. The UNRBA Monitoring Program was specifically designed to reduce the uncertainty and to re-examine the scientific assessment and modeling predictions used by DWR to support these rules.

1.3 UNRBA Re-Examination Strategy

In 2011, the UNRBA began a re-examination process of the regulatory framework for Stage II of the Rules. Full implementation of the nutrient reduction strategy, which is more stringent than any other nutrient strategy implemented in the State, will require extremely costly actions on the part of UNRBA member governments and other regulated parties. In addition, the practical ability to achieve the mandated reductions is uncertain. In light of the financial impact of the Rules and the regional importance of Falls Lake, the UNRBA began examining the technical bases and regulatory framework of Stage II requirements. Local governments within the UNRBA agree that protecting Falls Lake as a water supply and public resource is paramount. The members want to ensure that the rules applied to the watershed sufficiently reflect the lake's beneficial uses. Control requirements should be reasonable, fiscally responsible, and efficaciously improve the water quality of the resource. Based on a review conducted in 2013 (Cardno 2013), the Stage II Rules are not technically, logistically, or financially feasible. Given the high cost (approximately one billion dollars) of implementing Stage II and the uncertainty of achieving the chlorophyll-a current water quality standard, the scientific re-examination process relies on additional data collection and new modeling efforts to support revised lake response modeling, as well as the evaluation of various regulatory options.

The Rules require that the North Carolina Department of Environmental Quality (NCDEQ) issue a status update for the Falls Lake Nutrient Management Strategy every five years, beginning in 2016. The status update report was issued in March 2016 and is available on the NCDEQ website (https://www.deq.nc.gov/about/divisions/water-resources/water-planning/nonpoint-source-planning/falls-lake-nutrient-strategy#StatusReports-2766). The report summarizes progress toward implementation of the Rules and describes changes in nutrient loading to the lake and lake water quality. The 2016 status report highlights the improvements (reductions) in chlorophyll-a concentrations observed throughout the lake. The report also acknowledges the UNRBA as a collaborative partner to further the science with respect to reducing the lake modeling uncertainty, expanding the best management practices "toolbox" used for compliance and conventional and innovative nutrient control measures to improve water quality in the lake (NCDEQ 2016).

1.4 Objectives of the UNRBA Monitoring Program

The UNRBA Monitoring Program is designed to support the UNRBA's three main goals, as prioritized by the UNRBA Path Forward Committee:

1. Revise lake response modeling
2. Support alternative regulatory options as needed
3. Allocate loads to sources and jurisdictions (i.e., support watershed modeling)

This Final Monitoring Report for the Re-Examination provides a summary of data collected and compiled through the Monitoring Program for the UNRBA modeling efforts as part of the re-examination process and, to a large degree, represents the end of the intensive UNRBA monitoring efforts. It focuses on recent data collection by the UNRBA and DWR, but also looks at data collected by others as far back as the impoundment of Falls Lake. Data summaries, comparisons, discussions, and interpretations are provided to assist the modeling team and the UNRBA. Data summarized in this report provides key information to develop and calibrate the watershed and lake models. The models will be used to evaluate options for managing nutrients in the watershed and improving water quality in Falls Lake. The models will also shed light on what can be achieved in the reservoir in terms of water quality given the man-made construction characteristics of the reservoir and other forces beyond the control of the regulated entities in the watershed such as weather patterns, hydrodynamics, historic nutrient pools, and operations by the USACE. The models may also be used to evaluate regulatory options such as site-specific criteria and use attainability analyses to ensure existing uses continue to be met. The following models are included in the re-examination process as described in the DWR-approved UNRBA Modeling QAPP:

- The Watershed Analysis Risk Management Framework (WARMF) includes both a watershed model and a lake model.
- The Environmental Fluid Dynamics Code (EFDC) includes a hydrodynamic, water quality lake model and a sediment diagenesis module.
- A statistical model of Falls Lake applying both empirical and Bayesian techniques will be developed to predict lake water quality and provide linkages to designated uses.

Section 2 UNRBA Monitoring Program Protocol

This section summarizes the components and data acquisition protocol of the UNRBA Monitoring Program, which primarily comprises intensive multi-year tributary monitoring, a series of individual Special Studies, and the compilation of monitoring data from various other sources. A central focus of this report is on the UNRBA monitoring efforts from August 2014 through October 2018. The report also provides results and interpretation of water quality monitoring activities conducted by other groups in the Falls Lake drainage basin, including examination of previous monitoring efforts on Falls Lake. Additional information about the Routine Monitoring and Special Studies methodologies are provided in the UNRBA Monitoring Plan, the DWR-approved UNRBA Quality Assurance Project Plan, and in the Plan of Study for each Special Study. These files are available in the UNRBA resource library.

2.1 Routine Monitoring

Routine Monitoring was used to characterize the spatial and temporal variability of water quality in the Falls Lake drainage area (watershed). It includes Lake Loading (LL) stations near the mouths of the tributaries to Falls Lake and Jurisdictional Boundary (JB) stations further upstream on the tributaries near municipal boundaries and county lines. Data collection is managed by the UNRBA monitoring service provider. Table 2-1 outlines the Routine Monitoring efforts on the tributaries, and Table 2-2 lists the tributary stations and monitoring frequency. Routine Monitoring also includes coordination with DWR, which conducts monthly monitoring at seven long-term stations located on the Falls Lake Reservoir.

Table 2-1. Overview of Tributary Routine Monitoring Components of the UNRBA Program

Parameter	Start Date	End Date	Stations
Field Measurements			
Air temperature	Aug. 2014	Aug. 2015	All
Water temperature	Aug. 2014	Oct. 2018	All
Specific conductance	Aug. 2014	Oct. 2018	All
Dissolved Oxygen	Aug. 2014	Oct. 2018	All
pH	Aug. 2014	Oct. 2018	All
Reference-point tape-down	Jan. 2015	Oct. 2018	All
Dye velocity	Jan. 2015	Oct. 2018	All
Laboratory Analyses			
Total Kjeldahl nitrogen	Aug. 2014	Ongoing	All
Soluble Kjeldahl nitrogen	Aug. 2014	Oct. 2018	Lake Loading
Nitrate+nitrite	Aug. 2014	Ongoing	All
Ammonia	Aug. 2014	Ongoing	All
Total phosphorus	Aug. 2014	Ongoing	All

Table 2-1. Overview of Tributary Routine Monitoring Components of the UNRBA Program

Parameter	Start Date	End Date	Stations
Total soluble phosphorus	Aug. 2014	Oct. 2018	Lake Loading
Orthophosphate	Aug. 2014	Oct. 2018	Lake Loading
Total organic carbon	Aug. 2014	Ongoing	Lake Loading
Dissolved organic carbon	Aug. 2014	Jun. 2016	Lake Loading
Chlorophyll-a	Aug. 2014	Oct. 2018	Lake Loading
Total suspended solids	Aug. 2014	Oct. 2018	All
Volatile suspended solids	Jul. 2015	Oct. 2018	Lake Loading
Color (platinum cobalt)	Aug. 2014	Jun. 2016	Lake Loading
Visible absorbance at 440 (nanometer) nm	Aug. 2014	Oct. 2018	Lake Loading
UV absorbance at 254nm	Aug. 2014	Oct. 2018	Lake Loading
5-day carbonaceous biochemical oxygen demand	Aug. 2014	Jun. 2016	Lake Loading

Table 2-2. UNRBA Tributary Routine Monitoring Stations and Sampling Frequency

Name[a] (Station Type[b])	Subwatershed	Stream Name	County	Drainage Area (mi^2)	Sampling Frequency
NFR-41 (JB) [c]	Flat	North Flat	Person	12.7	Monthly
NFR-37 (JB) [c]	Flat	North Flat	Person	15.8	Replaced with NFR-41
NFR-32 (JB)	Flat	North Flat	Person	32.8	Monthly
SFR-30 (JB)	Flat	South Flat	Person	54.4	Monthly
FLR-25 (JB)[f]	Flat	Flat	Person	102	Monthly
DPC-23 (JB) [f]	Flat	Deep	Person	32.1	Monthly
FLR-5.0 (LL)	Flat	Flat	Durham	169	Monthly [e]
NLR-27 (JB) [f]	Little	North Fork Little	Orange	21.9	Monthly
SLR-22 (JB) [f]	Little	South Fork Little	Durham	37.4	Monthly
LTR-16 (JB)	Little	Little	Durham	78.3	Monthly
LTR-1.9 (LL)	Little	Little	Durham	104	Monthly [e]
ENR-49 (JB) [f]	Eno	Eno	Orange	60.5	Monthly
ENR-41 (JB)	Eno	Eno	Orange	73.2	Monthly
ENR-23 (JB) [f]	Eno	Eno	Durham	121	Monthly
ENR-8.3 (LL)	Eno	Eno	Durham	149	Monthly [e]
CMP-23 (JB)	Knap of Reeds	Camp	Durham	1.99	Monthly
KRC-4.5 (LL)	Knap of Reeds	Knap of Reeds	Granville	41.9	Monthly [e]
ELC-3.1 (LL)	Ellerbe	Ellerbe	Durham	21.9	Monthly [e]

Table 2-2. UNRBA Tributary Routine Monitoring Stations and Sampling Frequency

Name[a] (Station Type[b])	Subwatershed	Stream Name	County	Drainage Area (mi^2)	Sampling Frequency
UNT-0.7 (LL)	Unnamed	Unnamed	Granville	3.43	Monthly
PAC-4.0 (LL)	Panther	Panther	Durham	3.24	Monthly
LLC-1.8 (LL)	Little Lick	Little Lick	Durham	13.8	Monthly
LLG-0.9 (JB)	Little Ledge	Little Ledge	Granville	3.74	Monthly
LGE-17 (JB)	Ledge	Ledge	Granville	1.79	Monthly
LGE-13 (JB)	Ledge	Ledge	Granville	3.49	Monthly
LGE-5.1 (LL)[f]	Ledge	Ledge	Granville	20.3	Monthly
LKC-2.0 (LL)	Lick	Lick	Durham	10.8	Monthly
ROB-7.2 (JB)	Robertson	Robertson	Granville	4.43	Monthly
ROB-2.8 (LL)[f]	Robertson	Robertson	Granville	12.0	Monthly
BDC-2.0 (LL)[f]	Beaverdam	Beaverdam	Granville	12.7	Monthly
SMC-6.2 (LL)	Smith	Smith	Granville	6.3	Monthly
BUC-3.6 (JB)	New Light	Buckhorn	Granville	1.21	Monthly
NLC-3.8 (JB)	New Light	New Light	Wake	9.90	Monthly
NLC-2.3 (LL)[f]	New Light	New Light	Wake	12.3	Monthly
UBC-1.4 (LL)	Upper Barton	Upper Barton	Wake	8.26	Monthly
LBC-2.1 (LL)[f]	Lower Barton	Lower Barton	Wake	10.4	Monthly
HSE-11 (JB)	Horse	Horse	Franklin	3.88	Monthly
HSE-7.3 (JB)	Horse	Horse	Wake	7.11	Monthly
HSE-5.7 (JB)[d]	Horse	Horse	Wake	9.60	alternate site
HSE-1.7 (LL)[f]	Horse	Horse	Wake	11.9	Monthly
HCC-2.9 (LL)	Honeycutt	Honeycutt	Wake	2.76	Monthly

[a] *Name combines an abbreviation for the stream with the approximate distance from the station to Falls Lake (km).*

[b] *JB refers to a Jurisdictional Boundary station and LL refers to a Lake Loading station.*

[c] *NFR-41 was added in July 2015 to replace site NFR-37 due to concerns about safety and accessibility at NFR-37.*

[d] *HSE-5.7 was used as an alternate for HSE-7.3 in May-June 2015 while HSE-7.3 was inaccessible due to construction.*

[e] *Prior to July 1, 2016, samples were collected twice monthly at these stations.*

[f] *Transition Monitoring Site that will continue to be monitored by the UNRBA after October, 2018*

2.1.1 Lake Loading Stations on Tributaries in the Falls Lake Watershed

To characterize tributary inputs to Falls Lake and support watershed and lake response modeling, flow and water quality data are needed from the 18 LL stations as near as possible to the mouth (point of entry) for each of the lake's tributaries. UNRBA monitoring locations and United States Geological Survey (USGS) flow gage locations are shown on Figure 2-1. The USGS maintains ten flow gages and one stage gage in the watershed. Site characteristics for these gages are provided in the Comparison of Flow Estimation Methods Technical Memorandum (Cardno 2014a) available here.

In addition to monthly sampling at the 18 LL stations during Years 1 and 2 of the program, water quality sampling occurred twice a month on five of those tributaries to the upper lake. These five major tributaries contribute roughly 78 percent of the inflow quantity to Falls Lake. In Year 3, these five tributaries were targeted under the High Flow Event Special Study, and routine monitoring was reduced to monthly. This change was made to ensure collection of water quality across a wide range of flow conditions. It is important to have high confidence in nutrient loading for these tributaries because their water and nutrient contributions to the lake have the potential to drive much of the lake's chlorophyll response. Routine Monitoring parameters at LL stations were based on requirements of the Watershed Analysis Risk Management Framework (WARMF) and Environment Fluid Dynamics Code (EFDC) model originally used by DWR for Falls Lake, along with input from UNRBA member organizations.

Five tributaries contribute 78 percent of the flow to Falls Lake, and all five discharge upstream of I-85.

The program included collection of total and volatile suspended solids, total and dissolved organic carbon, and chlorophyll-a concentrations to provide data that was not available when DWR developed its model in support of the Rules. Parameter coverage, frequencies, and sampling locations have been revised occasionally to optimize data collection for the UNRBA's needs. For example, the first two years of monitoring showed a high correlation between total organic carbon (TOC) and dissolved organic carbon (DOC) ($r^2 = 0.99$), so DOC monitoring was suspended in 2016 to reduce laboratory costs. Five-day carbonaceous biochemical oxygen demand ($CBOD_5$) and Platinum-Cobalt color analysis also ceased in June 2016 as explained in the 2015 UNRBA Annual Monitoring Report.

2.1.2 Jurisdictional Boundary Stations on Tributaries in the Falls Lake Watershed

The Rules specify that nutrient loading from governmental jurisdictions in the Falls Lake watershed must be reduced. JB stations located between the jurisdictions and at key loading points such as outlets of major tributaries within a jurisdiction are included in the program to

1. Provide water quality data from points associated with all member jurisdictions
2. Prioritize best management practice (BMP) implementation in areas with the highest loading
3. Calibrate watershed models
4. Assess changes in loading over time

Twenty JB stations (Figure 2-1) were identified based on input from the UNRBA Path Forward Committee (PFC) and were monitored monthly to characterize water quality near JBs between UNRBA member governments. As with LL stations, data collection efforts at JB stations were reviewed to optimize value for the UNRBA. Monitoring at JB stations has only been slightly modified since the beginning of the program - beginning in July 2016, the frequency of TOC collection at JB stations was reduced from monthly to quarterly, while monthly collection continued at the LL stations for each tributary.

2.1.3 Falls Lake Monitoring

Monitoring within Falls Lake itself provides data to assess ambient water quality and to calibrate and validate revised lake models. Data for Falls Lake have been collected by DWR, the City of Durham, the

City of Raleigh, and North Carolina State University's Center for Applied Aquatic Ecology (CAAE). Data are collected under a DWR-approved QAPP at 30 monitoring stations (Figure 2-2) in 22 distinct locations on the lake (some locations are monitored by more than one organization. The City of Raleigh is in the process of securing DWR approval of their QAPP. The data summaries in this report do not include City of Raleigh water quality data. Subsequent data evaluations by the UNRBA as part of the adaptive management framework of the re-examination will include City of Raleigh data collected after approval of their monitoring QAPP.

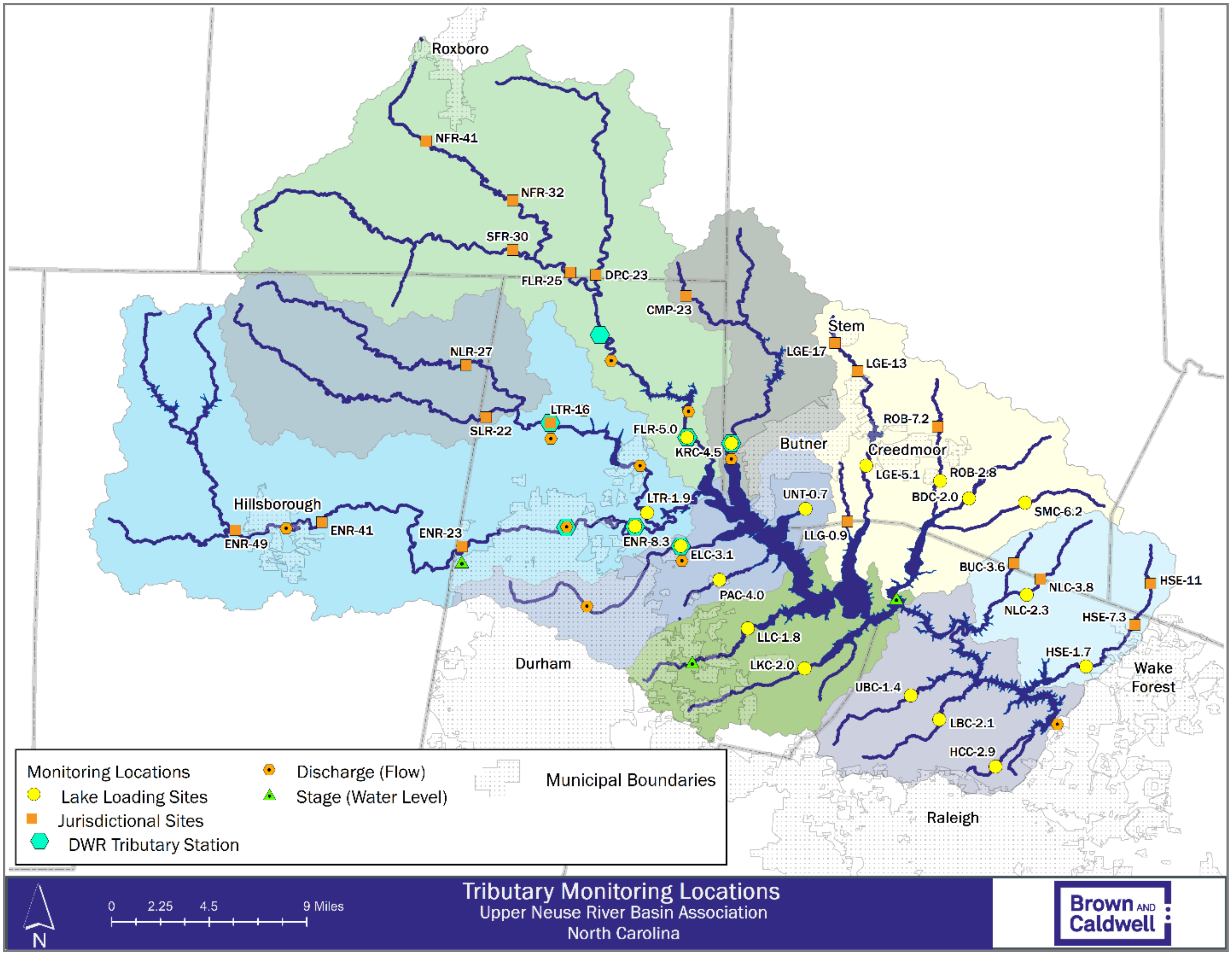


Figure 2-1. UNRBA Lake Loading and Jurisdictional Monitoring Locations (see Table 2-2 for station details) and Existing USGS Gages

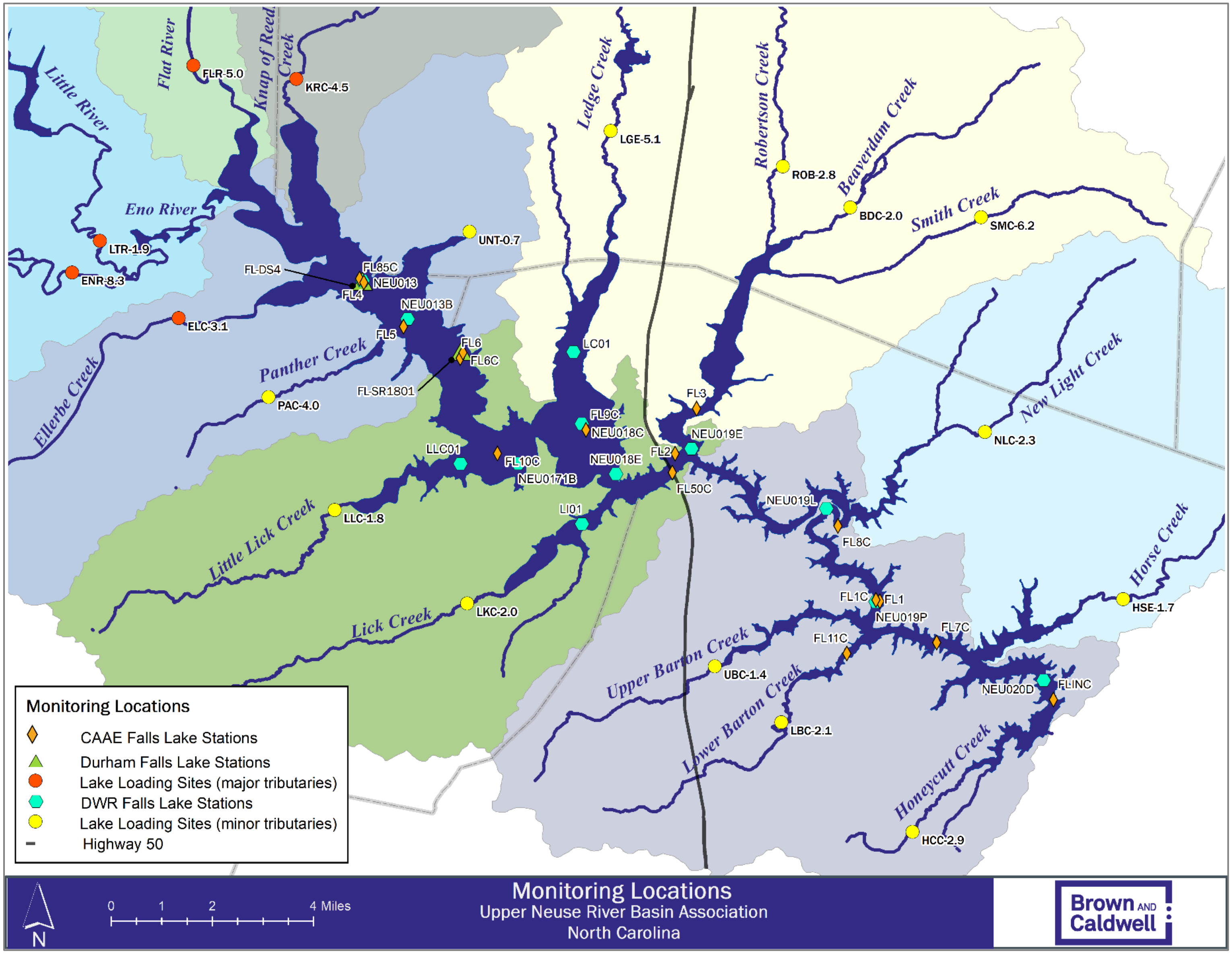


Figure 2-2. Falls Lake DWR, CAAE, and City of Durham Monitoring Locations, along with UNRBA Lake Loading Stations

Field data along with nutrient, chlorophyll-a, carbon and suspended sediment data obtained from photic zone composite water samples were obtained from all of the monitoring entities and compiled annually for inclusion in the UNRBA database. Chlorophyll-a water quality samples collected at discrete depths do not follow DWR's sampling protocol for water quality compliance assessment purposes. Chlorophyll-a samples require photic zone composites of the water column for DWR compliance assessment purposes. University researchers and others may collect chlorophyll-a samples using other protocols in order to obtain specific inference for other purposes. Because of the complexities in making comparisons across different agency data sets using different sampling methods, such data are archived separately and not compared directly to the photic zone composite data collected in the lake.

DWR collects samples monthly at 12 stations throughout Falls Lake and all parameters discussed in this report except field parameters are collected as photic zone composites. Annual data summaries for the parameters that DWR collects may be accessed through the DWR website (https://deq.nc.gov/about/divisions/water-resources/water-resources-data/water-sciences-home-page/intensive-survey-branch/falls-jordan-lakes-monitoring).

The City of Durham collects water quality samples from two stations on Falls Lake. These stations (at Cheek Road and I-85) are sampled weekly from April to October as photic zone composites. In addition to residing in the UNRBA database, City of Durham data are available online at http://www.durhamwaterquality.org/. Data from the City of Durham is reflected in several of the graphics in Section 3, although the time period represented by the City of Durham data is not directly comparable to the other stations because Durham conducts monitoring at a greater frequency during the growing season as opposed to monthly throughout the year as performed by the other organizations.

CAAE has collected chlorophyll-a samples as photic zone composites from 10 sites since before the UNRBA Monitoring Program began. Three of these sites are co-located with CAAE's automated sampling profilers at I-85, Highway 50, and the City of Raleigh water supply intake structure. These locations have collected chlorophyll data one to three times per month. The remaining seven sites (1C, 6C, 7C, 8C, 9C, 10C, 11C) have monthly chlorophyll-a data as photic zone composite samples. Beginning in April 2016, six sites added monthly photic zone chlorophyll-a sampling (sites FL1-6). Photic zone samples for nitrogen, phosphorus, carbon and total suspended solids (TSS) parameters began being collected twice-monthly at CAAE's three profiler sites and sites FL1-6. Field parameters are collected twice-monthly at the profiler sites and monthly at sites FL1-6. Specific parameters and their frequency of measurement by each of the monitoring organizations since the start of the UNRBA monitoring program (August 2014) are summarized in Table 2-3 and Table 2-4.

DWR collects data on the species abundance and biovolume estimates of algae at three stations in Falls Lake. This dataset provides information on how populations of different algal groups change and cycle through time. Mechanistic models like EFDC track and predict the mass of different algal groups in response to changing environmental conditions, and DWR's algal dataset can provide a useful point of comparison for model calibration or validation. In this report, algal biovolumes are aggregated into eight broad groups (e.g., green algae, diatoms, cyanobacteria, etc.) and graphed to provide a visual overview of the available data. Algal biovolume is a measure of biomass that combines both the number of cells present as well as their average size.

Table 2-3. Falls Lake Sampling Frequencies for Stations and Parameters Monitored by DWR and the City of Durham

Parameter	Collection Method	DWR Sampling Frequency (12 Stations)	City of Durham Sampling Frequency (2 stations)
TOC	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
DOC	Photic Zone Composite	Monthly	-
$CBOD_5$	Photic Zone Composite	Monthly	-
Chlorophyll-a	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
Total Nitrogen (TN)	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
Total Kjeldahl Nitrogen (TKN)	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
$NO_2 + NO_3$	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
NH_3	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
Total Phosphorus (TP)	Photic Zone Composite	Monthly	Weekly (Apr – Oct)
Ortho-phosphorus	Photic Zone Composite	-	Weekly (Apr – Oct)
Turbidity	Photic Zone Composite	Monthly	Weekly (Apr - Oct)
TSS	Photic Zone Composite	Monthly	-
Volatile suspended solids (VSS)	Photic Zone Composite	Monthly	-
pH	Depth Stratified	Monthly	Weekly (Apr – Oct)
Conductivity	Depth Stratified	Monthly	Weekly (Apr – Oct)
Dissolved oxygen	Depth Stratified	Monthly	Weekly (Apr – Oct)
Temperature	Depth Stratified	Monthly	Weekly (Apr – Oct)
Secchi Depth	Observed depth of visibility	Monthly	Weekly (Apr – Oct)

Frequency of sampling by CAAE is further dependent on monitoring station and these are summarized in Table 2-4.

Table 2-4. Stations and approximate sampling frequencies for stations monitored by the Center for Applied Aquatic Ecology (CAAE) at NCSU from August 2014 through December 2018

Station ID	Chlorophyll-a	TOC	Nitrogen (TN, TKN, NOx, NH_3)	TP	TSS	Field Parameters (Temp, DO, pH, Conductivity)	Secchi Depth
FL4	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly	Monthly
FL85C (Interstate 85)	Weekly	2x per month	2x per month	2x per month	2x per month	2x per month	Weekly
FL5	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly	Monthly
FL6C	Monthly	-	-	-	-	-	Monthly
FL6	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly	Monthly
FL10C	Monthly	-	-	-	-	-	Monthly
FL9C	Monthly	-	-	-	-	-	Monthly
FL50C (Highway 50)	Weekly	2x per month	2x per month	2x per month	2x per month	2x per month	Weekly
FL2	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly	Monthly
FL3	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly	Monthly
FL8C	Monthly	-	-	-	-	-	Monthly
FL1C	Monthly	-	-	-	-	-	Monthly
FL1	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly [a]	Monthly	Monthly
FL11C	Monthly	-	-	-	-	-	Monthly
FL7C	Monthly	-	-	-	-	-	Monthly
FLINC (Intake Structure)	Weekly	2x per month	2x per month	2x per month	2x per month	2x per month	Weekly

Notes:

[a] Samples for this station and parameter combination began to be collected as photic zone composites in April 2016.

Monitoring stations are listed in order from upstream to downstream.

2.1.4 Modifications to Routine Monitoring since 2018 Annual Report

The Routine Monitoring effort ended in October 2018, completing the tributary water quality data acquisition for the re-examination effort. Beginning in November 2018, a much-reduced "Transition Monitoring" effort was initiated to continue obtaining data from a smaller set of stations. Transition Monitoring continues the monthly sample collection at 12 stations (rather than the 38 used for Routine Monitoring) with a reduced parameter list to focus on nutrient loading constituents. While this reduction in monitoring effort on the part of the UNRBA allows for more resources to be allocated toward modeling and analytical efforts, other entities continue to monitor both Falls Lake and its larger tributaries (e.g., USGS, DWR, City of Durham, CAAE). This means there will still be beneficial data available to the UNRBA into the future for assessment and management purposes.

2.2 Special Studies

The UNRBA Monitoring Program includes Special Studies designed to address specific questions and information gaps. This section briefly summarizes Special Studies implemented as a part of the UNRBA's Monitoring Program (see Table 2-5). Each Special Study is guided by a Study Plan approved by the UNRBA Executive Director. These plans include details on data acquisition and quality assurance protocols and are available in the UNRBA resource library. Special Studies results obtained since the previous Annual Report are presented in Section 5. Summaries of Special Studies are provided in Section 3.4 with additional discussion of selected studies in Section 5.

Table 2-5. Summary of UNRBA Special Studies

Monitoring Program Component	Purpose
High Flow Sampling (Completed study - concluded in October 2018)	Obtained additional water quality grab samples when there is elevated flow at select LL stations. These data will be used to determine if water quality in these areas is different when flows are elevated and thus conveying more water and loading to the lake. These data will be used to ensure that loading estimates from these tributaries are representative of delivered loads and will support development of the watershed model. A summary of results of this study is presented in Section 3.4.
Lake Bathymetry and Sediment Mapping (Completed study - concluded in Fiscal Year 2017)	Obtained underwater topographic data for Falls Lake to improve representation by lake models. Collected data to estimate the depth of unconsolidated sediments to aid in the interpretation of the lake sediment samples collected during Fiscal Year 2015 and to aid in development of the sediment diagenesis module of the EFDC model. A summary of results of this study is presented in Section 5.
Falls Lake Constriction Point Flux Assessment (Completed study - initiated in Fiscal Year 2016 and concluded in Fiscal Year 2017)	Obtained water quality and velocity measurements through primary constriction points within Falls Lake to 1) provide data at a finer temporal scale than the routine DWR monitoring, 2) quantify how material moves from one lake segment to the next, and 3) provide data for lake model calibration to ensure that the model is accurately representing changing conditions at time steps that match short-term lake response. Results from this study were presented in the 2015 and 2016 Annual Reports available in the UNRBA resource library. A summary of results of this study is presented in Section 3.4.
Falls Lake Sediment Evaluation (Completed study – to be concluded in Fiscal Year 2018)	Evaluated nutrient concentrations in Falls Lake sediments to improve estimates of internal loading of nutrients from the lake sediments to aid in development of the sediment diagenesis module of the EFDC model. A summary of results of this study is presented in Section 5.
Storm Event Sampling (Completed study - initiated in Fiscal Year 2015 and concluded in Fiscal Year 2016)	Obtained water quality data with automated samplers throughout the elevated flow period associated with storms to improve loading estimates to Falls Lake. These data were used in the development of empirical loading estimates summarized in Section 5 and will also be used to help develop and calibrate the watershed model. Results of this study are described in the 2016 Interim Report available online at in the UNRBA resource library. A summary of results of this study is presented in Section 3.4.
Light Extinction Data Collection (Completed study - initiated and concluded in Fiscal Year 2016)	Evaluated historic light extinction data collected in Falls Lake to determine the relationship between actual light extinction measurements and Secchi depth. Light penetration is an important parameter for estimating algal production and this evaluation will aid in the development and calibration of the lake models. The results of this study were presented in the 2015 Annual Report available in the UNRBA resource library. A summary of results of this study is presented in Section 3.4.
Basic Evaluation of Model Performance	Use the existing models (EFDC, BATHUB, and the Falls Lake Framework Tool) and the conceptual empirical/probabilistic model to support the ongoing evaluation of and potential adaptations to the Monitoring Program by helping to ensure that data collected through the

Table 2-5. Summary of UNRBA Special Studies

Monitoring Program Component	Purpose
(Completed study - initiated and concluded in Fiscal Year 2016)	Program is appropriate and sufficient for future modeling efforts. The Model Performance Evaluation technical memorandum summarizes the study results available in the UNRBA resource library. A summary of key findings is presented in Section 3.4.
Recreational Use Assessment (Completed study - initiated and concluded in Fiscal Year 2016)	Compiled available recreational data for Falls Lake and conduct background research on recreational use evaluations on other lakes and reservoirs in the Southeastern United States and elsewhere to 1) assess the current status of the recreational use of Falls Lake and 2) support discussions with DWR and United States Environmental Protection Agency (EPA) on the need for additional recreational studies. The results of this study were presented in the 2015 Annual Report available in the UNRBA resource library. A summary of results of this study is presented in Section 5.
Support Development of Alternative Regulatory Options (Funded in Fiscal Year 2015. Continuing activities are expected to be part of the Modeling and Regulatory Support efforts.)	Meetings with regulators (NCDEQ and EPA) to discuss alternative regulatory strategies for Stage II of the Falls Lake Nutrient Management Strategy. These meetings will be used to identify their study expectations for support of alternate regulatory approaches and to be sure the UNRBA monitoring program collects or has access to this information. Future budgeting for such activities is expected to primarily be part of the Modeling and Regulatory Support Contract that was initiated in September 2016 available in the UNRBA resource library.

Section 3 UNRBA Monitoring Program Results

This section presents information generated by the UNRBA as well as by several other monitoring programs in the region. Graphics and summary information presented in this section are based on the UNRBA Monitoring Program period (August 2014-October 2018) unless otherwise noted. The section also provides a brief synopsis of the results of each UNRBA Special Study. More thorough discussions of the methods and results of each Special Study are provided in the Annual Reports for previous years. References to specific Special Study reports are provided.

Raw data observations are available online for the benefit of any UNRBA database users. The UNRBA monitoring service provider coordinates directly with the UNRBA's modeling contractors to assist in preparing, screening and providing data files for model development.

Data Available Online:

This report does not include raw data. The complete UNRBA database can be accessed from the UNRBA resource library*. Users can review raw data, generate summary statistics, and obtain detailed station information. Data available on the UNRBA website is only that acquired by the UNRBA or its contractors; Information from other sources such as government agencies may be obtained through their public portals or upon direct request to the monitoring entity.*

3.1 Data Visualization and Summary Techniques

Data collected by the UNRBA and other organizations are displayed in summary tables and graphics throughout this report. Most of the graphics are box and whisker figures that allow for comparison of data across sites, time, etc. As a guide for interpreting the box and whisker figures, an example is shown below (Figure 3-1) with meanings of each component labeled. The boxes represent the middle part of the data set with the lower end of the box representing the 25th percentile of the data and the upper end representing the 75th percentile of the data. The median (50th percentile) is shown as a horizontal bar across the box. Data points (black and white points) are randomly spread horizontally to better show points that would otherwise overlap. By statistical convention, the upper and lower extremes represented by the vertical lines extending out of the boxes show the range of values that fall below the 25th percentile (lower quartile) or above the 75th percentile (upper quartile) by up to 1.5 times the difference between the upper and lower quartile values.

To highlight data collected since the previous Annual Report (BC 2018), results from samples collected from January through October 2018 are shown in white, while outliers from previous results are shown in black. Observations below each parameter's reporting limits are shown as a red plus (+) symbol at the reporting limit.

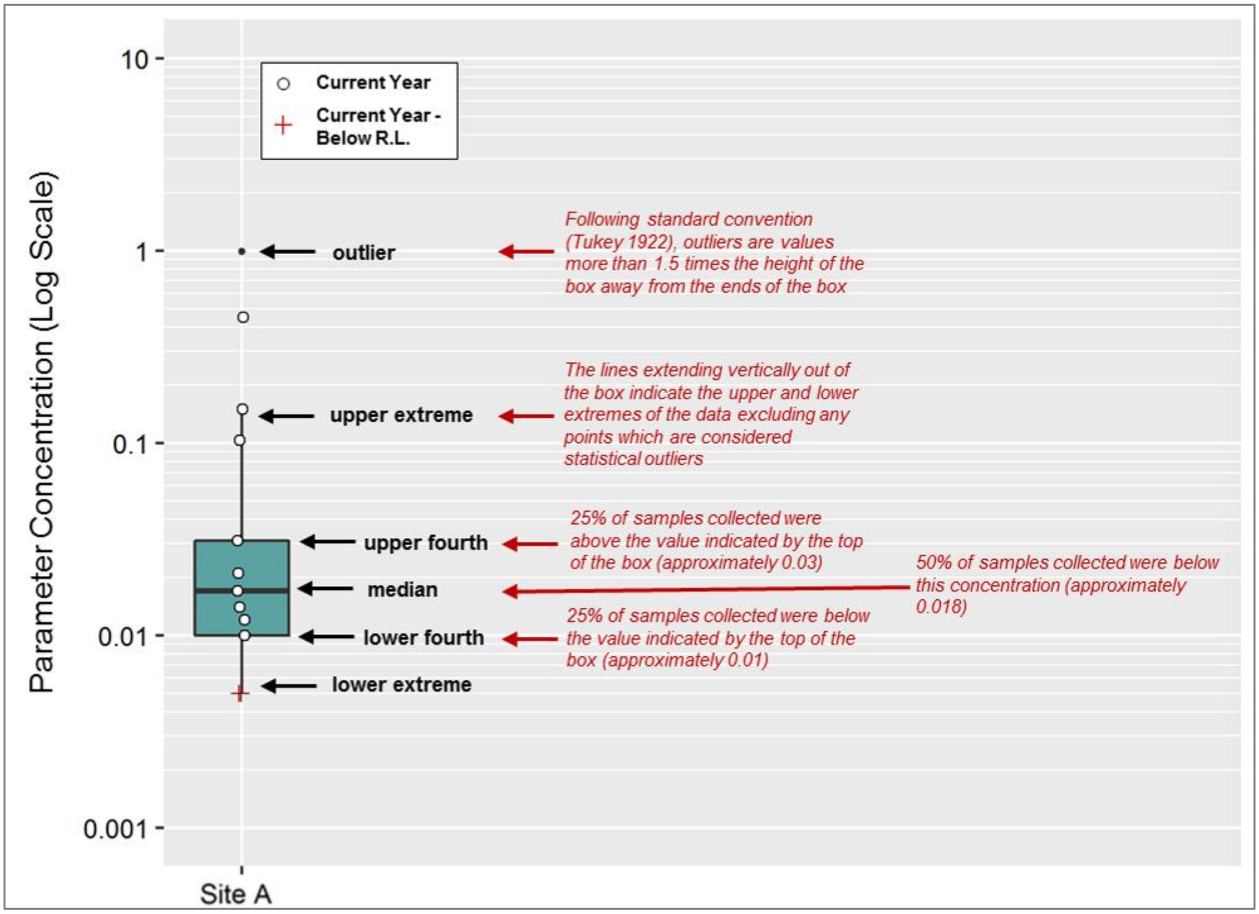


Figure 3-1. An example box and whisker figure as used in this report and the meaning of figure components Note that the y-axis is displayed using a logarithmic scale.

Many of the figures in this report use a logarithmic (log) scale for the y-axis to depict a broad range of concentrations observed within the data. These figures include the following statement under the figure title: “Note that the y-axis is displayed using a logarithmic scale.” Logarithmic scales, while allowing for visualization of data that spans multiple orders of magnitude, can cause low concentrations to appear more substantial. A comparison of ammonia data displayed in arithmetic scale to the same data displayed using a logarithmic scale is provided in Figure 3-2. Note in the top panel (arithmetic scale) that the majority of the data appears with a narrow horizontal band at relatively low concentrations. In the bottom panel (logarithmic scale), the same data is displayed, but the boxes are “stretched,” and the distribution of the data is more pronounced, making it easier to visually compare differences among the monitoring stations.

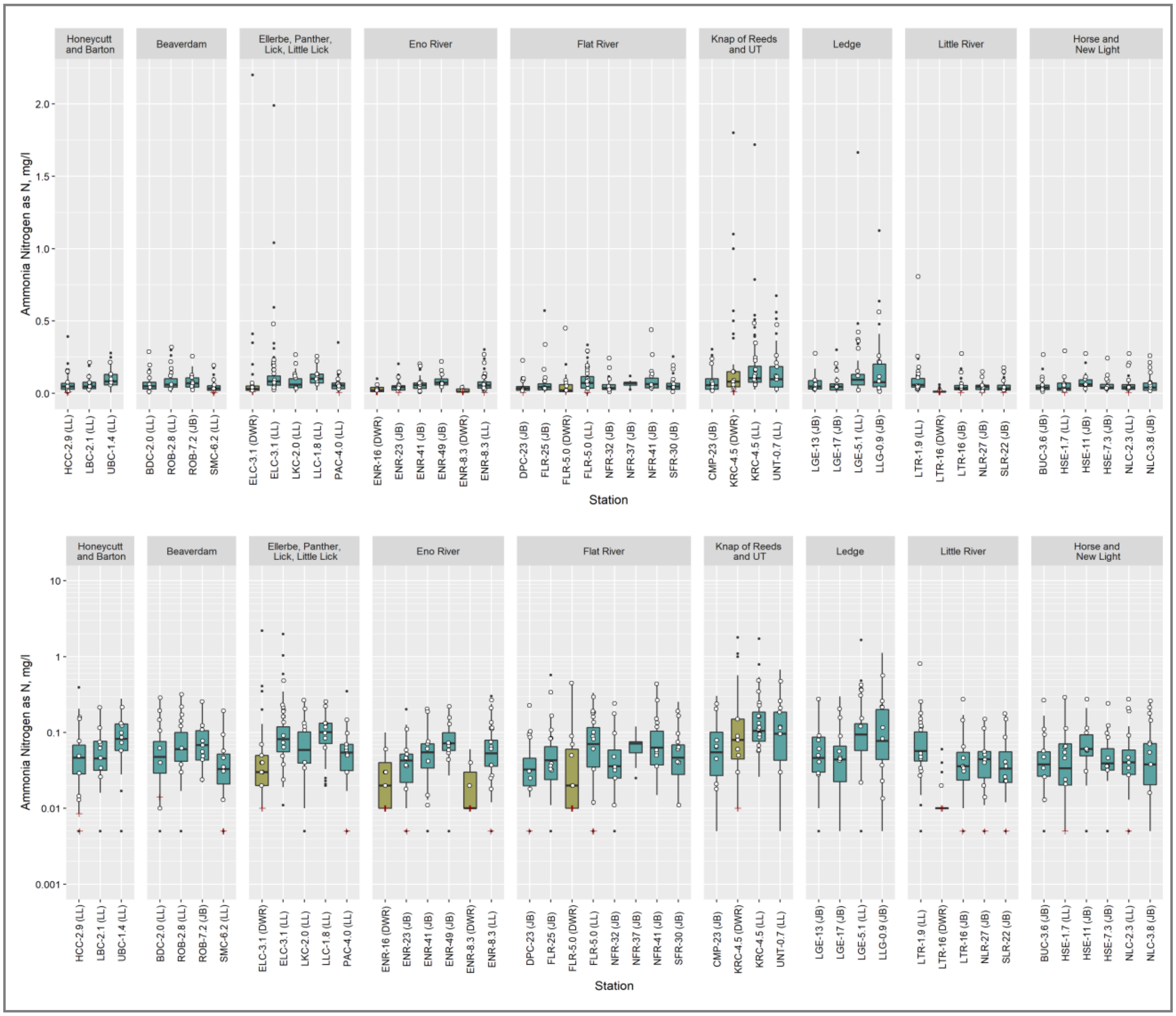


Figure 3-2. Comparison of the same set of ammonia data using an arithmetic scale (top panel) and logarithmic scale (bottom panel) for the y-axes

3.2 Overview of Hydrologic Conditions

The UNRBA Monitoring Program does not collect hydrologic data but relies on data from other public sources. The brief analysis in this section examines that data to provide hydrologic context for the overall Monitoring Program. The watershed and lake models being developed by the UNRBA will include comparisons to both the baseline period and the UNRBA monitoring period. These periods collectively include seven model years that represent a range of hydrologic conditions including severe droughts and record high flows. This range in simulated hydrologic conditions will provide a more complete record on which to base the revised nutrient management strategy.

To illustrate the overall hydrologic conditions for the monitoring period precipitation patterns in the Falls Lake watershed, the resulting Falls Lake water levels were evaluated. Observed values were then compared to historical averages to assess whether the monitoring period was substantially wetter or drier than average or exhibited unusual seasonal patterns. For this report, these analyses are primarily meant to provide a qualitative view of the monitoring period.

Precipitation data was obtained from National Climatic Data Center (NCDC) rain gages as well as USGS rain gages in the Upper Neuse Basin (Table 3-1). Annual and monthly precipitation totals were calculated for each gage and results compared among gages to identify the spatial variability and to compare observed precipitation amounts to the 30-year normal values for the region. It is important to note that while a given year may be wetter than normal, specific months can be relatively dry. For example, in 2017, only three months (April-June) out of the year had higher than normal rainfall totals whereas six months showed lower than normal rainfall totals. Total precipitation can vary substantially within the watershed. Across the weather stations, the recorded annual rainfall varied by up to 38 inches (2018) or by as little as 18 inches (2015).

*For the UNRBA monitoring period (2014 to 2018), the annual average rainfall total was 4 to 11 percent **higher** than the 30-year average. The baseline monitoring period (2005 to 2007) was 13 to 57 percent **lower** than the 30-year average. These two periods will be simulated by the UNRBA modeling and thus a wide range of hydrologic conditions will be simulated.*

Table 3-1. Precipitation Gages in the Falls Lake Watershed

Source	Station ID	Station Name	Longitude	Latitude
USGS	208706575	Beaverdam Creek at Dam near Creedmoor	-78.689167	36.02361
NOAA	GHCND:US1NCGV0010	Butner Filter Plant NC US	-78.7736	36.1414
USGS	360419078543145	Eno River near Durham	-78.908722	36.07211
USGS	360334078584145	Eno River near Huckleberry Spring	-78.978056	36.05944
USGS	2087182	Falls Lake above Dam	-78.583333	35.94111
USGS	355856078492945	Little Lick Cr at NC Highway 98 Oak Grove	-78.824833	35.98231
NOAA	GHCND:US1NCWK0006	Raleigh 6.8 NNE NC US	-78.6058	35.9114
NOAA	GHCND:US1NCWK0059	Raleigh 8.4 N NC US	-78.6812	35.9425
NOAA	GHCND:US1NCPN0011	Roxboro 7 ESE NC US	-78.8858	36.3464
USGS	360143078540945	West Murray Avenue at Durham	-78.902583	36.02867

In addition to total precipitation, timing of rainfall can also be important. For example, particularly wet springs can deliver large amounts of nutrients which then can fuel algae blooms throughout the summer. In 2006 which was selected as the baseline year to develop the Falls Lake Nutrient Management Strategy, drought conditions were present for much of the year, but two storm events late in the year brought the annual precipitation back up to the typical range. Extreme patterns such as these affect water quality much differently than if the same amount of rain were delivered evenly over the course of a year.

To assess whether monthly rainfall patterns were different from typical values over the past 30 years, precipitation totals by month were examined to identify months or seasons which were unusual. Years corresponding to the UNRBA monitoring period are presented first, followed by those associated with DWR's baseline modeling period (2005 to 2007). Table 3-2 provides a list of large storms that occurred in 2005 to 2007 (10 storms) and August 2014 to October 2018 (36 storms).

Table 3-2. 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)	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
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.*

Figure 3-3 shows how the monthly precipitation from rain gages differs from the 30-year average for the watershed - zero thus represents the 30-year average. Values above zero show periods with more rain than average and values below zero indicate drier periods. The darker shaded region shows the range of the middle 50 percent of precipitation values over the last 30 years and can be considered as a reference range for typical precipitation amounts (i.e., the shaded band can be qualitatively viewed as representing "normal" conditions). Precipitation is not uniform over the watershed and the spatial variation in total precipitation for each month is shown by the orange boxes in Figure 3-3. The boxes show the 25th, 50th, and 75th percentiles of precipitation over the region with whiskers extending to the full range of values observed at the various rain gauges. Measurements which are considered statistical outliers are shown as black dots. Additional information regarding the format and interpretation of box plots is provided in Section 3.3.1.

For most months, the majority of the monitoring stations had precipitation within the typical range so in general, the monitoring period appears to have been fairly normal in terms of precipitation. However, in 2015 the months of May and August were notably drier than normal while the months of November and December were wetter than normal. In 2016, the summer and early fall were wetter than average, while January was dryer than average. In 2017, the spring was much wetter than normal while the remainder of the year was close to normal or drier than normal. While 2018 experienced a wet spring and fall, precipitation for the majority of the year fell within normal ranges.

A related analysis was conducted on the water level (stage) of Falls Lake based on daily data collected by the USACE (see Figure 3-4). For this analysis, median values (dashed line) are based on data reported from 1987 to present. From January 2014 to March 2015, the observed stage (orange line) in Falls Lake was generally higher than normal (above the 75th percentile much of the time). From April 2015 to October 2015, lake levels were very close to the median value. From October 2015 through January 2016, lake levels were relatively high (generally above the 75th percentile for most of this time and exceeding the 95th percentile towards the end of December). In October 2016, lake levels again rose as a result of excess precipitation from Hurricane Matthew. In 2017, lake levels rose due to a particularly rainy spring and then gradually fell to below normal values that fall and winter. Lake levels in early 2018 were below normal before gradually rising to at or slightly above normal levels between February and September. Lake elevation then rose dramatically with the arrival of Hurricane Florence in mid-September and Hurricane Michael in October and remained elevated for the remainder of the year.

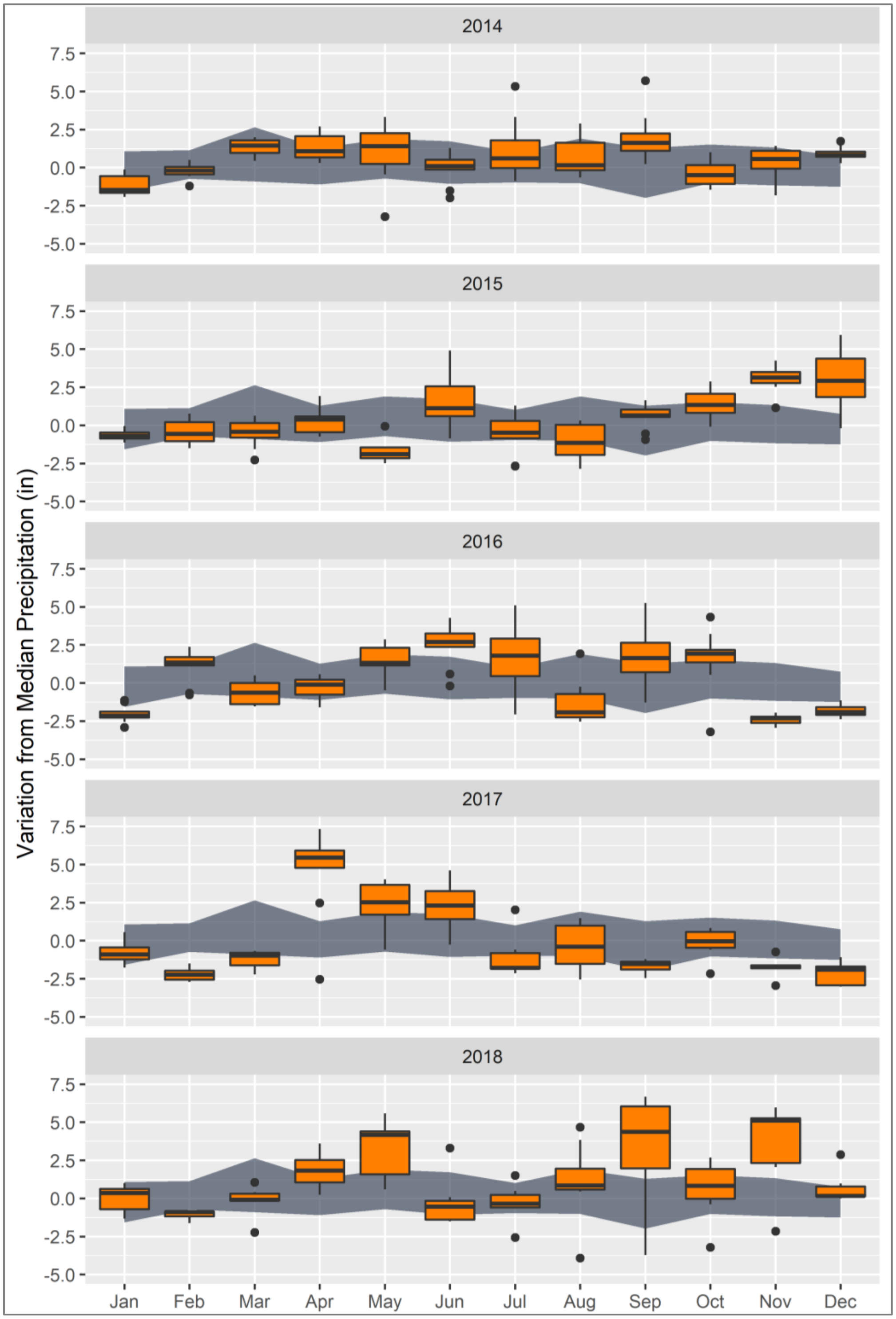


Figure 3-3. Variation from 30-Year Normal Monthly Precipitation Totals in the Falls Lake Watershed

The darker shaded region contains the 25th to 75th percentile range of departures from the 30-year normals for each month of the year. The orange boxes display the 75th (top), median (horizontal line), and 25th percentiles (bottom) of the departure from the same monthly medians at a series of weather stations across the watershed. Whiskers extend to the range of observed values; statistical outliers are displayed as black circles. 30-year median monthly rainfall totals range from 2.9 inches in February to 4.4 inches in July.

Figure 3-4. Observed Falls Lake Elevation from January 2014 through December 2018
Median values (dashed line) and percentiles are based on data 1987 to present.

The UNRBA Path Forward Committee expressed interest in seeing the relationship between long-term lake levels and those assessed by DWR in its EFDC modeling effort that was used to develop the Falls Lake Nutrient Management Strategy. Figure 3-5 shows lake levels for the DWR modeling period (March 2005 through September 2007), but the baseline year used to set the Falls Lake Nutrient Management Strategy nutrient load reduction targets was limited to 2006 (2006 was the only complete year of monitoring and modeling within the 3-year baseline period and there were some issues with DWR chlorophyll-a analysis that affected use of data from 2005). The region was experiencing a relatively severe drought during the modeling period, and lake levels were at or below median values from March 2005 through May 2006 and from May 2007 through December 2007. A small number of large storms, including Tropical Storm Alberto in June 2006, brought the lake levels up from June 2006 through April 2007. Because lake levels preceding these events were relatively low, much of the nutrient loading delivered to the lake from these storms was stored for extended periods of time and likely contributed to some of the highest chlorophyll-a concentrations measured in the lake over the past two decades. When lake levels are at or above normal, as with much of the more recent monitoring period, the residence time in the lake is generally shorter (because the USACE typically opens the spillway more at the dam) and algal concentrations tend to be lower. While 2014 to 2018 were 7 to 14 percent wetter than the 30-year average, the second half of 2017 was relative dry as demonstrated by the lake levels remaining along the median value without the fluctuations observed in the other years (Figure 3-4). Chlorophyll-a concentrations tended to be higher than the other recent monitoring years.

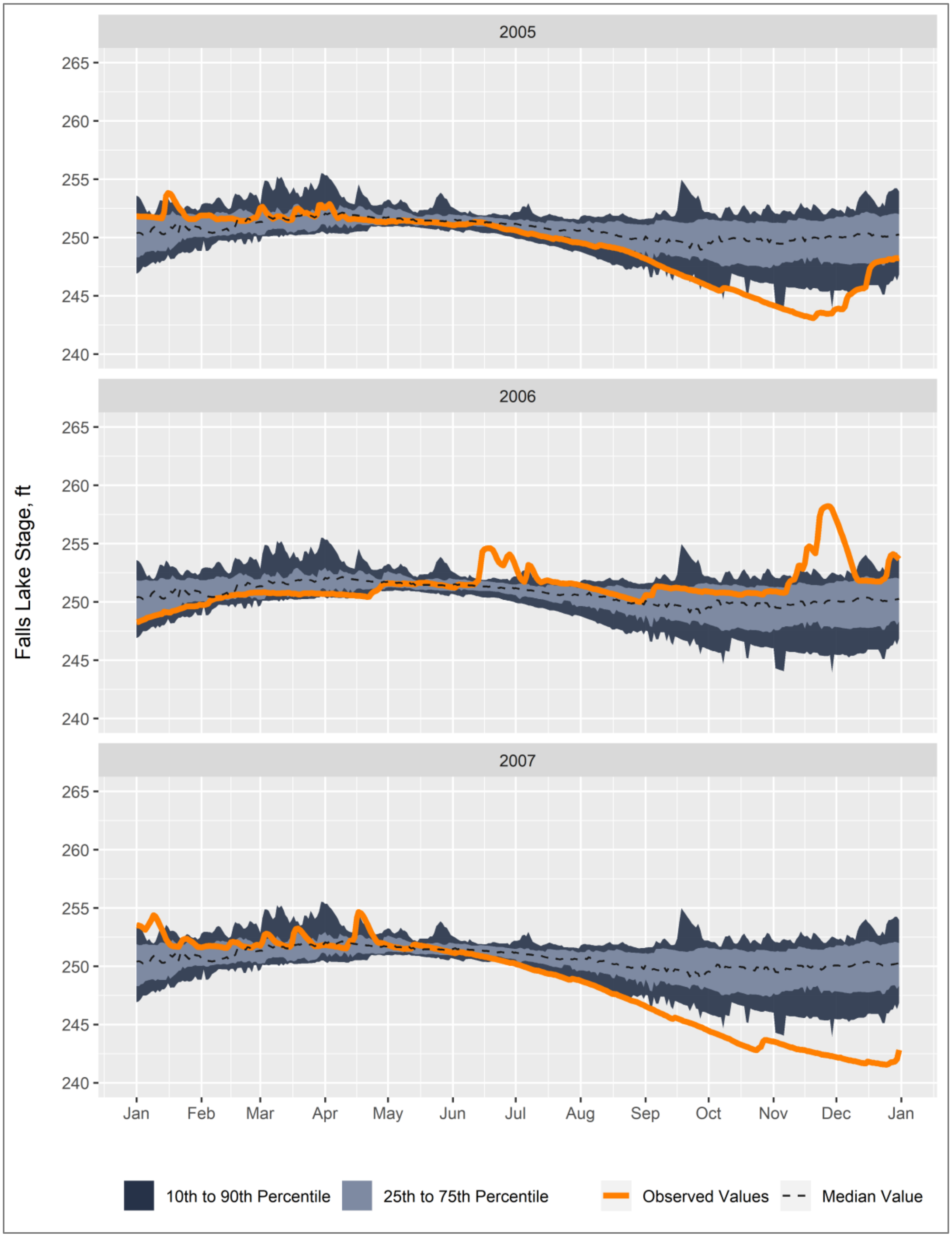


Figure 3-5. Falls Lake Elevation (stage) in Feet Above Mean Sea Level for the Period of DWR's EFDC Model Years 2005 through 2007 (Orange Line)

The historical median (dashed line) and reference ranges (shaded regions) for each day of the year are shown for 1987 through the present.

3.3 Overview of Routine Monitoring Results

This section offers a concise presentation of data for most of the parameters in the Monitoring Program. Most data values are reported as concentrations, which are expressed as milligrams per liter (mg/L) or micrograms per liter (µg/L).

The graphics and text below are intended to provide a general understanding of the water quality parameters and their context based on data observations during the monitoring period. Data are presented for all tributary stations first. Later, JB stations are placed in context with corresponding downstream LL stations. Section 3.3.2 also displays data from the LL stations, but instead places it in the context of Falls Lake water quality. In addition, preliminary comparisons of water quality related to compliance with water quality standards are also provided.

3.3.1 Tributary Stations

The UNRBA Monitoring Program includes at least one station near the mouth of each of 18 tributaries that drain to Falls Lake (Figure 2-1). These 18 stations are referred to as Lake Loading stations and station names include the "LL" designation. Larger tributaries include additional stations in upstream areas of the watershed situated near county lines and municipal boundaries. These Jurisdictional Boundary stations include the designation "JB." The series of graphics below provides a concise view of data from the JB and the LL monitoring stations between August 2014 and October 2018. Figures include UNRBA tributary monitoring stations as well as seven tributary sites monitored by DWR. Box and whisker plots represent a statistical summary of the data, but each data point is also superimposed to indicate the full distribution of the data. To highlight data collected since the previous Annual Report (BC 2018), results from samples collected from January through October 2018 are shown in white, while outliers from previous results are shown in black. Observations below each parameter's reporting limits are shown as a red plus (+) symbol at the reporting limit.

Within each figure, data are grouped by subwatershed and shaded based on the monitoring agency that collected the samples. Within each group, stations on the same tributary are displayed from the most upstream to the most downstream location. This arrangement allows quick inspection of whether spatial patterns are present. Table 2-2 provides a list of all tributary stations using the same station identifiers. All stations have had data collected over the full monitoring period, except in the Flat River watershed where monitoring at station NFR-37 was suspended in June 2015 due to access and safety concerns and replacement station NFR-41 began in July 2015.

Each parameter is presented below, along with general observations of patterns noted. Two parameters (dissolved oxygen and pH) monitored by the UNRBA at JB stations have numeric water quality criteria. The graphs below for those parameters indicate the level of the applicable state criterion for each parameter.

- **Dissolved oxygen (DO)** represents the amount of oxygen in the water available for respiration by aquatic organisms. Oxygen concentrations in surface waters can naturally range from 0 to 15 mg/L or higher. Observed oxygen concentrations are typically the result of a combination of physical and biological features. On the physical side, water temperature constrains the capacity of water to hold on to oxygen. Water can hold more than 14 mg/L of oxygen near freezing, but at 60°F, that is reduced to 10 mg/L, and at 78°F, water is saturated with oxygen at just 8 mg/L. Oxygen molecules exchange between the air and water such that, absent other factors, the oxygen concentration in the water approaches its temperature-based equilibrium. But, algae, bacteria, and other aquatic organisms can cause DO levels to rise above or fall below these saturation values through photosynthesis and respiration. As the concentration diverges from the waterbody's saturation point, physical processes work toward bringing the DO concentration back into equilibrium with the atmosphere. The aeration from fast moving, turbulent streams can bring the water back to equilibrium relatively quickly, but in the case of calm or even stagnant water, the oxygen exchange across the water surface can happen very slowly leaving the concentration to be driven primarily by biology. Bacteria breaking down decaying organic matter can draw oxygen levels down to very low levels. If atmospheric exchange is slow (as in the case of stagnant water), these depleted oxygen concentrations can persist for long periods of time unless replenished through photosynthesis by algae and plants, or a hydrologic event flushes the system. This ongoing give-and-take between physical and biological factors drives the variability observed among streams and within different areas of the reservoir.

Measured oxygen values are presented in Figure 3-6. The vast majority of DO concentrations were between 5 and 12 mg/L but tended to be lower at locations with slower-moving water or large wetland complexes, including Beaverdam Creek, Robertson Creek, Unnamed Tributary to Falls Lake, and Ledge Creek. The wide range of values observed within single stations is also explained by the underlying physical and biological factors described above. Nearly all the oxygen concentrations above 10 mg/L occurred during cold months with water temperatures below 60°F. The lower values tended to be observed in summer and fall when water temperatures were at their highest and the capacity of water to hold oxygen was at its lowest. Already low oxygen concentrations were exacerbated by warm and dry conditions which caused discharge from the creeks listed above to slow drastically. As a result, there were times when these monitoring locations were essentially stagnant pools of warm water in which bacterial decomposition of organic matter (which uses oxygen) could flourish.

Within some tributaries, an interesting difference was observed between the JB and LL stations. Compared to upstream JB stations, the LL stations on Flat River, Little River, and Ledge Creek all had lower DO concentrations than stations upstream on the same tributary network. For all three of these tributaries, the LL stations are located below reservoirs (Lake Michie, Little River Reservoir, and Lake Rogers, respectively) and the JB stations are above the reservoirs. Compared to the contributing streams, the reservoirs offer a different set of factors affecting oxygen concentrations, including physically slowed water, reduced turbulence, and an ecosystem capable of supporting more stable communities of algae and other planktonic organisms. These differences could have contributed to the lower DO observed downstream of the reservoirs. Alternatively (or in conjunction), reduced discharge from some reservoirs as they captured the water from upstream could have caused downstream conditions to become drier with slower moving water, also capable of leading to reduced oxygen concentrations. Monitoring stations which are not separated by reservoirs appear to have very similar DO concentrations (e.g., stations upstream of Lake Michie on the Flat River and its tributaries, Eno River, and the Horse Creek stations).

- **pH** is a measure of acidity or alkalinity using a log scale of 0 to 14. Various metabolic functions of aquatic organisms, as well as biogeochemical processes, can be affected by pH. Most fresh water bodies have pH levels near the middle of the pH scale (7), and North Carolina water quality criteria requires that pH be between 6 and 9. Field measured values of pH at the JB and LL stations are almost always within this range, with most values falling between 6.5 and 7.5 (Figure 3-7).

- **Specific conductance** is a measure of the ability of water to conduct electricity and is commonly used as a surrogate for the amount of dissolved ionic substances in the water such as sodium, chloride, magnesium, potassium, calcium, and others. These minerals occur naturally in water due to weathering of soils. Field-measured specific conductance values at the JB and LL stations are generally consistent throughout the watershed (Figure 3-8), with most values lying between 75 and 200 microsiemens per centimeter (µS/cm). Higher ranges of values tend to occur downstream of major wastewater treatment plants (WWTPs) and small package plants (e.g., Knap of Reeds, Ellerbe, and Upper Barton Creeks).

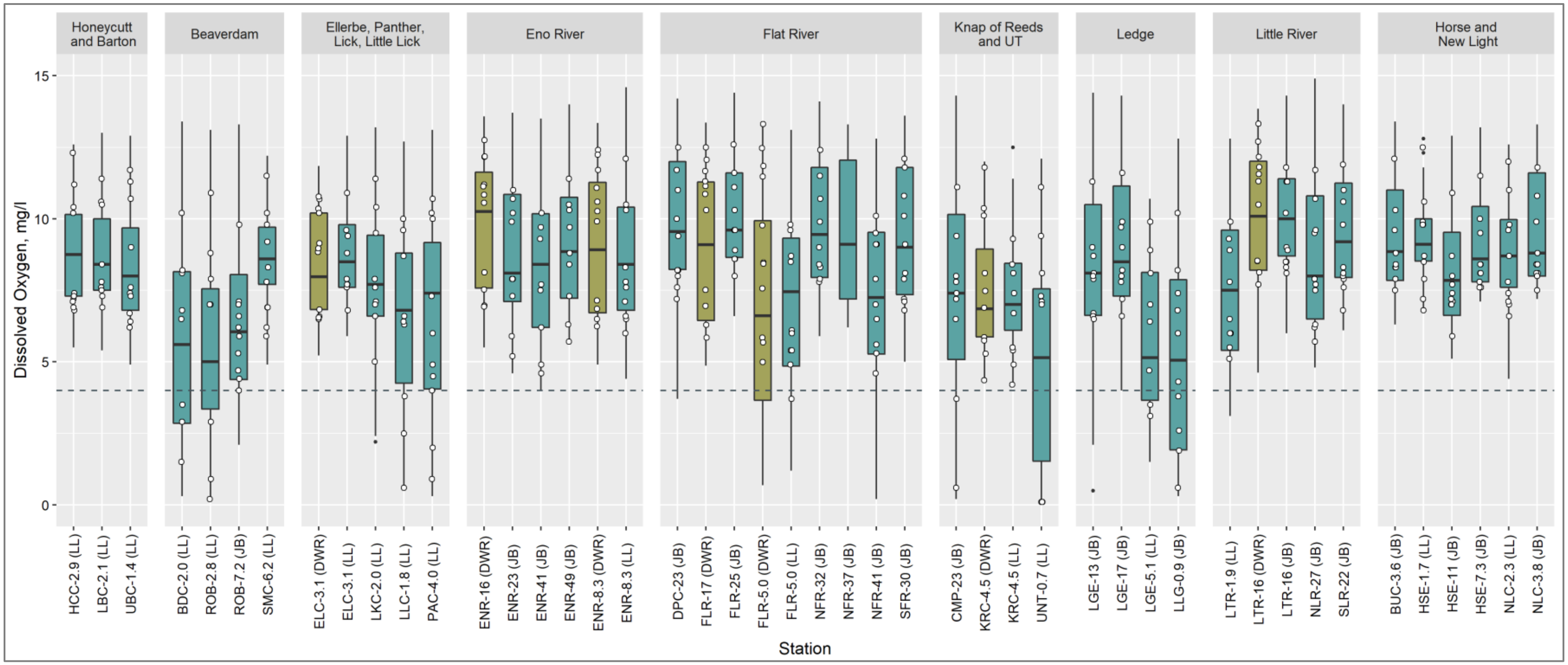


Figure 3-6. Dissolved Oxygen in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

The State's instantaneous dissolved oxygen criterion of 4 mg/L is shown as a horizontal dashed line.

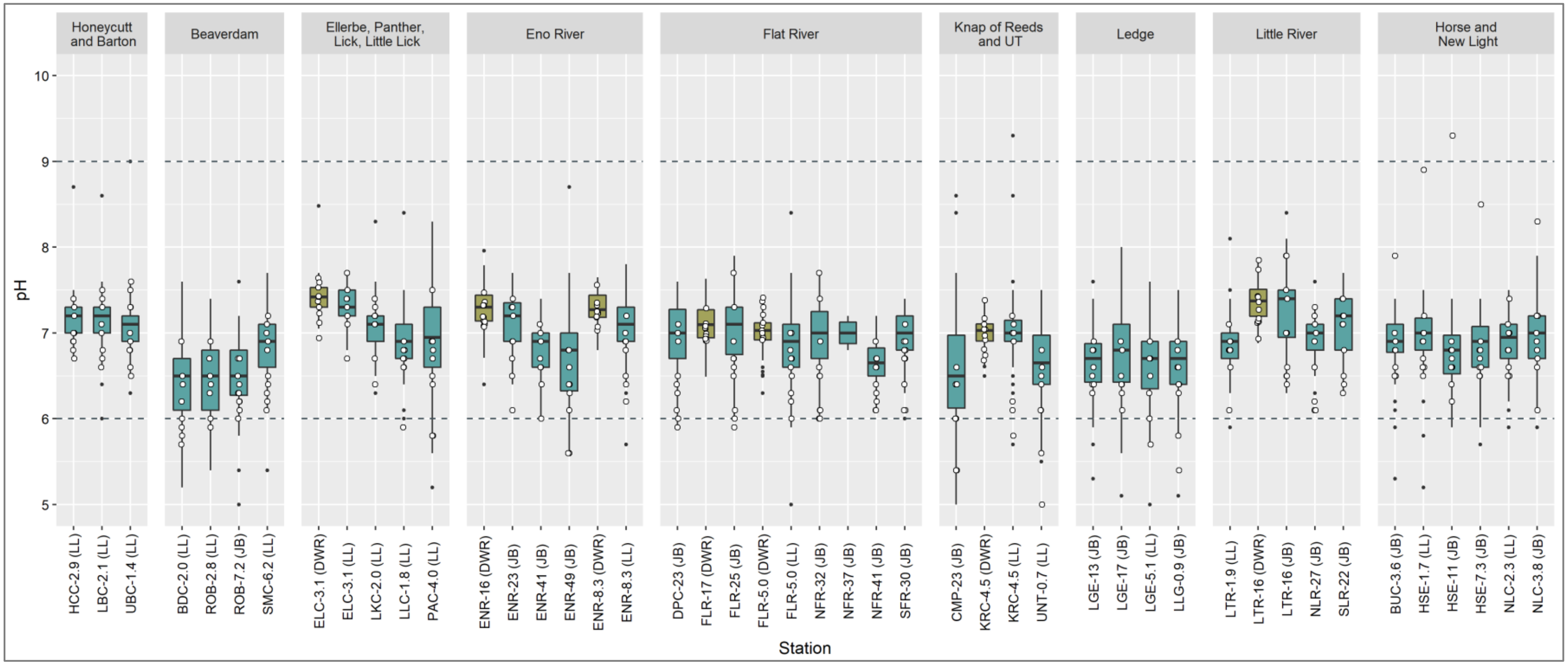


Figure 3-7. pH in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

The State's upper and lower pH criterions are shown as horizontal dashed lines at values of 9 and 6.

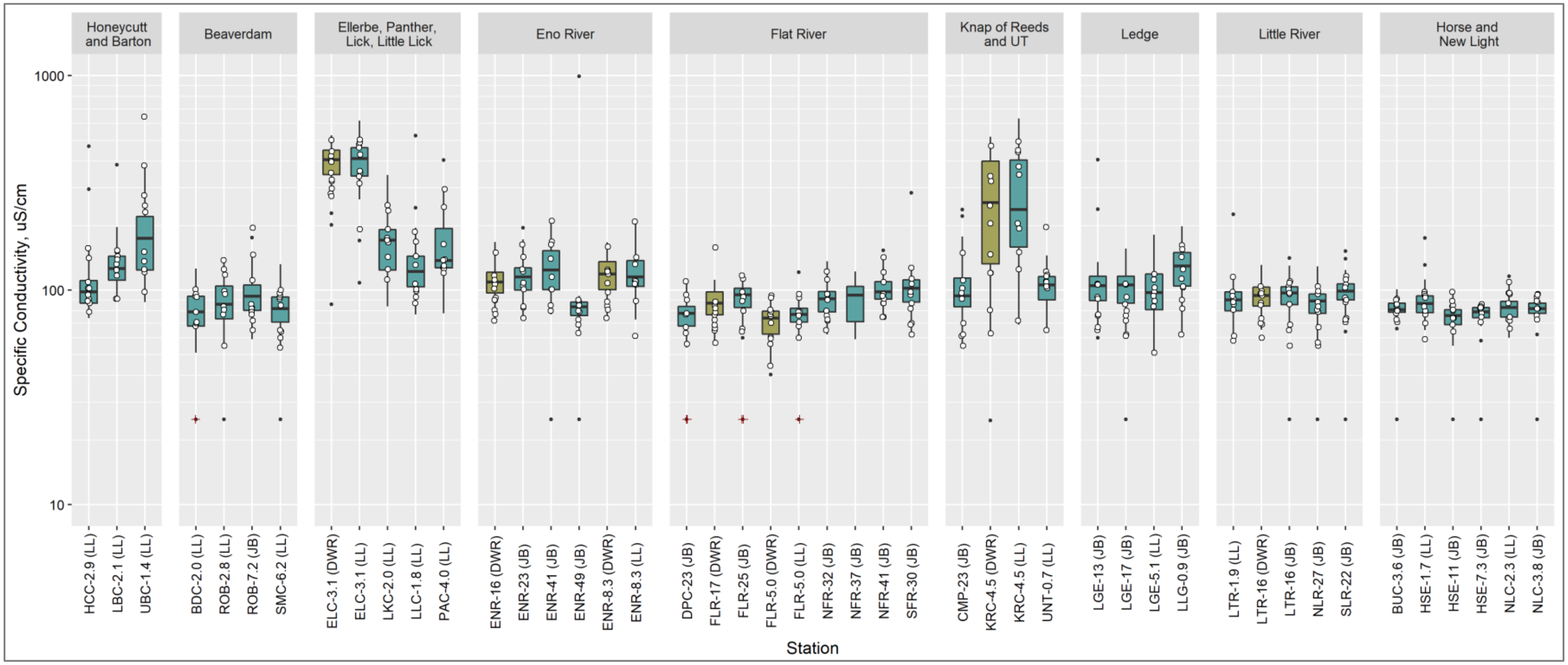


Figure 3-8. Specific Conductivity in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

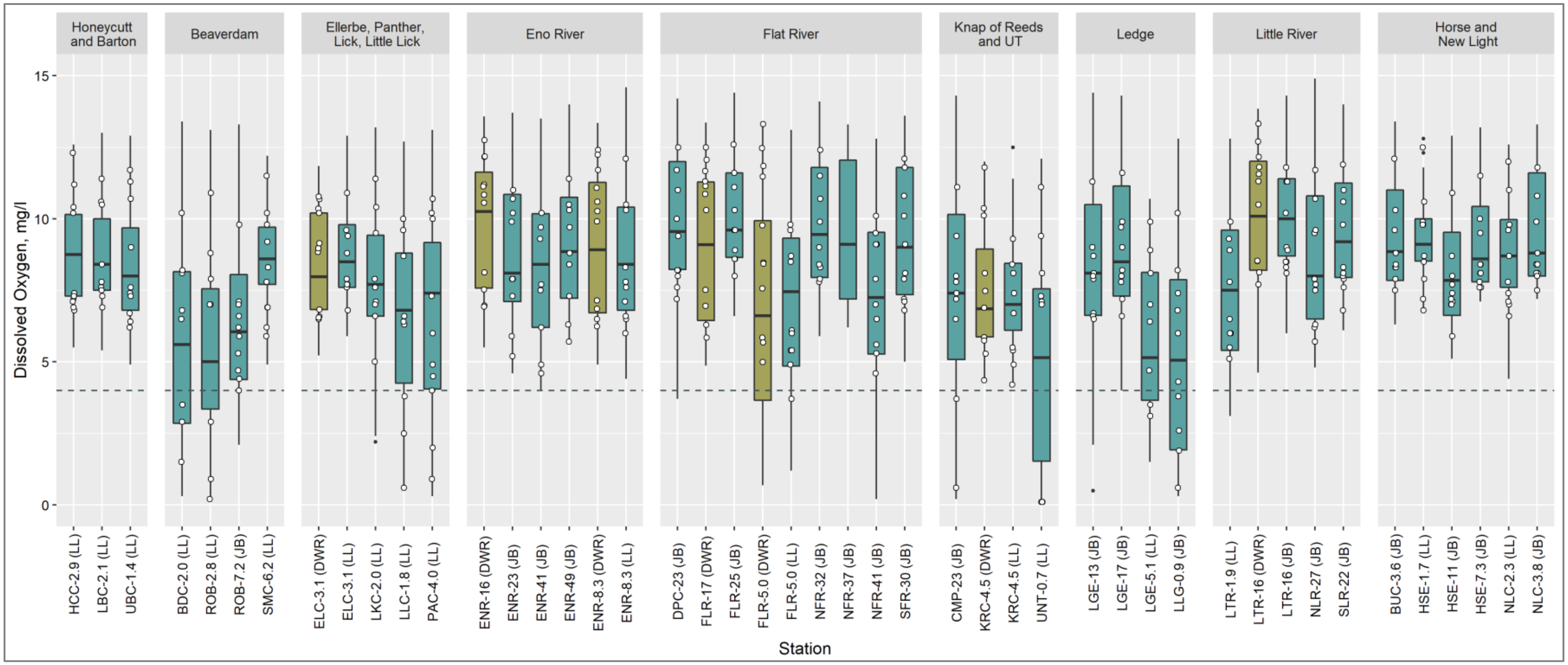


Figure 3-6. Dissolved Oxygen in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

The State's instantaneous dissolved oxygen criterion of 4 mg/L is shown as a horizontal dashed line.

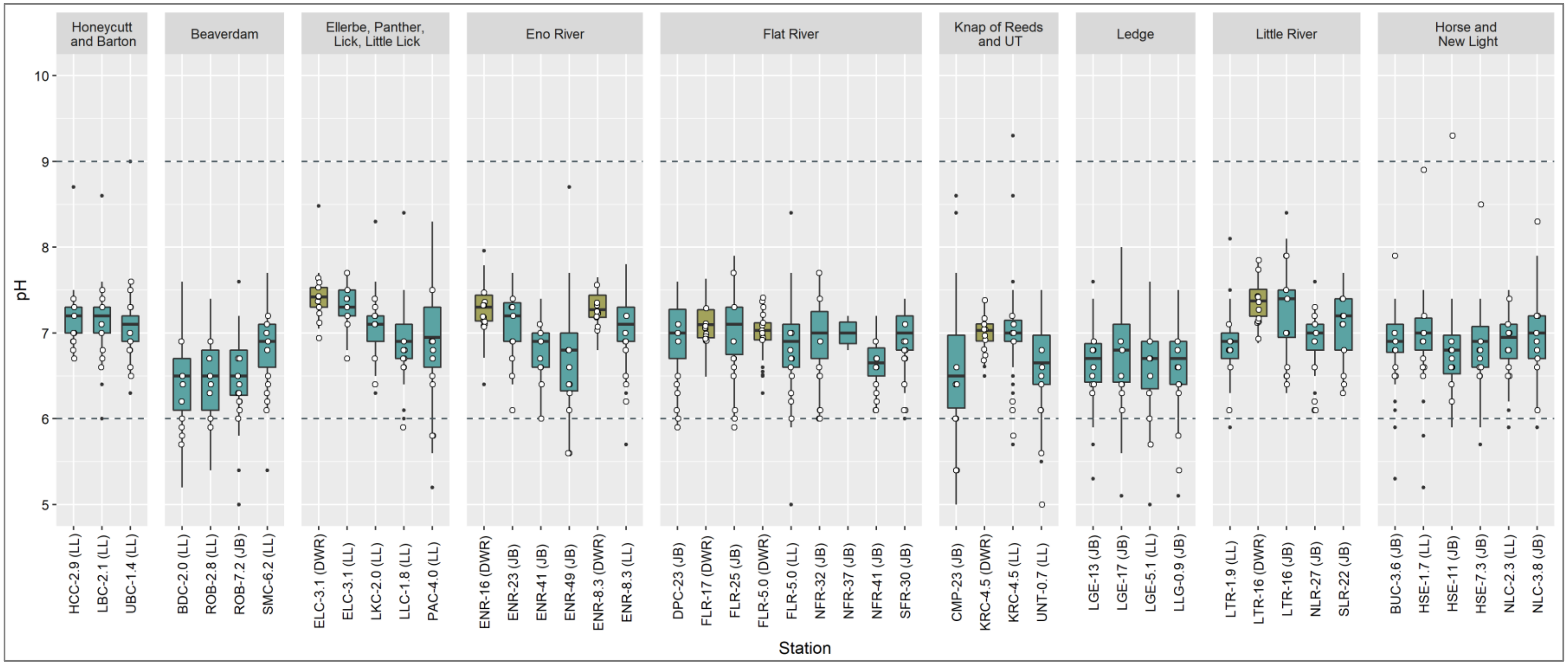


Figure 3-7. pH in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

The State's upper and lower pH criterions are shown as horizontal dashed lines at values of 9 and 6.

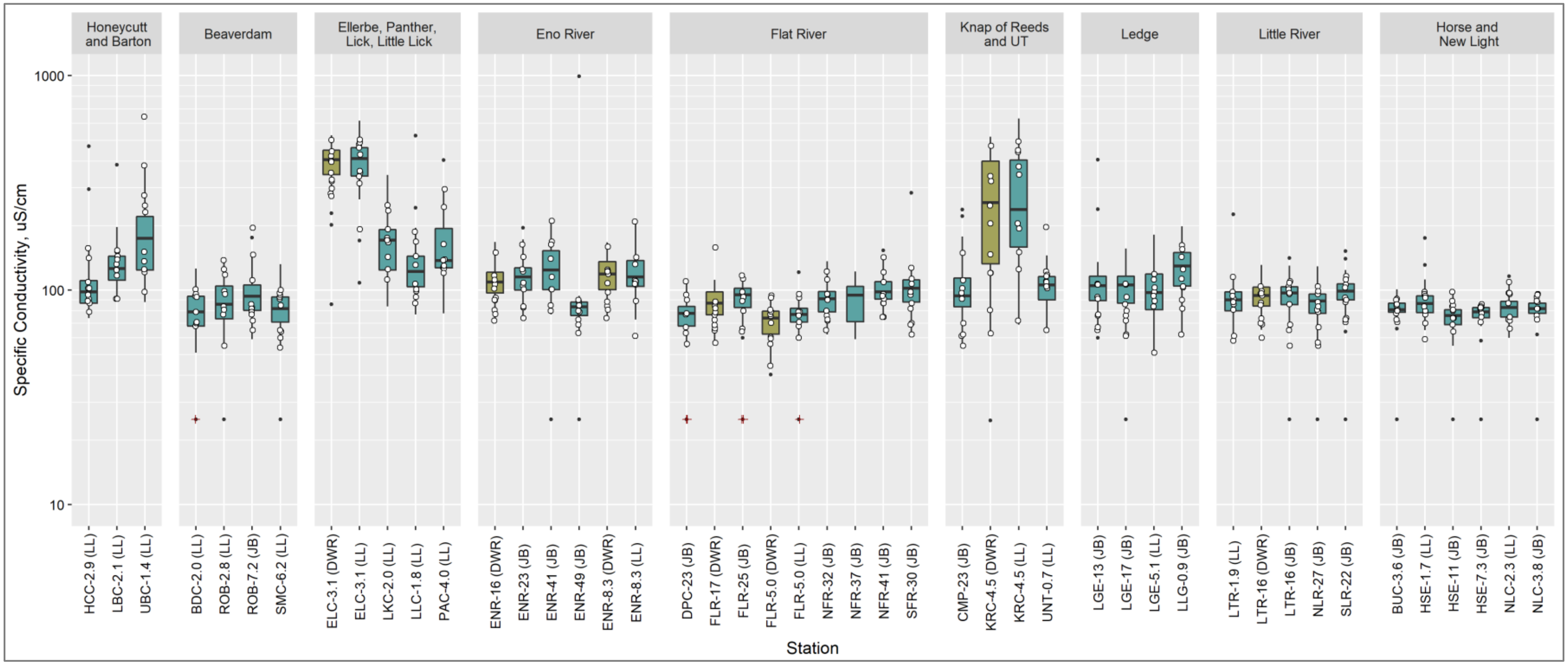


Figure 3-8. Specific Conductivity in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

- **Nitrogen** is an essential nutrient for all forms of life. Nitrogen generally comes from sources such as atmospheric deposition, surface runoff of rainwater, shallow groundwater, discharge from WWTPs or onsite disposal systems, residential or agricultural fertilizer, and manure. Nitrogen occurs in water in organic and inorganic forms. Organic nitrogen is in living organisms (including algae) and decomposing and sequestered organic matter. Inorganic forms include ammonia, nitrate, and nitrite which are more easily used by algae than organic forms. Some forms of organic nitrogen are resistant to biological processing and are virtually unavailable as a nutrient for algae. Total nitrogen (TN) is calculated as the sum of total Kjeldahl nitrogen (TKN) and nitrate+nitrite. TN at tributary stations is presented in Figure 3-9, nitrate+nitrite in Figure 3-10, ammonia in Figure 3-11, and organic nitrogen in Figure 3-12. Higher ranges of values for nitrate+nitrite and TN tend to occur downstream of major WWTPs and small package plants; higher values of ammonia and organic nitrogen occur downstream of these facilities and in areas dominated by very slow flowing, wetland conditions. Organic nitrogen (less available for assimilation by algae) comprises a substantial fraction of the TN observed. Ammonia (most available for algal uptake) is generally the smallest fraction of TN.

- **Phosphorus** is an essential nutrient that often enters water bodies in association with soil, because phosphorus tends to bind with soil particles (particularly with clay soils common in the Piedmont). Phosphorus is also a component of stormwater runoff, shallow groundwater, discharge from WWTPs or onsite disposal systems, fertilizers, and manure. TP includes the ortho-phosphate fraction which is the most available form for algal production. Most values at tributary stations were less than 0.1 mg/L, with higher values downstream of major WWTPs and in areas dominated by very slow flowing, wetland conditions (Figure 3-13). The highest concentrations were observed downstream of the South Granville Water and Sewer Authority (SGWASA) WWTP (KRC-4.5) in 2015. During this period, SGWASA had been undergoing WWTP upgrades and experienced some operational disruptions that resulted in relatively high concentrations. Data collected in 2016 through2018 did not have similarly high values.

- **Total suspended solids (TSS)** represent the amount of particulate material suspended in the water column. Most measured values were less than 10 mg/L, but there was notable variability among stations and between rainfall events within the stations (Figure 3-14). Stations draining relatively small watersheds and those located in very slow flowing areas tend to have higher concentrations of TSS. Sample collection following rain events is expected to result in samples with higher TSS associated with the increased turbidity and sediment transport.

- **Total organic carbon (TOC)** is a measurement of all organic forms of carbon in a water sample—living and non-living, particulate and dissolved. TOC is often used as a non-specific indicator of water quality. TOC in a water sample includes algae and other microorganisms, small fragments of decaying animal or plant material, and animal waste. The amount and characteristics of TOC can affect treatment costs for drinking water. Figure 3-15 shows the TOC data collected in tributaries of Falls Lake. TOC values were observed between 2 and 10 mg/L at most stations, with values ranging up to 20 mg/L in areas dominated by very slow flowing conditions and wetland complexes. Despite WWTP sites generally having higher nitrogen, phosphorus, and conductivity (all of which can be indicators of the presence of a WWTP), they do not have elevated TOC concentrations. This is unsurprising given that the treatment process is designed to remove most of the organic matter before it is discharged into receiving waters.

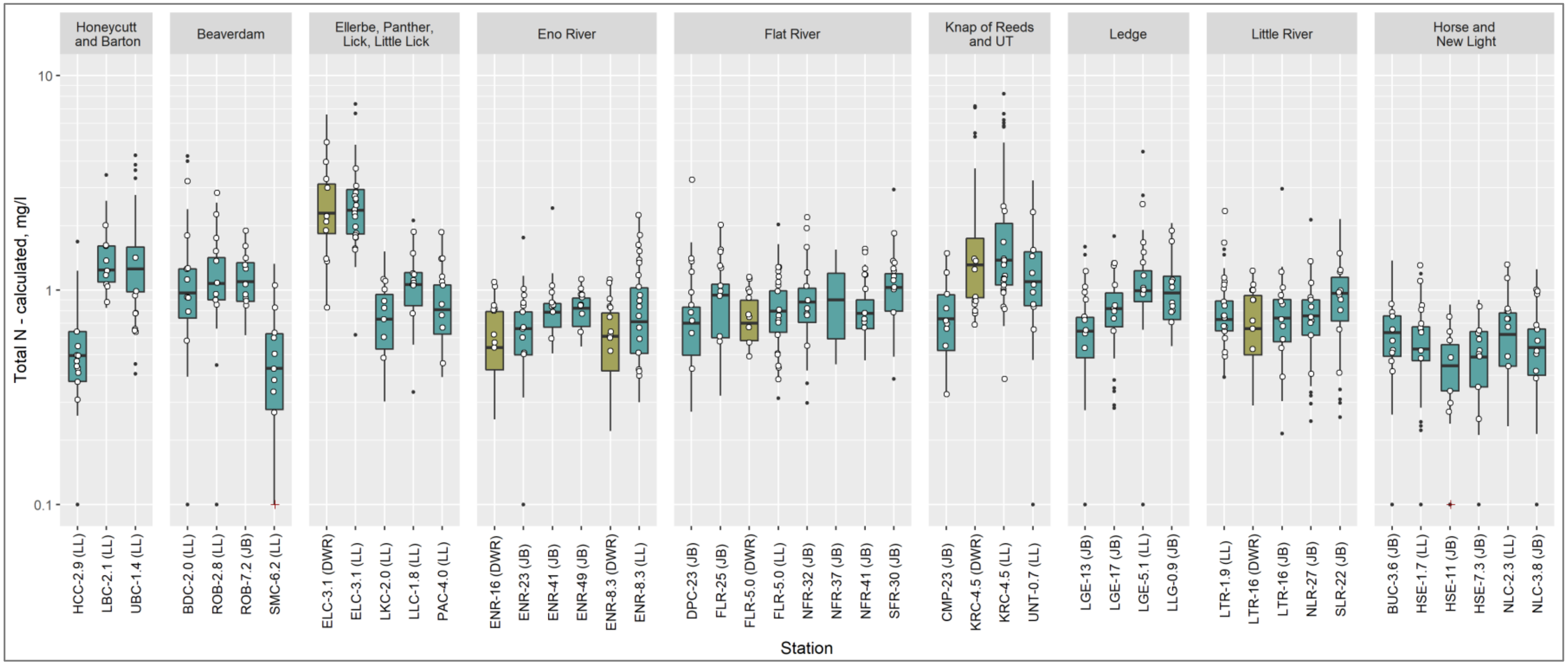


Figure 3-9. Total Nitrogen in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

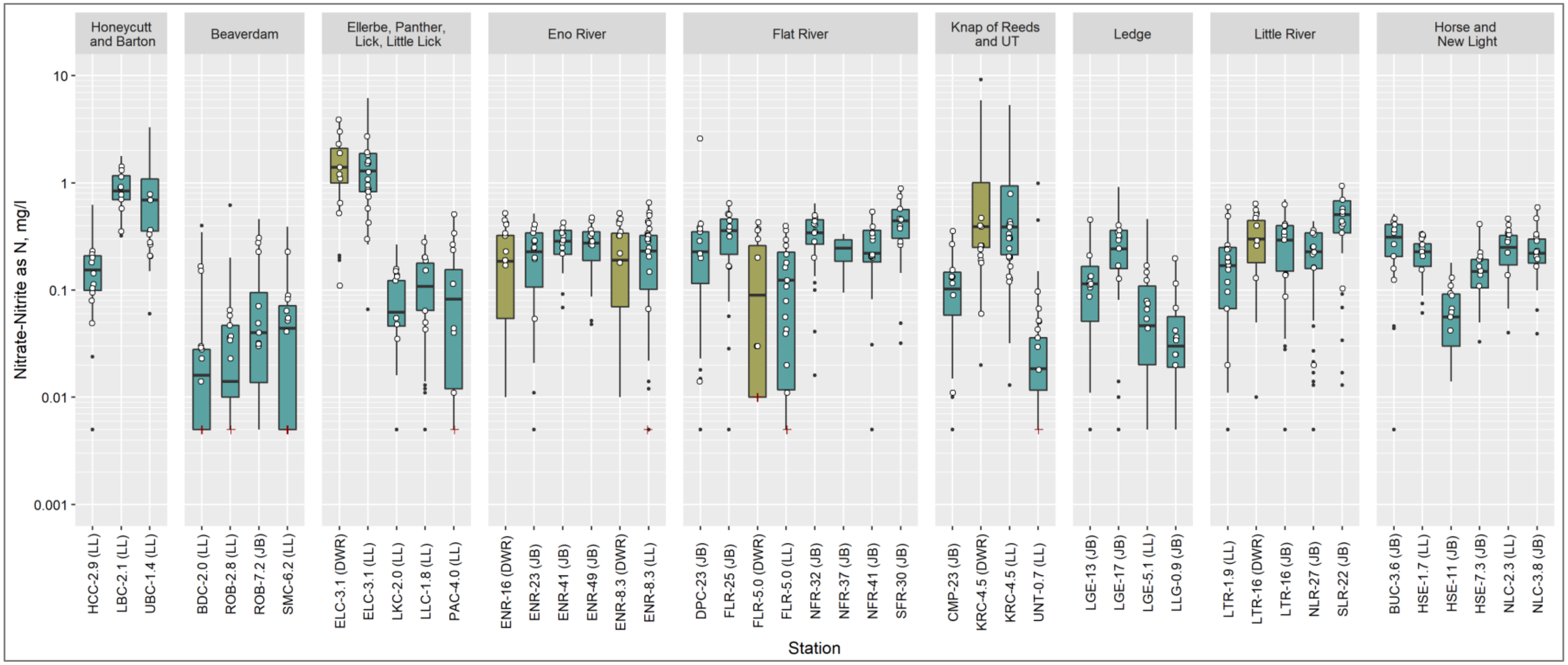


Figure 3-10. Nitrate+nitrite in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

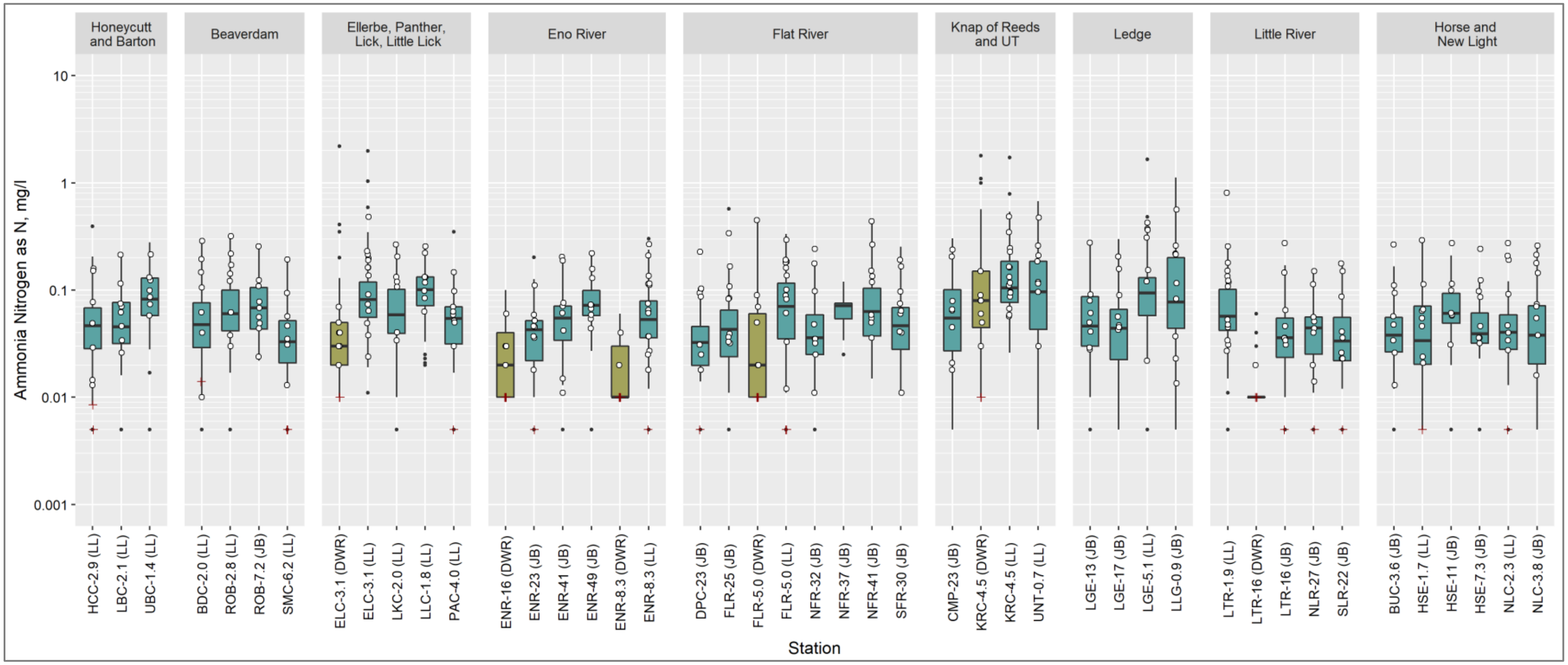


Figure 3-11. Ammonia in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

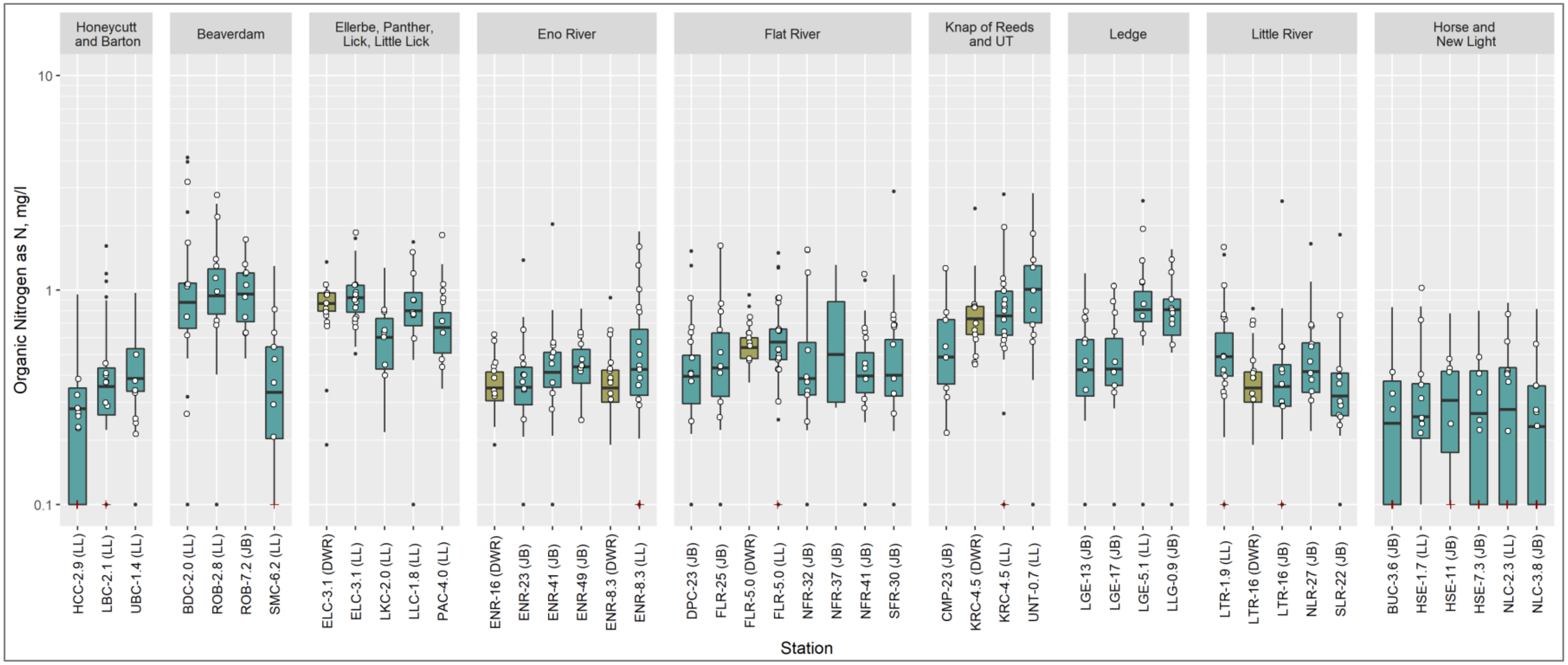


Figure 3-12. Organic Nitrogen in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

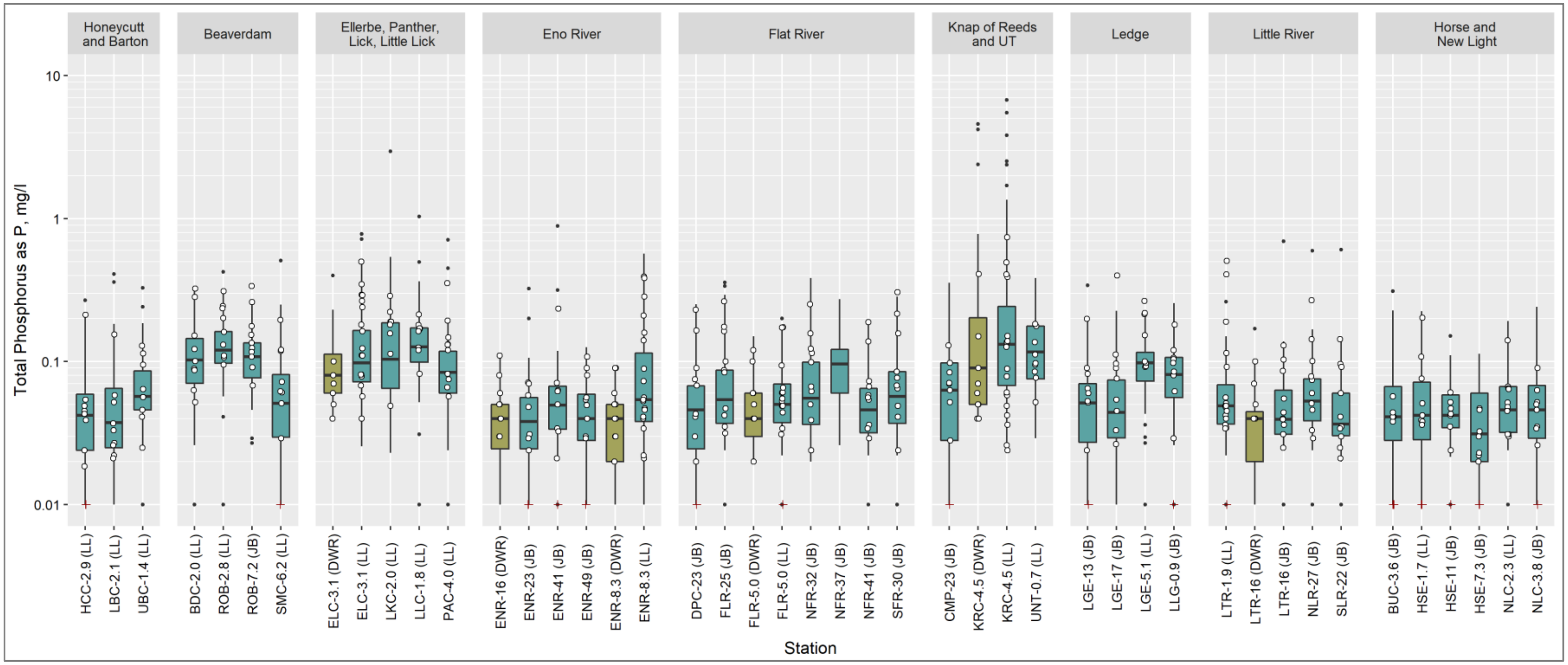


Figure 3-13. Total Phosphorus (TP) in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

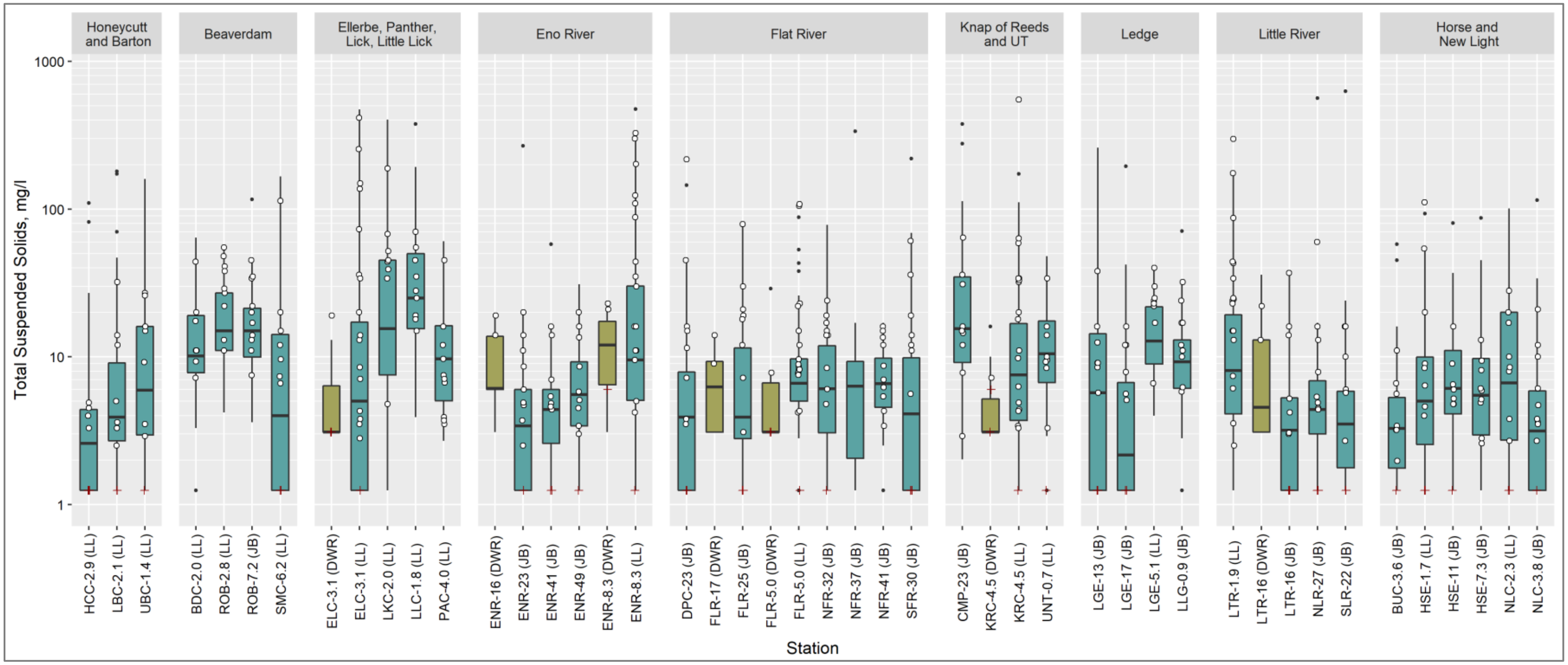


Figure 3-14. Total suspended solids (TSS) in Jurisdictional Boundary and Lake Loading Samples from August 2014 to October 2018

Note that the y-axis is displayed using a logarithmic scale.

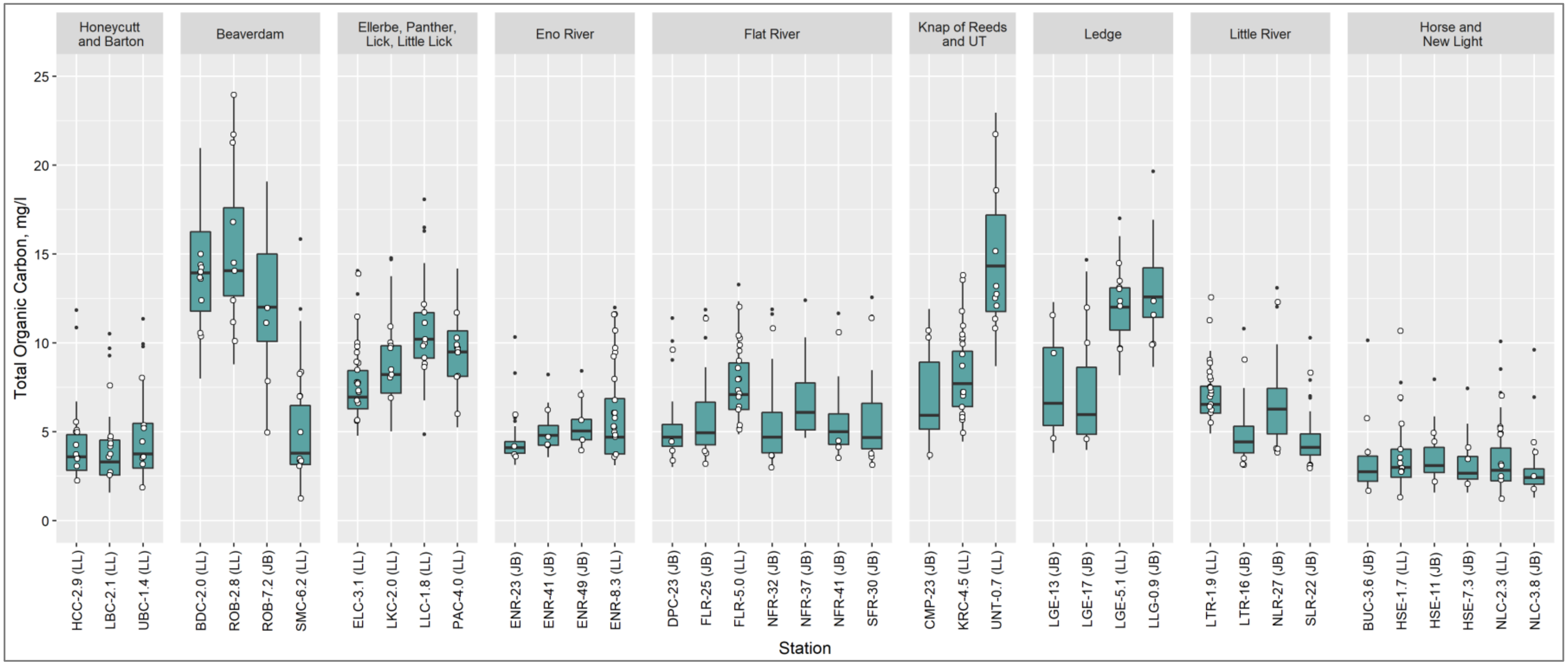


Figure 3-15. Total Organic Carbon (TOC) in Jurisdiction Boundary and Lake Loading Samples from August 2014 to October 2018

3.3.2 Lake Loading and In-Lake Water Quality Stations

The series of graphics below provides a comparative view of the data from the tributary LL stations and the in-lake DWR, CAAE and City of Durham stations between August 2014 and October 2018. Box and whisker plots represent a statistical summary of the data, with data points from 2018 superimposed to allow a visual assessment of substantial changes between 2018 and the prior years. They provide an overview of water quality for water entering the lake and within the lake itself. Box and whisker plots illustrate median and percentiles statistics. Elements of the boxes and whiskers above the reporting limit are not affected by differences in reporting limits. Thus, median values shown on the boxes can be compared across all stations.

Tributary stations are grouped on the left side of figures and in-lake stations are on the right side. Stations are presented from the top of the lake at the left toward the dam on the right. This layout facilitates visual assessment of spatial patterns among the tributaries or from upstream to downstream in the lake, and of apparent differences between tributary and in-lake concentrations. Only stations with data for each given parameter are displayed, thus there is variation in the number of stations displayed for each graph.

Lake data come from photic zone composite samples. DWR lake data consist of monthly values from the same monitoring period as the LL stations. City of Durham data are included for comparison but consist of weekly measurements from April through October and only after 2015 when their QAPP was approved by DWR. Nutrient and chlorophyll-a data from some CAAE stations (FL01-06) are limited to values since April 2016 when CAAE began collecting photic zone composite samples at these sampling sites; CAAE stations that include “C” in the name have data as photic zone composites for the entire UNRBA monitoring period.

Lake data are collected by several organizations with different sampling methods, frequencies, and at different locations. Collectively, this data provides a comprehensive data set for the modelers to utilize moving forward.

Reporting limits are shown as horizontal lines under the bar charts when available. Reporting limits are set by individual laboratories and monitoring projects and thus may be different across the stations displayed. All results reported by the lab as below reporting limits are displayed as the reporting limit. Observations below the reporting limits are shown as a red + symbol at the reporting limit. When more than half of the measured values fall below the reporting limit, the median is displayed at the reporting limit and indicates that the median is at or below the specified limit. Three parameters have numeric water quality criteria (dissolved oxygen, pH and chlorophyll-a). Graphs for these parameters show the state’s numerical criteria.

- **Dissolved oxygen** measurements at LL stations and in-lake stations are provided in Figure 3-16. DO levels in the lake and at most LL stations are usually well above the 4 mg/L criterion. LL stations in very slow flowing areas dominated by wetlands tend to have concentrations lower than the criterion due to the combination of slow-moving water and decomposition of organic matter (which consumes oxygen). The two City of Durham stations show DO ranges slightly lower than most other lake stations, which is attributable to the fact that sampling is only conducted during the growing season when warmer temperatures mean water can hold substantially less DO. DWR samples DO in the lake as part of their profile measurements (at discrete depths from the surface to near the bottom of the lake). The box plots show an average of the photic zone profile measurements for consistency with other parameters summarized in this report that are photic zone composites.

- **pH.** Most pH values for in-lake and LL stations fall within the state's criteria range of 6 to 9 (Figure 3-17). Values at LL stations were generally lower than in-lake stations. The higher pH in the lake is likely the effect of algal photosynthesis which acts to raise the pH of water. Lower pH is seen in tributaries with low elevation gradients and slow-moving water as a result of the natural organic acids which are prevalent in wetlands and slow-moving water as a result of the decay and breakdown of once living matter. The box plots show an average of the photic zone profile measurements for consistency with other parameters summarized in this report that are photic zone composites.
- **Specific conductivity** values measured at the LL stations are generally similar to those measured at the in-lake stations, except for locations downstream of major WWTPs and package plants (Figure 3-18). Within the lake, conductivity is somewhat lower at the downstream end than the upstream end. On Figure 3-18, note the difference in reporting limits between the tributary stations (50 µS/cm) and the DWR lake stations (14.9 µS/cm). Only two tributary measurements have been below reporting limits, as indicated by the red plus symbols on the reporting limit line for Flat River and Smith Creek. The box plots shown an average of the photic zone profile measurements for consistency with other parameters summarized in this report that are photic zone composites.

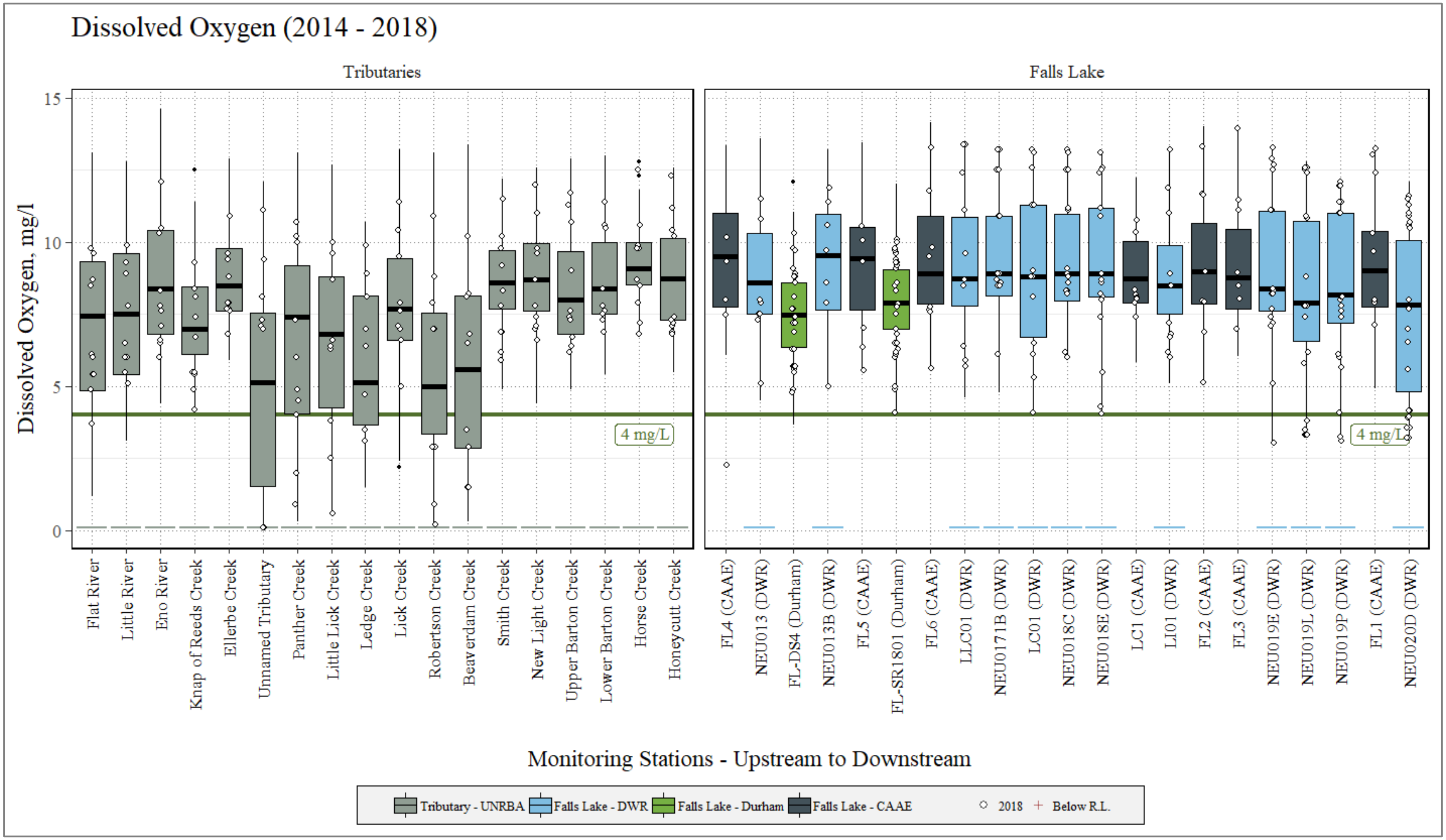


Figure 3-16. Average Photic Zone Dissolved Oxygen in Lake Loading and Lake Samples from August 2014 to October 2018

The State of North Carolina instantaneous dissolved oxygen (DO) criterion of 4 mg/L is shown as green line.
Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.
For this parameter, the box plots shown as an average of the profile measurements collected within the photic zone for the lake data.

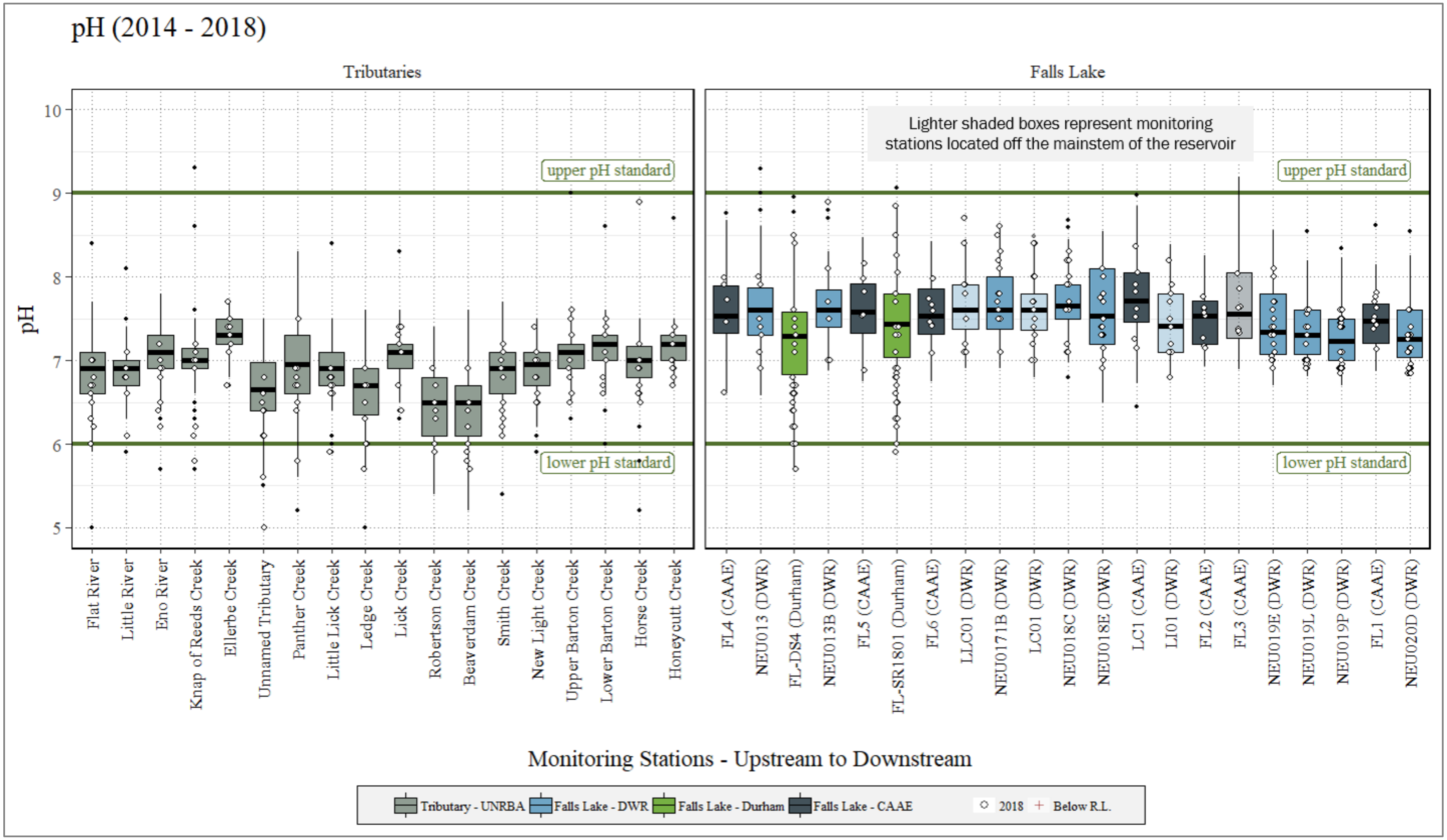


Figure 3-17. Average Photic Zone pH in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure. For this parameter, the box plots shown as an average of the profile measurements collected within the photic zone for the lake data.

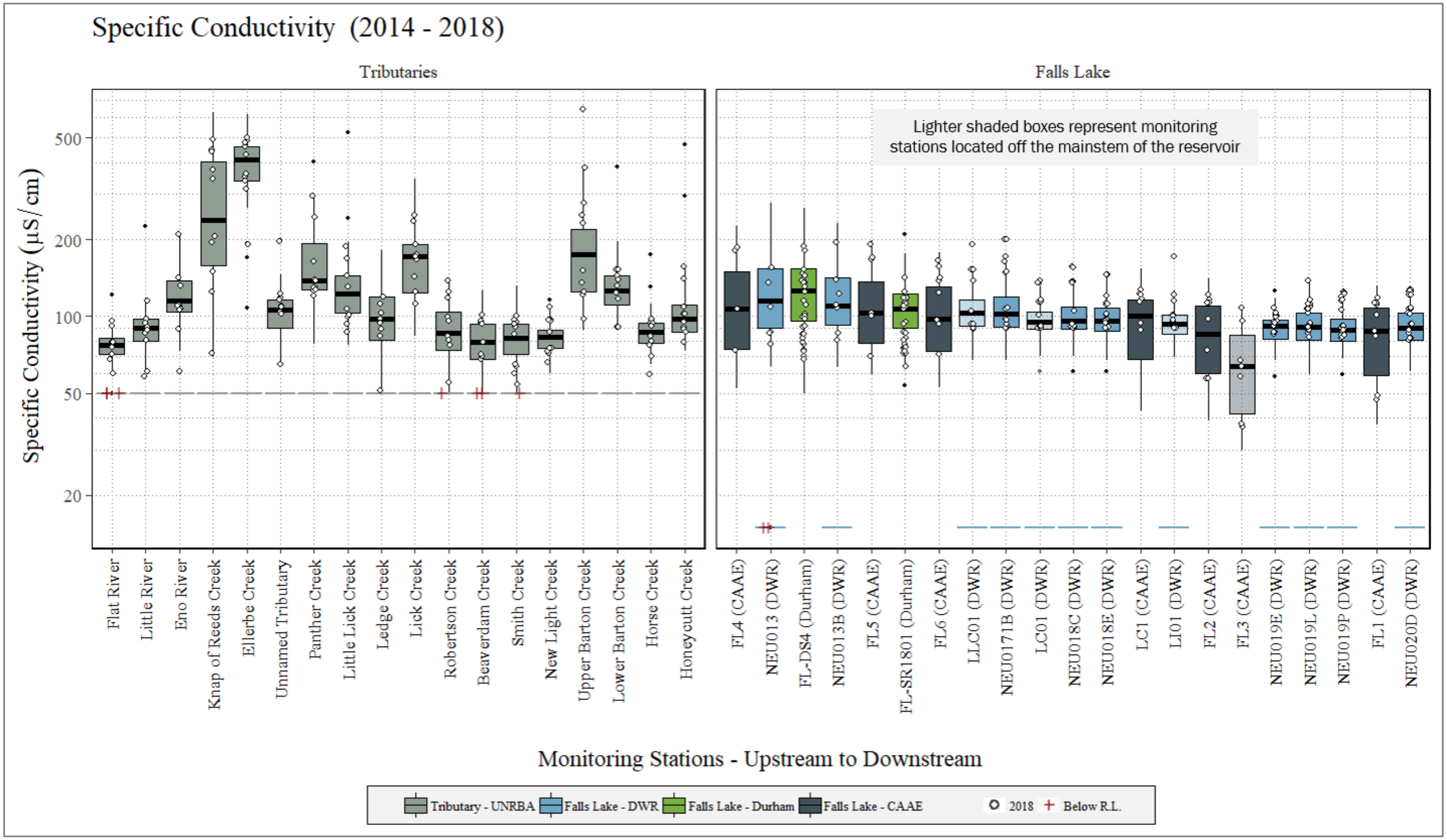


Figure 3-18. Average Photic Zone Specific Conductivity in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

For this parameter, the box plots shown as an average of the profile measurements collected within the photic zone for the lake data.

Note that the y-axis is displayed using a logarithmic scale.

- **Ammonia concentrations** (Figure 3-19) in the lake and watershed are generally less than 0.1 mg/L, and concentrations tend to be higher at the LL tributary stations compared to the in-lake stations. Concentrations of ammonia in the upper lake stations rarely exceed laboratory reporting limits despite being downstream from the tributaries often with the highest concentrations of ammonia. This indicates algae are very rapidly assimilating this form of inorganic nitrogen. Ammonia concentrations in the downstream end of the lake are more often above detection limits, suggesting there are periods of time when algal production in this region is limited by some other resource such as phosphorus. Previous lake modeling conducted by DWR indicate the upper part of the lake is limited by nitrogen approximately 80 percent of the time while the lower part of the lake is limited by nitrogen 40 percent to 50 percent of the time (DWR 2009).

- **Nitrate plus nitrite concentrations (nitrate+nitrite)** (Figure 3-20) are highest at tributary stations downstream of major WWTPs and small package plants. As with ammonia, concentrations within the lake are generally lower than in the tributaries, indicating this form of inorganic nitrogen is also quickly assimilated by algae.

- **Organic nitrogen concentrations** (Figure 3-21) decline from the upper end of the lake to near the dam in an amount which closely corresponds to a similar decline in median chlorophyll-a concentrations. Within the lake, TN concentrations are similar to the concentrations of organic nitrogen, indicating that most of the nitrogen in the lake is bound (sequestered) within living (or once living) organisms. For tributaries, organic nitrogen still contributes the majority of the TN (except for downstream from WWTPs and package plants) but inorganic forms of nitrogen make up a slightly larger portion of total than within the lake. The median organic nitrogen concentrations decline from the upper end to near the dam and corresponds to a decline in median chlorophyll-a concentrations.

- **Total nitrogen (TN) concentrations** (Figure 3-22) in tributaries are greatest downstream of major WWTPs and package plants, and in areas often observed to have slow moving conditions. In these slow-moving areas, the nitrogen is primarily in the form of organic nitrogen. Within the lake, TN decreases from upstream to downstream, and appears to correspond to the pattern seen for organic nitrogen, which is its predominant component.

- **Total Phosphorus (TP) concentrations** - Like TN, TP concentrations (Figure 3-23) at the LL tributary stations are generally higher and more variable than the in-lake stations, with the sites downstream of major WWTPs or located in very slow flowing, wetland areas having the highest concentrations. Within the lake, phosphorus concentrations show a steady decline from the upstream stations to the downstream stations. This suggests the lake is assimilating and storing phosphorus in its sediments.

- **Ortho-phosphate concentrations** (Figure 3-24) are shown for LL stations and the City of Durham stations. DWR does not collect this parameter in the lake because past measurements have indicated concentrations are typically below their reporting limit of 0.02 mg/L. The City of Durham's measurements of total ortho-phosphate all fall below their reporting limit of 0.16 mg/L. Concentrations of ortho-phosphate at the LL stations tend to be higher downstream of WWTPs than at other sites.

- **Chlorophyll-a** is a green pigment in algae that allows them to use energy from the sun to build living tissue through photosynthesis. Chlorophyll-a content is an indication of how much algae is present in the water. While algae are an important component of healthy aquatic ecosystems, too much algae can cause problems with treatability for drinking water, taste and odor problems, or drastic fluctuations in DO and/or pH that can cause problems for aquatic organisms. Chlorophyll-a data from tributary and in-lake stations are presented in Figure 3-25.
  One of the data gaps associated with the DWR monitoring period was a lack of chlorophyll-a data in the tributaries that discharge to Falls Lake. The tributary chlorophyll-a data collected by the UNRBA indicate that concentrations of chlorophyll-a are usually lower in the tributaries compared to Falls Lake (Figure 3-25). When DWR developed their Falls Lake model, this data was not available, and they were required to make an assumption for this model input. DWR assumed that the tributary concentrations were the same as the closest lake monitoring station. Because inlake chlorophyll-a is often much higher than tributary chlorophyll-a, the DWR model assumed large loads of chlorophyll-a were discharged to the lake. The UNRBA has the benefit of this additional data on which to develop and calibrate the lake model. This improvement to the model will be important when scenarios representing different nutrient management strategies are evaluated for the lake's response in terms of algal growth and chlorophyll-a.

  While concentrations in tributaries are generally lower than those observed in the lake, some elevated concentrations are sometimes observed in sluggish, wetland areas. Streams with fast moving water generally do not support large populations of free-floating algae (phytoplankton); rather, algae in these streams is typically found in forms attached to rocks and debris (periphyton) and therefore not collected within a chlorophyll-a water sample. When streams are slow-moving, or stagnant, phytoplankton may become more abundant.

  Within the lake, chlorophyll-a concentrations decrease from the upstream to the downstream end. Of the 987 observations collected by DWR and CAAE (2015 to 2018) above Highway 50 within the upper portion of the lake, 321 (33 percent) exceeded 40 µg/L. Of these exceedances, 26 occurred in the tributary arms of the lake (including Little Lick Creek (LLC01), Lick Creek (LI01), and Ledge Creek (LC01)). In 2018 alone, 83 out of 214 observations (39 percent) exceeded the 40 µg/L criteria stations above Highway 50 with 6 of these exceedances occurring in the tributary arms.

  Of the 572 measurements collected by DWR and CAAE (2015 to 2018) below Highway 50 and within the main channel of the reservoir, 54 exceeded 40 µg/L (9.4 percent). Of the 75 observations in tributary arms of the lake below Highway 50, 19 (25 percent) were above 40 µg/L during these years.

  In contrast with prior years, there were two distinctly elevated peaks in chlorophyll-a throughout the lake during 2017, one in February and the other in May. In both cases, levels dropped rapidly to more typical levels by the following monitoring event. There was a smaller peak in September 2017, but it did not involve all stations. The specific cause of these algal blooms is not known, although one of the two larger occurrences followed a large rain event by several weeks and may have been triggered by inputs of nutrients from that event. Lake levels in 2017 were generally at or below the median with the exception of three precipitation events in the middle of the year. These trends will be further explored by the lake models for Falls Lake. Section 5 includes additional discussion of upstream to downstream trends in Falls Lake, correlations of chlorophyll-a concentrations to nutrient loading and tributary inflows, and comparisons of the recent UNRBA monitoring period to the baseline period (2005 to 2007) and the historic period shortly after the lake was filled.

- **Total suspended solids (TSS)** values are shown in Figure 3-26. TSS concentrations are more variable over time within each tributary than within any lake site. This variation is a result of tributary flow conditions with high flows capable of carrying more material, eroding stream banks, and keeping sediment suspended longer than under low flow conditions. Median TSS concentrations observed in the five tributaries discharging upstream of I-85 are lower than those observed in the lake itself, although values during high flow conditions can be several-fold higher than median lake values. The wide and shallow shape of the upper lake allows for frequent resuspension of sediment, thus keeping TSS concentrations elevated even when inflows from tributaries have low TSS concentrations. Within the lake, TSS declines from median values around 20 mg/L near the Highway 85 Bridge to values less than 5 mg/L near the dam. This difference indicates a loss of TSS to the sediments as water travels downstream; the narrow, deeper shape of the lower part of the lake generally inhibits resuspension.

- **Volatile suspended solids (VSS)** (Figure 3-27) represents the fraction of TSS associated with combustible (organic) material. Monitoring of VSS began in July of 2015 in response to a review specific to a model application. VSS is a measure that includes organisms such as algae and zooplankton as well as dead and decaying material which could be used to support model parameterization and calibration. Within the lake, VSS is typically below DWR's quantitation limit except for the most upstream site near Interstate 85. Here, high chlorophyll-a concentrations and frequent resuspension of organic sediments likely contribute to measurable concentrations of VSS. In all tributaries except Little Lick Creek, more than half of VSS measurements were below reporting limits. Comparing the relatively low or undetectable VSS concentrations to TSS in the tributaries supports the idea that most of the suspended material entering the lake is not organic.

- **Organic Carbon** - Organic matter is a concern in water supply reservoirs because it can react with disinfectants used in water treatment to produce a wide assortment of chemical compounds generally called disinfection by-products (DBP). Some DBP have been recognized since the 1970s and some types are regulated by the United States Environmental Protection Agency (EPA) because of their potential negative health effects. However, hundreds of types of potential DBP exist with very little known about them, their risks, or details of how they form. Given the complexity of organic molecules and the sheer variety in molecular structures, research on DBP is relatively in its infancy.

  High concentrations of organic matter in source water can lead to higher concentrations of DBP and therefore higher treatment costs to reduce their formation, but not all types of organic matter react the same way or yield the same byproducts. Although characterizing the reactivity of hundreds of molecules in a water sample is not possible. Measuring visible and ultraviolet absorbance of water samples at specific wavelengths can provide some insight on the organic matter character.

  Organic matter can be measured as either TOC which includes particulate and dissolved forms or DOC. With respect to DPB formation, DOC is the primary focus. The TOC data shown in Figure 3-27 includes both particulate and dissolved fractions. Based on TOC and DOC data collected in the first two monitoring years, approximately 95 percent of the TOC was consistently in the dissolved form (DOC). Because DOC can be accurately estimated from TOC measurements, and since DOC is a relatively expensive parameter to collect, the UNRBA dropped DOC from the list of parameters collected at LL stations in Fiscal Year 2017 in favor of using TOC as a proxy. As shown in Figure 3-28, TOC concentrations at LL stations in the lower part of the watershed (mostly downstream of Beaverdam Impoundment) are generally lower and less variable than those observed at the other LL stations and within the lake. The highest concentrations are observed at LL stations dominated by wetland complexes and/or very slow flow conditions. Relationships between DOC, TOC, and chlorophyll-a are further discussed in Section 5.

- **Light Absorbance** at 440 nanometer (nm)/Color - Humic matter, often the major organic constituent of soil, can enter lakes through runoff and stream flow with two categories of impact to the reservoir. First, humic compounds can be precursors to disinfection by-products if not removed from water before chemical disinfection. Second, they can impart a yellow to brown hue to the water, and depending on its darkness, it can reduce the amount of light available to algae for photosynthesis. Color can be measured by visually comparing filtered water samples with known Platinum-Cobalt standards. Absorbance of visible light at 440 nm can also be used as an indicator of color since it specifically targets the yellow or brown material typical of humic substances. Because results from the two methods were well correlated, the UNRBA stopped using the more expensive and less precise Platinum-Cobalt method in Fiscal Year 2017. Figure 3-29 indicates that color is higher in tributaries that are slow-moving and most influenced by wetlands. This follows a similar pattern to the TOC concentrations, suggesting that humic substances may be a significant component of the TOC in tributaries. Color in the lake is generally lower than in the tributaries and decreases somewhat from the upper lake to the lower lake.

- **UV Absorbance** at 254 nm can be combined with measurements of DOC to measure carbon-specific UV-absorbance (SUVA) which is used as an indicator of the aromatic (ring-shaped) nature of the DOC structure. This molecular shape is also associated with the formation of DBPs. UV absorbance at 254 nm is presented in Figure 3-30. It presents a pattern similar to absorbance at 440 nm and indicates that humic matter is most prevalent in the tributaries with substantial wetland influence. Values within the lake show a slight downward trend from the upper lake to the lower lake.

- **Specific UV Absorbance** is a metric of the molecular complexity of the dissolved organic matter in a water sample which reflects how easily it can be digested by microorganisms. It is also correlated with the potential formation of disinfection by-products from water treatment. Specific UV Absorbance is shown in Figure 3-31. The SUVA in the lake samples is lower than in the tributary samples (indicating less complex forms of organic matter), consistent with algal production contributing to this material. Tributaries tend have higher (more complex) values, consistent with older, refractory terrestrial organic matter, although sites downstream from WWTPs also have lower values. This data was collected specifically to support development of the empirical model to better understand both the risks and management options associated with disinfection by-products resulting from water treatment.

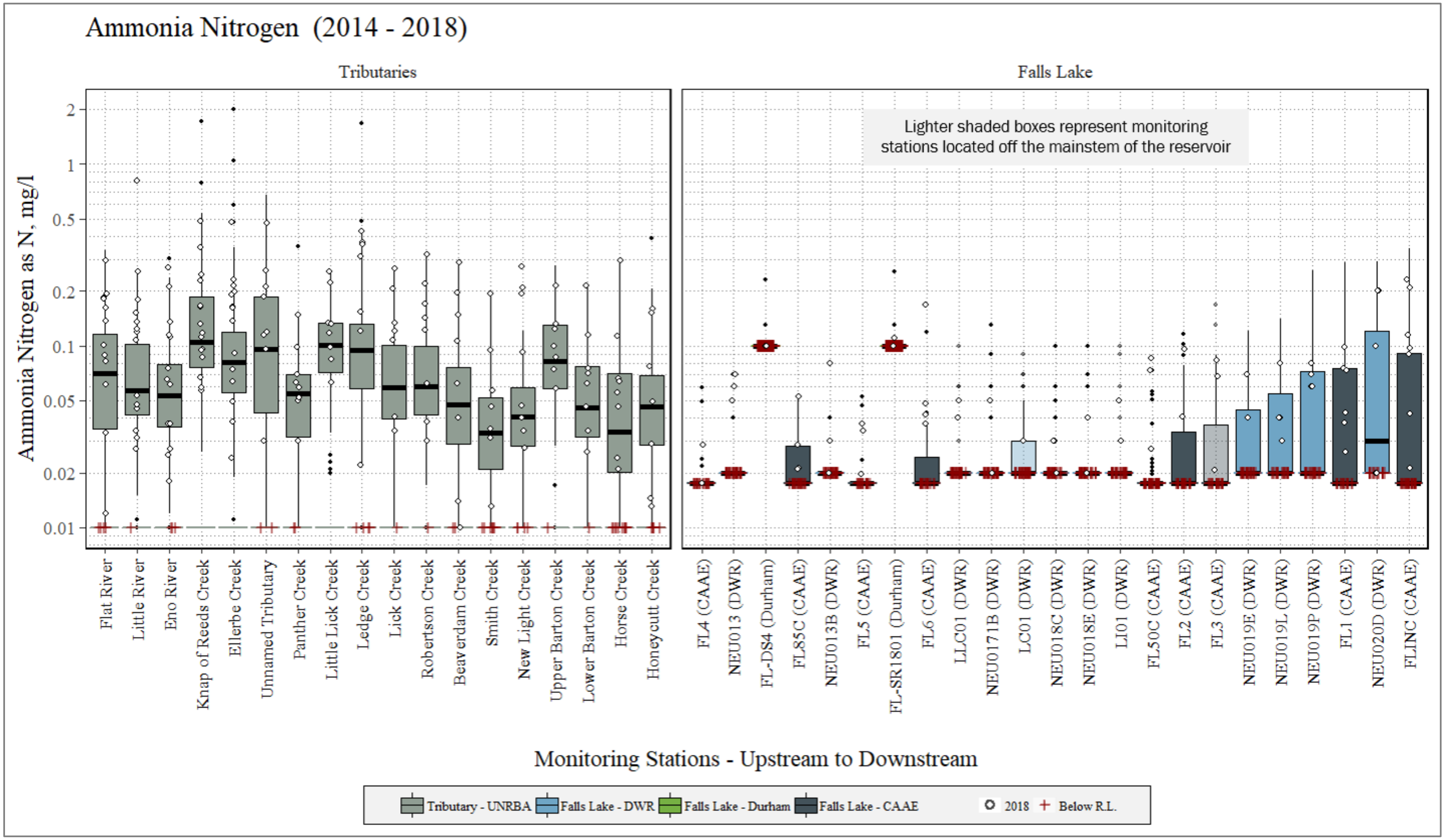


Figure 3-19. Ammonia in Lake Loading and Lake Samples from August 2014 to October 2018

Note the different reporting limits among monitoring organizations (0.1 for the City of Durham, 0.02, for DWR, 0.0175 for CAAE, and 0.01 for UNRBA).
Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

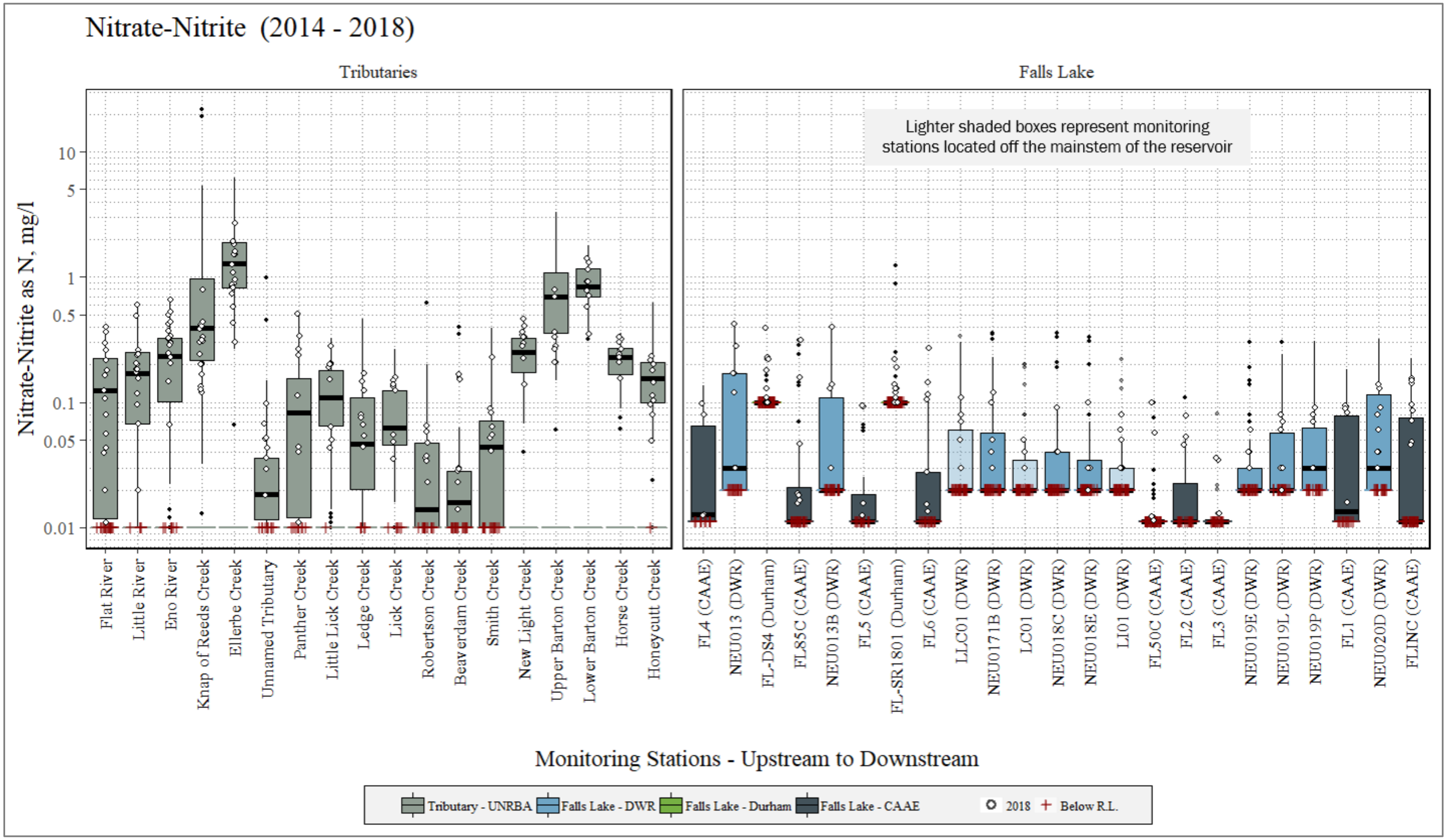


Figure 3-20. Nitrate+ Nitrite in Lake Loading and Lake Samples from August 2014 to October 2018

Different monitoring organizations have different laboratory reporting limits as seen by the distinct locations of the red symbols. Each red symbol indicates an observation below the respective laboratory reporting limit.

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

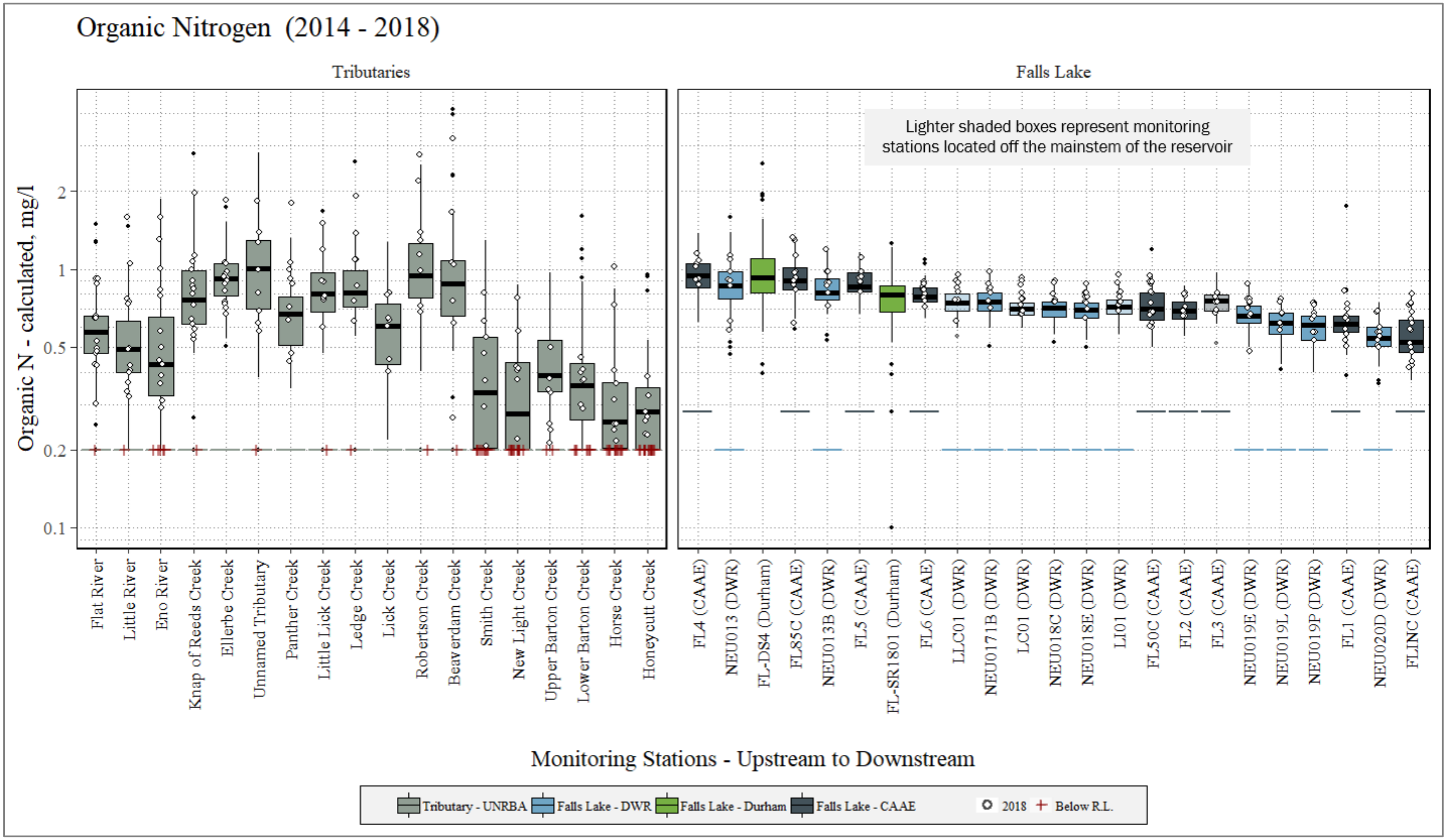


Figure 3-21. Organic Nitrogen in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

Note that 2018 TKN data is not available for the Durham sites due to quality control issues.

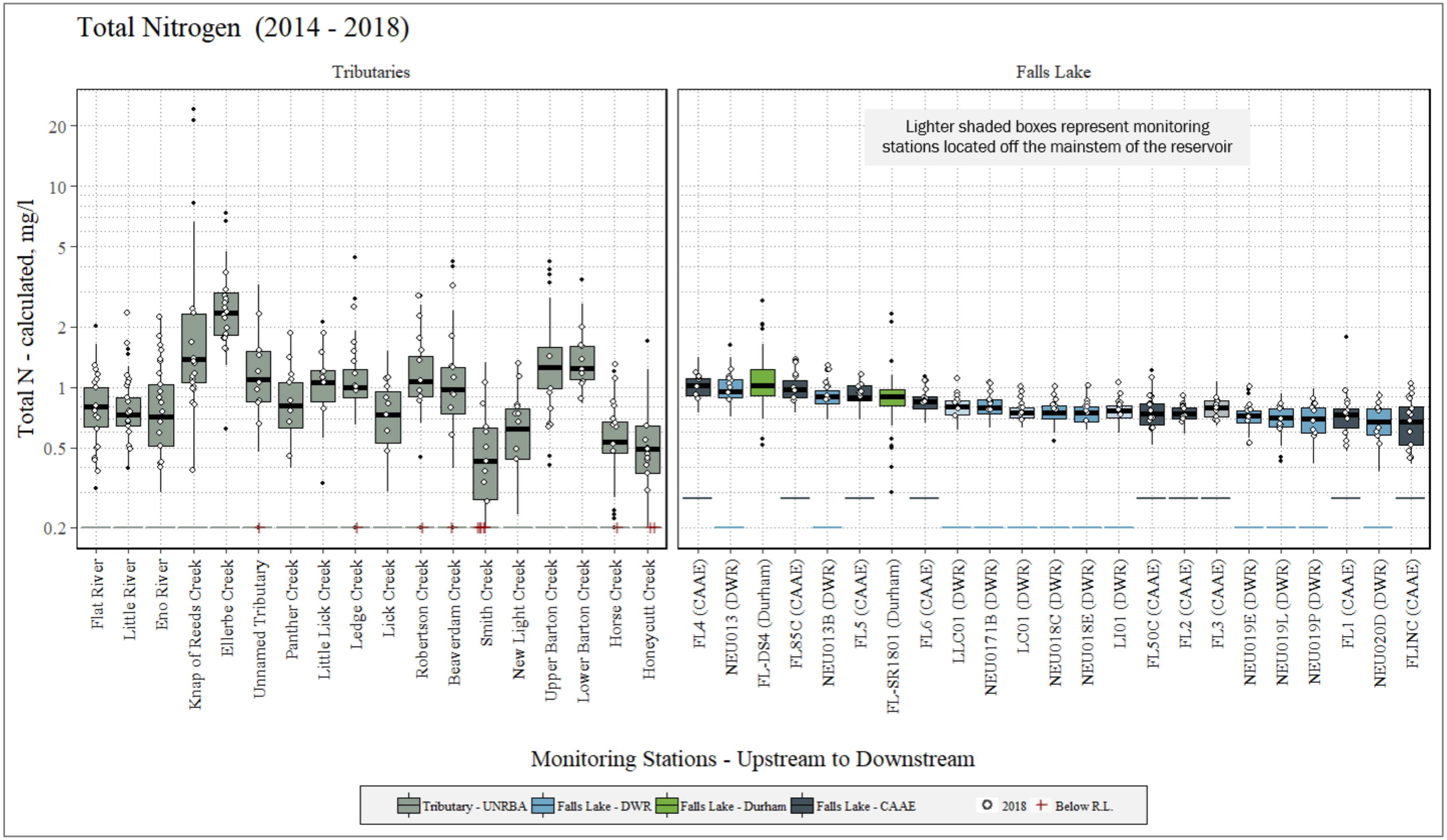


Figure 3-22. Total Nitrogen in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

Note that 2018 TN data is not available for the Durham sites due to quality control issues with TKN data.

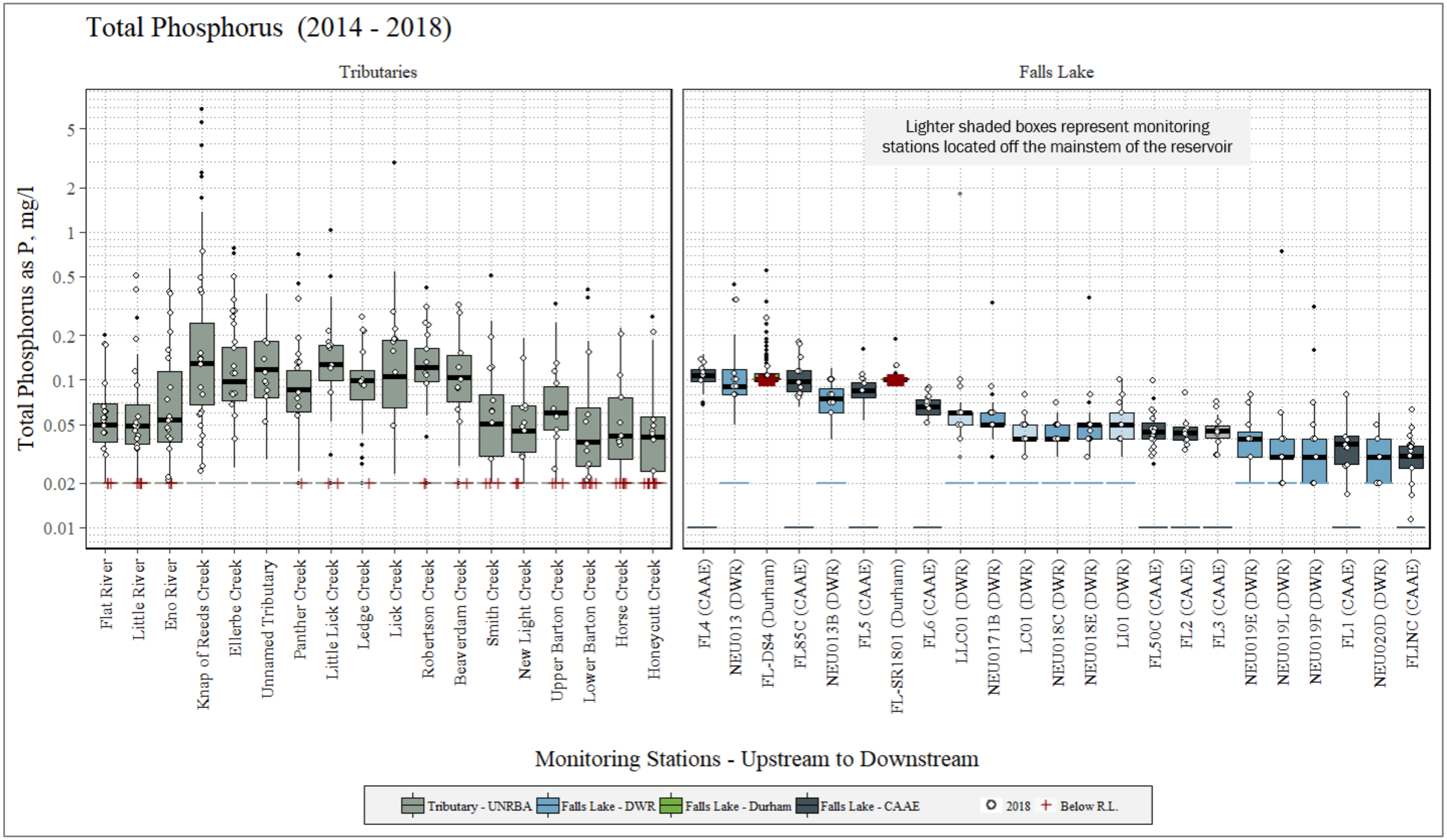


Figure 3-23. Total Phosphorus in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

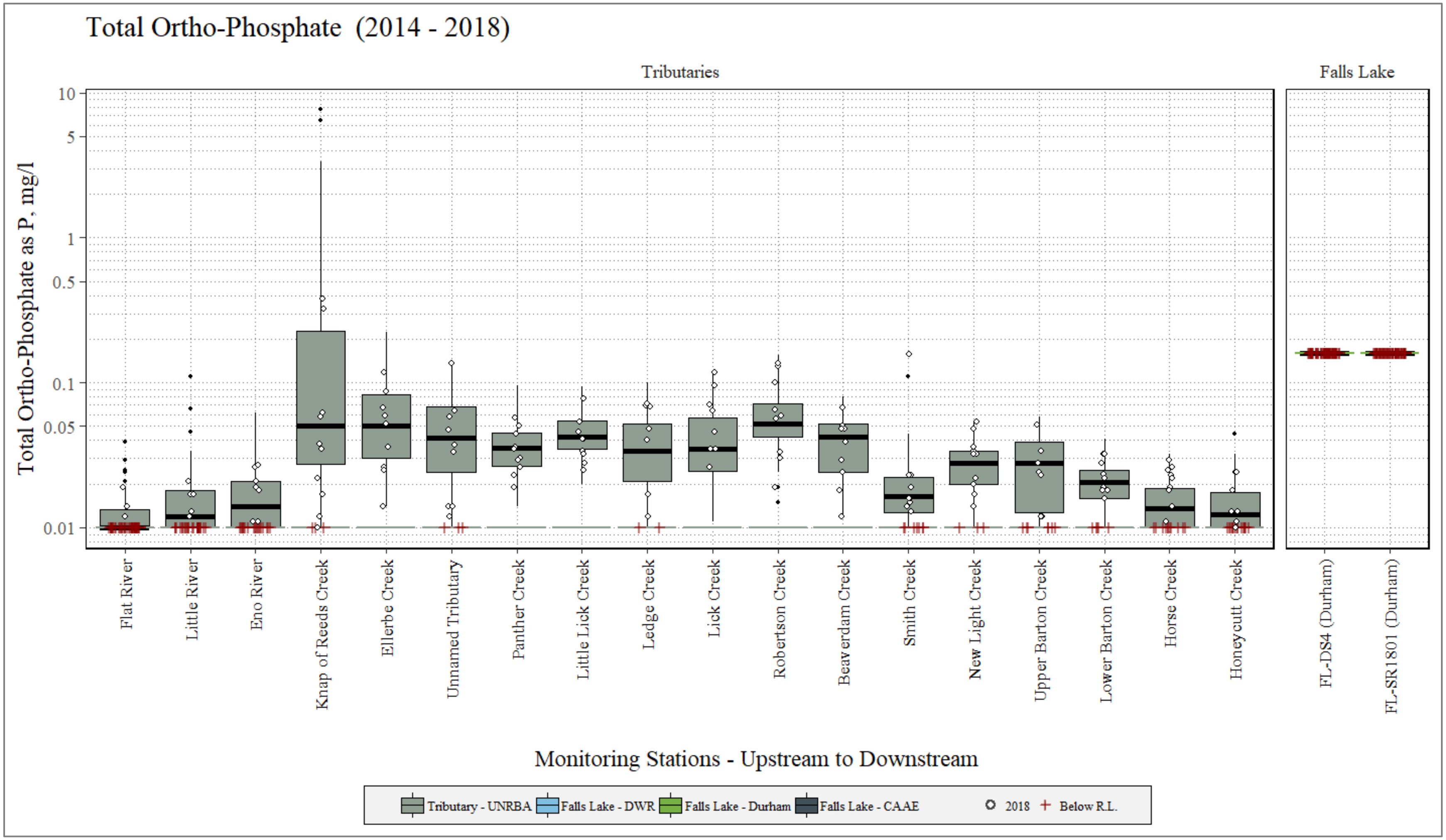


Figure 3-24. Ortho-phosphate in Lake Loading Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

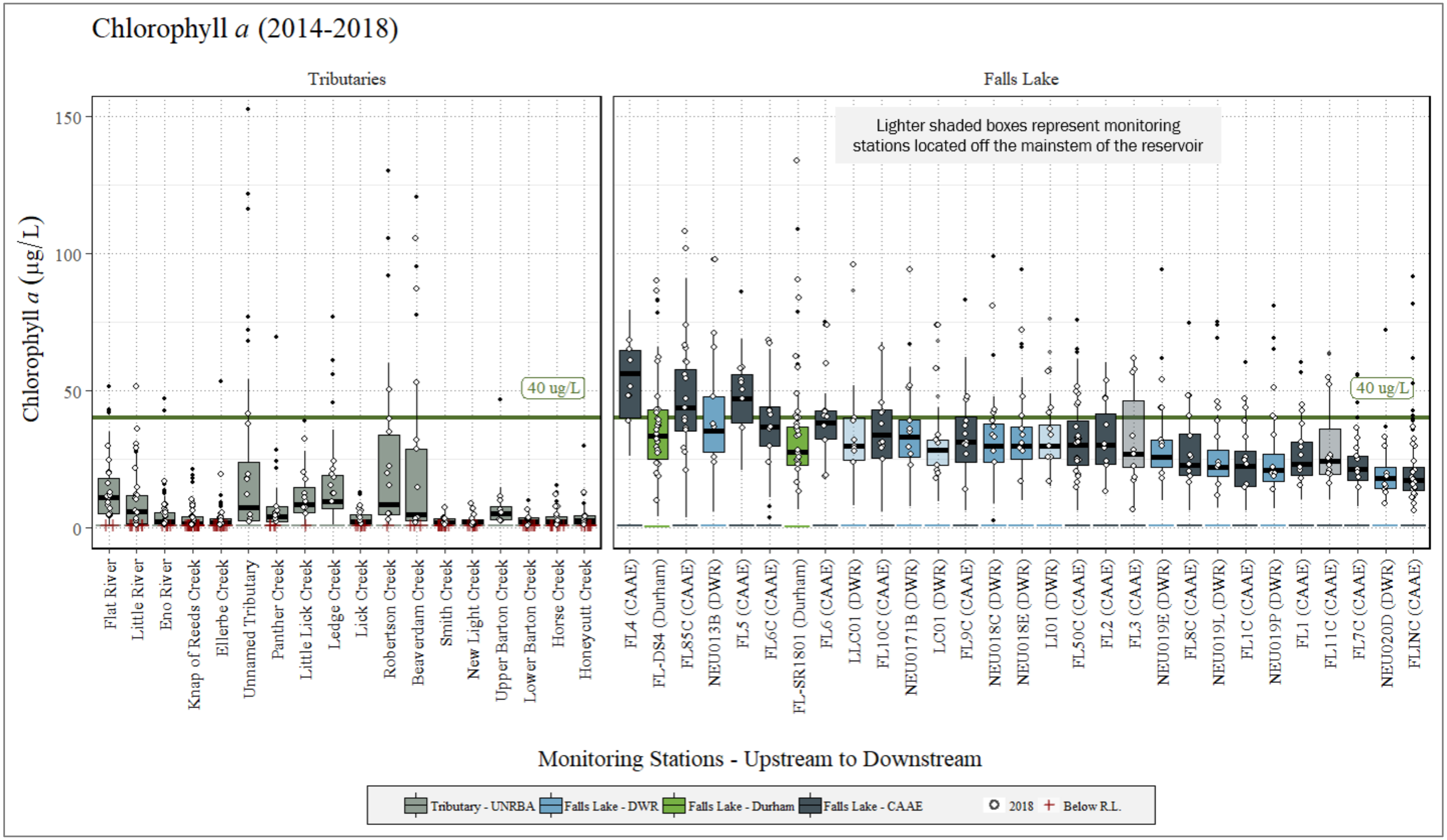


Figure 3-25. Chlorophyll-a in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

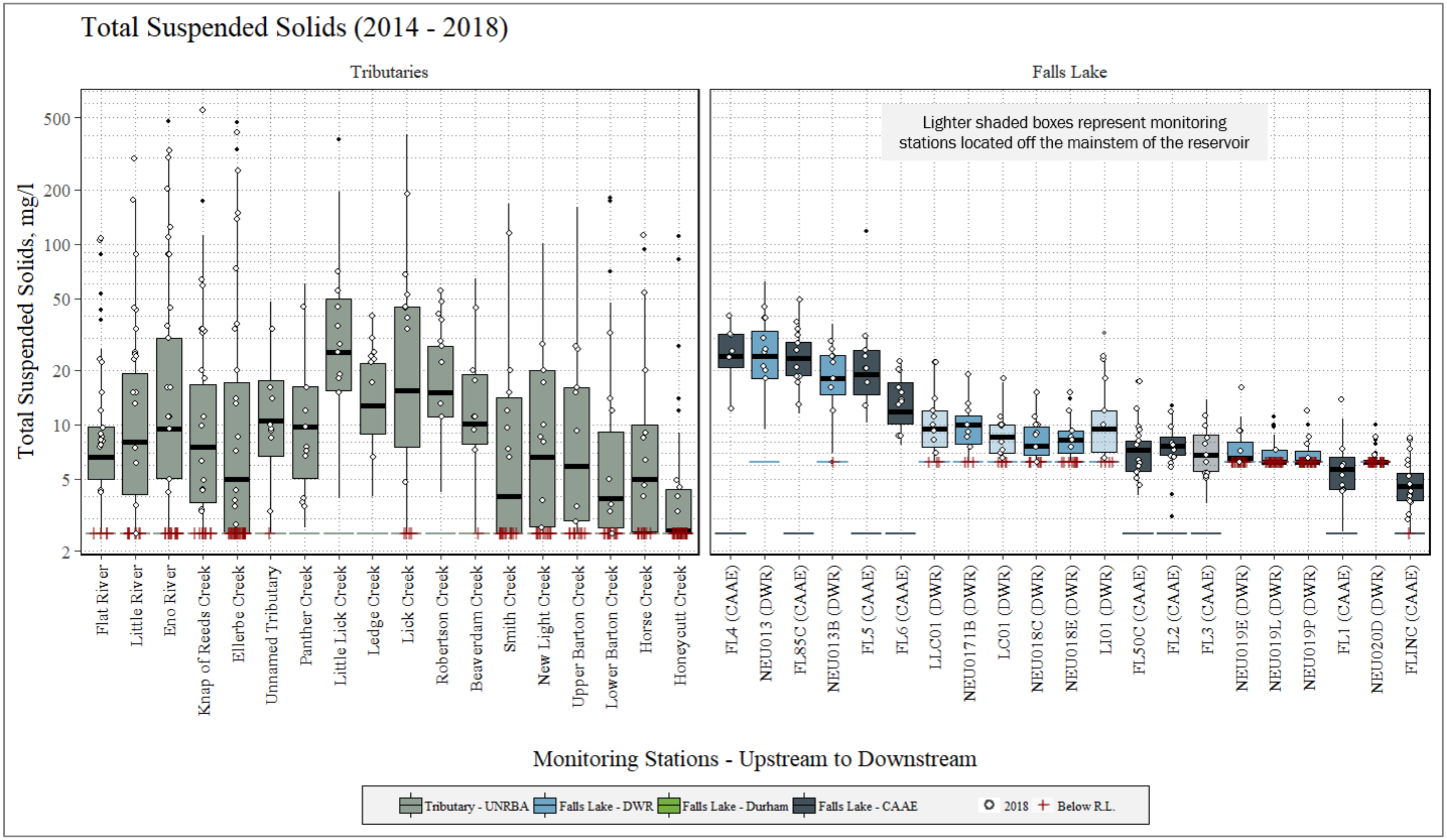


Figure 3-26. Total suspended solids (TSS) in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

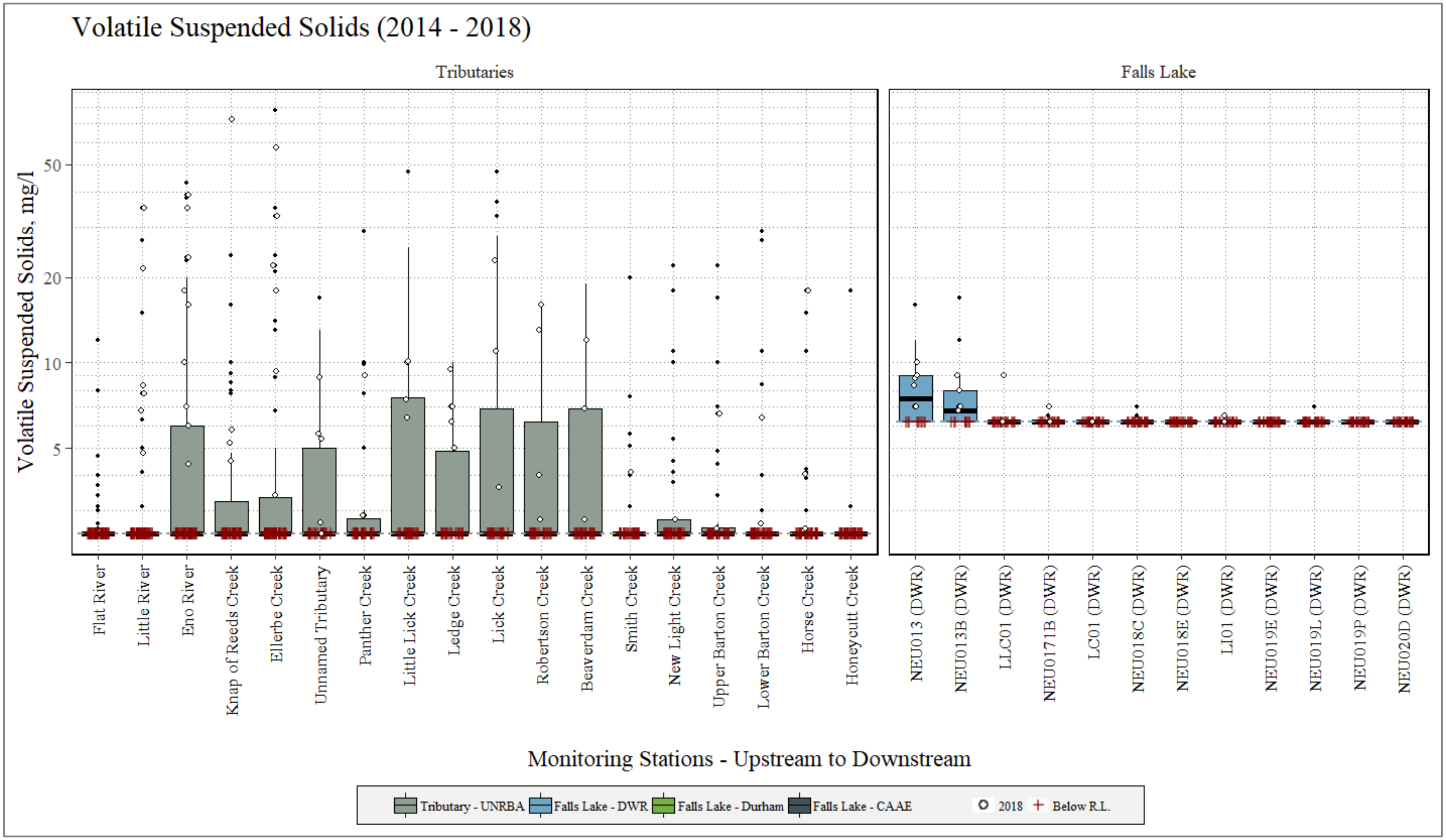


Figure 3-27. Volatile suspended solids (VSS) in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

Note that the y-axis is displayed using a logarithmic scale.

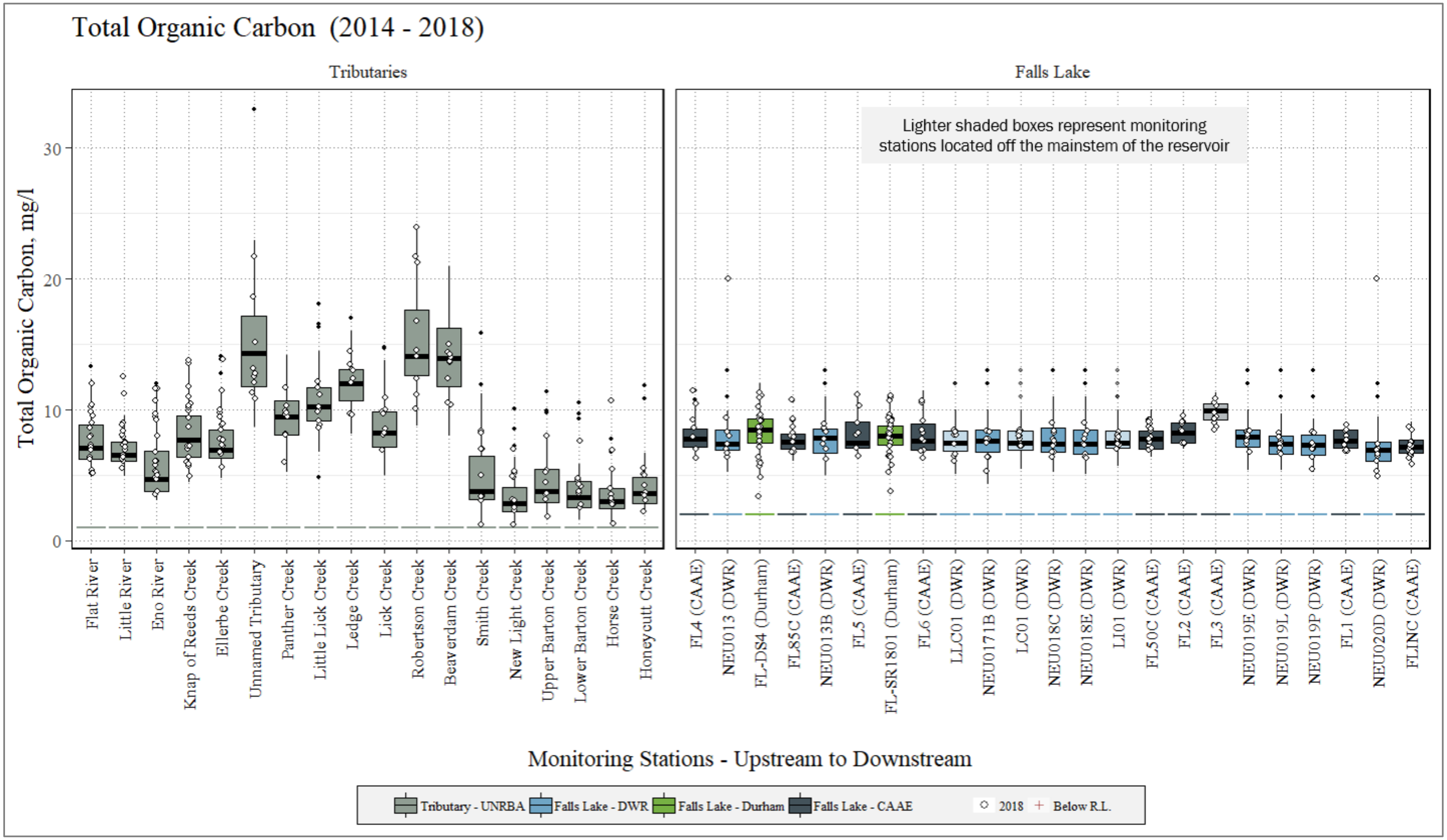


Figure 3-28. Total Organic Carbon (TOC) in Lake Loading and Lake Samples from August 2014 to October 2018

Note that CAAE stations FL1-6 began to be collected as photic zone composites in April 2016; only data collected as photic zone composites are provided on this figure.

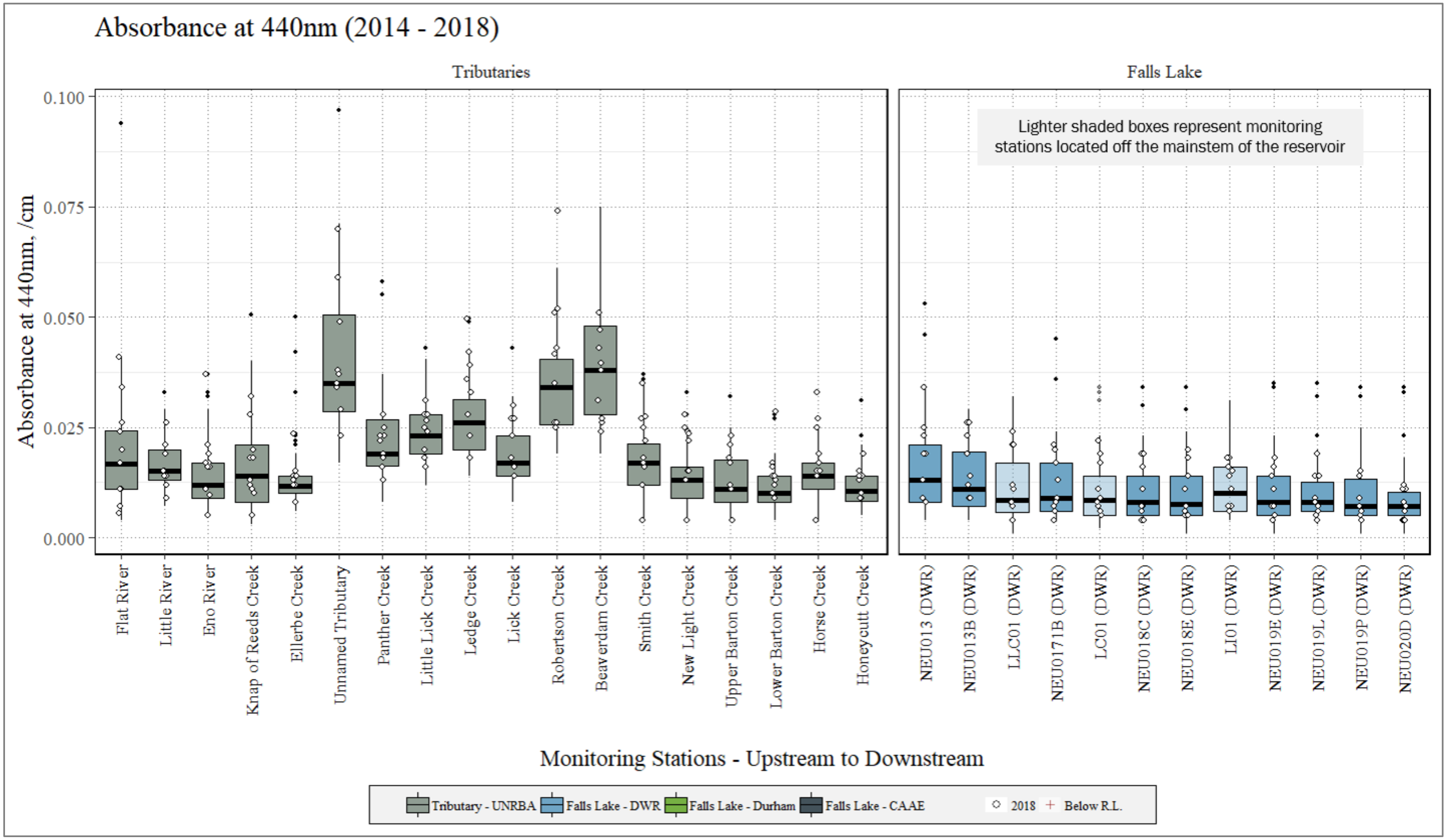


Figure 3-29. Color (absorbance at 440nm) in Lake Loading and Lake Samples from August 2014 to October 2018

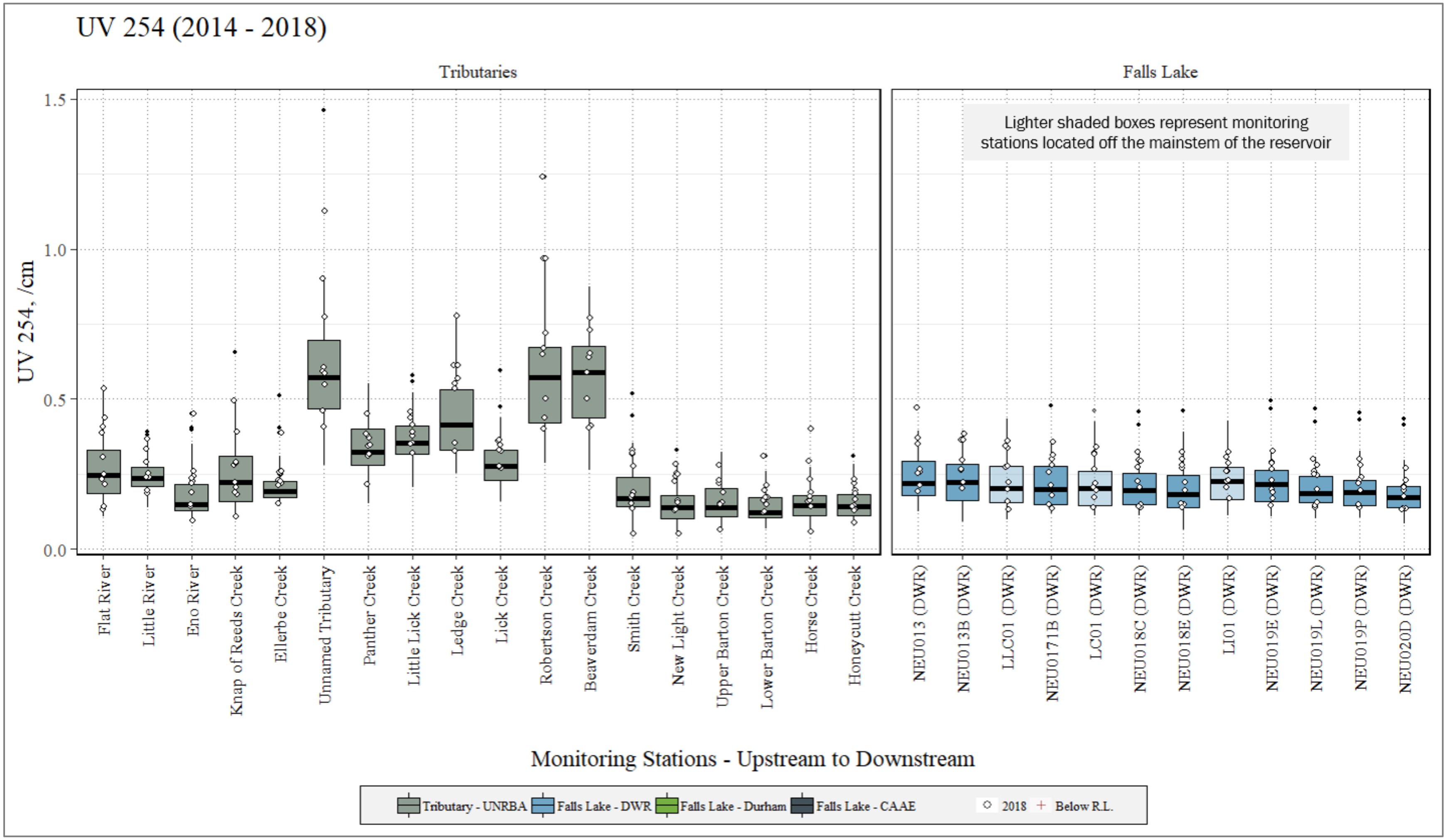


Figure 3-30. Absorbance at 254nm in Lake Loading and Lake Samples from August 2014 to October 2018

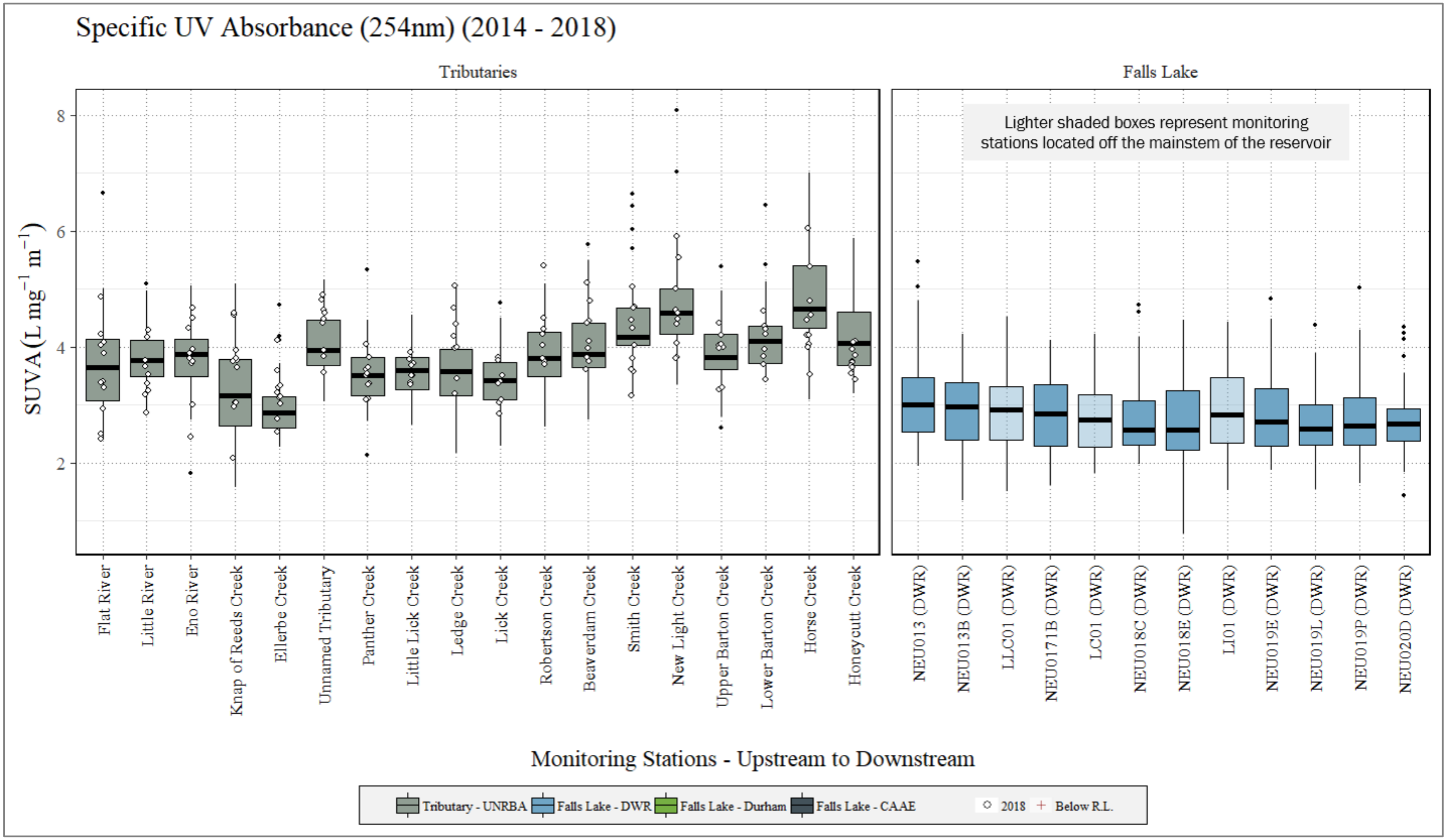


Figure 3-31. Specific UV Absorbance in Lake Loading and Lake Samples from August 2014 to October 2018

Note that only a limited amount of 2018 DOC data is available from DWR, so 2018 SUVA values have been excluded from this figure

Phytoplankton Algal Assemblage data collected by DWR - In addition to water quality measurements, DWR also conducts evaluations of phytoplankton algal assemblages from three locations in Falls Lake in order to assess changes over time (year-to-year and month-to-month). DWR has provided this data set and it is included in the UNRBA database. This section is primarily intended to provide a graphical overview of this dataset to show the kind of information available rather than an in-depth analysis of algal dynamics in Falls Lake. The algal speciation data will be used to inform development of the EFDC lake model, but phytoplankton community dynamics are complex, and mechanistic models are generally not able to predict taxonomic shifts with a great degree of accuracy. This data will also be evaluated for use in the statistical model developed by the UNRBA.

Figure 3-32 through Figure 3-34 show the estimated biovolume data for eight algal taxonomic groups at the upstream (NEU013B), mid-lake (NEU018E), and downstream (NEU019P) monitoring stations (2012 to2018). The figures illustrate the substantial biovolume differences among these eight phytoplankton groups, as well as the dynamic shifts in abundance within most of the groups through time. Visual comparison across the figures shows variation within the same algal group from one location in the lake to another, indicating that algal abundance is not uniform among segments of the lake at a given time. Blue-green algae show the strongest annual pattern, generally peaking in the latter half of the year and declining to low levels in the winter. Other algal groups either show less consistent patterns from year-to-year (e.g., diatoms) or relatively consistent low levels of biomass (e.g., green algae). For all three locations, the three taxonomic groups with the largest estimated biovolume are Blue-green algae, Diatoms, and Prymnesiophytes (haptophytes) which is common for eutrophic lakes and reservoirs. Aside from chlorophyll-a concentrations present in the algae, there are no regulatory standards or formal guidance on criteria regarding algal biovolume in North Carolina. Since the EFDC and WARMF models have algorithms to simulate production of diatoms, blue-green and green algae, these data provide value for the development and calibration of the lake models as well as evaluation of the lake response to nutrient management strategies. Analysis of algal community structure as related to various water quality parameters may reveal relationships that could be of assistance during empirical modeling efforts. The UNRBA Modeling Team will evaluate potential relationships as the empirical model is developed.

Figure 3-32. Algal Biovolumes at Station NEU013B (near Interstate 85)

Of all three monitoring stations, this site shows the clearest year-to-year patterns in algal biovolume for blue-green algae, prymnesiophytes (haptophytes), and euglenoids. Samples are collected monthly and only samples with these taxa present are shown—a data point on this figure means the taxa was present.

Figure 3-33. Algal Biovolumes at Station NEU018E (mid-lake)

Annual cycles of elevated summer and fall blue-green algae populations are apparent in this figure. The vertical scale on this figure (and across all sub-figures) is held constant across all three stations for ease of comparison.

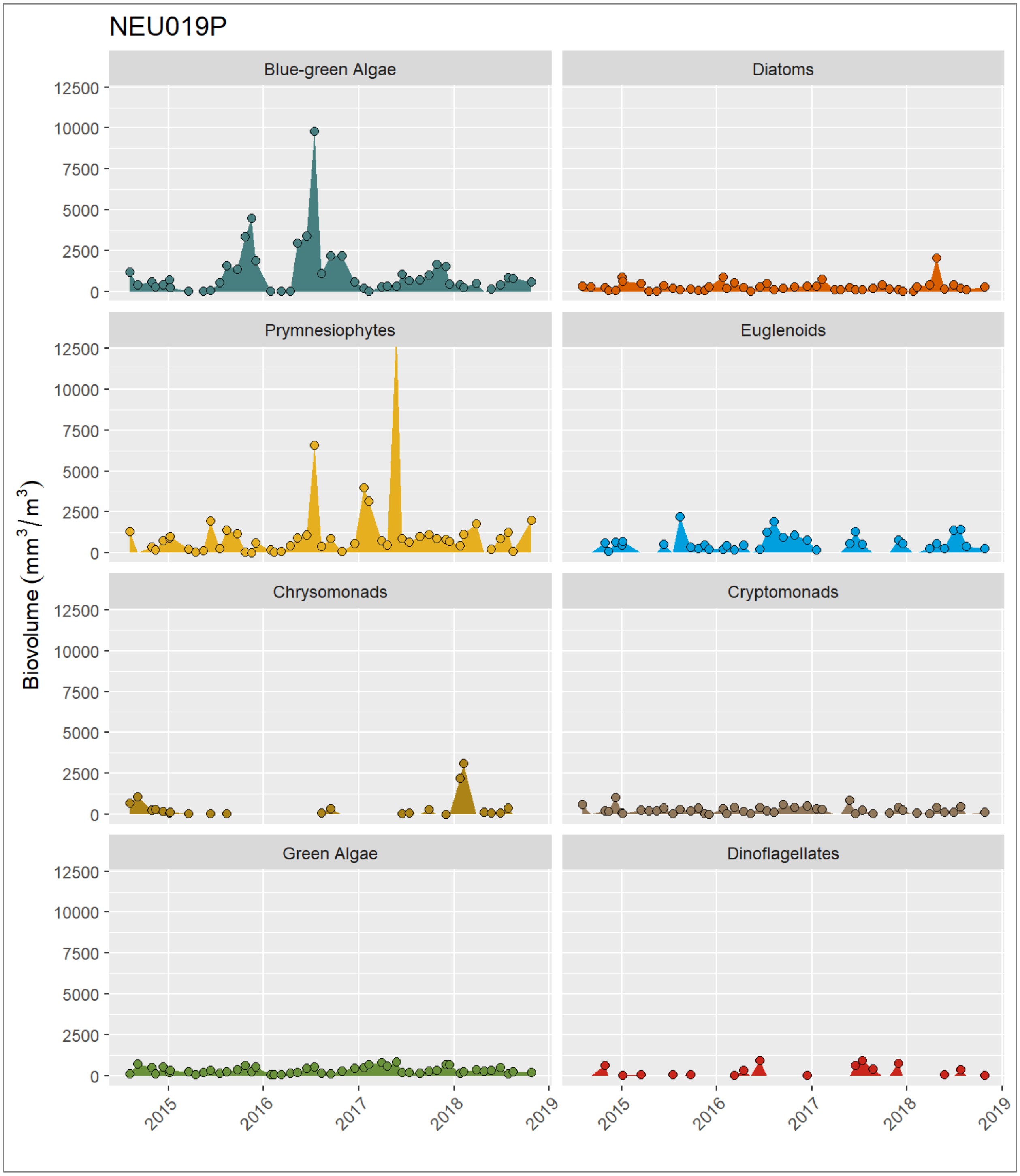


Figure 3-34. Algal Biovolumes at Station NEU019P (near Upper Barton Creek cove)

3.4 Summary of Special Studies

Since the inception of the UNRBA Monitoring Program, eight special studies have been conducted in the watershed and lake to support model development and inform development of the re-examination. Most of these were completed in previous years, and brief summaries of the studies are provided in this section. References to the more thorough descriptions of methods and results provided in previous Annual Reports are referenced in each section. These reports are available in the UNRBA resource library.

3.4.1 High Flow Sampling

This Special Study was used to obtain supplementary water quality grab samples from select tributaries to Falls Lake under high flow conditions which are typically under-represented by routine monitoring. High flow conditions are periods when stream flow increases markedly above normal flows in response to a rain event. This supplemental effort helped to ensure that water quality data were obtained when hydraulic loading to the lake was high. Data from this study helps to inform the development of watershed and lake models for Falls Lake.

This Special Study began in Fiscal Year 2015 and concluded in Fiscal Year 2018. Modifications to this special study were initiated in July 2016 to provide more frequent data collection from the largest tributaries under high flow conditions, as outlined in the Fiscal Year 2017 High Flow Study Plan. Updated results from this study are presented in the 2018 Annual Monitoring Report.

Key results of this study include the following:

- Collection of more water quality samples under high flow conditions during all seasons
- Representation of water quality across a range of hydrologic and seasonal conditions to improve statistical loading estimates which are presented in Section 5.6.3 of this year's annual report.

The UNRBA Monitoring Program included specific efforts to capture samples across a wide range of flow conditions. High flow sampling and load calculations (Section 5.4.3) shows that most of the loading enters the lake from very few high-flow events.

High flow sampling events are intended to measure water quality during elevated flows not typically captured by Routine Monitoring. These events can contribute relatively large volumes of water to Falls Lake and thus large loads of nutrients. For example, for the five largest tributaries, about 20 percent of the water delivered to Falls Lake comes from flows which occur during just one percent of the time, and 40 percent of the water delivered comes during about 5 percent of the time. This imbalance between water delivery and the time during which it occurs leads to an over-representation of low-flow conditions and an under-representation of high flow conditions when sampling occurs based on time intervals, such as monthly monitoring, instead of flow intervals. The timing of water delivery with respect to large storm events also impacts the degree to which loads can be managed by storm water control measures that aim to treat the first inch of runoff. The ability of these control devices to control nutrient loading to Falls Lake will be evaluated as part of the re-examination modeling effort.

The Flat, Eno, and Little Rivers along with Knap of Reeds Creek and Ellerbe Creek contribute 78 percent of the water delivered to Falls Lake. To assess the percentage of samples collected during different flow conditions for each of the top five flow contributors to Falls Lake, loading values were calculated and distributed amongst five equal groups (quintiles) based on the range of all loading values observed during the monitoring period. The percentage of samples collected from each quintile was then calculated for all five streams (Figure 3-35). 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 will improve development and calibration of the model during high-flow events. The DWR ambient monitoring program did not specifically target high flow conditions.

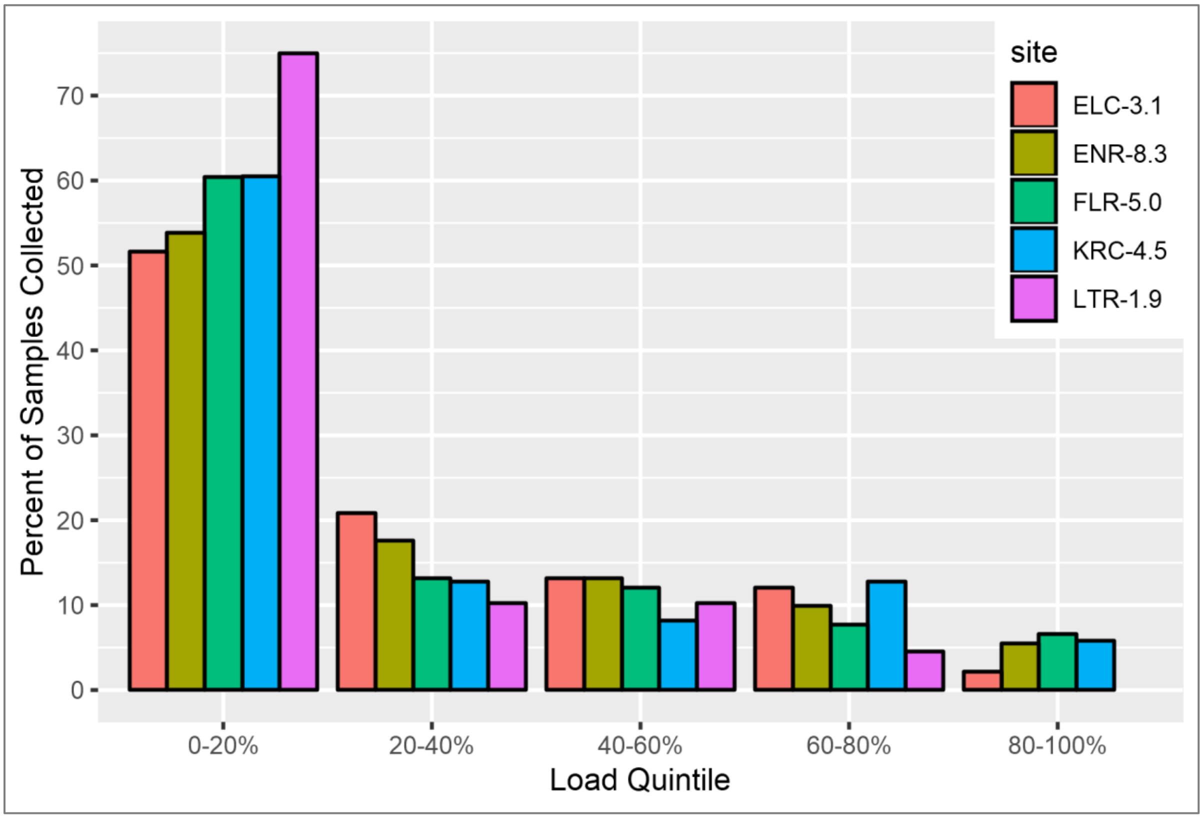


Figure 3-35. Percentage of samples collected during different loading quintiles for the five largest flow contributors to Falls Lake (August 2014 - October 2018)

Differences in chlorophyll-a, total phosphorous, TOC, and nitrogen (ammonia, nitrate+nitrite, and organic nitrogen) concentrations for samples collected during high flow conditions (load quintiles greater than 60 percent) and for samples collected during more normal flow conditions (load quintiles less than 60 percent) are presented in Figure 3-36. With the exception of nitrate+nitrite, sample concentrations are generally higher during high flow conditions. This is the generally expected pattern, since higher flows associated with rain events would be expected to carry material from surface runoff into the streams and result in saturated groundwater conditions that would move water and nutrients through the shallow groundwater zone into nearby streams. The pattern observed for chlorophyll-a is somewhat counterintuitive since planktonic algae would not be expected to proliferate in streams as a result of a rain event occurring just hours before. Potential reasons for this result are (1) higher flows may scour periphyton (attached algae) from stream beds, which is misinterpreted as phytoplanktonic algae, (2) phytoplankton are flushed from upstream reservoirs on several Falls Lake tributaries, or (3) certain materials (e.g., humic substances) carried into the stream by the storm event may introduce interference in the fluorescent method used to quantify chlorophyll resulting in the perception of erroneously higher chlorophyll-a levels.

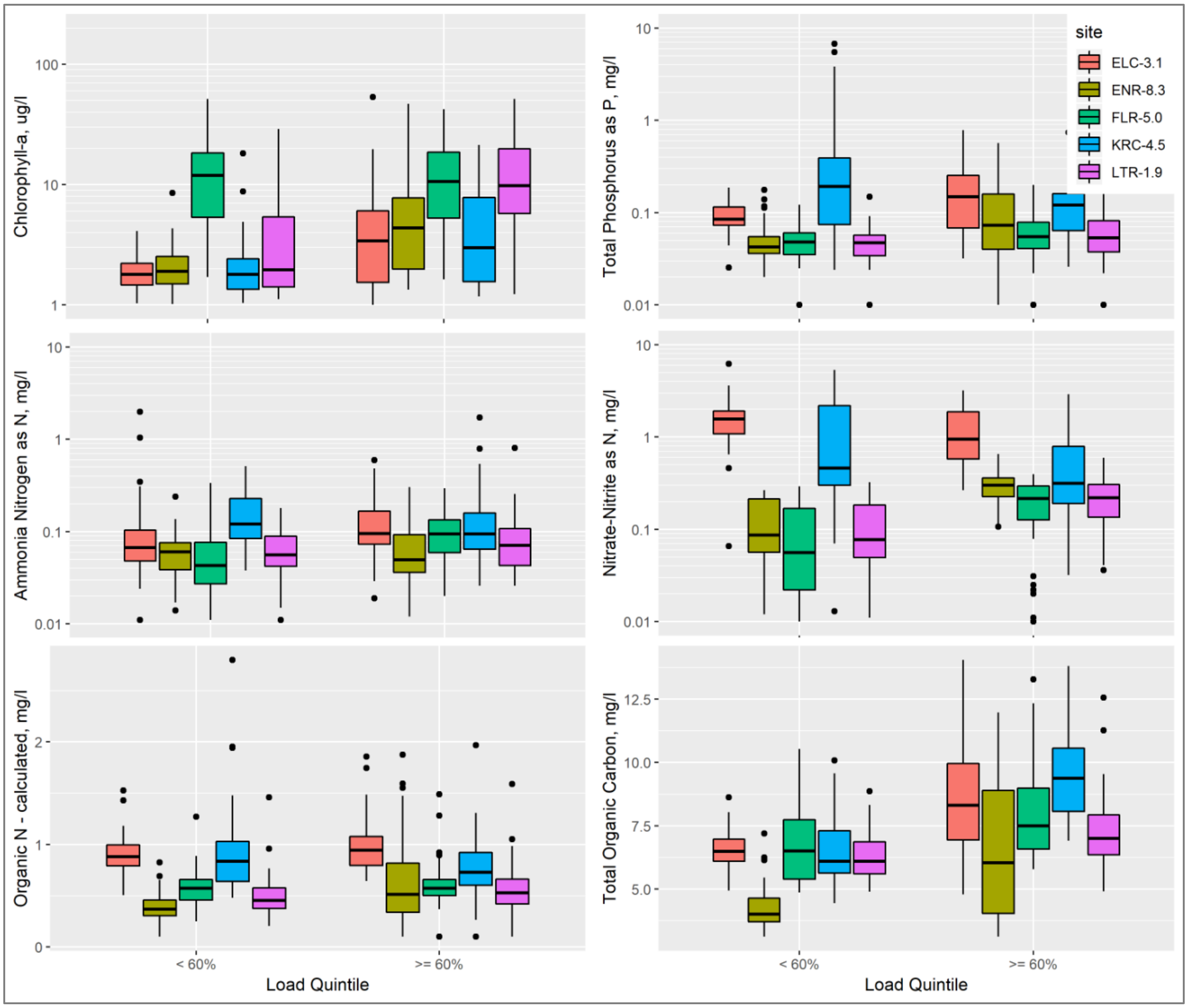


Figure 3-36. Differences in parameter concentrations for samples collected during high flow conditions and for samples collected during more normal flow conditions (August 2014 - October 2018)

High flow conditions are load quintiles greater than 60 percent. Normal flow conditions have load quintiles less than 60 percent

Note that for chlorophyll-a, ammonia, phosphorus, and nitrate-nitrite, the y-axis is displayed using a logarithmic scale.

3.4.2 Storm Event Sampling

The Storm Event Sampling Special Study focused on obtaining additional water quality data from major tributaries to Falls Lake under varying streamflow conditions over the course of a storm event. In contrast to the grab samples taken under the Routine Monitoring and High Flow Sampling, the storm event data collection used automated sampling equipment to collect multiple discrete samples as stream flows rise and then fall during and following a storm event. Such data allow for a better understanding of the contribution of nutrients and related parameters across the entire hydrograph of associated storm events. Data from this study will be used to better inform model development and calibration for simulating water quality conditions in Falls Lake and its watershed.

This special study was initiated in Fiscal Year 2015 and completed in Fiscal Year 2016. Results of this study are described in the 2016 Annual Report available online at https://unrba.org/content/resource-library.

This data will primarily be used to inform development and calibration of the UNRBA watershed model for high precipitation conditions:

- Collection of water quality samples along the rising and falling limbs of storm hydrographs to understand how concentrations and loading patterns vary with storms
- Comparison of loading patterns during different seasons

3.4.3 Lake Sediment Evaluation

The Lake Sediment special study examined the nutrient and organic carbon content of sediment samples from Falls Lake. These data support a more precise understanding of the spatial variability of sediment characteristics, bottom water and pore water nutrient concentrations, and benthic nutrient flux rates in Falls Lake. Nutrient flux assessment in this study focused on the transfer of specific nutrient species from sediments to the overlying water. This evaluation provides information to simulate spatial variability in benthic nutrient flux using the EFDC sediment diagenesis modeling that will be included in the revised Falls Lake modeling. Data collection for this special study was conducted in June 2015 and preliminary results of this study were presented in the 2015 Annual Report available online at https://unrba.org/content/resource-library. Final results of this study are discussed in more detail in Section 5.6.

The DWR version of the Falls Lake Nutrient Response EFDC Model assumed uniform nutrient flux conditions throughout the lake. Information from this study will help develop a better understanding of the importance of internal nutrient loads to the waters of Falls Lake.

Key applications of this data include the following:

- Allow for estimation of internal lake nutrient loading from lake sediments for comparison to other sources of loading in the watershed and how loading rates vary spatially in the lake (Section 5.5)
- Provide initial conditions data to set up the sediment diagenesis module in EFDC
- Improve development and calibration of the UNRBA lake models
- Establish a current conditions baseline for comparison to future years of management

3.4.4 Lake Bathymetry and Sediment Mapping

The goal of this special study was to improve the accuracy of lake models by providing data on the physical characteristics of the lake. The bathymetry component of this special study mapped the underwater topography of Falls Lake for a better understanding of volume, depth, and shape of the lake. Water depth data were collected along closely-spaced transects from the upstream to downstream end of the lake.

The sediment mapping component of this study was conducted concurrently with the bathymetric survey. The goal of sediment mapping was to identify the extent of the lake bottom which has accumulated sediment compared to areas of packed clay, sand and gravel, or even bedrock. The data collected during this study improves confidence in the application of the benthic flux estimates for use in model development and provides spatial data across the lake to enhance the resolution of the model application. Results from this study are discussed in Section 5.5, including using the sediment mapping data to extrapolate nutrient flux estimates from the Sediment Evaluation to the entire reservoir.

When DWR developed the Falls Lake Nutrient Response Model, only 17 depth transects were available. The bathymetric data collected under this special study has been incorporated into a revised model grid as part of the UNRBA revised lake modeling. The sediment mapping data have been used to extrapolate nutrient flux estimates from the Sediment Evaluation to the entire reservoir.

Key applications of this data set include the following:

- Develop the lake model grid for the UNRBA lake model using EFDC
- Extrapolate nitrogen flux rates from sediment cores to other areas of the lake based on sediment depth (Section 5.5.3)
- Improve development and calibration of the UNRBA lake models
- Establish a current conditions baseline for comparison to future years of management

3.4.5 Recreational Use Assessment

This Special Study evaluated recreational uses associated with Falls Lake that may relate to the attainment of water quality standards. Falls Lake is classified to protect recreational uses, which includes consideration of fishing, fish consumption, wildlife, and secondary recreation, defined as "wading, boating and other uses involving human body contact with water where such activities take place in an infrequent, unorganized or incidental manner." Findings from this study help inform the re-examination process with respect to aligning nutrient management efforts with maintenance of designated recreational uses. The study can also support discussions of alternative regulatory approaches where continued attainment of recreational uses is considered among the targets for adjusting water quality criteria or standards. Preliminary results of this study were presented in the 2015 Annual Report available online at https://unrba.org/content/resource-library. A further examination of recreational uses associated with Falls Lake is presented in Section 5.11. This more recent assessment relies on additional data sources beyond what was presented in 2015.

Key findings from the 2016 Recreational Use Study include the following:

- Recreational use in Falls Lake is limited by access and facilities, not water quality.
- Over 1 million visits to Falls Lake occur each year, and all expected forms of recreation occur.
- The sport fishery is healthy in Falls Lake.
- There were no statistically significant correlations between water quality and water-based recreation in Falls Lake.

3.4.6 Constriction Point Study

Water quality in Falls Lake may be driven by processes that occur at relatively short time steps. DWR samples water quality in Falls Lake at 12 locations monthly, but these data do not provide insight to in-lake dynamics during rapidly changing conditions such as following a large storm event.

The Constriction Point Special Study was developed to characterize conditions when water is moving at greater than usual rates between portions of the reservoir. Because the lake is segmented by several bridge causeways (i.e., constrictions), it is beneficial to understand how material moves from one area to the next. The bridge constrictions are points of concentrated flow and are an efficient location to monitor the downstream transport of water and material.

Collecting velocity and water quality data at these locations over multiday periods when flows are changing in response to storm events can provide enhanced understanding for model calibration as part of the re-examination strategy. Two data collection events were provided for in the Fiscal Year 2016 budget. The first took place in January 2016, and the results from this event were presented in the 2016 Annual Report available online at https://unrba.org/content/resource-library. The second event occurred in October 2016. Results from the second collection event were described in the 2017 Annual Report available online at https://unrba.org/content/resource-library.

Key applications of this data include the following:

- Provide measurements of water velocity and water quality at morphological transition points in the reservoir at more frequent intervals than DWR ambient lake monitoring
- Improve development and calibration of the UNRBA lake models

3.4.7 Light Extinction Data

This Special Study comprised a minor effort to analyze available data on light extinction from Falls Lake and to determine the strength of the relationship between actual light extinction measurements and Secchi depth. This evaluation can help to identify the degree of modeling uncertainty resulting from using Secchi depth data as a proxy for light extinction measurements. The historical data included measurements collected from the mid-1980s to the early 1990s. To support this evaluation, the UNRBA requested that DWR collect additional data to ensure the historic data was a reasonable representation of the light extinction/Secchi depth relationship under current conditions. The results of this study were presented in the 2015 Annual Report available online at https://unrba.org/content/resource-library.

Key applications of this data include the following:

- Confirmed the relationship between Secchi depth and light extinction measurements and that UNRBA resources were not needed to collect additional light extinction data
- Improve development and calibration of the UNRBA lake models

3.4.8 Basic Evaluation of Model Performance

This Special Study was included in Fiscal Year 2016 to help evaluate models for the re-examination of the Falls Lake Nutrient Management Strategy and determine whether or not the Monitoring Program design was sufficient or required revisions to address modeling needs. This study focused on modeling approaches the UNRBA would likely use for the re-examination and potential alternative regulatory approaches that may be evaluated. The Model Performance Evaluation technical memorandum summarizes the study results. This document is available online at https://unrba.org/content/resource-library.

Key applications of this data include the following:

- Modification to the Fiscal Year 2017 monitoring plans
  - Included more high flow sampling
  - Ceased measurement of $CBOD_5$ after two years of data collection
- Improve development and calibration of the UNRBA lake models

Section 4 Additional Studies and Information on Falls Lake and Other Reservoirs

This section provides historical perspective on Falls Lake by examining several studies developed as the impoundment was being planned and designed. By taking a reflective view of this historical perspective, the reader is offered an opportunity to compare current Falls Lake water quality measurements with those anticipated by the government agencies that funded and authorized construction of this reservoir. The reader is also offered the opportunity to compare improvements or declines in water quality over a number of decades since Falls Lake was constructed. This section also presents a brief review of technical literature published during the past 30 years on the characteristics of reservoir impoundments, including ways they differ from natural lakes. This is important because much of the science developed on factors affecting water quality in lakes was originally based on observations and measurements from natural lakes (and primarily lakes located in northern latitudes). Since reservoirs have distinct morphological and hydrologic differences from natural lakes, it is necessary to draw from the appropriate technical literature when developing models or otherwise attempting to understand or predict patterns and responses in reservoirs.

4.1 Pre-Impoundment Studies

The Falls Lake impoundment project was authorized by Congress as part of the Flood Control Act in 1965. The reservoir began filling in January 1983, following the completion of dam construction in February 1981. Design and construction of the impoundment were conducted by the USACE, which continues to manage the reservoir today.

Pre-impoundment studies predicted that the degree of eutrophication projected for the reservoir would "not interfere with any of the proposed project purposes" and that "water quality in Falls Lake will be highly satisfactory for all intended purposes provided that pollution control measures are carried out."

Prior to construction, a Final Environmental Statement (ES, revised) was prepared (USACE 1974) to document the projected effects of the reservoir construction and to predict future conditions in the reservoir. The 729-page, excluding appendices, document addressed all environmental facets of the project and included a section on anticipated water quality. The ES noted that the reservoir could be expected to experience vertical stratification during parts of the year, and that DO would be depleted in deeper portions of the lake during stratified conditions. The ES also predicted that phosphorus concentrations would be higher at the upper end of the lake than in the lower lake. It called for advanced treatment (relative to technologies used at the time) at wastewater facilities upstream of the reservoir as a primary strategy to reduce the potential for over-enrichment by nutrients (such treatment is now in place at each major facility in the basin).

The ES provided an in-depth discussion of the likely development of eutrophic conditions, the difficulty in precisely predicting the degree of such conditions, and the differences between natural lakes and man-made reservoirs with respect to nutrient dynamics and productivity. The ES concluded that the degree of eutrophication projected for the reservoir would “not interfere with any of the proposed project purposes.” At the time the ES was written, North Carolina used a narrative standard to assess eutrophication. North Carolina adopted the numeric criterion of 40 µg/L in August 1979.

The State of North Carolina Department of Natural and Economic Resources (DNER) prepared a Special Analysis of the Falls of the Neuse Project (DNER 1973) to “provide information and guidance that would be useful to the Secretary of the DNER, and others in developing positions regarding the Falls of the Neuse Project.” A primary conclusion of the report was that “water quality in Falls Lake will be highly satisfactory for all intended purposes provided that pollution control measures are carried out.” Like the ES, DNER recommended that treatment be improved at domestic wastewater treatment plants above the reservoir (it also noted that such upgrades would be required whether the reservoir was constructed or not as a result of the passage of the Clean Water Act [CWA]).

The DNER report discusses results of a pre-impoundment modeling effort that predicted in-lake concentrations of TP ranging from 0.04 to 0.13 mg/L across a range of “trapping factors” and nutrient management (including improved wastewater treatment) that would retain a portion of phosphorus in the watershed rather than delivering it to the lake. That range very closely mirrors TP levels in the reservoir during the UNRBA monitoring period, with the upper lake seeing TP at the upper end of the range and the lower lake seeing TP at the lower end of the range. The DNER report also noted that DO levels would be acceptable in the lake, but that the hypolimnion would experience anoxic conditions during summer stratification.

The modeling effort discussed by DNER (1973) considered TP trapping factors in the watershed but apparently did not look at the reservoir itself as a phosphorus trap, which it obviously is, given the decrease in TP levels from the upper end to the lower end. By acting as a nutrient sink, Falls Lake provides water quality improvement to the Neuse River downstream of the reservoir. This enhancement of water quality downstream was listed as a project objective in the 1973 report.

The Water Quality Section of the North Carolina Division of Environmental Management prepared a report (NCDEM 1983) examining water quality in Jordan Lake and Falls Lake. At the time the report was prepared, Jordan Lake and Falls Lake were still filling, so the analyses were predictive rather than observational. This evaluation was conducted after the chlorophyll-a criterion was adopted in 1979. The report summary notes:

> *Nutrient loadings to both Jordan and Falls of the Neuse Lakes are predicted to place them among the most eutrophic or enriched lakes in North Carolina. Municipal wastewater treatment facilities are a major source of the excessive nutrient inputs to both of these reservoirs. The predicted eutrophic conditions do not necessarily mean that uses of these reservoirs will be impaired.*

The report points to similarities and differences in predicted conditions for Jordan Lake and Falls Lake and notes that general concern over nutrient loading and resultant eutrophic conditions is higher for Jordan Lake because its watershed is more than twice the area of the Falls Lake watershed, and because nutrient loading per unit area was higher in the Jordan Lake watershed.

Chlorophyll-a is well below levels predicted by the NC Division of Environmental Management as Falls Lake was filling:

Source	June-September Average Chlorophyll-a (µg/L)		
	Upper Reservoir	Lower Reservoir	Lake-Wide
NCDEM 1983 Model Prediction	110	42	75
DWR Monitoring (Aug 2014-Oct 2018)	41	20	33

Quantitative predictions in the NCDEM (1983) report include a forecast of a lake-wide, summer (June to September) average chlorophyll-a level in Falls Lake of 75 µg/L, but the DWR monitoring data presented in Section 3 yields a lake-wide June-September average of 33 µg/L over the UNRBA monitoring period. Thus, some combination of modeling error, over-prediction of nutrient loadings, or underestimation of watershed management activities led to a substantially higher forecast of chlorophyll-a than has been observed.

NCDEM (1983) included a series of recommendations for controlling nutrient loadings to Falls and Jordan lakes. All of those recommendations have been employed, at least to some degree, including N and P removal by wastewater treatment plants, a ban on phosphate detergents, implementation of agricultural and forestry BMPs, land use planning and urban runoff BMPs, and erosion/sediment control during construction.

4.2 The Nature of Reservoir Systems

The UNRBA Monitoring Program and the DWR Falls Lake Monitoring Plan were designed with a broad knowledge of reservoir systems informed by historical studies and the scientific literature concerning the water quality of both lake and man-made reservoir systems. This discussion is intended to provide insight into how Falls Lake compares with the scientific understanding of man-made reservoir systems and the differences in expectations between natural lakes and man-made reservoirs

The Falls Lake Final Environment Statement (revised) (USACE 1974) pointed out that reservoirs often behave differently than natural lakes. For this report it is useful to place Falls Lake in context with natural lakes other reservoirs to note some similarities and differences that may be important when analyzing Falls Lake's water quality characteristics. Thornton et al. (1990) compiled chapters prepared by a group of experts with direct experience on reservoirs. Although nearly 30 years old, the book offers pertinent information and insights for understanding Falls Lake.

More recently, Walker et al. (2007) examined literature on nutrient management in lakes and reservoirs, closely following many of the themes in the earlier review and expanding upon them with more recent findings. Hart and Hart (2006) also reviewed reservoir literature published after the Thornton et al. book. The Hart review was commissioned to provide management guidance for reservoirs in South Africa but discusses literature from around the world and offers pertinent information for systems in the Southeastern United States as well, reflecting the global importance of reservoir management needs.

Thornton (1990a) observed that reservoirs generally comprise three zones: a “riverine” zone at the upper end which retains some of the characteristics of the flowing water body impounded to form the reservoir, a “lacustrine” zone at the lower end which has many characteristics of a lake, and a “transition” zone in between with characteristics somewhere in between the other two. Many of the differences between these zones are related to, or caused by, patterns of sediment transport and deposition along the reservoir. Thornton described the riverine zone of a reservoir as shallow and generally narrow, with sufficient water velocity to transport suspended solids further down the reservoir. The transition zone is commonly wider with deeper water, allowing for deposition of much of the suspended solids load. The lacustrine zone is often broad and deep, with clearer water and a greater potential for primary production due to better light penetration. Thornton summarizes by saying that reservoirs are a distinct category retaining specific characteristics of both the lentic and lotic environments.

Falls Lake fits this general model to some degree, but Falls Lake is not principally fed by a single large tributary, but by five primary tributaries with substantially different land use mixes in their basins. And the configuration of the upper lake, where those five tributaries essentially enter into a broad, shallow bay, is not “riverine” in the sense described by Thornton except under extreme drought conditions. The upper and lower boundaries of a “transition” zone are not obvious in Falls Lake but may be defined (or at least influenced) at times by the presence of the “constriction points” formed by several highway causeways. Finally, the lower portion of Falls Lake, while much deeper and exhibiting clearer water than the upper lake, has a much more river-like profile, with the reservoir confined to a relatively narrow channel defined by the constrained topography of the former Neuse River. These differences suggest that Falls Lake, while certainly a reservoir by definition, is not necessarily typical in at least some of its physical characteristics, and therefore may not be expected to exhibit behaviors consistent with other reservoirs. This is not surprising, and in fact, Ford (1990) states that “all reservoirs are unique, and specific reservoirs differ from year to year as a result to (sic) hydrodynamics and transport.”

Ford (1990) further distinguishes between reservoirs and lakes, noting that, since reservoirs are usually formed by impounding rivers, their hydraulic residence properties are very different from natural lakes (which are typically fed only by small streams and surface runoff). Thus, the mean annual hydraulic residence time for a reservoir may be a poor representation of the instantaneous effect of inflows in shorter time periods, and in fact, hydrodynamic fluctuations and irregularities may be more important than the average conditions in determining transport and mixing in reservoirs. In explaining reservoir transport processes, and in particular meteorological influences, Ford notes that “a reservoir is always in a state of flux and is never in equilibrium (steady state) with the forcing functions.” These dynamics can be important forewarnings for model development practitioners in constructing models to explain or predict reservoir behavior.

While natural lakes tend to be located in the upper portions of watersheds, reservoirs tend to be lower in the watershed, which means sediment transport in reservoirs can be very different from lakes, with more overall sediment input, and increased types of some sediments including pollutants and nutrients (Thornton 1990b). Natural lakes tend to receive sediment inputs more evenly distributed around the lake, whereas reservoirs tend to get most of their sediment inputs at the upper end of the water body. Studies have found order-of-magnitude differences in sedimentation rates from the upper to lower portions of reservoirs. This situation likely exists in Falls Lake, which commonly experiences high suspended solids from watershed erosion and sediment transport at its upper end, but not in the lower portion of the reservoir (see Figure 3-26). Additional discussion of rates of sedimentation observed in Falls Lake is provided in Section 5.4. Walker et al. (2007) refer to a reservoir classification system based on the part of the watershed where water is impounded. Under that classification, Falls Lake could be considered a “tributary-storage reservoir” which are impoundments of several low-order rivers lying toward the upper end of the overall watershed, as compared with impoundments on the mainstem of a single river farther downstream. Tributary-storage reservoirs are commonly used for flood control, and can have highly variable hydraulic residence times, both of which apply to Falls Lake.

A primary characteristic of most reservoirs is the ability to control outflows via releases from a dam or other control structure. Thornton (1990b) points out that water level fluctuations and changes in volume caused by management of water levels in reservoirs can influence sedimentation patterns, morphology, mixing regime, water exchange between coves and the main body of the reservoir, residence time, and other factors. When reservoir outflows are low (long residence time), sediment tends to fall out at the upper end of a reservoir, but when outflows are high (short residence time), sediment can be carried much farther down the reservoir. Sediment particles can also be transported differentially based on size or density as water levels change in a reservoir.

Water level fluctuations and sedimentation processes and patterns can substantially affect overall water quality and other ecological conditions in reservoirs. According to Thornton (1990b), fluctuating water levels are a "major biotic stress in reservoir ecosystems" affecting sedimentation patterns and aerobic/anaerobic spatial patterns. Sediment transport processes in the transition zone of a reservoir often lead to anoxic conditions in the hypolimnion, but the hypolimnetic volume in that zone is relatively small. Thornton (1990b) further notes that reservoirs are often viewed as plug-flow reactors, with longitudinal patterns of sedimentation commonly leading to eutrophic conditions in the upper reservoir and oligotrophic conditions in the lower reservoir. This spatial pattern could mean "the direct application of many nutrient loading models developed from lake databases to reservoirs may not be warranted" (Thornton 1990b). Walker et al. (2007) also advise such caution, saying “Because of the many differences between natural lakes and reservoirs with respect to nutrients and primary production, empirical models developed from dataset (sic) for natural lakes tend not to work well in reservoirs.” The UNRBA modeling team will evaluate databases for reservoirs including those compiled by the USACE and EPA.

Kennedy and Walker (1990) discuss nutrient dynamics in reservoirs, pointing out significant ways that such dynamics differ from those observed in most natural lakes. Many of their assertions parallel those of Thornton (1990a and 1990b) and Ford (1990) with respect to the importance of physical factors, hydrology, and sedimentation processes. A primary factor influencing chemical and biological processes is the strong advective component of water movement resulting from the fact that a reservoir is formed within a flowing system. Although reservoirs are often thought of as lakes, water generally moves through them from the upper end to the dam at rates much higher than in natural lakes. When dam releases are adjusted to control water levels or downstream flows, residence time for water in a reservoir can change substantially as discussed in Section 5.8.

Kimmel et al. (1990) reviewed algal productivity rates for more than 160 lakes and reservoirs and noted that the reservoirs were classified as eutrophic at more than twice the frequency of natural lakes. In contrast, Doubeck and Carey (2017) analyzed data from the EPA’s National Lakes Assessment database representing more than 1,000 lakes and determined that natural lakes are more eutrophic than reservoirs, averaging higher TN and chlorophyll-a levels across the country, although reservoirs in northern states have higher TP than natural lakes in the same region. They discuss these findings in light of lake morphometry, watershed and lakeshore land use, and other factors, but it is also important to note that areas with high numbers of natural lakes tend to have few impoundments, and vice versa.

Variability in reservoir inflows and discharges can set up interesting spatial patterns longitudinally (Kennedy and Walker 1990, Hart and Hart 2006). For example, if a rain event pushes a large volume of water into the upper end of a reservoir, and the higher stream discharge also carries higher nutrient concentrations than during lower flows, that volume of water may move down the reservoir as “plug flow” or a “pulse” that has a different potential for algal production than the water in front of it or behind it. For a long reservoir, a series of rain events could generate more than one pulse moving down the reservoir, with the size and spacing of the pulses dependent on the size and frequency of the rain events, and the rate of release at the dam.

Falls Lake seems likely to experience such patterns, given that (1) most of its input occurs at the upper end of the reservoir, (2) the UNRBA Special Study looking at water quality during high tributary flows showed increased levels of nutrients during storm events, and (3) the long, narrow character of much of the reservoir facilitates plug flow of water masses down the reservoir with minimal influences from horizontal mixing. Such spatial differences in nutrient and algal productivity distribution can have important ramifications for assessing and managing a reservoir like Falls Lake. For example, monitoring conducted shortly after a large storm event could show elevated TN, TP, and chlorophyll-a at one or two stations along the middle of the channel of Falls Lake, with lower levels at the other stations. The following month, the elevated nutrients and algae levels might appear at stations farther down the reservoir because the “pulse” from the storm is making its way toward the dam. Looking at data from these two months without considering the plug flow of the system moving pulses along, it might appear that different parts of the reservoir are simply susceptible to elevated nutrient and algae levels at unpredictable times and locations. But consideration of the hydrodynamics could reveal that the same pulse of water was actually measured twice at two different places along the reservoir (i.e. considering time of travel). The lake modeling underway by the UNRBA Modeling Team will include water movement and residence time in Falls Lake.

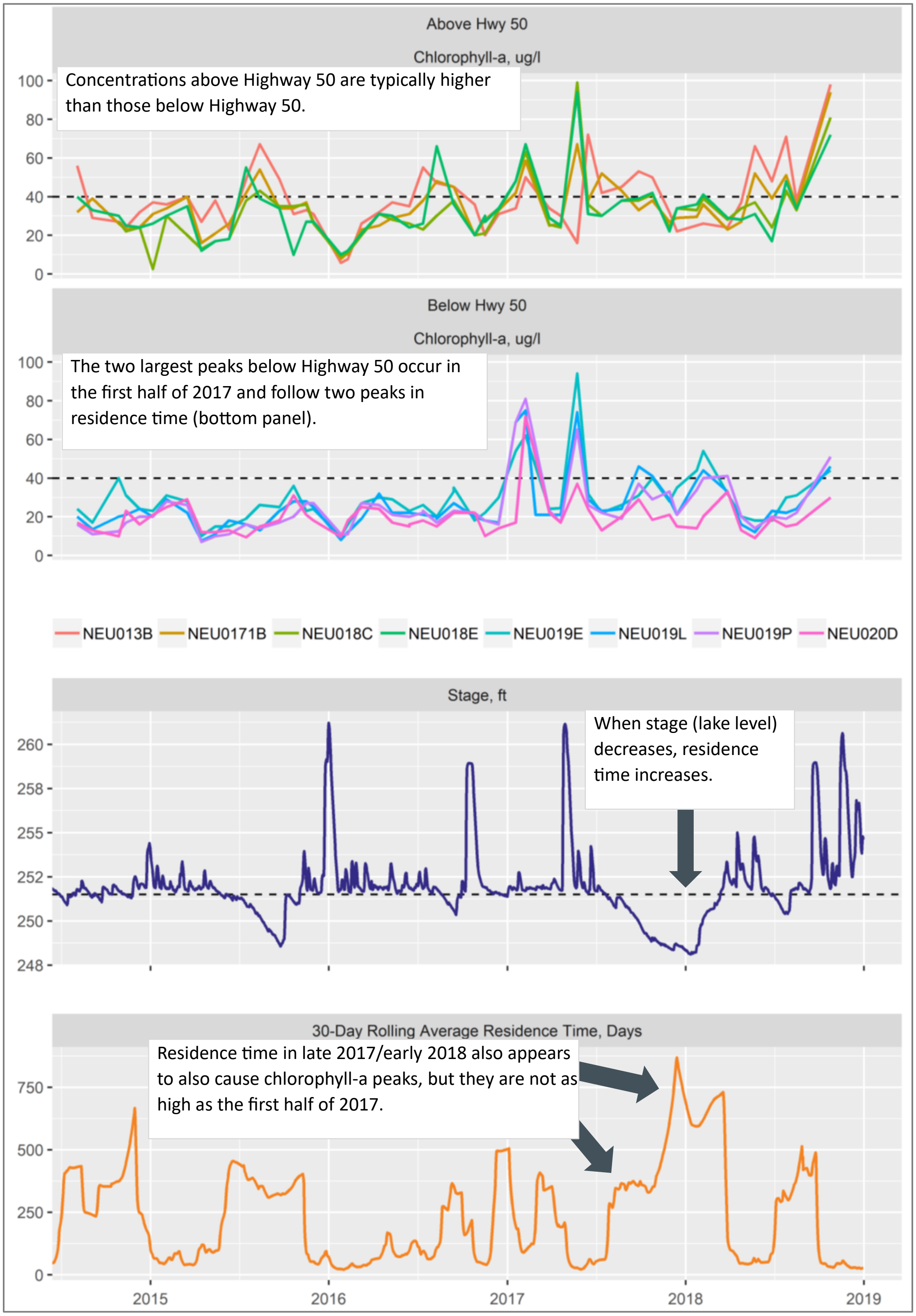
Water movement-time of travel- could be important when considering the degree to which a reservoir is experiencing high nutrient or chlorophyll-a levels, since assuming that two parts of the water body have elevated levels over a two-month period is different from assuming only one area is elevated, but it is moving down the reservoir. The UNRBA’s Special Study evaluating water quality dynamics associated with the “constriction points” (highway causeways) provided some insight into the movement of pulses of water from one part of the reservoir to another, but there are sufficient monthly monitoring data to look for longitudinal water quality patterns elsewhere in the reservoir and associate them with antecedent rainfall events. The UNRBA will consider evaluating these types of relationships as part of the empirical modeling being conducted to support the re-examination.

With respect to nutrient management, Kennedy and Walker (1990) note the substantial impact that dam releases can have on water quality in a reservoir, based on the configuration of the release structure and the degree of management exerted over discharges. If releases are managed without consideration of their influence on water quality, adverse changes may occur. But managing releases with an understanding of their potential to change water quality may offer another tool for maintaining or improving reservoir conditions. This is also emphasized by Walker et al. (2007), who note: “Numerous studies have shown a strong relationship between hydraulic residence time and primary production, with long residence times being associated with higher abundances. Because hydraulic residence time is closely linked with primary production, lands and reservoirs can be classified by residence time as part of nutrient criteria development."

Echoing the model outlined by Thornton (1990a), Kimmel et al. (1990) discuss productivity as related to the three zones in a reservoir, opining that "the dynamic nature of reservoir inflow and discharge explains a great deal about why individual reservoirs can appear so different from one another." They also acknowledge the possibility of having algal productivity controlled by managing dam releases to reduce residence time in a reservoir. They point to analyses of relationships between hydraulic residence time and algal standing crop in rivers, lakes and reservoirs, but also suggest that direct control of algal abundance is likely restricted to systems with residence times of less than 60 to 100 days. Changes in the Falls Lake dam release rate can cause the instantaneous residence time to drop well below 100 days for extended periods (Figure 5-46), suggesting it may be possible for dam release rates to control algal abundance in the reservoir (Kennedy 2005) provides a detailed discussion of how the nature and timing of water releases can affect water quality and other conditions within and below a reservoir. Once the hydrodynamic water quality model for Falls Lake is developed and calibrated, the UNRBA may consider developing scenarios that include lake operations to understand the effects on water quality and potential management strategies.

Figure 4-1 is a time series of chlorophyll-a levels at the in-lake stations as well as the lake surface elevation and lake residence time (Section 5.8) observed during the UNRBA monitoring period. The prior 30-day rolling average residence time is shown in this figure to demonstrate conditions in the lake preceding the monthly lake sampling conducted by DWR. From this figure, it is clear that chlorophyll-a levels among monitoring stations – and over time - are quite variable. Chlorophyll-a levels commonly differ by more than 25 µg/L from the lowest to the highest value within a given month (with the exception of January 2016, when the water level rose nearly ten feet in response to a large storm event). Peaks at some stations during some months correspond to low levels at other stations (e.g., late 2016). Seasonal differences are also apparent; the sudden increase in lake level at the beginning of 2016 (winter) was followed by a dramatic, lake-wide decrease in chlorophyll-a, while a very similar increase in lake level in 2017 (late spring) was followed by an equally dramatic, lake-wide increase in chlorophyll-a concentration. Thus, there are factors affecting primary productivity at a relatively small scale and other factors that influence the entire reservoir.

In general, Figure 4-1 suggests that periods when the lake is at or below its normal pool level (251.5 feet) exhibit some of the greatest variability in chlorophyll-a among monitoring stations (e.g., late 2015, mid 2016, and fall of 2017). The dramatic responses to changes in lake level (and/or the subsequent rapid release of water through the dam) seen in early 2016 and mid-2017 seem to indicate the potential for affecting water quality by managing lake level and/or residence time in Falls Lake. However, the complexity of the relationship is evident in the apparently opposite responses in chlorophyll-a levels noted above, and the fact that a sudden seven-foot increase in lake level (and equally sudden drop) in the fall of 2016 appeared to have no effect at most of the monitoring stations. Further exploration by the modeling team may reveal more predictive patterns.



Concentrations above Highway 50 are typically higher than those below Highway 50.

The two largest peaks below Highway 50 occur in the first half of 2017 and follow two peaks in residence time (bottom panel).

When stage (lake level) decreases, residence time increases.

Residence time in late 2017/early 2018 also appears to also cause chlorophyll-a peaks, but they are not as high as the first half of 2017.

Figure 4-1. Chlorophyll-a concentration at DWR monitoring stations along the channel of Falls Lake as well as the lake surface elevation and 30-day rolling average residence time during the UNRBA monitoring period

The UNRBA may consider exploring spatio-temporal patterns to determine whether there is value in considering them as part of the linkage between water quality and assessment, management or restoration efforts. Longitudinal patterns and temporal variability in water quality may be informative in the development of "assessment units" for Falls Lake. If the lake exhibits nutrient dynamics and algal production along a spatial continuum, with variability strongly influenced by hydrodynamics, assessment delineations could be developed to reflect that pattern. Kennedy and Walker (1990) also point to the concept of "riverine," "transition," and "lacustrine" zones in reservoirs, but note that boundaries between the zones are difficult to locate and temporally unstable. This amplifies the need to consider the relationship–and dependence–of water quality conditions in one part of the reservoir with that of the other portions in regulatory assessments.

Kimmel et al. (1990) list a series of factors that can affect algae production, pointing to the paradigm that one factor limits algal growth, such that an increase in that factor would allow increased algal growth until another factor becomes limiting. But they further assert that "because the planktonic environment is physically, chemically, and biotically dynamic, the concept of a complex of environmental factors controlling algae growth is more appropriate than that of control by a single factor." They point out that nutrient and light availability can certainly limit algal productivity in reservoirs, but that both of those factors are highly dependent upon reservoir inflows, which deliver nutrients, but also carry suspended solids that affect light availability. This seems to describe the pattern in Falls Lake, where the upper end of the lake receives the majority of nutrient inputs but is also characterized by high turbidity which may actually limit the expression of nutrients (at least until sediment drops out of the water column further down the lake. The UNRBA may consider evaluating the relationship between suspended solids (turbidity) and algae growth as part of its analyses. It would be beneficial to know whether controlling watershed erosion to lower turbidity could lead to different phytoplankton dynamics because of changes in the light regime. These relationships may be evaluated using the hydrodynamic water quality model under development by the UNRBA.

The issue of light availability is particularly interesting for Falls Lake because of recent research led by Hall (2019) which found that the algal community in Jordan Lake NC shows far better shade adaptation than has previously been assumed and used in mechanistic models for the lake. Laboratory tests which exposed aliquots of water from the Jordan Lake reservoir to various levels of irradiance showed that algal production (measured as carbon assimilation) was saturated at irradiance levels between 20 and 80 micro Einsteins per meter squared per second ($\mu E/m^2/sec$). Hall noted that previous modeling work on Jordan Lake assumed saturation levels on the order of 500 $\mu E/m^2/sec$. This means algal communities in the reservoir appear to be much more efficient in capturing light than had been previously assumed. This finding is directly transferable to Falls Lake, given that the algal communities of the two systems in adjacent watersheds are likely to be very similar. Hall's findings will be considered when setting up irradiance-production relationships in the Falls Lake models.

Embayments where tributaries enter the reservoir can have different water quality and other limnological characteristics from the main stem of the reservoir, leading to even greater spatial variability than occurs longitudinally along the impoundment (Hart and Hart 2006). This situation is clearly evident on Falls Lake, where a broad range of conditions is represented among the various arms of the reservoir.

Hart and Hart (2006) point to studies suggesting that releases of methane and carbon dioxide from reservoir sediments may contribute considerably to greenhouse gas emissions. The EPA is currently conducting a study on methane emissions from Falls Lake, as an extension of a prior study of a number of Midwestern reservoirs (Walker 2019). The bathymetry and sediment mapping data acquired by the UNRBA will be provided to the EPA to support its study.

Global climate change is anticipated to affect reservoirs in a number of ways, including changes in the timing and magnitude of rainfall (which may affect not only reservoir hydrology, but also runoff patterns and erosion conditions), increases in air and water temperatures (which may affect the growing season, growth rates, and species composition of algal communities), changes in watershed conditions such as humidity and soil moisture, and even the potential migration of exotic species and certain waterborne disease vectors northward as conditions become suitable for their survival (Hart and Hart 2006). Obviously, some of these risks are outside the scope of the re-examination of the Falls Lake Rules, but to the extent that the mechanistic or empirical models consider watershed and lake hydrology or air and water temperatures in predicting lake processes, sensitivity analyses can be performed to examine how the system might behave under modified rainfall and temperature regimes predicted by various climate change models.

The modeling team will use southeastern reservoirs as the basis of model constants and coefficients preferentially over values from northern or natural lakes. Further, the modeling team will continue their engagement with the UNRBA subject matter experts and consider their guidance when appropriate in discussing potential model applications for consideration by the UNRBA to support the re-examination:

- Longitudinal spatial patterns and dynamics in Falls Lake and how they may be related to the magnitudes and temporal patterns of inputs at the upper end of the reservoir. Consideration of how spatio-temporal patterns may affect assessment and management efforts for the lake.
- General zonation common to most impounded rivers, acknowledging different expectations for the riverine, transition, and lacustrine zones along the reservoir.
- Consideration of longitudinal zonation with respect to the evaluation of regulatory and management approaches for Falls Lake to avoid attempting to force one portion of the reservoir to have conditions that may be difficult or impossible, given the biogeochemical factors and gradients throughout the remainder of the system.
- Consideration of water level and residence time changes in the reservoir brought about by both inflows and by managed releases through the dam. Such changes likely affect sediment transport; longitudinal, vertical, and horizontal changes in water quality; and the location, degree, and duration of hypoxic conditions.
- Consideration of relationships between suspended solids (turbidity) and algae growth and particularly the degree of shade adaptation of phytoplankton in the region and impacts on irradiance saturation values and related parameters, with potential sensitivity analyses to examine the effects of shade adaptation, nutrient limitation, and other factors controlling algal production.

Section 5 Extended Analysis and Discussion

This section provides the results of supplemental analyses of selected portions of the data presented in Section 3, as well as presenting a series of additional subject areas related to water quality in Falls Lake. Topics include spatial water quality patterns, relationships between watershed characteristics and water quality, nutrient loading estimates and patterns, reservoir bathymetry and morphology, sediment characteristics, hydraulic residence time, nutrient limitation, algal toxins, and recreational use evaluation. These evaluations support the three UNRBA Monitoring Program objectives: revise lake response modeling, allocate loads to sources and jurisdictions (i.e., support watershed modeling), and support alternative regulatory options as needed. This information is offered for consideration by the UNRBA and its Executive Director, Subject Matter Experts, PFC and the Modeling Team members as they evaluate and plan for future analyses, modeling, and the development of policy recommendations for consideration by UNRBA members. All reference materials cited can be made available upon request.

5.1 Water Quality

5.1.1 Upstream to Downstream Trends in Lake Water Quality

Falls Lake is a long, drowned, and man-made river system reservoir that spans over 20 miles upstream of the dam. Figure 5-1 depicts an upstream to downstream visual comparison of nine different water quality parameters. For most of the parameters, reported values consistently decrease from upstream to downstream: chlorophyll-a, TN, organic nitrogen, TP, and turbidity. Secchi depth increases from upstream to downstream as water clarity increases. These patterns indicate an improvement in water quality from the upper part of the reservoir to the downstream part near the dam and the City of Raleigh's intake. These longitudinal trends were predicted prior to the construction of the reservoir (DNER 1973, USACE 1974). The trends are also entirely consistent with the pattern observed in many reservoirs, as discussed in Section 4.2. This gradation along the reservoir is a function of its morphology and the fact that water and other materials are continuously moving through it. It also means it would be difficult or impossible to manage the entire reservoir to attain a uniform water quality condition along its length because the physical and biogeochemical process that occur from the top off the system to the bottom will always result in a gradient of conditions along its length. In contrast with the parameters listed above, TOC concentrations are relatively consistent from upstream to downstream. The City of Raleigh closely monitors TOC in the lake as higher concentrations can require additional treatment for drinking water.

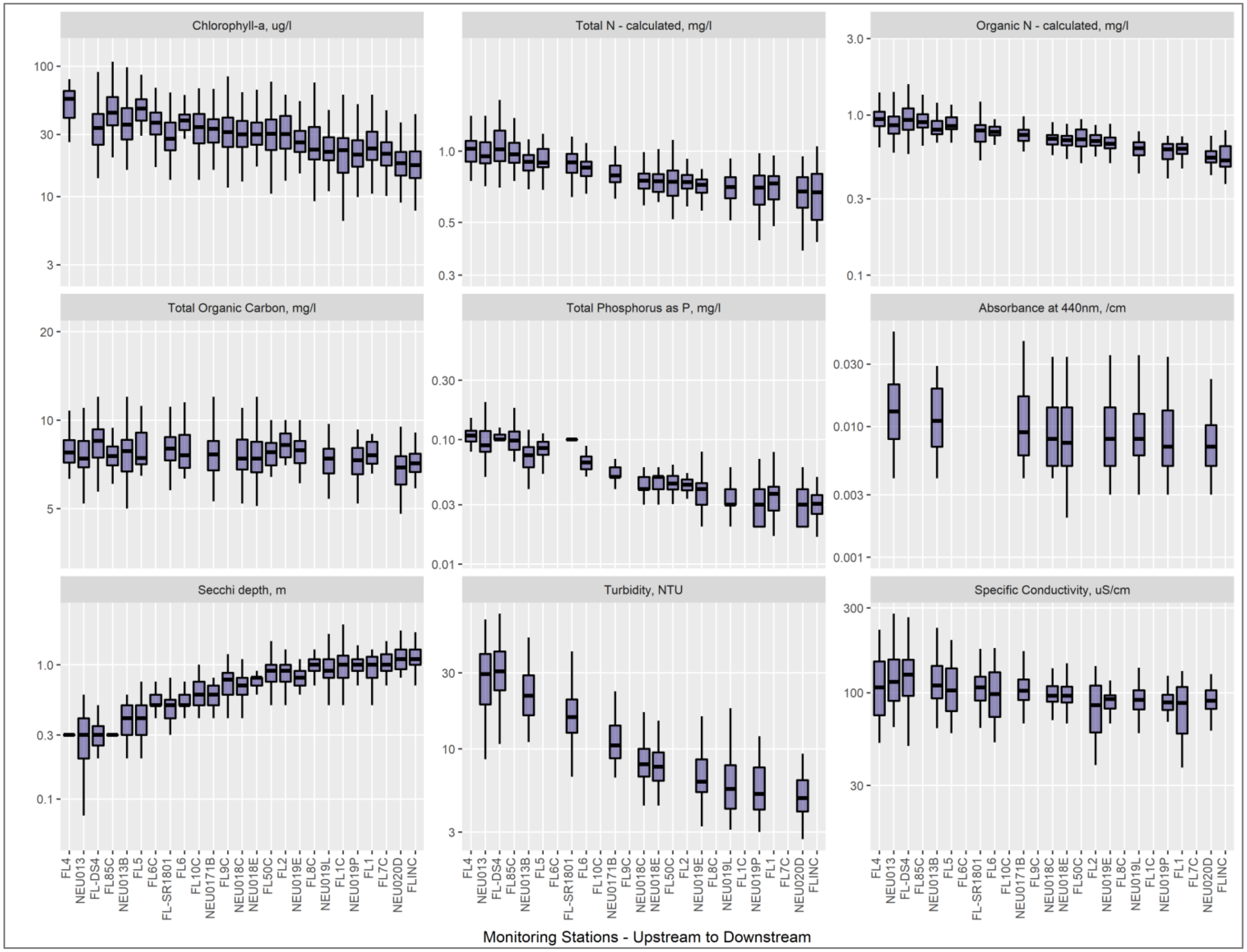


Figure 5-1. Upstream to downstream trends of key lake water quality parameters (August 2014 - October 2018).
All parameters are displayed using a logarithmic scale

5.1.2 Evaluation of Chlorophyll-a Relative to Other Water Quality Parameters

As noted previously, portions of Falls Lake have been listed as “Impaired” on North Carolina’s 303(d) list based on occurrences of chlorophyll-a concentrations above 40 µg/L, including several portions of the reservoir listed as not meeting the chlorophyll-a standard in the draft 2018 Integrated Report produced by DWR. A primary consideration of the re-examination effort is to identify factors in Falls Lake or its watershed that may be associated with elevated chlorophyll-a concentrations to inform the development of a management strategy that can improve water quality conditions. As one part of the examination of such relationships, in-lake concentrations of chlorophyll-a were compared to other water quality parameters from August 2014 to October 2018.

Of the monitored in-lake parameters, most show no substantial positive or negative correlation with chlorophyll-a concentration, based on linear regressions using data from all months and all stations. It is possible that stronger relationships exist either within portions of the lake, or during portions of the year; such relationships may be elucidated through the modeling efforts. A small number of parameters do show some degree of relationship with chlorophyll-a levels. Figure 5-2 is a set of scatterplots showing relationships between chlorophyll-a and six other parameters. Each individual scatterplot also depicts data points along a continuum from stations in the upper portion of the lake in green to the lower lake in blue, to assist in visually determining whether relationships may differ along the length of the reservoir. Visually, the strongest relationship to chlorophyll-a is with organic nitrogen. This is expected since organic nitrogen comprises a substantial portion of the algal cells that contain chlorophyll-a. The same scatterplot suggests a somewhat different relationship between organic nitrogen and chlorophyll-a in the upper lake than in the lower lake, with a broader spread of the green symbols (i.e., greater variability in the upper lake) than the blue symbols (i.e., a stronger linkage in the lower lake).

A similar, but more variable relationship can be seen between TN and chlorophyll-a because most of the TN is in the organic form. The scatterplot for TP shows that it generally rises with increasing chlorophyll-a. Like organic nitrogen, phosphorus is a constituent of living algal cells, and thus is expected to be positively correlated with chlorophyll-a. But the relationship is complex for a number of biogeochemical and physiological reasons, so the relationship shows a great degree of variability. As discussed in Section 4, the relationship between chlorophyll-a and turbidity is complicated by the fact that mineral turbidity (i.e., suspended particles like silt and clay) can prevent algal growth by limiting light penetration in the water, but algal cells themselves can contribute substantially to turbidity by reducing light transmission in the water. Since specific conductivity is a measure of dissolved ionic substances in the water, its minor relationship to chlorophyll-a is likely due to the inclusion of various nutrients and micronutrients represented as part of that parameter.

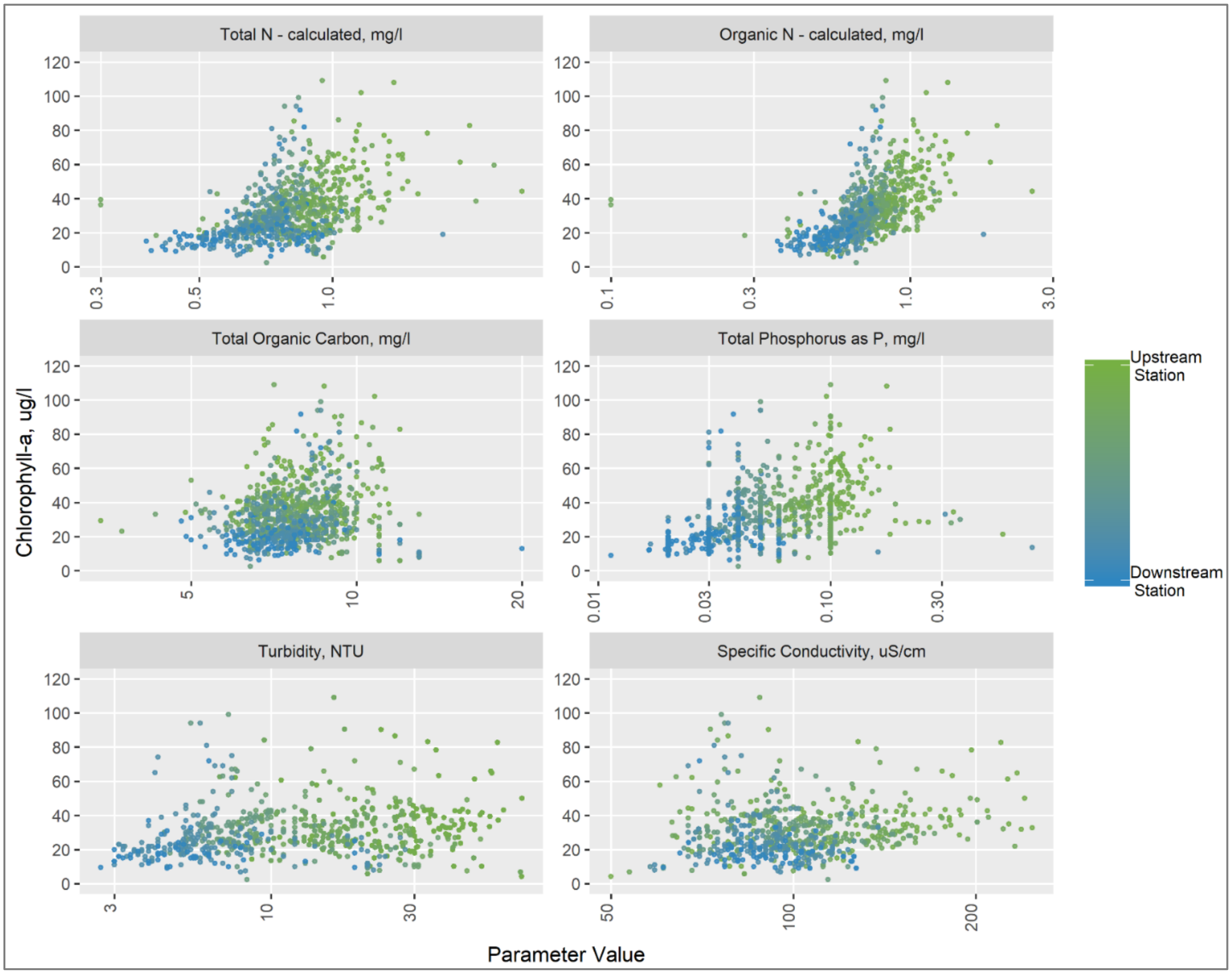


Figure 5-2. Comparison of chlorophyll-a concentrations to other lake water quality parameters (August 2014 – October 2018)

Note that all x-axes are displayed using a logarithmic scale.

A primary concern for drinking water treatment is TOC levels in Falls Lake because of the potential for increased treatment costs to avoid undesirable disinfection by-products. As with nitrogen and phosphorus, living algal cells contain organic carbon, so it is reasonable to assume some relationship would exist between organic carbon and chlorophyll-a. However, data points in the scatterplot relating TOC and chlorophyll-a in Figure 5-2 show more of a circular, “shotgun” pattern than each of the other five parameters, suggesting a generally weak relationship. To evaluate this relationship further, a multiple regression was performed between TOC and chlorophyll-a on a station-by-station basis (Table 5-1). Data from each monitoring station (DWR, CAAE, and City of Durham) were analyzed, initially with full-year data, and then with growing-season-only data, yielding 36 individual regressions. Essentially all results showed very weak relationships between chlorophyll-a and TOC, with the full-year data yielding an average r^2 value of 0.05, and the growing-season-only data r^2 values averaging 0.10. The highest observed r^2 value was 0.36 (for growing-season-only data at CAAE station FL1 - near Upper Barton Creek arm). These results indicate that TOC in the reservoir does not vary with chlorophyll-a levels to any significant degree, even on a station-by-station or growing-season-only basis. This is not unexpected based upon visual comparison of Figure 3-25 which shows a clear pattern of higher chlorophyll-a levels in the upper portion of the reservoir and declining levels throughout the reservoir toward the dam–with Figure 3-28–which shows relatively constant levels of TOC throughout the reservoir with relatively little variability. If chlorophyll-a was significantly related to TOC, Figure 3-25 and Figure 3-28 would appear more similar. The lack of a meaningful relationship between these parameters is also consistent with the finding described previously that nearly all TOC in the reservoir is in the form of DOC. This means most TOC exists outside of algal cells in a form small enough to pass through the filtration process involved in quantifying DOC, likely originating from the decomposition of organic material originating in the reservoir or delivered from the watershed by tributaries and not within algal cells.

Table 5-1. Correlation of Chlorophyll-a and TOC at Monitoring Stations in Falls Lake

Organization - Station	r^2 for Annual Data	r^2 for Growing Season Data
CAAE - FL4	0.036	0.214731
Durham - FL-DS4	0.068	0.062724
CAAE - FL85C	0.130	0.276458
DWR - NEU013B	0.064	0.076077
CAAE - FL5	0.038	0.019955
Durham - FL-SR1801	0.053	0.053694
CAAE - FL6	0.096	0.10282
DWR - NEU0171B	0.010	0.142637
DWR - NEU018C	0.002	0.065437
DWR - NEU018E	0.003	0.057007
CAAE -	0.090	0.006718
CAAE - FL2	0.001	0.023651
DWR - NEU019E	0.001	0.010156
DWR - NEU019L	0	0.002243
DWR - NEU019P	0.021	0.124054
CAAE - FL1	0.183	0.360289
DWR - NEU020D	0.001	0.000545
CAAE - FLINC	0.082	0.197622

Algal productivity can depend on an array of factors, as discussed by Kimmel et al. (1990). The complexity of factors can make it difficult to find meaningful relationships between water quality parameters and chlorophyll-a concentrations. This dynamic complexity complicates the development of defensible numeric nutrient criteria and the implementation of management strategies to control algal growth. The UNRBA's lake response modeling effort will use a broad array of simulation techniques to represent these complex relationships and explain or predict chlorophyll-a levels based on numerous variables. The empirical modeling effort will also explore relationships among parameters that will incorporate regional datasets for initial development and refinement based on data collected in Falls Lake.

5.1.3 Comparability of UNRBA and DWR Tributary Data

Five UNRBA tributary monitoring stations were co-located with stations monitored monthly by North Carolina Department of Environmental Quality (NC-DEQ) as part of the DWR's Ambient Monitoring System program. Samples collected by the two organizations are not necessarily collected on the same day, and for any given month, the samples could be collected up to 15 days apart. Because samples are not collected at the same time by both organizations, they cannot be considered duplicate samples and there is no a priori expectation that the measured nutrient concentrations fall within any specific threshold of each other. However, to the extent that measurements collected over a long period of time are expected to be representative of the average conditions at a particular location, then the distributions of values observed would be similar for the two data sets.

Distributions of values for characteristics measured by both DWR and the UNRBA monitoring programs are shown in Figure 5-3 (field parameters) and Figure 5-4 (lab measurements) below. For each location and characteristic, a Wilcoxon signed-rank test was performed to quantify whether measurements from DWR and the UNRBA follow statistically similar distributions. This statistical test is non-parametric and therefore does not assume measurements follow a normal distribution; because it focuses on measurement ranks rather than mean values, it is also fairly insensitive to measurements subject to censoring by reporting limits (i.e. less than values).

Of the field parameters depicted in Figure 5-3 water temperature, DO, and specific conductivity, did not differ significantly between DWR or UNRBA samples at any of the five stations. pH showed very small differences for Flat River, Eno River, and Ellerbe Creek, with differences in median values of 0.2 standard unit (su) or less. Laboratory measurements (Figure 5-4) were also similar across DWR and UNRBA samples except for the Eno River location's TP and TKN observations. The difference between median values for TP on the Eno River was 0.01 mg/L, which is half of the reporting limit for both DWR and the UNRBA. The difference between median values for TKN was a bit higher at 0.05 mg/L in absolute terms but was just 11 percent of the average TKN concentration measured for the Eno River location (Table 5-2). Much of the data collected at each station for each parameter measured within the 25th to 75th percentile range (represented by the boxes) overlap at each station which indicates comparability across the two data sets.

The distributions of ammonia measurements suggest that DWR values are consistently slightly lower than those measured as part of the UNRBA monitoring program (Figure 5-4). The smallest differences in median values were 0.01 mg/L (Flat River) and 0.02 mg/L (Little River and Eno River). Knap of Reeds Creek and Ellerbe Creek had the highest average ammonia concentrations and also had the highest differences between median values from UNRBA and DWR. At the Knap of Reeds Creek site, the median ammonia value measured by UNRBA was 0.03 mg/L higher than the median DWR measurement; for Ellerbe Creek, the median value measured by UNRBA was 0.04 mg/L higher than the median DWR measurement. The UNRBA Modeling Team will need to consider these data limitations when developing and calibrating the watershed and lake models. Ammonia is a small fraction of the overall nitrogen pool. TKN concentrations, which include ammonia) are similar across the organizations and much higher than the ammonia concentrations. Nitrate plus nitrite concentrations are also similar, and much larger than ammonia and represent a larger pool of inorganic nitrogen for uptake by algae. Thus, the uncertainty associated with the low-level ammonia concentrations will not significantly affect the total simulated nitrogen load to the lake or the response in terms of chlorophyll-a.

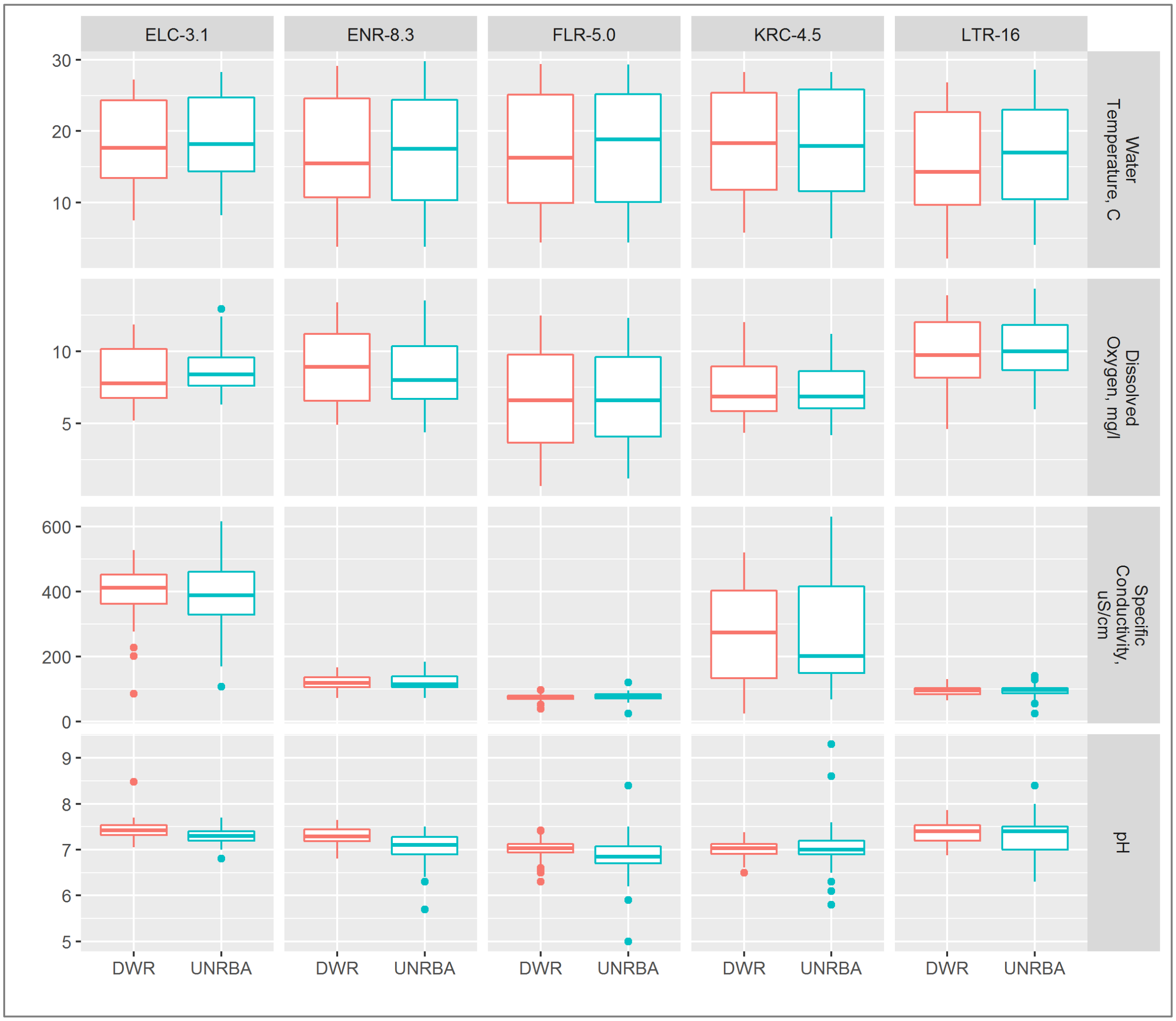


Figure 5-3. Distribution of field values measured between August 2014 and October 2018 at stations monitored both as part of the UNRBA monitoring program and the DWR Ambient Monitoring System.

Figure 5-4. Distribution of laboratory measurements between August 2014 and October 2018 at stations monitored both as part of the UNRBA monitoring program and the DWR Ambient Monitoring System. All values are censored at a common reporting limit of 0.02 mg/L.

Table 5-2. Difference between the median concentrations measured by UNRBA and DWR for all parameter and station combinations that have 95% confidence that the difference between the medians was greater than zero (using the Wilcoxon signed-rank test).

Parameter	Knap of Reeds Creek	Flat River	Little River	Eno River	Ellerbe Creek
Water Temperature (C)	-	-	-	-	-
Dissolved Oxygen (mg/L)	-	-	-	-	-
Specific Conductivity (uS/cm)	-	-	-	-	-
pH (su)	-	-0.2	-	-0.2	-0.1
Total Phosphorus (mg/L)	-	-	-	0.01	-
Nitrate + Nitrite (mg/L)	-	-	-	-	-
Total Kjeldahl Nitrogen (mg/L)	-	-	-	0.05	-
Ammonia (mg/L)	0.03	0.01	0.02	0.02	0.04

5.1.4 Comparability of DWR, City of Durham, and CAAE in-lake Data

The two organizations that collect the majority of the water quality data in Falls Lake are DWR and CAAE. The City of Durham also collects data from two stations at the upper end of the reservoir during the growing season. For most of the water quality parameters, there is very little difference in the visual distribution of samples across the organizations (see figures in 3.3.2). While the nutrient levels reported by CAAE are relatively similar to those reported by other organizations, the chlorophyll-a concentrations often appear substantially higher than adjacent DWR and City of Durham stations.

Review of Figure 3-25 and its underlying data suggests substantial differences in the distribution of some chlorophyll-a concentrations between DWR, City of Durham, and CAAE monitoring stations located near to each other. As one example, DWR station NEU019E and CAAE station FL2 are both located just down-lake of the Highway 50 causeway. Figure 3-25 indicates that chlorophyll-a samples from both stations have comparable lower quartile values, and the CAAE station has a slightly higher median value, but the upper quartile of the data from CAAE FL02 is above 40 µg/L, while that of DWR station NEU013E is closer to 30 µg/L. This apparent variance can be resolved by examining the period of record for each station. CAAE station FL2 did not begin collecting chlorophyll-a samples as photic zone composites until 2016, while DWR used that procedure during the entire UNRBA monitoring period. Comparing only the 2016 to 2018 data from the two entities yields much better agreement.

Another example is DWR station NEU013B and CAAE station FL5, both of which are located near the mouth of Panther Creek in the upper part of the reservoir. The median chlorophyll-a level at the DWR station is about 35 µg/L, while data from nearby CAAE station yields a median of nearly 50 µg/L. Again however, the period of record is different between the data sets depicted in Figure 3-24 and comparing only the concurrent monitoring periods brings the data sets into better alignment. Other pairs of closely-located DWR and CAAE stations did not show the same degree of difference.

Differences between chlorophyll-a results from CAAE and City of Durham are even more apparent in Figure 3-24. CAAE station FL85C is located very close to City of Durham station FL-DS4 near the I-85 causeway, and CAAE station FL6C is at the same location as City of Durham station FL-SR1801. The ranges displayed for both of those station pairs in Figure 3-24 appear quite dissimilar. One difference between the underlying datasets is that City of Durham only collects samples during the growing season, while CAAE monitors year-round. However, that difference would be expected to yield higher median chlorophyll-a values for the City of Durham stations, but in fact, the CAAE medians are higher. When considering only growing season data values for stations FL-DS4 and FL85C, there still appears to be a substantial variance. Across the 2015 through 2018 growing seasons, City of Durham reported 34 percent of its 111 chlorophyll-results above 40 µg/L, while CAAE reported 75 percent of its 76 results above 40 µg/L. The same pattern occurred within each sampling year as well, with CAAE always reporting at least 65 percent of its values above 40 µg/L and City of Durham generally reporting at least 60 percent of its values below 40 µg/L. A similar bi-modal distribution is evident between City of Durham station FL-SR1801 and CAAE station FL6C, but overall chlorophyll-a levels are lower in that portion of the reservoir, so there were far fewer values reported over 40 µg/L.

The cause of these discrepancies is unknown. Unfortunately, there is not a DWR station located near either of these station pairs to provide additional insight into which data set might be biased. DWR station NEU013B is located between the two pairs of stations and shows a range of chlorophyll-a values somewhat higher than the two City of Durham stations, but lower than CAAE station FL85C and similar to CAAE station FL6C.

Modeling and analytical efforts using these data must be cognizant of such discrepancies to control the potential effects of sample bias. In addition, such efforts must take account of general variability within and among data sets. For example, there are cases where City of Durham and CAAE samples collected within just days of each other differed by as much as 40 µg/L.

5.1.5 Comparison of UNRBA Monitoring Period to Post-Impoundment Monitoring of Falls Lake

Previous UNRBA Annual Reports have included limited examination and discussion of data collected prior to the UNRBA Monitoring Program's data collection period (August 2014 – October 2018). The 2018 UNRBA Annual Report (BC 2018) reviewed chlorophyll-a data collected by DWR as far back as 1984 to compare historical measurements to levels reported in recent years. The DWR database from the very early years of the Falls Lake reservoir is limited.

There is however, a substantial data set from the years immediately following the filling of the impoundment. The U.S. Army Corps of Engineers (USACE) commissioned a four-year water quality study to evaluate conditions in the new reservoir. That study shares several characteristics with the UNRBA data compilation effort: (1) it encompassed four years of data collection (July 1983 to June 1987), (2) it used water quality data collected multiple times annually at stations oriented along the thalweg (deepest points) of the reservoir along the length of the reservoir, and (3) it focused primarily on nutrients and algae (phytoplankton) dynamics. The USACE study also reported on several other indicators of lake conditions such as vertical stratification, aquatic vegetation, and fish. Results of the study were published in four annual volumes, with the fourth report providing a summary of the entire study period (Water and Air Research [WAR] 1988).

The 1983 through 1987 USACE-sponsored monitoring documented spatial, seasonal, and year-to-year differences, just as the UNRBA program has observed since 2014. Vertical stratification was documented during the warmer months, particularly in the lower portion of the lake. Phosphorus concentrations were higher in the upper portion of the reservoir than near the dam (as they are today, see Figure 3-23). WAR (1988) documented higher algal cell densities in the upper portion of the reservoir during summer months, but also reported both cell density and algal biovolume varying over orders of magnitude both spatially and temporally. For example, cell density was measured at less than 150 cells per milliliter (cells/ml) in the upper lake in the winter 1987, but at more than 150,000 cells/ml the following spring, and algal biovolume was 20,000 mm^3/m^2 (cubic millimeters per square meter) in the upper lake in the summer of 1986, while it was only 1,100 mm^3/m^2 near the dam. WAR (1988) also noted seasonal patterns in the relative abundance of phytoplankton groups. Blue-green algal species were generally more abundant during warmer months, with a transition to green algae in the late fall, to a predominance of (or co-dominance with) diatom species during the winter and spring months.

Although there were substantial changes between years, there were few consistent directional changes in nutrient or chlorophyll-a levels across between seasons during the initial years. A comparison can be made between a summary graphic presented in WAR (1988) and a similar graphic created with DWR lake monitoring data collected during the UNRBA monitoring period. Figure 5-5 presents a direct comparison between the chlorophyll-a, phosphorus, and nitrogen levels during the first four years of Falls Lake's existence (WAR 1988) and its most recent four years. The side-by-side graphics each contain individual columns representing the average photic zone concentrations for all monitored stations along the reservoir (six stations in 1983 through 1987 and nine in 2014 through 2018), with individual presentation of cool season and warms season means, as well as annual means. The y-axis scales for each of the paired graphs is the same, allowing for direct visual comparison of reported concentrations. The figure shows that average chlorophyll-a levels during the warmer months were substantially lower during the recent years than in years just after the reservoir was filled. Year-round (annual) TP and TN levels (as reflected by the overall height of the columns) have been markedly lower in recent years than in the early years which are typical of a new reservoir, with some of the difference in TN levels attributable to lower ammonia and nitrate-nitrite concentration in the recent years.

Figure 5-6 provides a comparison of time series for chlorophyll-a concentrations, TN loading, TP loading, and hydraulic loading between 1983 through1987 and 2014 through2018. The loading graphs reflect loading from the six largest tributaries, with the 1983 through1987 loadings calculated from USGS flow and water quality monitoring data from those streams (WAR 1988). The comparison indicates generally lower and much less variable chlorophyll-a concentrations, as well as lower TN and TP loading from the six largest tributaries in recent years. The overall range and the variability of hydraulic loading appears more similar between the two periods than do nutrient loads and chlorophyll-a levels.

While the comparisons in Figure 5-5 and Figure 5-6 are not station-by-station evaluations, and thus may obscure other localized changes between the two periods, there is a strong indication that current overall nutrient and algal levels in Falls Lake are not higher than, and may be lower than, when it was first impounded.

Section 4.2 describes common patterns in the aging of reservoirs, including increases in nutrient concentrations and algal and/or macrophyte productivity. The above comparison suggests Falls Lake has not experienced this situation. There may be value in additional review of the underlying data from the 1983 through1987 study to see if more refined comparisons can be made to identify changes in specific portions of the reservoir.

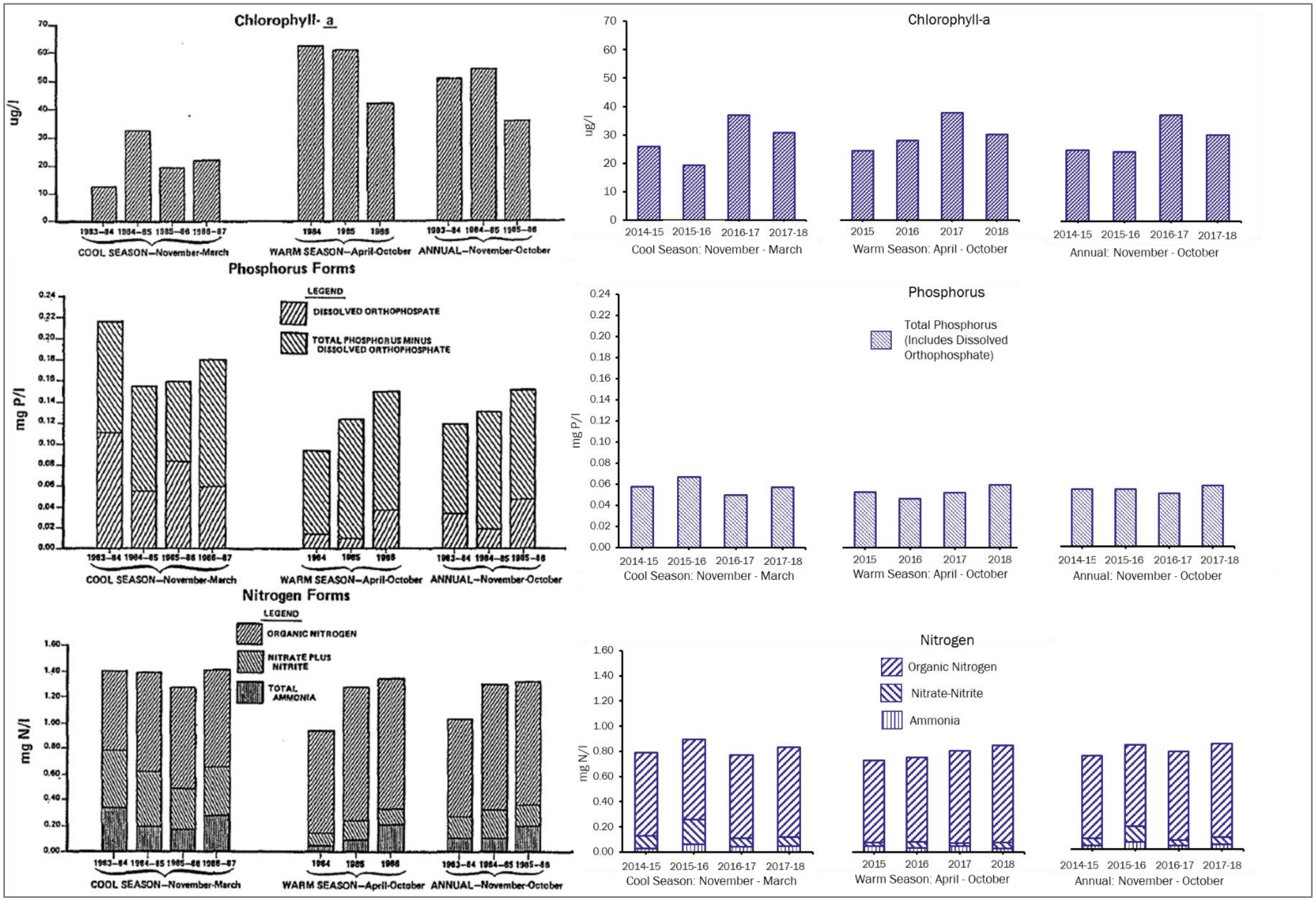


Figure 5-5. Comparison of lake-wide cool season, warm season and annual mean concentrations of Chlorophyll-a, TP and TN from 1983-1987 and 2014-2018 monitoring. Graphics on the left are from WAR (1988); graphics on the right are based on mainstem DWR samples.

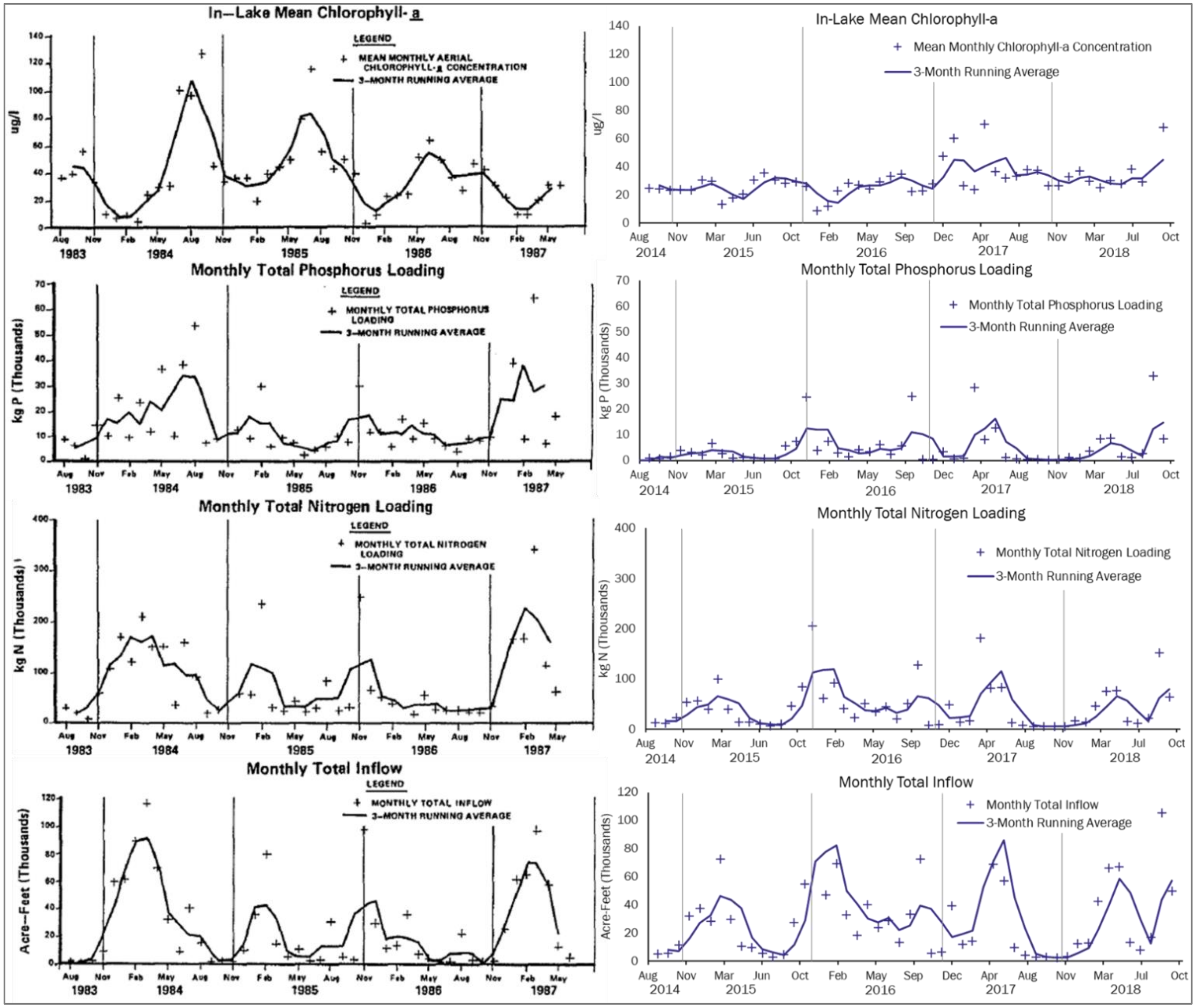


Figure 5-6. Comparison of temporal patterns in in-lake Chlorophyll-a, and TP loading, TN loading, and inflows from primary tributaries from 1983-1987 and 2014-2018. Graphics on the left are from WAR (1988); graphics on the right are based on mainstem DWR samples.

5.1.6 Comparison of In-Lake Chlorophyll-a from UNRBA Monitoring Period with DWR Baseline Period

In addition to the comparisons to post-impoundment data, comparisons between the UNRBA monitoring period (August 2014 to October 2018) to the baseline period of the Falls Lake Nutrient Management Strategy were also conducted. Overall, there is less difference between these two periods compared to the post-impoundment period.

Figure 5-7 compares growing season average and annual average data for the recent monitoring period and the baseline period. These comparisons only include data collected by DWR along the thalweg of Falls Lake, and the averages include all of the stations. For the baseline period, only one year (2006) had a complete year of monitoring, so the comparisons of annual averages only include 2006. Similarly, 2018 is excluded from the annual comparisons because this report does not include data past October 2018. For both TP and TN, the annual average concentrations in Falls Lake for the recent monitoring period are similar to those from the baseline period. For chlorophyll-a, the annual averages for 2014 to 2016 show a decreasing trend and were each less than 2006; the annual average in 2017 was higher than 2006. As described previously, 2017 was a relatively dry year. While water delivery and pollutant loading to the lake was lowest in 2017 relative to the other recent monitoring years, the chlorophyll-a concentrations were higher. This result is expected as dryer years tend to have greater residence times and higher rates of algal growth. For the growing season averages, the recent monitoring period generally has lower TN and TP concentrations compared to the baseline period. Chlorophyll-a concentrations for three growing seasons were lower than baseline; two growing seasons had average concentrations that were similar to baseline.

Figure 5-8 provides a temporal comparison of the chlorophyll-a in-lake concentrations, nutrient loads, and hydraulic loading between the baseline and recent monitoring periods. As with the comparisons of average conditions between the baseline and recent monitoring periods shown in Figure 5-7, the time series comparison indicates similar ranges of chlorophyll-a concentrations observed in both periods. TN and TP loading from the four largest tributaries are also relatively similar. The overall range and the variability of hydraulic loading appears more similar between the two periods than do nutrient loads and chlorophyll-a levels.

Monitoring data from 2014-2018 suggests nutrient and chlorophyll-a levels in Falls Lake are similar to, or lower than, conditions observed during the 2005-2007 baseline monitoring period. Given that flows into the lake were higher during the latter period, the fact that the loads were not higher may be attributable to implementation of new development rules in 2011 that limit nutrient loading from new development, improvements at WWTPs, reductions in atmospheric deposition of nitrogen, changes to farming practices, and overall reductions in agricultural land in the basin.

Figure 5-7. Lake-wide Annual Average Chlorophyll-a and Nutrient Concentrations for both the baseline and UNRBA monitoring period

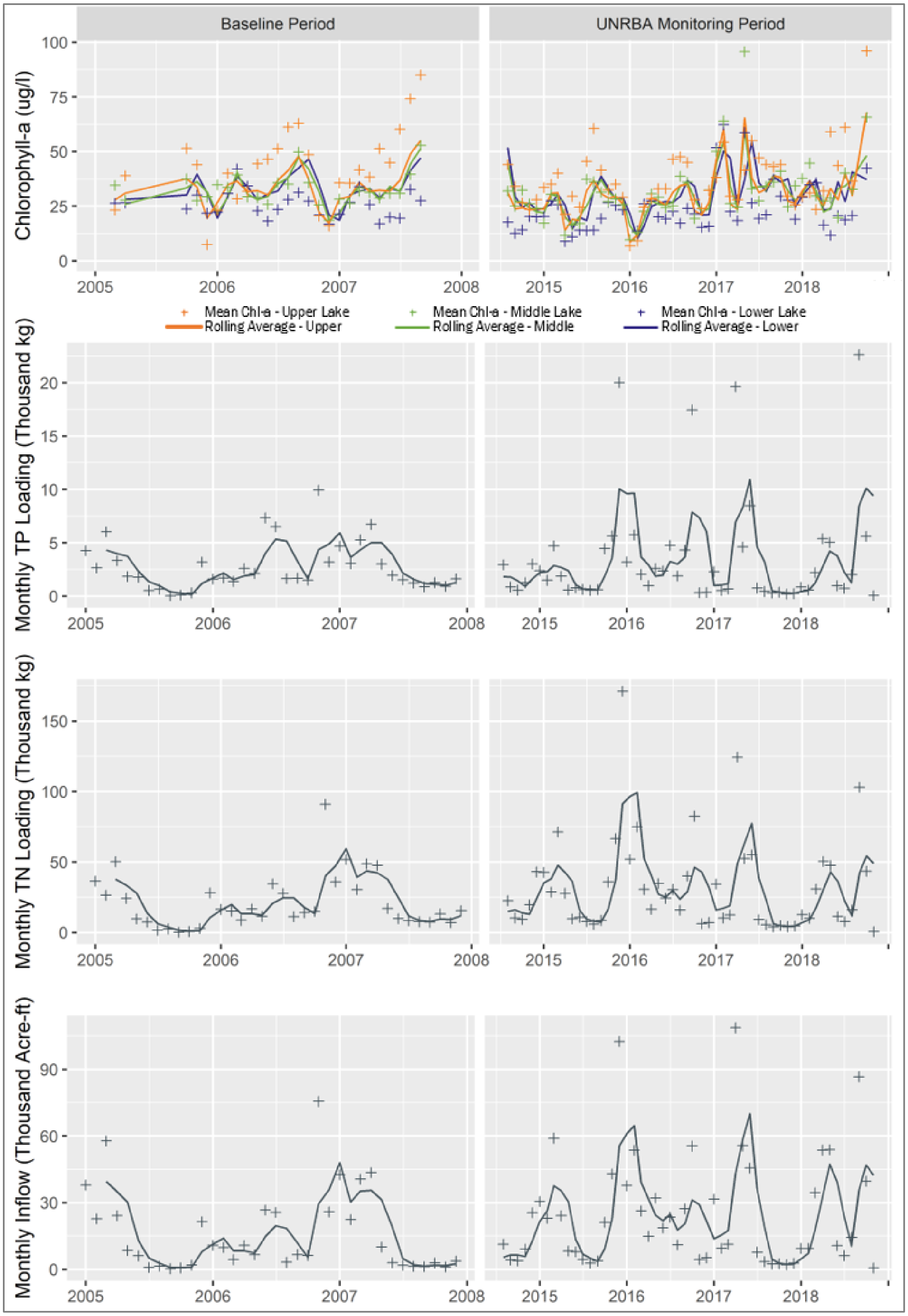


Figure 5-8. Comparison of temporal patterns in in-lake Chlorophyll-a, and TP loading, TN loading, and inflows from primary tributaries from 2005-2007 and 2014-2018

5.1.7 Evaluation of Water Quality Relative to Regulatory Criteria

North Carolina uses numeric criteria to assess waters for Clean Water Act purposes in the state. Related to eutrophication, these parameters include pH, dissolved oxygen, and chlorophyll-a. A small proportion of the pH, dissolved oxygen, and chlorophyll-a values reported by the UNRBA from tributaries to Falls Lake exceeded North Carolina surface water criteria. In the vast majority of instances, the exceedances were from tributary monitoring locations characterized by slow-moving water with abundant decaying organic (plant) matter. These kinds of tributaries can commonly experience low oxygen and pH levels and elevated chlorophyll-a concentrations. The application of the water quality standards' numeric criteria to these areas should carefully consider 15A NCAC 02B .0205 where natural waters may on occasion, or temporarily, have characteristics outside of the normal range established by the standards for regulatory decisions.

5.1.7.1 Tributary Chlorophyll-a

Chlorophyll-a is a central focus of concern for the Falls Lake re-examination process because in 2008 it was first identified on North Carolina's CWA Section 303(d) list of waters as not attaining the state's water quality criterion of 40 µg/L (15A NCAC 02B .0211(4)). Since 2008 the methodology for evaluating attainment of the water quality criterion has changed several times. The NC Environmental Management Commission (EMC) most recently approved changes to the NC 303(d) listing and delisting procedures for the CWA water quality assessment reporting process in March of 2018.

On March 8, 2018, the EMC approved changes to the North Carolina 2018 CWA Section 303(d) listing methodology for the designation of waters not attaining water quality standards. The 2018 NC 303(d) methods add more rigor to any decision to remove water bodies from an impairment status. This new assessment methodology may be of particular interest to the UNRBA since additional rigor will be required to consider waters to have attained water quality standards criteria. The 2018 assessment methodology period typically includes data from 2012 to 2016. The 2018 NC 303(d) listing and delisting methodology is more complex than previous assessment methods because it now includes methods for both listing and delisting waters in addition to new assessment methods for small data sets of less than ten observations. The new NC 303(d) assessment methodology is available on the DWR website at the following location:
https://files.nc.gov/ncdeq/Water%20Quality/Planning/TMDL/303d/2018/2018%20Listing%20Methodology_ApprovedMarch2018.pdf

During the UNRBA Monitoring Period, only the UNRBA collected tributary chlorophyll-a data and only at LL stations. Table 5-2 summarizes the tributary chlorophyll-a data relative to the 40 µg/L criterion. Of 1,099 chlorophyll-a values measured at the tributary stations from August 2014 to October 2018, 1,056 (96 percent) were below the 40 µg/L criterion. During the most recent monitoring year (2018), 6 out of 206 (3 percent) observations exceeded 40 µg/L in 4 of the monitored tributary stations. Most of these elevated values occurred during times of below average streamflow. Chlorophyll-a concentrations were generally lower in 2018 compared to 2017 when 5 percent of samples exceeded 40 µg/L.

For the Unnamed Tributary, Beaverdam, Ledge, Upper Barton, and Robertson Creeks, nine out of ten of the observed chlorophyll-a concentrations above 40 µg/L occurred during times when field-measured surface velocities were less than 0.5 cubic feet per second (cfs) and discharge estimates based on basin proration of nearby USGS gages were less than 7 cfs. Algal proliferation is not unexpected in shallow, sluggish water bodies, including wetlands, which are characteristic of four of these tributaries. North

Carolina water quality standards include a provision that "Water quality standards will not be considered violated when values outside the normal range are caused by natural conditions" (15A NCAC 02B .0205).

For the original lake model developed by DWR, very limited chlorophyll-a data were available for the tributaries entering the lake. Thus, DWR assumed that concentrations in the tributaries were similar to the closest in-lake stations. Samples collected in the lake were then interpolated and used to assign daily concentrations of tributary chlorophyll-a as time series inputs to the model. However, as reflected in Figure 3-25, chlorophyll-a levels in the tributaries are typically well below the concentrations observed at the in-lake stations—in fact, the median values for *all* LL stations are lower than the median values for all reservoir stations. The highest median chlorophyll-a level at any LL station is about 10 µg/L (Flat River) which is still 8 µg/L lower than the lowest median for reservoir stations (about 18 µg/L near the dam). Because the DWR-assumed tributary chlorophyll-a concentrations were much higher than most recent modeling indicates, the original modeling has greater uncertainty regarding the growth of algae in Falls Lake and the predicted response to reduced nutrient loading. The revised lake modeling will utilize the more recent data in development and calibration of the lake model and reduce the uncertainty associated with this previous assumption.

Although the median tributary concentrations are well below lake values, there are a small number of tributary observations which are well above what is typically seen in the lake. These elevated chlorophyll-a concentrations have predominately been observed in smaller tributaries which are among the lowest contributors of discharge to Falls Lake and during times when even their typically low discharge was among its lowest levels (i.e., stagnant conditions). Thus, the negligible volume of flow results in an insignificant amount of chlorophyll-a being contributed to the reservoir, and therefore these chlorophyll observations have relatively no effect on reservoir chlorophyll-a concentrations. Even during rain events that substantially increase streamflow, these streams are rapidly flushed of their elevated phytoplankton biomass and the runoff-generated streamflow that follows has much lower chlorophyll-a concentrations. During times of normal discharge, chlorophyll-a concentrations at these sites has typically been less than half of that observed in Falls Lake.

Table 5-3. Stations with chlorophyll-a measured above the NC state criterion between August 2014 and October 2018

Subwatershed	Station ID	Number of Chlorophyll-a Values Measured	Chlorophyll-a Values Reported above 40 µg/L	Percent of Total Values above 40 µg/L
Beaverdam Creek	BDC-2.0 (LL)	53	11	21
Ellerbe Creek	ELC-3.1 (LL)	90	1	1
Eno River	ENR-8.3 (LL)	92	2	2
Flat River	FLR-5.0 (LL)	88	4	5
Ledge Creek	LGE-5.1 (LL)	50	4	8
Panther Creek	PAC-4.0 (LL)	50	1	2
Robertson Creek	ROB-2.8 (LL)	53	10	19
Upper Barton Creek	UBC-1.4 (LL)	46	1	2
Unnamed	UNT-0.7 (LL)	50	9	18

Table 5-3. Stations with chlorophyll-a measured above the NC state criterion between August 2014 and October 2018

Subwatershed	Station ID	Number of Chlorophyll-a Values Measured	Chlorophyll-a Values Reported above 40 µg/L	Percent of Total Values above 40 µg/L
All Lake Loading Stations		1,099	43	4

5.1.7.2 In-Lake Chlorophyll-a

Chlorophyll-a concentrations measured within Falls Lake are summarized in Figure 3-25. In-lake data from DWR, City of Durham and CAAE monitoring stations for the past four years are presented for consistency with other summaries in this report that focus on the UNRBA monitoring period. Stations are ordered from upstream to downstream. The table provides the number of values reported for each monitored station and the number of values above the 40 µg/L criterion. In addition, annual arithmetic means and geometric means were calculated for both full years and for growing seasons. Geometric means are commonly employed when a data set is skewed or has occasional large outliers. The growing season was defined as April through October for these calculations. The City of Durham collects data only during the growing season, thus (12 month) annual averages are not possible for their two stations.

Like Figure 3-25, Table 5-4 indicates that the upper portion of the lake (above Highway 50) has a greater tendency to experience chlorophyll-a values above 40 µg/L than the lower lake (below Highway 50). This is consistent with the scientific literature on reservoirs presented in Section 4 and with past data reports concerning chlorophyll variability. This discriminating observation is important relative to the UNRBA's ongoing work on the re-examination and its consideration of alternate regulatory approaches. Table 5-5 and Table 5-6 provide a summary of the annual values for all stations in each year (2014 through October 2018) by row for the entire lake. Several summary observations are notable:

- The annual mean for **stations above Highway 50** was about 10 µg/L higher on the average than the mean for **stations below Highway 50** (34 versus 24 µg/L), while the average of the growing season means differed by 17 µg/L between the two groups (40 versus 23 µg/L).
- For all station-years taken together, the difference between the average of **annual means** and **annual geometric means** was only about 3 µg/. The same magnitude of difference is seen between **growing season** means and **growing season geometric means**.
- **Annual geometric means** averaged about 3 µg/L lower than **annual means** for stations above Highway 50 (31 versus 34 µg/L) and differed by a similar margin (2 µg/L) for stations below Highway 50. A similar pattern is seen for **growing season geometric means** relative to **growing season means**, but with even smaller differences between the averages (about 2 µg/L and 3 µg/L respectively).

Calculating means of means can obscure variability in the underlying data. Individual station-years can show differences as high as 13 µg/L between annual means and growing season means, and as high as 15 µg/L between growing season geometric means and annual geometric means.

Using geometric means to describe chlorophyll-a data from Falls Lake might not result in substantially different values from arithmetic means for large segments of the reservoir. Employing the geometric mean for environmental data (including chlorophyll-a) is widely accepted and does minimize the effect of occasional outliers on the resulting statistics. Variability among stations and between years reflects the dynamic nature of chlorophyll-a in large reservoirs. This temporal and spatial variability is a complexing factor in judging compliance with established chlorophyll criteria or the development of new numeric criteria for nutrients (including potential modification of the current chlorophyll-a criteria), as well as the interpretation of such criteria in permits and management strategies.

Table 5-4. Chlorophyll-a (µg/L) summary metrics for Falls Lake

Location	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
Average of All Station-years	29	31	26	28
Average of Station-years above Hwy 50	34	40	31	37
Average of Station-years below Hwy 50	24	23	22	21

Table 5-5. 2014-October 2018 Chlorophyll-a (µg/L) summary metrics for Falls Lake monitoring locations above Highway 50.

Location	Year	n	n (%) > 40 µg/L	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
CAAE - FL4	2016	9	7 (78%)	51	50	50	48
	2017	10	6 (60%)	55	66	52	64
	2018	7	6 (86%)	-	55	-	54
Durham - FL-DS4	2015	28	11 (39%)	-	39	-	35
	2016	31	5 (16%)	-	29	-	26
	2017	24	14 (58%)	-	40	-	39
	2018	28	8 (29%)	-	41	-	38
CAAE - FL85C	2015	35	20 (57%)	44	60	37	58
	2016	32	16 (50%)	40	47	33	45
	2017	28	19 (68%)	50	58	47	57
	2018	18	12 (67%)	-	58	-	54
DWR - NEU013B	2014	12	4 (33%)	36	42	33	40
	2015	12	3 (25%)	38	43	37	40
	2016	12	3 (25%)	31	43	27	42
	2017	12	6 (50%)	40	46	37	42
	2018	8	4 (50%)	-	64	-	61
CAAE - FL5	2016	9	3 (33%)	43	42	42	42

Table 5-5. 2014-October 2018 Chlorophyll-a (µg/L) summary metrics for Falls Lake monitoring locations above Highway 50.

Location	Year	n	n (%) > 40 µg/L	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
	2017	11	7 (64%)	49	58	46	56
	2018	7	6 (86%)	-	54	-	53
CAAE - FL6C	2015	12	3 (25%)	35	37	32	34
	2016	12	3 (25%)	30	39	24	38
	2017	11	6 (55%)	43	49	42	48
	2018	9	5 (56%)	-	49	-	47
Durham - FL-SR1801	2015	27	1 (4%)	-	29	-	27
	2016	31	2 (6%)	-	26	-	25
	2017	23	7 (30%)	-	38	-	36
	2018	28	10 (36%)	-	41	-	38
CAAE - FL6	2016	9	2 (22%)	35	34	34	33
	2017	11	3 (27%)	41	46	40	45
	2018	10	6 (60%)	-	49	-	48
DWR - LLC01	2014	12	4 (33%)	35	36	33	34
	2015	12	2 (17%)	31	35	30	33
	2016	12	2 (17%)	28	36	25	34
	2017	12	5 (42%)	42	49	39	47
	2018	9	1 (11%)	-	46	-	41
CAAE - FL10C	2015	12	4 (33%)	33	36	31	34
	2016	12	1 (8%)	28	32	24	32
	2017	11	9 (82%)	44	49	42	49
	2018	10	4 (40%)	-	42	-	40
DWR - NEU0171B	2014	12	3 (25%)	34	33	31	32
	2015	12	2 (17%)	33	35	32	34
	2016	12	2 (17%)	28	35	25	34
	2017	12	5 (42%)	40	45	38	44
	2018	9	3 (33%)	-	54		51
DWR - LC01	2014	12	1 (8%)	32	29	31	28

Table 5-5. 2014-October 2018 Chlorophyll-a (µg/L) summary metrics for Falls Lake monitoring locations above Highway 50.

Location	Year	n	n (%) > 40 µg/L	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
	2015	12	0 (0%)	25	28	24	27
	2016	12	0 (0%)	24	26	22	25
	2017	12	3 (25%)	37	40	35	39
	2018	10	2 (20%)	-	37	-	32
CAAE - FL9C	2015	12	2 (17%)	31	34	29	31
	2016	12	2 (17%)	25	26	22	26
	2017	11	8 (73%)	44	50	41	46
	2018	10	2 (20%)	-	35	-	34
DWR - NEU018C	2015	12	1 (8%)	26	31	22	29
	2016	12	0 (0%)	24	28	22	27
	2017	12	4 (33%)	42	47	38	43
	2018	9	2 (22%)	-	44	-	40
DWR - NEU018E	2014	12	3 (25%)	34	31	31	28
	2015	12	1 (8%)	27	29	25	25
	2016	12	1 (8%)	28	34	25	31
	2017	12	4 (33%)	42	46	38	42
	2018	9	3 (33%)	-	40	-	36
DWR - LI01	2014	12	2 (17%)	36	30	33	29
	2015	12	2 (17%)	29	30	28	29
	2016	12	2 (17%)	29	31	27	30
	2017	12	4 (33%)	42	42	40	40
	2018	9	3 (33%)	-	36	-	33
CAAE - FL50C	2015	35	3 (9%)	27	28	25	26
	2016	32	5 (16%)	28	29	24	28
	2017	31	17 (55%	42	43	39	41
	2018	24	6 (25%)	-	29	-	28

Table 5-6. 2014- October 2018 Chlorophyll-a (µg/L) summary metrics for Falls Lake monitoring locations below Highway 50.

Location	Year	n	n (%) > 40 µg/L	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
CAAE - FL2	2016	9	0 (0%)	26	25	25	24
	2017	11	5 (45%)	40	40	37	39
	2018	10	3 (30%)	-	30	-	29
CAAE - FL3	2016	9	0 (0%)	25	24	24	23
	2017	11	6 (55%)	40	40	37	37
	2018	10	3 (30%)	-	25	-	24
DWR - NEU019E	2014	12	2 (17%0	31	25	29	24
	2015	12	0 (0%)	23	23	22	22
	2016	12	0 (0%)	24	25	23	24
	2017	12	3 (25%)	39	41	36	36
	2018	9	3 (33%)	-	28	-	27
CAAE - FL8C	2015	12	0 (0%)	21	17	20	16
	2016	12	0 (0%)	20	22	19	22
	2017	11	3 (27%)	37	34	34	33
	2018	10	3 (30%)	-	26	-	24
DWR - NEU019L	2014	12	2 (17%)	28	20	26	20
	2015	12	0 (0%)	20	18	19	17
	2016	12	0 (0%)	20	22	19	22
	2017	12	5 (42%)	39	40	35	36
	2018	9	2 (22%)	-	25	-	23
CAAE - FL1C	2015	12	0 (0%)	20	15	18	14
	2016	12	0 (0%)	17	19	16	19
	2017	11	3 (27%)	32	30	29	28

Table 5-6. 2014- October 2018 Chlorophyll-a (µg/L) summary metrics for Falls Lake monitoring locations below Highway 50.

Location	Year	n	n (%) > 40 µg/L	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
	2018	10	2 (20%)	-	25	-	23
DWR - NEU019P	2014	12	2 (17%)	28	21	24	18
	2015	12	0 (0%)	19	15	17	14
	2016	12	0 (0%)	20	21	19	21
	2017	12	3 (25%)	37	33	32	30
	2018	9	2 (22%)	-	25	-	23
CAAE - FL1	2016	9	0 (0%)	20	20	20	20
	2017	11	4 (36%)	32	30	28	26
	2018	10	2 (20%)	-	26	-	25
CAAE - FL11C	2015	12	0 (0%)	23	23	22	22
	2016	12	2 (17%)	25	25	22	24
	2017	11	6 (55%)	40	42	35	39
	2018	10	2 (20%)	-	28	-	27
CAAE - FL7C	2015	12	0 (0%)	19	15	18	14
	2016	12	0 (0%)	17	18	16	17
	2017	11	4 (36%)	33	32	30	30
	2018	10	0 (0%)	-	25	-	25
DWR - NEU020D	2014	12	2 (17%)	27	18	23	17
	2015	12	0 (0%)	19	16	18	15
	2016	12	0 (0%)	18	18	17	18
	2017	12	1 (7%)	25	24	23	22
	2018	9	0 (0%)	-	18	-	17
CAAE - FLINC	2015	35	0 (0%)	17	14	16	13

Table 5-6. 2014- October 2018 Chlorophyll-a (µg/L) summary metrics for Falls Lake monitoring locations below Highway 50.

Location	Year	n	n (%) > 40 µg/L	Mean (Annual)	Mean (Growing Season)	Geometric Mean (Annual)	Geometric Mean (Growing Season)
	2016	32	0 (0%)	16	17	16	17
	2017	31	6 (19%)	30	26	25	24
	2018	24	0 (0%)	-	17	-	16

5.1.7.3 Tributary Dissolved Oxygen

North Carolina water quality criteria specify that DO is to be no less than 4 mg/L at any time except swamp waters, lake coves, or backwaters, and lake bottom waters may have lower values if caused by natural conditions (15A NCAC 02B .0211 (6)). Of the 1,978 DO measurements in Falls Lake tributaries between August 2014 and October 2018, approximately 92 percent were above the criterion and 8 percent fell below 4 mg/L, as listed in Table 5-5. Stations with lower DO tend to be in areas with low slopes, very slow velocity, and limited flows, and many are within wetland-dominated areas. “Water quality standards will not be considered violated when values outside the normal range are caused by natural conditions” (15A NCAC 02B .0205).

Table 5-7. Stations with Dissolved Oxygen Measurements below the NC State Criterion between August 2014 and October 2018

Subwatershed	Station ID	Number of DO Values Measured	DO Values Reported below 4 mg/L
Beaverdam Creek	BDC-2.0 (LL)	51	19 (37%)
Camp Creek	CMP-23 (JB)	46	11 (24%)
Deep Creek	DPC-23 (JB)	50	1 (2%)
Flat River	FLR-5.0 (LL)	72	15 (21%)
Ledge Creek	LGE-13 (JB)	38	2 (5%)
Ledge Creek	LGE-5.1 (LL)	48	13 (27%)
Lick Creek	LKC-2.0 (LL)	38	4 (8%)
Little Lick Creek	LLC-1.8 (LL)	51	11 (22%)
Little Ledge Creek	LLG-0.9 (JB)	50	22 (44%)
Little River	LTR-1.9 (LL)	73	6 (8%)
North Flat River	NFR-41 (JB)	40	6 (15%)
Panther Creek	PAC-4.0 (LL)	50	12 (24%)
Robertson Creek	ROB-7.2 (JB)	44	7 (16%)
Robertson Creek	ROB-2.8 (LL)	51	18 (35%)
Unnamed	UNT-0.7 (LL)	50	20 (40%)
All Monitored Stations		1,978	167 (8%)

5.1.7.4 In-Lake Dissolved Oxygen

Spatial trends of low DO concentrations within Falls Lake were examined using profile data collected at 18 monitoring sites by DWR and CAAE from 2006 through October 2018. Example profile data using data collected by DWR at 12 locations in June and December 2016 is provided in Figure 5-9. As is common in lakes and reservoirs, the water is not stratified in the winter, and the DO concentrations are similar throughout the water column. In the summer months when stratification is more likely, the DO at the surface is higher and decreases along the depth of water column with a sharp drop at the thermocline.

To identify the median water depths where low DO values typically occur, depths of observed DO measurements below 4 mg/L and below 1 mg/L were identified. If no low DO values were recorded at a monitoring site for the sampling day, DO values below 1 mg/L were assumed to be present at a depth of 0.5 m above bottom of the lake. Similarly, DO values below 4 mg/L were assumed to be present at a depth of 1 m above the bottom of the lake. DO is expected to approach zero near the sediment water interface, so these assumed depths of low DO were needed to account for this phenomenon. Of the 2,915 profiles collected in the lake since June 2006 (by either DWR or CAAE); 1,880 profiles included a DO concentration less than or equal to 4 mg/L and 1,473 profiles included a DO concentration less than or equal to 1 mg/L. Half of the profiles collected in Falls Lake did not include DO concentrations below these thresholds, so the assumed depths described above were used to approximate low-DO depths.

Water depth values were then converted to elevations using the water surface elevation of the lake at the time of sampling to normalize the data and aid in comparisons from one station to another. To visualize the relative volume of water affected by hypoxia, the median elevations corresponding to each low DO concentration range were displayed on graphs representing the cross-sectional area of the lake at each monitoring site. Figure 5-10 shows the median depths during the growing season (April through September) where DO concentrations are less than 1 mg/L and 4 mg/L based on profiles collected by DWR and CAAE. Figure 5-10 is organized as follows:

- Cross sections at each lake monitoring station are displayed to demonstrate the depth of water that low DO occurs
- The median depths represent where in the water column DO concentrations are lower than the threshold value half of the time
- Stations are organized from upstream to downstream, reading left to right and then down the figure
- Water level in Falls Lake is assumed at normal pool for this figure

Based on the profile data collected in Falls Lake, the following observations can be made regarding the growing season DO concentrations in Falls Lake:

- The upper limits (higher elevations) of hypoxic conditions occur very rarely and are generally within 1 to 2 meters of the median, so it is very rare for hypoxia to extend very far up in the water column.
- The median elevations for the 1 mg/L and 4 mg/L thresholds are close together because half of the profiles collected in the lake did not have DO concentrations below these values and representative depths of 0.5 m and 1 m were assumed, respectively.
- In the upper, shallow area of the lake as well as the middle of the lake until the New Light Creek arm, the depth of the reservoir at normal pool is between 10 and 30 feet (the cross sections generally fall between the normal pool elevation [250 feet] to approximately 230 feet). In these relatively shallow areas of the lake, the median depths where low DO occurs is confined to the very deepest part of the historic channel representing a very small part of the cross section.
- Downstream of the New Light Creek arm where the depth of the reservoir ranges from 30 to 40 feet, the depth where low DO occurs is greater, but the majority of the water column is still greater than 4 mg/L. This phenomenon is expected in deeper parts of reservoirs during warmer months of the year when the lake becomes stratified and oxygen is depleted in the hypolimnion (Thornton 1990b).

- A figure showing this data for all months in the year was also generated. While the area below the DO thresholds is smaller, the figures look very similar and only the growing season version is provided in this report as warmer temperatures and lower DO tend to occur in the growing season.

The State of North Carolina Department of Natural and Economic Resources (DNER) prepared a Special Analysis of the Falls of the Neuse Project (DNER 1973) that predicted that dissolved oxygen levels would be acceptable in the lake, but that the hypolimnion would experience anoxic conditions during summer stratification (Section 4.1).

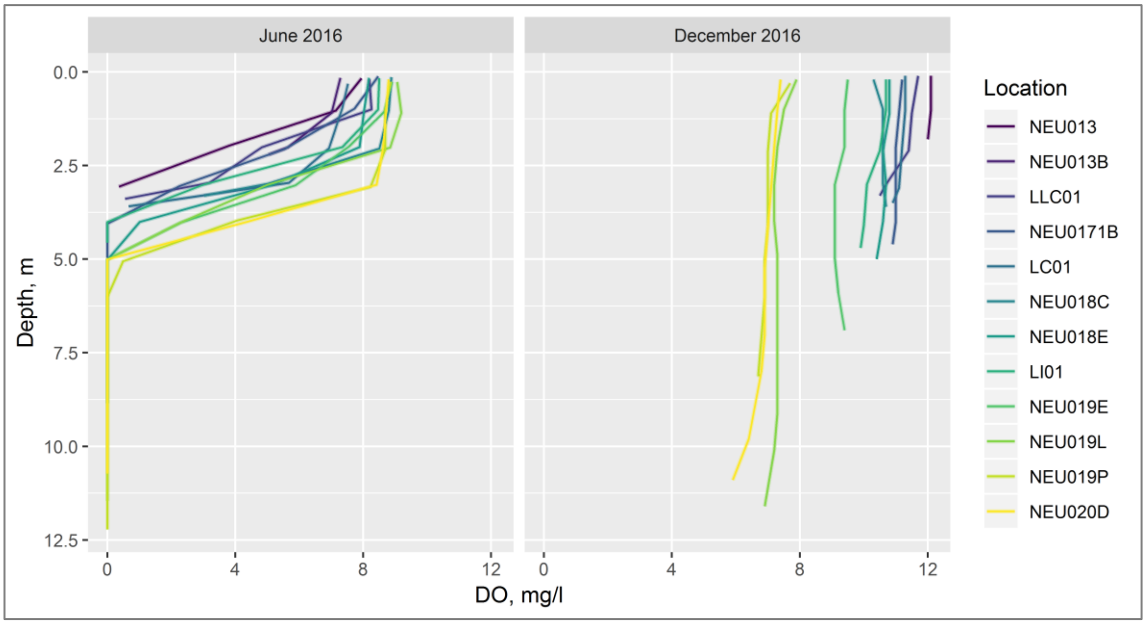


Figure 5-9. Example Profile Data Using Data Collected by DWR at 12 Locations in June and December 2016

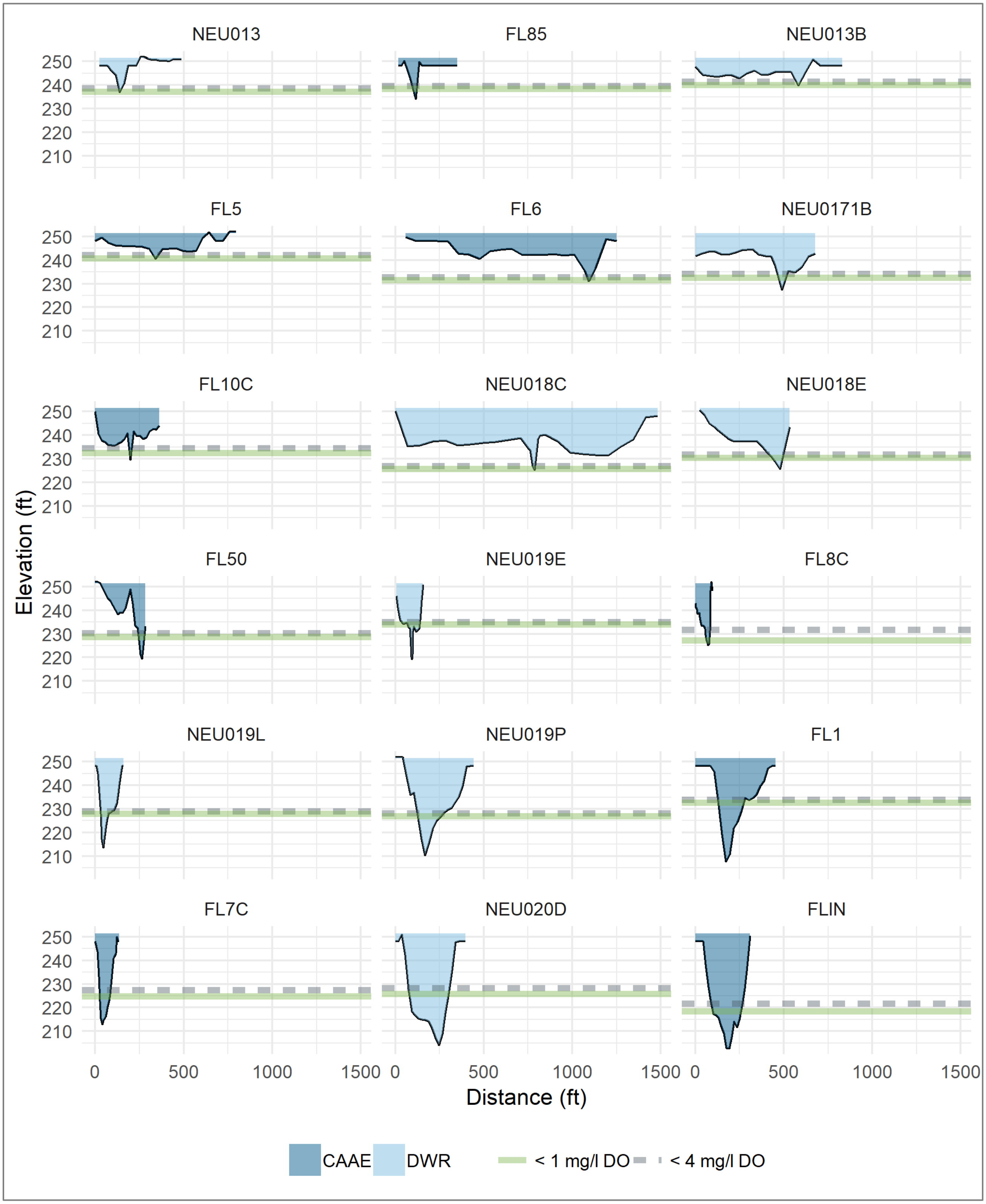


Figure 5-10. Median depths where low DO concentrations occur within Falls Lake based on data collected from April to September. Shaded areas represent the cross-sectional area of the lake at each monitoring site at normal pool.

The DO profile data can also be evaluated in terms of the percent of the water volume below certain thresholds. Figure 5-11 displays the low DO concentrations down to 0 mg/L in dark purple and the higher DO concentrations in light purple. For each day during the monitoring period, the profile data was evaluated along with the lake stage to estimate the percent of the water column with DO less than 1 mg/L (dark purple), less than 4 mg/L but above 1 mg/L (medium shade), and greater than 4 mg/L (light purple). This data indicates that essentially none of the reservoir volume experienced hypoxic conditions (less than or equal to 4 mg/L) during the cooler months, and 100 percent of the water column is displayed as light purple during these periods. During the warmest months, hypoxia may extend to as much as 30 to 40 percent of the lake volume. As shown on Figure 5-10, hypoxia is restricted to the deeper portions of the reservoir in the historic river channel.

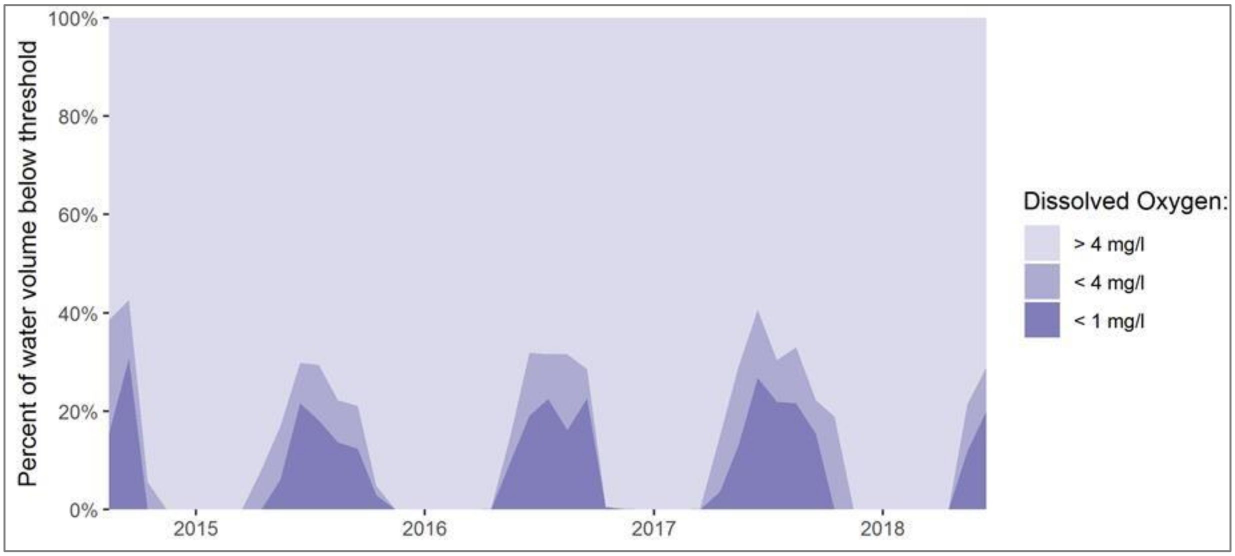


Figure 5-11. Percent of the Water Volume Below DO Thresholds Based on DWR Profile Data Collected at 12 Locations in Falls Lake

5.1.7.5 Tributary pH

The North Carolina water quality criteria specify that pH be between 6.0 and 9.0. Tributary station data from August 2014 through October 2018 showed approximately 97 percent compliance with the criterion, as reflected in Table 5-6. North Carolina water quality standards include a provision that pH levels in "swamp waters may have a pH as low as 4.3 if it is the result of natural conditions" [15A NCAC 02B .0211(14)], and further provide that "Water quality standards will not be considered violated when values outside the normal range are caused by natural conditions" (15A NCAC 02B .0205).

Observations of pH outside the 6.0 to 9.0 range were observed in less than 1 percent of reported values and at a very small proportion of monitored stations and thus are not addressed further here.

Table 5-8. Stations with pH observed below the NC state criterion between August 2014 and October 2018

Subwatershed	Station ID	Number of pH Values Measured	pH Values Reported below 6.0	pH Values Reported above 9.0
Beaverdam Creek	BDC-2.0 (LL)	51	11 (22%)	-
Buckhorn Creek	BUC-3.6 (JB)	48	3 (6%)	-
Camp Creek	CMP-23 (JB)	46	8 (17%)	-
Deep Creek	DPC-23 (JB)	50	1 (2%)	-
Eno River	ENR-41 (JB)	50	1 (2%)	-
Eno River	ENR-49 (JB)	50	5 (10%)	-
Eno River	ENR-8.3 (LL)	75	1 (1%)	-
Flat River	FLR-5.0 (LL)	72	3 (4%)	-
Horse Creek	HSE-11 (JB)	50	2 (4%)	1 (2%)
Horse Creek	HSE-7.3 (JB) & HSE-5.7 (alternate)	48	3 (6%)	-
Horse Creek	HSE-1.7 (LL)	50	2 (4%)	-
Knap of Reeds Creek	KRC-4.5 (LL)	71	2 (3%)	1 (1%)
Ledge Creek	LGE-13 (JB)	38	3 (8%)	-
Ledge Creek	LGE-17 (JB)	42	2 (5%)	-
Ledge Creek	LGE-5.1 (LL)	47	2 (4%)	-
Little Ledge Creek	LLG-0.9 (JB)	50	4 (8%)	-
Little Lick Creek	LLC-1.8 (LL)	51	1 (2%)	1 (2%)
Little River	LTR-1.9 (LL)	73	1 (1%)	-
New Light Creek	NLC-3.8 (JB)	51	1 (2%)	-
New Light Creek	NLC-2.3 (LL)	50	1 (2%)	-
Panther Creek	PAC-4.0 (LL)	50	4 (8%)	-
Robertson Creek	ROB-7.2 (JB)	44	3 (7%)	-
Robertson Creek	ROB-2.8 (LL)	51	7 (14%)	-
Smith Creek	SMC-6.2 (LL)	45	1 (2%)	-
Unnamed	UNT-0.7 (LL)	50	5 (10%)	-
All Monitoring Stations		1,978	77 (4%)	3 (0.2%)

5.2 Tributary Water Quality and Watershed Hydrologic Soil Groups Patterns

Routine Monitoring data indicates that stations located in non-flowing, wetland dominated areas tend to have higher concentrations of TP, TOC, and chlorophyll-a and lower concentrations of dissolved oxygen. Wetlands have different hydrologic and water quality characteristics than other undisturbed land uses in a watershed and understanding how wetlands may affect the water quality characteristics of the tributaries and the lake will be an important consideration for the re-examination strategy and nutrient management plans that are developed for the watershed. Wetlands are often located in areas with poor draining soils, and the NRCS classifies soils into hydrologic soil groups (HSG) based on their drainage characteristics. Figure 5-12 shows a map of HSGs in the watershed relative to the location of the UNRBA monitoring stations. Soils in the watershed range from those with moderately high infiltration rates (HSG B) to those with low infiltration rates (HSG D). Due to the poor drainage characteristics of HSG D soils, they are often associated with the presence of wetlands. Figure 5-13 shows the distribution of water quality parameters based on the dominant HSG within each monitoring station's catchment area. HSG B was dominant in 23 catchment areas draining to a monitoring site, HSG C was dominant in 7 catchments, and HSG D was dominant in 10 catchments. For TP, ammonia, and organic nitrogen, concentrations at sites with HSG D soils tend to be somewhat higher than those with HSG B or C soils. For nitrate+nitrite, higher concentrations are observed at sites with HSG B or C soils. For TOC, concentrations tend to increase as infiltration rates decrease, with HSG D soils having the highest concentrations of TOC observed in the watershed. For chlorophyll-a, HSG B tends to have lower concentrations than many sites located on HSG C or D soils. All tributary chlorophyll-a concentrations greater than 56 µg/L were observed in tributaries dominated by stagnant, wetland areas.

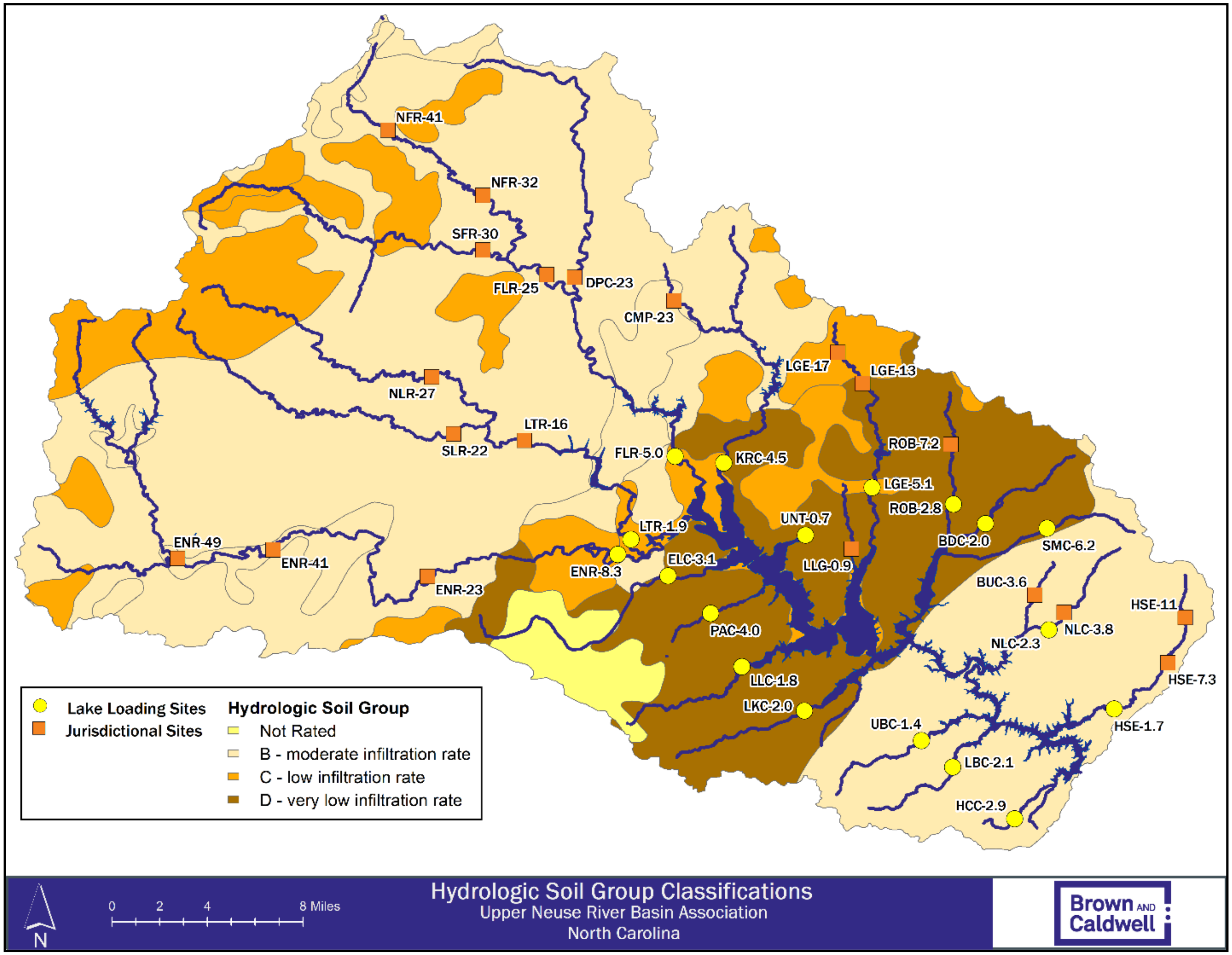


Figure 5-12. Hydrologic Soil Groups in the Falls Lake Watershed

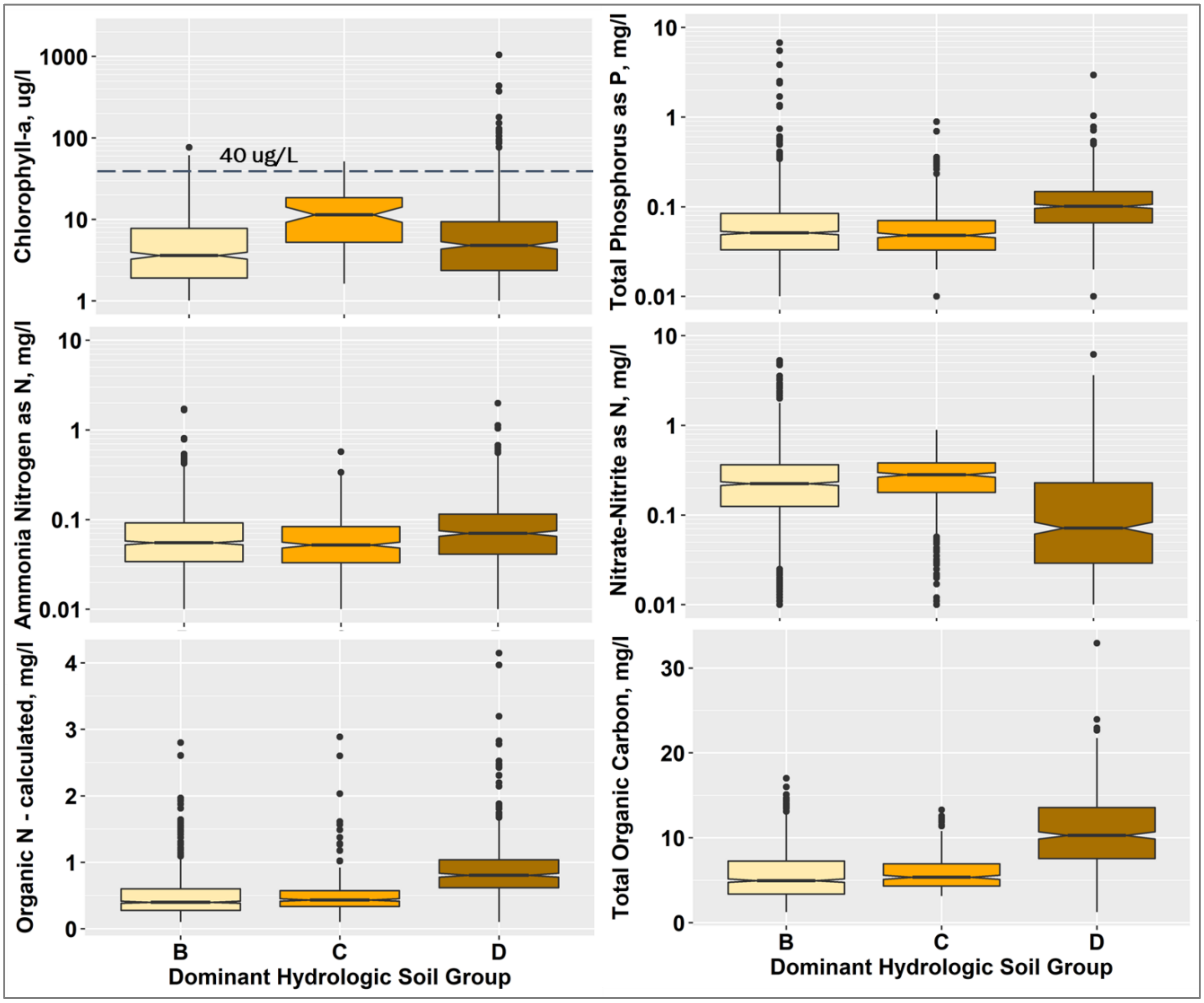


Figure 5-13. Distribution of Water Quality Parameters by Hydrologic Soil Group in the Falls Lake Watershed

Note that the Chlorophyll-a, Total Phosphorous, Ammonia, and Nitrate-Nitrite plots are shown on a logarithmic scale.

Note that Chlorophyll-a outliers were observed in watersheds dominated by stagnant, wetland areas.

5.3 Water Quality in Tributaries Upstream and Downstream of Wastewater Treatment Plants

Stations were also categorized by the presence of an upstream WWTP as either a major facility (more than 1 million gallons per day [MGD]) or a minor facility (i.e., a package plant) (Figure 5-14). Major WWTPs are found upstream of four UNRBA monitoring stations while 11 monitoring stations are downstream of minor WWTPs. There are 25 monitoring stations that are not downstream of any WWTPs. In the Falls Lake watershed, nitrogen concentrations (ammonia, nitrate+nitrite, and organic nitrogen) collected during the monitoring period tend to be higher downstream of major WWTPs; for TP, the concentrations are similar across the three groups, which may be due to recent upgrades at the Durham and SGWASA WWTPs. TOC concentrations are fairly similar at sites with major and minor WWTPs; sites without WWTPs tend to have more variability in this parameter and the highest concentrations are observed at stations without WWTPs (these higher concentrations may be associated with non-flowing, wetland dominated areas). Chlorophyll-a concentrations tend to be lower downstream of major WWTPs, which may be due to the increased flow rates that prevent low-flow conditions and the associated higher algal densities. Chlorophyll-a concentrations at stations with higher flow are usually lower than levels measured under low/non-flowing conditions. All tributary chlorophyll-a concentrations greater than 56 µg/L were observed in tributaries dominated by stagnant, wetland areas.

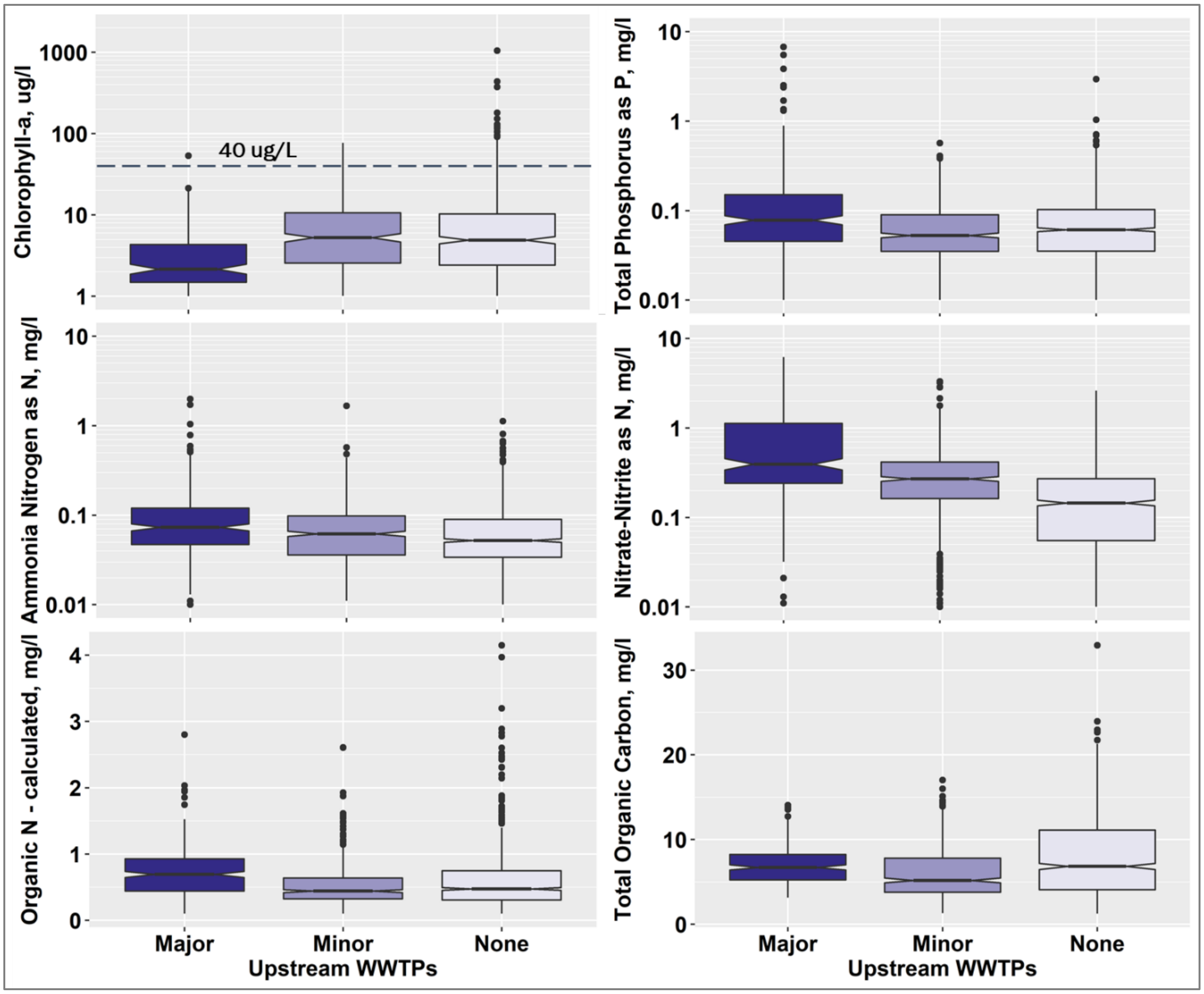


Figure 5-14. Comparison of Water Quality Parameters Relative to the Presence of a Major or Minor (Package Plant) WWTP

Note that the Chlorophyll-a, Total Phosphorous, Ammonia, and Nitrate+Nitrite plots are shown on a logarithmic scale.

Note that Chlorophyll-a outliers were observed in watersheds dominated by stagnant, wetland areas.

5.4 Reservoir Bathymetry and Sediment Mapping

In Fiscal Year 2017, the UNRBA conducted a bathymetric survey and sediment mapping study of Falls Lake using dual-sonar frequency technology. Underwater topography (bathymetry) influences the retention and movement of water and thus partially determines the biological processing of nutrients that can affect the growth of chlorophyll-a (algae). An accurate representation of underwater topography and flow restrictions is an essential element in understanding the volume of water within each segmented portion of Falls Lake and helps to determine the amount of time water remains within each segment to facilitate algal growth. Hydrodynamic models which aim to accurately represent the movement of water and its associated constituents such as suspended sediment, chlorophyll-a, and nutrients are constructed using the most accurate measurements of the lake's morphological features as is possible to obtain. The lack of accurate lake morphology can impair a model's ability to simulate water quality conditions across a range of flow regimes. DWR collected bathymetric data at 17 transects in 2006 and used these to inform grid development for their EFDC-based Falls Lake Nutrient Response Model. However, 17 transects over the entire 20+ mile length of Falls Lake and its coves does not provide a detailed picture of Falls Lake's bathymetry. Before this UNRBA study, there were no additional data on the bathymetry of Falls Lake other than pre-reservoir USGS topographic maps.

A primary goal of this study was to significantly enhance the bathymetric data available to build a more robust hydrodynamic model for Falls Lake by collecting depth data on transects averaging every tenth of a mile throughout the reservoir. The data produced by this effort has been used by the UNRBA modeling team to refine the grid for the hydrodynamic model, provide more accurate depths for each model grid cell, and calculate average water depths and thus retention time in each segment. Although not a primary goal of the mapping effort, this survey can also provide a point of comparison with past and future surveys to estimate sedimentation rates. The USACE has shown keen interest in this data.

A second goal of this study was to provide data on the thickness of the sediment layer throughout Falls Lake. During the course of the sediment coring field work (Section 5.5), significant variability in sediment thickness was observed, with some areas of the lake having little to no accumulated sediment able to be collected in cores. Measuring the sediment thickness involved simple equipment addition to the bathymetric survey to improve estimates of benthic nutrient flux. At a minimum, mapping locations with and without sediment accumulations provides a simple way to extrapolate measured fluxes to the areas of the lake with documented sediment accumulation. Correlations between sediment thickness and estimated flux rates were developed to determine if sediment thickness could be used to extrapolate flux rates in areas of the lake that cores were not collected. The bathymetric and sediment mapping survey results were analyzed in conjunction with the sediment core data discussed in Section 5.6 to develop lake wide estimates of benthic nutrient fluxes.

The field data necessary to develop the bathymetric and sediment layer maps were collected over two weeks in March and April 2017. Over four million depth sounding samples were collected throughout the lake using a boat mounted dual-frequency echosounder. Sampling transects were typically spaced between 500 and 1000 feet apart though intervals were adjusted as needed in the field according to the degree of local depth variation (Figure 5-15). Shallow, gently sloped regions required less tightly spaced transects than regions with greater degrees of change. Following the field collection effort, the four million data points were digitized by Water Cube, Inc. After

The bathymetry data (water depth) has been used by the UNRBA Modeling Team to develop the model grid for the EFDC lake model. Application of the sediment thickness data to estimate internal lake loading of nitrogen from the sediments is provided in Section 5.5.

removing interferences from floating debris and aquatic organisms, the data were used to identify the top-of-sediment depth (from the high-frequency acoustic signal) and the maximum penetration depth of the low-frequency acoustic signal. The difference between the depths of penetration for the two acoustic signals was interpreted as the depth of sediment accumulation.

Complete gridded data sets for the sediment thickness layers and water depth were obtained through Delauney triangulation of the spatially referenced point data and are shown in Figure 5-16 and Figure 5-17, respectively.

Relationships between water depth, surface area, and volume can be generated using the bathymetric data for the entire lake and individually for separate lake segments. Figure 5-18 compares the relationship between surface area and depth for select segments of Falls Lake. The integration of depth and surface area provides a visual representation of the volume of water in each of the segments. For instance, despite very different shapes, the volume of water in Falls Lake is almost evenly split between the upstream half (above Highway 50) and the lower half (below Highway 50). Approximately 50 percent of the total water volume in the lake is above Highway 50, and 50 percent is below Highway 50 (with about 6 percent in the Beaverdam impoundment).

Similarly, reservoir segments have different patterns of sedimentation. The lines on Figure 5-19 suggest that nearly all sediment in the segment above I-85 is less than 3 inches thick, while about 30 percent of sediment below Highway 98 is more than 6 inches thick. Despite receiving water draining from the majority of the watershed, sediment accumulation in the upper portion of the lake is much lower than that in the lower half of the lake, largely owing to the differences in lake shape. The shallower and wider upper lake is more exposed to wind and therefore experiences more sediment resuspension, which allows sediment to continuously be moved down the reservoir, reducing the accumulation at the upper end. Differences in sediment thickness can have a substantial effect on nutrient flux potential, as discussed in Section 5.5.

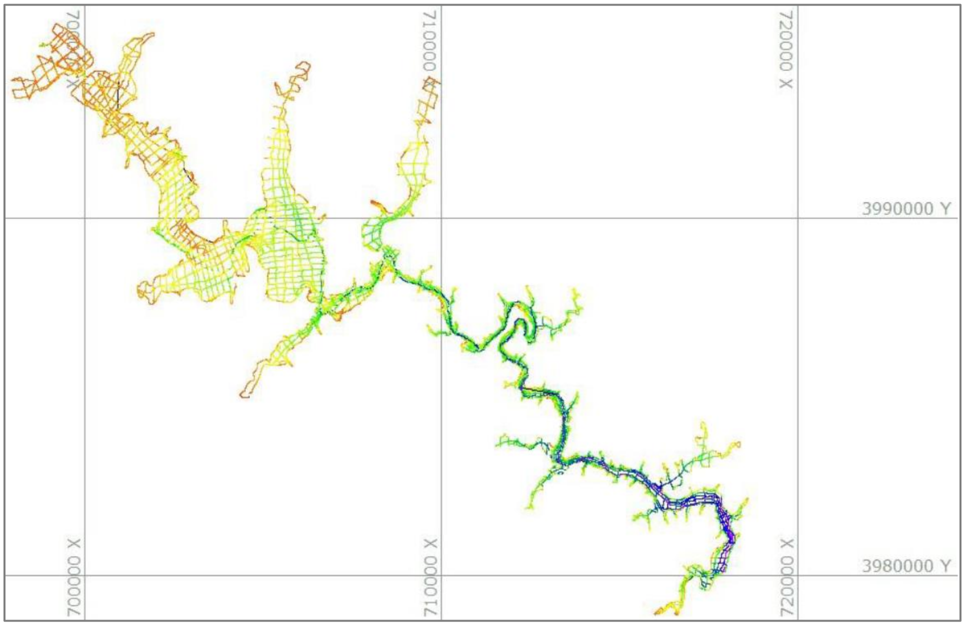


Figure 5-15. Track line locations for the bathymetric and sediment depth survey

Color is shown to provide a visual interpretation of water depth.

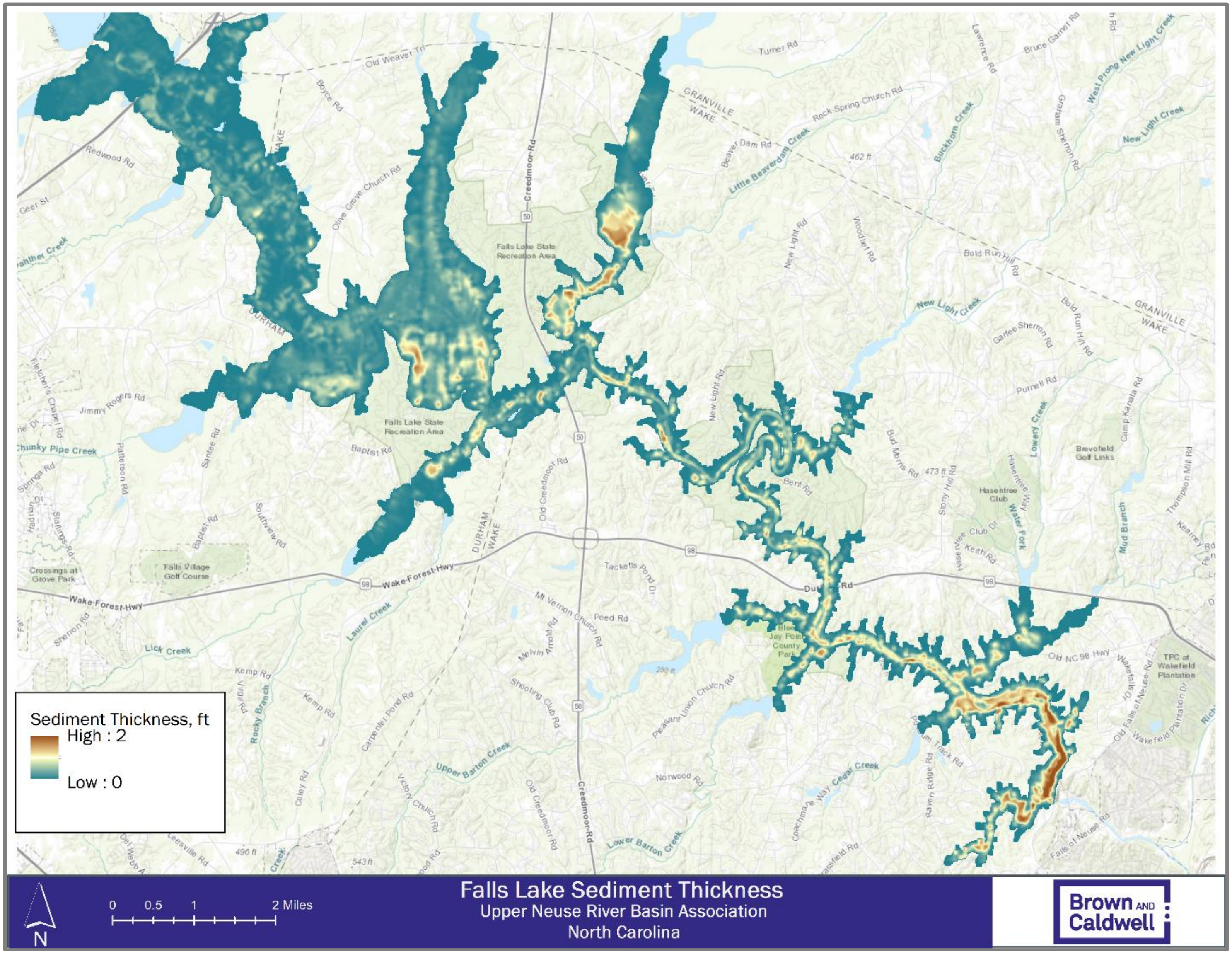


Figure 5-16. Sediment Thickness in Falls Lake

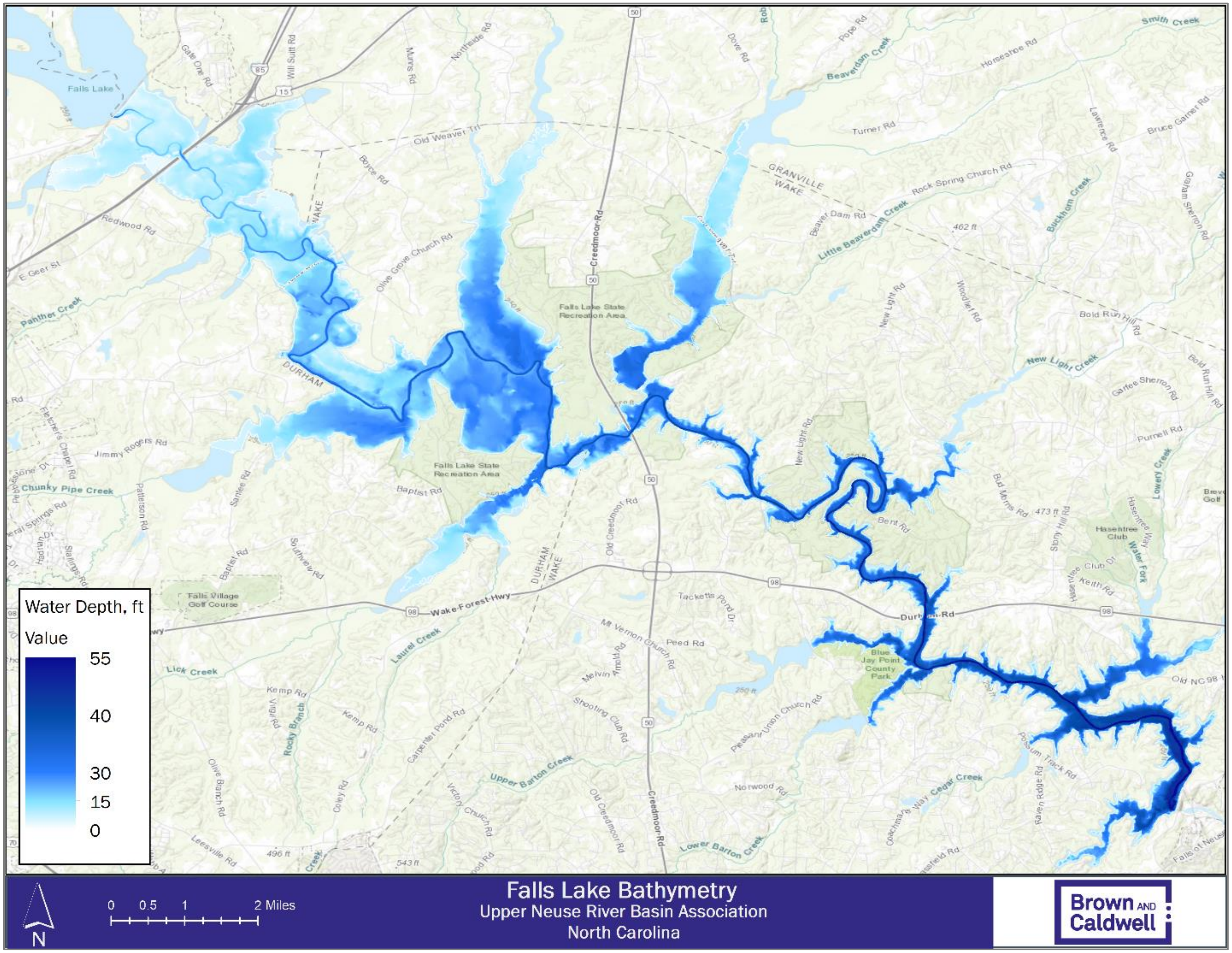


Figure 5-17. Water Depths of Falls Lake

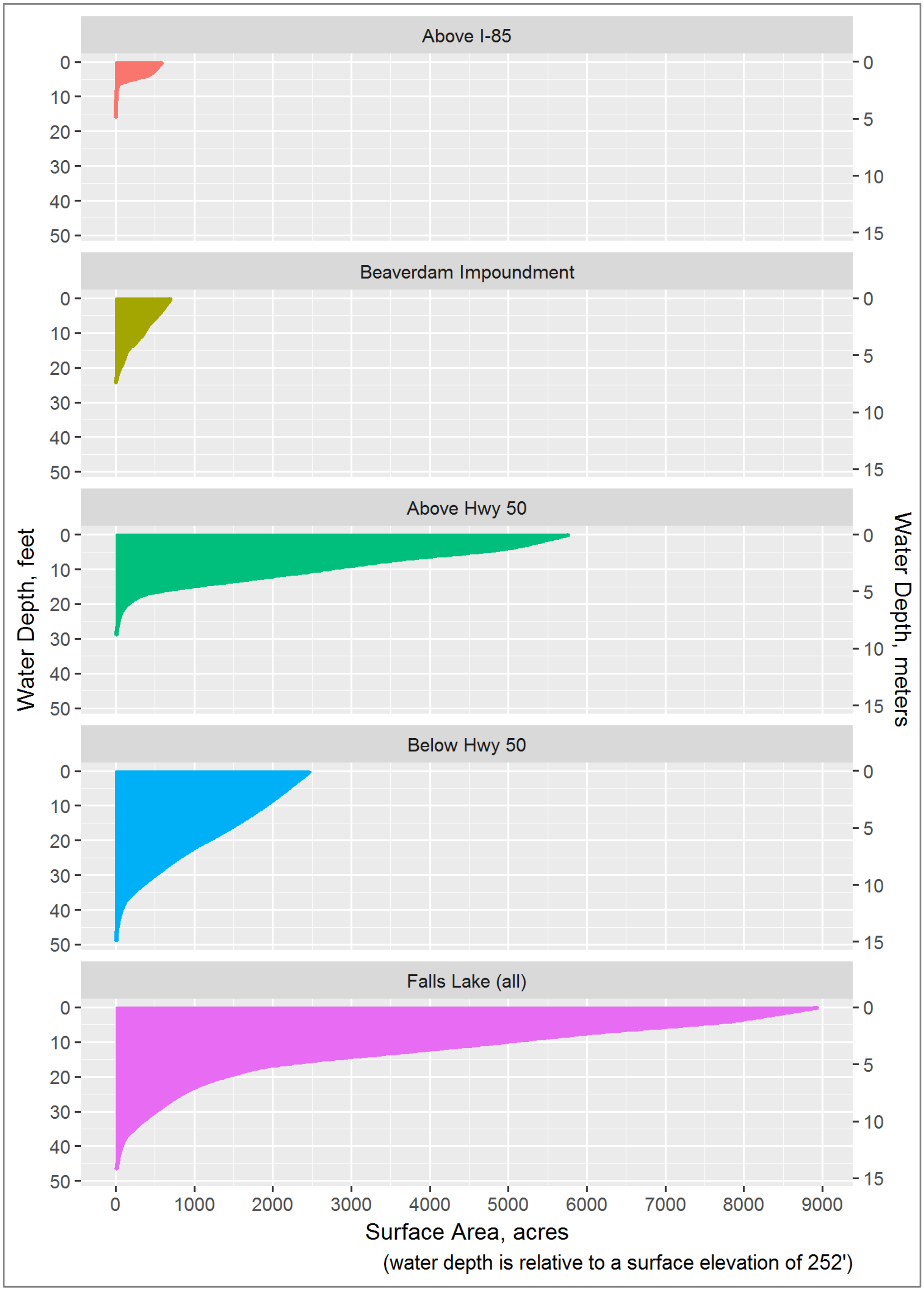


Figure 5-18. Water Depths in Segments of Falls Lake

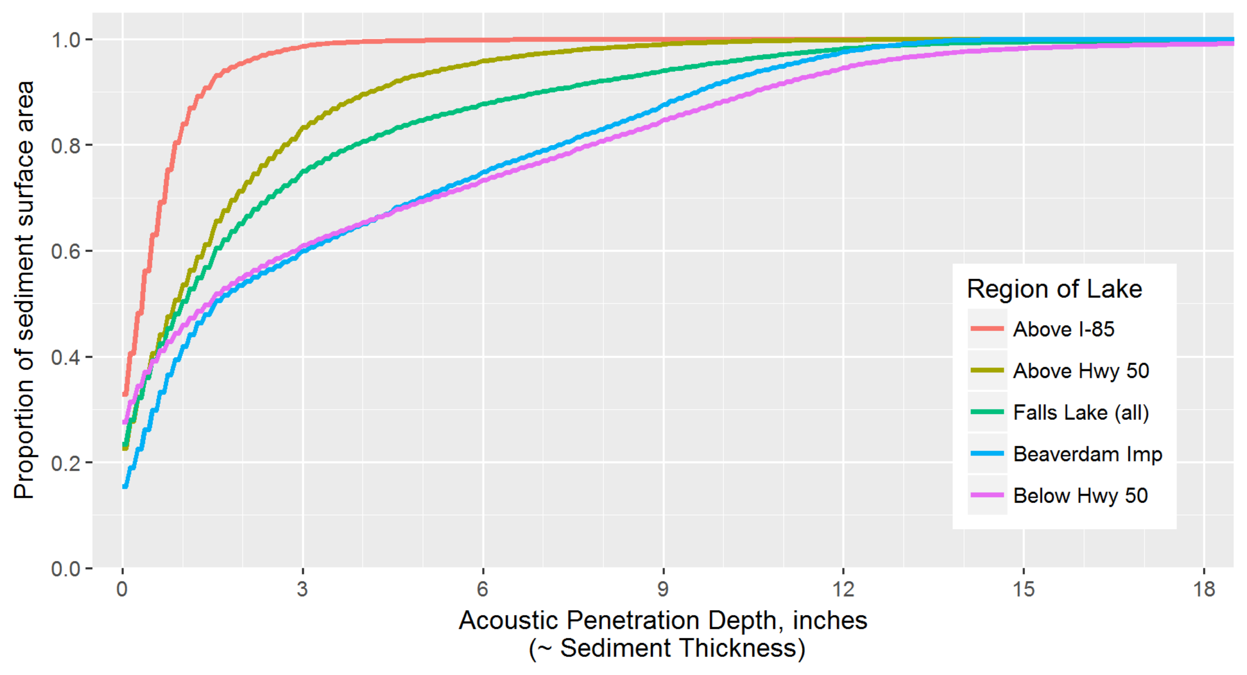


Figure 5-19. Comparisons of sediment accumulation patterns in different regions of Falls Lake

Shallower areas above Highway 50 generally have less accumulation (e.g., red and yellow lines) that the deeper, narrower areas downstream of Highway 50.

5.5 Sediment Quality and Internal Nutrient Loading

A UNRBA Special Study led by Dr. Marc Alperin of the University of North Carolina's Marine Science Department was initiated in 2015 to evaluate sediments in Falls Lake. The study looked at sediment cores collected from more than 20 locations along the lake which were analyzed for a suite of parameters. This data provides information on the characteristics of the lake sediments which will help better define the role of bottom sediments on lake water quality and support the UNRBA modeling effort. Lake sediments include both historic deposition and legacy nutrients in the deeper layers as well as "younger" sediments near the surface. Sediment studies have also been conducted by DWR and EPA on Falls Lake. This section summarizes the two studies that occurred during the UNRBA Monitoring Period and provides estimates of nutrient flux rates from the lake sediments.

5.5.1 UNRBA Reservoir Sediment Evaluation

In 2015, a Special Study commenced to evaluate sediments in Falls Lake. Dr. Marc Alperin of the University of North Carolina's (UNC's) Marine Science Department was the Principal Investigator for that study (Alperin 2018). The UNRBA commissioned report prepared by Dr. Alperin is available here.

The Plan of Study developed for the sediment evaluation (also available on the UNRBA

Internal loading from lake sediments comprises over 200,000 pounds per year (14 percent) of the total nitrogen loading to the lake and up to 14,000 pounds per year (9 percent) of the total phosphorus load to the lake.

website in the resource library) summarized the purposes of the effort:

- Quantify the nutrient and organic carbon content of sediment samples from Falls Lake
- Develop a more precise understanding of the spatial variability of sediment characteristics, bottom water, pore water, and benthic nutrient fluxes in Falls Lake
- Provide site-specific information which can be used to simulate spatial variability in benthic nutrient flux
- Develop a better understanding of the importance of internal nutrient loads to the waters of Falls Lake.

A reconnaissance visit to the lake was conducted in May 2015, with sample collection occurring on June 8 and 10, 2015. Data acquisition involved the collection of 29 sediment cores from 27 locations in the lake. Replicate cores were taken at two locations to provide information on small-scale variability. Core collection focused on the historic river channel and the adjacent “shelf” (i.e., historic river floodplain), but several cores were also obtained from historic tributaries to the river and from the “slope” between the river channel and the shelf. Coring locations were generally associated with DWR’s monthly water quality monitoring locations and extended from the vicinity of the I-85 causeway in the upper lake to the City of Raleigh intake structure in the lower lake Figure 5-20 shows the locations where cores were obtained. The red boxes denote sampling sites centered on the historic channel. Blue boxes are sites that were tributaries to the Neuse River before dam construction. The 12 stations marked by blue and red boxes are at the same locations as the DWR monthly water quality sampling sites. Three additional upper arm stations (green boxes) were added to include the portion of the Falls Lake above I-85, and those stations were sampled in collaboration with Dr. Mark River (formerly at Duke University). The nine stations with diagonals represent transect sites where cores were collected perpendicular to the main lake axis.

At each coring location, water quality samples were collected from approximately 1 meter above the sediment (“overlying water”) and analyzed for total dissolved phosphate (PO_4), ammonia nitrogen (NH_3) and nitrate+nitrite. Each core was sectioned at 3-cm intervals, and those sections were sub-divided for various analyses. For each section, porosity and loss-on-ignition as an indicator of organic material were measured.

A porewater sample was extracted from each section and analyzed for total phosphate and NH_3. The solid sediment material from each section was analyzed for percent organic carbon and percent TN. Phosphorus was also quantified in the solid phase of the sediment material; the majority is in mineral form and thus not available to move into the water column. Replicate cores were also taken at two locations to provide information on small-scale variability. Additional methodology details are provided in the full report.

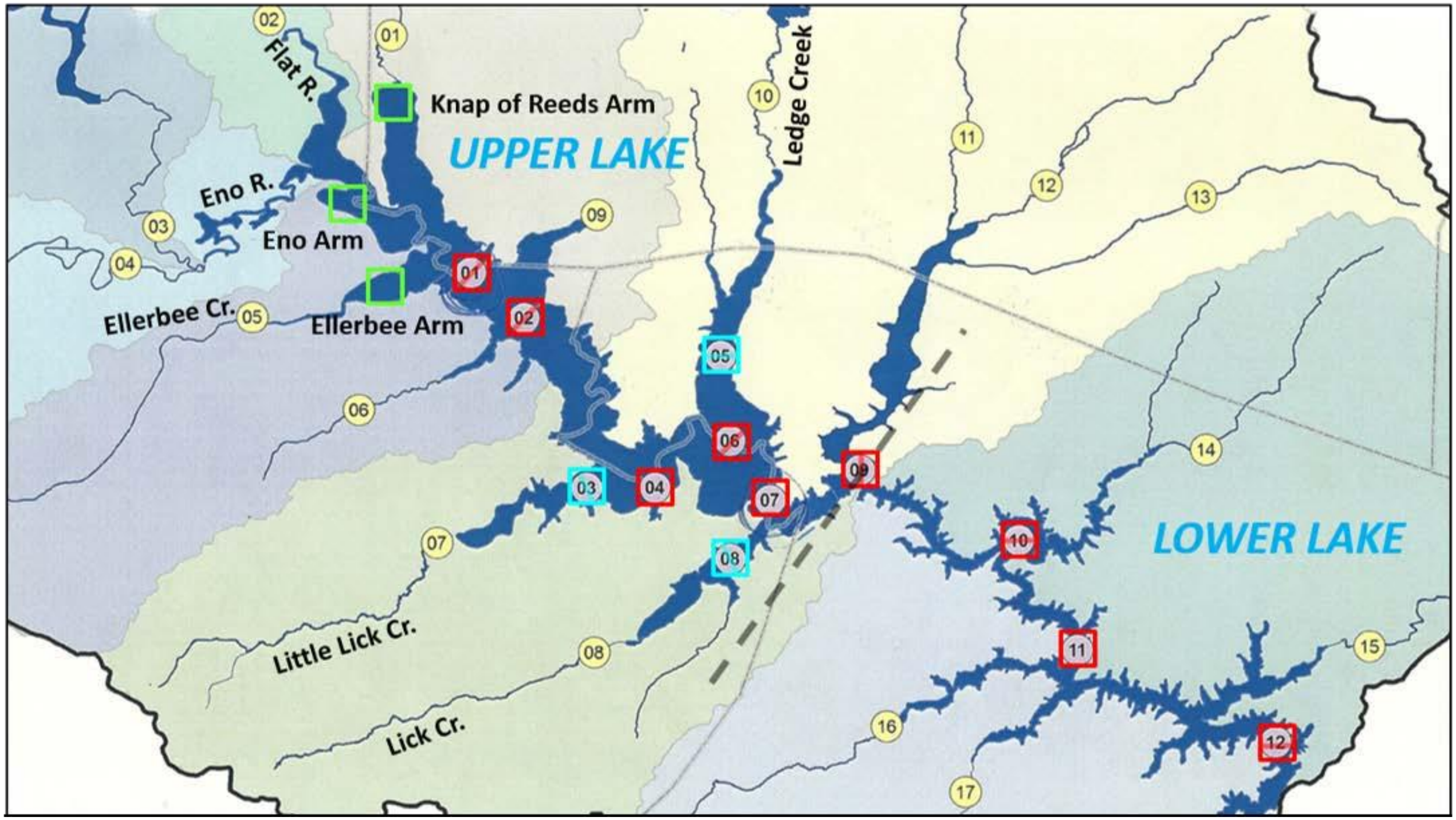


Figure 5-20. Locations of sediment core sampling in Falls Lake in June 2015

An interesting observation during collection of the cores was the variability in the thickness of the unconsolidated sediment layer (muck) among the locations. In general, the river and tributary channels had substantial sediment with cores ranging from 13 to 40 centimeters (the upper limit of the corer). In contrast, areas along the "shelf" typically had much less accumulated sediment, with cores ranging from less than 5 to just over 20 centimeters. Some shelf areas had little to no sediment, where the corer simply contacted hard clay, sand or gravel.

All data analysis was conducted under the direction of Dr. Alperin. This analysis included refinement of a mathematical model to estimate nutrient fluxes. That model and its output are described in the full report from the Special Study. Table 5-9 reproduced from Dr. Alperin's report summarizes the laboratory results of the core analysis.

Table 5-9. Summary of Laboratory Results for Sediment Cores Collected from Falls Lake in June/July 2015.

Parameter	Units	Count (n)	Minimum	Mean	Maximum	Comment
Solid phase						
Porosity	%[1]	185	0.19	0.76	0.93	Decreases with sediment depth
Loss on Ignition	%[2]	185	0.2	8.0	23.4	High value contained wood fragments
Organic Carbon	%[2]	152	0.06	2.08	4.67	High value contained wood fragments
Total Nitrogen	%[2]	152	0.00	0.21	1.08	No pattern with depth
Total Phosphorus	%[2]	152	0.001	0.061	1.24	No pattern with depth
Porewater						
Total Phosphate	μM[3]	119	0.3	1.2	13.6	Porewater contains higher concentrations of Total Phosphate
Total Ammonia	μM[4]	119	43.9	1387	4466	and Total Ammonium, suggesting a flux from sediments to lake
Bottom Water						
Total Phosphate	μM[3]	26	0.2	0.3	0.62	No spatial pattern to Total Phosphate
Total Ammonia	μM[4]	26	0.3	22.8	146	Low DO water has high Total Ammonium
Nitrate+ Nitrite	μM[4]	26	0.1	0.3	0.8	Nitrate + Nitrite is the minor form of Dissolved Inorganic Nitrogen

[1] *mL porewater per 100 mL wet sediment.*

[2] *per cent dry weight.*

[3] *To convert μM P to μg P/L, multiply by 31.*

[4] *To convert μM N to μg N/L, multiply by 14.*

Porosity is a measurement of the void spaces between solid particles within the sediment, and smaller particle sizes yield greater porosity. Overall, porosity ranged from about 0.2 (i.e., 20 percent void space) to about 0.9, with cores from within the river channel typically having porosity in the range of 0.8 to 0.9. In general, porosity decreased with increasing sediment depth as a result of compaction.

Loss on Ignition (LOI) is a measure of the non-mineral fraction of the sediment that is liberated when dried sediment is heated to 550°C (more than 1000°F) in an oven. LOI in Falls Lake cores ranged from near 0 to about 23 percent, with cores from the lower portion of the lake having generally higher LOI values than cores from the upper lake.

The decay of organic matter buried in lake sediments transforms organic nutrients into inorganic forms (e.g., NH_3 and $P0_4$) which may then be released back into the water column. Because decomposition is the source of nutrients, it is important to characterize the organic content within the sediment pool in conjunction with assessments of benthic nutrient flux. The organic content of each core was assessed through the determination of LOI and measurement of TOC concentration.

TOC in Falls Lake cores ranged from near 0 to about 5 percent, with generally the same spatial pattern seen for LOI. This is because TOC and LOI are often highly correlated, since the volatile and combustible organic substances in the sediment comprise much of what is burned off during the LOI process. For the Falls Lake cores overall, the correlation analysis of LOI and TOC yielded an r^2 of 0.72, indicating a high degree of correlation. This relationship can be of value since the cost of measuring TOC is higher than for LOI, so being able to use LOI as a surrogate can save money in future evaluations. Organic carbon was also correlated with porosity (r^2 of 0.62), indicating that organic matter is associated with the finer grained sediments.

Nutrients can move out of the sediment through diffusion across the sediment-water interface as well as through physical activity of organisms such as burrowing worms (“bioirrigation”). Diffusion is determined by the concentration gradient between the sediment pore water and the overlying water and therefore the nutrient concentrations of both were measured. NH_3 concentrations in bottom water were low at stations less than5 meters deep (mean = 0.014 mg/L), but increased dramatically at deeper stations, with Station 12 yielding a NH_3 concentration of 2.0 mg/L. Concentrations of nitrate+nitrite in the bottom water averaged 0.004 mg/L and were similar across all stations. PO_4 levels averaged 0.009 mg/L and were also relatively constant among the stations.

Higher nutrient concentrations in the sediment porewater are necessary for net diffusive flux to move nutrients from the sediments to the water column. This study found conditions suitable for NH_3 movement from the sediment to the water at every location where a core was collected, with the average NH_3 porewater concentration in the upper section of the sediment being some 2.5 mg/L higher than the overlying water. The highest observed difference between the upper sediment section porewater and the overlying water was nearly 10 mg/L. NH_3 concentrations increased with depth in the sediment porewater in all 24 cores, indicating the presence of a gradient to drive a net upward flux.

Concentrations of nitrate+nitrite were also higher in the upper layer of porewater than in the overlying water, but nitrate+nitrite did not increase with depth in the sediment profile like NH3, because the anoxic conditions prevented the nitrification of ammonia to an oxidized form. Similarly, PO4 in the sediment porewater ranged from about 2 to 20 times greater than concentrations in the overlying water at all sampled locations, indicating the potential for an upward flux. This concentration gradient would drive the release of P from the sediment during anoxic conditions, but since dissolved oxygen is present at the sediment-water interface across much of the reservoir most of the time, the diffusive flux of PO4 into the water column is generally believed to be minimal.

As noted above, a mathematical diagenetic model was developed by Dr. Alperin to estimate inorganic nitrogen flux using the bottom water and pore water profiles of NH_3 and nitrate+nitrite concentrations. The model applies known relationships and sediment processes and is described in the final report from the Special Study.

Nitrogen fluxes were typically dominated by NH_3, with nitrate+nitrite generally making up less than 2 percent of the total flux. Estimates of NH_3 fluxes were widely variable among cores, ranging from less than 1 to 90 milligrams per meter squared per day ($mg/m^2/d$) (Figure 5-21). Although no consistent pattern is apparent along an upstream to downstream location gradient, a few patterns did emerge which can explain some of the observed spatial variation. On average, NH_3 fluxes from cores collected within the historic river channel were more than three times higher than the cores which were collected nearby, but outside of the historic channel (58 and 16 milligrams of nitrogen per meter squared per day ($mg\ N/m^2/d$), respectively, p less than $1x10^{-7}$).

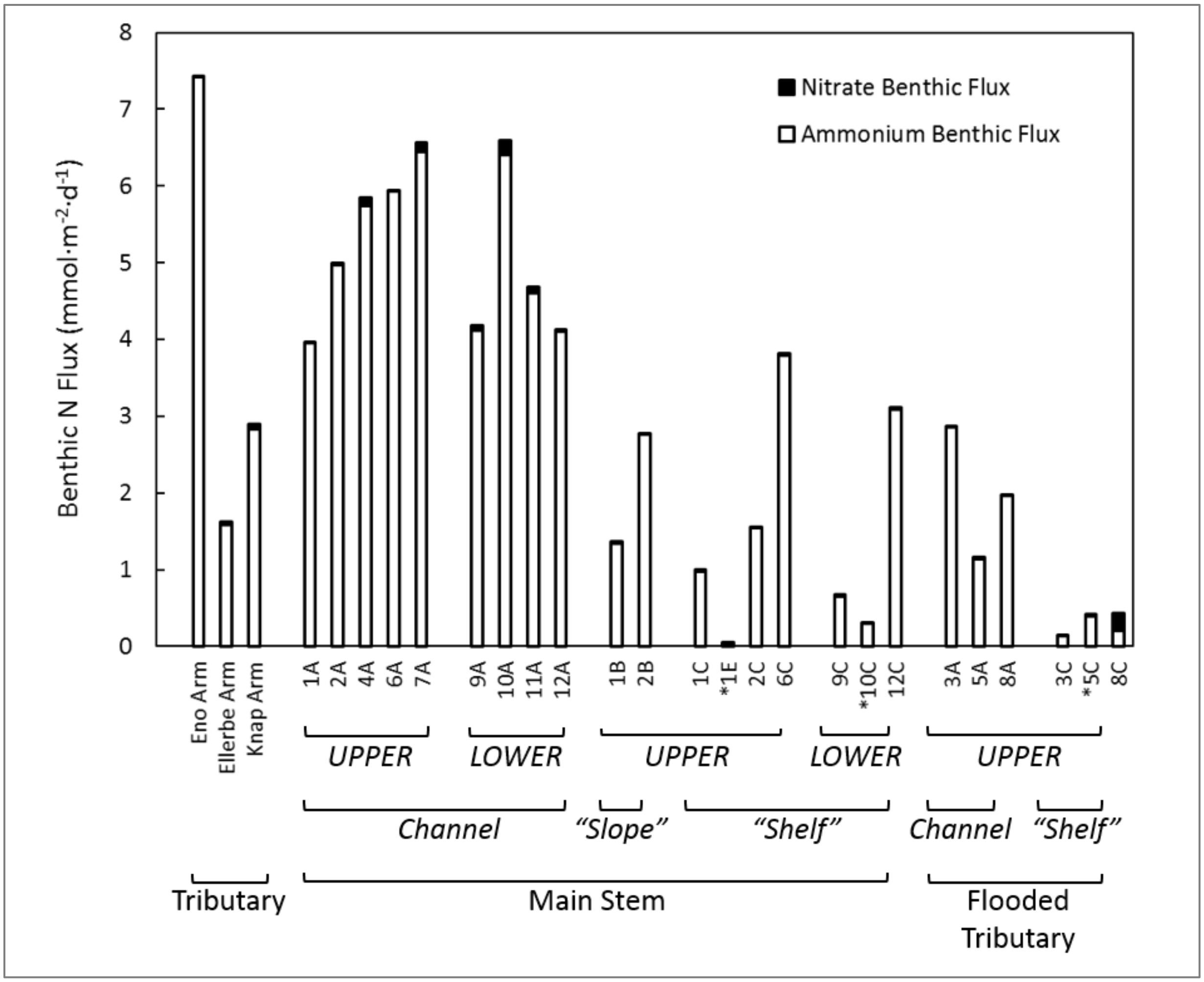


Figure 5-21. NH_3 and Nitrate+Nitrite sediment flux rates estimated using data from cores collected in Falls Lake in Summer 2015.

To convert units to mg N m^{-2} d^{-1}, multiply the flux by the atomic weight of nitrogen (14 grams per mol (g/mol).

Alperin (2018) noted the following nitrogen flux patterns from the results:

- Ammonium flux from main-stem, channel sediments in the Upper Lake steadily increases between stations 1A and 7A.
- Ammonium flux from main-stem, channel sediments in the Lower Lake is generally uniform.

- Benthic ammonium flux decreases from channel to “slope” to “shelf” sediments at all sites.
- The benthic ammonium flux from channel sediments that were Neuse River tributaries prior to dam construction is lower than that of main-stem channel sediments and does not follow a pattern along the lake’s longitudinal axis.

The average nitrogen flux from this core analysis is very similar to two values obtained by the North Carolina Division of Water Quality (now DWR) in 2006 using sediment chambers (DWR 2006). That study estimated an average flux of 50 mg/m^2/d within the historic channel near this study’s station 2A (between I-85 and Cheek Road). The DWR value is within 20 percent of the average flux estimated from all channel cores and within 30 percent of the core-based estimate from the same location. Near station 7 (upstream of Highway 50), DWQ’s study estimated a flux of 10 mg/m^2/d. Based on the water depth recorded for this chamber location (4.7 meters), this estimate was not within the historic Neuse River channel (depth of 8.5 meters). Although the UNRBA survey does not include a ‘shelf’ core at this particular location, DWQ’s value (10 mg N/m^2/d) is near this study’s lake-wide average from all cores collected outside of historic channels (16 mg N/m^2/d). The ranges of values observed in both studies overlap and underscore the large potential for spatial variation within the lake.

The importance of bathymetry in controlling benthic ammonium fluxes is clearly illustrated at the nine transect sites. On average, the ammonium flux from channel sediments is 3.4±1.7 (n=7) times larger than from “shelf” sediments (the average omits stations 3 and 10 that appear to be outliers in this metric; the “shelf” channel flux ratio at these two stations is approximately 20).

The benthic ammonium flux from channel sediments that were Neuse River tributaries prior to dam construction is lower than main-stem channel sediments and does not follow a pattern along the lake’s longitudinal axis. Little Lick Creek (site 3), Ledge Creek (site 5), and Lick Creek (site 8). Sediments at these sites are less important as nitrogen sources to the lake than the main stem.

Dr Alperin also examined phosphorus flux, but because the in situ benthic flux of phosphate depends on the concentration of oxygen in the bottom water (phosphorus is generally only released from sediments under anoxic conditions), the diffusive phosphate flux from the sediments should be considered a “potential” flux. The average potential diffusive phosphate flux calculated from the phosphate concentration gradient at the sediment-water interface is 0.004 mmol Phosphorus per square meter per day (mmol P·m-2·d-1) (range: 0.0003 to 0.016 mmol P·m-2·d-1). In contrast, the average diffusive ammonium flux calculated from the ammonium concentration gradient at the sediment-water interface is 1.26 mmol Nitrogen per square meter per day (mmol N·m-2·d-1) (range: 0.038 to 5.04 mmol N·m-2·d-1). On average, the benthic ammonium flux is more than 300 times the potential phosphate flux. Allowing for the 16:1 N:P ratio in phytoplankton, Falls Lake sediments appear to provide a 20-fold excess of available nitrogen compared to phytoplankton requirements for phosphorous. Figure 5-22 indicates the potential phosphate flux estimated from each core. The pattern among the cores is different from the nitrogen fluxes seen in Figure 5-21, suggesting that nitrogen and phosphorus do not share analogous flux potentials across Falls Lake.

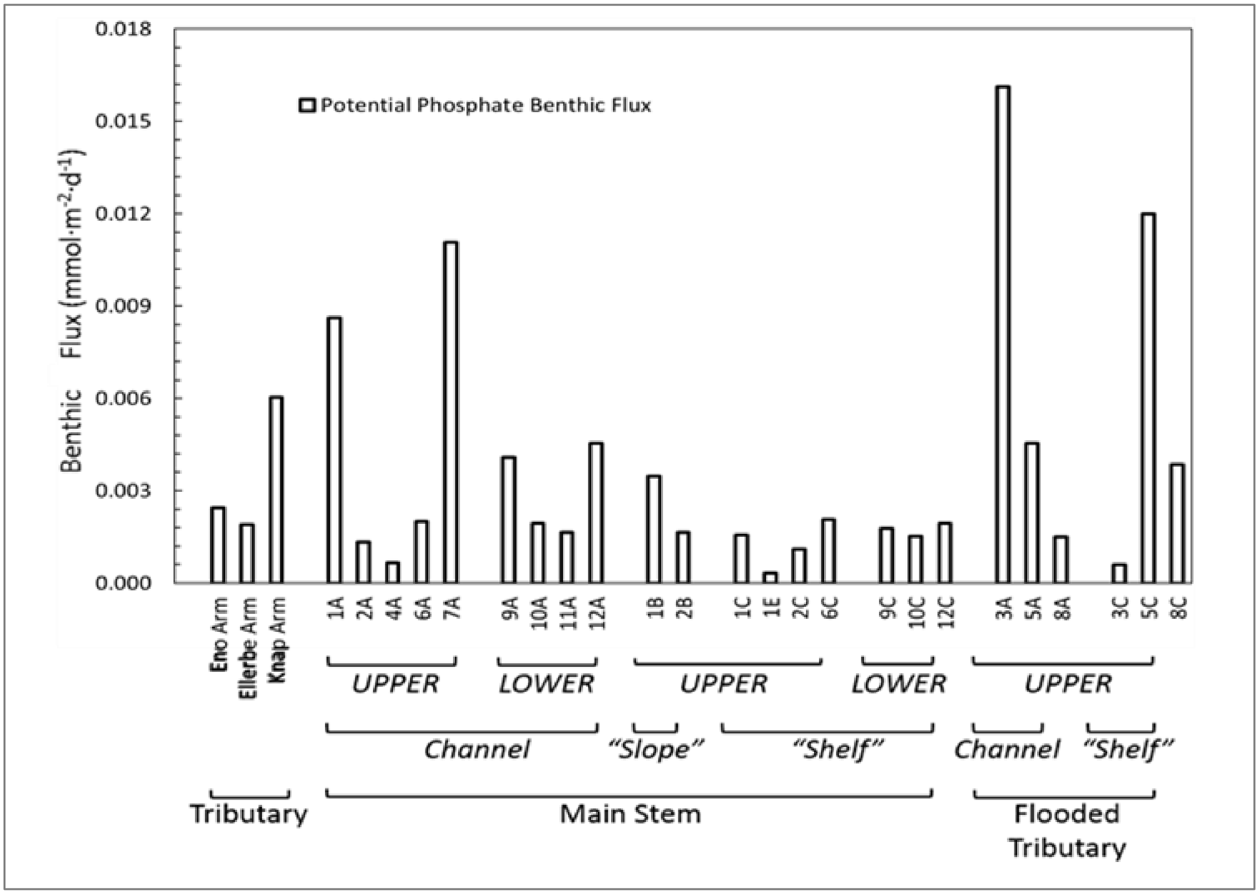


Figure 5-22. Potential orthophosphate sediment flux rates estimated using data from cores collected in Falls Lake in Summer 2015. To convert µM PO_4^{3-} to µg P/L, multiply by 31.

Alperin (2018) drew these conclusions from his evaluation of Falls Lake sediments:

- Sediments are a source of reactive nitrogen to the water column at all 27 Falls Lake stations sampled in this study.
- Sediments are also a source of available phosphate to the water column at all 27 Falls Lake stations sampled in this study. The average potential diffusive flux of phosphate from sediments is less than 0.3 percent (mole/mole) of the average diffusive flux of ammonium.
- Patterns in the spatial distribution of benthic ammonium fluxes appear to be related to location and bathymetry within the lake.

- Benthic nitrogen fluxes from this study may be used as boundary conditions for the next generation of the Falls Lake nutrient response model.

During his October 2016 presentation to the UNRBA Path Forward Committee, Dr. Alperin indicated that current stores of nitrogen in lake sediments are sufficient to release nitrogen for decades, even under a hypothetical condition of no additional loading to the lake from other sources in the watershed or atmosphere.

5.5.2 EPA Sediment Evaluations

In June 2018, the EPA conducted a Sediment Oxygen Demand and Nutrient Flux evaluation of Falls Lake (EPA 2018). The NCDEQ requested the assistance of Region 4 Science and Ecosystem Support Division (SESD) Field Services Branch (FSB) in conducting the study.

Data collection by SESD included:

- Sediment Oxygen Demand measurements
- Sediment Nutrient Exchange rates

While the UNRBA (Alperin 2018) sediment study and the EPA effort (EPA 2018) had some similar characteristics, they were distinctly different in several ways:

- The Alperin effort collected sediment cores from 20 locations, while the EPA study used triplicate in situ chambers placed at three locations
- The EPA study examined sediment oxygen demand while the Alperin study did not.
- The Alperin study involved the collection of samples and laboratory analysis to determine nutrient concentration gradients between sediments and the overlying water, while the EPA study temporarily placed SCUBA-diver deployed chambers on the bottom of the reservoir and made field measurements and collected water samples over time from its chambers and then calculated in situ flux rates based on observed rates of change in concentration.

The EPA project team has extensive experience in this type of study, Dr. Alperin and Brown and Caldwell (BC) staff provided site-specific information and recommendations to EPA for its consideration. The primary recommendations related to selection of sampling locations to facilitate comparison of results between the two efforts.

EPA station FL01 was in shallow water in the lake segment below the Fish Dam Road causeway. It was closest to, and likely similar to, station 2C used by Alperin (i.e., a “shelf” station in the upper lake). EPA station FL03 was in the channel in the large embayment south of Ledge Creek. It was closest to, and likely similar to, Alperin’s station 6A (i.e., a “channel” station in the upper lake). EPA station FL04 was in the channel downstream of the Beaverdam arm of the reservoir. It was closest to, and likely similar to, Alperin’s stations 9A and 10A (i.e., a “channel” station in the lower lake).

Table 5-10 provides a comparison of the estimated flux rates from the two studies. The rates for NH_3 flux are quite similar, particularly given that the two field efforts were conducted three years apart and did not attempt to use the same specific sampling locations or methods. EPA's TP flux values were less similar to the average value reported by Alperin, but both studies reflect the relatively low potential for TP release from the sediments. The general comparability of the two studies, as well as the agreement between the Alperin (2018) results and the earlier DWR work, increases the level of confidence in using the flux estimates for developing the lake response model.

Table 5-10. Comparison of Sediment Nutrient Fluxes determined in UNRBA Study (Alperin 2018) and EPA Study (EPA 2018). Stations are grouped by location to facilitate comparison.

Study	Station ID	NH_3 Flux (g/m2/d)	TP Flux (g/m2/d)[1]
UNRBA	2C	0.03	0.000121
EPA	FL01	0.023	-0.0024
UNRBA	6A	0.083	0.000121
EPA	FL02	0.070	0.0088
UNRBA	9A	0.057	0.000121
UNRBA	10A	0.088	0.000121
EPA	FL03	0.161	0.0203

1 Alperin did not report P flux for each station; this value is the mean for all analyzed cores (range = 0.0000093 to 0.000496, with most values toward the lower end of the range, based on the TP concentration gradients shown in Figure 5-22).

EPA (2018) also reported TKN flux values similar to its NH_3 values, indicating that the majority of the TKN was represented by NH_3. Alperin (2018) did not evaluate TKN. Alperin reported very low nitrate+nitrite fluxes relative to NH_3 fluxes. EPA did not detect nitrate+nitrite in any of its samples at a detection limit of 0.05 mg/L.

EPA (2018) reported a sediment oxygen demand of 1.77 g O2/m2/d at station FL01 (equivalent to 1.15 g O2/m2/d after adjustment to 20 C). The other two stations were sufficiently deep that, at the time of the field effort (June 7), the water column was stratified, and the sediment surface was anoxic, which prevented measurement of SOD at those locations.

Hart and Hart (2006) discuss the trapping of phosphorus within reservoirs, which happens as phosphorus becomes entrained in the sediments. If the top of the sediment layer becomes anoxic, some of the phosphorus can be released into the water column again, contributing to the nutrient pool available for algae growth. As discussed previously, vertical profile data for Falls Lake suggest that areas of hypoxia are generally limited to the deepest portions of the lake in the former river channel. This suggests that phosphorus deposited in the large portions of the reservoir that are not subject to frequent or extensive hypoxia may be more likely to be retained in the sediment and unavailable to algae.

In addition to its Falls Lake SOD and nutrient study, Falls Lake is also being included in a methane study by EPA (Walker 2019). That effort is part of the national Air Emissions Inventories project. EPA is working to refine its estimates of air emissions nationwide, and particularly greenhouse gases. The agency is looking at multiple emissions sources (industrial, transportation, agriculture, etc.). A presentation by EPA staff (Beaulieu et al. 2017) summarized methane emissions from 32 reservoirs in the Midwest, and the Falls Lake investigation is an extension of that effort. As of April 2019, monthly samples have been collected from 30 stations on Falls Lake over the course of a year. Results have shown that methane emissions are generally higher at the upper end of Falls Lake, but there are interesting patterns in the lower lake as well. The bathymetry and sediment mapping efforts by the UNRBA may be valuable to EPA in examining or understanding some of the patterns observed (Walker 2019). Falls Lake is the only Southeastern United States reservoir involved in the methane study to date. It was selected because it is very close to the local EPA laboratory, and it has a nutrient management strategy, which might allow for future exploration of whether control of nutrient inputs results in reductions in methane emissions.

5.5.3 Integration of Sediment Quality and Sediment Mapping to Estimate Nitrogen Loading from Lake Sediments

Although nutrient flux estimates from the sediment cores are widely variable, the number of cores collected allows for a better understanding of benthic fluxes across the lake and how fluxes might vary with other measurable properties. BC used the full set of flux estimates generated by Alperin (2018) and found that the best predictor of nitrogen flux was the length of the core (Figure 5-23, $r^2 = 0.71$, $p < 1 \times 10^{-7}$). That is, a thicker sediment layer tended to have higher N flux. From this relationship, it is possible to integrate Dr. Alperin’s work with the results of the UNRBA Special Study on bathymetry and sediment mapping. The synthesis of the two efforts allows for the development of lake wide estimates of nutrient flux, with far greater resolution of location and sediment thickness than has been possible before. In addition, the modeling efforts can examine the relative magnitudes of nutrient flux from the sediments and from other loading sources to the reservoir.

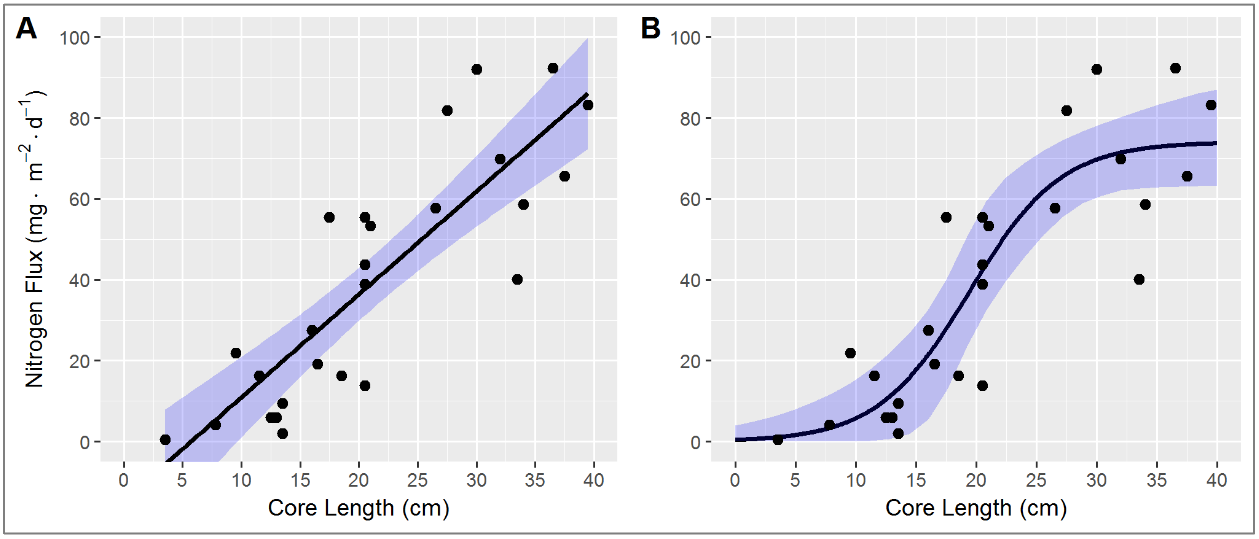


Figure 5-23. Relationships between estimated benthic nitrogen flux and length of sediment cores

*Model A is a simple linear regression (y = 2.55 * Length – 14.5) with R2adj = 0.71, RSE = 16.1 and p-value < 1 x 10-7. Model B is y = a / (1 + exp(-(b + c * Length))), with a=74.1, b=-5.09, and c=0.262, and RSE=15.0.*

The sediment mapping study shows that depths of accumulated sediments are greater in the lower areas of the lake (Figure 5-16). Sediments that settle in the shallow, upper areas of the lake are more easily displayed by the movement of water while sediments that accumulate in the historic channel tend to be trapped. By intersecting the observed sediment depths with the Model B regression shown in Figure 5-23, lake wide estimates of nitrogen flux can be estimated. Figure 5-24 shows the estimated nitrogen flux rates from lake sediments in Falls Lake. Below Highway 50 (including the Beaverdam impoundment), the annual nitrogen flux rate is approximately 140,000 pounds of nitrogen per year (lb-N/yr). The surface area below Highway 50 is 3,370 acres, and therefore the per acre loading rate is 42 pounds of nitrogen per acre, per year (lb-N/ac/yr). Above Highway 50, the annual flux rate is approximately 67,000 lb-N/yr, the surface area is 8,800 acres, and the per acre loading rate is 7.6 lb-N/ac/yr.

There are other means for using sediment quality data to estimate nitrogen fluxes from the lake sediments. For example, fluxes determined for specific cores can simply be extrapolated to the channel or floodplain data surrounding each core. This results in a much higher flux estimate because the sediment thickness is not accounted for and all areas of the lake are assumed to release nitrogen based on the data from the closest core, regardless of the sediment thickness.

The sediment diagenesis module of EFDC will also predict sediment flux. The sediment quality data will be used to set the initial conditions of the model, and the simulated fluxes will be compared to the other lake wide estimates. This module also has the ability to simulate the reduction in nitrogen stores under a nutrient reduction strategy. These methods will be compared and contrasted in subsequent documentation for the modeling effort.

As described in Section 5.6, internal loading from lake sediments comprises approximately 14 percent of the total nitrogen loading to the lake. Dr. Alperin's sediment quality study indicated that current stores of nitrogen in lake sediments are sufficient to release nitrogen for decades even if no additional loadings of nitrogen enter the lake.

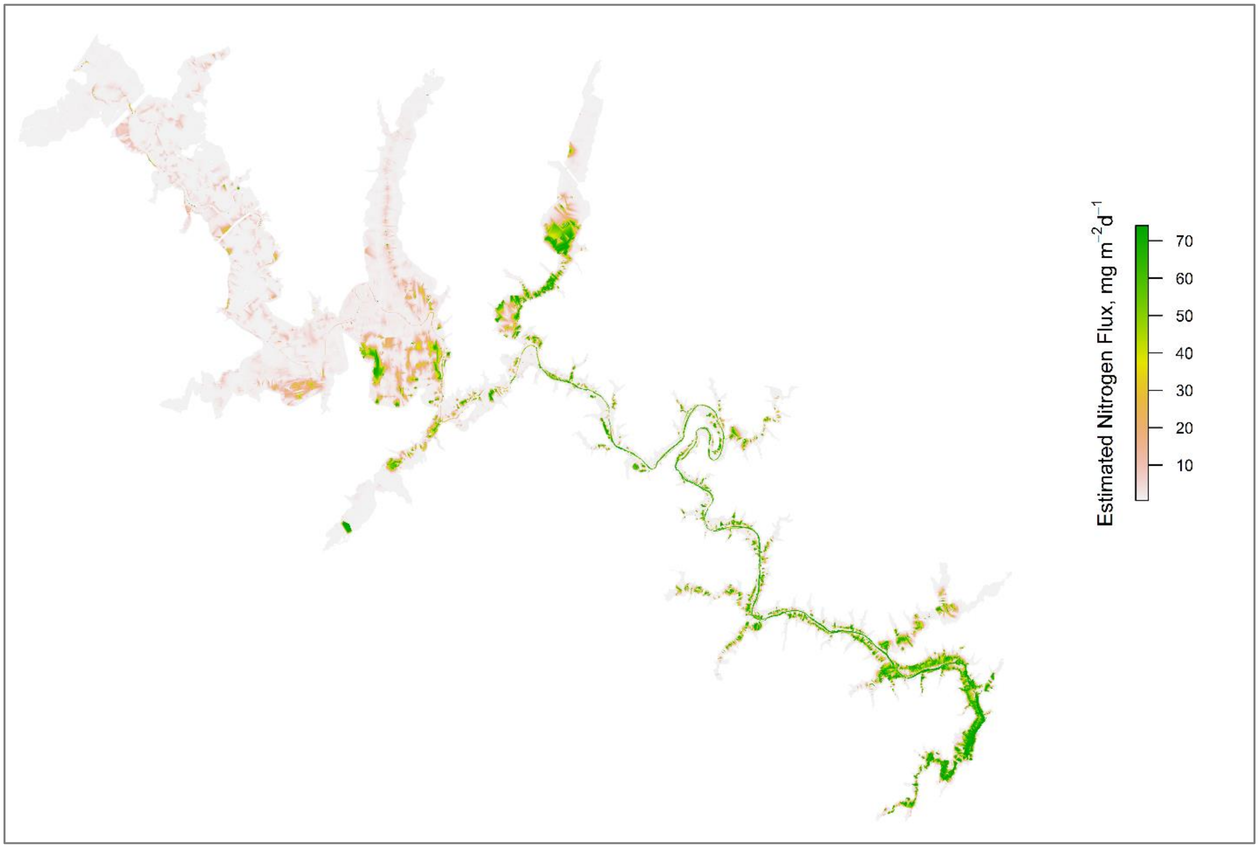


Figure 5-24. Estimated Nitrogen Flux Rates in Falls Lake

5.5.4 Integration of Sediment Quality and Oxygen Profile Data to Estimate Potential Phosphorus Loading from Lake Sediments

As described in Section 5.6.1, the spatial patterns of nitrogen flux are different than those for potential phosphorus flux. While nitrogen flux rates can be reasonably estimated from the concentration profiles in the sediment cores and overlying water, the chemical and biological mechanisms controlling phosphorus flux are more complicated and continue to be an active area of research (Nurnberg 2009). A gradient of porewater phosphorus concentrations was measured in each sediment core as part of the UNRBA's sediment study that provides the information needed to estimate diffusive phosphate flux in the same manner as nitrogen flux. However, under some conditions, phosphate can be immediately sorbed at the sediment-water interface making the diffusive flux calculations an over-estimate of potential flux. Using the sediment core results, potential phosphate fluxes ranged over three orders of magnitude from 0.00001 to 0.0005 $g/m^2/d$. The average flux estimate was 0.00012 $g/m^2/d$, which if applied to the entire lake surface yields an annual load of 4000 pounds of phosphorus. This represents the phosphorus flux rate assuming an oxygenated water layer above the sediment.

The diffusive estimate of phosphate flux also misses the potential for phosphate already bound at the sediment-water interface to be released under anoxic conditions which has the potential to be a significant source of phosphorus to the water column. Although the sediment core analyses did not capture this flux directly, they did provide measurements of TP in the top 3 cm of the sediment. Not all of this phosphorus is available to be released, but literature studies have provided estimates of anoxic phosphorus release as a function of sediment P concentrations (e.g., Nurnberg 1988, $r^2 = 0.21$). Based on the Nurnberg equation and the average sediment phosphorus concentration of 0.6 mg P per g dry weight, an estimate for anoxic sediment release would be approximately 4 $mg/m^2/d$ (from sediments overlain with anoxic water).

Using the monthly dissolved oxygen profiles coupled with the detailed bathymetry of Falls Lake, it is possible to estimate the sediment area exposed to water with low dissolved oxygen (Figure 5-25) and apply the anoxic sediment flux rates to that surface. For the period between 2015 and 2017, this would add approximately 10,000 pounds of phosphorus per year to the water column. Combined with the lake-wide diffusive flux estimate from the sediment cores of 4000 pounds per year, this makes a total sediment load of approximately 14,000 pounds phosphorus per year.

Phosphorus releases from sediments in Falls Lake may contribute up to 9 percent of the total phosphorus load to the lake.

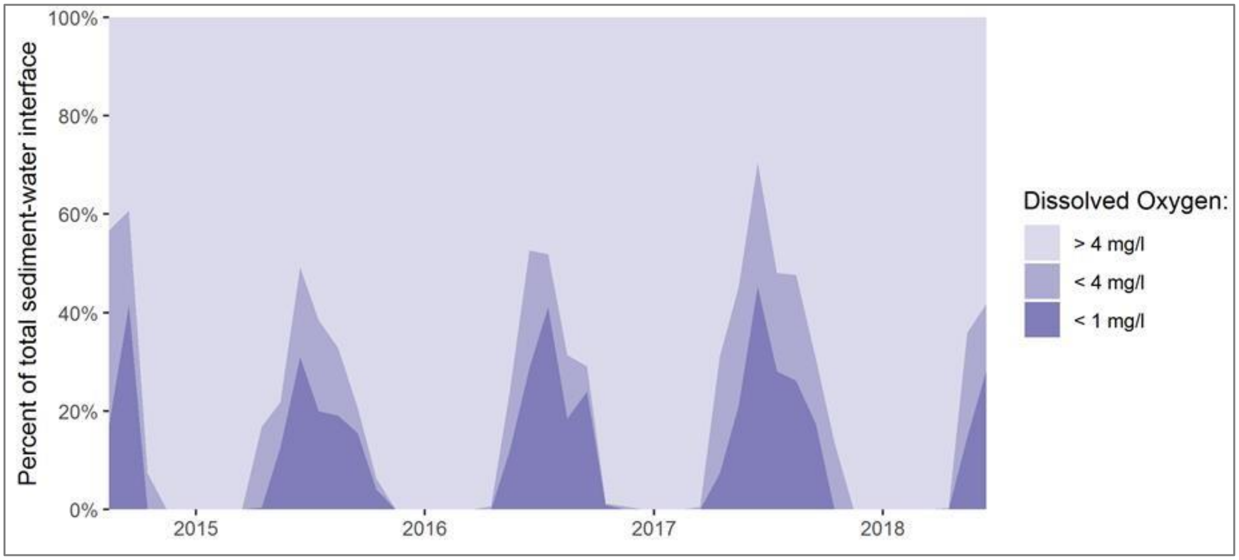


Figure 5-25. Extent of Anoxia Expressed as the Fraction of Lake Sediments in Contact with Water below either 4 mg/L DO or 1 mg/L

5.6 Nutrient Loading Analysis

There are different sources of nutrient loading to Falls Lake from the watershed (external) and from the lake itself (internal). Stormwater runoff is a primary external loading source that carries naturally-occurring and anthropogenic nutrients from urban, suburban, agricultural, and natural areas, and also causes the erosion and transport of suspended solids which can contain additional nutrients. Atmospheric deposition contributes nutrients across the watershed and onto the lake surface itself. Wastewater treatment plants release treated water into several tributaries to the lake. Groundwater inflows can convey nutrients from natural sources, fertilized landscapes, and onsite septic systems, to the streams as well as directly to the lake (although it should be noted that migration through soil can remove nutrients from water as well).

The effective load from most of these external sources, and the biogeochemical processes that affect how they are transported to the lake, are reflected in the water quality samples collected at the UNRBA LL stations. Two exceptions are the nutrients deposited directly onto the lake from the atmosphere, and runoff and groundwater contributions occurring in the portion of the watershed that is downstream of LL stations (i.e., Unmonitored Area – discussed below).

Internal loading is the recycling of nutrients that previously entered the reservoir and became entrained within the sediments through various processes. Some of those nutrients can be released back to the water column under certain conditions. Because the residence time of Falls Lake is at times relatively short (particularly during high rainfall periods), some of the nutrients released to the water column can be flushed from the lake rather than simply recycled back to the sediments. This means if external nutrient loading is reduced, then internal loading should also decline over time as the sediment nutrient pool is depleted by resuspension and flushing. Even without flushing, denitrification processes in the sediment can result in nitrogen being released to the atmosphere. The internal phosphorus cycle, unlike nitrogen, has a minimal atmospheric component, so its elimination must either be via permanent binding within the sediment or outflow through the dam. Reducing internal loading is generally a long-term process, as recognized by Schindler and Vallentyne (2008), who wrote "altogether, it is apparent that by far the most cost-effective measure to restore a eutrophic lake is to reduce external loading and be prepared to wait, perhaps for more than a generation." Fortunately, the short residence time of Falls Lake should reduce the length of the process substantially, compared with a natural lake. Under the hypothetical condition that all external sources of loading to the lake were eliminated, preliminary estimates developed through the UNRBA Sediment Study (Section 5.5) indicate that it would take 20 to 40 years to deplete the nitrogen stores in the sediments. The UNRBA Modeling and Regulatory Support Project is developing a watershed model using WARMF. This model will use available data and model simulations to estimate the loading from each of these watershed sources to Falls Lake. The EFDC lake model will simulate nutrient releases from the lake sediments using its sediment diagenesis module. Both the WARMF and EFDC models will simulate lake water quality by accounting for these sources of loading.

While the WARMF and EFDC models are under development, BC evaluated existing sources of data, including the data summarized in this report, to estimate loading to Falls Lake or its tributaries. Some individual sources can be estimated for this report based on available information including wastewater treatment plant discharges (Section 5.6.1), atmospheric deposition to the lake surface (Section 5.6.2), and internal loading from the lake sediments (Section 5.5). All sources of loading from the watershed are accounted for by the tributary loading estimates described in Section 5.6.3.

5.6.1 Major Wastewater Treatment Plants

Permitted point source discharges can be a significant source of pollutant loading in a watershed depending on their size and type. Wastewater treatment plants discharge treated effluent and are regulated by National Pollutant Discharge Elimination System (NPDES) permits. Wastewater treatment plants that are considered "major" for permitting purposes discharge more than 1 MGD of treated effluent. There are three major wastewater treatment plants that discharge to tributaries in the Falls Lake watershed (Table 5-11). The location of these facilities is shown on Figure 2-1. All three of these tributaries enter Falls Lake upstream of Interstate 85.

The North Durham Water Reclamation Facility (NDWRF) is the largest of the three systems in the Falls Lake watershed with a permitted flow rate of 20 MGD; NDWRF discharges to Ellerbe Creek. The SGWASA facility is permitted to discharge 5.5 MGD to Knap of Reeds Creek. The Hillsborough WWTP is the smallest of the three facilities, and it discharges to Eno River. Both the size of the facility and the size of the tributary determine the extent to which the discharge effects water quality in the receiving water.

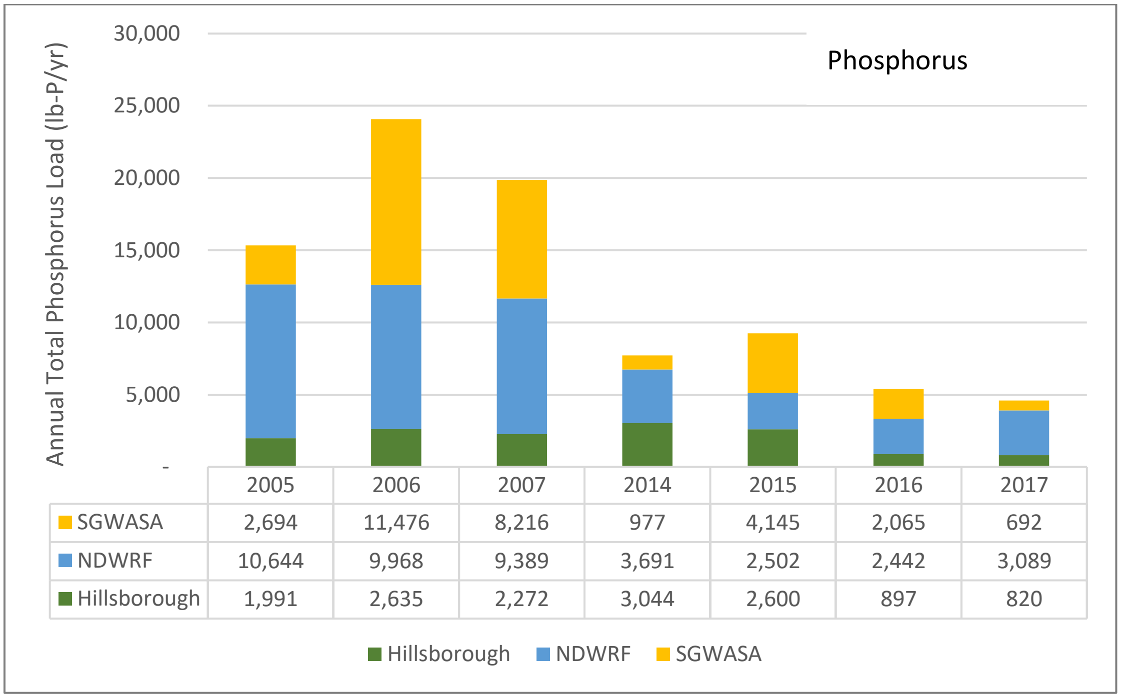
Table 5-11. Major Wastewater Treatment Plants in the Falls Lake Watershed

Permit Number	Facility Name	Permitted Flow (MGD)	Receiving Stream
NC0023841	North Durham WRF (NDWRF)	20	Ellerbe Creek
NC0026433	Hillsborough WWTP	3.0	Eno River
NC0026824	South Granville Water and Sewer Authority (SGWASA)	5.5	Knap of Reeds Creek

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). The organizations are still compiling the 2018 data for the UNRBA Modeling Team, so the discussion below only includes data through 2017. The watershed model will also include loading from the minor facilities that discharge less than 1 MGD but loads from these are not summarized in this report because they contribute a small fraction of the total load to the lake.

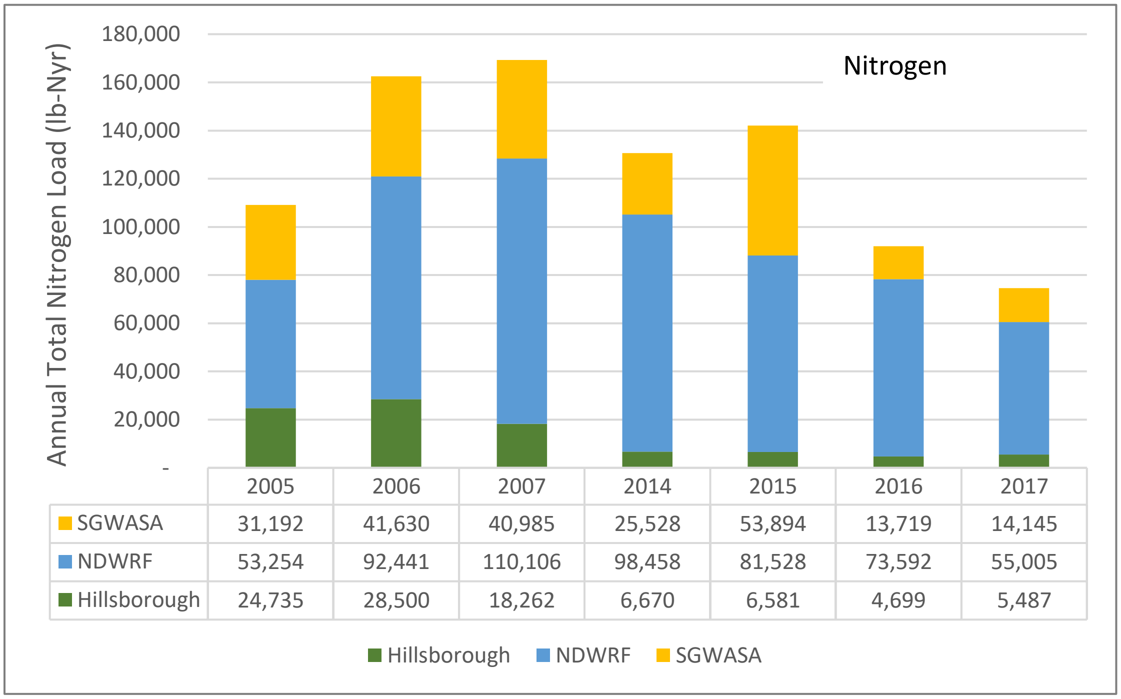
Figure 5-26 shows the annual loads of TP for years within the two modeling periods, and Figure 5-27 shows the values for nitrogen loading. Each of the three facilities have invested in either plant upgrades or optimization, or both, since the baseline year that have resulted in these reductions in loading to the watershed. Prior to the baseline year in 1995, the NDWRF plant implemented Bardenpho 5-stage biological nutrient removal process to remove nitrogen from the treated discharge; the Eno River package plant was taken offline at this time.

Comparing annual loads discharged in 2017 to those discharged in the baseline year of the rules (2006), total phosphorus loads from WWTPs have been reduced by approximately 19,500 pounds per year (81 percent reduction) and total nitrogen loads have been reduced by approximately 88,000 pounds per year (54 percent reduction). Relative to the total loading to the lake estimated for 2006, these improvements result in overall reductions in loading of 12 percent and 5 percent, respectively.



	2005	2006	2007	2014	2015	2016	2017
🟨 SGWASA	2,694	11,476	8,216	977	4,145	2,065	692
🟦 NDWRF	10,644	9,968	9,389	3,691	2,502	2,442	3,089
🟩 Hillsborough	1,991	2,635	2,272	3,044	2,600	897	820

Figure 5-26. Annual Total Phosphorus Loads from Major Wastewater Treatment Plants in the Falls Lake Watershed



	2005	2006	2007	2014	2015	2016	2017
🟨 SGWASA	31,192	41,630	40,985	25,528	53,894	13,719	14,145
🟦 NDWRF	53,254	92,441	110,106	98,458	81,528	73,592	55,005
🟩 Hillsborough	24,735	28,500	18,262	6,670	6,581	4,699	5,487

Figure 5-27. Annual Total Nitrogen Loads from Major Wastewater Treatment Plants in the Falls Lake Watershed

5.6.2 Atmospheric Deposition to the Surface of Falls Lake

Atmospheric deposition of pollutants occurs as both dry deposition (i.e., the settling of particulates) and wet deposition (associated with precipitation). Deposition that occurs on the watershed may be taken up by plants, infiltrated into the soil, or washed off surfaces by stormwater runoff. The net effects of atmospheric deposition in the watershed are indirectly accounted for in tributary water quality sampling which accounts for pollutants from all sources that are delivered to the sampling location.

Atmospheric deposition also occurs directly to the surface of Falls Lake which has a surface area of approximately 12,000 acres at normal pool. The EPA Clean Air Status and Trends Network (CASTNET) measures the dry deposition of particles at 90+ site locations across the United States (Clean Air Status and Trends Network (CASTNET) | US EPA). The National Atmospheric Deposition Program's National Trends Network (NADP-NTN) collects wet deposition data for 263 sites in the United States, Puerto Rico, and the Virgin Islands. Recently CASTNET simulated[1] wet plus dry inorganic nitrogen deposition rates (as load per area) for the CASTNET site located in the Research Triangle Park. Figure 5-28 shows annual deposition rates of wet plus dry total inorganic nitrogen based on the rates simulated by CASTNET at this site multiplied by the surface area of Falls Lake. The overall decrease in nitrogen deposition is attributable to regional and global reductions in emissions from vehicles and stationary sources like power plants.

Since the baseline year of 2006, total inorganic nitrogen deposition to the lake surface has decreased by approximately 38,500 lb-N/yr (2 percent of the 2006 total nitrogen load to the lake from all sources).

These sources of deposition data are being incorporated into the UNRBA watershed and lake models along with other available information including a recent study by the City of Durham. The goal of the study was 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 TN load from atmospheric sources (AMEC 2012). The City of Durham study confirmed that the majority of the nitrogen deposited from the atmosphere is inorganic (greater than 95 percent) and that organic nitrogen is deposited as well. The City of Durham study also demonstrated that deposition of phosphorus is minimal (not detected). The UNRBA Modeling Team is evaluating this data collected by the City of Durham to determine how the study results can be used to inform estimates of air quality and precipitation chemistry throughout the two modeling time periods of interest.

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[1] From the CASTNET website: Annual wet, dry and total (wet + dry) deposition fluxes at CASTNET sites. Flux values are calculated using the NADP/TDep measurement model fusion method (https://nadp.slh.wisc.edu/committees/tdep). Values are extracted and averaged from the grid cell containing the CASTNET site and 9 surrounding grids.

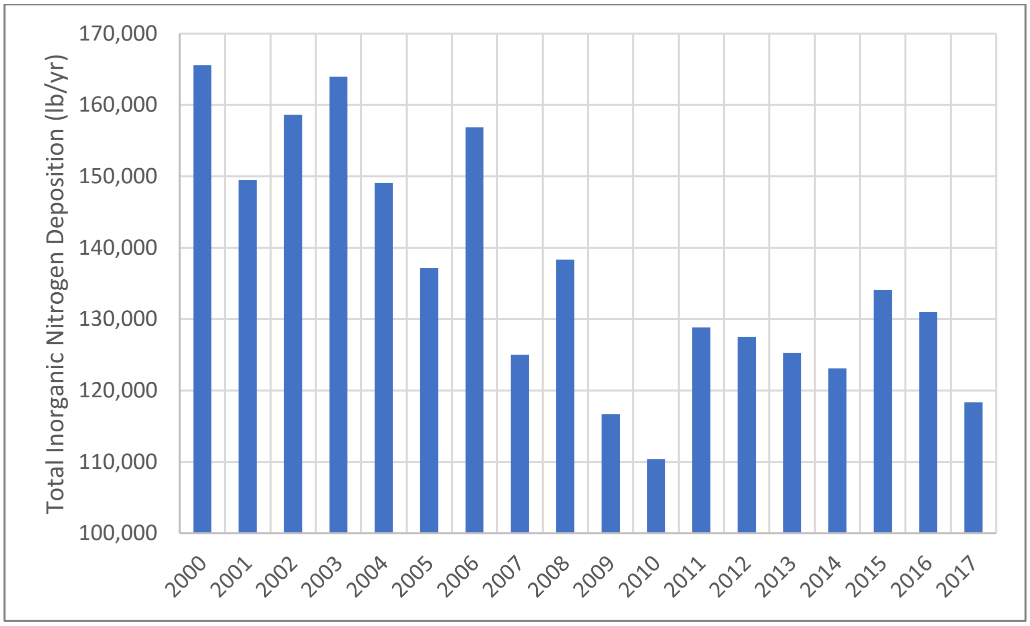


Figure 5-28. Annual Total Inorganic Nitrogen Atmospheric Deposition to the Surface of Falls Lake Based on Rates Simulated by CASTNET multiplied by the Surface Area of Falls Lake

5.6.3 Tributary Loading

The figures presented in Section 3 of this report display observations in terms of the quantified amount of a substance that occurs in one liter of water and represent concentrations present at the time of measurement. Concentrations, however, are not indicative of the total amount of a substance that is actually moving downstream and entering the lake. If high concentrations of a constituent are measured in a stream with very little moving water, the total amount of constituent delivered to Falls Lake will be low despite the high concentrations observed. Therefore, it is important to quantify the total load of each constituent (i.e., mass delivered) which depends on both concentration and the volume of water delivered by each contributing tributary to Falls Lake.

Nutrient loading is derived from two primary factors:
Load = Concentration * Flow

Figure 5-29 shows the relative total water volume of each tributary to Falls Lake based on the basin proration method which was previously evaluated for the UNRBA (Cardno 2014a). This proration method calculates flow for ungaged streams using drainage areas and flow measurements obtained from gaged streams in the Falls Lake watershed between August 2014 and October 2018. LL stations in the figure are ordered left to right from highest to lowest drainage area. The stations with the two largest drainage areas (Flat and Eno Rivers) together account for more than 50 percent of the water delivered to Falls Lake. The five largest tributaries account for 78 percent of the water delivered to Falls Lake. In contrast, the five smallest tributaries together account for less than 4 percent of the water delivered to Falls Lake. The influence of constituent concentrations is greatest when they occur on tributaries delivering the most water to Falls Lake. Elevated concentrations on small tributaries could contribute to localized regions of higher concentrations near stream outlets.

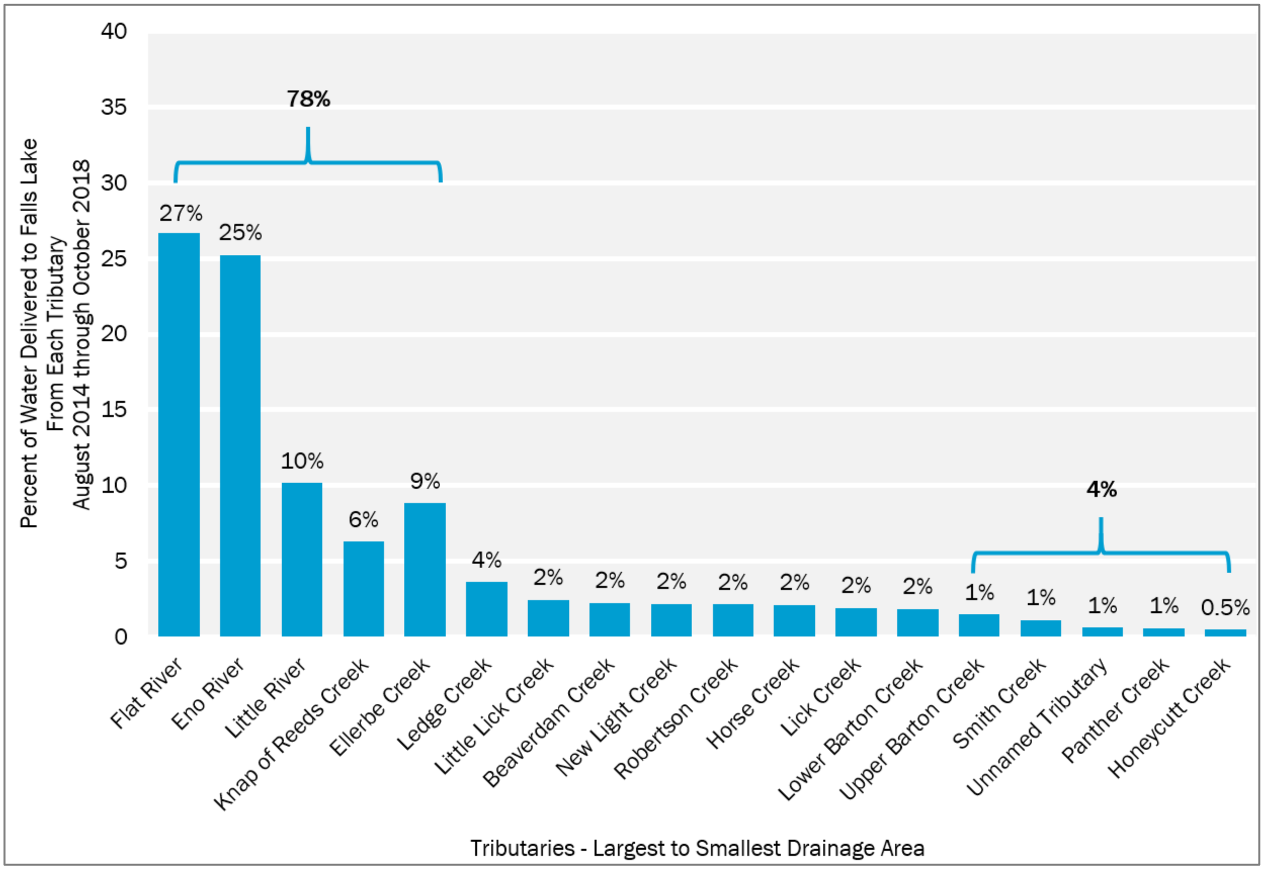


Figure 5-29. The Contribution of each Tributary to the Total Water Load to Falls Lake during the Monitoring Period of August 2014 through October 2018

The contribution is provided as an estimated percentage of total water delivered to Falls Lake coming from each tributary. Tributaries are ordered from largest to smallest drainage area (left to right).

Ultimately, lake models require estimates of tributary loading through time. Several techniques can be used to interpolate between measurements, and the choice of technique can impact the load estimates. Sections 5.6.3.1 through 5.6.3.4 present watershed loading estimates using a variety of these techniques and comparing different periods.

5.6.3.1 LOADEST Modeling

The USGS LOADEST tool is a statistical package developed by USGS that correlates nutrient concentrations with flow at a given location. Paired observations of flow and concentration are used by the model to develop regression equations that estimate load. The regression equations can then be used to predict load for days that paired observations of flow and water quality are not available. More information on the LOADEST program details and software can be found at the following location: http://water.usgs.gov/software/loadest/.

Several of the larger tributaries to Falls Lake have co-located 15-minute flow and water quality data for which LOADEST models were developed by BC. Loads at UNRBA water quality monitoring locations that do not have flow observations were also evaluated using the flow estimation technique developed for the watershed (Cardno 2014a). Observed and estimated 15-minute flows were paired with water quality observations to develop LOADEST models for each tributary monitored by the UNRBA. Models were generated for each of the 38 stations based on the water quality data collected by the UNRBA from 2014 to 2018. Models were developed for TN, TP, and TOC.

Nine statistical relationships are included in the LOADEST package that include variations on model parameters including flow rate, time period, and seasonality. To generate the preliminary load estimates for this Annual Report, model 8 was selected. This model includes a term for flow, flow squared (to address parameters that are more dependent on flow like sediment), time period, and seasonality. While applying this model means that LOADEST includes each potential term in the load equation, the coefficients on these terms may be very close to zero, indicating that term is not an important predictor of load.

As described in Section 2.1, the UNRBA Monitoring Program was designed to collect water quality data at each station on a monthly basis. Prior to using LOADEST to predict loads for days without observed water quality measurements, the modelers compared 51 daily loads generated from pairing water quality observations with observed or estimated flows (paired estimates) to 51 daily loads predicted for the same day using the LOADEST models. Figure 5-30 shows that LOADEST Model 8 generates similar daily loads when compared to those calculated from paired measurements. The medians of the daily loads at each station are similar, and the boxes including the 25th to 75th percentiles overlap almost entirely at each station. As expected, the daily loads increase in a downstream direction along a tributary. Note that some of the stations that are grouped together are on different tributaries, and the ordering of the boxes indicates where each tributary enters the system. Thus, not all of the groupings show an increasing trend because the stations are not necessarily on the same tributary.

This comparison provides confidence in the use of the LOADEST models to predict loads across the watershed for days when observations are not available.

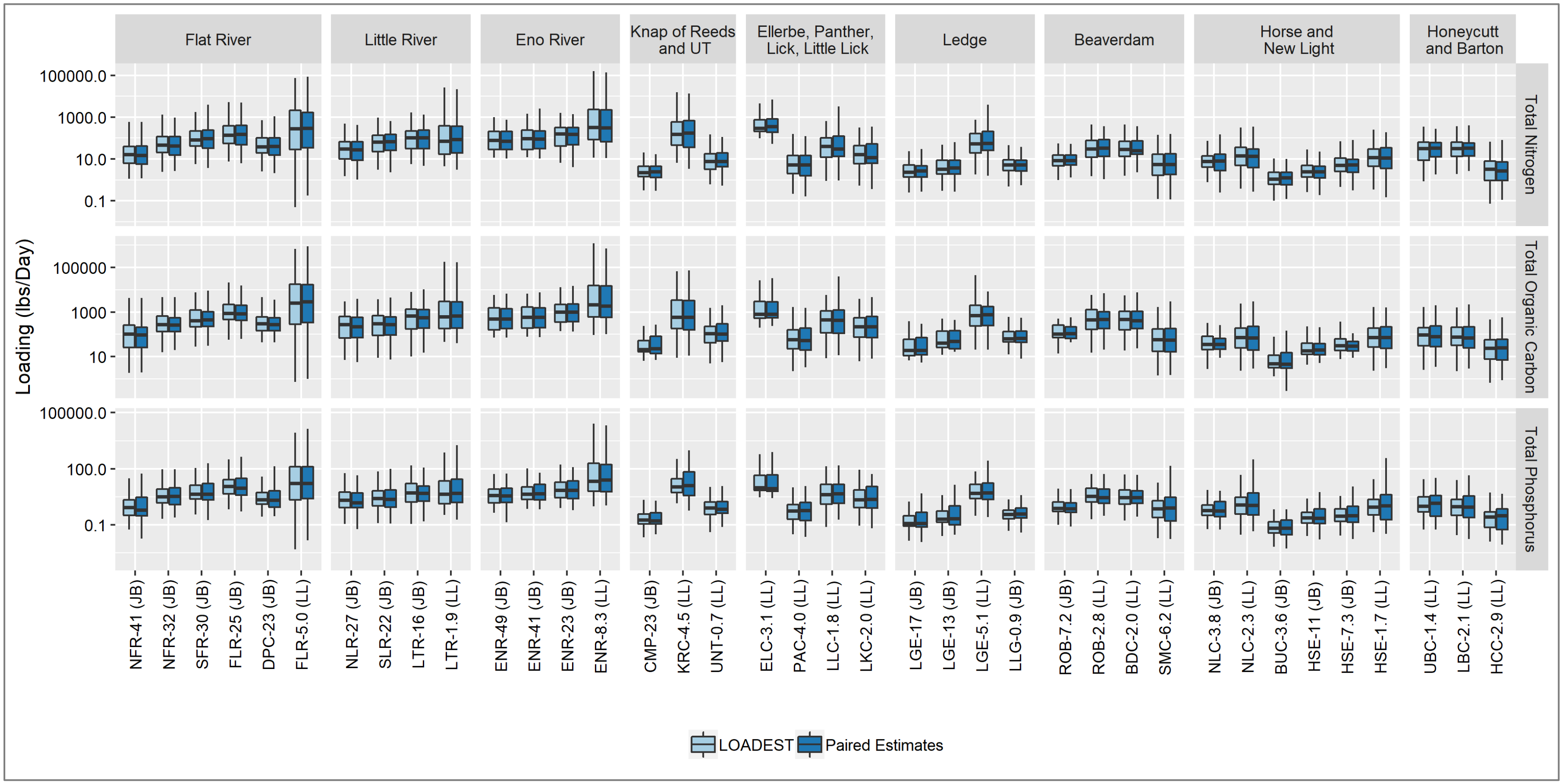


Figure 5-30. Comparison of Daily Loads Based on Paired Estimates (Water Quality Observations and Observed or Estimated Flows) to LOADEST Predictions (Daily Loads Estimated by LOADEST for the Same Days where Paired Measurements are Available)

Following confirmation that LOADEST provides a reasonable estimate of loading at each UNRBA water quality monitoring station, daily loads were estimated for each day of the year to estimate annual load. Figure 5-31 shows the annual load (pounds per year) for 2015 through 2018 for the 18 LL stations. The five tributaries at the upstream end of the lake contribute the majority of the loading every year for the three parameters modeled. For reference, the total annual flow in millions gallon per year (MG/yr) is also shown on this. Because load is calculated by multiplying flow by concentration, and flow is the more variable of the two parameters, annual loads are primarily driven by flow. In other words, when flows to the lake are higher, loading is higher. Figure 5-31 shows that 2018 had the highest loading of the four-year monitoring period and 2017 was generally the lowest, though not at every station. Total nitrogen and total phosphorus loads to the lake were 46 percent and 52 percent lower, respectively, in 2017 compared to 2018. This is not surprising given that 2018 was a wetter year. The hydrologic patterns also drive chlorophyll-a response in the lake.

> *While loading to the lake from the tributaries was highest in 2018, the chlorophyll-a concentrations were generally higher in the lake in 2017 when loading was lower. Less flow into the lake results in a longer residence time and better conditions for algae to grow.*

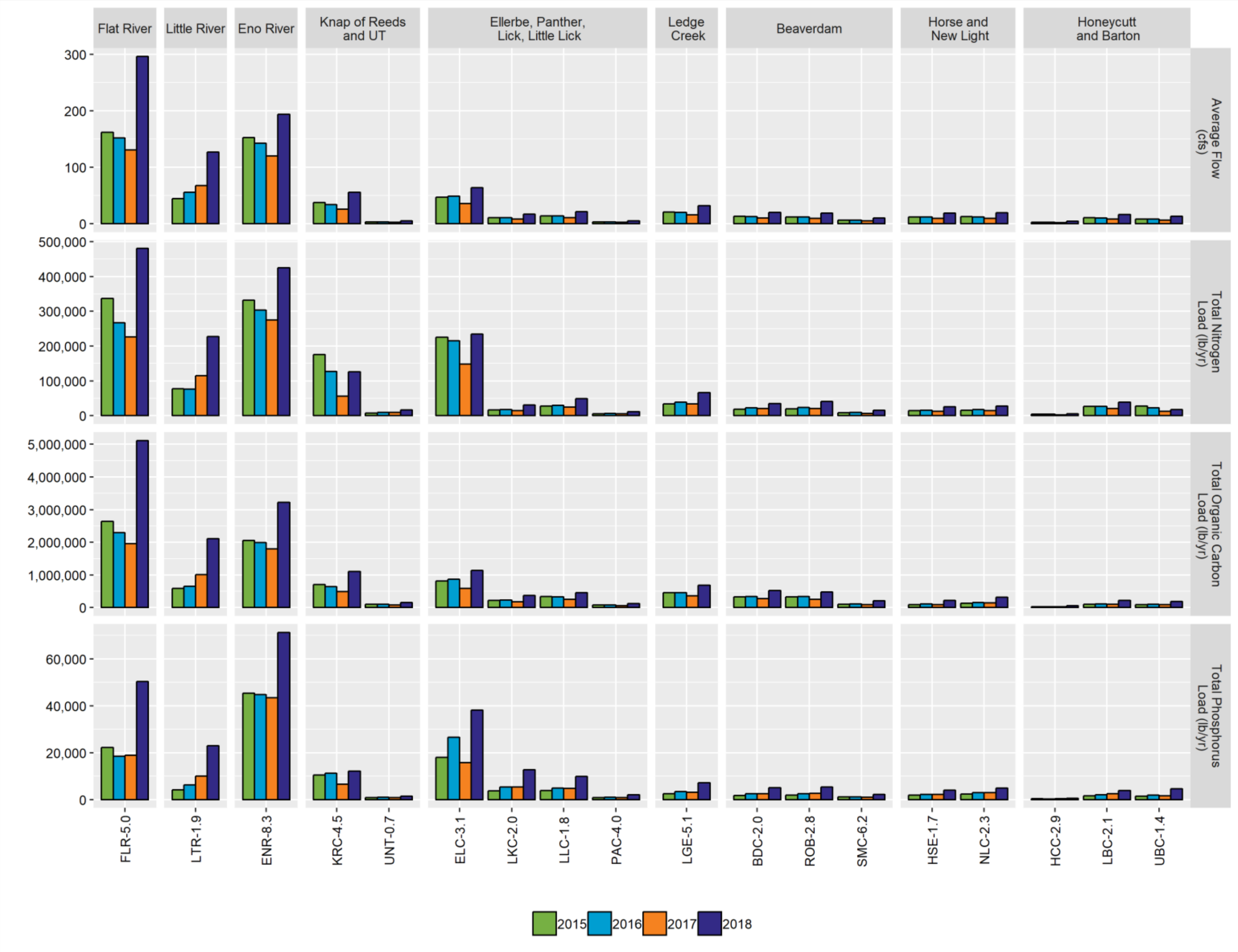


Figure 5-31. Average Annual Flows and Total Annual Loading Rates (Including WWTP Discharges) for the Lake Loading Stations

To compare the effective concentrations at each LL station, the annual loads at each station (mass) were divided by the annual flow (volume) and converted to concentration units of mg/L. This transformation provides a flow-weighted comparison of loading from each watershed for a more comparable comparison among drainage areas that vary greatly in their size. Figure 5-32 provides an estimate of annual average flow-weighted concentration for TN, TP, and TOC. These flow-weighted concentrations are different than those that would be calculated by simply taking the averages of the raw concentrations summarized in Section 3. The concentrations shown in Figure 5-32 represent the average concentration for the total volume of flow at that station. The variability in the concentrations is much lower than the loads shown in Figure 5-31 because the effect of the contributing area and flow volumes has been eliminated for each monitoring station. For TN, most of the LL stations have TN concentrations ranging from 0.25 mg/L to 0.5 mg/L; the highest flow weighted TN concentrations are observed downstream of WWTPs on Knap of Reeds and Ellerbe Creeks. These two stations also show decreases in flow-weighted TN concentrations over the monitoring period which are likely attributable to improvements and optimization at the WWTPs. Flow-weighted TOC concentrations entering Falls Lake are generally higher in the unnamed tributary, Beaverdam, and Robertson Creeks which are dominated by stagnant areas of flow. TOC concentrations generally increased slightly at each station across the monitoring period in coordination with increased annual flows which are shown on Figure 5-31; higher flows tend to flush out stagnant, wetland areas that contain higher amounts of detritus and tannic materials. Flow-weighted TP concentrations where generally highest in Ellerbe and Lick Creeks and ranged from 0.075 mg/L to 0.15 mg/L; Ellerbe Creek concentrations are likely due to the presence of the WWTP; higher concentrations in Lick Creek will be explored with the UNRBA watershed modeling but may include the presence of waterfowl impoundments, urban development, and the stagnant nature of the reach. The other LL stations had annual average flow-weighted concentrations of TP ranging from 0.025 mg/L to less than 0.1 mg/L.

As the size of a watershed increases, loads generally increase unless there is a loss from the system (e.g., settling in an impoundment). Figure 5-33 displays the flow and loading data normalized by area (rather than flow) to allow for a comparison of loading rates across the watershed. The loading rates expressed on a per acre basis are less variable across the stations than the total loads, and the per acre loading rates were generally higher in 2018 which was the highest flow year during the recent monitoring period. The opposite trend occurs for TN in watersheds with WWTPs where the increased flow volumes in 2018 effectively dilute the loading from the plants and result in lower per acre loading rates than dryer years when a more significant fraction of the nitrogen loads come from the WWTPs. Over the four-year period, these per acre loading rates are highest in the Ellerbe Creek watershed because the watershed is relatively small and the wastewater treatment has the highest permitted capacity in the basin. Thus, the amount of per acre loading estimated from that watershed is higher than the others.

All of the figures in Sections 5.6.3.1 through 5.6.3.3 include loads from WWTPs in the watershed. Section 5.6.3.4 breaks out the loading from WWTPs. After the UNRBA develops the watershed model, loading from other sources can be further distinguished.

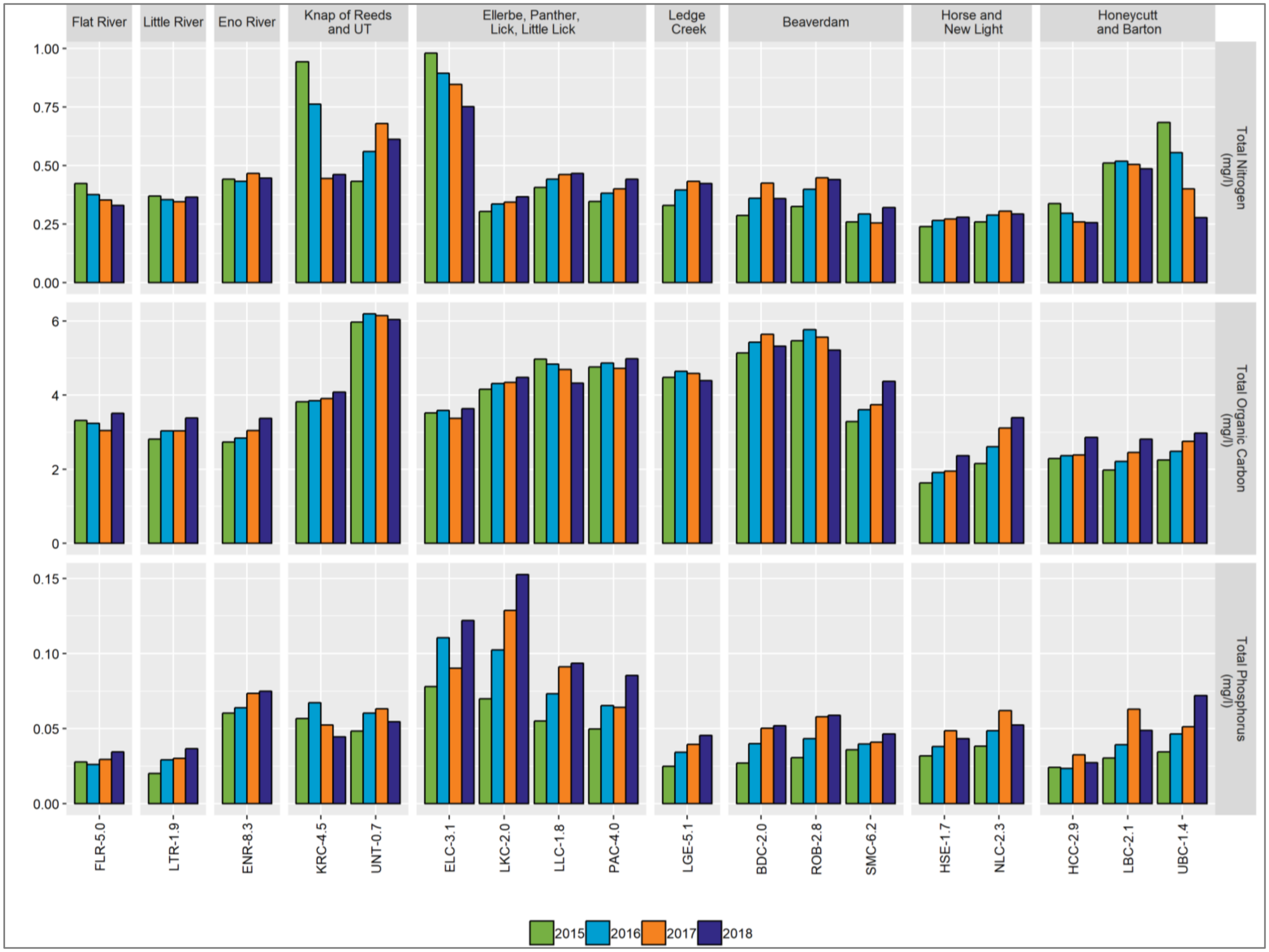


Figure 5-32. Average Annual Flow-Weighted Concentrations of TN, TOC, and TP for the Lake Loading Stations (Including WWTP Discharges)

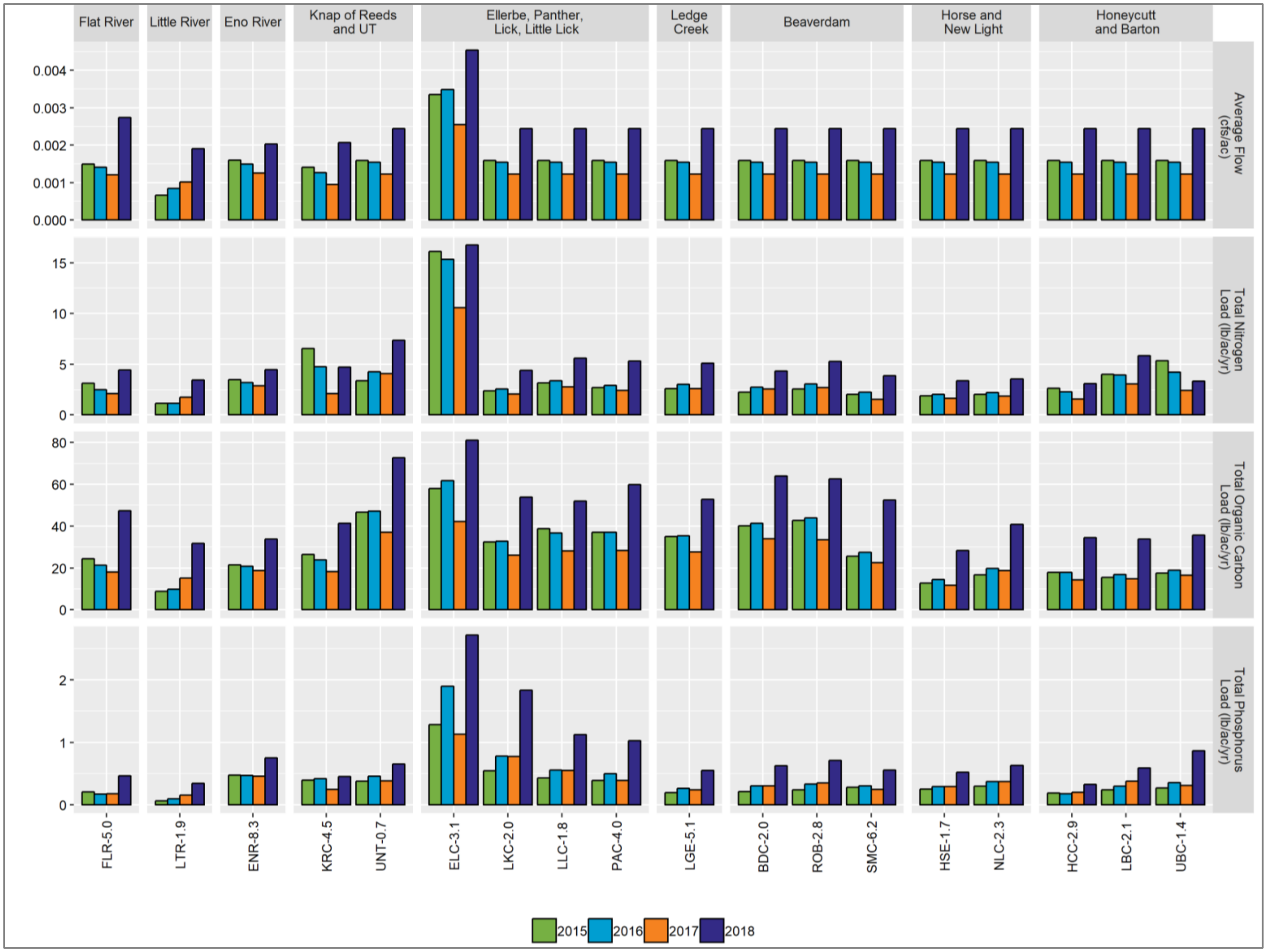


Figure 5-33. Average Annual Flows and Nutrient Loads Per Acre for the Lake Loading Stations (Including WWTP Discharges)

To compare contributions to loading across the watershed, area-based loading rates for TN, TP, and TOC are displayed on Figure 5-34 through Figure 5-36. The loading rates on these figures represent the average annual load estimated for each monitoring station (i.e., the average of the annual per acre loads estimated for 2015, 2016, 2017, and 2018). These area-based loading rates include all sources of loading upstream of each monitoring station, including WWTPs. Because loads from WWTPs are included, the area-based loading rates from Ellerbe Creek and Knap of Reeds Creek are not representative of the loads only from land-based sources. The Eno River watershed also includes a major WWTP, but the size of that facility compared to the drainage area of the basin reduce the importance of the WWTP on the area-based loading rate. The two subwatersheds with the highest areal loading rates of TN are Knap of Reeds Creek and Ellerbe Creek which both have major wastewater treatment plants and relatively small drainage areas compared to larger tributaries. The two subwatersheds with highest areal loading rates of TP are Ellerbe Creek and Little Lick Creek. The watersheds with the highest areal loading rates of TOC are Ellerbe Creek and the subwatersheds dominated by wetlands and stagnant areas.

Each of the maps reflecting loading rates includes an “Unmonitored Area” immediately surrounding Falls Lake. This is the land area downgradient of the LL stations, above which water quality and streamflow information were combined to yield loading estimates. Thus, nutrient loads in surface water and groundwater from land below those stations are not represented in the loading analysis discussed here. A substantial portion of this land (approximately 25,600 acres, or about twice the surface area of the reservoir itself) is owned and managed by the USACE or state and local agencies who lease lands from the USACE for recreational uses (USACE 2013). Based on 2011 land cover data (Figure 5-24), the Unmonitored Area is approximately 12 percent developed land, 10 percent agriculture, 6 percent wetlands and open water, and 72 percent forest/shrub/grassland. Although the Unmonitored Area represents a significant portion of the overall watershed, and is the portion nearest to the reservoir itself, the fact that nearly 80 percent of the area is wetlands and undeveloped uplands suggests that nutrient loading from this area should be at the lower end of the range for the overall watershed. Nutrient loading from this area will be evaluated further with the watershed modeling.

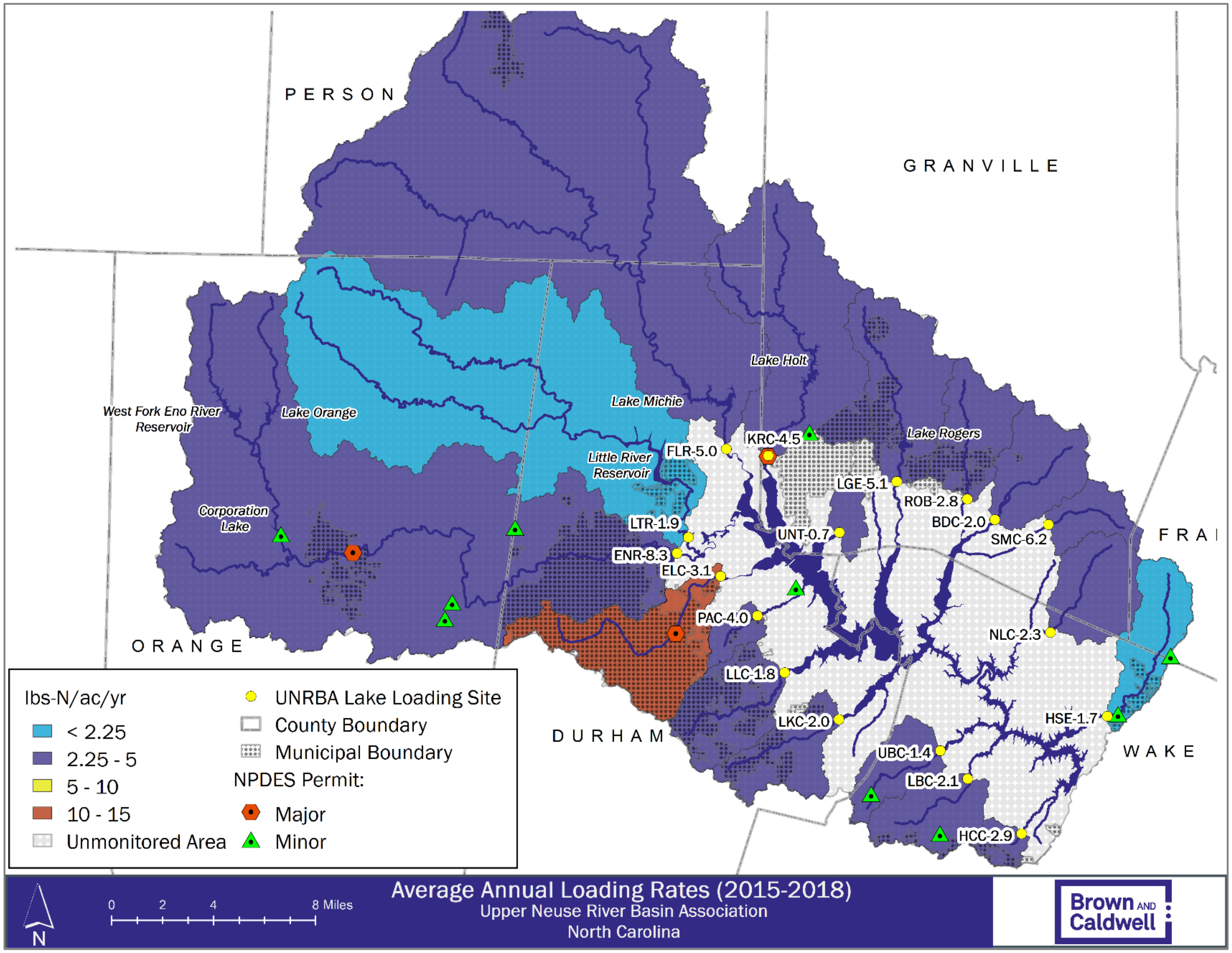


Figure 5-34. Average Annual Total Nitrogen Loads Normalized by Drainage Area for the Lake Loading Stations (Including WWTP Discharges)

Per acre nitrogen loads from the Ellerbe Creek drainage would be 9 lb-N/ac/yr without the WWTP discharge.

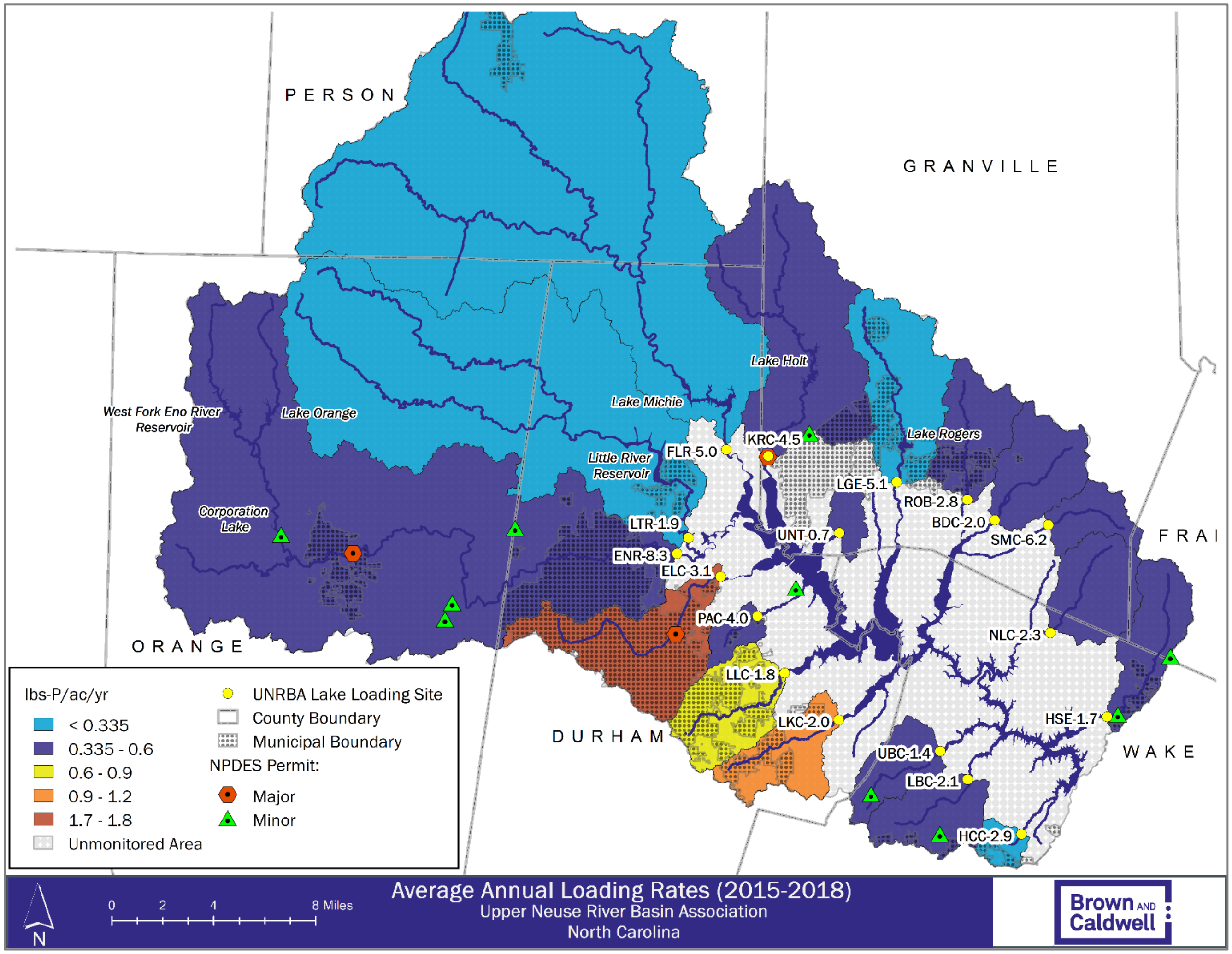


Figure 5-35. Average Annual Total Phosphorus Loads Normalized by Drainage Area for the Lake Loading Stations (Including WWTP Discharges)

Per acre phosphorus loads from the Ellerbe Creek drainage would be 1.25 lb-P/ac/yr without the WWTP discharge.

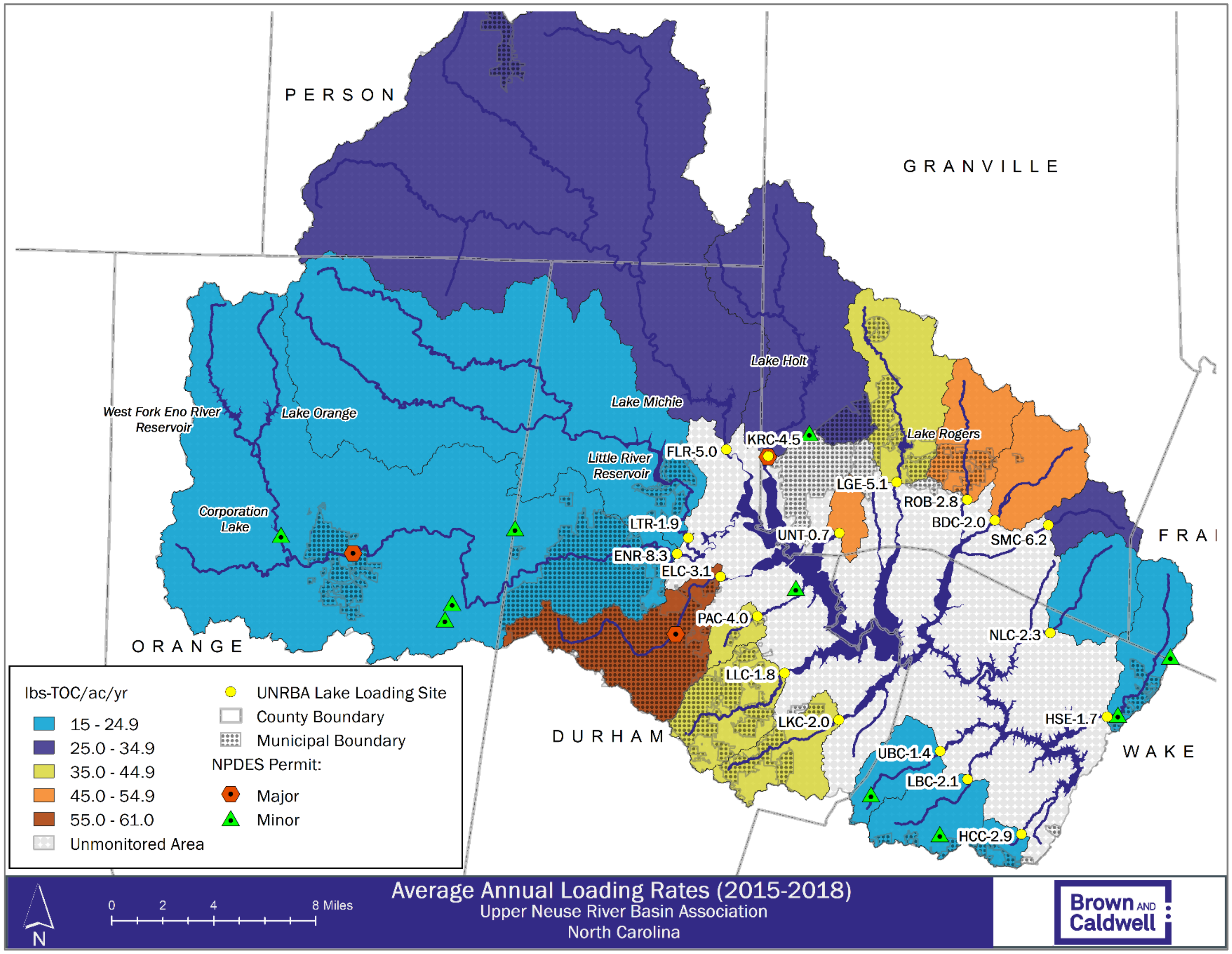


Figure 5-36. Average Annual Total Organic Carbon Loads Normalized by Drainage Area for the Lake Loading Stations (Including WWTP Discharges)

Per acre TOC loads from the Ellerbe Creek drainage would be lower than those shown without the WWTP discharge.

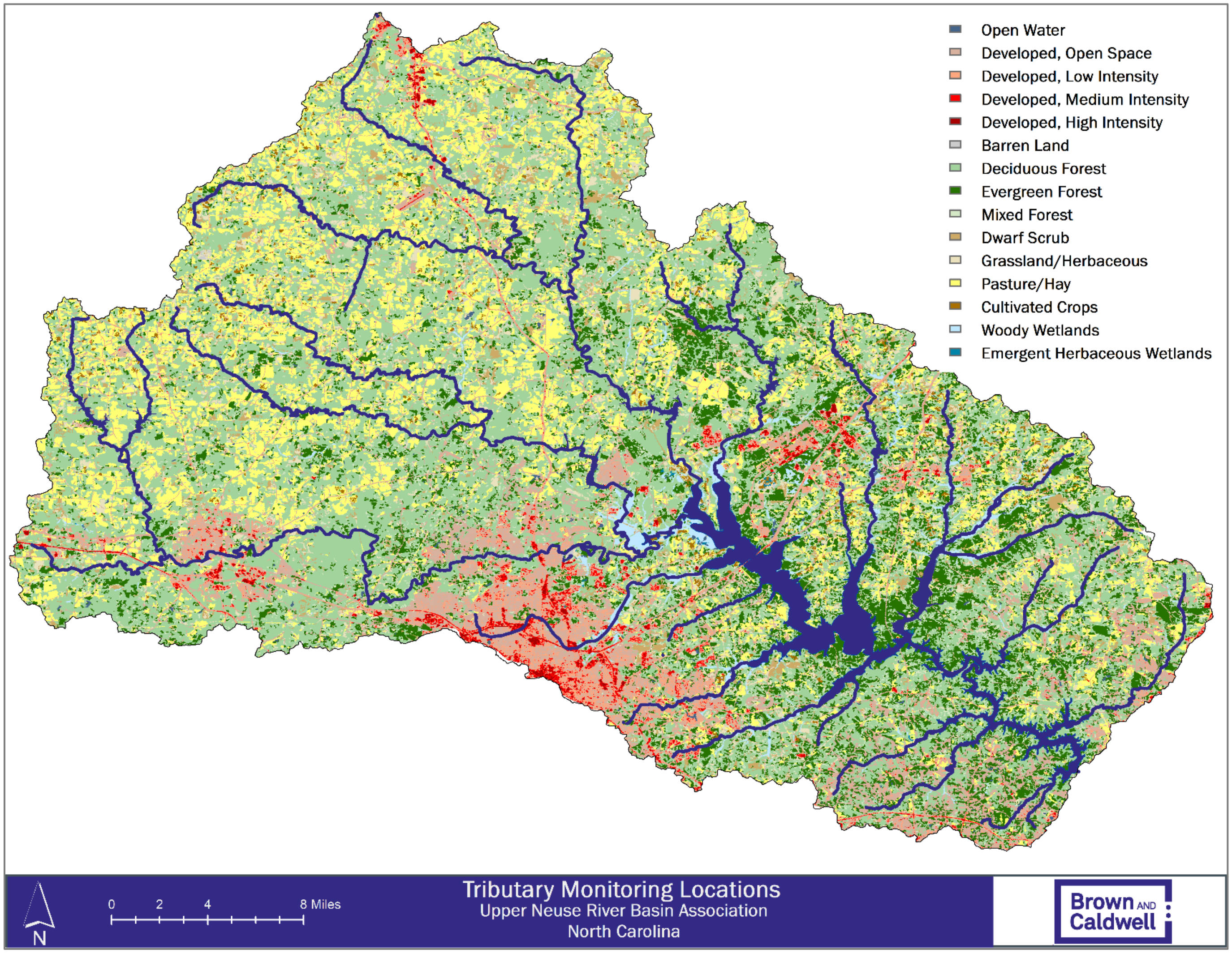


Figure 5-37. 2011 Land Use Classifications and UNRBA Monitoring Stations

5.6.3.2 Comparison of Nutrient Loading to the Baseline Period

Since the passage of the Falls Lake Rules, stakeholders in the Falls Lake Watershed have acted to control nutrient loading to Falls Lake. As noted in Section 5.6.1, upgrades and optimization at wastewater treatment facilities have reduced nutrient loading to the lake by approximately 88,000 pounds of nitrogen per year and 19,500 pounds of phosphorus per year. Local governments implemented new development stormwater controls in 2012 that require stormwater control measures to maintain nutrient loading from the site at levels specified in the Falls Lake Nutrient Management Strategy (N.C. Rules Review Commission 2010). These loading targets for new development (2.2 lb-N/ac/yr and 0.33 lb-P/ac/yr) were set such that development would not cause an increase in loading to Falls Lake. Local governments have also implemented stormwater retrofits, stream restoration projects, and regional controls to reduce nutrient loading from existing development in the watershed. Both agriculture and the NC Department of Transportation have met or exceeded their nutrient reduction requirements under Stage I of the Rules.

Based on reports from WWTP operations, agriculture (Watershed Oversight Committee), and NCDOT have met or exceeded their reduction requirements under Stage I of the Rules. New development requirements have been in place since 2012 to limit increases in nutrient loading from development.

In order to compare the loading estimates associated with the UNRBA monitoring period (2014 to 2018) to the baseline period simulated for the rules (2005 to 2007), LOADEST models were developed for stations that were monitored during both periods. The baseline monitoring sites were predominately monitored by DWR, and data collected from 2005 to 2007 were used to develop the regression equations for the baseline period. Four sites on Flat River, Eno River, Knap of Reeds Creek, and Ellerbe Creek (representing approximately 68 percent of the total flow to Falls Lake) have the historic water quality data required for this comparison (sites FLR-5.0, ENR-8.3, KRC-4.5, and ELC-3.1). For the recent period, the LOADEST models described in 5.6.3.1 were used for this comparison.

Figure 5-38 through Figure 5-40 provide comparisons of the baseline and recent monitoring periods using the same metrics are those shown in Figure 5-31 through Figure 5-33 for the recent period. For the comparison of baseline and recent periods, bars that are shaded light purple represent 2005 to 2007, and bars shaded dark purple represent the period 2014 to 2018. Figure 5-38 shows the average annual flow and total annual loads for each of these years for the four sites that data are available. As expected, flows in the recent period are higher than those in the baseline period which included long, intense drought periods with a few large storms. As a result, loads of TN and TP are higher at Flat River and Eno River where nutrient loading is dominated by nonpoint sources. Nutrient loads at Knap of Reeds and Ellerbe Creeks are similar across the two periods. While the recent period was generally wetter and had higher nonpoint source loading, the two WWTPs invested in improvements that resulted in load reductions from point sources. These increases and decreases in loading from different sources resulted in little change in total load from baseline to recent conditions for these two watersheds. The WWTP in the Eno River watershed operated by the Town of Hillsborough also had significant reductions in loading. However, the loading from this facility is low compared to the nonpoint source loading from the entire Eno River watershed, so improvements at this facility are less apparent when compared to the Ellerbe and Knap of Reeds Creeks which have much smaller drainage areas. The Ellerbe Creek watershed also has a relatively high percentage of impervious area that also contributes to increased runoff.

Upgrades and optimization at wastewater treatment plants has resulted in reduced nutrient loading and average concentrations in streams. Even though precipitation rates and tributary flows were higher in the recent monitoring period, these reductions in average concentration resulted in lower loading to Falls Lake from these two tributaries.

Figure 5-39 shows the average annual flow-weighted concentrations for the baseline and recent periods. For Flat River and Eno River, the TN and TP concentrations decreased slightly. For Knap of Reeds and Ellerbe Creeks, the flow-weighted nutrient concentrations decreased significantly due to the upgrades at the WWTPs.

Figure 5-40 shows the area-weighted flows and nutrient loads for the two periods. The patterns in this figure are similar to those shown in Figure 5-38. The higher rates of precipitation in the recent period compared to the baseline period result in higher nutrient loading from nonpoint sources in the watershed. This increase is more evident in the watersheds that do not have large WWTPs relative to the size of their drainage area: Eno and Flat Rivers.

Figure 5-38. Annual Flows and Loads for both the baseline and UNRBA monitoring period

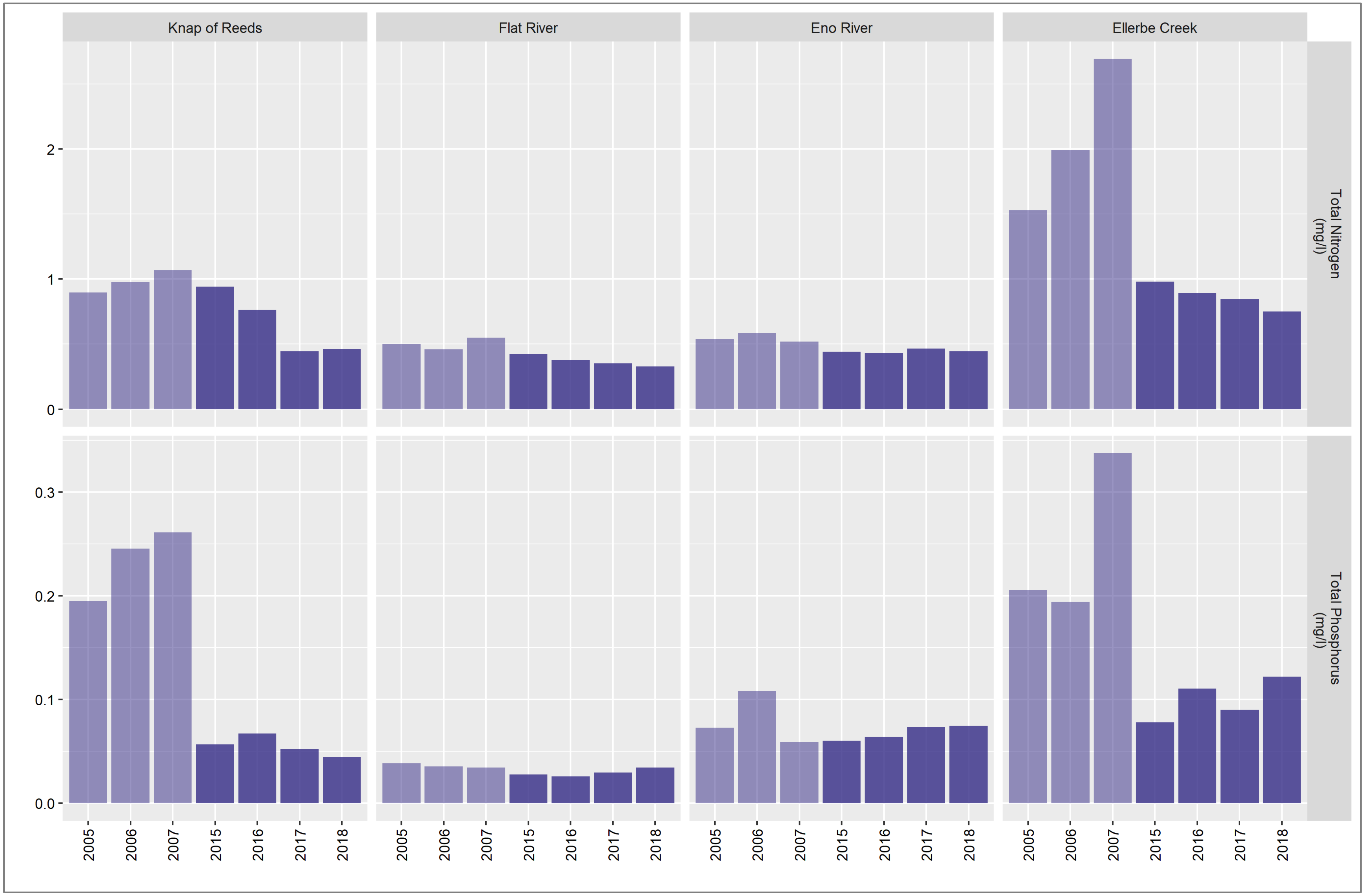


Figure 5-39. Average Annual Flow-Weighted Concentrations for both the baseline and UNRBA monitoring period

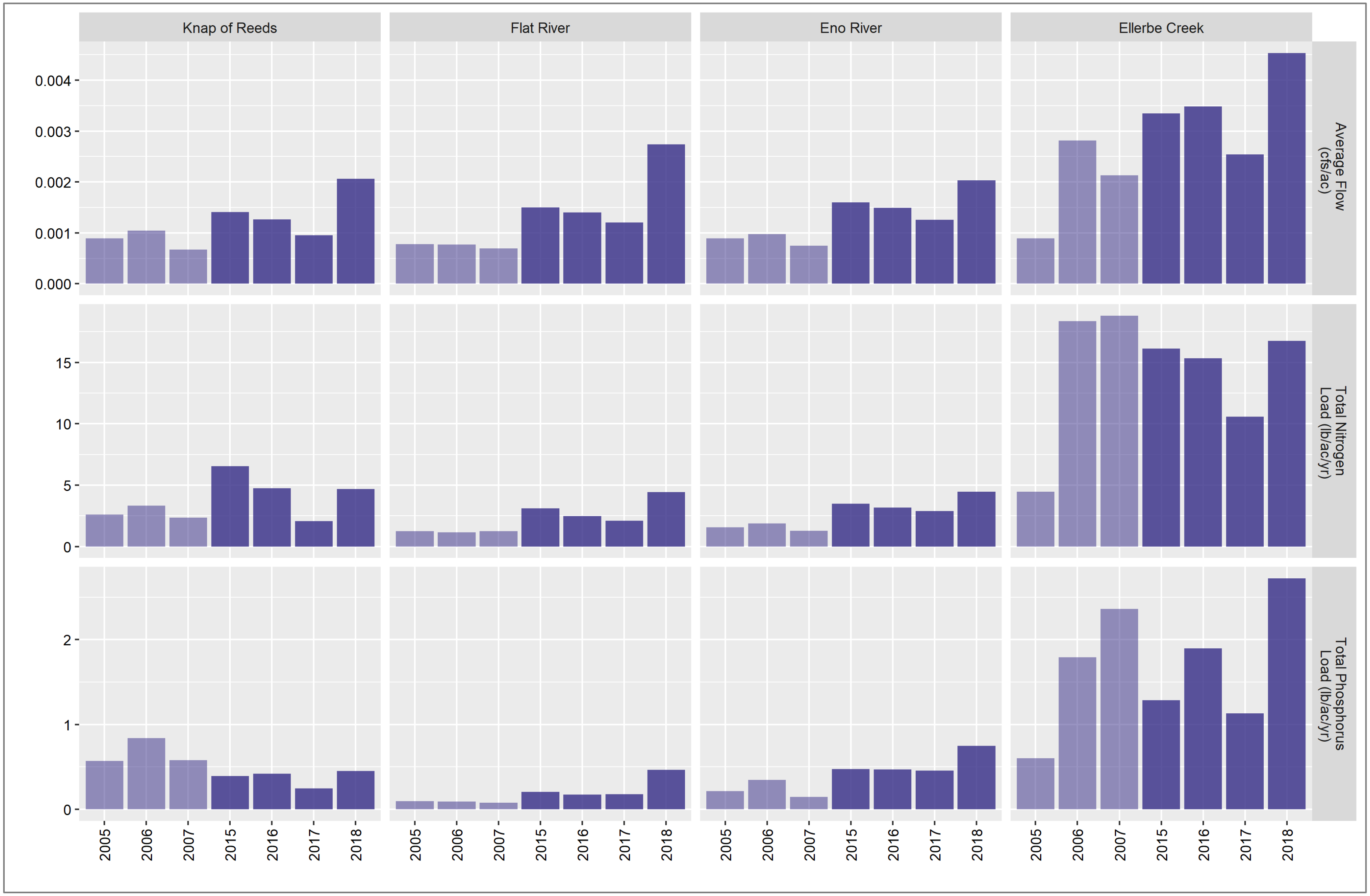


Figure 5-40. Annual Flows and Loads Per Acre for both the baseline and UNRBA monitoring period

5.6.3.3 Nutrient Loading Trends Since the Impoundment of Falls Lake

The LOADEST models described above for the baseline and recent period were generated by using flow and water quality data collected during each period and developing separate statistical models using LOADEST. An alternative statistical model was developed using a generalized additive model (GAM; Hastie and Tibshirani, 1990) to compare nutrient loads over the past four decades using the full set of water quality and flow data. This analysis provides a comparison to the LOADEST models and allows for comparisons over a longer period.

Nutrient loading is derived from two primary factors: nutrient concentrations and stream flows. Nutrient concentration data from 1980 through 2018 is shown below for the four tributaries to Falls Lake monitored by NC-DENR (Figure 5-41). The watersheds of these four tributaries make up approximately half of the total drainage area for Falls Lake. Since the early 1980s, significant decreases in phosphorus concentrations are apparent in Knap of Reeds Creek, Eno River, and Ellerbe Creek. Phosphorus data in the Flat River are not available until the late 1980s, and concentrations have been relatively consistent since data collection began. TN concentrations have also decreased since the early 1980s in Knap of Reeds Creek, Eno River, and Ellerbe Creek. Ammonia concentrations have decreased substantially in both Knap of Reeds and Ellerbe Creeks, and nitrate+nitrite has fluctuated over time. Organic nitrogen is similar to slightly lower across in all four drainages. Overall, nutrient concentrations in the Flat and Eno Rivers show less change over time. Nutrient loading in these two drainages is dominated by nonpoint sources. Reductions in nitrogen and phosphorus concentrations in Knap of Reeds and Ellerbe Creeks reflect major improvements in nutrient removal at upstream WWTPs.

The second factor in nutrient loading, stream flow, is largely driven by weather patterns (wet years, droughts), discharges from major wastewater treatment plants, and operations of upstream impoundments. The annual variation in discharge is quite high with back-to-back years showing several-fold differences in average annual discharge (stream flow) (Figure 5-42). As a result, most of the year-to-year variation in the tributary nutrient load to Falls Lake is a result of differences in how much water moves through the tributaries (Figure 5-43). While the year-to-year variability in stream flow is high, the average hydrologic conditions have not changed much over the past four decades. The fact that nutrient loading has decreased over this period at Knap of Reeds Creek, Eno River, and Ellerbe Creek indicates that improvements in water quality are driving the load reductions.

Data are also available for the Little River; however, the monitoring station is upstream of the Little River Reservoir and its associated nutrient processing (e.g., uptake, sedimentation) and therefore it does not reflect nutrient concentrations in the water delivered to Falls Lake.

Since the 2005-2007 baseline period, reductions in total loading at Knap of Reeds and Ellerbe Creeks appear to be driven by improvements at WWTPs given that discharge was higher in 2014 to 2018 but loading was lower. For the Flat and Eno Rivers, increased loading between baseline and the UNRBA monitoring period is predominately the result of higher stream flows.

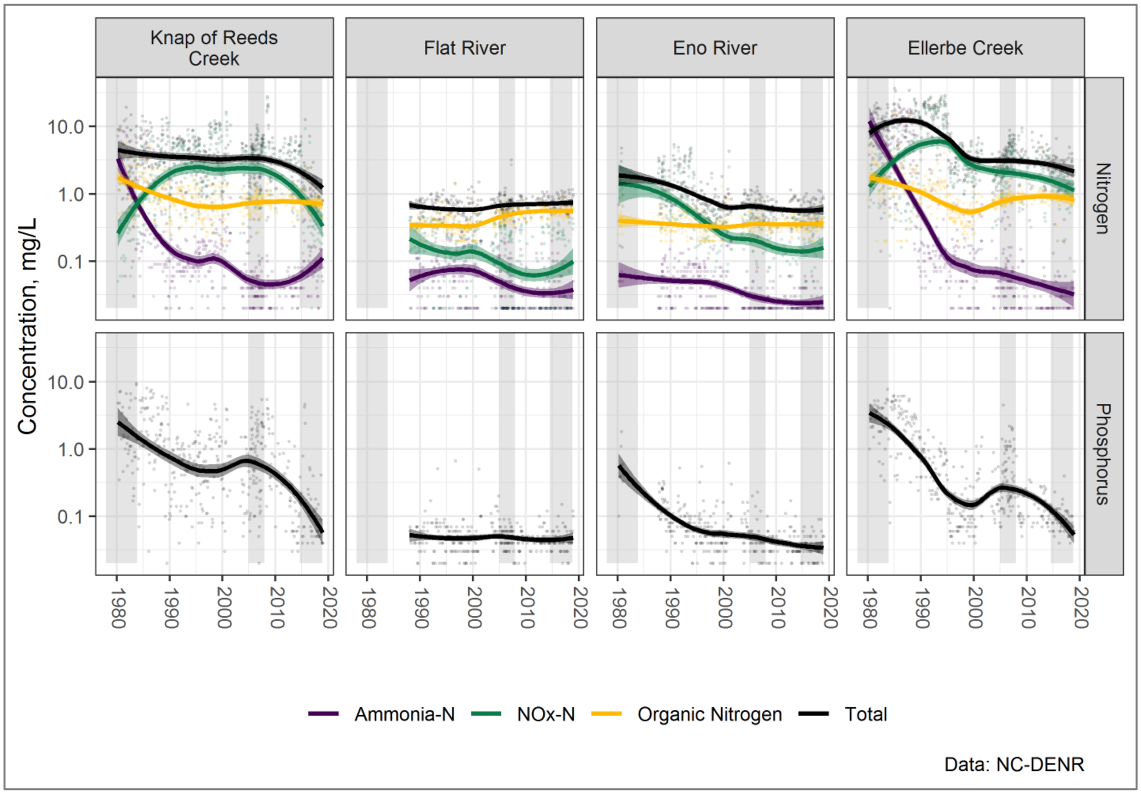


Figure 5-41. Nitrogen (top) and Phosphorus (bottom) concentrations in NC-DENR monitored tributaries from 1980 through 2018.

Shading on the figure background shows the periods of reservoir construction and filling (1978 – 1983), the Falls Lake Rules baseline period (2005 – 2007), and the UNBA monitoring period (2014 – 2018). The colored lines represent a moving average developed through non-parametric local polynomial regression (LOESS: locally estimated scatterplot smoothing) and help to demonstrate the overarching trends in the data. The shaded region behind the smoothed line is the 95% confidence interval on the regression. Note that y-axes are displayed using a logarithmic scale.

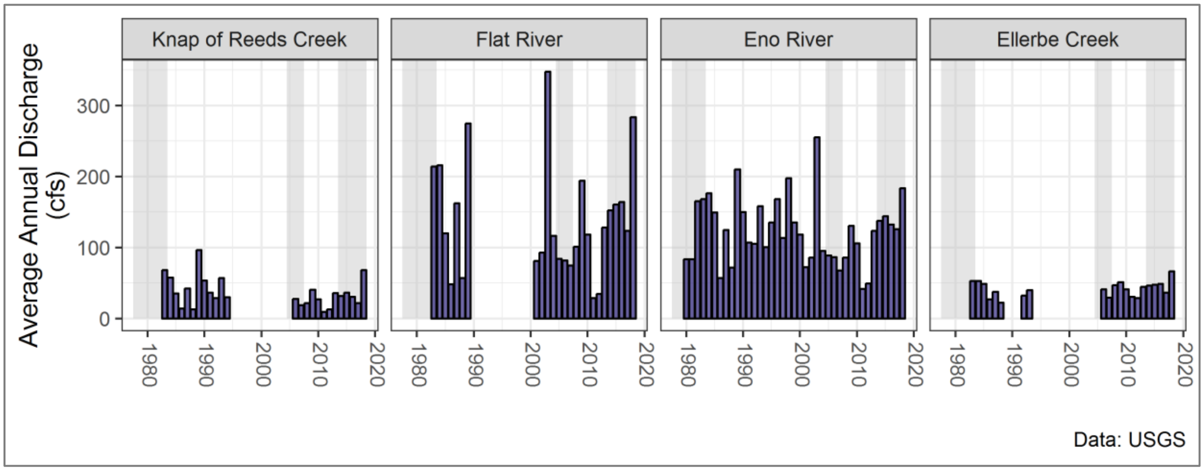


Figure 5-42. Annual average discharge (stream flow) to Falls Lake from four gaged tributaries.
Data shown are the averages of the USGS-reported daily values. Gaps indicate periods where discharge was not measured. Shading on the figure background shows the periods of reservoir construction and filling (1978 – 1983), the Falls Lake Rules baseline period (2005 – 2007), and the UNBA monitoring period (2014 – 2018).

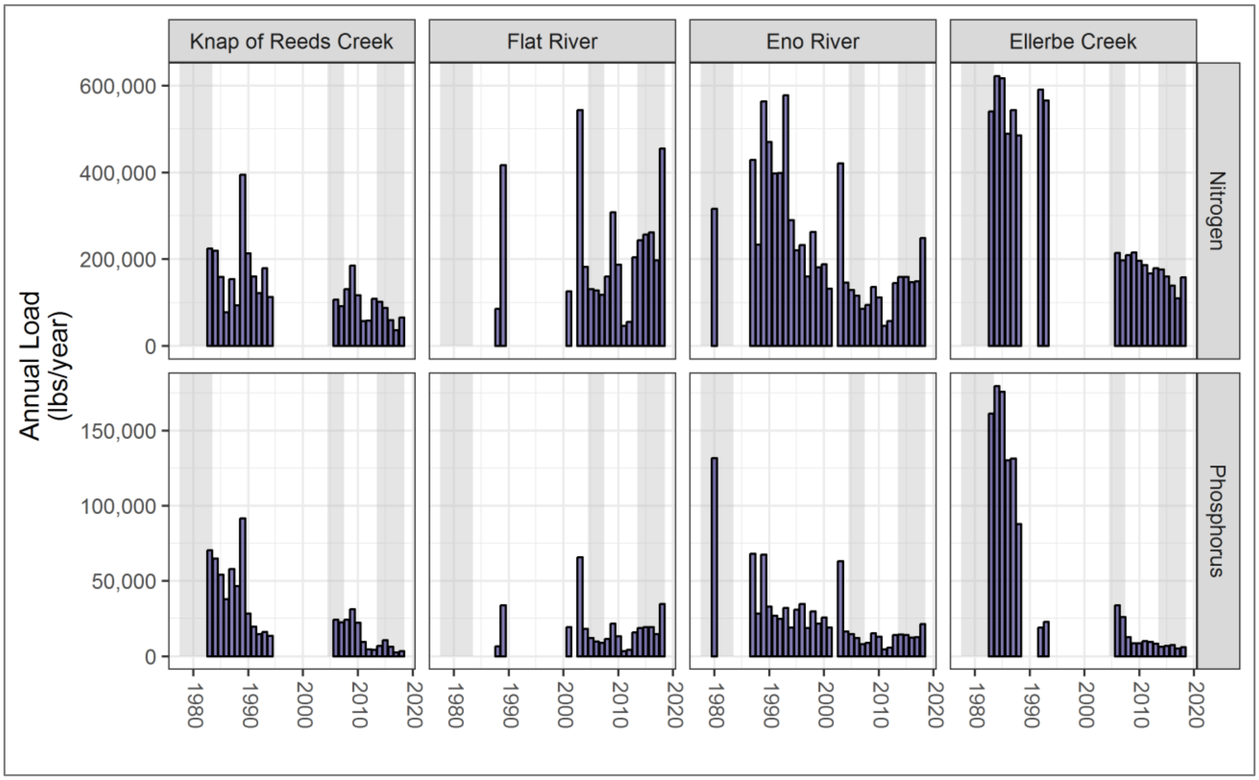


Figure 5-43. Annual load estimates using for periods of existing data on discharge (USGS) and water quality (NC-DENR).
Loads estimated from daily discharge and nutrient concentrations estimated from monthly data using a generalized additive model (GAM) for each nutrient. Shading on the figure background shows the periods of reservoir construction and filling (1978 – 1983), the Falls Lake Rules baseline period (2005 – 2007), and the UNBA monitoring period (2014 – 2018).

5.6.3.4 Nutrient Loading Contributions to Falls Lake by Source

As described in Section 5.6.3.10, LOADEST models for TN and TP were developed to provide estimates of annual nutrient loading to the lake. These tributary loads include all sources of loading upstream of the monitoring station: wastewater discharges, atmospheric deposition to the watershed, onsite wastewater treatment systems, etc. Using data provided by the operators of the major wastewater treatment plants, the tributary loads can be broken down into loading from major wastewater treatment plants and "other watershed loads" for this report. After the watershed model is developed, the other watershed loads can be further classified.

The tributary sources of loading to Falls Lake can also be compared to loading from direct atmospheric deposition to the lake surface and nutrient releases from the lake sediment based on the UNRBA Special Study on sediments. While atmospheric deposition of inorganic nitrogen has decreased over time based on CASTNET data, nutrient releases from sediments originate from accumulations that represent long-term stores. For this analysis, the releases from the lake sediments are assumed to be the same during the baseline and recent monitoring periods. This assumption is reasonable given that long-term stores are projected to release nutrient loads over several decades based on data and analyses conducted as part of the UNRBA Lake Sediment Study (Section 5.5). The EFDC lake model will simulate long-term changes in nutrient releases from lake sediments resulting from nutrient management using the sediment diagenesis module.

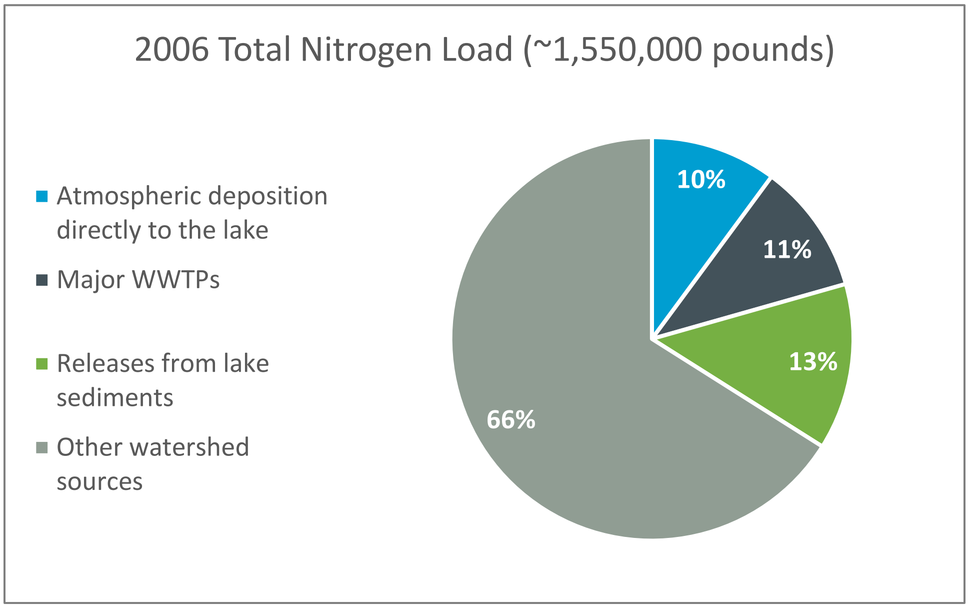
Figure 5-44 and Figure 5-45 show the relative contributions of nitrogen and phosphorus, respectively, from the sources that can be quantified with available information. As noted above, the loading from other watershed sources (as opposed to major WWTPs) will be allocated further after the watershed modeling is complete. For this comparison of sources, year 2006 is shown on the top of each figure to represent the baseline year of the Rules; year 2017 is shown on the bottom of the figure as it is the latest year for which loading estimates from all quantifiable sources are available.

Nitrogen and phosphorus loads to Falls Lake in 2017 have decreased relative to 2006 by 13 percent and 15 percent, respectively. Of this reduction, WWTPs contributed approximately 40 percent of the nitrogen load reduction and 80 percent of the phosphorus load reduction.

Approximately one-seventh of the nitrogen load during both 2006 and 2017 originates from lake sediments (Figure 5-44). Major wastewater treatment plants and atmospheric deposition <u>directly to the lake surface</u> each contribute one-ninth or less of the nitrogen load, and percent contributions from both have decreased from 2006 to 2017. Other sources of nitrogen in the watershed including atmospheric deposition to land surfaces, minor wastewater treatment facilities, nutrient application, and groundwater inputs contribute the majority of the nitrogen load to Falls Lake.

The contributions to the phosphorus load are apportioned to three source categories because atmospheric deposition of phosphorus is negligible (Section 5.6.2). Major wastewater treatment plants contributed 14 percent of the phosphorus load in 2006 and approximately 5 percent of the load in 2017 (Figure 5-45). The majority of the load to Falls Lake originates from other sources of phosphorus in the watershed. Estimates of potential loading from lake sediments are also provided on the figure. These represent the maximum potential phosphorus load based on the sediment core analysis discussed in Section 5.5. However, phosphorus is released from sediments only under anoxic conditions which are generally confined to limited areas of Falls Lake where the historic channel is rather deep (Section 5.1.7.4). During some years, these releases could be much lower than the maximum potential loads. The EFDC sediment diagenesis modeling will provide further information about the extent of phosphorus loading from the sediments in Falls Lake.

As noted previously, nutrients can be conveyed to the lake via groundwater inputs. Such inputs to tributaries upstream of the LL stations are represented in the UNRBA samples collected from 2014 to2018. Groundwater inputs from the unmonitored area below those stations or directly to the reservoir are not quantified but are generally assumed to be small relative to other external and internal loading sources; this will be explicitly simulated with the watershed model.



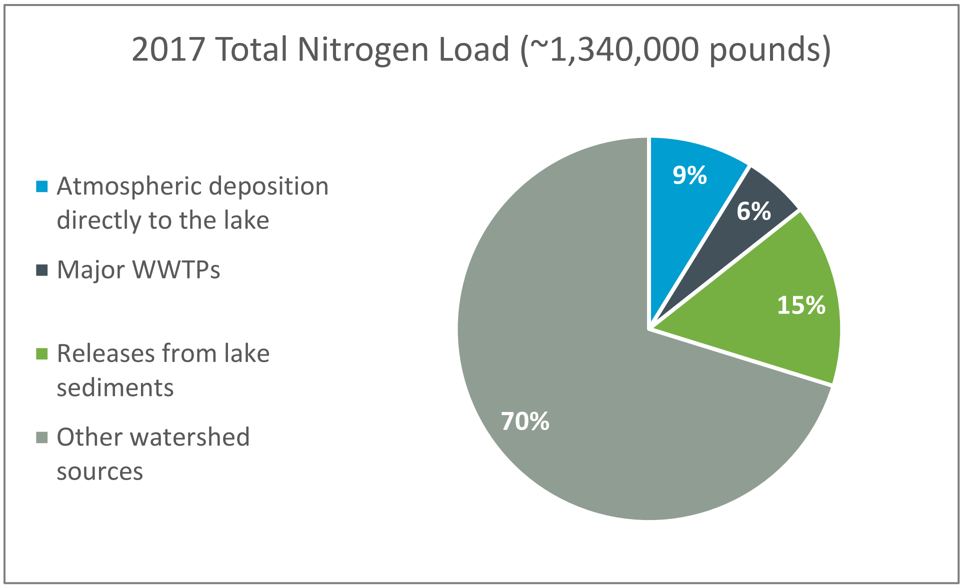


Figure 5-44. Estimated Contributions of Total Nitrogen in 2006 Compared to 2017

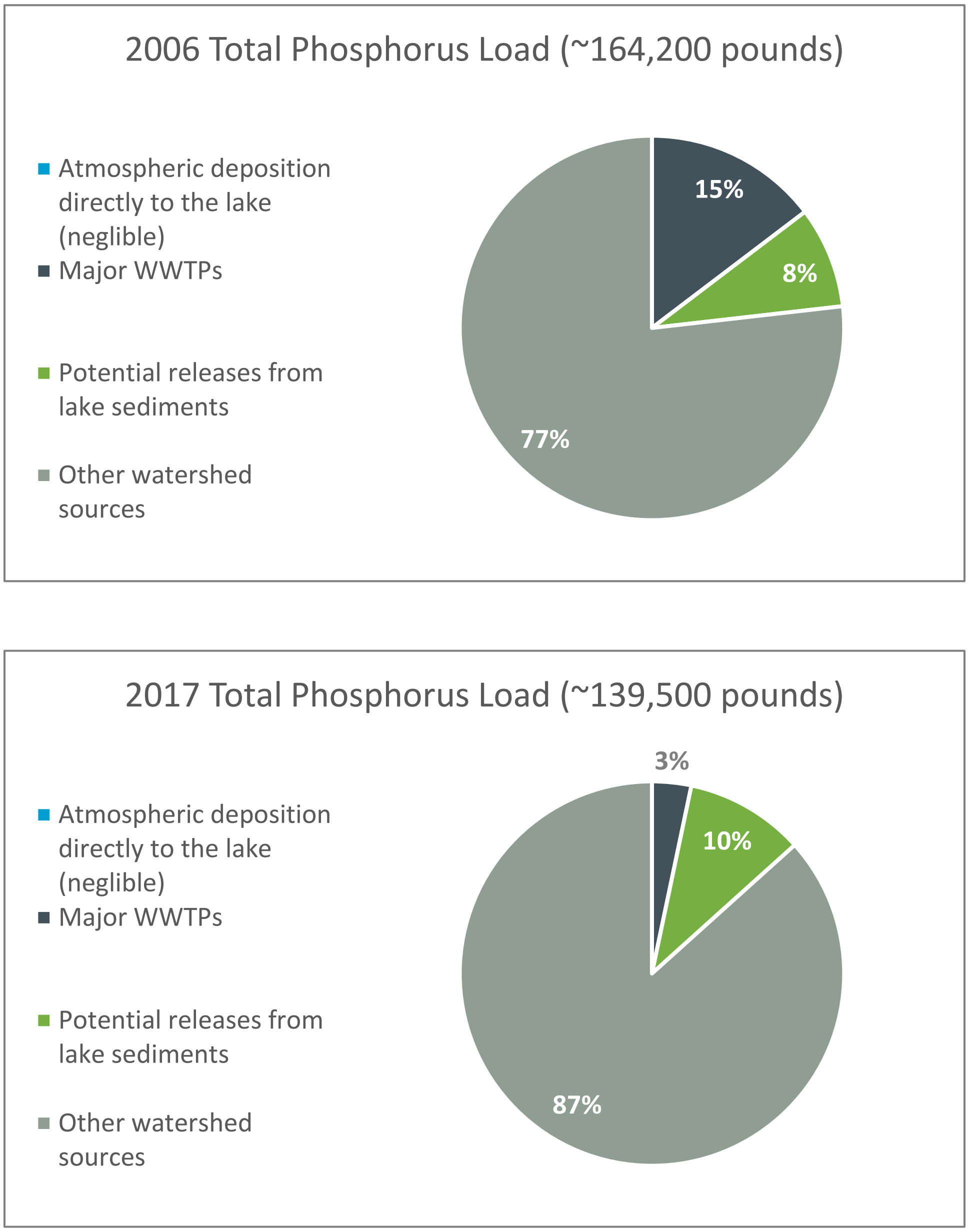


Figure 5-45. Estimated Contributions of Total Phosphorus in 2006 Compared to 2017

5.7 Relationships between Lake Morphometry and Chlorophyll-a

There is substantial spatial variability associated with the Falls Lake reservoir across many metrics including morphometry and bathymetry, water and sediment quality, watershed characteristics and inputs, etc. While it may be analytically possible to reduce certain metrics to an average or median value for Falls Lake, that in no way implies that the entire reservoir can be adequately represented by simple statistics. The discussion in Section 4 above addresses differences observed and expected in reservoirs as a result of their characteristics as impounded systems, and reasons are presented for why Falls Lake may not be a “typical” reservoir in some respects. Section 5.1.5 compared historic and recent water quality monitoring records and found that the reservoir has apparently always demonstrated distinct spatial and temporal patterns, with higher nutrient levels in the upper lake and lower levels near the dam.

The development and implementation of a nutrient management strategy for Falls Lake will consider its spatial and temporal characteristics, and such consideration will be based on the factors that lead to the observed variability. The Falls Lake Rules include reference to several geographic breakpoints along the reservoir in addressing timeframes for attaining compliance with the management strategy (e.g., Highway 98 crossing, Highway 50 crossing, I-85 crossing). Locations like causeway crossings are convenient because they are clearly recognizable, permanent features. Such crossings may even have a physical influence on the reservoir's behavior by altering or restricting the movement of water, as was investigated by the UNRBA Constriction Point Special Study.

The UNRBA bathymetry information was used to calculate morphological metrics for segments defined by the three roadway crossings referenced in the Falls Lake Rules. Additional evaluations of the bathymetry data will be conducted to inform the modeling segments for Falls Lake required by both the WARMF lake model and the empirical lake model.

Bathymetry-based statistics for each portion of the reservoir are presented in Table 5-12. To calculate these values, any area of the reservoir that was not accessible during the bathymetry mapping process was assumed to have a water depth of 1 meter (3.3 feet). Additionally, the water level of the lake was assumed to be at the USACE guide curve elevation (251.5 feet). Examination of the values in these tables shows substantial differences among the lake areas referenced by the Falls Lake Rules. There are notable differences between the mean depth of segments in the upper lake (above I-85 and I-85 to Highway 50) and lower lake (Highway 50 to Highway 98 and Highway 98 to the dam). For example, the mean depth of the segments near the dam are nearly three times greater than those at the upper end of the lake, and the maximum depth is approximately twice as high. In terms of surface area, the segment between I-85 and Highway 50 is approximately ½ the surface area and the volume.

In terms of chlorophyll-a concentrations (measured between August 2014 and October 2018), 73 percent of samples collected by CAAE and City of Durham exceed the 40 µg/L threshold in the area of the lake above I-85 (DWR does not monitor chlorophyll-a in this part of the lake). The fraction of samples exceeding 40 µg/L continually decreases in the downstream direction. The Falls Lake Rules (N.C. Rules Review Commission 2010) state that the segment from Highway 98 to the dam should comply with nutrient-related water quality standards by January 2016. Even with the relatively high concentrations observed in 2017 resulting from dry conditions and long residence times in the lake, only 7 percent of chlorophyll-a samples exceed the threshold. The compliance date for the segment between Highway 50 and Highway 98 is January 2021, and for the segment between I-85 and Highway 50 is January 2036. The upper most segment above I-85 has a compliance date of 2041.

As discussed above, reservoirs can often have three primary zones – riverine, transition and lacustrine – with differing characteristics and processes (Thornton 1990a, Kimmel et al. 1990, Kennedy and Walker 1990). Modeling and regulatory support efforts will consider these influences in the evaluation of nutrient management strategies and simulated outcomes. Visual examination of selected boxplots in Section 3 and the map of monitoring stations (Figure 2-2) suggests there are breakpoints along a general continuum from the upper to the lower lake. For example, TSS (related to turbidity), specific conductance, and TP each appear to experience a noticeable change in magnitude and/or variability between DWR stations NEU013B and NEU017B. This is near the Lick Creek arm and just above a natural constriction in the lake and may be the general location of the interface from the riverine zone to the transition zone. Likewise, Section 3 boxplots for TP, Chlorophyll-a, nitrate+nitrite, and ammonia each appear to have a change in character beginning around DWR station NEU019E, just below the Highway 50 causeway, which is a morphologically reasonable location for the interface of the transition and lacustrine zones (and which is used by the Falls Lake Rules to designate the “upper” and “lower” lake segments). Such patterns will be examined by the modeling and regulatory support team to evaluate their utility in establishing segments for analysis and assessment.

As noted throughout this report, different zones of the lake behave differently in terms of their response to nutrients and growth of algae. Many of these differences are attributable to the hydrodynamics (water movement), water depth, light extinction, and loading patterns to the reservoir. As most of the loading enters the lake above I-85 and this part of the lake is the shallowest, the highest rates of algal growth occur in this area and concentrations of chlorophyll-a will be higher at the upper end of the lake and improve in a downstream direction. The UNRBA believes that the lake should be assessed for compliance with water quality standards in a manner that considers the bathymetric and geomorphologic conditions of the lake as well as the limnological expectations of water quality. The UNRBA will continue to support an assessment methodology in harmony with the lake’s functions and designated uses.

Table 5-12. Bathymetry Characteristics Based on Compliance Breakpoints in the Falls Lake Rules (Segments do not include the Beaverdam Impoundment) and Summary of Chlorophyll-a Data Collected between August 2014 and October 2018

Name	Mean Depth (ft)	Max Depth (ft)	Surface Area (Acres)	Volume (Acre-ft)	Number of Chlorophyll-a Samples	Median Chlorophyll-a (µg/L)	% Samples above 40 µg/L
Above I-85	4.5	21	1,341	6,040	26	56.2	73%
I-85 to Hwy 50	10.1	35	5,595	56,620	668	35.1	35%
Hwy 50 to Hwy 98	16.9	45	1,189	20,074	317	27.0	19%
Below Hwy 98	20.5	54	1,735	35,583	366	19.4	7%

5.8 Reservoir Residence Time

Residence time is the average amount of time that a given parcel of water remains in a water body and can be calculated as the volume of the water body (which changes as a function of inflows to the lake) divided by its outflow. The stage to volume relationship is known for Falls Lake, so its residence time can be calculated for any given time using USGS reservoir stage data and USGS discharge data for the Neuse River at the dam. Figure 5-46 provides time series for both residence time and lake stage during the UNRBA monitoring period. To reduce excessive noise, the lines depict residence time on the figure as a 15-day rolling average after the daily stage reading. This increment was chosen as temporal ranges within which lake water quality might be expected to change. Because the USACE may make operational changes depending on lake level and downstream stream flows, the following 15-day rolling average residence time provides a forward-looking view of how lake operations based on stage may affect residence time.

Despite the use of a rolling average, frequent and dramatic changes in residence time are still apparent. This is because the lake can see rapid increases in stage in response to large rain events (e.g., multi-day rainfall or tropical storm activity), as well as sudden decreases in stage when the spillway at the dam is opened to allow maximum discharge to the Neuse River. As Figure 5-46 shows, residence time and stage are inversely related during some periods since the USACE controls discharge at the dam in response to rainfall patterns. Thus, when water levels in the lake rise rapidly after a storm event, discharge at the dam is increased, meaning that residence time decreases. In the summer of 2016, the lake stage had fallen below the normal management level of 251.5 feet, and the USACE closed the dam causing the residence time to briefly rise to almost 600 days. But in early October of 2016, Hurricane Matthew caused the lake level to rise more than six feet very quickly, and the USACE opened the dam, which resulted in the residence time falling to about 25 days until the dam began to be closed several weeks later. Relatively slight changes in lake stage can also be associated with substantial changes in residence time. For example, in December 2014, the lake level rose from about 251.5 feet to about 252.5 feet, and during the same period, the USACE operated the dam such that the average residence time dropped from more than 700 days to around 50 days.

A change in residence time across an order of magnitude in a matter of days would be very uncommon in natural lakes. As discussed in Section 4.2, this is a characteristic of artificial reservoirs where water levels and downstream flows are managed to prevent flooding. For Falls Lake, management of lake level and discharge is entirely controlled by the USACE according to a release schedule designed to minimize flood risk. The December 2014 discharge pattern noted above is, at least in part, because the USACE seeks to control the level in Falls Lake at 251.5 feet. During that time, area rainfall continued to raise the lake level over several weeks, so the USACE opened the spillway to hold the lake level as close to 251.5 feet as possible.

The relationship among lake level, residence time, and bathymetry is also of interest for examining conditions in Falls Lake. Figure 5-46 indicates four occasions during the UNRBA monitoring period where lake level increased by about six feet in response to a storm event. Based on the mean water depths provided in Table 5-11, such an increase in water depth above the reservoir's normal pool elevation would mean the volume of water above I-85 would more than double in response to a six-foot increase, while the volume below Highway 98 would only increase by about 30 percent. This suggests the potential for more substantial responses in the upper portion of the lake (and any other shallow areas that suddenly become much deeper) for any processes where hydraulics and hydrology are factors. Such processes include those related to the occasional inundation of riparian areas that are normally above the water line and may contribute nutrients and other materials to the lake when they are flooded.

Since the USACE actively regulates reservoir discharges (and therefore residence time), some portion of the behavior of any parameter that is positively or negatively correlated with residence time is subject to a water resource management program generally outside the influence of the governmental jurisdictions around the lake or NCDEQ water quality standards. This fact will be considered when exploring nutrient management alternatives for the reservoir.

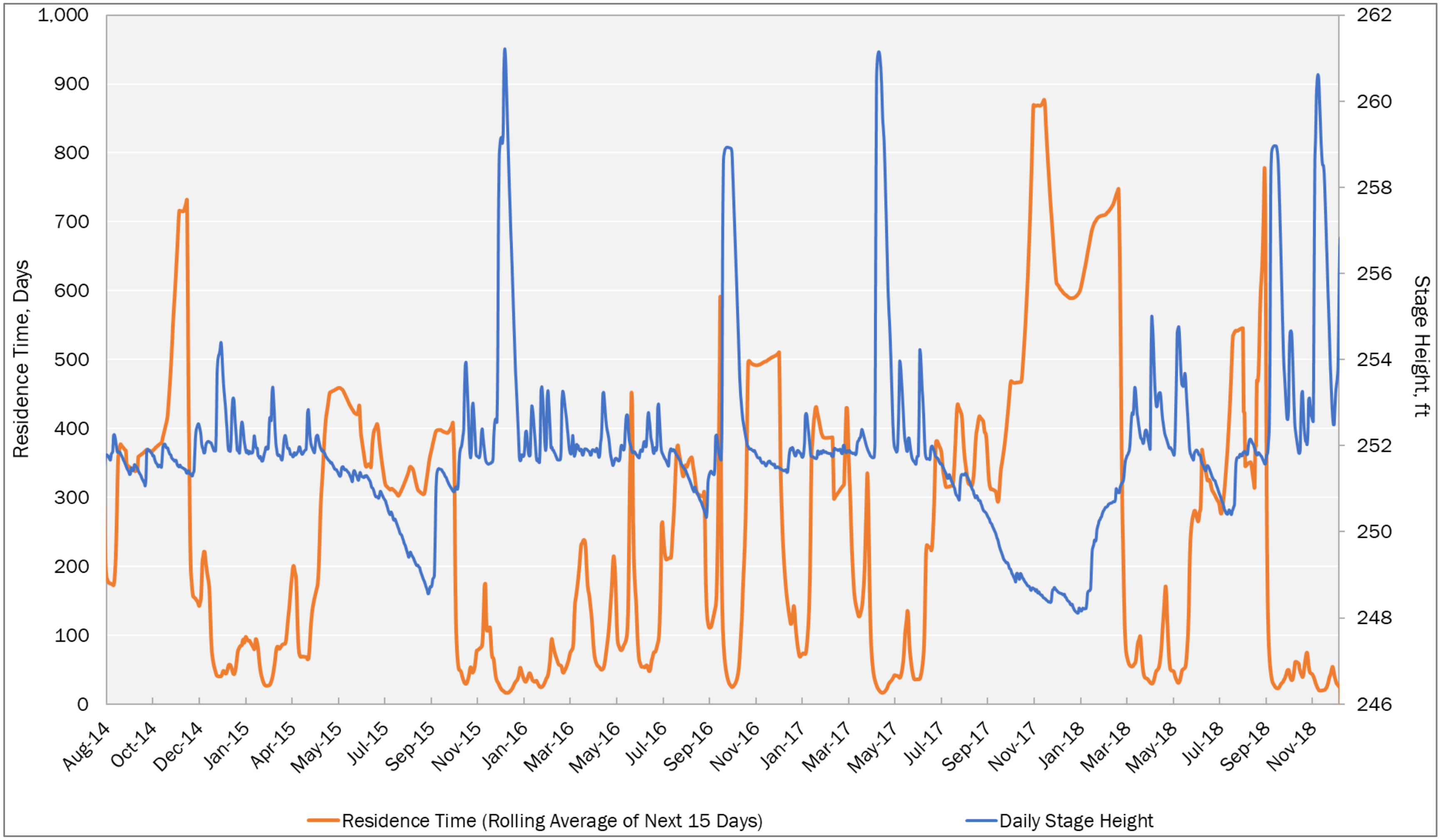


Figure 5-46. Residence time and reservoir stage during the UNRBA monitoring period

5.9 Nutrient Limitation

Algal growth can be influenced by a variety of physical and chemical factors such as residence time and nutrient levels. Some algal species may also compete for other resources based on specific physiological needs (e.g., micronutrients or sunlight), but within the algal community as a whole, it is common to find growth to be limited by nutrients, light, residence time, velocity, and mixing.

For some water bodies, it is easy to determine whether the availability of nitrogen or phosphorus is limiting the growth of algae. Simple guidelines have been developed to indicate which nutrient is likely to be limiting. For example, a molar ratio of 30:1 for N:P could suggest that phosphorus availability is limiting, while a N:P ratio of 10:1 could suggest that nitrogen is limiting. Ratios in between 30:1 and 10:1 might indicate the possibility of "co-limitation" by N and P. These particular ratios are not directly applicable to N and P concentrations expressed in mg/L. There has been extensive limnological research on this topic, with a broad diversity of findings, and numerous exceptions to every hypothesis.

Like many reservoirs in the Southeastern United States, Falls Lake is eutrophic, meaning it is relatively nutrient-rich and can support an abundant algal community. Thus, even if N or P is shown to be "limiting," it does not mean that algae may not be abundant. It simply means that additional increase in the phytoplankton population might be controlled by further reducing the supply of the limiting nutrient. General calculations based on the ranges of TN and TP concentrations represented in Figure 3-22 and Figure 3-23 above yield an N:P ratio (on a molar basis) on the order of 20:1 at the upper end of the lake, 35:1 in the middle section, and 50:1 at the lower end. Based on the guidelines noted above, these ratios suggest that P would limit algal growth from the dam through the middle section of the lake, but the upper end of the lake could see algae limited by both N and P.

It is important to note that measuring TN and TP in water samples is not necessarily the same as quantifying the available supply of these nutrients to algae. Much of the nutrient pool in the water column of a lake (and in water samples from the lake) is assimilated within living algae and thus not readily available to grow new algae.

Unfortunately, nutrient limitation is far more complex than the simple set of calculations and predictions above. Algal communities are complex and dynamic. A nutrient ratio that is optimal for one species group may be inhibitory to another, and some species are more efficient at using certain forms of N and P. Such nutrient preference patterns are part of the reason for shifts in the algal community of a lake both spatially and temporally (as seen in Figure 3-32 through Figure 3-34). Therefore, managing nutrients in a lake to control algal abundance (or chlorophyll-a) is not a simple cause and effect undertaking. Because N and P are naturally-occurring in the environment, implementing tight constraints on their delivery to a water body can be a very challenging prospect. These are issues that will be considered during the upcoming modeling and regulatory support efforts.

5.10 Algal Toxins

Certain species of algae are known to have the capability to produce toxins but the basis for why and when toxins are produced is not well understood. A small proportion of blue green algae species (cyanobacteria) are most commonly known for toxin production. Some blue-green strains produce cyanotoxins which include microcystin, cylindrospermopsin, saxitoxin, anatoxin-a, and beta-Methylamino-L-alanine. Little is known about the triggers for production of toxins, and not all algae that can generate toxins actually do so (Wiltsie et al. 2017). North Carolina has not established water quality criteria for these toxins. The World Health Organization (WHO) microcystin guideline for drinking water is 1 µg/L, and the EPA draft recreational guideline is 4 µg/L.

As part of its ongoing monitoring of the water quality of Falls Lake as a water supply, the City of Raleigh measures algal toxin data at several locations in Falls Lake. Figure 5-47 shows the results of assays for microcystin, cylindrospermopsin, and anatoxin-a at six locations in the lake. For many sampling events, toxins were not detected. From a total of some 180 samples, microcystin and cylindrospermopsin were each detected in about 13 to 30 percent of the samples across the six monitored stations, and anatoxin was found in 10 to 20 percent of the samples across stations.

Algal toxin concentrations in lake arms tend to be higher than in the main channel. No samples of microcystin exceeded either the draft EPA recreational guideline nor the WHO drinking water guideline. Cylindrospermopsin was generally lower than microcystin, and anatoxin-a was sometimes higher than microcystin. Less is known about these toxins and guidelines have not yet been issued.

During the reexamination process, all water quality parameters/issues that may be raised relative to potential impairments of uses, will likely have to be addressed. The potential for algal toxins has been raised in other reservoirs in the state with chlorophyll-a concentrations that exceed the State criterion. The UNRBA is engaged in discussions with the UNC Collaboratory regarding potential studies of Falls Lake. As the Collaboratory recently completed an algal toxin study on Jordan Lake, a similar study on Falls Lake is a possibility. This study would further inform the UNRBA empirical model for Falls Lake.

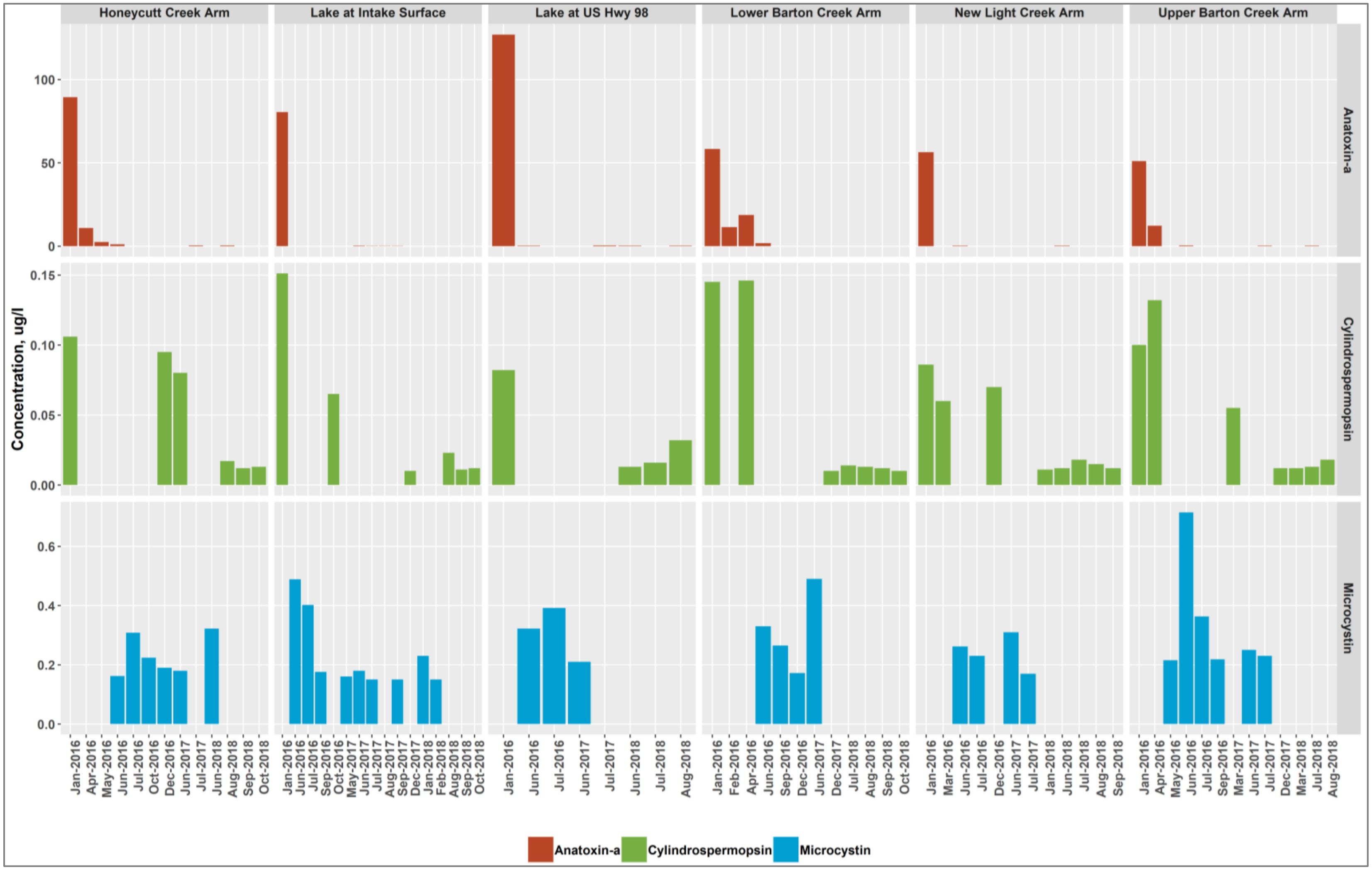


Figure 5-47. Algal Toxin Data Collected in Falls Lake

Note that each column represents one monthly monitoring event, but the horizontal axis is not a continuous time series; missing months in the series represent events where none of the three toxins were detected at a given station.

5.11 Recreational Uses Evaluation

The UNRBA 2016 Annual Report (Cardno 2016) provided the results of a Special Study on Recreational Use Assessment. That assessment summarized the recreational facilities on the reservoir, types of recreational activities undertaken, and estimates of annual recreational visits (well over 1,000,000 visitors per year) including data from the Wake County, City of Raleigh, North Carolina Wildlife Resource Commission, North Carolina Division of Parks and Recreation, and the USACE. It looked for apparent relationships between recreational user counts and water quality conditions and concluded that water quality did not have a significant influence on recreational usage of the reservoir. This conclusion is consistent with statements USACE Falls Lake Master Plan (USACE 2013): “The quality of surface water within the reservoir is influenced by conditions throughout its watershed, including land use patterns and the presence of pollution sources. Despite water quality concerns throughout the watershed, water quality in the reservoir allows for all forms of recreational use to continue.” The plan also states, “Recreational facilities at Falls Lake currently meet the most popular recreational activities highlighted in the SCORP[2]. In some cases, such as with motorized boating, the resources at Falls Lake have met their carrying capacity to support certain recreational activities. Monitoring regional demands and the ability of the Falls Lake resources to meet these needs will allow USACE, North Carolina, and the other management partners to provide natural resource-based recreational opportunities in the future.”

According to the USACE (2013), all types of recreational uses for Falls Lake are being met. Limitations on the number of visits are due to the carrying capacity of Falls Lake and its facilities, and water quality is not a factor.

Based on the findings of the Recreational Use Assessment Special Study, the 2016 Annual Report recommended that the UNRBA suspend the investment of additional resources for evaluating recreational uses because it appears the lake is providing for the full range of such uses. A brief summary of this Special Study is provided in Section 3.4.5.

Beyond evaluation of recreational count data, online resources provide the opportunity to obtain impressions directly from recreational users of the Falls Lake Reservoir without the need for formal surveys. Such resources offer narrative descriptions of the users’ experiences along with quantitative rankings to yield an overall image of the perceived value of the recreational experiences. While information contained in individual reviews might be biased for various reasons, the average of numerous rankings offers a reasonable representation of the overall user impressions.

5.11.1 Informal User Perception Information: General Recreation

The TripAdvisor website (www.TripAdvisor.com) contains more than 150 user reviews of “Falls Lake State Recreation Area” with an average rating of 4.5 out of 5, and a ranking as “#1 of 15 things to do in Wake

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[2] North Carolina State Comprehensive Outdoor Recreation Plan

Forest." Fifty-one percent of all user reviews have a rating of 5, and 42 percent are a rating of 4. Six percent were a rating of 3, and two reviews gave a rating of 1. One of the low ratings was attributed to "rude" rangers at one of the parks.

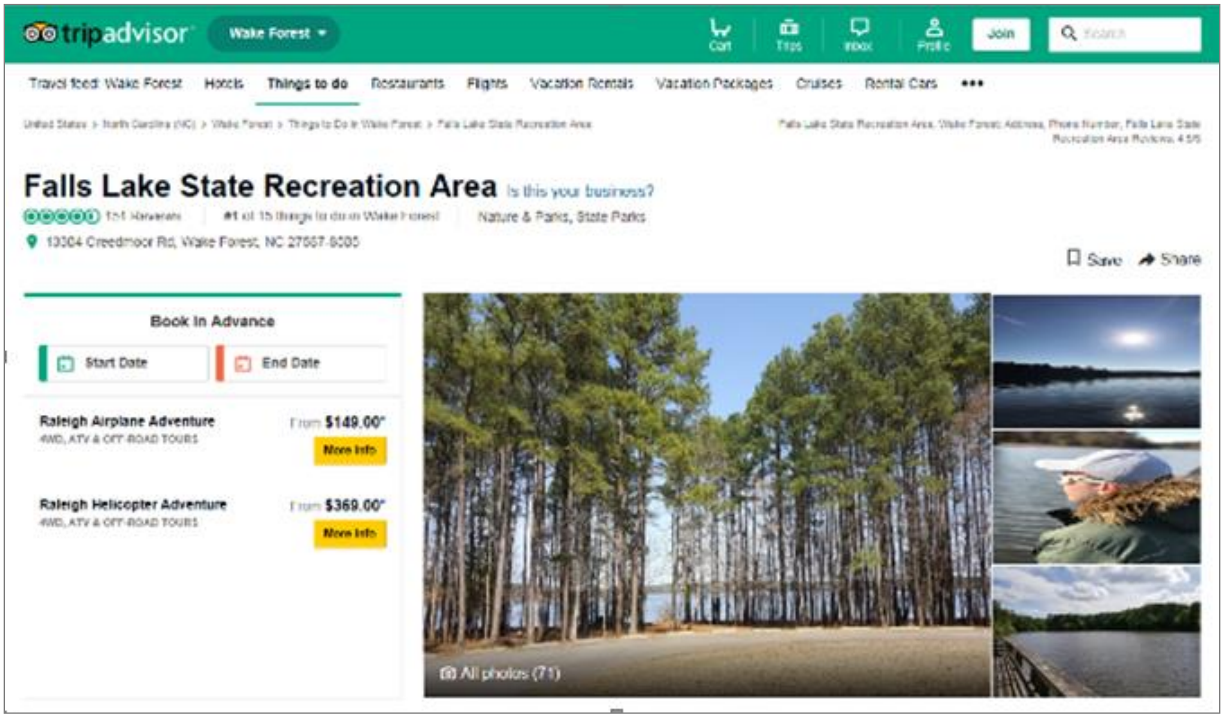

Figure 5-48. TripAdvisor Landing Page for Falls Lake State Recreation Area

As reflected by the rankings, the large majority of reviews had positive things to say about the lake, often referring to aesthetic environmental features, but only a few refer to the water in the lake. One reviewer observed that the "water is pretty clear." Another noted "dirty water" but did not provide further detail, and one of the two lowest rankings called it a "disgusting lake" with no explanation. No reviews contained words normally associated with objectionable water quality conditions, like "algae," "murky," "green," "brown," or "odor." The only reference to "smell" was a reviewer describing the "fresh air."

There are also 35 TripAdvisor reviews for Blue Jay Point County Park, 27 for Rolling View Falls Lake State Park, 9 for Falls Lake Visitor Assistance Center, and 7 for Beaverdam Recreation Area, with overall rankings similar to or higher than those discussed above for Falls Lake State Recreation Area. None of those reviews contained negative comments on water conditions in the lake.

In all, these reviews represent some 230 individuals who put time and thought into posting their observations and impressions of Falls Lake through an on-line medium that allows for a complete range of comments from very positive to very negative. More than 90 percent of the reviewers ranked their experience as "Excellent" or "Very Good" across a broad range of recreational activities. Less than one percent of the reviewers noted something negative about the lake water, and they offered no details or explanation about the conditions they observed.

The website www.yelp.com yields similar information to that on TripAdvisor, but with fewer reviews. Yelp reviews also do not contain negative comments about lake water, algae, etc.

5.11.2 Informal User Perception Information: Sport Fishery

The Recreational Use Assessment in the 2016 Annual Report also included a brief discussion of the fishery in Falls Lake, including a summary of the results of ongoing fisheries monitoring in the lake by the North Carolina Wildlife Resources Commission. While the report included estimates of the number of anglers using the reservoir, it did not provide information on angler success or impressions about the lake.

Even more voluminous than the general recreational user reviews on TripAdvisor is the amount of online information regarding fishing on Falls Lake. There are numerous online resources for sharing information about fishing in general, ranging from government agency websites, to business entities marketing goods and services, to fishing interest groups, to user blogs. As a well-known fishery in North Carolina and the Southeast, Falls Lake is very well-represented in this medium.

Table 5-13 provides a very brief sampling of the online information about fishing on Falls Lake. Overall, the information spans more than a decade of postings representing many thousands of hours of fishing activity. The end of the table contains a sampling of the fishing tournaments held on Falls Lake, indicating that the fishery is attractive not only to local recreational anglers, but also to competitive anglers. The Major League Fishing Pro Bass Tour (https://majorleaguefishing.com/event/2019-bass-pro-tour-stage-three-raleigh-nc/info/), which held three of its six tournament rounds on Falls Lake in late March 30, 2019 with 80 professional anglers, paid a total purse of more than $700,000, including $100,000 for the tournament winner.

Table 5-13. Representative Online Information About Fishing the Falls Lake Reservoir.

Websites with Information on Falls Lake Fishing

Title	Fishing at Falls Lake
URL	https://www.aa-fishing.com/nc/nc-fishing-lake-falls.html
Sample of Content	Fishing for largemouth bass, channel catfish, flathead catfish, blue catfish, black crappie, white crappie, bluegill, white bass, white perch, yellow perch, striped bass and chain pickerel at Falls Lake in North Carolina. Largemouth bass tend to garner a great deal of the fishing attention here at Falls Lake, yet this healthy fishery has so much more to offer. This sprawling 12,400-acre lake in the northeast part of the state, on the outskirts of Durham, NC offers a wide variety of fish species. catfish, crappie, white bass, stripers, perch and chain pickerel all provide anglers with an opportunity for a fun day of fishing. The water maintains a nice stain most of the time and there are sections of trees and stumps in many of the coves. Spinnerbaits, square bill crankbaits and jigs are popular when fishing shallow. Creek channels, ledges, humps and other structure often hold concentrations of fish, especially in summer and winter. Over 300 campsites, some with RV hookups are conveniently located around the lake. Public boat ramps, the marina and boat rentals are available to enhance your stay at Falls Reservoir.
Title	Fishidy
URL	https://www.fishidy.com/map/us/north-carolina/falls-lake
Sample of Content	193 catches, 1,000+ followers, 145 spots One of North Carolina's best for big Largemouth Bass. This is a trophy fishery, with recent studies showing 70% of the fish exceeding 14 inches! Lots of cats and crappie as a bonus.
Title	Carolina Sportsman
URL	https://www.carolinasportsman.com/content/march-for-lunkers-on-north-carolinas-falls-of-neuse-lake/

Table 5-13. Representative Online Information About Fishing the Falls Lake Reservoir.

Sample of Content	March for lunkers on North Carolina's Falls of Neuse Lake. Is Falls of Neuse the best bass-fishing lake in North Carolina? It may be, at least in March. Plenty of bass will be staging and biting this month at Falls of Neuse Lake when all the planets align. Learn how to get the most from one of North Carolina's top fisheries. Around the Raleigh-Durham area, some disagreements exist among anglers about which of three local lakes — Shearon Harris, Jordan or Falls of the Neuse — offers the fishing for largemouth bass. For tournament bass fishermen, the answer has been clear the past several years. For numbers of fish and the probability of landing a lunker, Falls of the Neuse draws the highest approval rate.
Title	Numerous video clips of fishing on Falls Lake
URL	www.YouTube.com
Sample of Content	Entering "Falls Lake" in the YouTube search line yields a number of video sub-categories, including: Falls Lake fishing; Falls Lake bass fishing; Falls Lake catfish fishing; Falls Lake crappie fishing Each sub-category contains multiple video clips of fishing on the reservoir during all times of the year. Many clips were recorded during tournaments, while others are casual recreational fishing.
	Sampling of Fishing Tournaments Held on Falls Lake
Title	Major League Fishing - Bass Pro Tour Taps Raleigh, N.C., Lakes for March 2019 Destination
URL	https://www.visitraleigh.com/media/press-release/post/mlf-bass-pro-tour-taps-raleigh-nc-lakes-for-march-2019-destination/
Sample of Content	Falls Lake, Shearon Harris Reservoir and Jordan Lake are the waters to share in the prestige of hosting bass fishing's newest and highest profile tournament series, which features 80 of the best professional anglers in the country. Falls Lake gets high marks as a bass fishery. The 26-mile-long lake is said to have three very distinctive segments across its length, meaning that at least one area could be at the peak of bass spawning activity in the late March timeframe, potentially increasing the chances of a bass 10 pounds or more showing up.
Title	Anglers Channel Tournament
URL	https://anglerschannel.com/tournaments/
Sample of Content	American Bass Association – AFT – D16 – Falls Lake – February 16, 2019
	MLF Bass Pro Tour – Falls Lake – March 26 – 31, 2019, 03/26/2019 TO 03/31/2019
	Fishers of Men Team – North Carolina Central – Falls Lake– June 8, 2019; LEDGE ROCK
	FOMNTT – Legacy – North Carolina Central – Falls Lake – June 15, 2019; UPPER BARTON'S CREEK
	Collins Boating Bass for Cash Series - Falls Lake June 22, 2019; LEDGE ROCK
Title	The 2018 CKA Tournament of Champions
URL	https://www.carolinakayakanglers.com/?tag=falls-lake
Sample of Content	We are happy to announce the location of the 2018 CKA Tournament of Champions. This 2 Day, No Entry Fee event will be held on beautiful Falls Lake in Wake County, NC. We will have our trophy presentations for AOY and ROY on Saturday at the post event check in, and the TOC trophy will be unveiled Sunday. This will be an incredible time of year to be on this lake. The fall bite will be on and we picked Falls knowing that we can possibly see a record breaking 3 fish limit from this lake at this time of year. As some Lake of you may recall, Falls Lake was rated in 2016 as the 8th best bass fishery in the Southeast by B.A.S.S. We fished it in June of 2016 as a CKA event and fished it again in early spring of 2017 as a combined CKA/KBF Trail event, but this is our first autumn visit to this fishery and only our 3rd visit ever to the lake. The lake has plenty of room for our exclusive field: Falls Lake is a 12,410-acre reservoir located in Raleigh/Durham North Carolina. Falls Lake extends 28 miles up the Neuse River to its source at the confluence of the Eno and Flat Rivers. The defined river channels and creek beds will probably allow anglers to discover bass chasing shad, and the grass beds, ledges and structure will hold fish that are still in summer patterns.
Title	Piedmont Bass Classics Tournament - 2018
URL	http://piedmontbassclassics.com

Table 5-13. Representative Online Information About Fishing the Falls Lake Reservoir.

Sample of Content	Josh Fletcher & Bryson Peed dominated the 87-boat field in the PBC Academy Sports & Outdoors Spring Bass Trail Q#6 at Falls Lake May 12th with 5 bass weighing 27.46 lbs. for a winning total of $1,450. Great job by 2 young guns
Title	Fishing League Worldwide Tournament 2017
URL	https://www.flwfishing.com/results/2017-07-08-falls-lake
Sample of Content	David Wright of Lexington, North Carolina, caught five bass weighing 23 pounds, 2 ounces, Saturday to win the T-H Marine FLW Bass Fishing League (BFL) Piedmont Division tournament on Falls Lake presented by Navionics. For his efforts, Wright pocketed $5,122.
Title	Cashion Rods –Falls Lake Open – 2016
URL Sample of Content	http://piedmontbassclassics.com
	Cashion Fishing Rods sponsored the 'Falls Lake Open, with 30 teams showing up, even with the weather forecast calling for heavy rains in the am. The day started off in the low 60's and afternoon temps around 79. It did rain hard from about 5am to 6am then quit for the day!! The winds were 0 to 12 mph for most of the day and the water level was right at normal pool. Water temps averaged 72 degrees and the water clarity was fairly good. 120 bass were weighed in for a total weight of 378 pounds for an average of 3.15 lbs. each. The fish have pretty much spawned out and are starting to work their way back to deeper water. It was really a pretty day for bass fishing with a lot of 4 and 5 pounders caught!!!
	Piedmont Bass Classics $10,000 Spring Team Bass Trail - March 31 – Falls Lake
Title	Cashion Rods – College Clash - 2015
URL	http://cashionrods.com
Sample of Content	The second stop for the Cashion College Clash qualifying season is in the books. The field consisted of 13 teams from six universities. Rain soaked anglers for most of the tournament day; however, the NC college anglers proved they can catch them regardless of the weather.

There is a growing number of mobile device applications that allow anglers to share information on their fishing locations, tactics and success. For example, when a search is conducted in the FishBrain app (see www.fishbrain.com), the result indicates more than 700 individual catches, comprising over 20 species, including more than 400 largemouth bass, 60 channel catfish, nearly 100 crappie and numerous additional panfish and rough fish. The map function of the app provides specific locations where anglers caught fish, showing hundreds of locations extending from above I-85 to the dam. Figure 5-49 is a screen capture from FishBrain indicating catch locations near the I-85 bridge crossing, in a portion of the reservoir that is listed as impaired for chlorophyll-a. Figure 5-50 shows catch locations at the lower end of the reservoir. Zooming in on the map in the mobile app reveals additional locations, with catches reported in virtually all portions of the lake and its tributary arms. As with the TripAdvisor reviews discussed above, social media used by anglers yields an abundance of user-specific information on Falls Lake that, while not obtained through standardized surveys or under a rigorous quality assurance plan, undoubtedly provides insight into the level of usage and success of anglers on the reservoir.

Perhaps the most immersive view into fishing activity on Falls Lake is offered by the many dozens of video clips posted to YouTube (www.youtube.com). With search terms like “Falls Lake fishing” or “Falls Lake tournament,” YouTube yields seemingly endless videos taken throughout the reservoir showing anglers catching various species of bass, catfish, crappie, panfish and rough fish. Anglers in most videos discuss their locations, tactics, successes, and impressions of fishing the reservoir. The videos also provide a visual indication of conditions in and surrounding the reservoir, with respect to water clarity, shoreline conditions, vegetation, etc. Although it could be quite time-consuming and is beyond the scope of this report, such videos could be reviewed to compile a broad variety of information on fishing the Falls Lake reservoir to assist with fishery and related resource management efforts. It is also noteworthy that many of the video clips posted to YouTube have been viewed numerous times. The 80 most-viewed clips have each been viewed more than 1,000 times each, with some of them approaching 20,000 views. This suggests there is interest in Falls Lake fishing by a relatively large number of individuals beyond those who post their videos online. In addition to videos of fishing activity, YouTube also has numerous clips of skiing, boating, and personal watercraft on Falls Lake, which provide further visual perspective on recreational uses of the reservoir.

The empirical modeling effort will consider the value of online information sources, which may provide information on user patterns or opinions associated with recreational uses of Falls Lake. In particular, numerical rankings used in some forms of social media might offer information roughly analogous to expert opinion elicitation, as commonly used in Bayesian network analysis. Similarly, consideration of the economic values of Falls Lake will include review of the local business revenues associated with recreational uses of the lake, as well as the value of the winnings from tournaments conducted on the lake.

An additional consideration regarding recreational uses is the degree to which other resources in the region may compete with Falls Lake for users. There are currently water resource policy and management efforts under way for other reservoirs in the region (e.g., Jordan Lake and High Rock Lake). Changes in the regulation or management of one recreational use destination may have a disproportionate effect on usage, based on how other destinations in the region are managed. Cole and Ward (1996) created a model of angler usage and economic benefits for reservoirs and reported that management decisions implemented at one reservoir are not independent from the effects of management actions at other reservoirs. They conclude that “Multiple site models provide a mechanism for agencies with different jurisdictions and missions to be more effective in coordinating management for increased public benefit.” This viewpoint will be explored in the empirical modeling and economic evaluations of Falls Lake to ensure they consider the potential effects of differential degrees of regulation and management among regional reservoirs.

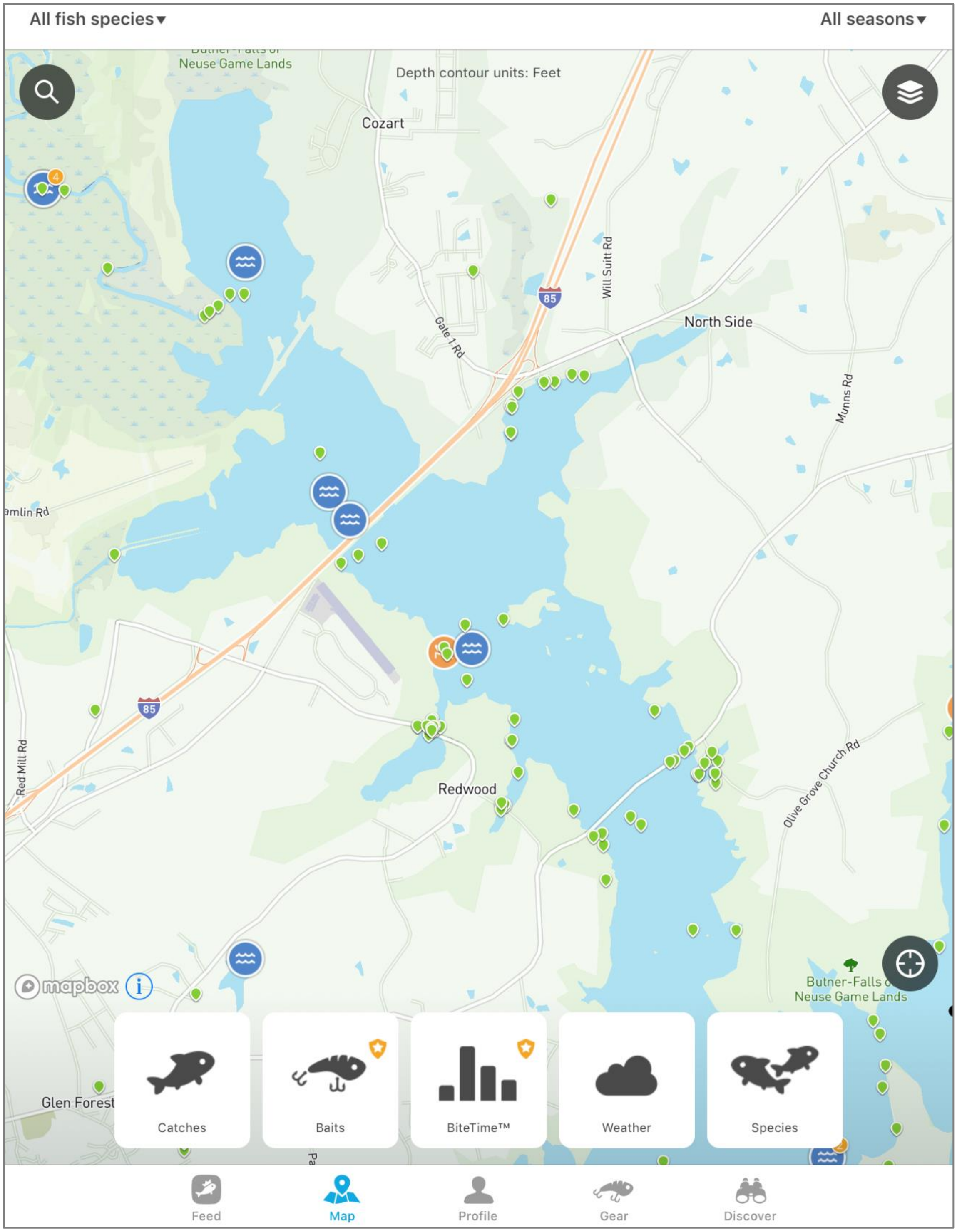

Figure 5-49. Screen capture from the FishBrain mobile device application showing Falls Lake in the vicinity of the I-85 crossing. Blue symbols and the smaller green symbols are catch locations reported by anglers. Zooming into the map with in the application reveals additional catch locations.

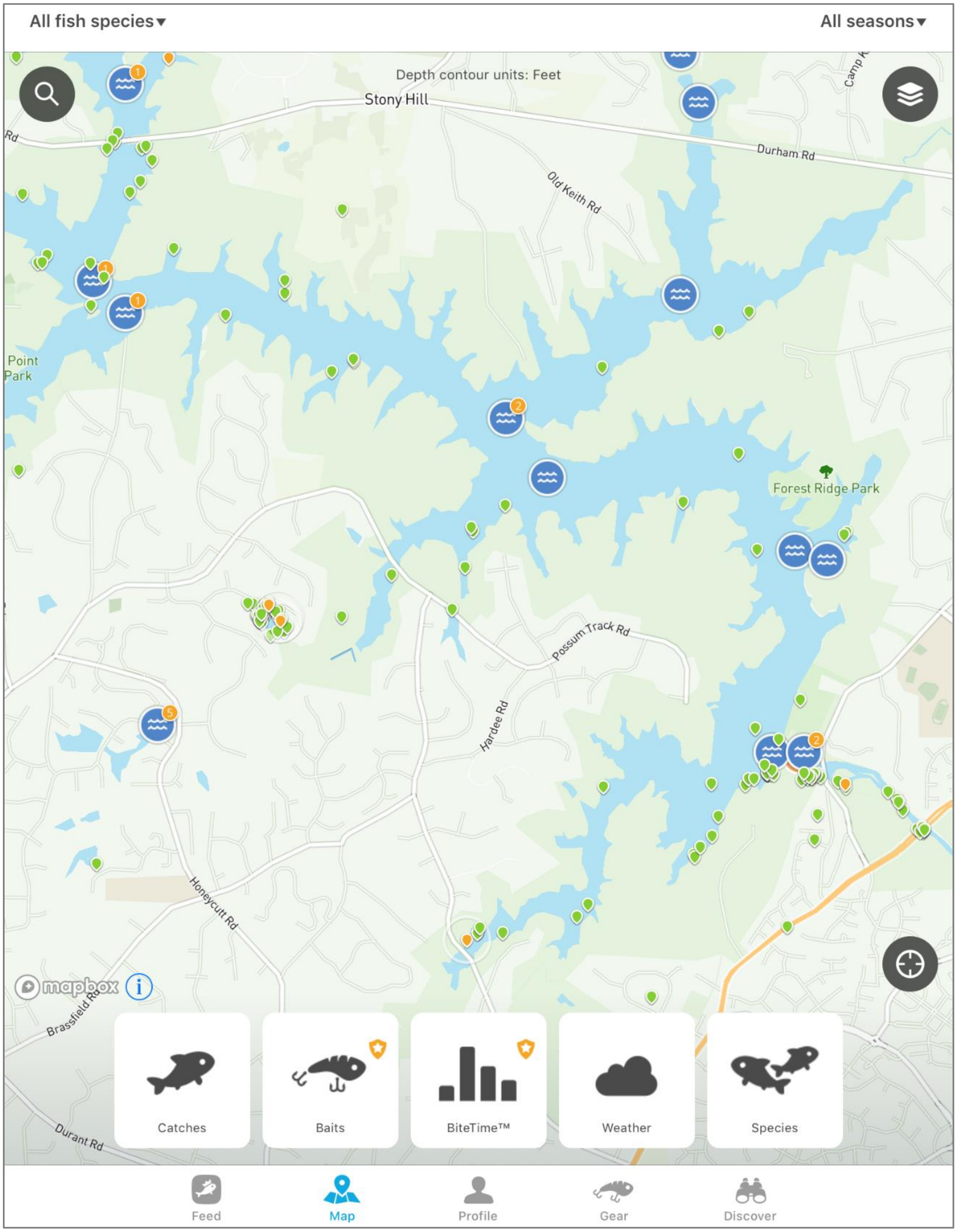

Figure 5-50. Screen capture from the FishBrain mobile device application showing Falls Lake from the Highway 98 crossing to the dam. Blue symbols and the smaller green symbols are catch locations reported by anglers. Zooming into the map with in the application reveals additional catch locations.

Section 6 Quality Assurance

This section addresses the confidence and reliability associated with data generated through the UNRBA Monitoring Program. All analytical data collected through the program (both from Routine Monitoring and from Special Studies) are evaluated for compliance with the quality objectives outlined in the UNRBA Monitoring QAPP. Data accuracy, precision, and completeness reviews are performed following each monitoring event and reviews of field and laboratory practices are performed on a routine basis. Data collection efforts associated with Special Studies are subject to the same general quality assurance/quality control (QAQC) considerations and scrutiny as for the Routine Monitoring. This section does not address data collected by other entities, however, only water quality data obtained under a state-approved Quality Assurance Plan are included in the analyses and interpretations in this report.

6.1 Representativeness and Completeness

QAQC are primary considerations for the UNRBA Monitoring Program. All analytical data collected through the program (both from Routine Monitoring and from Special Studies) are evaluated for compliance with the quality objectives outlined in the UNRBA Monitoring QAPP. Data accuracy, precision, and completeness reviews are performed following each monitoring event, and reviews of field and laboratory practices are performed on a routine basis. Data collection efforts associated with Special Studies are subject to the same general QAQC considerations and scrutiny as for the Routine Monitoring. This section does not address data collected by other entities, however, only water quality data obtained under a state-approved QAPP are included in the analyses and interpretations in this report.

Data accuracy, precision, and completeness reviews are performed following each monitoring event. Reviews of field and laboratory practices are performed on a routine basis. Since the beginning of the UNRBA Monitoring Program, more than 98 percent of all planned sampling events in which the sampling location had flowing water were completed as planned. Through the end of 2018, there have been no cases of samples where results for Laboratory Control Sample (samples of known concentration analyzed along with field samples) associated with UNRBA data were out of compliance with method criteria.

6.1.1 Field Sampling

The UNRBA Routine Monitoring program was designed to collect data from representative sites in the Falls Lake basin and at regular time intervals in order to capture data during conditions representing the entire monitoring period. All efforts are made to adhere to this sampling plan; however, some samples may be understandably missed due to factors such as dry stream conditions, extreme weather, or unexpected site access limitations. Since the beginning of the UNRBA monitoring program in 2014, more than 98 percent of all planned sampling events in which the sampling location had flowing water were completed as planned, while dry stream conditions caused approximately 4 percent of planned sampling events to be skipped. In all, more than 94 percent of sampling events have been completed as planned (Table 6-1).

Table 6-1. Summary of planned sampling events missed because of dry streams, site inaccessibility, or weather-related concerns

	Calendar Year				
	2014	2015	2016	2017	2018
Scheduled Sampling Events	208	516	486	456	380
Missed due to dry conditions	20	37	4	13	11
Missed due to inaccessibility	2	9	4	2	1
Missed due to ice or floods	0	8	1	0	8
Total Missed (%)	11%	10%	2%	3%	5%

The number of sampling events planned per year varies because of the project start date, and because of changes to monitoring frequency at a sub-set of locations.

Dry streams, typically during summer and fall periods, have been the primary cause of missed samples throughout the routine monitoring program, causing approximately 71 percent of the missed sampling events. Although these planned sampling events were missed, they were the direct result of a lack of water. They do not negatively affect the representativeness of the dataset. Two-thirds of the stations skipped because of dry conditions occurred in JB monitoring locations with smaller contributing drainage areas than the LL stations closer to Falls Lake.

A handful of events have been missed due to temporary limitations to accessibility such as road construction, icy and unsafe streambanks, and vegetation overgrowth. Altogether, these limitations caused approximately 15 percent of the missed sampling events. Finally, weather related causes contributed to the remaining 14 percent of missed sampling events: icy roads from winter storms in February 2015 prevented completion of that month’s sampling at eight locations, flooding in 2016 prevented access to a single location, and eight streams were completely covered with thick ice at their monitoring locations in January 2018.

The UNRBA monitoring database includes comments that describe the reasons for missed samples.

6.1.2 Laboratory Analysis

Extensive efforts are made by the analytical laboratory to complete sample analysis attaining all necessary quality assurance requirements including all applicable sample holding times. Over the course of the monitoring program, four sets of samples needed to be analyzed outside of specified holding times because of equipment malfunctioning (Table 6-2). These results were appropriately qualified in the UNRBA database with the ‘Q2’ flag, indicating that the holding time was exceeded.

Table 6-2. Sample batches analyzed outside of specified sample hold times

Parameter	Samples affected
Nitrate-Nitrite	October 2015
Total Phosphorus	May-June 2016
Total Kjeldahl Nitrogen	June 2016
Ammonia Nitrogen	May 2017

6.2 Accuracy, Precision, and Measurement Uncertainty

All environmental measurements are subject to uncertainty owing to a variety of sources which may include sampling (natural heterogeneity in the ecosystem, environmental conditions), preservation and storage conditions, analytical factors (sample processing, equipment errors, purity of reagents and labware, operator error), and computational factors (selection of calibration model, result truncation, and round off). When properly quantified and documented, measurement uncertainty does not imply that data are unreliable or invalid. In fact, clearly documenting the range of values that could reasonably represent each environmental measurement can improve user confidence in data and allow end users to properly evaluate how well the dataset fulfills their intended purpose.

The UNRBA quality assurance project plan specifies accuracy and precision targets based upon specific project goals as well as limits of analytical capabilities. Because these objectives were specified *a priori*, continued evaluation has been necessary to assess the degree to which these targets have been met and to which they have been achievable with samples collected outside of controlled laboratory conditions. The monitoring program was therefore designed to collect the necessary quality assurance samples to calculate and document the true accuracy and precision of the analytical methods under variable field conditions.

Accuracy can be assessed with field blank samples and laboratory control samples (LCS) of known concentrations. LCS samples are analyzed with each batch of samples to provide verification that the analytical procedure is producing accurate results. To date, there have been no cases of samples where the LCS results associated with UNRBA data were out of compliance with method criteria. Indeed, the QAPP specifies if that were to happen, the issue would need to be corrected and all samples associated with the error would be re-run. Field blank results assess whether a method can adequately distinguish samples with no analyte present from samples with analyte present. Reporting limits are intended to reduce the likelihood of ‘false positives’ (type I errors) in which results are recorded for water quality constituents which are not actually present. Field blank results above the reporting limit may be a sign that the reporting limit is set too low and increases the chances that some field samples are being recorded as having low concentrations which are not in fact present.

Table 6-3 lists all the parameters collected as part of the UNRBA monitoring program along with their associated reporting limits, the number of blank samples collected 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.

Table 6-3. 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 Ortho-Phosphate as P, mg/L	350	-	0	< 0.01	0.01
Total Organic Carbon, mg/L	169	-	0	< 1.0	1.0
Total Ortho-Phosphate 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

TP and ammonia both have more than 5 percent of their field blank results greater than the reporting limit specified in the QAPP. The remaining parameters all have 2 percent or less of blanks exceeding the reporting limit. The blank concentration for which 95 percent of blanks were lower was 0.03 mg/L for TP and 0.04 mg/L for ammonia nitrogen. 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. One means of addressing this issue would be to censor values for which there is not 95 percent confidence that the value is greater than zero. For ammonia, the revised reporting limit would mean that approximately 64 percent of field samples were greater than zero (with 95 percent confidence) while 36 percent of samples were not distinguishable from zero. For TP, 83 percent of samples would have values above the reporting limit, while 17 percent would be deemed indistinguishable from zero.

In addition to field blanks, field duplicates provide data necessary to quantify a large part of measurement uncertainty by pooling a number of potential sources of variation which may vary between samples collected on a single day and analyzed together. Field duplicates do not provide information on error sources arriving from day-to-day variation such as differences in instrument calibration and uncertainty among batches of reagents and standards. However, those factors do not typically form the dominant contribution to the overall uncertainty estimate for a given parameter, but they can be assessed through LCS and matrix spike (MS) recoveries over many separate analytical runs.

Individual pairs of field duplicates are assessed for their consistency with QAPP targets through the calculation of relative percent difference (RPD).

$$RPD = \frac{|C_A - C_B|}{0.5(C_A + C_B)} \times 100$$

where:

- CA = measured concentration of field duplicate A
- CB = measured concentration of field duplicate B

RPD is sensitive to the mean measurement for each pair of field duplicates; when measured values are low, even small differences between the duplicates can cause RPD to be very high. Because of this sensitivity, the RPD it is not applied when measurements are less than five times the laboratory's method detection limit (5x MDL). The RPD targets for each parameter and the number of duplicate pairs with an RPD greater than those targets are shown in Table 6-4.

Table 6-4. Field duplicate precision targets and number of duplicate pairs with RPD greater than the target from August 2014 through October 2018

Parameter	RPD Target %	No. of Pairs	N > Target	% > Target
Dissolved Organic Carbon, mg/L	30	46	0	-
Total Organic Carbon, mg/L	30	165	0	-
Chlorophyll-A, µg/L	30	102	4	4
Total Ortho-Phosphate as P, mg/L	30	102	0	-
Total Phosphorus as P, mg/L	30	200	15	8
Nitrate-Nitrite as N, mg/L	30	201	1	0
Ammonia Nitrogen as N, mg/L	30	196	45	23
Total Kjeldahl Nitrogen as N, mg/L	30	201	10	5
Volatile Suspended Residue, mg/L	30	77	9	12
Total Suspended Residue, mg/L	30	200	28	14
Absorbance at 440nm, /cm	30	101	7	7
UV 254, /cm	30	100	1	1
CBOD5, mg/L	40	46	1	2

RPD values for individual duplicate pairs cannot be specifically associated with any individual measurements other than the duplicate pairs themselves. Pooled over time and repeated samples, however, these duplicate RPD measurements can be used to define the overall precision of the method and the standard deviation of the expected measurement uncertainty.

Where the fraction to the left of the multiplication symbol is simply the average of multiple RPD measurements and d2 is a statistical factor equal to the expected RPD for two independent normally distributed random variables with the same mean and a standard deviation equal to 1. It is often referred to as the control chart constant. For the expected range of two values from such a distribution (as in duplicate samples), d2 is equal to 1.128.

The standard uncertainty is statistically analogous to a standard deviation of a normal distribution and provides an estimate of the precision of repeated measures for each analyte. For all parameters except ammonia, the precision estimate is less than the 30 percent target for each parameter. (Table 6-5).

Applying a coverage factor, k, of 2 produces an expanded uncertainty representing a 95 percent confidence interval--the range of values that a given measurement could represent with 95 percent confidence. Except for ammonia, TP, and total suspended residue, each of the parameters has a 95 percent CI below 30 percent of the measured value. The values provided in Table 6-5 can be applied by data analysts to better understand the level of confidence associated with each data point. As an example of applying this uncertainty, with an Expanded Uncertainty of +/- 9 percent, a reported chlorophyll-a value of 40 µg/L has a 95 percent confidence that the actual chlorophyll-a in that sample fell between 36.4 µg/L and 43.6 µg/L.

Table 6-5. 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 Ortho-Phosphate 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%

For parameters in which the relative uncertainty was sensitive to the measurement range, separate confidence intervals have been calculated for low- and high- values.

Section 7 Conclusions, Recommendations, and Next Steps

The UNRBA's Monitoring Program to support the re-examination has generated a very large, high-quality database including multi-year information on reservoir and tributary water quality, precipitation patterns, lake levels, inflows, outflows, and algal abundance and taxonomy. The UNRBA has also collected, compiled, and analyzed information on nutrient loading, bathymetry, sediment quality and quantity, historic water quality conditions, recreational uses, and other topics related to characterizing water quality conditions in Falls Lake. In addition to providing a broad variety of insights into the status and condition of the reservoir as presented in this report, this information provides a robust foundation for modeling and analytical efforts that are under way now to complete the re-examination process in a sound and defensible manner.

Recommendations and next steps in this process include:

7.1 Continuation of the Transition Monitoring Program

The UNRBA initiated the Transition Monitoring in November 2018 to continue monitoring water quality of selected tributaries to Falls Lake. This scaled-back program provides continuity that will allow the UNRBA to track water quality in the watershed and aid adaptive management of the watershed and the lake. When anomalous conditions occur (like the relatively high in-lake chlorophyll-a concentrations observed in 2017), having water quality data to estimate loading and evaluate patterns of lake response is important to understand the causes. Transition Monitoring can also be used to understand how future weather events (large storms, drought periods) affect loading and lake response. As the regulated community implements the revised nutrient management strategy, having a continuous dataset will assist with program evaluations and modifications in the future. Continuation of the program during the 2020 fiscal year is recommended, but the program should be looked at each year to determine if continuation is appropriate.

In addition to continuing the Transition Monitoring as it is currently being implemented, it is recommended that the UNRBA request that DWR add a tributary monitoring station on Little River. During the design of the Transition Monitoring, one of the UNRBA's LL stations was assumed to be also monitored by DWR. The UNRBA should request that DWR add monitoring of the Little River at Old Oxford Highway to the set of other stations it monitors at the upper end of the Falls Lake reservoir (Latitude: 36.081667, Longitude: -78.854722). This will ensure that each of the largest tributaries delivering water to Falls Lake are monitored.

7.2 Coordination Among Entities

As the UNRBA continues the Modeling and Regulatory Support Project, continued coordination with other entities is important to ensure that all sources of data and information are being considered as the re-examination proceeds. The following interactions are planned:

- The UNRBA Monitoring Team leaders will coordinate with the Modeling Team to ensure they have all raw data and other materials developed through the UNRBA Monitoring Program.
- The UNRBA Monitoring Team members will be available to respond to Modeling Team inquiries about this report, the underlying data, etc.

- The UNRBA should continue to obtain and review results from DWR, City of Durham, and CAAE ongoing monitoring programs.
- The UNRBA is communicating with the UNC Collaboratory regarding potential opportunities for collecting additional data that will support the re-examination and modeling effort.
- The UNRBA will continue to work with NCDEQ regarding appropriate assessment units for Falls Lake that are consistent with the functionality of the lake, the processing of nutrient loads that enter the upper part of the lake, and continued protection of designated uses.

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